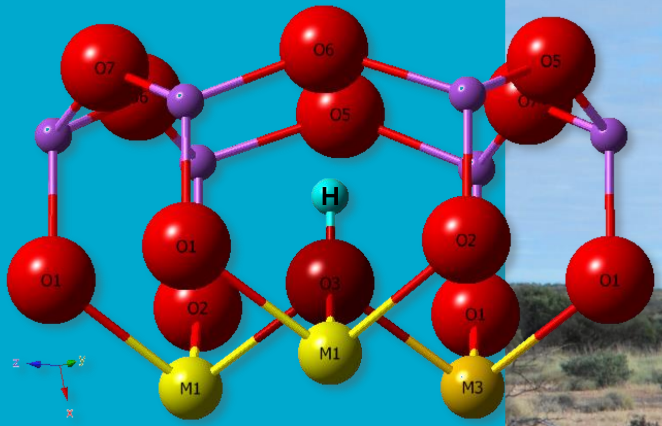


The significance of field and drill core spectral sensing for mineral exploration

Carsten Laukamp & Ian Lau
CSIRO Mineral Resources

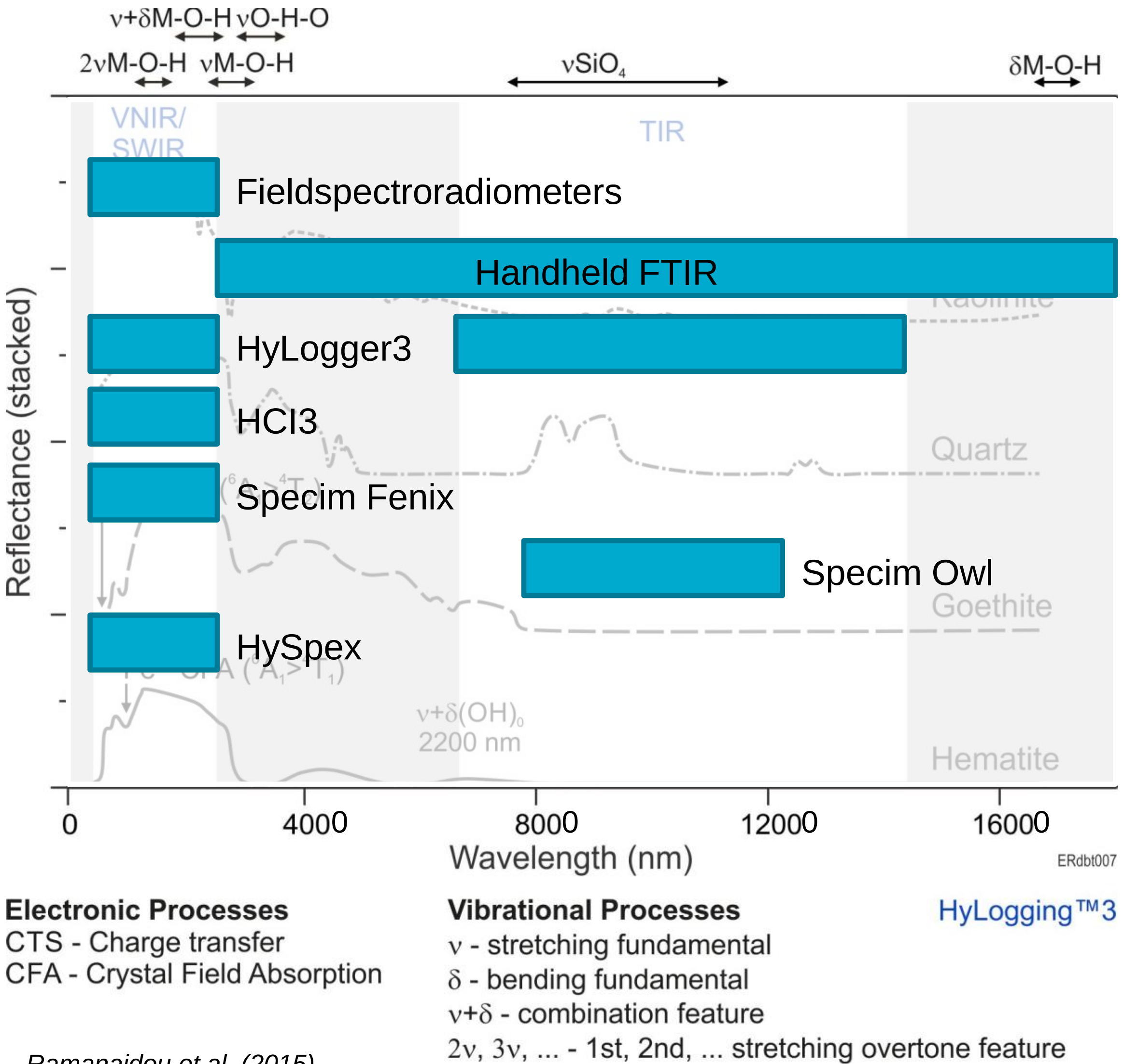
26.10.2017

Overview

- Introduction into spectral sensing
- Instrumentation and examples of Applications
  - Field VNIR/SWIR sensors
  - Field & Lab FTIRs
  - Hyperspectral Drill Core Sensing
- Australia’s National Virtual Core Library concept
- Spectral Libraries
- Standardisation of feature extraction scalars
- Modelling geochemical indices from hyperspectral data

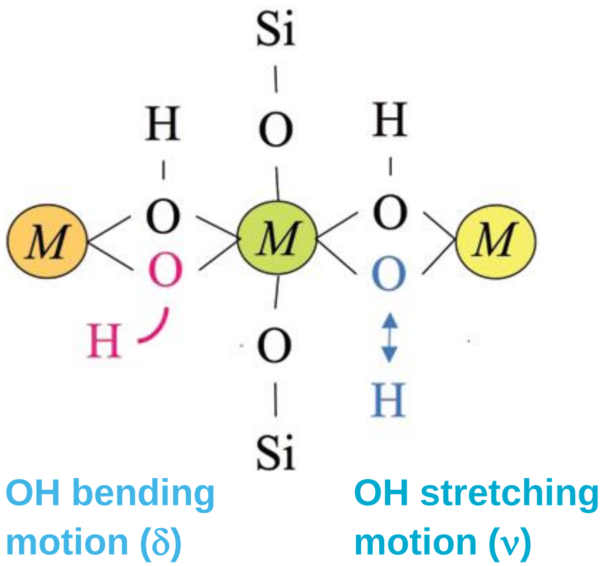
Spectral signatures of rock-forming minerals

Electronic modes:
Involve the transfer of electrons from lower to higher energy states within electron orbits (***crystal field***) or from the ligand to the cation (***charge transfer***)



Ramanaidou et al. (2015)

OH vibrations in phyllosilicates
(modified after Bishop et al., 2008)

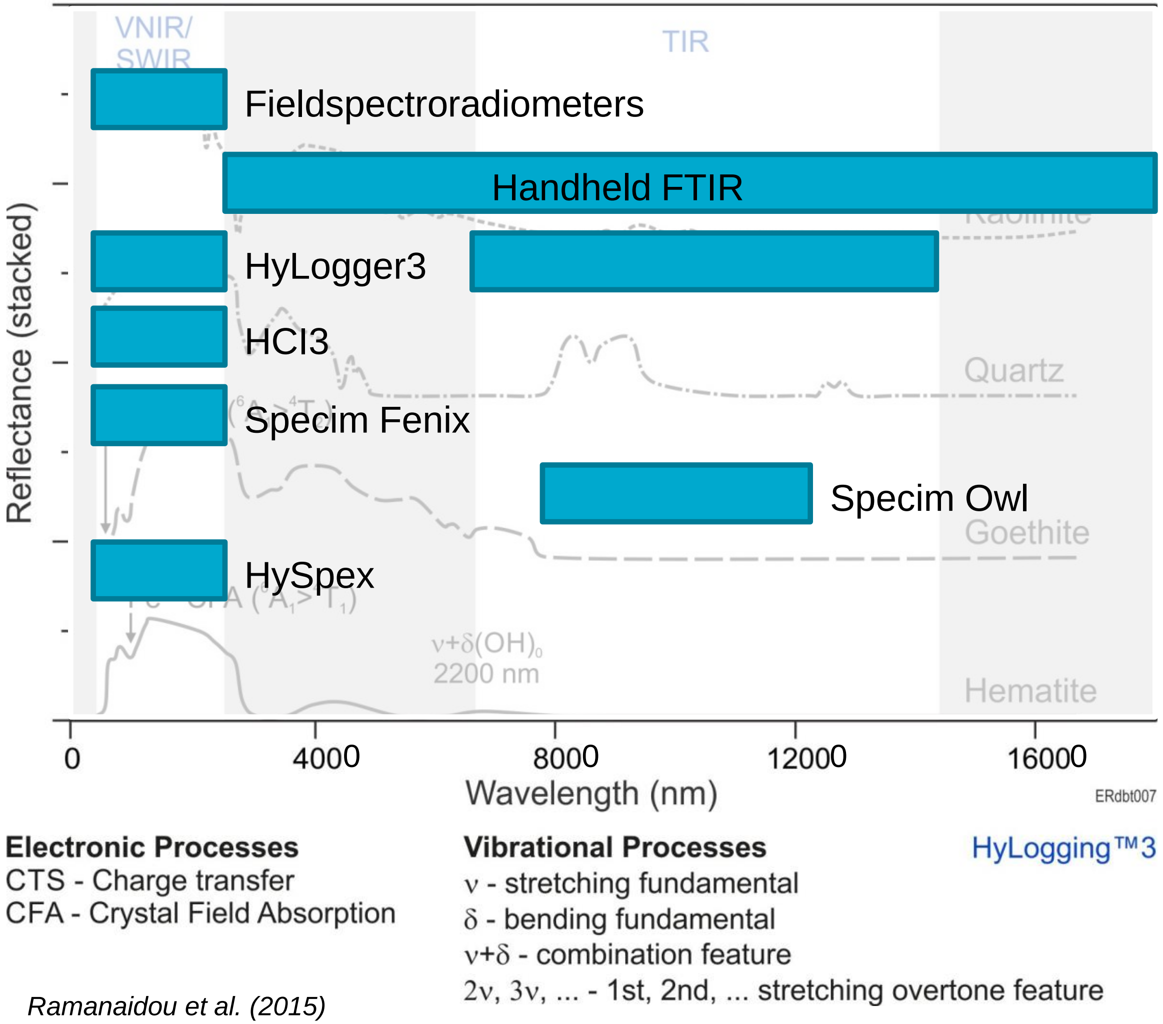


Spectral signatures of rock-forming minerals

Empowering the Geologist with Mineralogy >>> Applicable to all commodities

Objective measure:

- **lithological classification**
- **Metamorphic grade**
- **Alteration mineral assemblage**
- **In selected cases ore (e.g. Cu-sulfates, Cu-chlorides)**
- **Regolith mapping**
- **Relative mineral abundance**
- **Mineral composition**
- **Crystallinity**
- **Water content/bonding**
- **(Grain size)**



Ramanaidou et al. (2015)

Modelling based on calibration data set:

- **Quantitative mineralogy**
- **Geochemistry**
- **Petrophysics**
- **Geometallurgy (e.g. ultrafines content)**
- **…**

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Key vector minerals and their exchange vectors

mineral group	exchange vector	Common name	Band assignment	Lower limit [nm]	Upper limit [nm]	literature	Deposit style
white mica $KAl^{VI}_2Al^{IV}Si_3O_{10}(OH)_2$	Tschermak Substitution $Al^{VI}Al^{IV}$ $[Mg,Fe]_{-1}Si_{-1}$	"AlOH"	$\nu+\delta$(Al, Mg,Fe^{2+}, …)$_2$OH	2185 ([VI]Al-rich)	2215 ([VI]Al-poor)	Vedder & McDonald (1963)	**Orogenic gold, VHMS, porphyry, …**
chlorite $(Mg,Fe)Al^{VI}_2Al^{IV}_4Si_6O_{20}(OH)_{16}$	$MgFe_{-1}$	"FeOH"	$\nu+\delta$(Mg,Fe^{2+}, …)$_2$OH	2248 (Mg-rich)	2261 (Fe^{2+}-rich)	McLeod et al (1987)	**Orogenic gold, VHMS, porphyry, …**
alunite $(K,Na)Al_3(SO_4)_2(OH)_6$	NaK_{-1}	n.a.	$2\nu M_nOH$, $\nu+2\delta H_2O$ (Na/K)	1473 (K-rich)	1491 (Na-rich)	Bishop & Murad (2005)	**Porphyry, epithermal**
garnet (ugrandite series): grossular: $Ca_3M_2(SiO_4)_3$ with M = Cr, Al, Fe^{3+}	$AlFe^{2+}_{-1}$ $Fe^{2+}Cr_{-1}$	n.a.	ν_3Si-O (asymmetric stretch)	11628 (Al-rich; grossular)	12118 (Fe^{2+}-rich; andradite)	Geiger et al. (1989); McAloon & Hofmeister (1995)	**Skarn, metamorphosed SEDEX**
Plagioclase $NaAlSi_3O_8$ (Albite) - $CaAl_2Si_2O_8$ (Anorthite)	$NaCa_{-1}$, $SiAl_{-1}$	n.a.	νSi-O	15440 (Na-rich; albite)	16160 (Ca-rich; anorthite)	Thompson (1951)	**Orogenic gold, (porphyry, IOCG), …**

Field Spectrometers – VNIR-SWIR (350 to 2500 nm)

Analytical spectral devices ("ASD") Malvern Panalytical

TerraSpec 4 Standard & Hi-Res Mineral Spectrometers

TerraSpec Halo Mineral Identifier

	FieldSpec/Terra Spec 4 Standard-Res	FieldSpec/Terra Spec 4 Hi-Res	TerraSpec Halo Mineral Identifier
VNIR [nm]	3 @ 700	3 @ 700	3 @ 700
SWIR [nm]	10 @ 1400 10 @ 2100	8 @ 1400 8 @ 2100	9.8 @ 1400 8.1 @ 2100
Weight [kg]	5.44	5.44	2.5

http://www.panalytical.com/NearInfrared-spectrometer-products.htm

Spectral Evolution

SR-6500 and Miniprobe

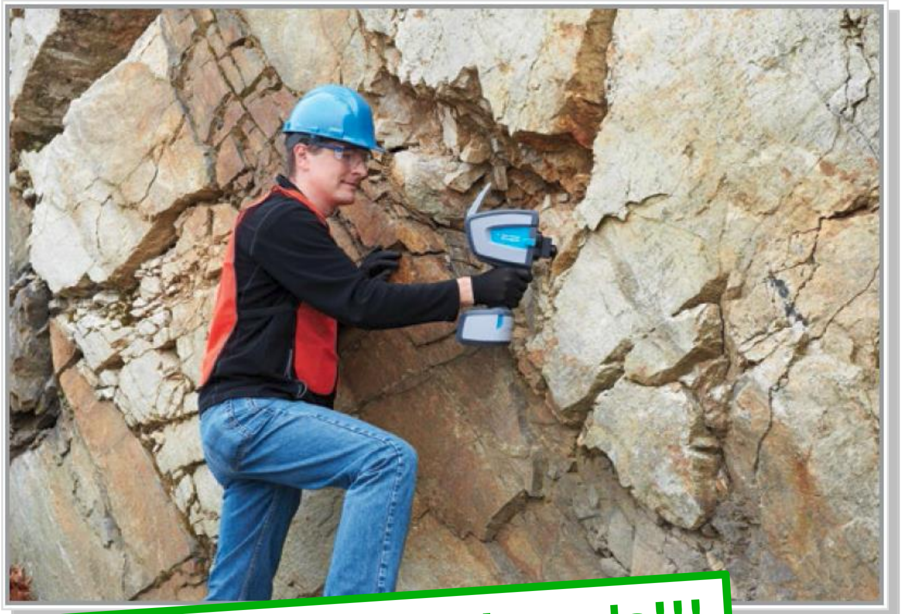
	SR-6500	PSR+ 3500
VNIR [nm]	1.5 @ 700	3 @ 700
SWIR [nm]	3.0 @ 1500 3.8 @ 2100	8 @ 1500 6 @ 2100
Weight [kg]	3.5	3.5

http://www.spectralevolution.com/

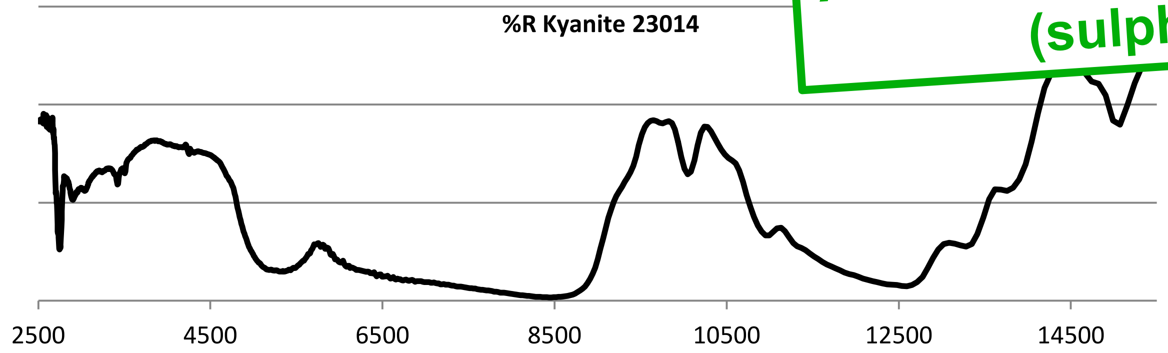
Handheld FTIR

Agilent 4300 DTGS system:

- Spectral Range DTGS: 2222 nm (4500 cm^{-1}) to 15384 nm (650 cm^{-1})
- Resolution: 4 - 16 cm^{-1}
- Various sample interfaces: Diffuse reflectance best for geological samples
- Warmup time: 10 min
- Batteries: 4 hr Li ion
- Size: 10 x 19 x 35 cm
- Weight: 2.2 kg (with batteries)

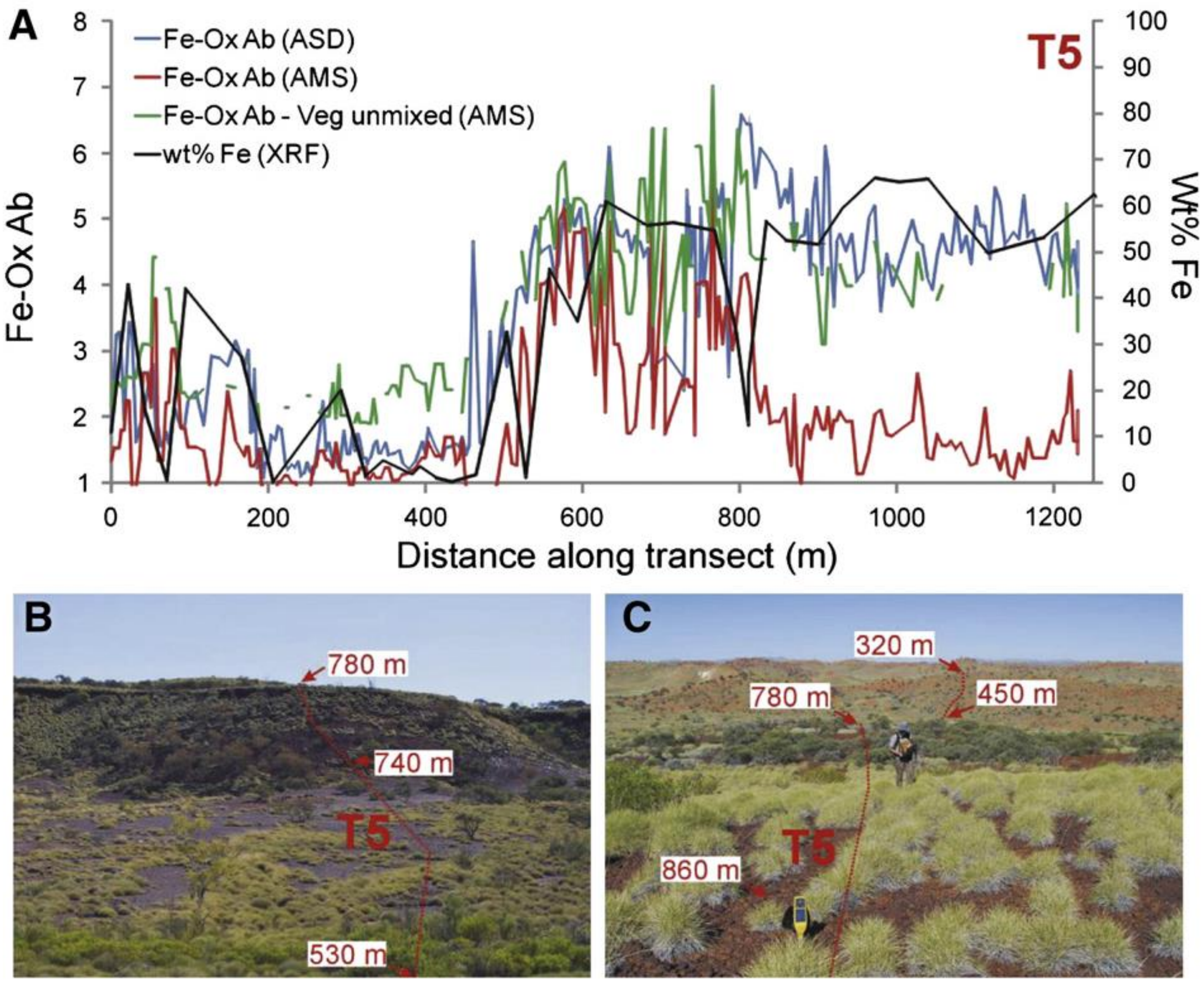


All rock forming/vector minerals!!!
(sulphides tricky!)



