Government of **Western Australia**
Department of **Mines and Petroleum**

RECORD 2010/17

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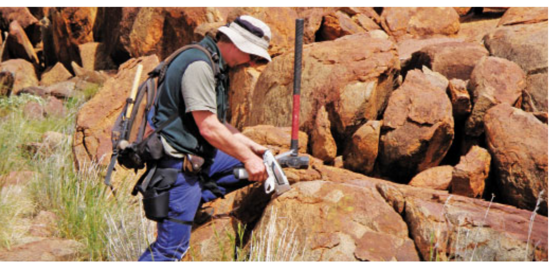

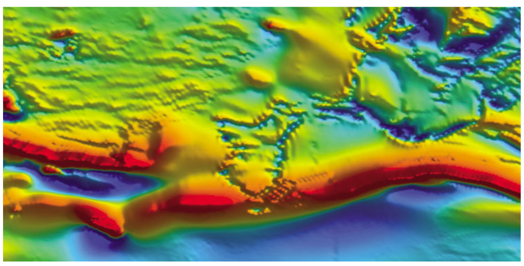

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THE GSWA NVCL HYLOGGER: RAPID MINERALOGICAL ANALYSIS FOR CHARACTERIZING MINERAL AND PETROLEUM CORE

by
EA Hancock and JF Huntington[1]

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Perth 2010

Geological Survey of Western Australia

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The GSWA NVCL HyLogger: rapid mineralogical analysis for characterizing mineral and petroleum core

by

EA Hancock and JF Huntington[1]

Abstract

HyLogging is a suite of new spectroscopic core and chip logging and imaging systems developed by CSIRO's Minerals Down Under (MDU) Flagship program. HyLogging uses rapid reflectance spectroscopy to help identify a wide range of minerals, including iron oxides, and minerals containing hydroxyl (OH), water (H_2O), carbonate (CO_3), and ammonia (NH_4), such as phyllosilicates, clays, carbonates, and sulfates. Many of these minerals, especially the phyllosilicates, are difficult to consistently and objectively map with the naked eye. Thus, HyLogging data can provide new information regarding host-rock and alteration mineralogy, vectors to mineralization, objective characterization of lithostratigraphic units and their boundaries, and refined inputs to resource block modelling and geometallurgical characteristics.

The Geological Survey of Western Australia (GSWA), along with other Australian State and Territory Geological Surveys, is a participant in the Federal government's National Collaborative Research Infrastructure Scheme (NCRIS)-funded AuScope National Virtual Core Library (NVCL) project, whose aim is to deliver high resolution images and mineral composition data from drillcores throughout Australia. The drillcore information obtained from Australian public core libraries will be made widely available for all forms of earth science research.

The NVCL uses HyLogger-2 systems, which utilize automated core tray handling, continuous visible and infrared spectroscopy (400–2500 nm wavelength region), and digital imaging, along with advanced software to identify dominant minerals on core, at a spatial resolution of about 10 mm for spectral data and 0.1 mm for images. The HyLogger-2 can log up to 500 m of core per day. Associated 'The Spectral Geologist' software (TSG-Core) is used for importing, processing, analysing, and displaying the hyperspectral core logging data.

GSWA HyLogger-2-2 was installed in July 2009 at the Perth Core Library, and has relevance for both petroleum and mineral core. At the present, this instrument does not include the mid-infrared module (6000–14 000 nm wavelength region). To test the mineralogical and geological potential of this technology, Hylogger-2 spectral data were collected from selected drillcores stored at GSWA's Carlisle Core Library. The results from the Kunzea 1 drillcore (Crossland Platform, Canning Basin) highlight lithological boundaries and provide additional information on the distribution of clay minerals, in turn reflecting the presence of free water within the succession, a characteristic of potential value for petroleum exploration. HyLogging of core from the Minnie Springs molybdenum prospect in the Gascoyne Province highlights significant mineralogical variations in the alteration system associated with molybdenum mineralization. Phengitic white mica, chlorite, and epidote reflect a low temperature Fe–Mg-bearing alteration environment that overprints an earlier stage of more acidic muscovite formation. These sericitic and propylitic-like alteration assemblages are shown to be spatially associated with disseminated molybdenite and quartz–pyrite–molybdenite veins.

KEYWORDS: absorption spectroscopy, FTIR spectroscopy, core logging, drill core, mineral alteration, mineralogy, petroleum.

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Introduction

Drilling is a key activity for most mineral and petroleum exploration programs. Australian Bureau of Statistics data (catalogue 8412.0) show that in 2009, 7.38 million metres of drilling was carried out as part of mineral exploration projects in Australia. These data do not include a breakdown on a State or Territory basis, but an estimate of the amount of drilling in Western Australia can be gauged by relating it to the State's share of mineral exploration expenditure for the same period (54%); as a result, approximately 4 million metres of drilling was carried out in Western Australia. In the petroleum sector, $2752 million was spent on exploration in Western Australia in the same year. Nationally, 67% of petroleum exploration expenditure was spent on drilling, which equates to almost $1900 million spent on petroleum-related drilling in Western Australia alone.

With such a significant expenditure on drilling, it is crucial that the maximum amount of information is recovered from drillcore or drill chips. To date, most logging practices involve either a field geologist's interpretation of core or chips, or the costly removal of samples and subsequent chemical, mineralogical, or rheological analysis. Reflectance spectroscopy is particularly well suited to the non-destructive recognition of many minerals. For rapid mineralogical identification of drillcore or chips, two field-portable spectrometers are currently available: the ASD (Analytical Spectral Devices)-FieldSpec, and PIMA-SP (Integrated Spectronics Pty. Ltd.; Thompson et al., 2009). A recent trend in ground-based reflectance spectroscopy can be seen in the development of semi-automated core loggers, such as SpecCam (Spectra-Map Ltd., England), or the Specim (from Finland) and prototype CoreScan (from Western Australia) drillcore imagers. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) developed the semi-automated, ASD-based HyLogging* spectral profiling system for rapid, cost-effective, and semiquantitative measurement of mineralogy from drillcore and rock chips, and the simultaneous acquisition of high-resolution digital photographs of the scanned core or chips.

Currently, there are smaller HyLogging systems (known as HyChips machines) commercially available at two laboratories in Perth, which provide industry with routine access to visible to shortwave infrared (400–2500 nm wavelength region) data.

The HyLogger-2 systems (Fig. 1) incorporate fast Fourier Transform Infrared (FTIR) line-profiling technologies that provide information of a range of iron oxides and OH-bearing silicates, including kaolinites, white mica, Al-smectites, Fe- and Mg-smectites, chlorite, epidote, amphibole, and talc, as well as carbonates and sulfates. This suite of minerals is important for determining parent rock composition, and the superimposed effects of metamorphism, metasomatism, and weathering (regolith development).

* HyLogging, HyLogger, HyChips, TSG, and TSA are trademarks of CSIRO Australia

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Figure 1. GSWA's HyLogger-2 unit

All HyLogging instruments can be programmed to analyse in two basic modes, namely:

- Continuous line-profiling, e.g. of diamond drillcore. Further details of this mode are discussed in this Record.
- Step-and-measure, e.g. for drill chip trays (Fig. 2). In this mode, the chip trays are moved in a discontinuous step-and-measure mode, allowing for variable spatial sampling intervals. This mode can also be used for scanning drillcore and chips at variable sampling intervals, and is utilized by the HyChips series of instruments.

The final component of the HyLogging system is the software used to process reflectance spectra into mineralogical information, and to integrate and visualize these data with high spatial resolution visible imagery of the core and associated imported assay and other sample data. A version of CSIRO's 'The Spectral Geologist' software, called TSG-Core, has been developed for this purpose, and includes 'The Spectral Assistant' (TSA) routine, which attempts to classify a spectrum into its apparent dominant minerals automatically.

The National Virtual Core Library (NVCL)

The Geological Survey of Western Australia (GSWA), along with other Australian State and Territory Geological Surveys, is a participant in the National Collaborative Research Infrastructure Strategy (NCRIS) 'Structure and Evolution of the Australian Continent' project (known as AuScope: <http://www.auscope.org.au>), a component of which is the National Virtual Core Library (NVCL). The NVCL project aims to deliver high-resolution images and mineral composition data from publicly available drillcores throughout Australia, thereby providing

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Figure 2. Example of an ASD-based HyLogging system measuring drill chip trays

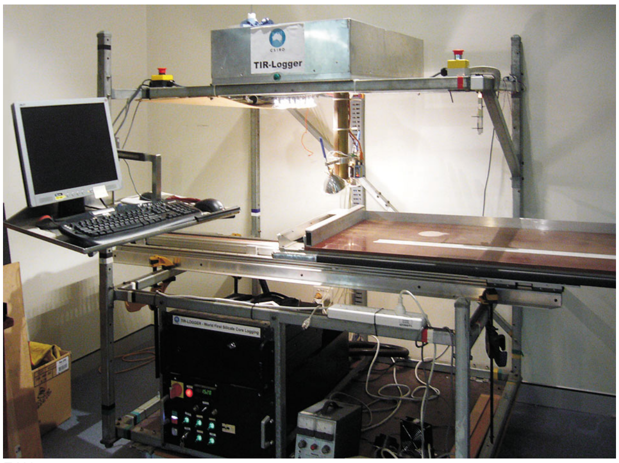

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Figure 3. CSIRO's prototype TIR-Logger

important information on the material properties and composition of the upper 1–2 km of the Australian continent. The overall objective is to facilitate research into understanding Australian mineral and basin systems, by allowing information from drillcores to be integrated with other geological, geophysical, and geochemical data in support of the 4D AuScope Earth Model.

When processed, the drillcore mineralogy, images, and spectral reflectance data will be accessible worldwide through a web service on the AuScope portal at <http://portal.auscope.org/gmap.html>. Drillcore information from the many Australian public core libraries will thus be widely available for all forms of earth science research, and to industry projects.

At the time of writing, eight HyLogger-2 instruments have been built, with six delivered to Australian State and Territory Geological Surveys. This record discusses the operation and application of the HyLogger-2 unit located at the GSWA Perth Core Library, in Carlisle.

In 2011, the NVCL HyLogger-2 systems will be upgraded to HyLogger-3 status. This incorporates a 6000 – 14 000 nm range thermal-infrared spectrometer (TIR), a prototype of which is shown in Figure 3. This will allow the sensing of non-OH-bearing silicates, such as quartz, feldspars, pyroxenes, garnets, and olivines, and will improve detection of carbonates and sulfates.

HyLogger operation at GSWA

In 2004–05, core from GSWA's Joe Lord Core Library in Kalgoorlie was scanned using the HyLogger-1, based on CSIRO's airborne line-profiling visible-to-shortwave Operational Airborne Research Spectrometer (OARS; Hausknecht et al., 2001) system. In addition, selected cores were measured using CSIRO's prototype TIR-Logger. In total, more than 33 000 m of core were scanned (Table 1) and processed by staff from CSIRO and GSWA's regional office in Kalgoorlie (Huntington et al., 2007).

