

**3D Mineral Spectroscopy of the Earth's Skin  
The 1<sup>st</sup> National Virtual Core Library Symposium**

July 8-9<sup>th</sup> 2010

**A Topical Symposium of the Australian Earth Science  
Convention (AESC-2010)**

National Convention Centre Canberra ACT Australia

**ABSTRACTS**

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## **Hidden Mineral Systems in Our Drill Core Archives - The NVCL Opportunity**

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The establishment of a National Virtual Core Library through the AuScope infrastructure program has positioned Australia's geological surveys at the forefront of unravelling the composition of the top 1km of Australia's crust. The development of the NVCL is unrivalled globally. The visual and spectral information obtained from HyLogger scanning also provides us with a unique opportunity to develop real world, system scale characterisation of mineral systems. This is of paramount importance for state geological surveys which are part of key economic development agencies (e.g., Primary Industries and Resources, South Australia) with a primary aim to provide non rival and non exclusive pre-competitive geoscientific information and data to the minerals industry.

Our core libraries likely house indicators of hidden mineral systems that if understood and unravelled can lead to major new discoveries. However, a significant challenge is to recognise the mineral systems' regional footprint and particularly the outer edges of such systems. The nature of the core library archives is dominantly distal from ore deposits and therefore mineral system footprints will be subtle. Mineral system alteration and geochemical zonation models have been developed at best on the mine to camp scale, and traditionally have only been visualised in schematic plans, cross sections and/or longitudinal sections. With increasing computer hardware and software capacity and data availability deposit scale systems are now being viewed in three-dimensional spatial reality. However, expanding this visualization and data density to the regional scale is an additional challenge. Therefore the vision of utilising the NVCL data in the minerals industry requires mineral systems to be understood at the regional scale in order to recognise the outer footprints, and for the results to be visualised in three dimensions.

The Geological Survey of South Australia is embarking on research programs to address this through international, national and multi-client projects. These include collaboration with the Geological Survey of Saskatchewan to assess the unconformity uranium mineral potential of the Cariewerloo Basin in South Australia, and collaboration with the Deep Exploration Targeting CRC to understand the mineral system scale footprint of iron oxide-copper-gold-uranium deposits in the eastern Gawler. A critical component of these studies is to ground-truth the geological and mineralogical controls on the spectral data and to develop innovative visualisation techniques to display the data.

Operational and logistical challenges are also faced by the geological surveys in terms of people, time, space and finances, resulting in under usage of the HyLogger facilities. Solutions to such issues may come through collaboration with the private sector such as analytical service providers, industry contracts and possibly collaboration with other research organisations.

## Algorithms for fast modelling and interpretation of mixed mineral spectra

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The generation of large volumes of mineral reflectance spectra by HyLogging™ and other spectroscopic measurement systems has led us to develop fast algorithms and software for “unmixing” large volumes of such data. The software is called The Spectral Assistant (TSA™), and it is embedded inside another CSIRO commercial package, called The Spectral Geologist (TSG™). For historical reasons, there are in fact two versions of TSA, one for spectra measured at visible and near infrared wavelengths (VNIR), and one covering shortwave infrared (SWIR) wavelengths. A third version, covering thermal infrared (TIR) wavelengths, is under development.

All three unmixing algorithms are based on the following: (i) three libraries of spectra of “pure” materials (mostly minerals), with several replicates of each material, so that we can estimate their within-class variabilities; (ii) a linear mixture model which not only includes the library materials but also functions representing the (lower frequency) background; (iii) the use of a suitable Mahalanobis (as opposed to a Euclidean) distance as a goodness-of-fit measure; and (iv) fast subset selection procedures. To illustrate the importance of component (iv), consider our SWIR library, which consists of 60 materials. On occasion, expert spectral geologists can observe 4 materials in a SWIR spectrum, although mixtures of smaller numbers of materials are more common. The number of possible combinations of 1, 2, 3 and 4 materials out of 60 is 60, 1770, 34720 and 487365 respectively! A typical HyLogger data set will contain tens to hundreds of thousands of spectra. So fast subset selection is a very important issue.

The SWIR version of our software (the most developed and most widely used) will be illustrated using a number of examples. We will highlight some shortcomings of the current unmixing algorithm, especially when trying to identify 3<sup>rd</sup> or 4<sup>th</sup> components in a mixture, whose contribution to the variability of the spectrum is usually small. These shortcomings are in turn mainly due to inadequacies in both the deterministic and statistical components of the underlying mixing model. There are 5 major issues which we are currently addressing: (i) different levels of noise at different wavelengths and from different instruments; (ii) inadequacies in the model for the background; (iii) how to model the position of particular absorption features (e.g. the 2200 nm White Mica feature) which can change **continuously** using mineral classes where the relevant features have **discrete** locations; (iv) small **non-linearities** in the mixing, which are apparent in relative depths of important features which are not predicted by a linear mixture model; (v) different variabilities within different classes (the Mahalanobis distance measure implicitly assumes that these are all equal). Improving our model to deal with these issues, and ensuring that the associated algorithm still finds the best fitting subsets quickly is a major challenge. We will illustrate some progress that we have made on some of these issues using the examples.

## **Mineral Spectroscopy: Surprises and Lessons Learned from Exploration of the Earth and Planets**

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Imaging spectrometers acquire data with enough spectral range, resolution, and sampling at every pixel in a raster image so that individual absorption features can be identified and spatially mapped. Furthermore, with such sampling, the information in the spectral data is inherently self-verifying, in many cases using known information in the remote scene. This verification allows refinement and monitoring of spectral wavelength calibration (e.g., using known absorptions) as well as surface reflectance (e.g., spikes and offsets are "non-physical") and the discovery of new conditions and compounds. Imaging spectrometers are being used to map minerals, amorphous materials, man-made materials (on the Earth), and to measure solids, liquids, and gases on the Earth and throughout the Solar System, sometimes with great surprises.

Interpretation of spectroscopic data of solar system solid surfaces remains a challenge. Presently, we have no theoretical models that can generate spectra of molecular solids, and the radiative transfer models currently in use have deficiencies. While modeling is important for understanding compositional details, those models must employ basic spectroscopic data derived from laboratory measurements. Because there are tens of thousands of compounds, many having complex elemental substitutions into lattices causing shifting of absorption band positions, combined with temperature and pressure effects, radiation damage/modification, and grain size effects, decades of laboratory research have only scratched the surface of what is needed to rapidly interpret exotic planetary surfaces.

New absorption features and spectral effects have been discovered in planetary data for which there were no known compounds that match, thus driving the need for expansion of spectral databases as well as models. Some laboratory data only exists in one wavelength region (e.g., mid-infrared transmittance), when the preponderance of remotely-sensed spectra of solar system ices are from the UV to near infrared (reflected solar radiation wavelength range, ~0.1 to ~5 microns).

The last few years have been an amazing period for science with visible to near-infrared imaging spectrometers in orbit around the Moon, Mars, and Saturn, in aircraft flying around the Earth, and now instruments examining cores from within the earth. These and other instruments have returned a wealth of new imaging spectroscopy data that has resulted in many new discoveries. Among those discoveries are the roles of water, both adsorbed and as ice, and nano-sized particles of metallic iron and iron oxides.

Spectroscopy is playing a key role in the identification of nanoparticles and the signatures of Rayleigh scattering and Rayleigh absorption. These processes are observed in the laboratory, on surfaces throughout the solar system, and on the Earth. The interplay of Rayleigh absorption and Rayleigh scattering creates a variety of colors observed on planetary surfaces, ranging from dark red to light blue. Nanoparticles are pervasive on the Earth and nanophase iron oxides make up many of the colors we see in rocks and soils. Native Americans used nanophase iron oxides as pigments in their rock art and spectroscopy has been used to characterize those pigments.

The talk will review some of the findings, including the discovery of widespread water in the sunlit lunar surface, the role of nanoparticles in the Saturn system on the icy satellites and in the rings, and water and hydroxyl-bearing minerals on Mars. Water is now found on all these bodies, adsorbed on the Moon, both adsorbed and as ice on Mars, and as ice in the Saturn system. Many of these discoveries have only been possible with UV to near-infrared spectroscopy and the spectral signatures that did not fit a classical view. Examples will include surprises such as the penetration of the haze layers of Saturn's moon Titan with near-infrared spectroscopy to map organic compounds on the surface and the technology transfer to map thick oil in an oil spill in the ocean. All these discoveries and applications point to near-infrared spectroscopy as an amazing and diverse tool.