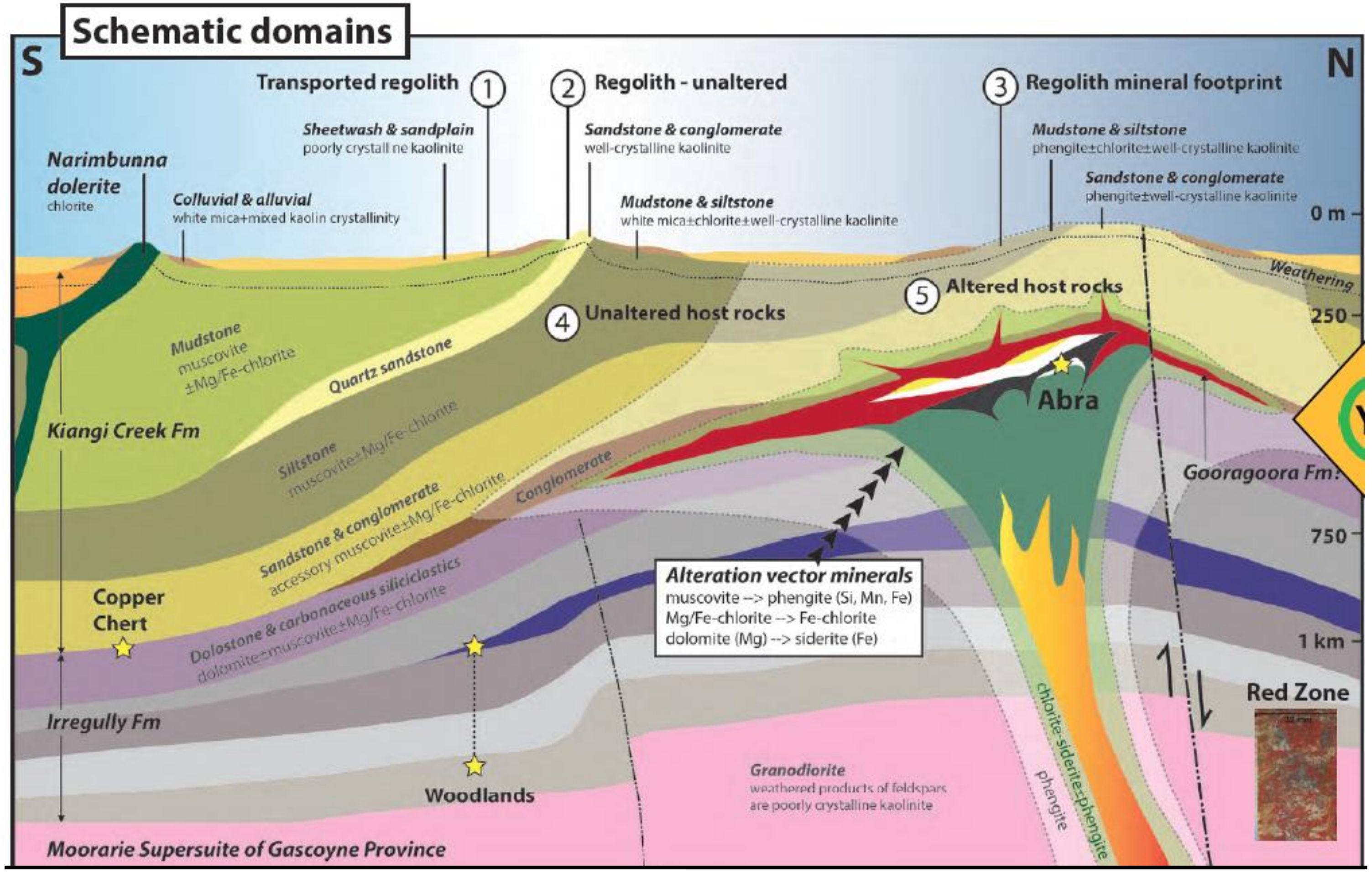
Fieldwork: Fieldspec/pXRF/sampling

- Regolith mapping
- Vectoring
- Ground validation of remote sensing data



Haest et al. (2013)

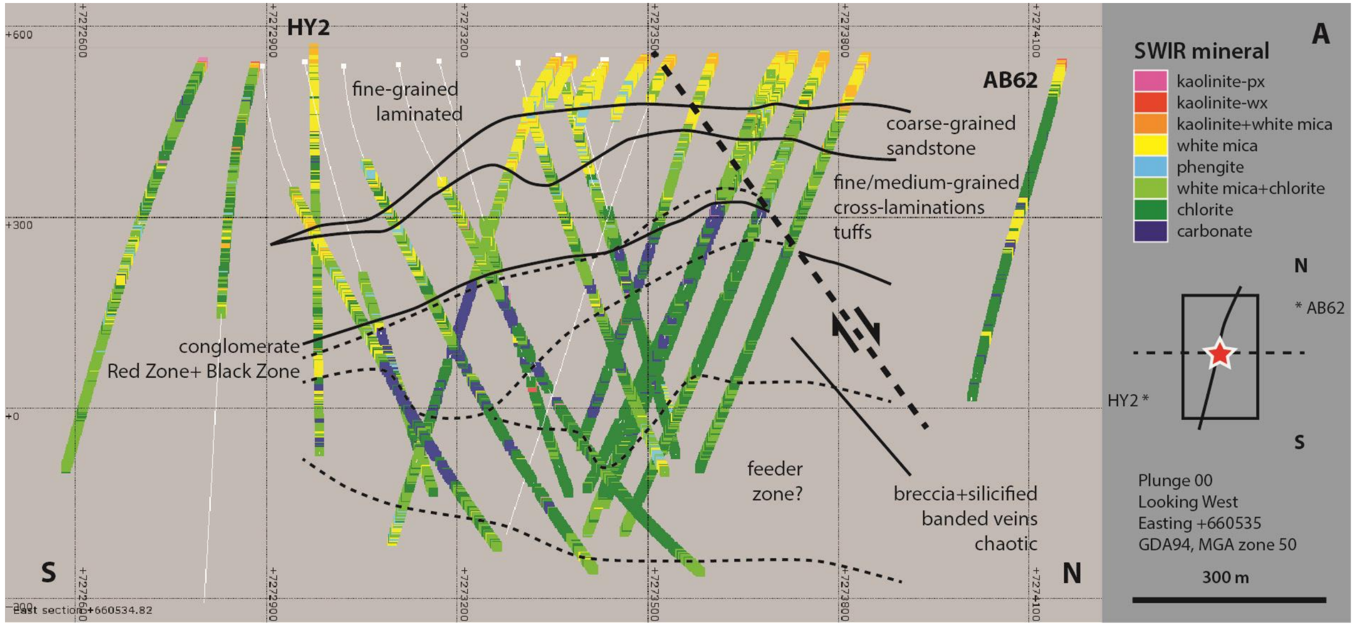
Exploration THROUGH Cover - Abra Pb-Zn-Ag

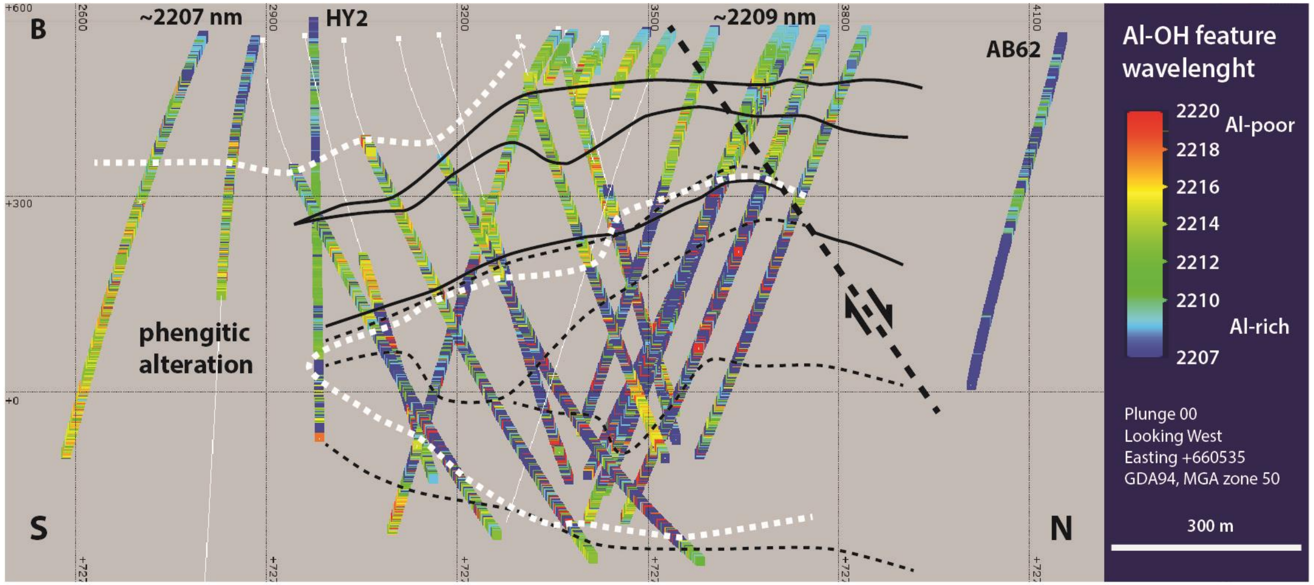


Lampinen et al. (Econ. Geol., in press)