As part of the Australia-wide AuScope NVCL project, the second generation HyLogger-2-2 instrument was delivered to the GSWA Perth Core Library in July 2009. This instrument is currently located in a custom-built container, which ensures a dust-free and temperature-controlled workspace with an attached shelter protecting the core from adverse weather conditions (Fig. 4). The HyLogger is operated by a full-time geologist responsible for data processing and interpretation, and two part-time technicians responsible for core preparation and initial data analysis. Up until May 2010, the GSWA HyLogger 2-2 has scanned more than 15 500 m of mineral and petroleum core from 57 holes and wells, and the data has been successfully processed (Table 2).

Core HyLogging is conducted on a priority basis, according to the GSWA work program, the geological significance of drillcore, core availability, and the location of drilling within the Australian Geotransect zone — a part of the National GeoTransect Program for construction

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Figure 4. Custom-built container and shelter for the GSWA HyLogger at the Perth Core Library, Carlisle

Table 1. Mineral core processed through the HyLogger-1 at the Joe Lord Core Library in Kalgoorlie

Hole name	*Site name*	*Total (m)*	*TIR measured*
16 holes	Kanowna Belle	5 975.00	✓
24 holes	St Ives	5 945.50	✓
HND002	Hannans North	155.60	✓
HND006	Hannans North	87.25	✓
KD1	Kambalda	180.00	✓
PDP2C	GSWA Marble Bar	45.30	✓
TRAINOR	GSWA	703.20	✓
PAGDO13	Fimiston/Federal Lode	85.90	
PRD76	Fimiston/Birthday South Lode	192.55	
WMD28	Chalice	56.75	✓
BM5346	Lake View/Eastern Main Lode	76.40	✓
BM5969	Gt Boulder/Western Main Lode	38.73	✓
MAO4167	Fimiston / Oroya Shoot	97.00	
GPD1464	Golden Pig (Marvel Loch)	109.30	✓
MC982	Mount Charlotte	86.00	
CHUD022	Fimiston	108.30	
FMM397	Frasers (Marvel Loch)	106.75	✓
GTC8400.2	New Celebration/Ghost Crab	50.30	✓
QGCD690	Quarters Mine	101.60	✓
KDU058	Kanowna Belle	115.00	
HBC1150_18	New Celebration Hampton Boulder	265.40	
GUD175	Gosling	65.60	✓
SKGD8	Birthday South	128.40	
CD28	Binduli Project/Centurion	70.50	
BUGD049	Bullant	200.30	✓
SUD821	Black Swan Nickel Mine	53.00	✓
OD15	Stanley–Nabberu East	87.20	✓
NSDDH6	North Star/Malcom	151.85	
UG340	Nepean	185.70	
WTB29	Teutonic Bore	278.85	✓
WTB5	Teutonic Bore	142.96	✓
DD97CB038A	Carr Boyd Rocks	300.00	✓
SCMD1	Scotia Mine Project	55.40	
GUD174	Gosling Ni	58.60	✓
GUD173	Gosling Ni	53.60	✓
SED185	Forrestania/Diggers Rocks	268.00	✓
CBD181	Forrestania/Cosmic Boy	83.70	✓
BUR2037	Bulong Rotary	13.90	✓
BUR2035	Bulong Rotary	17.80	✓
BUR2034	Bulong Rotary	20.00	✓
LPU976_20	Perserverance (Leinster U.G.)	209.30	
OBDDH2	Ora Banda Sill	170.00	✓
EMD10	Superpit	305.70	
ENGD007	Superpit/Lakeview South	493.00	
PC2	Ponton Creek/Cundeelee	306.50	
CDD002	Cundeelee	256.54	
CDD001	Cundeelee	205.88	
NJD1	Pitcher Range–Seismic line	408.88	

Table 2. Mineral and petroleum core processed through the GSWA HyLogger-2 at the Perth Core Library

Hole name	*Location*	*Geotransect*	*Total (m)*
Equatorial Minnie Springs MSD2	Gascoyne Complex	Capricorn	272.00
Equatorial Minnie Springs MSD1	Gascoyne Complex	Capricorn	118.00
Equatorial Minnie Springs MSD3	Gascoyne Complex	Capricorn	150.00
Pilbara Drilling Project PDP2C	Pilbara Craton, North Pole Dome	Rudall	45.30
Pilbara Japanese Project ABDP2	Pilbara Craton	Rudall	249.00
Pilbara Japanese Project ABDP3	Pilbara Craton	Rudall	150.00
Pilbara Japanese Project ABDP5B	Pilbara Craton	Rudall	14.60
Pilbara Japanese Project ABDP6	Pilbara Craton	Rudall	287.20
Blina 4	Canning Basin, Lennard Shelf	Tanami	15.50
Pilbara Japanese Project ABDP5	Pilbara Craton	Rudall	195.00
Pilbara Japanese Project ABDP1	Pilbara Craton, Marble Bar	Rudall	264.00
ilbara Japanese Project ABDP4	Pilbara Craton	Rudall	195.00
Cleaverville 1	Coastal Pilbara Terrane		659.00
Cleaverville 2	Coastal Pilbara Terrane		44.40
Cleaverville 3 DX	Coastal Pilbara Terrane		100.60
Deep Time Drilling Project ABDP8	Pilbara Craton	Rudall	311.50
Deep Time Drilling Project ABDP10	Pilbara Craton	Rudall	207.30
Pilbara Drilling Project PDP1	Pilbara Craton	Rudall	104.00
Pilbara Drilling Project PDP2A	Pilbara Craton, North Pole Dome	Rudall	50.60
Pilbara Drilling Project PDP2B	Pilbara Craton, North Pole Dome	Rudall	17.50
Acacia 1	Canning Basin, Barbwire Terrace	Rudall	1 169.70
CRA Admiral Bay DD87SS7	Canning Basin, Willara Sub-basin		581.30
Blina 5	Canning Basin, Lennard Shelf	Tanami	12.00
Deep Time Drilling Project ABDP9	Pilbara Craton	Rudall	880.10
Blina 3	Canning Basin, Lennard Shelf	Tanami	54.00
Donnybrook 1	Perth Basin		29.78
Donnybrook 2	Perth Basin		14.74
Donnybrook 3	Perth Basin		15.22
Donnybrook 4	Perth Basin		12.15
Looma 1	Canning Basin, Broome Platform	Rudall	171.00
Kunzea 1	Canning Basin, Broome Platform	Rudall	441.50
Cummins Range DD84CDD1	Pilbara Craton		180.10
Cummins Range DD84CDD2	Pilbara Craton		109.50
Equatorial Minnie Springs MSD4	Gascoyne Complex	Capricorn	131.70
Equatorial Minnie Springs MSD5	Gascoyne Complex	Capricorn	165.50
Equatorial Minnie Springs MSD6	Gascoyne Complex	Capricorn	144.50
Equatorial Minnie Springs MSD7	Gascoyne Complex	Capricorn	156.00
Equatorial Minnie Springs MSD8	Gascoyne Complex	Capricorn	168.00
Equatorial Minnie Springs MSD9	Gascoyne Complex	Capricorn	198.00
09 THD 028	Officer Basin		288.90
09 THD 029	Officer Basin		305.60
09 THD 030	Officer Basin		198.90
09 THD 031	Officer Basin		255.80
09 THD 032	Officer Basin		309.30
EPT062	Pilbara		229.90
Boab 1	Canning Basin, Barbwire Terrace	Rudall	1 022.20
Solanum 1	Canning Basin, Barbwire Terrace	Rudall	827.65
Santalum 1A	Canning Basin, Broome Platform	Rudall	376.40
Triodia 1	Canning Basin, Barbwire Terrace	Rudall	492.00
Ficus 1	Canning Basin, Barbwire Terrace	Rudall	1 045.50
Sally May 2	Canning Basin, Barbwire Terrace	Rudall	494.00
MNDD0001	Murchison GG Terrane	Dampier	610.40
MNDD0002	Murchison GG Terrane	Dampier	388.30
MNDD0003	Murchison GG Terrane	Dampier	574.80
MNDD0004	Murchison GG Terrane	Dampier	480.50
RKD005	Pilbara, Rocklea Dome		30.80
Cockburn 1	Perth Basin		80.00

of a three-dimensional image of the Australian plate and its evolution. In addition, drillcore generated as part of the Western Australian Government Co-funded Exploration Incentive Scheme Drilling Program is routinely scanned with the HyLogger. The GSWA also carries out HyLogging analysis of petroleum cores.

In early 2011, two major additions will be made to GSWA's HyLogging system. Firstly, a capability for logging rock chips will be added, followed by the installation of a TIR spectrometer to increase the spectral range, and therefore the number of detectable minerals.

Fundamentals of HyLogging spectroscopy

Currently, the HyLogging concept involves measuring scattered (reflected and transmitted) light from the sample surface, within the wavelength range of visible to near-infrared (VNIR; 380–1000 nm), shortwave-infrared (SWIR; 1000–2500 nm), and optionally TIR (6000 – 14 000 nm) in the electromagnetic spectrum (Fig. 5). Wavelengths of light are differentially absorbed as a result of two basic molecular processes, namely electronic and vibrational interactions (Clark, 1999). The absorption features commonly observed in the VNIR spectral range are typically related to electronic processes, such as charge transfer and crystal field effects, which in turn reflect the presence of ferric (Fe^{3+}) and ferrous (Fe^{2+}) iron (Fig. 6). Sources of spectral features in the SWIR range are typically vibrational processes related to the bending and stretching of molecular bonds in minerals. This spectral range includes harmonics of fundamental absorption features attributed to OH, H_2O, CO_3, NH_4, AlOH, FeOH, and MgOH molecular bonds, and is therefore useful for the determination of a wide range of mineral groups, including phyllosilicates, hydroxylated silicates, sulfates, carbonates, and ammonium-bearing minerals (Pontual, 2008).

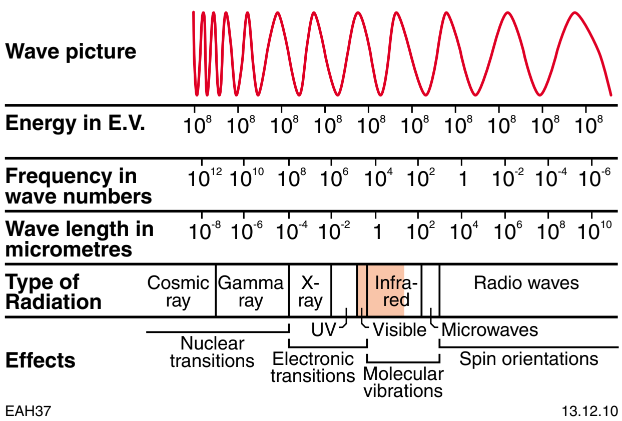

Figure 5. Electromagnetic spectrum, showing variations in energy, frequency, wavelength, radiation type, and interaction with matter. The red rectangle shows the HyLogging system's range of sensitivity (figure courtesy of CSIRO)

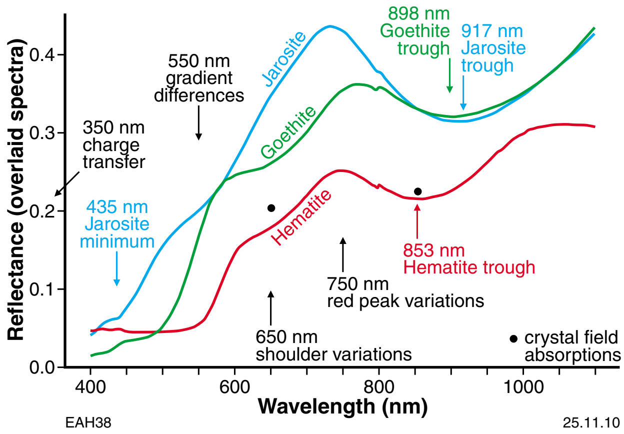

Figure 6. Visible to near-infrared (VNIR) spectra of iron oxide minerals (figure courtesy of CSIRO)

There are a number of physical relationships that constrain the behaviour of reflectance spectra, including Beer's Law, which relates the mineral diagnostic absorption coefficient to the intensity of the transmitted light through a given sample, namely:

$$I = I_o e^{-kx}$$

I — observed light intensity
I_o — original light intensity
k — mineral absorption coefficient
x — distance that light travelled through the mineral

The actual process is much more complex for reflectance spectra, as other factors are involved including contrast in the real parts of the refractive indices (which drives the amount of reflected versus transmitted light at each interface — Fresnel reflectance relationship); mineral anisotropy (including the scattering cross sections of directional light); and particle size effects. With respect to this last point, as the size of the scattering centres (particle size) approaches the wavelength of the radiation, many materials yield brighter spectra (for transparent materials like clays in the SWIR) but weaker absorptions, due to a greater surface area and less volume scattering. Those interested in learning more about the fundamentals of mineral spectroscopy are directed to the United States Geological Survey webpage — <http://speclab.cr.usgs.gov>.