## **Application of SWIR spectral techniques to the Hellyer/Fossey/Que River and Mt Charter footwall alteration systems, western Tasmania.**

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The Hellyer – Mt Charter area in the Mt Read Volcanics belt, western Tasmania, has produced in excess of +20Mt of high grade base metal mineralisation with grades in excess of 13% Zn, 7% Pb, 0.4% Cu, 170 ppm Ag and 2.6 g/t Au. The production to date has come from the Hellyer (17Mt) and the Que River (3.3Mt) deposits with production commencing from the Fossey deposit later in 2010 (0.9Mt). The Fossey deposit was discovered by Bass Metals in 2007. Unexploited gold mineralisation associated with barite occurs at Mt Charter (6.6Mt) and at Fossey (1.5Mt) with moderate Au (+1.2 g/t) and Ag (36g/t) grades.

These four deposits are all examples of volcanogenic massive sulphide (VMS) mineralisation. The deposits are all hosted within the Que – Hellyer Volcanics a dominantly mafic/intermediate stratigraphic package near the top of the Mt Read Volcanics and formed essentially contemporaneously. The deposits overlie a large broadly contiguous footwall alteration zone.

Bass Metals exploration strategy has been to fingerprint the footwall alteration around the known deposits using SWIR and multi element geochemistry. This characterises the alteration around the known deposits and allows determination of proximity indicators for to focus follow up drilling. A total of 66,270 SWIR using a Terraspec ASD and 3,451 multi-element geochemical samples were collected from 186 drill holes.

The hydrous phases in the footwall alteration are predominantly sericite with minor chlorite. The other ubiquitous alteration phase is silica. The sericite and chlorite is zoned around each deposit with long wavelength phengite and short wavelength chlorite occurring in the direct footwall to the mineralisation and becoming shorter wavelength muscovite and longer wavelength chlorite both laterally and at depth away from the deposits. These alteration mineralogies are interpreted to reflect near neutral conditions of deposition around the deposits and becoming more acidic away from the deposits, the exact opposite to what was originally predicted.

The interpretation of these results is still ongoing however preliminary interpretation are that hot reduced acidic metal bearing fluid (muscovite forming) are generated at depth and travel along fractures toward the sea floor. In zones of high permeability and high hydrothermal fluid flux ingress of modified seawater mixes with this hydrothermal fluid – neutralising the metal bearing fluid and forming phengite, but not depositing the metals. Metal deposition occurs at or near the sea floor due to oxidation and rapid temperature reduction and forms the deposits. In areas of lower permeability and probable lesser hydrothermal fluid flux the hydrothermal fluid does not interact with seawater until at or near the sea floor and subsequently continue forming muscovite.

## Joint Interpretation of SWIR and TIR HyLogging Data

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The next generation of HyLogging instruments will soon be producing large volumes of high resolution, low noise spectra measured from 0.4  $\mu$ m to 14  $\mu$ m. This data will offer exciting opportunities for recognition of quartz, feldspars, pyroxenes, olivines, garnets and other minerals not seen by earlier instruments. The availability of TIR data will also enable much more reliable interpretation of carbonates in some mixtures that are currently difficult using SWIR information alone.

However the physics of reflection, and consequently the interpretation of TIR data, is different to that at shorter wavelengths. In some ways the process is simpler, in others more complex. In the shortwave infrared, features appear because light is only absorbed at diagnostic wavelengths as it is scattered around *inside* the crystals close to the surface. In the thermal infrared there is *only* scattering *from* the surface, and only at wavelengths where the mineral has a diagnostic response. This means that responses from the two regions may produce unexpected results for a given mineral or mixture.

Analysis of a number of drill holes with joint SWIR/TIR data sets has revealed enough of these surprises to convince us that automatic interpretation will have to cope with much wider variability in the reflectance properties of minerals than we have become accustomed to working with SWIR data alone. In moving to the TIR we expected to encounter greater variability in spectral signatures due to variability in crystal orientation, solid solution chemistry, polymorphism and surface condition, and we have indeed found variability. However in most situations it is difficult to identify its source and, in these early stages, we must cope through a combination of manual interpretation and unmixing using carefully tailored libraries of reference reflectance curves.

Nevertheless, once the library has been optimised, automatic unmixing procedures on the TIR data alone can produce sensible mineral assemblages of up to four minerals. These results can be further optimised using the SWIR data in two ways. Firstly by forcing minerals into the TIR mix when they are obvious in the SWIR data and secondly by rejecting certain mixtures suggested by the TIR analysis when it is clear, from the SWIR data, that these minerals are not present. The converse process can also be used to improve the SWIR interpretation. This is most effective for the carbonates that are distinctive in the TIR but more difficult to interpret in the SWIR when present in mixtures.

This paper will discuss the major differences between interpretation in the SWIR and the TIR and will review the manual and automatic interpretation results from a number of drill holes where both types of data are available.

## Mineralogical Validation of the AuScope NVCL

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The AuScope National Virtual Core Library (NVCL) is being built from nodes in each Australian State and Territory Geological Survey using voluminous mineral spectroscopy of hundreds of thousands of metres of legacy cores. The mineral spectroscopy is undertaken using hardware and software HyLogging™ technologies and the results, in the form of logs and images, are being databased and intended for Web publication. Three critical steps underpin the collection and utilisation of these data: calibration, validation and explanation. The outcomes of these three steps bear importantly on the confidence and benefits that can be ascribed to the outputs and, ultimately, to the downstream utilisation of the geological knowledge contained in the logs and databases by the wider earth science community.

Calibration ensures that the spectroscopy is conducted according to comparable and traceable standards and is provided as part of routine measurement processes. Validation is the process whereby the spectroscopically-estimated mineralogy is confirmed by a series of independent processes on representative sub-samples. These two steps are critical to having the confidence to go to the third stage. Explanation is the final step that ascribes interpretation and meaning to the observed mineralogical results in terms of geological processes, paragenesis and potential benefit to some branch of the earth sciences, and commonly utilises integration with other geological observations and measurements. This paper concerns itself with the second of these steps based on experiences gained so far from operation of the NVCL.

In the day-to-day research and building of the NVCL validation has multiple purposes. It is not only about confirming that mineral x really does occur at location y, but does so with some probability, and that estimates of the proportions of minerals in an assemblage are more or less correct in some relative or absolute sense. Results of this then not only feed into downstream use but backwards to improvements in the measurement technology and algorithms and software that provide these estimates.

Armed with the broad brush spectroscopic and mineralogic domains spatially evident in HyLogged drill holes we have used various techniques to validate the outputs. These have included so far, replicate measurements, thin section petrography, x-ray diffraction, SEM, electron microprobe and multi-element geochemical measurements. These have been focussed mainly on confirming the mineralogy of spatially coherent domains and also on specific mineral samples where often something unexpected has become evident. Examples are given below. Multiple validation techniques are often needed as not all methods are truly reliable for all cases; e.g. separation of some clay species by XRD is often also difficult and infrared spectroscopy may in fact be the better method.

The potential to map stratigraphically-significant enstatite distribution in high-grade, complexly folded gneiss at the Challenger gold mine, South Australia, was an unexpected find using the HyLogger. A recurring and distinctive spectrum, not present in the TSA training library, was confirmed by petrographic investigation to the presence of the orthopyroxene.

Petrology, microprobe and SEM have been used to validate the HyLogging of alteration minerals associated with IOCG-style mineralisation in Emmie Bluff drillhole, SAE6. A distinct spectral response for dickite and illite, noted in the cover sequence of Pandurra Formation sandstone, was confirmed by XRD and SEM. With calibration, the paragenetic

sequence of kaolinite / dickite / and variously crystalline illite / white mica, reflecting depth of sandstone burial, could be reliably mapped using the NVCL HyLogger.

## **The Diversity of Imaging Spectroscopy Science and Application Objectives Pursued with the NASA Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS)**

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The NASA Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS) was the first imaging spectrometer to measure the full solar reflected spectrum from 400 to 2500 nm. AVIRIS first flew in 1986 and has measured imaging spectrometer data sets in every year since. Many important lessons have been learned. Since 1986 every key subsystem of AVIRIS has been upgraded to support 21<sup>st</sup> century science measurement performance. Most recently AVIRIS has been used in the response effort to the U.S. Gulf of Mexico oil spill in May 2010. In this case AVIRIS measured the carbon to hydrogen bond absorption in the oil on the water to map occurrence and assess concentration. AVIRIS imaging spectroscopy measurement have been used for geology and a wide range of other science and application objectives. Currently there are over 600 refereed journal articles that reference AVIRIS in the title or abstract. In this paper an overview is given of the diversity of AVIRIS results spanning: the atmosphere, ecology and terrestrial vegetation, geology and soils, coastal and inland waters, snow and ice hydrology: fires, environmental hazards, calibration, modeling, algorithm advancement, human infrastructure and others. In the past decade, based upon AVIRIS results, it has become clear that a spaceborne global mapping imaging spectrometer is required to understand and constrain critical elements of climate change. Finally, NASA has recently begun development of the Next Generation Airborne Visible/InfraRed Imaging Spectrometer (AVIRISng). AVIRISng will exceed the spectral, radiometric and spatial measurement capabilities of AVIRIS-classic and support existing and new science and application objectives. The science measurement characteristics of AVIRISng and development status are presented.