Abra Pb-Zn-Ag:

- ASTER mineral maps,
- K-radiometrics,
- fieldspectrometer,
- HyLogger3
- XRD
- regolith geochemistry





Lampinen et al. (in prep)

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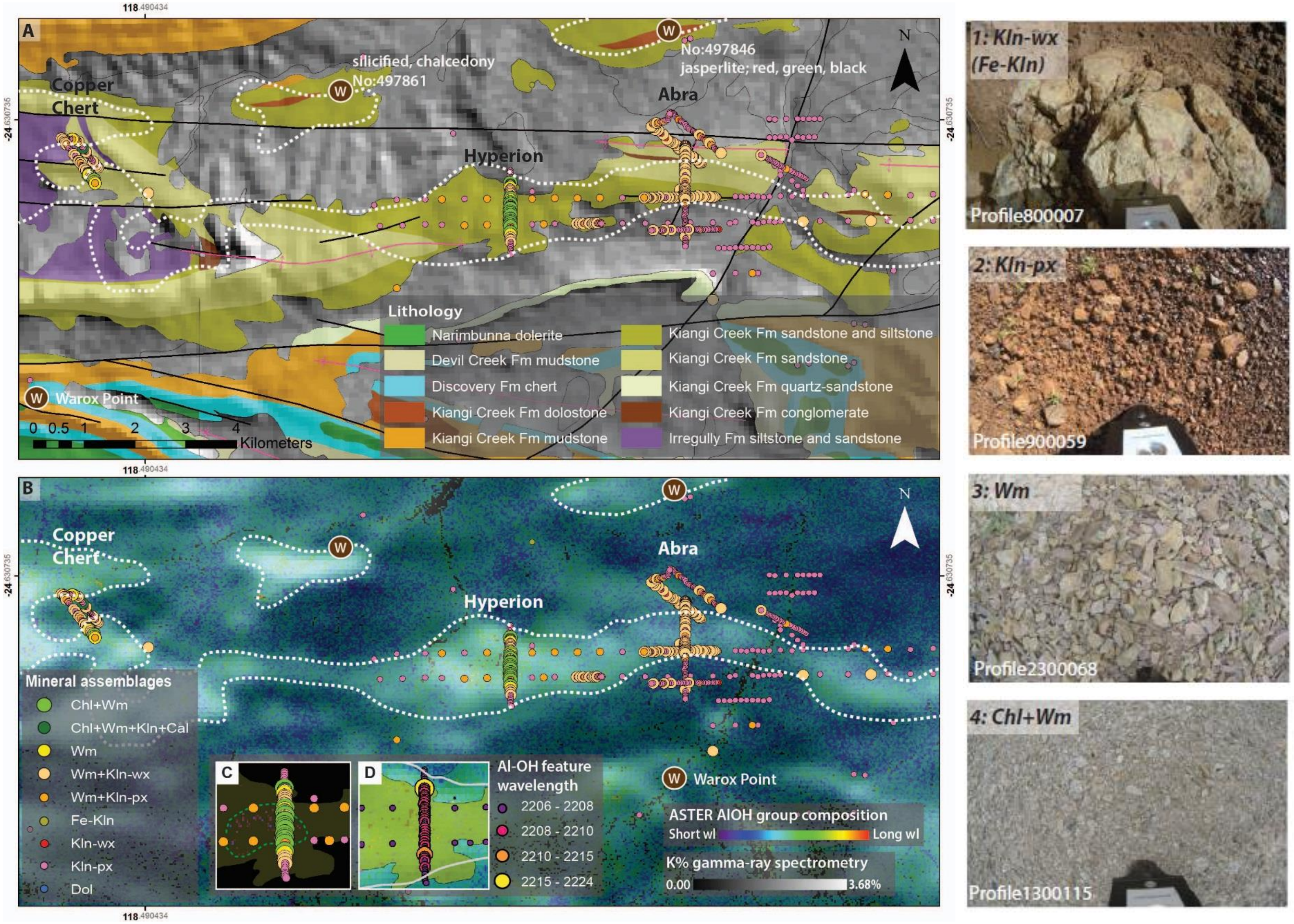


Regolith mineral assemblages determined from SWIR reflectance spectra displayed over:

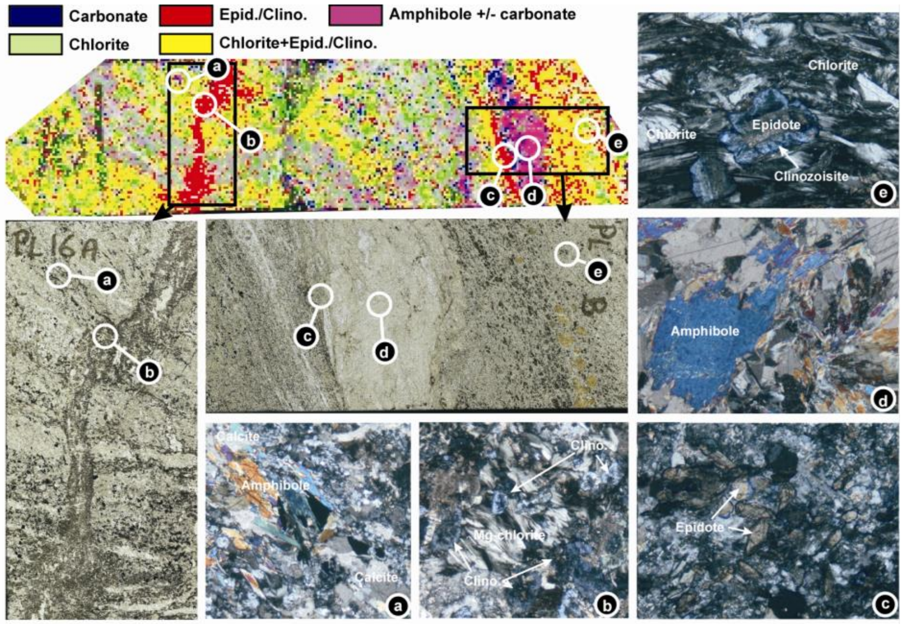
A) detailed lithologies (outcrop only with regolith landforms set transparent);
B) on combined map of ASTER AlOH group composition (Cudahy et al., 2012) and GRS potassium content (Brett, 2014), white dashed line outlines east-west trending anomaly of high potassium and long wavelength AlOH group composition.

Lampinen et al. (Econ. Geol., in press)

Hyperspectral drill core sensing

Imaging

- Corescan's HCl
  http://www.corescan.com.au/
- TerraCore's HCIS (Hyperspectral Core Imaging System) http://terracoregeo.com/
- Specim's SisuROCK
  http://www.specim.fi/
- HySpex http://www.hyspex.no/

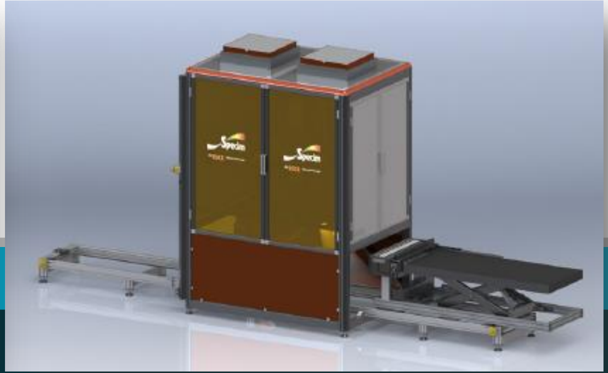


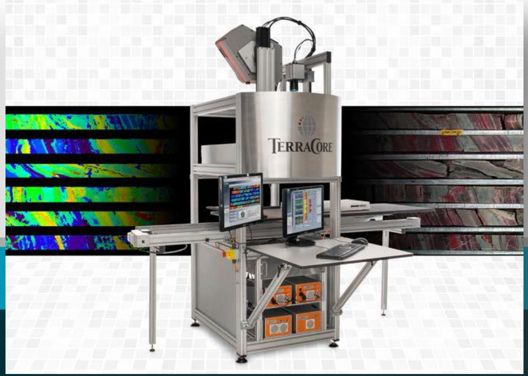
Pushbroom scanning mode/ HySpex VNIR-1600 (160 bands, 415 - 992nm @ 3.7nm, 0.19 x 0.38mm/px)/ HySpex SWIR 320m-e (256 bands, 968 - 2501nm @ 6.25nm, 0.75mm/px)

Laukamp et al. (2012) Eur. J. Min.

Line profiling

- HyLogger™
  - 0.4-2.5 µm (VSWIR)
  - & 5-14 µm (TIR)
  - diamond drill core/ chip tray logging
  - ~700m / day
  - 1 cm line-profile