The natural mixing of minerals in a given sample or measurement can complicate the accuracy of these methods for extracting the desired mineral information. For example, <20% carbonate abundance in a sample mixed with clay is difficult to spectrally measure (Thompson et al., 1999), although clay abundances can often be detected in the same mixture down to <5%. Furthermore, when mixed together in different proportions, clay absorption depths show a linear correlation with clay abundances, whereas the corresponding carbonate absorption depths show a non-linear correlation with the carbonate abundances (Cudahy, written comm., 2010).

In addition to mineral identification, SWIR spectra can also provide information on the degree of structural

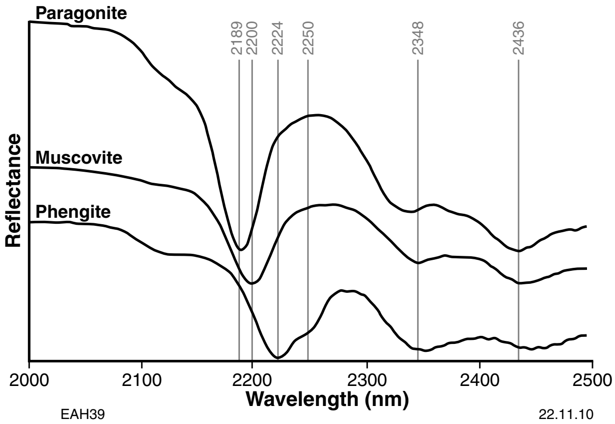

Figure 7. Reflectance spectra for three white mica species (from Scott and Yang, 1997); note the characteristic change in the wavelength representing the AlOH absorption feature between 2189 and 2224 nm.

ordering of some minerals, based on variations in the sharpness of absorption features. Furthermore, shifts in the wavelength positions of diagnostic absorption features can be related to compositional variations within many mineral groups (Fig. 7).

Most drillcore may return spectra, and particularly spatial domains of spectra, for which the mineralogy is not familiar or interpretable, but which are quite distinct from their neighbours. Thus, HyLogging is also effective in terms of characterizing (domaining) core, even though a specific mineral name may not be able to be ascribed.

HyLogging methodology

Core preparation

The HyLogger accepts drillcore of any diameter, presented in standard core trays. The core must be dry and clean, and devoid of any wrapping material, but otherwise requires minimal preparation. Dusty core is cleaned using a portable vacuum cleaner, whereas rusty and marked core is rolled over in the tray. The required metadata, including the drillhole's location and depth, is recorded at this stage.

White plastic trays, used increasingly by companies for core storage, can cause problems for HyLogging analysis, depending on the lighting arrangement. The light colour of the tray produces a strong reflectance carrying the composition of the plastic, and results in a spectrum that can compromise the identification of minerals. The resulting reflectance is often high enough to produce interfering spectra when light scatters off the walls of the core trays onto the rock sample. This is of particular concern when the drill sample is positioned lower in the drillcore tray so that there is more of this tray-reflected light, and can also have greater impact when the rock's natural spectrum is very weak or 'aspectral'. A short-term solution is to use trays made of a spectrally inactive material (e.g. aluminium, galvanized iron, powder coated sheet metal, or black plastic), or to insert black shields both on the sides of trays and in empty tray areas, minimizing the amount of tray-reflected light. More permanent solutions include the development of an improved lighting arrangement, more spectrally friendly core trays, or a more sophisticated algorithm to reliably separate the contaminating spectra from the mineral spectra.

HyLogger hardware

The HyLogger-2 system comprises an integrated suite of spectroscopic, imaging, lighting, and materials-handling tools (Fig. 8). Scanning is carried out using a computer-controlled X–Y plane table, which continuously moves the core in a zigzag path beneath the scanner at a rate of approximately one metre every 20 seconds (Table 3). One core tray can be scanned in three to five minutes, depending on core diameter and tray size. Theoretically, over 700 m of core could be measured in one day, although 300 m is more operationally realistic.

The HyLogger-2 currently uses a CDI (Control Development Incorporated) developed silicon CCD (Charge Couple Device) array grating spectrometer for the VNIR wavelengths, and a Designs and Prototypes (D&P — USA) developed FTIR spectrometer for the SWIR wavelengths (Fig. 9). Liquid nitrogen is used to cool the indium antimonide (InSb) photovoltaic detector in the SWIR spectrometer. Both spectrometers measure radiance that is converted to reflectance relative to a NIST (US National Institute of Standards) traceable Spectralon standard. Regular cross-calibration of this Spectralon panel is required to maintain its NIST traceability.

The spectrometer's instantaneous-field-of-view (IFOV) is 10 mm in diameter, but spectra are sampled every 4 mm and averaged in pairs to increase the signal to noise ratio. Because of table motion during measurement, the output spectral sample is actually about 18 mm along (after averaging) and 10 mm across the core (Fig. 10). Read outs every 8 mm provide for considerable oversampling and statistical redundancy, features valuable for mineralogical unmixing and interpretation.

The high spatial resolution core imaging camera uses a digital three-colour (red, green, and blue wavelengths) area array detector in linescan mode with a resolution of about

Table 3. HyLogger-2 system characteristics

System characteristic	*Specification*
Spectrometer spectral range	380–2500 nm
Spectral sample interval	4 nm
Number of spectral channels	530
Raw spectrometer spatial resolution	4 mm (8 mm after averaging)
Raw number of spectra per metre	250 (125 after averaging)
Linescan camera spatial resolution	0.1 mm
Robotic x/y table scanning rate	48 mm/sec
Typical daily acquisition rate	300 m
Laser profilometer resolution	0.1 mm
Light source	quartz halogen

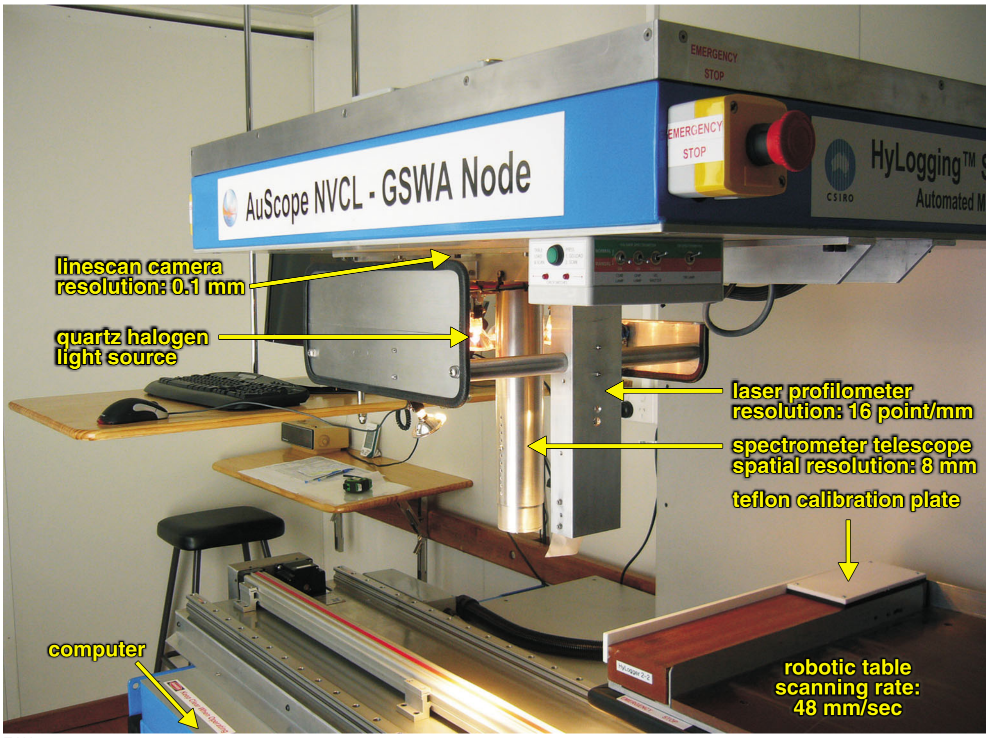

Figure 8. **GSWA's HyLogger-2 system: an integrated suite of spectroscopic, imaging, lighting, and materials handling tools**

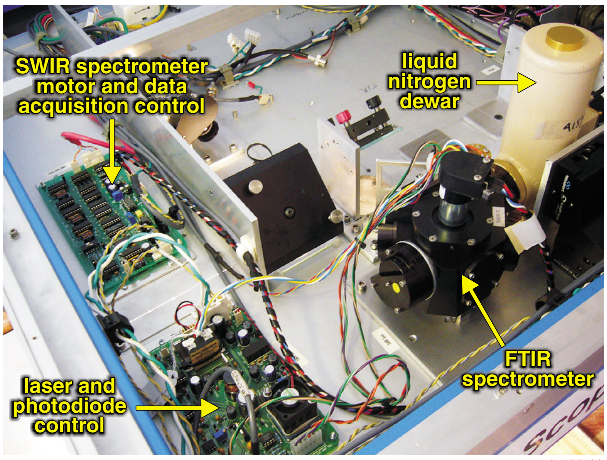

Figure 9. **Top view (with lid open) of the HyLogger-2 FTIR spectrometer and other electronics**

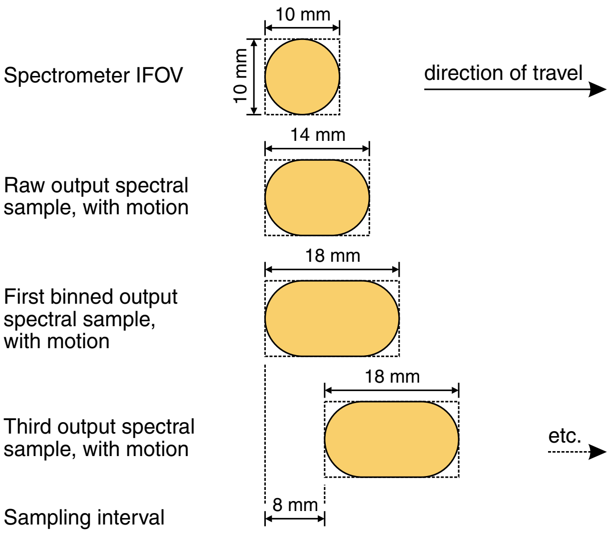

Figure 10. **HyLogger-2 spectrometer's instantaneous-field-of-view (IFOV), binned by 2 samples**

0.1 mm. It builds up a continuous image of the core, frame by frame, as the tray passes beneath.