## **Quantification of HyLogging data for the development of a 3D physicochemical model of channel iron ore**

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Hyperspectral data have been collected from drill cores through the Murchison Metals' owned channel iron deposit of the Rocklea Dome – Hamersley basin. Spectra from visible to short-wave infrared light (e.g. 380 to 2500 nm) were taken for 14 RD and ~ 150 RC cores at a 1 cm and at a 1 m resolution respectively. Mineral abundances and compositions have been extracted from these hyperspectral data with publicly-available 'batch-type' scripts, using 'The Spectral Geologist – TSG™' software. Minerals of interest included: Fe-oxides and their subtypes (hematite, vitreous goethite and ochreous goethite), clays (kaolin group minerals and Al-smectite) and carbonates (calcite, dolomite and magnesite). The abundance of these minerals was estimated by calculating the depth of absorption features that are the result of specific atomic bonds within these minerals. The Fe-O bond in Fe-oxides has for example a typical absorption feature around 900 nm and the depth of this feature is related to the abundance. The composition of the Fe-oxides is function of the position of this feature, e.g. when the absorption feature has its minimum below 900 nm, the sample tends to contain more hematite, while a position towards 920 nm and higher indicates more goethite. A similar reasoning has been used to extract information about the abundance and composition of clay minerals and carbonates

The accuracy of these abundance and composition scripts depends at least on two factors: (1) the measurement accuracy and (2) the script accuracy. (1) The measurement accuracy was estimated from daily repeated hyperspectral measurements of the same set of 'test-rocks' that included Fe-oxides, clays and carbonates over a period of 7 months. For example, the measurement accuracy of Fe-oxide amounted to 0.01D (2\*Stdev), meaning that the depth of the ~ 900 nm absorption feature varied with no more than 0.01 from the average over that 7 month period for 95 % of the data. The Fe-oxide composition shows a measurement accuracy of 0.9 nm (2\*Stdev) over the same period. Similar accuracy estimations have been done for all other minerals of interest. (2) The script accuracy could be estimated by comparing hyperspectral mineral results with 1 m chemical assays from the RC cores. Approximately 5000 samples from these RC cores have been hyperspectrally scanned and assayed, providing a first, large and publicly available quantification dataset. The basic Fe-oxide script shows a broad correlation with the Fe % assays (RMSE = 11.3 %). However, transformation of the data using a function based on the amount of bound water improves the correlation between the hyperspectrally determined Fe-oxide abundance and chemical assays to 8.6 % RMSE. The combined error from the measurement and script accuracy estimations for Fe-oxides is 9 %.

The hyperspectral mineral abundance and composition data were introduced in a 3D environment in which they show large spatial correlation, although a low combined accuracy was calculated. In this environment the hyperspectral data were further evaluated in 3D with the chemical assays and both show a very similar spatial distribution, with the big advantage for hyperspectral data being that it shows volumes of minerals, opposite to assays which just show gradients in geochemical abundances that for example do not allow easy differentiation of iron ore subtypes, e.g. vitreous goethite versus ochreous goethite. The mineral mapping data also reveal patterns in the clay and carbonate mineralogy not apparent in the geochemical data, which provide insights into the genesis and exploration vectors for CIDs.

In conclusion, hyperspectral analysis will not replace precision, laboratory chemical assays for basic ore grade patterns, such as bulk Fe content. In contrast, its value is found in its potential to rapidly provide voluminous sample data for a range of important ore attributes that allow better characterisation of the physicochemical architecture of 3D ore systems.

## **A 3D model of a Supergene Gold Deposit derived from spectrally derived mineralogy**

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This paper describes a 3D mineralogical model of a supergene gold deposit. Within this deposit, two distinct sub-horizontal gold enrichment layers are clearly apparent. However in detail the gold does not form flat horizontal sheets. The way in which intercepts could be joined from drill hole to drill hole was ambiguous and this had a significant impact on the resource modeling for the deposit. The resource geologist commissioned a spectral mapping study to see if it could improve confidence in the way the mineralized intercepts were correlated from hole to hole. Most of the drilling is RC, with a small percentage of diamond drill core. The spectra were measured with an ASD Terra Spec instrument. There is 12,000 meters of drilling. One spectrum was measured on every meter of core or chips.

The deposit is hosted within an Archaean pillow basalt sequence. The basalts are intruded by numerous narrow diorite porphyries. There is a steep south-east dipping Archaean unconformity, with the basalts overlain by sandstone and siltstone. There is a flat lying Tertiary unconformity, with transported sediments overlying oxidized Archaean bedrock.

If the wavelength of the 2200nm feature in kaolinite-bearing samples is plotted against the width of the feature and a kaolinite crystallinity index, then three very distinct kaolinite types are apparent. These are kaolinite in the transported sediment, kaolinite in weathered basalt, and kaolinite in Archaean sediments. There is a layer of supergene alunite formed at the Tertiary unconformity, so the alunite plus kaolinite type was used to model the Tertiary unconformity. The chlorite-sericite altered Archaean sandstone is surprisingly difficult to distinguish from altered basalts in RC chips. The picks of the Archaean unconformity in the diamond drilling combined with the boundary in kaolinite types in the oxide zone was used to model the Archaean unconformity.

Within the weathering profile, there is a surprisingly sharp transition from goethite-kaolinite to fresh chlorite-sericite. This was modeled as the base of weathering. This surface has a distinct linear depression that runs parallel to the trend of gold distribution.

Higher in the weathering profile, there is a boundary between a very pervasive hematite blanket and pervasive goethite. This boundary was modeled, and it also showed a linear depression that was slightly offset from the depression in the base of weathering. Between the two depressions in the weathering fronts, there is a planar but somewhat patchy distribution of hematite within the goethite zone. These patterns in the weathering minerals are clearly mapping a fault. A fault surface was modeled that joined the dip in the hematite-goethite boundary, ran down the hematite zone, and ran along the dip in the base of weathering. This defines a fault plane dipping about 60 degrees to the south east. This plane runs sub parallel to the Archaean unconformity, but is around 50 meters back into the basalts.

Within the fresh basalts, there are two very distinct groups in the chlorite compositions. The distinction is based on either the wavelength at 2250nm or the wavelength at 2340nm. This maps the boundary between an Fe-tholeiite and an Mg-tholeiite.

All of this information together provided a geological framework within which to examine the distribution of gold. The controls on the gold distribution are  
the Archaean fault,  
supergene enrichment of gold in the transitional weathering zone  
supergene enrichment of gold at a palaeo-water table  
a high grade supergene pod at the intersection of the fault with the contact between the two basalts.

The gold does not sit right on the fault, but rather as the water table has dropped, the gold descended vertically, and now sits on the footwall of the SE-dipping fault. Leapfrog was used to model the grade distribution. Leapfrog creates 3D grade contours. Rather than interpolating the grade in an isotropic manner, search directions with a variable degree of bias can be applied. Leapfrog can apply a grade distribution skew biased along multiple surface orientations simultaneously. The grade shells in this model were biased to follow the base of weathering surface and the fault plane at the same time.

This project took 12 days to measure the spectra and 3 days to interpret the spectra and build the model. The data was interpreted and modeled using a combination of TSG, ioGAS and Leapfrog. This has produced a much more robust geological model and improved confidence in grade modeling and continuity.

## **Characterisation of Canning Basin petroleum core and Gascoyne Province molybdenum prospect core – cases studies from GSWA's NVCL HyLogging**

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The application of HyLogger technology for mineral and petroleum exploration is illustrated using data from four wells (2 800 m petroleum core) from the Canning Basin and 9 holes (1 500 m mineral core) from the Minnie Springs molybdenum prospect in the Gascoyne Province.