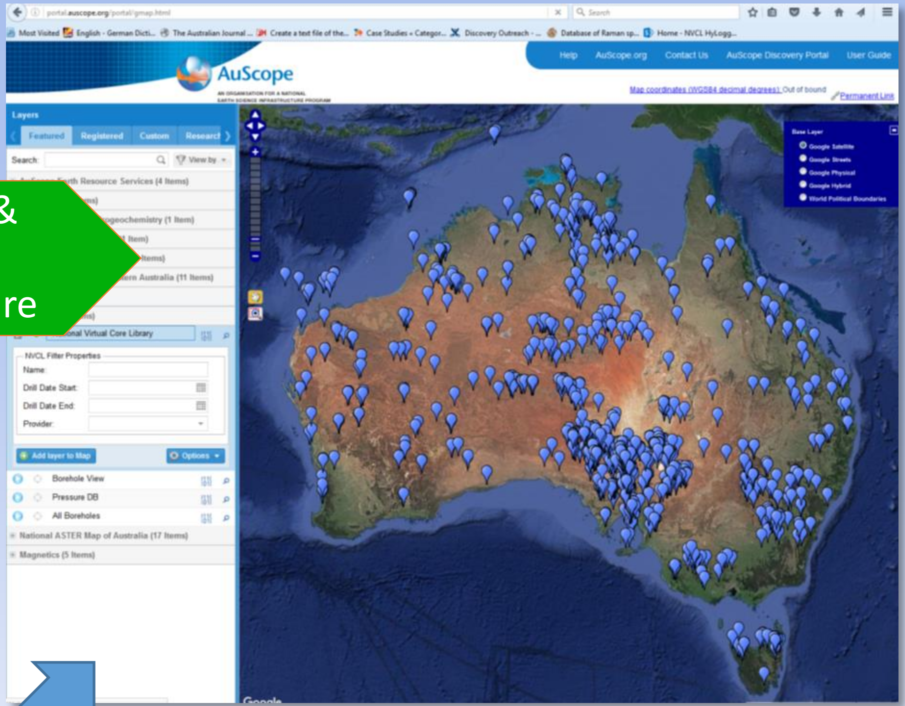
National Virtual Core Library

Material Infrastructure

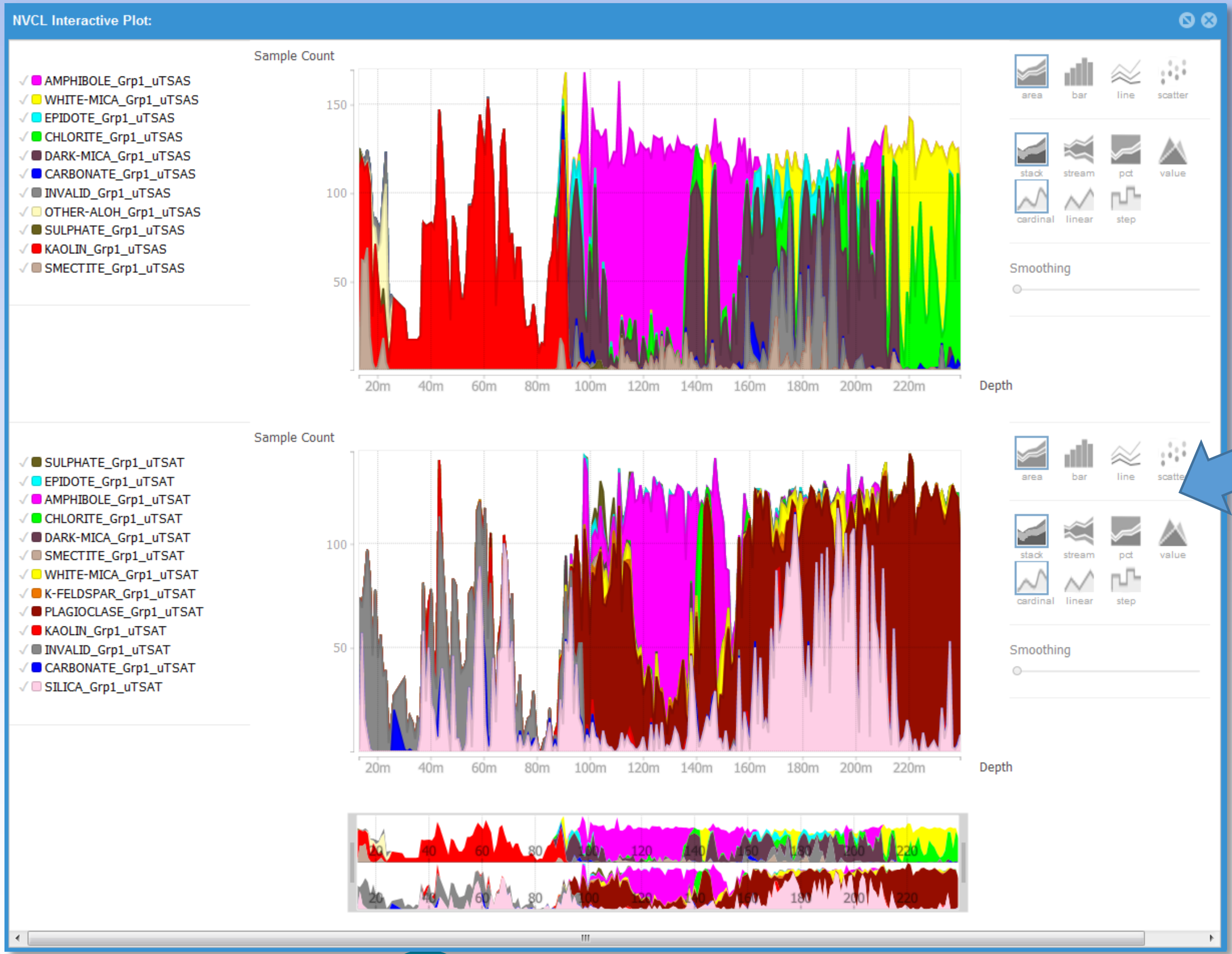
Technology Infrastructure

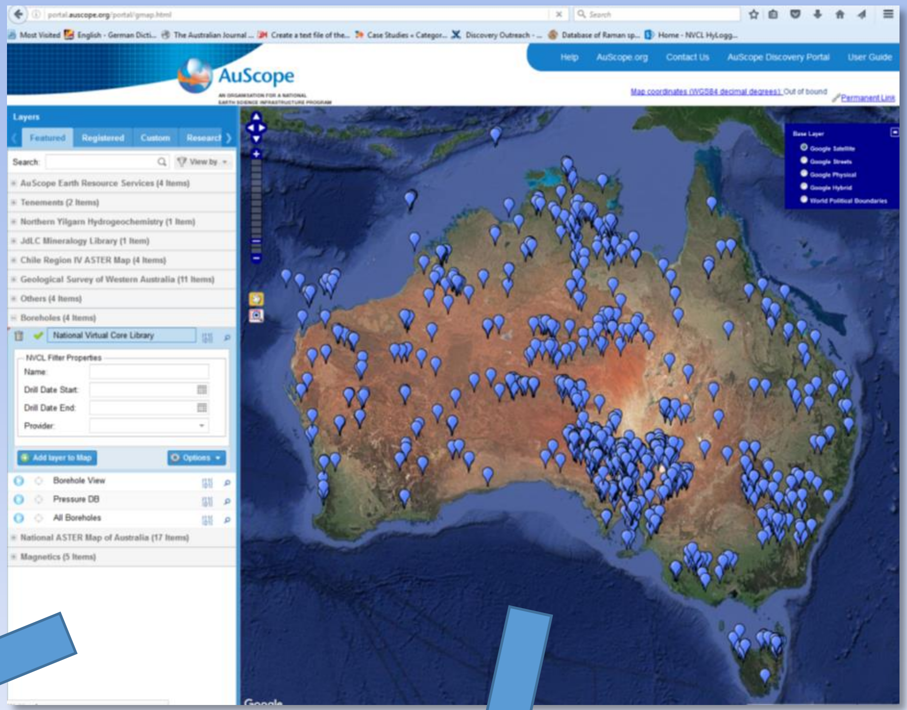
Human Infrastructure

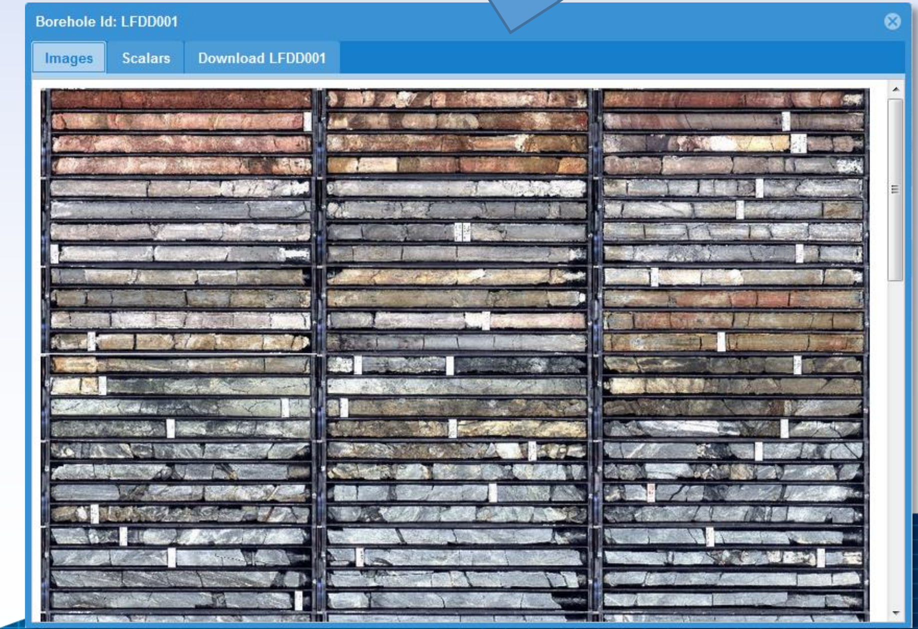
Database & Access Infrastructure



National Virtual Core Library







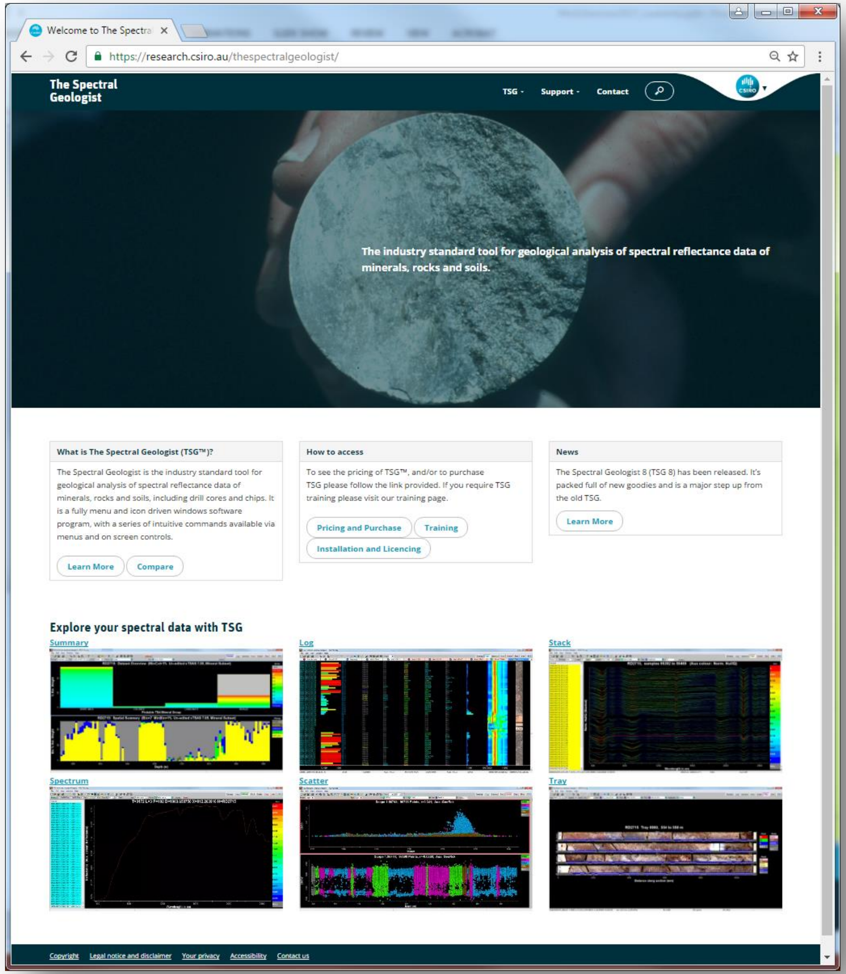
Summary

- Field spectrometers now able to characterize almost all rock forming minerals and vector minerals **<<< choose right system for your campaign!**
- Drill core/chips scanning allows rapid **collection of statistically significant amount of mineralogical data** (and you can ship drill core scanners on site!)
- Spectral sensing provides mineral chemistry that otherwise requires highly detailed lab work **<<< nature of the respective absorption features has to be understood**
- Geochemical (and petrophyscial, …) data can be modelled from hyperspectral data using chemometric methods
  - **identifying missed sample intervals**
  - **reducing costs**
- **Integration with other geoscience data!**
- **Understanding of mineral footprints in cover!!!**