The system also incorporates a laser profilometer, which is used to measure the height of the core every 0.1 mm. This helps to identify fractures and breaks, assisting both in geotechnical assessment, and in the control of other aspects of the system. The spectrometer, image, and profilometer data are all captured simultaneously (though physically offset and put back together using timing control) with a single traverse of the core tray.

The HyLogger's spectral calibration is an important part of the routine measurement process. Routine measurements use a white Teflon panel that is scanned at the start of every core tray. This panel needs to be kept clean by periodic washing and abrasion, and is also periodically calibrated against the associated Spectralon standard, which is locked away in a clean environment when not in use. Each morning, the signal from the Teflon standard is compared with the highest signal obtained during original calibration of the HyLogger upon delivery, and adjustments are made if required. In addition, a plate of ten known minerals and materials (Fig. 11) is scanned each day to provide information on the instrument's wavelength calibration, and as a temporal record of instrument performance. Internal calibration is also conducted using a dark background for every strip of core.

Targeted minerals

The HyLogger-2 described in this report did not include the TIR module, and is therefore limited to the measurement of iron oxides, and minerals containing hydroxyl (OH), water (H_2O), carbonate (CO_3), and ammonia (NH_4), including clays, carbonates, and sulfates; the HyLogger can also measure variations in individual mineral species (Table 4). Many of these minerals and their chemical variants are particularly difficult to recognize objectively with the naked eye. The present measureable spectral range is not well suited to mapping many ore-related minerals, such as specific sulfide minerals. However, some sulfides and other opaque phases, such as carbon black (graphite), share similar, dark, flat spectral shape at all VNIR–SWIR wavelengths, making this group measurable and mappable (Cudahy et al., 2008). Some rare earth element bearing minerals, and phases with substantial Fe^{2+} in their lattices, also have distinctive VNIR and SWIR spectra.

The next generation system (HyLogger-3) will add a TIR spectrometer, covering wavelengths from 6000–14 000 nm, which will increase the HyLogger's capabilities to include the detection of anhydrous silicates, such as feldspars, pyroxenes, olivines, garnets, and quartz (Cudahy et. al., 2009).

Data volume

The HyLogger-2 produces a large amount of data, typically about three megabytes per metre of drillcore scanned. The largest part of this dataset is the high spatial resolution visible colour imagery, which is important in allowing the geologist to visualize and assess core colour, textures, and condition. Due to the standard sampling procedure, a typical 500 m drillhole may contain about 62 500 spectral samples. Even though this large amount of data can be processed easily on a modern laptop computer, the analyst needs simple software tools to permit the rapid assessment of the major characteristics, domains, zones, lithologies, and mineral assemblages, without the need for highly specialized spectroscopic expertise. These software tools are a critical part of the complete HyLogging system, and are contained in the TSG-Core software package.

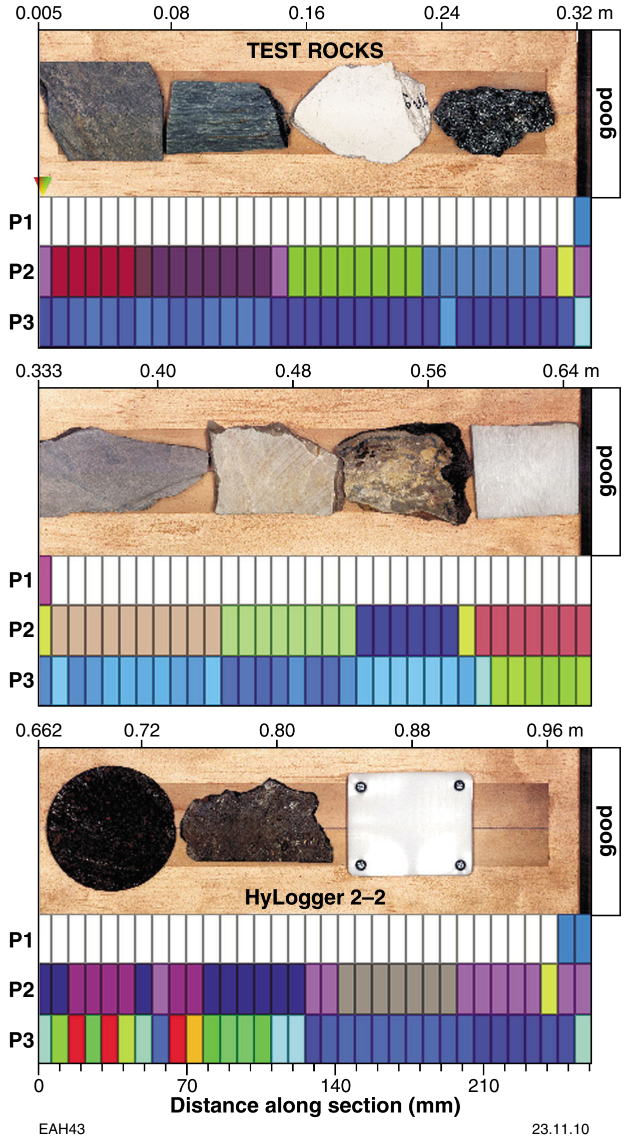

Figure 11. Quality assurance/control data generated by TSG for the Test Rocks dataset, which is used for HyLogger calibration and testing. Plots P1 and P3 refer to the HyLogging diagnostic and interpretation error, respectively (see Fig. 12 for legend). Plot P2 represents mineral detection from SWIR of test samples (from left to right, top to bottom): illitic phengite, serpentine, magnesite, Fe–Mg chlorite, pyrophyllite, calcite, kaolinite PX, talc, hematite (from VNIR), Fe^{3+} goethite, teflon.

Table 4. Database of minerals potentially detected by the HyLogger-2

Mineral group	*Mineral*
VNIR spectrometer	
Iron oxide	Hematite, goethite, jarosite
SWIR spectrometer	
Kaolin	Kaolinite WX (well crystalline), kaolinite PX (poor crystalline), dickite, nacrite
White mica	Muscovite, phengite, paragonite, illitic muscovite, illitic phengite, illitic paragonite
Smectite	Montmorillonite, nontronite
Other AlOH	Pyrophyllite, gibbsite, palygorskite, diaspore
Chlorite	Mg-bearing chlorite, Fe-bearing chlorite, intermediate Mg/Fe chlorite
Dark Mica	Biotite, phlogopite
Mg clay	Incorporating saponite, hectorite, sepiolite
Amphibole	Hornblende, tremolite, actinolite, reibeckite
Serpentine	Serpentine (antigorite, chrysotile, lizardite)
Other MgOH	Talc, brucite
Sulfate	Jarosite, Na-bearing alunite, NH-bearing alunite, gypsum
Epidote	Epidote, clinozoisite, zoisite
Tourmaline	Tourmaline, rubellite
Other OH-bearing silicates	Prehnite, topaz, opal
Carbonate	Calcite, dolomite, magnesite, ankerite, siderite

Software and processing

The HyLogger hardware is complemented by TSG-Core software, developed by CSIRO for the spectral analysis, mineralogical interpretation, and interactive visualization of spectral, image, and mineralogical data, plus the creation of output products. A free version of TSG (TSG-Viewer) for examining previously processed datasets is available from <http://www.thespectralgeologist.com>.

Using TSG, geological interpretation is accomplished using a variety of methods, including parameterizing the spectral shapes with indices or scalars created from batch scripts for particular purposes, and by reference to spectral reference libraries. Using a spectral reference library built into TSG, identification of minerals is made using an updated version of the TSA algorithm (Huntington et al., 1997; Berman et al., 1999), along with estimates of relative mineral proportions and fitting errors. This algorithm carries out supervised classification and unmixing by fitting the observed spectra to a training library of about 500 'pure' reference spectra, representing about 60 common minerals. The process indicates the most likely primary and secondary spectrally active minerals in each spectrum for the VNIR and SWIR (in total, four minerals for one spectral sample), their relative weights (relative proportions), and an error measure (standardized residual sum of squares, or SRSS). The user is able to establish thresholds for both weights and error measures to refine the interpretation. Mixtures of three minerals are also optionally available. However, mixing progressively smaller proportions of more materials can lead to ambiguous results. In the HyLogger-2 configuration, the data for each core tray is passed to a special software module called TSG-QC, which carries out a first-pass mineralogical interpretation and a variety of checks within 25–30 seconds of scanning (Fig. 12). This processing permits quality assurance and quality control on system and data performance to be completed before moving to the next core tray.

After importing into TSG-Core, data preprocessing includes trimming imagery to reduce dataset size, applying masks to hide non-geological materials, depth logging, checking and editing of erroneous classifications, creating new numeric scalars to highlight additional mineralogical properties of the core, and importing external information, such as lithological logs and assays. The TSG-Core analysis results in a series of numeric and graphic logs, and output products that can be printed, converted to PDF files, exported to external packages via CSV files, or placed into the NVCL relational database. As mentioned previously, the processed data set size is about three megabytes per metre, whereas the size of the raw data is between five and seven times greater. Raw (non-TSG) or machine data, referred to as Level 0, are archived; processed (TSG) data are referred to as Levels 1–5, depending on the stage of the processing.

Basic observations of the core, such as colour, texture, veining, fractures, and weathering state, are important for high-quality spectral interpretation. Dark samples, small particle sizes, organic matter, coatings, and complex mixtures pose challenges for any automated interpretation systems, and can lead to some TSA errors on occasion (Huntington et al., 1999); software tools are provided to identify and remedy these issues. TSA mineral classification is a very important aid when used wisely, and can quickly provide an overall characterization and indication of trends of drillhole mineralogy. However, it should be supported by the calculation of appropriate scalars to corroborate the initial mineral suggestions and distributions. Extensive tools are provided for this in the TSG software package.

Validation of the spectroscopically estimated results, using a series of independent techniques such as petrography, x-ray diffraction, and scanning electron microscopy, is recommended (Green et al., 2010). However, armed with HyLogger characterization, the locations of samples for checking is easily decided, and the number of samples required is reduced. These ancillary data check the presence and relative proportions of minerals, with results feeding back to improve HyLogger measurements and software methods.