The HyLogging results for petroleum core highlight lithological boundaries, and provide additional information on the distribution of smectites and recrystallised dolomite that can be related to changes in porosity and permeability. 3D modelling demonstrates spatial correlations between lithological units and tectonic dislocations along the basin subdivisions. Spectral results are consistent with XRD and petrographic analysis, as well as Neutron, Gamma-Ray, Delta-T and density data.

HyLogging data from drillcore at the Minnie Spring molybdenum prospect indicate two alteration assemblages that are spatially associated with disseminated molybdenite and quartz-pyrite-molybdenite veins. A phengite-chlorite-epidote assemblage reflects low temperature Fe-Mg-bearing alteration related to shear zone formation, and overprints an earlier stage of higher temperature and more acidic quartz-muscovite formation. HyLogging data have been confirmed by SEM-EDX, TIR-Logger and XRD analysis.

## Applications of Near Infrared Core Imaging

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Near infrared imaging of drillcore continues to develop as an exciting technology providing significant additional value to traditional core logging. The data provides rapid *in-situ* non-destructive mineral evaluation and captures mineral habits and associations through the imagery. This technology provides similar information to that captured by a Geologist while visually logging core. It records mineralogy and the context in which these minerals occur, which is information that the Geologists assimilate and interpret using their experience and expertise. Core imaging does not replace the geologist in logging core, but rather provides much needed tools to allow objective correlations, domaining, and zonation of rock units uniformly across the project area.

The concept of core imaging has developed from early proof of concept studies (Kowalik *et al.*, 1991, Kruse, 1996, and Linton *et al.*, 2004), through the development of specific prototype systems (Harris *et al.*, 2006), to the practical demonstration of large scale, and volume, core imaging campaigns (Linton *et al.*, 2009). Significant instrument and core imaging system advances have begun to make core imaging a practical option. Systems that are now being offered provide coverage across the near infrared, including the visible-near infrared (VNIR 450nm-1000nm) and the shortwave infrared (SWIR 1000nm-2500nm).

The capture of data from many geological projects suggests multiple applications for core imaging. Primarily the data provides a method for geological characterisation of the drillcore through the recording of an objective, digital and analytical log. The mineralogical patterns provide key information that assists in the understanding of the geology. These patterns can help characterise the ore body, or define vectors to economic mineralisation. Alteration and mineral facies mapping can aid in ore zone delineation and, in cases where correlations to grade are defined, can be used in grade control. Detailed imagery provides information that can be used for correlation of stratigraphic units or geozones. Minerals, and their habit, provide a direct link to the physical properties of the rock and can be used in geometallurgy where knowledge of the rock behaviour is required. Continued core image data acquisition, processing, and interpretation are leading to more applications being recognised. This will permit better management of our mineral resources.

Core imaging is, however, not without its challenges. Instrumentation requires development and automation in a robust fashion that can survive under extreme operational conditions. A significant challenge to instrument developers is the requirement for detection across greater wavelength ranges. The demand for more wavelength range coverage, and higher spatial resolution raises the significant challenge of data handling. These systems require automated data processing and mineral identification solutions. Textural information needs to be combined with the mineralogical data and extracted in a usable fashion for the Geologists. The Geologist, who is the end user of the data, has to be able to visualise and integrate these datasets into the geological model. This is where the most value is derived from the data. Notwithstanding these challenges there is massive value to be obtained out of core imaging and we are on the path of an exciting journey through these technological developments.

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## **The AuScope National Virtual Core Library – Establishment and Achievements**

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The AuScope NVCL was established to facilitate wide ranging earth science research into the mineralogy and composition of the top two kilometres of the Australian continent, using the millions of metres of core stored in State and Territory Geological Survey and company core libraries. Traditionally these libraries are physically visited by a small number of geologists wishing to compare and understand the characteristics of mineral deposits sampled over the last 50 years during past exploration programs and now deposited with the Surveys for public use. In addition, cores drilled through public stratigraphic programs, oil and gas exploration, and basin analysis programs are also stored. Such visits are based primarily on visual, experiential and subjective analysis and often require expensive travel to the distributed core libraries.

The AuScope NVCL component's goal is to radically improve the ease, user experience and knowledge derived from these past drill core holdings, plus future drilling, to contribute to the other AuScope objective, a more robust and objective four-dimensional earth model of the Australian continent.

Using a new generation of Australian-developed hyperspectral logging technology, CSIRO's HyLogging™ Systems, each State and Territory Geological Survey has been equipped to mineralogically log and image as much of their archived core as possible, to interpret the contained mineralogy, and to database the outputs so they can be interrogated and published via the Internet, in a consistent and standard manner.

Phase 1 of the project involved CSIRO designing and constructing seven HyLogger-2 generation instruments. This phase utilised investment from the Federal Government's NCRIS program and the CSIRO. Phase 2 involves each Geological Survey hiring or assigning staff to operate these instruments in each jurisdiction's core libraries, and interpreting the spectral results using TSG-Core software developed by the CSIRO. This part of the project involves substantial ongoing investment by each Geological Survey. Phase 3 comprises the building of a series of distributed relationship databases and their associated infrastructure in each jurisdiction. These databases are built by synchronisation with the TSG-Core processing software. Using web services technology (Phase 4) these databases are then able to be interrogated by users anywhere in the world and the logged data and images visualised, explored and partially downloaded from the Internet, or delivered by disk on request. Phase 4 is being developed in partnership with the AuScope Grid component. Every one of these Phases poses significant new territory and challenges across a number of quite different disciplines.

At this time six Geological Surveys have operational NVCL nodes based in each capital city, namely Brisbane, Sydney, Hobart, Adelaide, Perth and Darwin. The Melbourne node will be established in late 2010. After training phases, involved with establishing procedures and protocols for standardised logging, the geological survey teams are now logging several hundreds of metres per day. Issues that have arisen at this stage include manpower and scheduling derived from moving large amounts of core around day-in, day-out, plus dealing with sometimes very old and severely degraded cores. Notwithstanding these set-up challenges over 100,000 metres of cores from hundreds of drill holes have been logged and new mineralogical findings documented. The difficulties involved in consistently interpreting geology, as well as host rock, metamorphic and alteration mineralogy, by conventional visual means, is gradually being replaced by the more objective HyLogging strategy and is producing long lasting digital records that will be available for generations to come. Many examples will be given in the paper.

In several States and Territories new collaborative, publically-assisted drilling programs are also providing new, up-to-the-minute cores that are now required to be logged, thus keeping the NVCL potentially fresh and relevant.

Once the cores are logged a validation phase is also commonly undertaken to clarify, on selected subsamples, the mineralogy evident in the HyLogged cores. This is being conducted using a variety of supporting analytical techniques such as XRD, SEM, electron microprobe, thin section petrography, etc., and is an important part of confirming and justifying confidence in the NVCL.

The logging priorities in each State/Territory are defined by the AuScope Geotransects program and with the intent to cover the nation's "classic" ore deposit types and stratigraphic sequences. The NVCL logging infrastructure is also available by arrangement for students, individual researchers and research consortia, (e.g. AMIRA, MERIWA, CRCs, etc.), as well as industry. Discount rates are available to researchers.

The NVCL goes far beyond logging alteration mineralogy. Mineralogical and lithological characterisation can be used in many other pursuits, for example, in oil and gas exploration and formation characterisation, for basin analysis, for geothermal research, for geometallurgical characterisation, for studies on the carbon sequestration characteristics of subsurface formations, indeed anywhere where an improved and objective understanding to the geology and past geological processes, and "stratigraphic" correlation is required.

The AuScope NVCL offers an unprecedented collaboration between Federal and State agencies, CSIRO and industry, and in time for every earth scientist who wishes to augment their research by using the sensing, data or knowledge infrastructure. Please find out more by visiting <http://www.auscope.org.au/content.php/category/id/15> .

## **C3DMM - Building a seamless 3D mineral map of the Australian continent**

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Mineralogy is a (the) fundamental key for understanding mineral systems and the exploration of economic deposits. The measurement of mineralogy allows us to map lithologies and superimposed alteration. In contrast, traditional laboratory-based geochemical techniques provide multi-, trace element and isotopic composition of samples, allowing the interpretation of metasomatic processes and related fluid/rock physicochemistries at the time of ore formation. New technologies like portable XRF geochemistry will bring this discipline, albeit for a limited range of elements, into the field making geochemical data rapidly available to geologists. At the same time, geophysics remains an important tool for delivering valuable, relatively large “rock-volume” information (up to kilometres depth) from which the geological architecture can be gauged. The various geophysical applications can be used in borehole, surface and remote sensing situations and have proved valuable for both green- and brownfields exploration. However, all of these traditional tools for exploration do not provide direct measurement of a wide range of minerals.