TSG8 - The industry standard tool for geological analysis of spectral reflectance data from drill cores and chips

TSG (Premium Functionality) Timed license system	TSG Viewer
3 Years – $\$4500^{00}$	$\$0^{00}$
1 Year – $\$1800^{00}$	
90 Days – $\$495^{00}$	
30 Days – $\$170^{00}$	
7 Days – $\$100^{00}$	
24 Hours – $\$85^{00}$	

academic licenses @ reduced pricing available upon request



https://research.csiro.au/thespectralgeologist/

Andrew.Rodger@csiro.au Peter.Mason@csiro.au

Thank you

CSIRO Mineral Resources

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NVCL Project Leader

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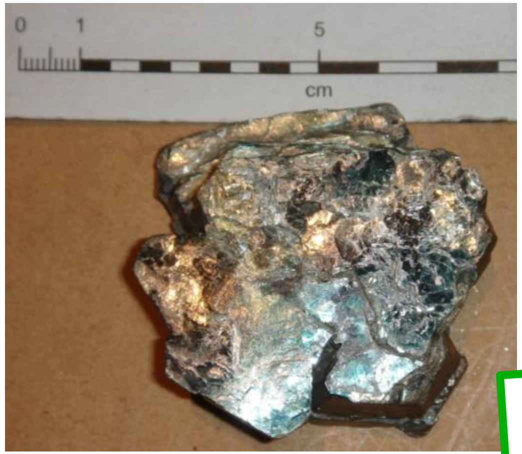
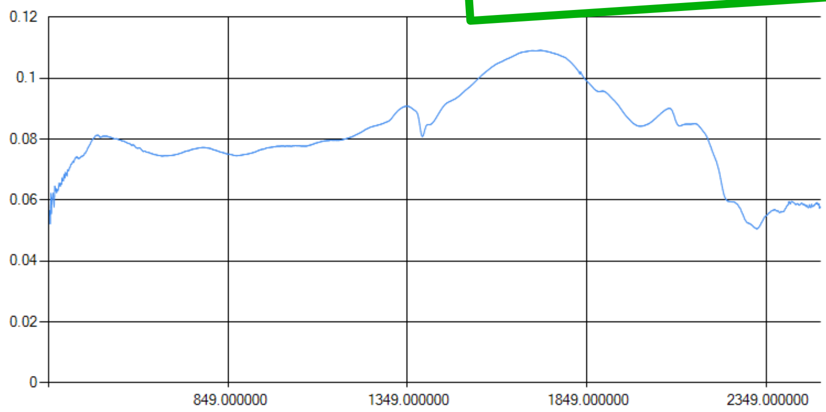
Spectral Reference Libraries

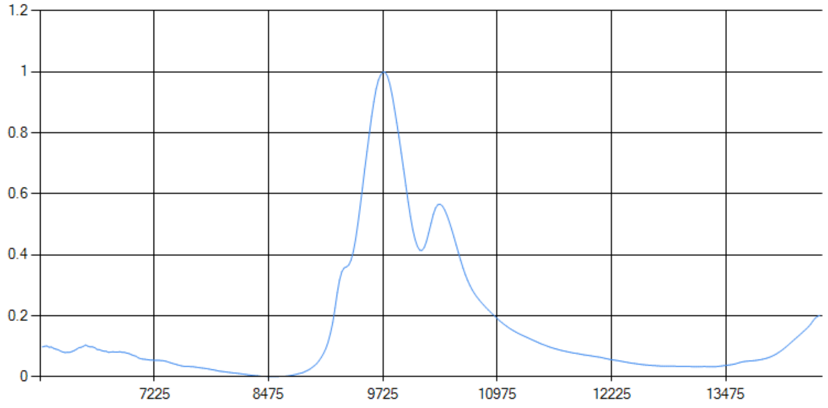
- CSIRO mineral spectral library: http://mineralspectrallibraries.csiro.au/Home/Samples
- Johns Hopkins University Spectral Library (JHU speclib: http://speclib.jpl.nasa.gov/documents/jhu_desc),
- USGS Digital Spectral library (USGS speclib: http://speclab.cr.usgs.gov/spectral-lib.html)
- Arizona State University Spectral Library (http://speclib.asu.edu/)
- JPL Spectral Library (http://speclib.jpl.nasa.gov/documents/jpl_desc; as part of ASTER Spectral Library 2.0).



Chlorite
IGSN: http://hdl.handle.net/10273/CSMS36

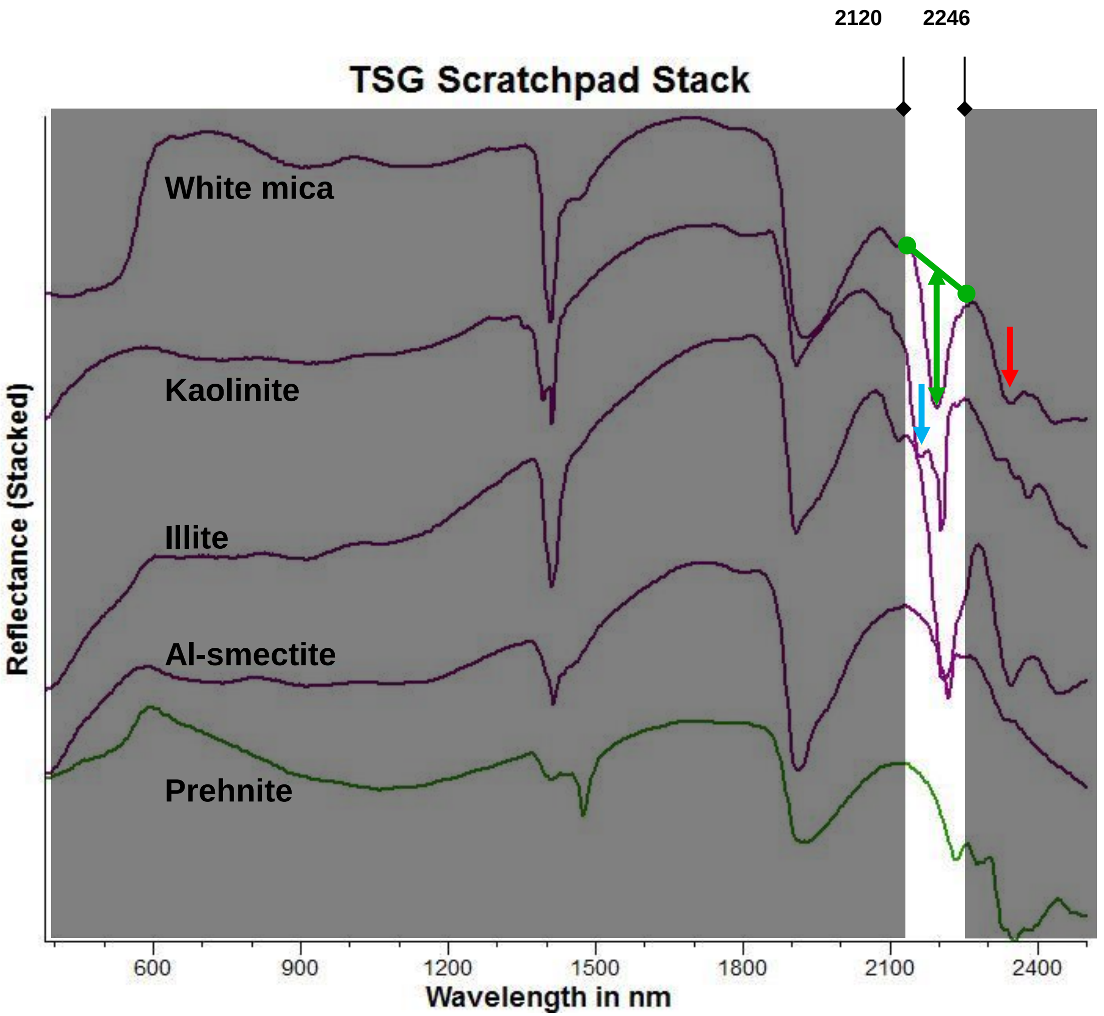
Validation!!!