Applications for exploration

A major goal of the HyLogging methodology is to improve the objectivity of drillcore logging, and increase the amount, quality, and value of information obtained from an expensive type of exploration activity (Huntington et al., 2007). Other exploration benefits include the ability to:

- determine the signatures of mineralized environments (alteration types and zones)
- characterize primary rock types

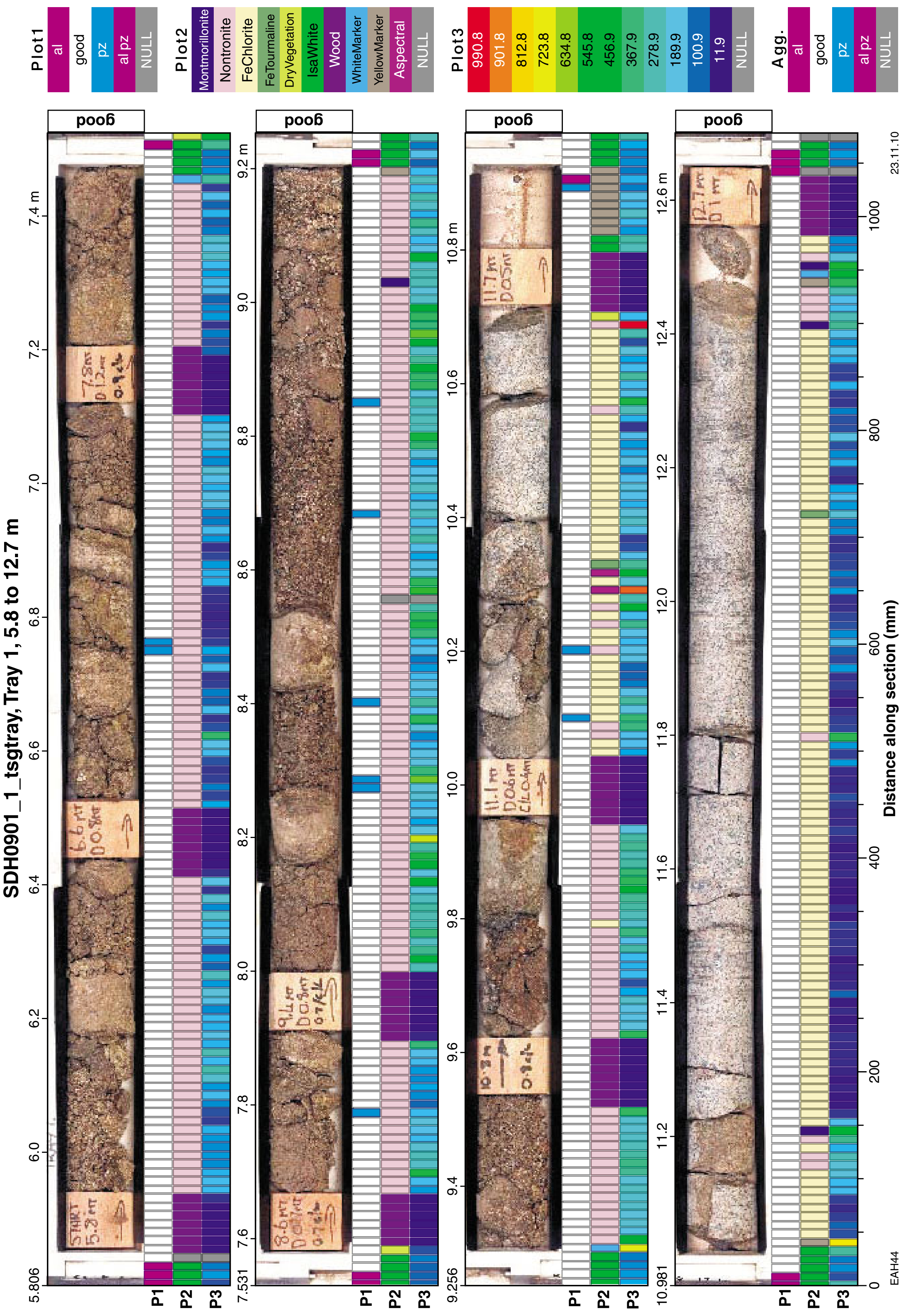

Figure 12. Image showing quality assurance/control information generated during TSG data acquisition for one core tray. Plots P1, P2 and P3 correspond to the HyLogging diagnostic, mineral1 from SWIR, and interpretation error, respectively

- highlight possible new vectors to mineralization
- create indicators of weathering regimes and processes
- discriminate between transported and residual regolith
- provide indicators of chemistry and temperature
- assist with determining metallurgical and geotechnical properties.

Although the GSWA HyLogger is being heavily used for logging of historically archived core from various parts of the State, HyLogging should ideally be carried out as soon as possible after drilling, when the core is fresh, and the available information can be integrated from the outset with other exploration data.

Case studies

Canning Basin petroleum wells

The application of the HyLogger to petroleum core analysis is a new direction for GSWA. Recent acquisition of spectral data for several kilometres of petroleum core from the Canning Basin has provided information about lithostratigraphic unit boundaries, and mineral controls on permeability, porosity, and water content, all of which will assist in exploration targeting. Data can be used for building 3D models of the distribution of alteration assemblages and lithological boundary correlation (e.g. <http://c3dmm.csiro.au>).

The Kunzea 1 well is located on the Crossland Platform of the Canning Basin, Western Australia (Fig. 13). The well intersected 260 m of clay-rich siliciclastic Permian Grant Group, lying above 190 m of Ordovician dolostone and limestone assigned to the Carribuddy Group and the Nita and Goldwyer Formations (Ghori and Haines, 2006; Haines and Ghori, 2010). HyLogger results from the Kunzea 1 core (Fig. 14) are presented as a summary for each two-metre section of core (bin = 2), with minimum of 5% minerals in each bin. An example mosaic of all the core trays, built from high-resolution photography, is shown in Figure 15.

The HyLogging data correlate well with observed lithological boundaries, but also provide additional information. The major change in mineralogy occurs around 270 m depth (Fig. 16a), corresponding to the transition from Permian sandstone to Ordovician calcareous rocks (Fig. 16b–c). The petrophysical parameters extracted from geophysical data, such as density and porosity of core, also change markedly over this interval (Fig. 16d–f).

To validate the spectral data from this petroleum core, petrographic descriptions of some thin sections from Acacia 1 and Solanum 1 wells were compared with the HyLogger results for the same intervals (Table 5). The framework grains of sandstone are anhydrous silicates that are aspectral in the HyLogger-2, as is a small amount of pyrite. However, spectra indicative of white mica, seen throughout the drillcore, is consistent with the alteration of microcline. The presence of shell fragments or anhydrite in a few samples is also reflected in HyLogging results showing 100% dolomite or gypsum, respectively. The remaining spectral data correlate well with the percentages of carbonate cement seen in the sandstone matrix.

Minnie Springs molybdenum mineralization

The Minnie Springs molybdenum–copper prospect is located in the southeast-trending Ti Tree Shear Zone (Fig. 17), which cuts Proterozoic granitic rocks of the Minnie Creek Batholith in the Gascoyne Province (Pirajno et al., 2008). Two mineralization styles have been identified within the prospect: disseminated molybdenite in potassic-altered granite; and molybdenite-bearing quartz veins and veinlets hosted in sericitized foliated granite. Diamond drilling at the prospect was carried out in a 700 m long by 100 m wide strip along the shear zone, and extended to an average depth of 150 m. 1500 m of core from nine drillholes (MSD1–MSD9) in this area were scanned using the HyLogger-2.

These data indicate that white mica, chlorite, epidote, and kaolinite are the dominant minerals in the alteration system, accompanied by minor amounts of montmorillonite and secondary calcite (Fig. 18). The surface oxidization zone can be traced by the development of both crystalline and poorly crystalline kaolinite down to a depth of 10–25 m. This change is locally accompanied by the increased presence of montmorillonite, especially in the southeast of the prospect.

Significant variations in white mica composition are found throughout the prospect. Muscovite and phengitic mica were distinguished on the basis of the wavelength of the AlOH 2200 nm absorption. Substitution for octahedral aluminium in white mica slightly changes Al–O–H bond lengths, and is reflected in the absorption band position. Shifting the wavelength position from 2189–2224 nm (Fig. 7) indicates a decreasing amount of Al^{3+} in white mica from paragonitic mica or muscovite, to phengitic mica (Scott and Yang, 1997). Results show that phengitic mica dominates throughout the prospect, although values fall off in a northeast direction. Illitic phengite associated with strong water absorption at 1910 nm (this water is assumed to be located in the white mica and not any other mineral) is common in the surface oxidized zone, but is also a component of the known alteration system in the northwest of the prospect (drillhole MSD6). Muscovite is present in small amounts throughout much of the Minnie Springs prospect, but is a dominant mineral in the central part of the drilling area. There are also pervasive developments of Fe- and Mg-rich chlorite as small veinlets in the system (Fig. 19), especially in southeast parts of the shear zone.

The distribution of white mica clearly has a strong primary lithological control, as observed in hole MSD2 (Fig. 18). Here, phengitic mica characterizes the granodiorites, whereas muscovite is distributed within leucogranite units. However, separate white mica assemblages are also present, and appear to have developed during younger metamorphic and/or alteration events. A density plot of white mica from drillhole MSD2 drawn on the basis of 2210 nm absorption width and wavelength, illustrates this feature by showing three apparent density clusters, or separate spectral populations, of white mica (Fig. 20).

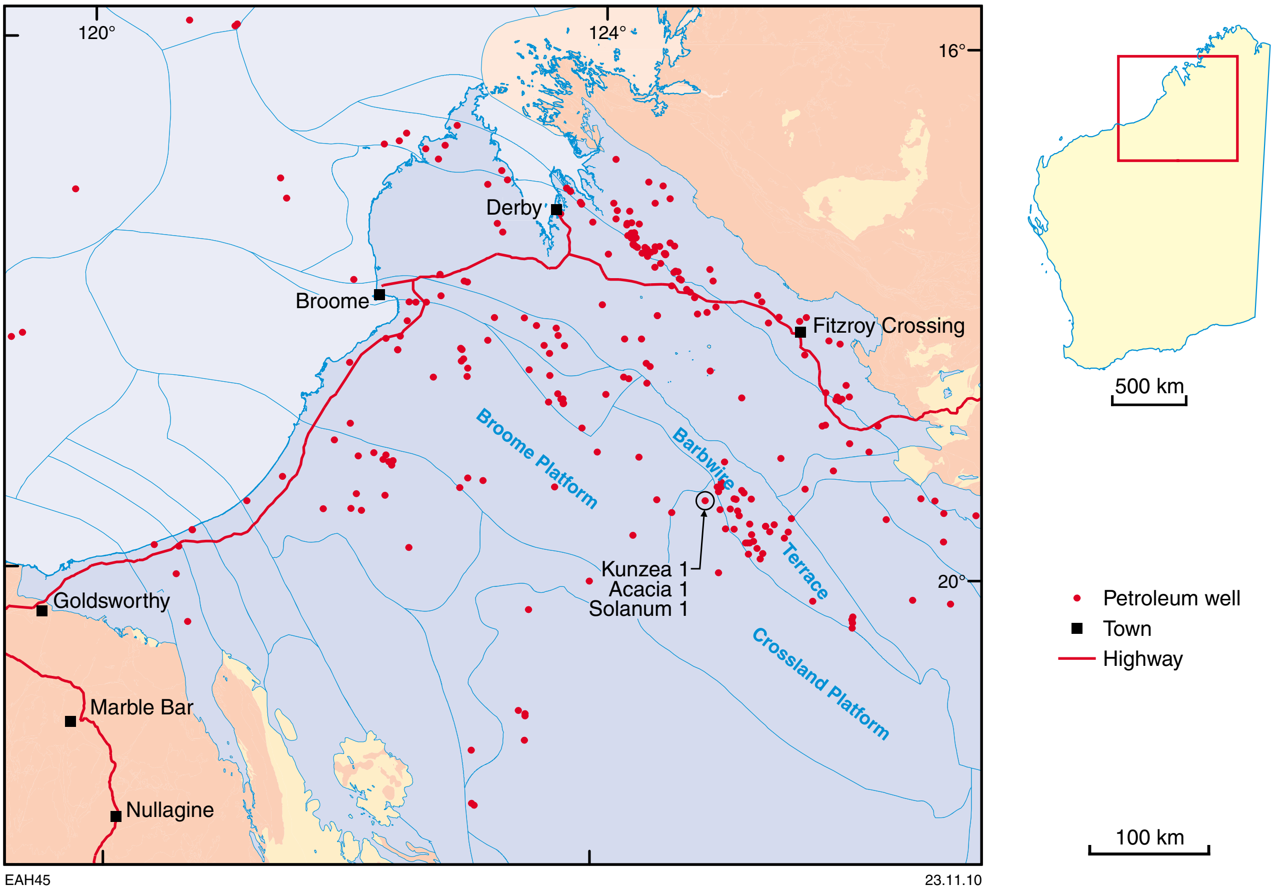

Figure 13. Tectonic location of Kunzea 1, Acacia 1, and Solanum 1 wells in the Canning Basin (data from GeoVIEW.WA <http://www.dmp.wa.gov.au/GeoVIEW>)