Visible through to thermal infrared spectroscopy from drill core to satellite systems is a technology that can provide this mineralogy. Mineral spectroscopy allows measurement of not just the abundance, but also the physiochemistry of specific minerals. Furthermore it's a non-destructive method, saving for example drill core samples for potentially later analyses.

The Western Australian Centre of Excellence for 3D Mineral Mapping was established in March 2009 to develop capabilities that efficiently deliver seamless, accurate, traceable (with error estimation) 3D mineralogy generated from available surface and subsurface visible and infrared spectroscopy data. The challenges in achieving the vision of a 3D mineral map of Australia include:

- Securing access to hyperspectral data (spatially and temporally);
- Processing large volumes of hyperspectral data;
- Reduction of the hyperspectral data to calibrated, traceable units (e.g. reflectance);
- Accurate extraction of the required geoscience information products from the reduced hyperspectral data;
- Traceable error assessment of the derived geoscience information products (standards); and
- Development of information systems that can efficiently deliver these geoscience products to sufficiently informed (technology transfer) decision makers.

Based at the Australian Resources Research Centre in Perth, the multi-disciplinary C3DMM team and the associated researchers in CSIRO enable us to draw the bow from km-scale to microscopic research and provide geoscience information for a range of user needs. To demonstrate the successful development of its capabilities, C3DMM is preparing at least two public geoscience case histories. One of these is the Rocklea Dome Channel Iron Deposit, which is using diamond and RC drill chip core measurements from the ANVCL (<http://nvcl.csiro.au>) and CSIRO's Hyloggers™ commercially accessible in Perth (AMMTEC and AMDEL laboratories) as well as airborne hyperspectral AMS imagery and drill core geochemical data to build a validated 3D mineral/chemical model of the CID system and its environment. This work is revealing differentiation of iron ore subtypes (vitreous versus ochreous goethite) and patterns of kaolin, Al-smectites and carbonates that provide insights into the evolution of the CID and possibly provide new vectors for exploration. Archaean Au and iron oxide Cu-Au case histories are also being assembled. These deposit/prospect scale studies are coupled with regional mapping of surface composition using geoscience-tuned remote sensing systems, such as airborne HyMap and satellite ASTER and hyperspectral sensor data. The C3DMM is working with geosurveys across Australia as well as international satellite development organisations to capture the opportunity for continent-scale land surface composition mapping. For example, C3DMM in collaboration with Geoscience Australia and Primary Industry and Resources of South Australia have just publicly released a 110 scene ASTER geoscience mosaic of the Gawler-Curnamona region (<http://c3dmm.csiro.au>).

## **Comparisons between the Canadian Athabasca and South Australian Cariewerloo Basins: HyLogging Insights into Unconformity Related Uranium.**

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The Athabasca Basin, Saskatchewan, Canada hosts the world's largest high-grade unconformity-style uranium deposit with the McArthur River deposit containing 192,085 t of Uranium within ore that grades up to 22.28% (Jefferson and Delaney, 2007). The basin covers an area of about 100, 000 sq km and the thickness of the basin sediments reaches 1500 m. The relatively flat lying and unmetamorphosed Athabasca Sandstone group of the Athabasca Basin overlies highly metamorphosed Archaean to Paleoproterozoic granitoid and gneiss basement which hosts a graphitic metapelite susceptible to fault reactivation and subsequent uranium deposition. Uranium deposits do not solely occur as veins within the highly metamorphosed basement but also as lenses within the sandstone at the unconformity (Jefferson et al., 2007).

Many of the key ingredients present within the Athabasca Basin mineral system are also present within the Cariewerloo Basin, South Australia and given the almost ubiquitous elevated uranium content of the underlying crystalline basement, it has significant potential for unconformity style uranium deposits. The Cariewerloo Basin is defined by the extents of the Mesoproterozoic Pandurra formation, a thick, monotonous unit of flat lying, unmetamorphosed arenaceous sediments (Cowley, 1991). It is overlain by Neoproterozoic sediments and associated units of the Stuart Shelf. Basement underlying the Pandurra Formation consists of Mesoproterozoic uraniumiferous Hiltaba Suite granites and comagmatic Gawler Range Volcanics, as well as Palaeoproterozoic gneissic granite and metasediments. Overlying the Pandurra, the following upwards sequence can be expected: Tapley Hill Formation (a grey carbonaceous shale intercalated with carbonate); Whyalla Sandstone (a friable, coarse, red bed, sandstone); Tregolana Shale (a fissile red shale member).

In order to delineate the location of possible controls on uranium mineralisation, a 3D model of the Cariewerloo Basin is being constructed using geological cross sections, geophysical modelling, airborne electromagnetic survey data, sequence stratigraphy from visual logging, structural measurements, seismic profiles and portable XRF (Niton) analyses. To differentiate subtle variations between primary stratigraphy and secondary alteration within the Pandurra formation, mineralogy gained using the AuScope NVCL HyLogger-2<sup>TM</sup> is being used as a fundamental input data set in constructing the model.

The HyLogger-2 automated spectroscopic core scanner was used to analyse some 32 diamond drill holes from within the Cariewerloo Basin, 15 of which intercepted the lower unconformity. The HyLogger captures reflected light spectra in the VNIR and SWIR region of the electromagnetic spectrum (380-2500nm) at 1cm intervals which it uses to establish semi-quantitative mineralogy. Concurrent with spectra collection, the HyLogger captures imagery of the core at 0.1mm resolution and laser profilometer data in order to characterise the surface of the drill core. These physical measurements along with powerful processing provided by the associated software, The Spectral Geologist (TSG Core<sup>TM</sup>), provides the opportunity for the development of an unconformity-style uranium alteration model for the Pandurra Formation.

The mineralogy of the sequence under consideration includes pervasive muscovite throughout, dickite in the upper Pandurra, paragonite, illite, phengite and montmorillonite. Siderite and highly crystalline kaolinite also form a significant component of the system. One drill hole had a significant portion of pyrophyllite. Fe- and Mg-chlorites characterise basement units.

At the unconformity interface, montmorillonite is often present perhaps formed as part of a palaeo-weathering surface. The presence of preserved regolith may be an important parameter for uranium mineralisation. Phengite occurs at the base of the formation moving upwards into muscovite dominated mineralogy. Dickite occurs above the muscovite in the drill hole, sometimes with highly crystalline kaolinite in the middle of the dickite. Dickite-bearing Pandurra gives way to a basal dolomite of the Tapley Hill Formation. At the top of the Tapley Hill Formation is another dolomite member on which the Whyalla Sandstone was deposited. At the base of the Whyalla Sandstone phengite sometimes occurs. If the Tapley Hill Formation is absent dickite occurs both sides of the stratigraphic boundary between the two red bed sandstones.

Of additional interest to the explorers is the relative permeability of the units within the Pandurra Formation, and the spatial relationship with alteration zones (and therefore fluid flow). Two surrogates for porosity, an essential prerequisite for permeability, are being explored with the HyLogger. First is the presence of gypsum. When the core dries, evaporitic residue often lodges on the surface of the core. Recording the amount of gypsum present may offer a correlative to porosity. The other surrogate is surface roughness of the sandstone. The more friable sandstone will potentially have greater porosity and the friability can be measured by determining the roughness computed from the laser profilometer data.

By utilising the HyLogger to unravel the complex alteration versus stratigraphic variation, and combining this with derived information concerning potential fluid pathways, a powerful tool can be introduced to modelling mineral systems in 3D. In particular, this approach can provide insight into the uranium potential and targeting in comparing the Cariewerloo and Athabasca Basins

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## **Seeing the wood for the trees: what spectral wavebands are suitable for your geological setting?**

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The increased take-up of spectral geology in industry and in the Geological Surveys is leading to a growing demand and development of spectrometers that cover a wider range of wavelengths from the visible-near infrared (VNIR) through the shortwave infrared (SWIR) to the thermal infrared (TIR). In particular, the HyLogger-2 and HyChips semi-automated logging systems currently cover the VNIR-SWIR and a TIR HyLogger prototype is now operational and is currently being used in Sydney to build spectral reference libraries. The HyLogger-3 systems, which will combine all three spectral regions, will be heading out to the Geological Surveys during the latter part of this year.

The result of this ongoing development means that users will have access to very large amounts of data with increased coverage in both the spatial and spectral domains. The challenge to users is how to get the most out of these data and also how to make decisions on what aspects of the data will be relevant to the geological settings they are working in.