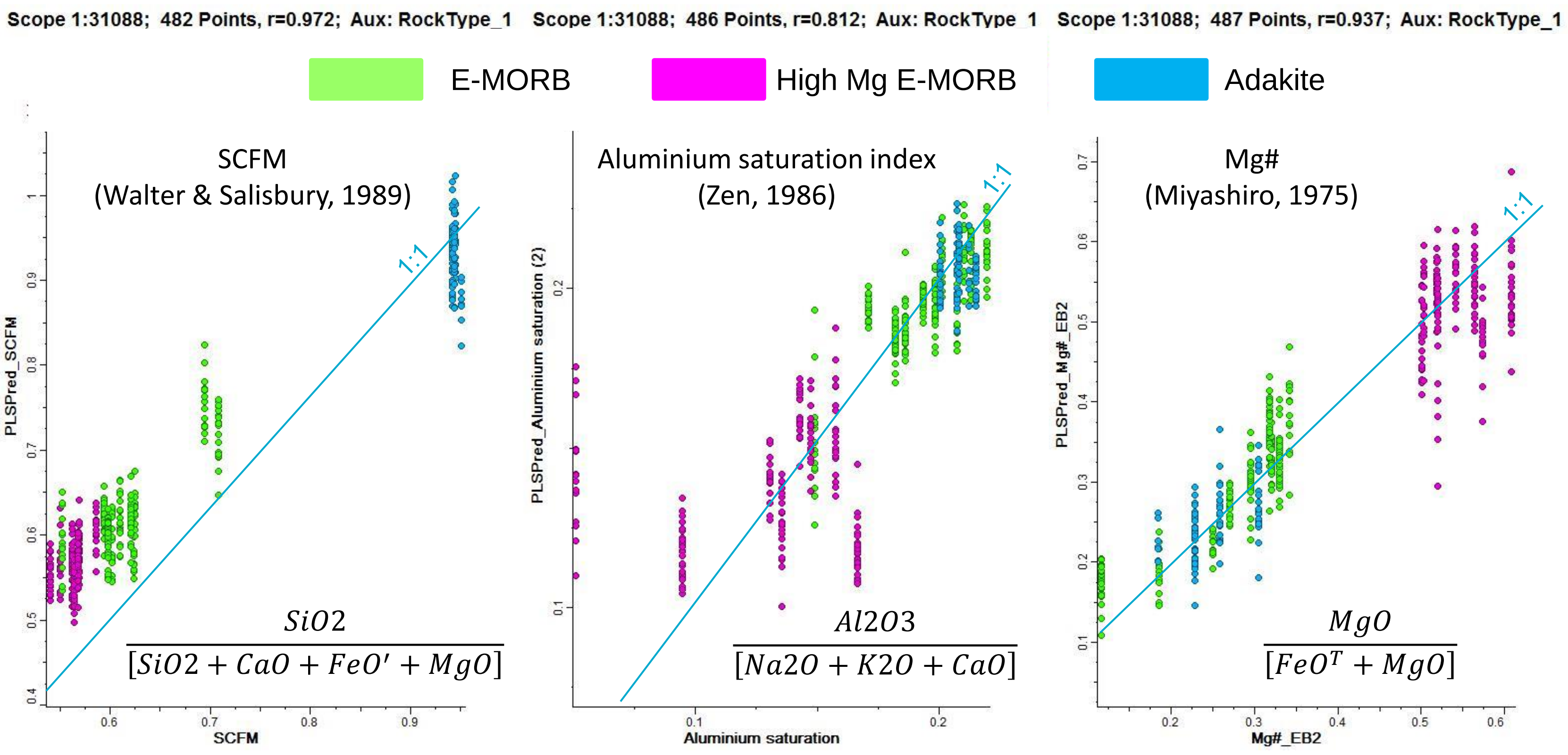
Standardisation of scalars for VNIR-SWIR and TIR active minerals

- "batch scripts"
  - Relative depth (all λ) or peak height (TIR) = relative abundance
  - Wavelength position = composition
  - Assymmetry, FWHM = crystallinity, composition
- Multiple Feature Extraction Method
  - mineral group relative abudance/composition
- Implementation of other published scalars in The Spectral Geologist (TSG8)
  - Illite Spectral Maturity Index (ISM, Doublier et al., 2010)
  - Amphibole/talc abundance index (Laukamp et al., 2012)
  - Iron Oxide Composition Index (Haest et al., 2012)
  - Plagioclase composition index (Cudahy et al., 2009)
  - …



Eucla Basin case study - workflow

5. A Partial Least Squares (PLS) regression method was applied to model geochemical indices from hyperspectral data by using GSWA's geochemical analyses as calibration samples.