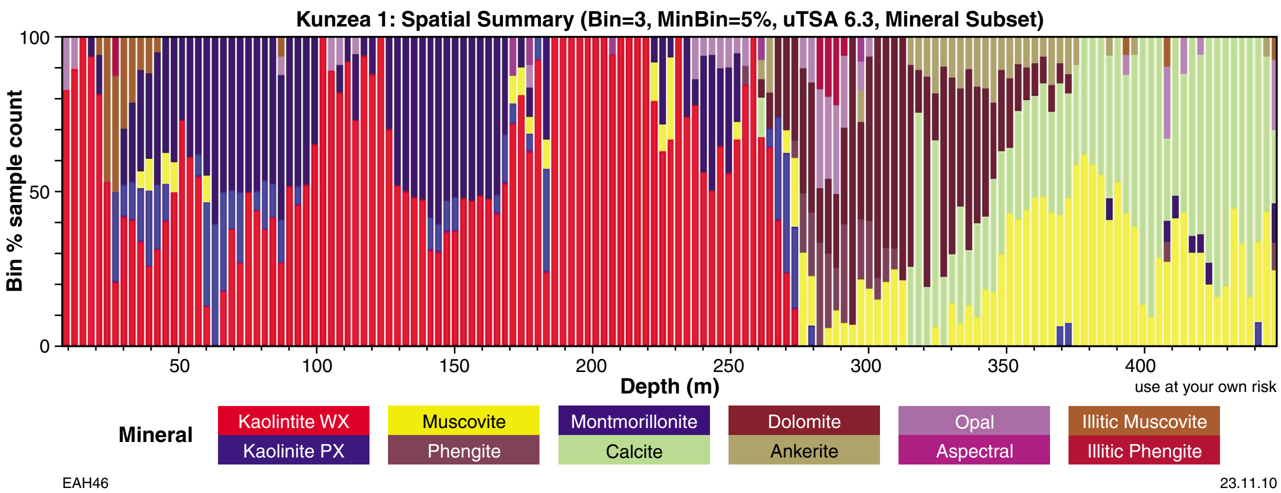

Figure 14. Relative mineral abundance distribution in the Kunzea 1 well, as obtained from HyLogger analysis

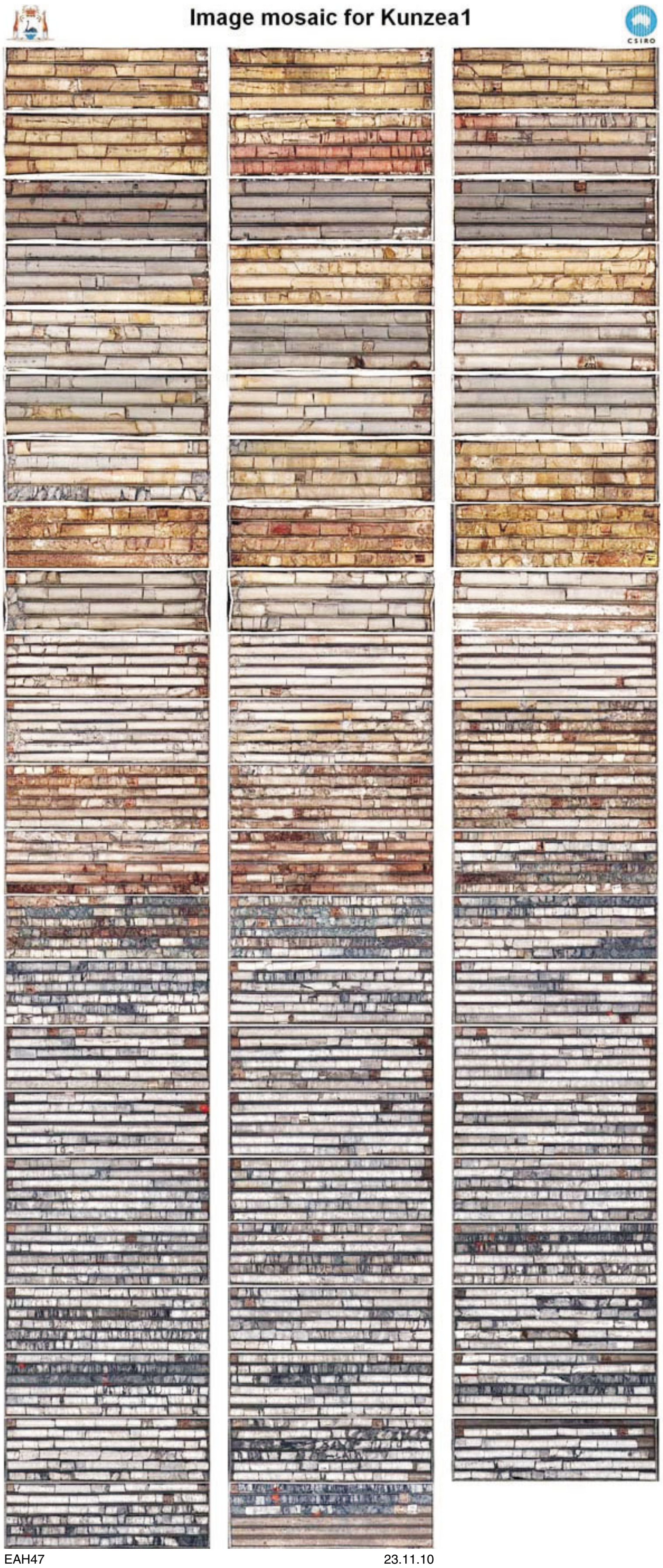

Figure 15. High-resolution mosaic image of 68 trays of core from Kunzea 1 well (trays 1–3 — the first row)

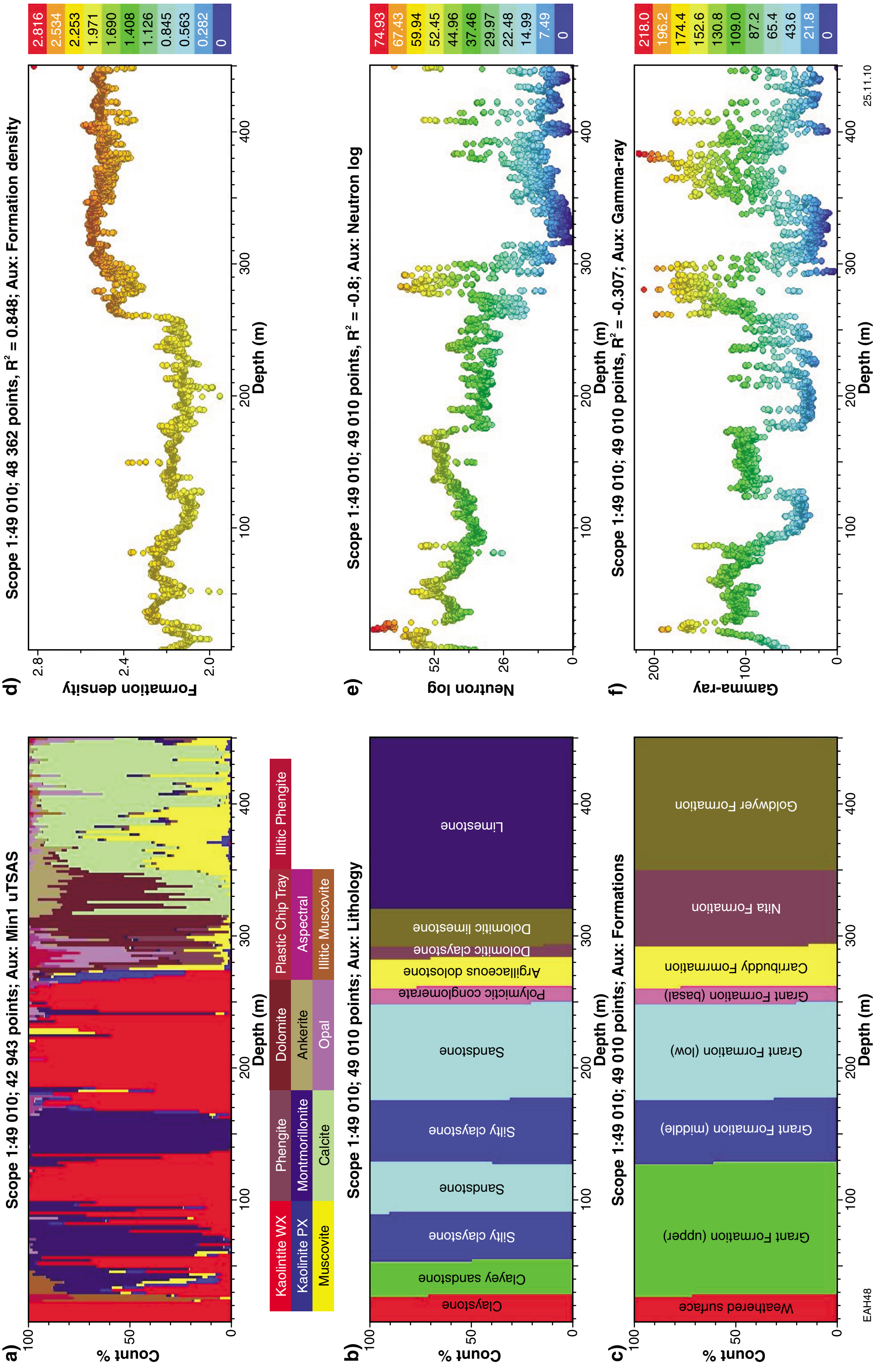

Figure 16. TSG graphic logs for Kunzea 1 core: a) HyLogger results of the dominant mineral distribution; b) lithology from originally logged rock units; c) interpreted formations; d–f) petrophysical data from GSWA report, imported into the TSG-Core software. Left hand plot summed into 2 metre intervals