This presentation will discuss the spectral characteristics of key minerals typical of selected geological settings across all three spectral regions. In addition, case study examples will be used to examine the importance of the different spectral regions in different geological settings. Given these spectral characteristics, the influence of overprinting by weathering and multiple phases of alteration will also be addressed. The aim is to demonstrate the practical rather than the theoretical advantages and limitations of the different spectral regions when trying to detect key alteration minerals in a range of geological settings.

## **The Iron Chefs: Modelling spectral mixtures of iron oxides and clays for applications in the iron ore industry**

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Iron ore is a fundamental source of export income for Australia with production in 2008-2009 of around 320 Mt or A\$ 30 billion. Australia has enormous reserves of iron ore, approximately 32 billion tonnes which are essentially situated in the Hamersley Province of Western Australia. Two major iron ore types are mined: the bedded iron deposits, BID (such as Mount Whaleback, Mount Tom Price, Marandoo, Mining Area C and West Angelas) are derived from the supergene alteration of banded iron formation or BIF, and the channel iron deposits, CID, which are ooidal deposits (Mesa J and Yandi).

The mineralogy of iron ores is often considered simple but detailed studies have given a much more complex picture. The ore minerals include major hematite and goethite with minor magnetite, maghemite. The texture of hematite and goethite can vary, respectively, from martitic to specular and from ochreous to vitreous. Compositional variations are dominated by aluminium substitution in both hematite and goethite. Deleterious minerals include mainly kaolinite with minor quartz, smectite and gibbsite.

Reflectance spectroscopy between 400 to 2500 nm is now a recognized technique for mineral analysis in exploration and mining, and is being increasingly used to characterise the iron oxide and clay mineralogy in numerous iron ore deposits. Better control and characterisation of contaminant phases are becoming more important with iron ore companies now seeking methods to quickly and efficiently quantify the type and abundance of waste minerals in iron ore.

The main purpose of this paper is to understand the spectral behaviour of the minerals occurring in iron ores by conducting a comprehensive spectral investigation of a suite of various iron oxides and clay minerals mixtures.

In this study, variations of diagnostic spectral adsorption features in the shortwave wavelength range of kaolinite, montmorillonite and gibbsite in standardized mixtures, of known proportions, were well correlated to the alumina content. Magnetic susceptibility measurements of mixtures with known amounts of synthetic hematite, goethite and magnetite were also associated with spectral changes to the large crystal field absorptions generated by the electronic processes in the visible and near infrared part of the spectrum of iron oxides.

## Linking Drill Core, Field Sample and Airborne Mineralogy: Lachlan Orogen and Broken Hill Examples from the NSW NVCL Node

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An initial HyLogging program conducted by the Geological Survey of New South Wales has focussed on “type deposits” from mineral districts around New South Wales. The scanning has targeted several diverse mineral systems in NSW (Lewis and Downes 2008), including Woodlawn and Captains Flat (VHMS), Dargues Reef (a granite-related gold deposit) and Thackaringa (a hydrothermal-metamorphic base metal deposit). This paper discusses the integration of HyLogger data into regional geological and spectral frameworks.

The spectral data generated by HyLogger is efficient in identifying broad alteration related to mineralisation, particularly when used in conjunction with similar resolution datasets – logs, assays and petrophysics (Mauger et al 2007, Reid 2009, Clissold and Reid 2009). The system commonly identifies previously unrecognised minerals in the drill core or increased differentiation of known minerals by their spectral variability. However, best constraints on the interpretation of alteration systems are achieved by integration of ancillary paragenetic controls – thin sections, isotope data, structural interpretation, etc. The Dargues Reef deposit is a good example, with isotope data indicating an open, single phase alteration system (McQueen and Perkins 1995) These data accommodate the resolution gap (and the resulting ambiguities) delivered by the HyLogger and permit accurate interpretation of the alteration system.

High resolution hyperspectral scanning technology is used to define spectral and spatial fingerprinting of the Dargues Reef mineral system. Interpretation is constrained by geological and mineralogical control, as well as metal system studies of the prospect. Applied to regional air- or space-borne satellite data, potential for Dargues Reef-style alteration systems is determined. Geological controls and the resolution of regional spectral data (both spatial and spectral) in the study region set limitations on the applicability of the approach. A selection of hand samples taken during the field program has been HyLogged to ground truth spectral response and constrain petrogenesis and spectral response. In Broken Hill, Thackaringa-type galena-siderite-quartz veins have been targeted with both HyLogger and HyMap (Mauger and Clissold 2009, Clissold and Reid 2009, Cudahy et al. 2009). Identified alteration data generated from scanned drill holes can be extrapolated to regional prospectivity and exploration, by generating spectral (or mineralogical) regional vectors towards unrecognised mineralisation –reducing exploration risk.

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## HyLogging applied to gold exploration: validation and potential for industry uptake

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HyLogging™ is actively being used in the mineral exploration industry, but there is substantial scope for further investigation into spectrally-derived mineralogical parameters that will continue to make the technology more attractive to explorers. The challenge in HyLogging applied to mineral exploration is one of scale: to be able to go down scale to identify potentially useful minerals as well as up-scale to verify if spectral mineralogy is spatially-detectable within exploration datasets. An example of this approach will be presented here using a newly-defined parameter, epidote-clinozoisite.

The epidote-clinozoisite parameter is particularly appealing because it has the ability to characterize both end-member phases and it is spectrally characterized by a diagnostically-deep absorption feature at approximately 1550 nm that is common to few other minerals. Visual mineral validation against what was predicted from the spectra has resulted in several iterations of modification including peak fitting improvements within the TSG™ software. In addition to this, the spatially-referenced linescan images collected by HyChips™ aided the discrimination of numerical thresholds and increased geological confidence in spectral interpretation through direct photographic confirmation.

A subsequent step in spectral validation is to place the interpreted spectral mineralogy into a geological framework. A particularly good example of a deposit-scale case study is the Victory-Defiance transect at the St Ives gold mine, where hyperspectral data are spatially linked across an approximately 4km-long cross-section. The key validation goal in such a model is to demonstrate that the minerals being mapped within the geological model are of similar origin to those characterized in thin section. In this case, epidote and clinozoisite may be predominantly restricted to certain lithologies, but the mineralogical gradients defined by the gross change from one mineral to another may be distinguished from purely lithological effects due to these mineralogical changes being highly-discordant to stratigraphic contacts. Furthermore, metamorphism is an unlikely control due to repeated mineralogical changes with proximity to gold mineralization.

In order to display the transferability of the spectral products to exploration targeting, a case study was compiled from the Barrick Lawlers bottom of hole (BOH) hyperspectral dataset. This dataset comprises spectra collected from the bottom of RAB and air-core drill holes that approximately cover a 15x15 km area. The same indices as used within the Victory-Defiance model and other case studies were used in the Lawlers study. The only precaution in the transferral of spectral indices from primarily fresh rock to partially weathered rock is to assess whether spectral features that are indicative of secondary minerals overlap with primary mineral features, which would then lead to the incorrect detection of primary alteration. In the case of the Lawlers BOH dataset, the epidote-clinozoisite index was affected by secondary gibbsite, which was masked from interpretation by the depth of the 2330nm absorption feature.

A range of spectral indices – including epidote-clinozoisite - were trialled for use in exploration targeting at Lawlers. The additional indices, chlorite and white mica composition, are represented by wavelength variations in the 2200 nm and 2250 nm absorption features, respectively. Diagnostic end-member chlorite and white mica compositions delineate one or more of the deposits at Lawlers within deep drill holes that are primarily focussed on known mineralization, but upon assessment of the shallow BOH data alone, the only spectral index to highlight any of the deposits was epidote-clinozoisite. This ability may stem from not needing to mask as many weathered samples compared to the other indices, because there are relatively few secondary minerals that contain an absorption feature within the 1550 nm region compared to the 2200 nm (AlOH), 2250 nm (FeOH) regions. Additionally, it appears from the Lawlers case study that the ~1550 nm absorption feature is preserved within the spectra of samples that have been heavily kaolinized/montmorillonized. Therefore, the addition of the epidote-clinozoisite index to the repertoire of existing spectral indices used in BOH hyperspectral interpretation has the potential to maximize the delineation of drilling targets.

## Exploring Mars in the Thermal Infrared

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Thermal infrared spectrometers have been used to investigate Mars since the 1960s. The first one intended for geologic exploration was launched in 1996 on a re-flight of a mission that failed to reach orbit in 1993. The Thermal Emission Spectrometer (TES) on the Mars Global Surveyor orbiter began its mapping phase in 1999. From its near-polar orbit over the next 7 years, it mapped most of the surface with a spatial resolution of ~3 km cross-track and ~6 km along-track with spectral coverage of ~200-1670  $\text{cm}^{-1}$  (~6-50  $\mu\text{m}$ ). The TES instrument was followed by an orbiting multi-spectral thermal imager (THEMIS) and two Miniature Thermal Emission Spectrometers (Mini-TES), one each on the Mars Exploration Rovers named Spirit and Opportunity. The rovers arrived at two different locations on the Martian surface in 2004 and continue to operate today. Each Mini-TES observes the surface and atmosphere with a 20 milliradian field-of-view and spectral coverage of ~350-2000  $\text{cm}^{-1}$  (~5-29  $\mu\text{m}$ ). All four instruments have been developed and operated at Arizona State University (ASU).

To support the interpretation of thermal emission spectra from Mars, an emission spectroscopy laboratory was developed in the Mars Space Flight Facility at ASU. I led the effort to design and build the modifications to a commercial spectrometer and devise a calibration strategy that would attend to the various spectral contributions inherent in laboratory thermal emission spectroscopy. Following the successful implementation of these developments, we have produced an internet-accessible spectral library of common rock-forming minerals spanning the spectral range of 200-2000  $\text{cm}^{-1}$  (5-50  $\mu\text{m}$ ). Over the years, a range of additional mineral and rock spectra have been added, some in response to discoveries from Mars.

Spectra from the TES instrument were used to identify two globally distributed units that were interpreted as basaltic and basaltic-andesite compositions. Known as surface type 1 (ST1) and surface type 2 (ST2) respectively, they subsequently have been divided into a greater range of classes. The ST2 unit (basaltic-andesite) has been the subject of ongoing investigation and debate focused on the possibility that it represents aqueously altered material rather than a primary volcanic lithology. Unambiguous evidence in TES spectra of aqueously-derived minerals is rare. For example, no global or regional scale occurrences of carbonate or clay minerals have been found although local occurrences are known from other instruments. One major exception is the discovery with TES spectra of gray, crystalline hematite covering tens of thousands of square kilometers in Meridiani Planum and several other smaller occurrences. Laboratory spectral studies demonstrated that goethite was the likely precursor phase. Based on the strong evidence for an aqueous origin of the hematite, the Mars rover Opportunity was sent to Meridiani Planum in search of possible habitable environments. The Mini-TES instrument onboard confirmed the hematite identification along with data from the Moessbauer spectrometer. Unexpectedly, sulfate-rich layered outcrops were identified in situ that are not identifiable from orbit. Together, the hematite and sulfate phases along with other observations, clearly demonstrate the role of water in this location sometime in the past.

The Spirit rover was sent to Gusev Crater based on geomorphic evidence that it once hosted a lake. Mini-TES spectra showed that olivine-rich basalts cover the plains around the landing site and perhaps bury any evidence for an ancient lake. However, a remarkable variety of rock types and degrees of alteration were encountered in the nearby Columbia Hills. Most notable with regard to aqueous activity is the discovery led by Mini-TES of outcrops and soil rich in opaline silica surrounding an eroded volcanoclastic construct known as Home Plate. The geologic setting of these materials suggests a volcanic hydrothermal system was active for some period of time before explosive eruptions buried the site in tephra and pyroxene-rich flows. The timing and duration of the various events remains uncertain, but the clear evidence for a hydrothermal system is sufficient to suggest the possibility that an ancient habitable environment existed in Gusev Crater.

## **A new reference library of thermal infrared reflectance spectra of minerals and rocks derived from CSIRO'S TIR-HyLogger.**

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CSIRO have developed a variety of HyLogging systems to acquire voluminous hyperspectral reflectance spectra of drill core and drill chips to identify and quantify the mineralogical composition of host rocks and mineralised systems. The HyChips and HyLogger instruments acquire reflectance spectra from the visible and near infrared (VNIR) to the shortwave infrared (SWIR) between 400 and 2500 nm suitable for OH-bearing silicates, oxides and carbonates. The latest development is the TIR-HyLogger which covers the thermal infrared wavelength range from 5 to 14  $\mu\text{m}$  (5,000 to 14,000 nm) discriminating non-OH-bearing silicates such as quartz, feldspars, garnets and pyroxenes.

A rock's reflectance spectrum can be considered as a mixed spectrum of the constituent weighted single spectra of the individual mineral crystals as a function of their fractional area of the scanned surface. These fractions can be estimated, e.g. using spectral unmixing approaches, from spectral libraries of pure reference materials. There are several existing overseas spectral libraries of reference minerals described in the literature; however, all have been measured with different instruments and using different measurement methods and geometries. To ensure a high accuracy of the mineralogical results from the operational TIR-HyLogger a new library of reference minerals, measured with the same system to be later used operational, is considered an important requirement. Particularly of it is representative of Australian terrains and Australian user requirements.

The heart of the TIR HyLogger is a Fast Fourier Transform spectrometer which scans bi-directionally the drill core mounted on a computer controlled x/y table moving the core in the x direction or to move a sample to a specific defined place on the table for static library measurements. Two heat bars are used as the light source. The spatial resolution is nominal 10 by 10 mm but smeared to 10 x 14 mm due to the table movement in core scanning mode. The spectral resolution is 20 nm at 5,000 nm and 170 nm at 14,000 nm. The signal-to-noise ratio (SNR) for a 100% reflecting target is averages 850:1 between 9,000 and 12,000 nm. The wavelength calibration is achieved by comparison with the known and well described quartz feature at 8,625 nm and the well known absorption feature of a polystyrene plastic film. Additionally a line scan camera simultaneously acquires imagery of the scanned core.

To develop the TIR-HyLogger's reference library, pure and solid samples (as opposed to particulate samples) of representative mineral and rock specimens were collected to be representative of the target samples (solid core samples). The samples have been described macroscopic, microscopic and/or by geochemical analyses for validation purposes. All spectra have been acquired in radiance and have been calibrated to absolute radiance which has been required to remove the increase of the baseline towards the longer wavelengths due to sample heating during spectral acquisition. The conversion to reflectance data was performed by dividing the sample reflectance by the reflectance of a 100% diffuse reflecting gold standard.

Research has shown that for a given mineral a large amount of spectral variation can occur. This variation is thought to be due to surface roughness, crystal or sample anisotropy, relative to the bi-directional measurement geometry, and to natural chemical variation. The first two subjects have a large influence on the thermal infrared signal and can cause a change in spectral features. For example the surface roughness can cause volume scattering to become dominant, instead of surface scattering which causes a decrease in spectral contrast (low magnitude), or to a dramatically change from a

reflectance peak to a reflectance minimum. Additionally crystal orientation effects can result in a wavelength shifts of significant mineral spectral feature positions (e.g. reflectance peaks). As with surface roughness effects a crystal surface oriented at a certain angle can also lead to an increase or decrease in the absolute magnitude of the spectrum. In this case a “specular” reflectance occurs. To deal with natural variations in spectral signature resulting from chemical variations in different species a large number of different mineral samples is required to ensure covering the maximum range of naturally occurring spectra.

So far more than 200 different mineral specimens (feldspars, pyroxenes, carbonates, amphiboles) and different sheet silicates have been measured resulting in more than 850 single reference spectra. Many of these have been generously loaned by Australian museums, universities and Geological Surveys.

HyLogging systems produce very large datasets so new methods and algorithms are being developed to provide qualitative and quantitative analyses capable of representing with all these natural variations and to ensure reliable automated mineral interpretation results. The library is continuously growing as new material comes to hand and is available on request and the geoscience community is invited to submit characterized samples for expansion of the library.

## **Validation of HyLogging data with Geochemistry and Geologic Information at the GSQ NVCL node.**

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The GSQ-AuScope National Virtual Core library (NVCL) initiative has HyLogged thousands of metres of mineral and stratigraphic cores that fall within the AuScope defined Geotransects, that are available in the core library at Exploration Data Centre at Zillmere, Brisbane. Considerable mineralogical information has been gathered and it is now time to compare the data obtained with other existing datasets. A validation exercise has been carried out on the HyLogged data using three drill cores; two from the Kalman region (K47 & K69 – cores supplied by Kings Minerals NL) and one from the Lighthouse Gully region (LGP001 – Paradigm Metals Ltd.). The HyLogged data were compared with geochemistry obtained using a portable handheld X-ray fluorescence spectrometer (NITON) for these holes, and with lithologic logs. Cu and Mo anomalies were specifically examined and are discussed in the presentation.