Table 5. Petrographic and spectral data comparison for selected petroleum well samples

Sample interval	*Lithology*	*Petrographic description*				*HyLogger results*					
		Framework grains and other minerals	*Carbonate cement*	*Silt matrix*	*Porosity*	*Muscovite*	*Phengite*	*Dolomite*	*Ankerite*	*Siderite*	*Gypsum*
			(%)								
Solanum 1, 625.1 m	Sandstone	Quartz, microcline	10	10	?10	70	–	–	30	–	–
Solanum 1, 633.0 m	Sandy siltstone	Quartz, microcline, pyrite	35	20	0	70	–	30	–	–	–
Solanum 1, 640.2 m	Sand	Quartz, microcline, pyrite	15	5	20	–	27	–	–	73	–
Solanum 1, 657.57 m	Dolomite	Quartz, microcline	75	5	0	–	30	70	–	–	–
Solanum 1, 664 m	Sand	Quartz, microcline	30	15	3.5	–	70	–	30	–	–
Solanum 1, 685.35 m	Carbonaceous sandstone	Pellets, shell	30	0	0	–	–	100	–	–	–
Solanum 1, 697.7 m	Sand	Quartz, microcline	15	17	8	100	–	–	–	–	–
Solanum 1, 703.85 m	Sandy dolomite	Quartz, algal flakes and pellets	30	10	0	–	–	100	–	–	–
Solanum 1, 786.22 m	Dolomite	Quartz, shell, pyrite	80	10	0	–	–	100	–	–	–
Acacia 1, 1077.1 m	Carbonaceous sand	Quartz, microcline, chlorite (<1%), pyrite	10	60	0	–	100	–	–	–	–
Acacia 1, 1101.3 m	Argillaceous sand	Quartz, microcline, pyrite	5	20	?10	80	–	–	–	–	20
Acacia 1, 1116.3 m	Argillaceous, bioturbated sand	Quartz, microcline, chlorite (<1%), pyrite	29	0	6	–	–	–	76	–	24
Acacia 1, 1127.25 m	Sand	Quartz, microcline	5.5	15	5.5	–	57	–	43	–	–
Acacia 1, 1138.7 m	Sand with anhydrite crystals	Anhydrite, quartz, pyrite	15	10	0	–	–	67	–	–	33
Acacia 1, 1173.9 m	Sand	Quartz, microcline, chlorite (<1%)	0	7.7	9.3	78	–	–	–	–	22
Acacia 1, 1183.0 m	Sand	Quartz, microcline, chlorite (<1%)	5	15	15	72	–	–	–	–	28

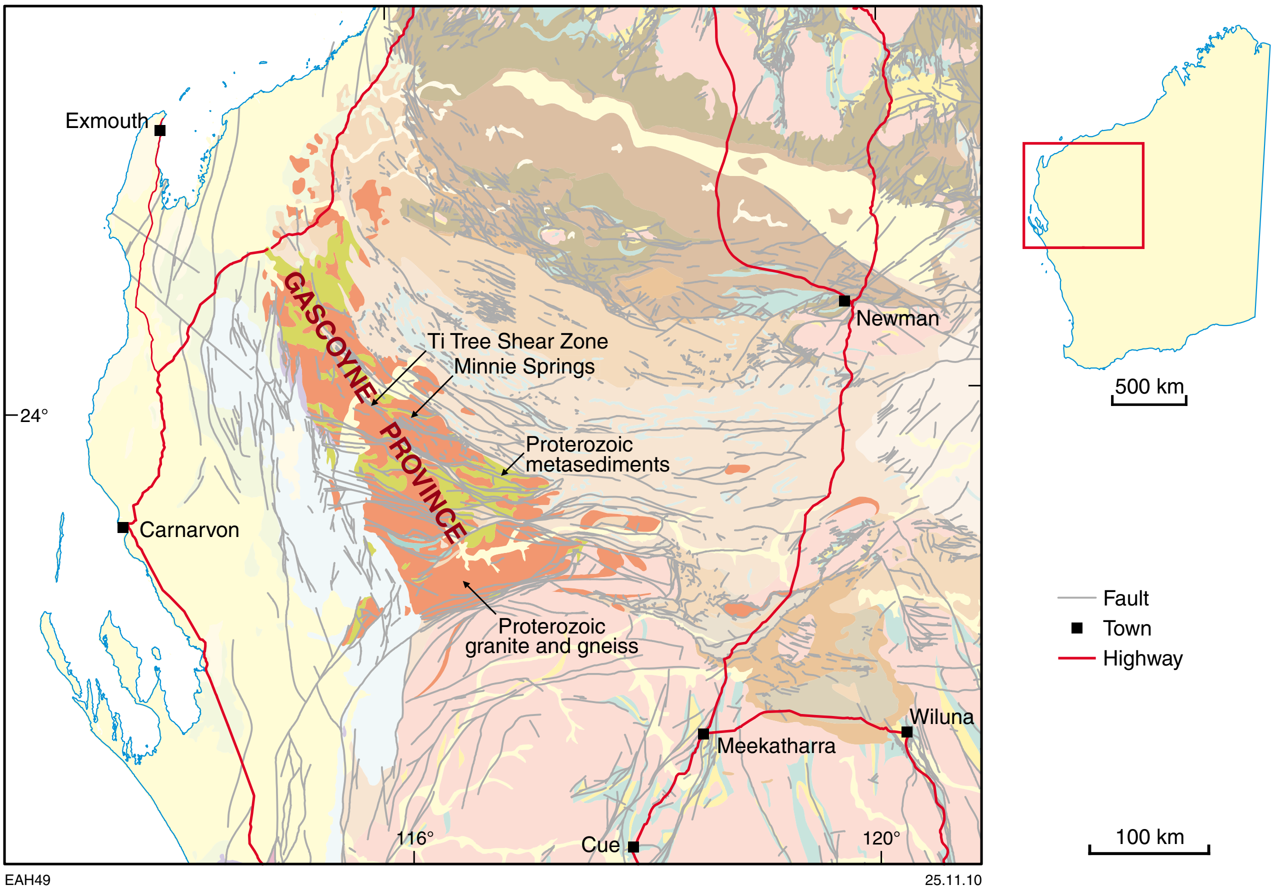

Figure 17. Geological location of the Minnie Springs molybdenum–copper prospect (data from GeoVIEW.WA <http://www.dmp.wa.gov.au/GeoVIEW>)

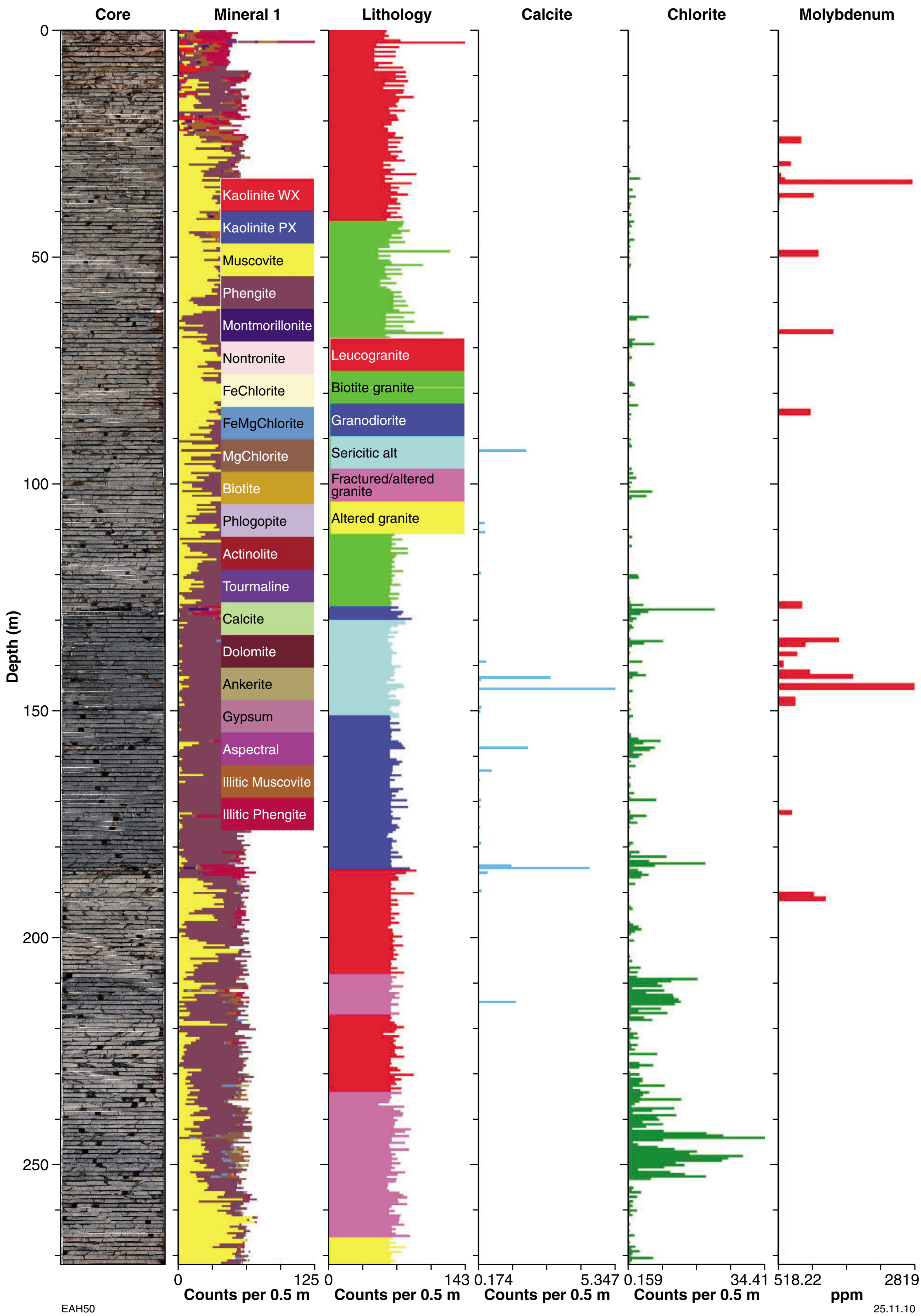

Figure 18. TSG graphic logs for Minnie Springs core, drillhole MSD2

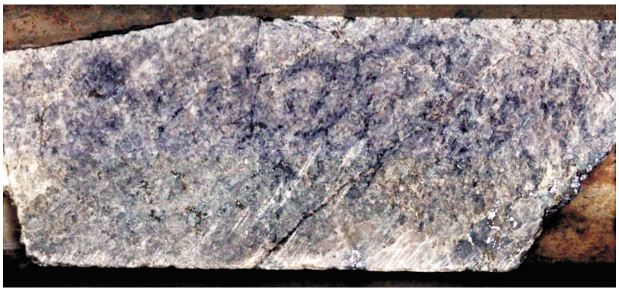

Figure 19. TSG image of Mg-chlorite veinlets in granite from Minnie Springs drillhole MSD1