## **Quantitative spectral mineralogy of bauxites.**

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Quantitative analysis is an important requirement in exploration, mining and processing of minerals. There is an increasing need for the use of quantitative mineralogical data to assist with exploration, grade control, feed to processing plants and monitoring of solid process residues. Typically the use of X-Ray Powder Diffraction requires fine grinding, and the addition of a reference material, or the application of Rietveld<sup>1</sup> analysis to XRD patterns to provide accurate analysis of the suite of minerals present. Whilst accurate quantitative data can be obtained in this manner, the method is time consuming and limited to the laboratory. Near Infrared Spectroscopy (NIR) has been used for quantitative on-line/in line analysis and control in a range of processing applications which include, moisture control in clay and textile processing, fermentation processes, wheat analysis, gasoline analysis and chemicals and polymers<sup>2</sup>.

NIR analysis is increasingly being used in the mineral exploration industry and has been underpinned by the development of portable NIR spectrometers and spectral libraries of a wide range of minerals. Data acquisition time of NIR instruments is of the order of seconds and sample preparation is minimal. Consequently these types of spectrometers have great potential for rapid method of analysis.

The combination of NIR spectrometry with multivariant analysis such as Partial Least Squares regression analysis<sup>3</sup> (PLS) has been used for rapid quantitative analysis of a diverse range of ore types, including nickel laterites, oil shales and mineral sand.

PLS uses the correlations between mineral concentrations and spectral absorption intensities to give factors, which influence heavily the mean of the spectral set. Each of the factors is weighted or loaded to give unique spectral, and therefore, compositional information about those mineralogical components most highly correlated with the analysis. Specific bauxite samples were used to develop factors and loadings for the respective calibration sets. These calibration sets were used to predict the quantity of the components of the unknown bauxite samples from their individual NIR spectra.

The successful application of this technique to North Queensland bauxite will be described. The development of calibration models, based on chemistry, mineralogy and critical processing parameters will be will be discussed and the accuracy, precision and reproducibility of results will be presented.

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## Mapping of Physicochemical Gradients in Mineral Systems

*John L Walshe*

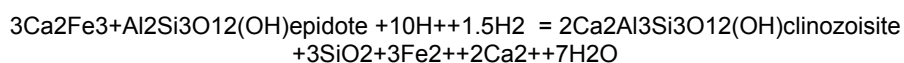
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Metal transport and deposition capacities of mineral systems are closely linked to propagation of redox and related physico-chemical gradients (pH, aH<sub>2</sub>, aHCl, aH<sub>2</sub>S, aSO<sub>2</sub>, aCO<sub>2</sub>, aCH<sub>4</sub>, aH<sub>2</sub>O, etc) Measuring these gradients in the field offers perhaps the best opportunity of assessing the capacity of a particular system, defining critical elements of the system such as fluid pathways or fluid aquitards, and identifying potentially productive parts of systems. Logging of mineralogy using reflectance spectroscopy allows the possibility of rapidly mapping mineral systems at various scales to identify the critical gradients spatially related to sites of mineral deposition. Mineralogical mapping, in part supported by stable isotope studies in Au and base metal deposits of the Eastern Yilgarn have identified both redox and pH gradients spatially associated with mineralization. These gradients appear coupled in that reduced assemblages formed in acidic environments and oxidized assemblages formed in neutral to alkaline environments. Redox gradients across the Victory - Defiance Gold Complex, St Ives Gold Mine

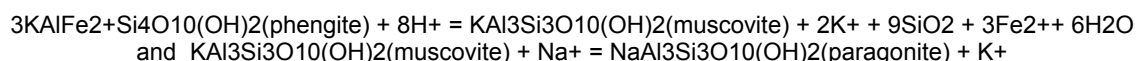
The Victory-Defiance Complex is hosted by rocks of the Kalgoorlie Sequence; a sequence of mafic and ultramafic rocks with interflow sediments. The spectral logging, supported by visual logging, magnetic susceptibility measurements and multi-element data, was used to map reduced and oxidized alteration assemblages across the complex (Reduced: clinozoisite ± chlorite ± pyrite ±pyrrhotite, Transitional: amphibole ± feldspar and biotite ± amphibole ± albite ±pyrite, Oxidized: magnetite ± quartz ± pyrite± albite, epidote ± magnetite ± pyrite, anhydrite ± phlogopite). Oxidized assemblages occur in the core of the complex, zoning laterally and vertically to reduced assemblages. Both the Conqueror and East Repulse Lodes occur on the transition between reduced and oxidized assemblages. A study of redox sensitive stable isotopes support the mineralogical evidence for redox gradients (δ<sup>13</sup>C carbonate and δ<sup>34</sup>S sulphide values are > 5 and 0 ‰ respectively in reduced assemblages and < 5 and 0 ‰ in oxidized assemblages).

### Coupling of redox and pH gradients

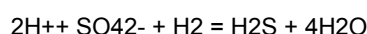
The distribution of clinozoisite versus epidote (mapped by the variation of the SWIR band at 1550 nm) in the mafic rocks of Victory - Defiance Complex illustrates the coupling between redox and pH, with reduced and acidic conditions favouring the formation of clinozoisite, viz:



In the felsic rocks that host the Kanowna Belle gold deposit the equivalent pH gradient is recorded in a transition from phengite in the footwall of the deposit through to muscovite and paragonite in the hangingwall, using the SWIR band at 2200 nm.



Chloritoid, tourmaline and prehnite are other phases stable in acidic assemblages that may be logged using reflectance spectroscopy. At the district-scale, the distribution of these assemblages is strongly fault controlled. Assemblages of phengite ± albite ± K-feldspar appear more focused on oxidized intrusive centres. Such relationships help differentiate fluid-dominated domains from rock-dominated domains in mineral systems. The coupling of pH and redox gradients may be explained by interaction of reduced and oxidized fluids buffering the pH through reactions such as



## Getting Quantitative with Mineral Spectroscopy – Calibration of HyLogging Spectral Data to Mineral Abundance

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HyLogging™ spectral data, such as the intensity or depth of absorption bands, have been used directly to measure relative changes in mineral abundance. Such simple approach is effective, especially for exploration applications, wherein the relative change in abundance of certain minerals between various parts of an ore system is of main concern to geologists.

For mining and geometallurgy, however, mineral abundance needs to be defined in terms of weight percentage to allow quantitative treatment and processing of ore material through a series of well-controlled procedures. This requires that HyLogging spectral data be calibrated and converted to weight abundances of minerals.

Calibration can be achieved by using a set of samples ('standards') with known mineral compositions. The partial least squares (PLS) regression method is commonly used in infrared spectroscopy as a calibration tool. By using the PLS method on a set of standards, HyLogging spectral data are treated as multi-variant vectors, and are compared against mineral compositions (in weight percentage) of the standards, to derive correlations between the spectral data and the abundance of the relevant minerals for the set of standards. The particular form of correlation for a given mineral derived from PLS analysis of the standards is then taken as a model for predicting the abundance (weight percentage) of the mineral in unknown samples.

The precision of quantification by this approach depends on the quality of the standards selected for calibration. Ideally, the set of standards should mineralogically represent unknown samples, and cover the full range of mineral assemblages and abundance variations likely to be encountered amongst the unknown samples. In such situations excellent quantitative predictions of the abundances can be achieved. What can become a challenge, however, is if the mineral system represented by the initial set of standards changes, say spatially, and the prediction model no longer truly applies. Error analysis and methods for dealing with such situations need to be built into the analysis methodology.

The accuracy of spectral quantification is ultimately determined by the accuracy of the ancillary data of the standards. XRD, MLA and QEMSCAN are currently available and commonly used methods to derive ancillary mineral abundance data for standards. Note that all these analytical methods also have their own limitations of application. The error in the ancillary mineral abundance data of standards derived from these methods is likely to be propagated fully to the spectrally quantified results. A set of standards with high quality ancillary data is a pre-requisite for the spectral prediction method.

The functions of PLS calibration and prediction are now built into the TSG-Core™ software package. To minimise effects on HyLogging spectra caused by non-mineralogical variations, various spectral pre-processing techniques are also enabled in TSG-Core so that prediction errors on mineral abundances are minimised.

HyLogging has been successfully used quantitatively in feasibility studies to derive mineral abundance in weight percentage for talc (a mineral deleterious to recovery of Ni sulphide in mineral flotation plants) in Ni sulphide deposits, and clay minerals (related to the efficiency of leaching) and carbonates (acid consuming) in a calcrete uranium deposit. In both cases, a very large number of samples were spectrally measured using the HyLogging method and the derived abundance data of the targeted minerals used directly for resource and reserve definition and for mine planning.