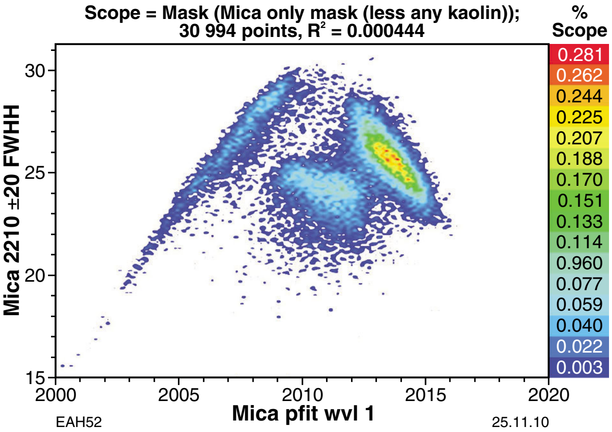

Figure 20. Density plot of 2210 nm mica absorption feature width (Mica 2210 ± 20 FWHH) versus absorption wavelength (Mica pfit wvl 1), Minnie Springs drillhole MSD2

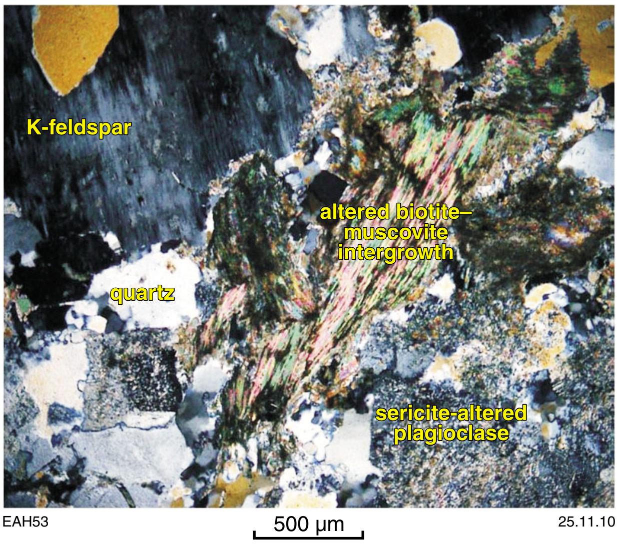

Figure 21. Thin section example of altered biotite–muscovite intergrowth within a mosaic of coarse fresh K-feldspar, sericite-altered plagioclase, and scattered finer granular quartz, from granodiorite in Minnie Springs drillhole MSD8

The shorter wavelength cluster (2206–2208 nm) identifies muscovite, whereas the longest one (2214 nm) reflects the presence of increasingly phengitic white mica, with the intermediate class a part of the white mica solid solution series tending to phengitic mica.

No biotite was identified by the HyLogger in the Minnie Springs drillcore, despite the measurement of more than 227 000 spectral samples. However, petrographic examination shows the presence of biotite, which has been partly replaced by a fine-grained mixture of muscovite, chlorite, and epidote (Fig. 21). In contrast, fresh biotite was identified spectrally in a monzogranite sample from outcrop of the Minnie Creek batholith a few kilometres away from the prospect area. Thus, it appears that in a single 8 mm by 8 mm spectral sample, depending on the presence of other spectrally active minerals, a minimum of 20% fresh biotite should be present for recognition by the HyLogger. Other leucocratic minerals present in the granitic rocks, such as quartz and feldspar, do not have any absorption features in the core analysed. However, hydrothermal saussuritic alteration of plagioclase can be identified through the recognition of epidote and muscovite (fine grained 'sericite'; Fig. 21).

Comparisons were also made with hand specimens obtained from surrounding outcrops within a radius of 5–6 km from the Minnie Springs prospect (Fig. 22). These show the presence of muscovite in the monzogranite batholith and phengitic mica in crosscutting granodiorite dykes. One sample with montmorillonite was collected from the surface oxidation zone of the batholith. The results are similar to mineral assemblages from the area of mineralization. However, the presence of 'unaltered' biotite indicates that the surrounding rocks are less altered, and probably were not subjected to hydrothermal alteration.

If the interpretation of two coexisting white micas is correct, then a possible alteration history involves the development of phengitic white mica, chlorite, and epidote associated with low temperature Si–Fe–Mg-bearing fluids overprinting an earlier alteration assemblage of quartz–sericite–pyrite. The 3D geometry of this mineral alteration zonation is presented in Figure 23. Importantly, these phyllic and propylitic mineral assemblages are spatially associated with disseminated molybdenite and quartz–pyrite–molybdenite veins. The latter are more related to fracture zones and boundaries between lithologic units, and are tracked by calcite veins in some cases. Pirajno (written comm., 2010) confirms the presence of a quartz–pyrite–muscovite (sericite) assemblage in the roof zone of the Minnie Creek batholith, reflecting an earlier stage of greisenization. This is best developed in the central and northwestern part of the study area, and is probably associated with the formation of disseminated molybdenite within the prospect area. This greisenization event was followed by the formation of propylitic-style (quartz–chlorite–epidote) alteration, especially along the Ti Tree Shear Zone in the southeastern and central part of the area. Molybdenite–quartz veins also appear to have formed during this last stage. The higher temperature potassic alteration event recognized by Pirajno et al. (2008) could not be identified confidently by HyLogging analysis. It is the earliest hydrothermal event in the system, and as such, has been largely overprinted by the later alteration assemblages.

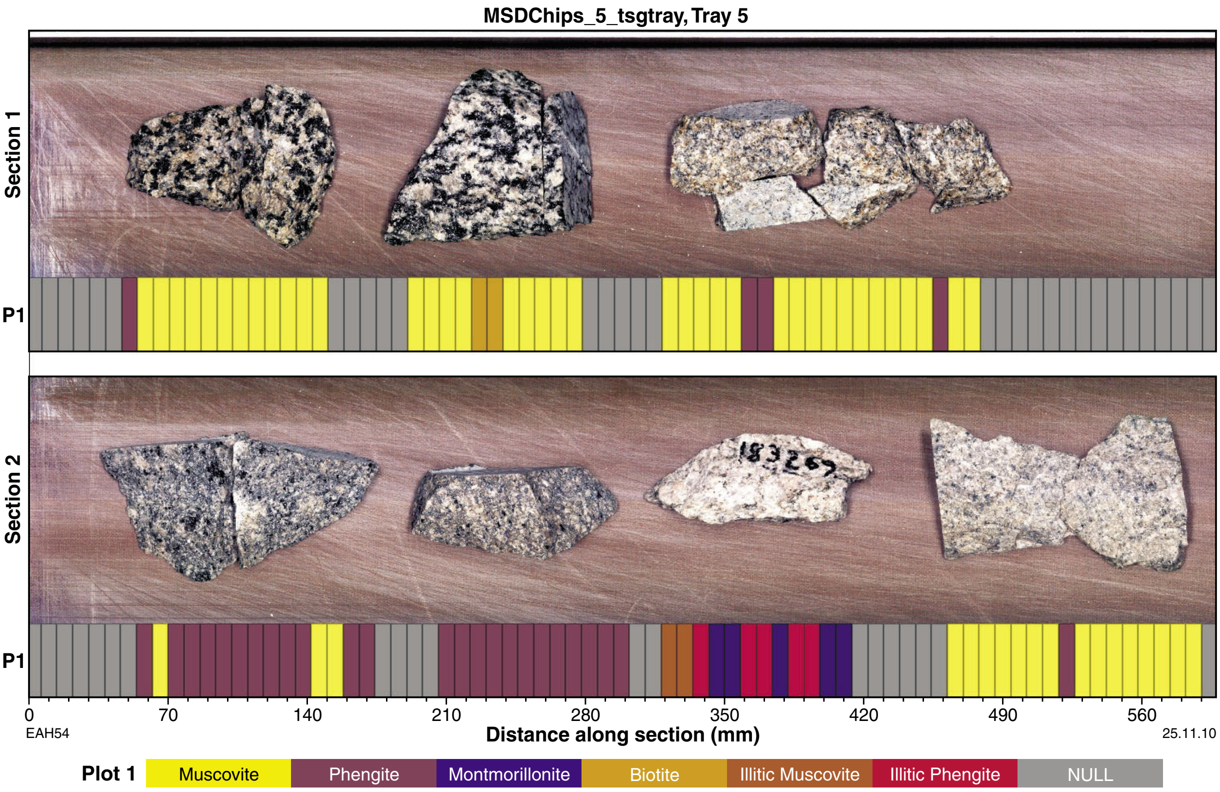

Figure 22. TSG image, showing mineral distribution in hand samples from outcrops around the Minnie Springs prospect. Rock types from top left to the bottom right are biotite granodiorite, porphyritic monzogranite, porphyritic monzogranite, porphyrytic granodiorite dyke, monzogranite dyke, leucocratic syenogranite, and biotite monzogranite dyke

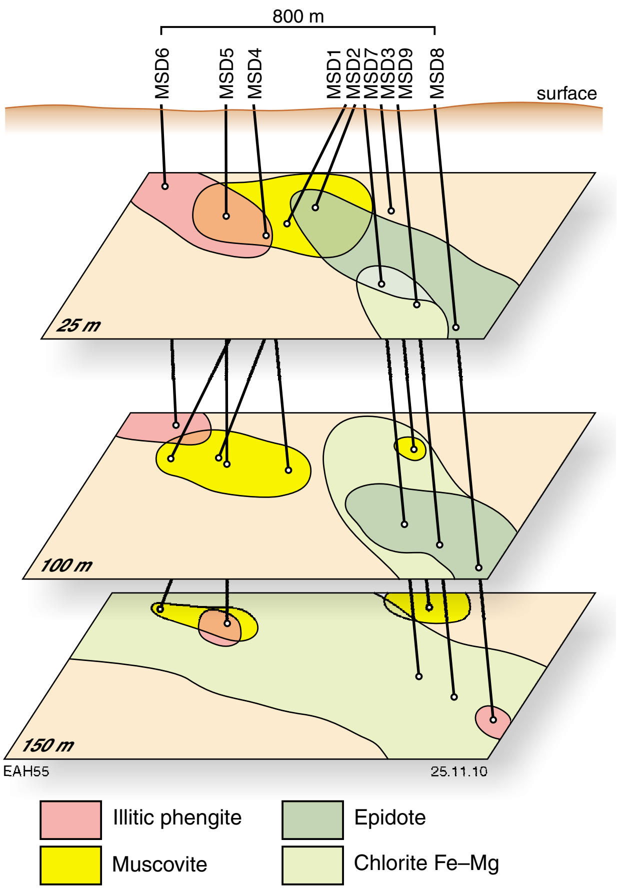

Figure 23. Diagram showing the distribution of alteration minerals at the Minnie Springs prospect

Conclusion

The HyLogger is a valuable, automated, and complementary means of quickly and objectively analysing mineral and petroleum drillcore. It can provide new insights into the primary and alteration mineralogy associated with mineralization, and can also assist in the objective determination of lithostratigraphic units and their boundaries. HyLogging analysis is non-destructive, and does not require special core preparation. Currently, the TSG-Core software, which supports the HyLogger, can recognize about 60 minerals including iron oxides, phyllosilicates, hydroxylated silicates, sulfates, carbonates, and ammonium-bearing minerals. The addition of a new TIR spectrometer will expand the spectral range of the HyLogger, allowing a wider variety of anhydrous mineral species, including framework silicates and orthosilicates, to be sensed.

The GSWA's HyLogger data will be made widely available to the public, and for all forms of earth science research, through the AuScope NVCL project's online libraries.

Acknowledgements

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