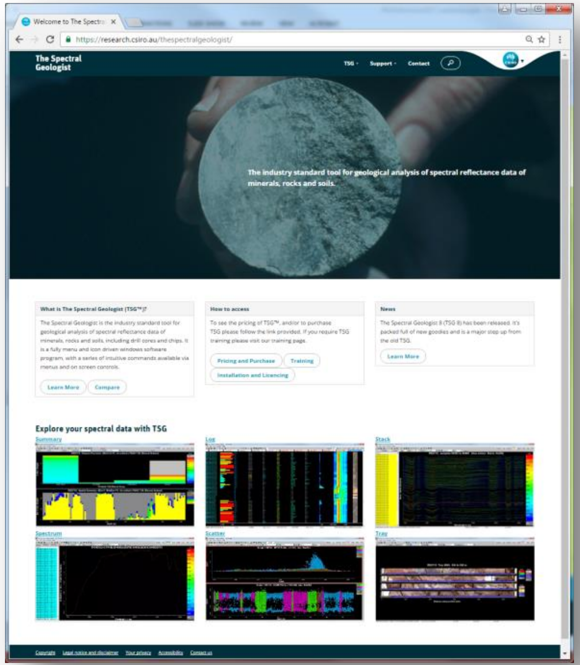


TIR active minerals

SWIR & TIR active minerals

SWIR active minerals

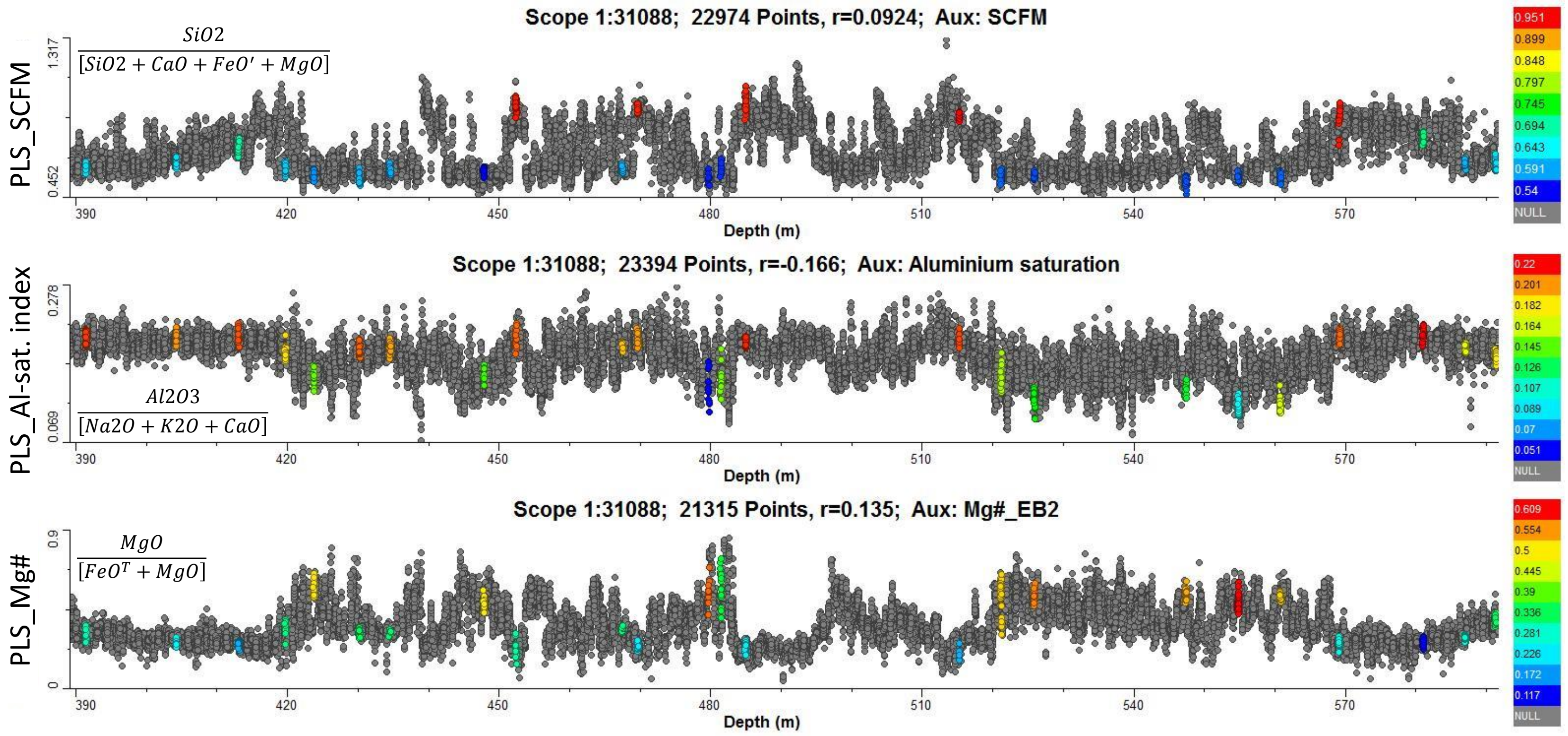
PLS module in TSG8



https://research.csiro.au/thespectralgeologist/

Eucla Basin case study - workflow

6. Modelled geochemical indices allow more detailed characterisation of basement rock types.

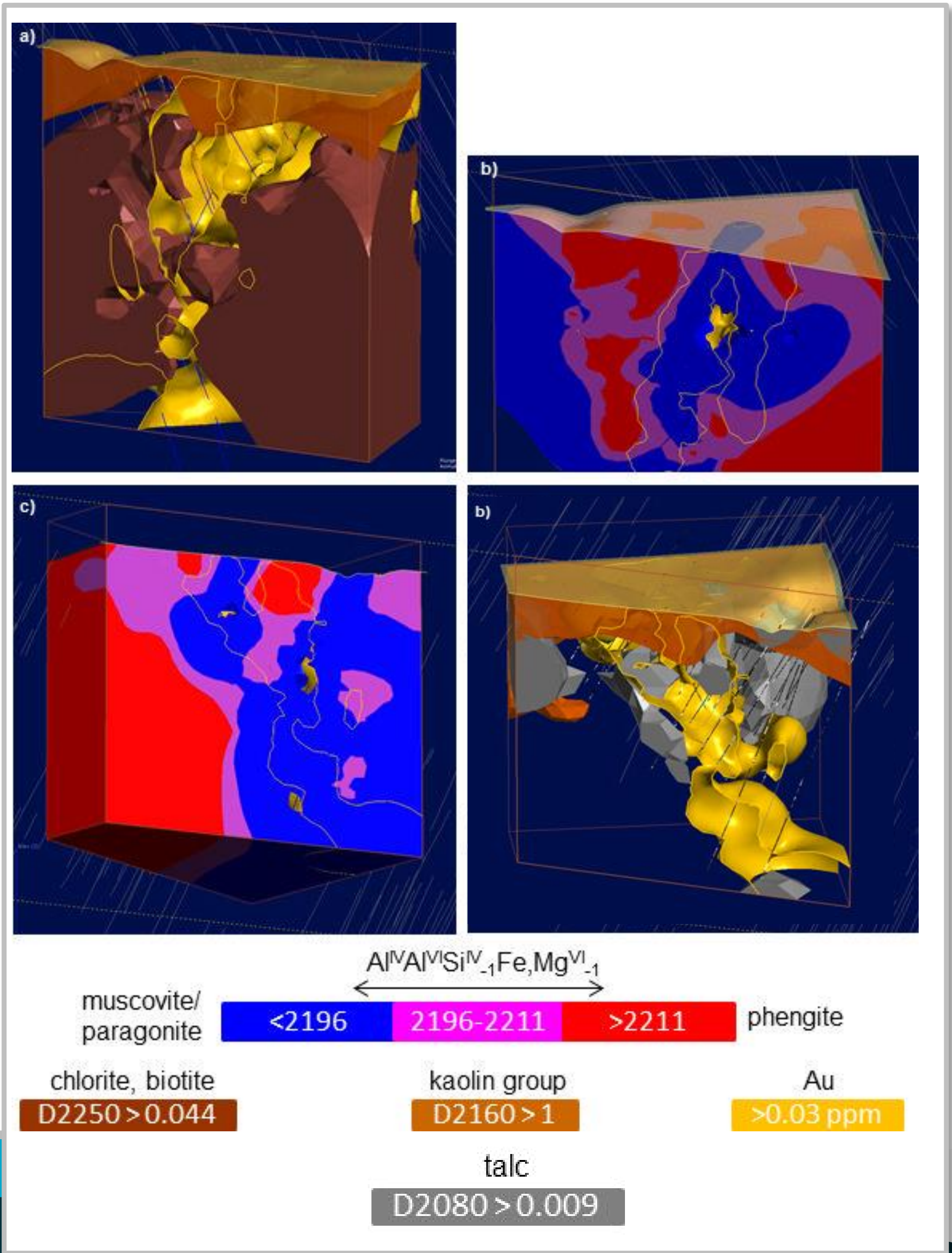


Modelled geochemical indices (coloured by actual values calculated from reported XRF results) show trends within basement rock types and across lithological boundaries

Integration of surface and subsurface data:
3D mineral mapping

- HyLogger (2500 chip samples)
- pXRF (250 chip samples)
- HCl3 (22 drill cores; 1850m)
- whole rock geochemistry
- airborne hyperspectral

- Talc-carbonate alteration and Al-rich white mica halo around NNE-trending, NW-dipping ore deposit.
- Al-poor white mica distal. However, signal of the NW side of footprint is overlapping with Fe-rich kaolinite closer to the surface (white frame).
- Fe-rich kaolinite and Fe/Mg-smectites currently investigated as potentially surface expressions of host-rocks OR alteration pattern.
- TIR-HyLogger data being investigated whether sodic or potassic mica.



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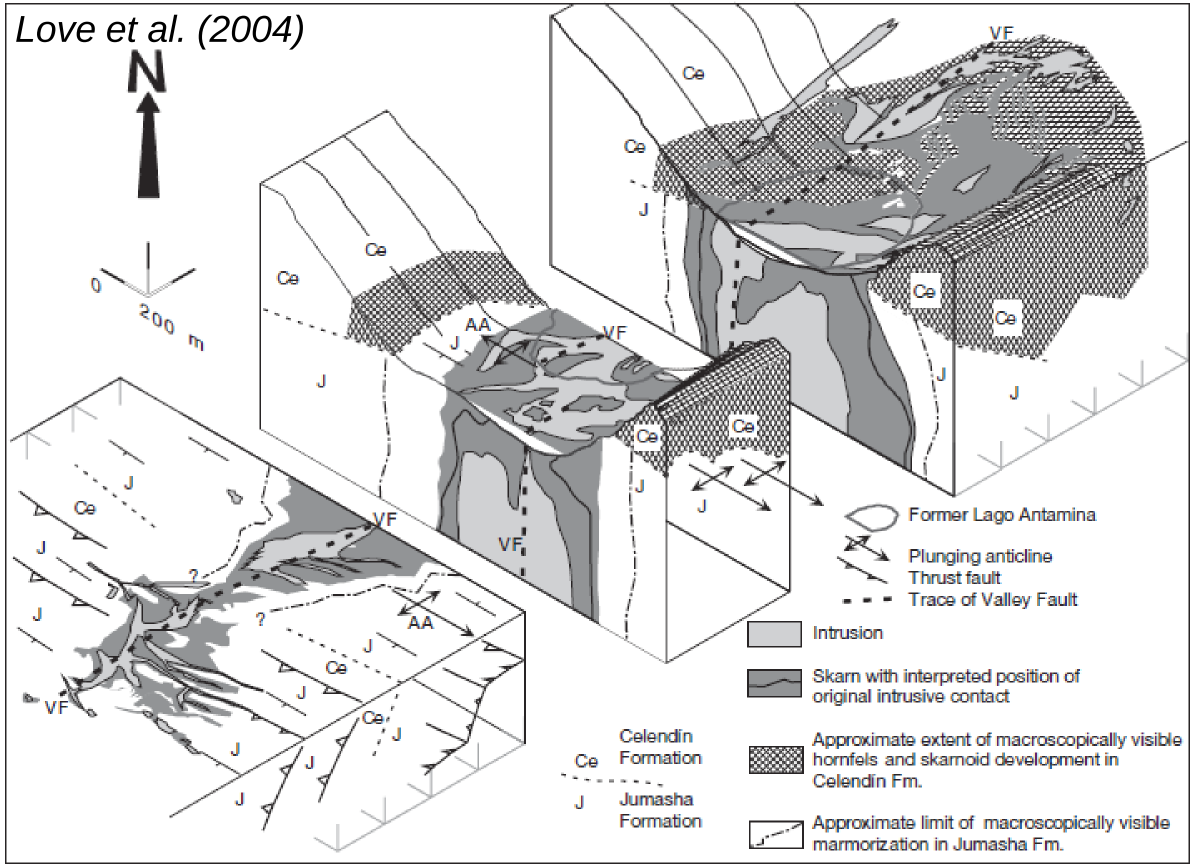
Antamina skarn-hosted Cu-Zn-Mo deposit, Peru

- Quartz monzonite porphyry intruded Upper Cretaceous sedimentary rocks of the Jumasha and Celendin Formations,
- Skarn alteration along contact and crosscut by later stage hydrothermal breccias.
- **Mineralisation:**
  - **mainly Cu, Zn, Mo ± Ag and Bi,**
  - **majority of Cu-Zn ore present in <u>exoskarn</u> and,**
  - **majority of Cu-Mo ore in <u>endoskarn</u>**



Antamina skarn-hosted Cu-Zn-Mo deposit, Peru

Aims:

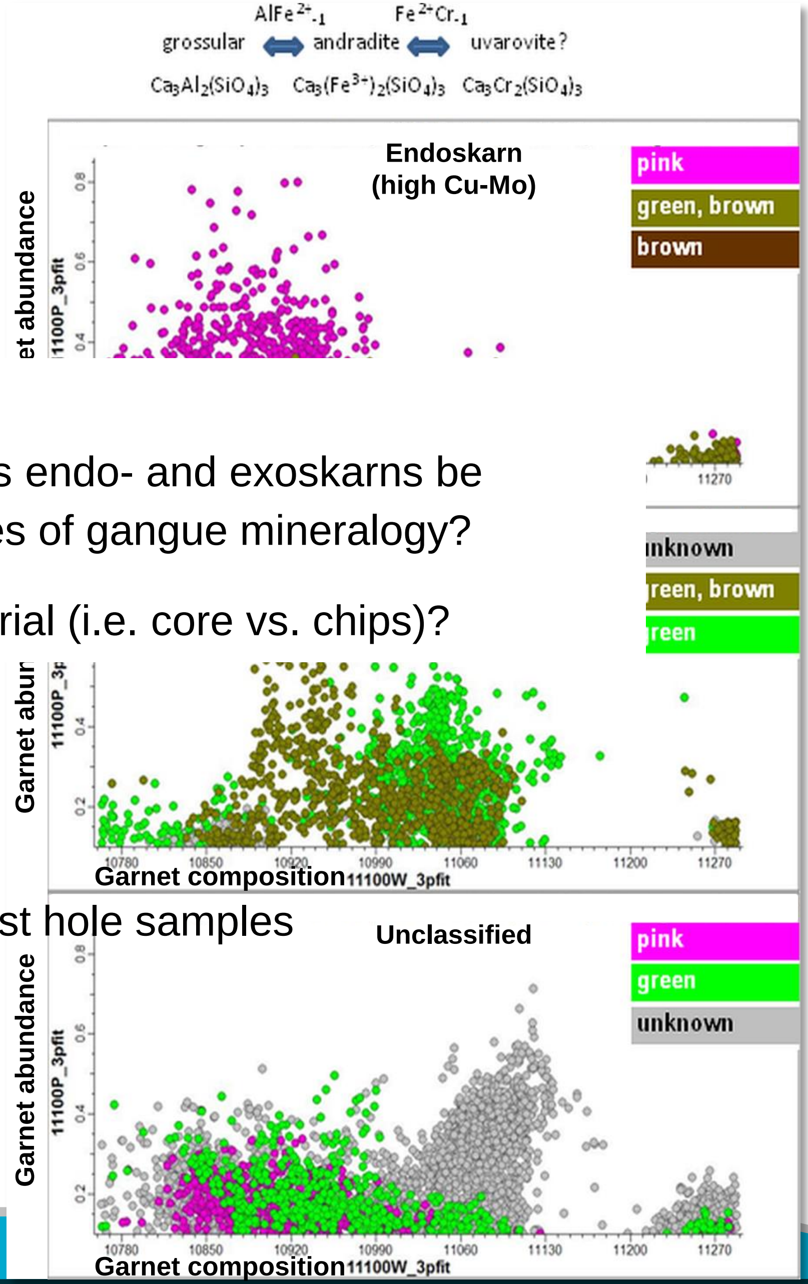
- Can ore variations of base metal ratios across endo- and exoskarns mapped on the base of compositional changes of gangue mineralogy?
- Variations of base metal ratios across endo- and exoskarns associated with changes in gangue mineralogy (that is mineral assemblages and compositional changes, for example, in garnets)

ss endo- and exoskarns be
jes of gangue mineralogy?

terial (i.e. core vs. chips)?

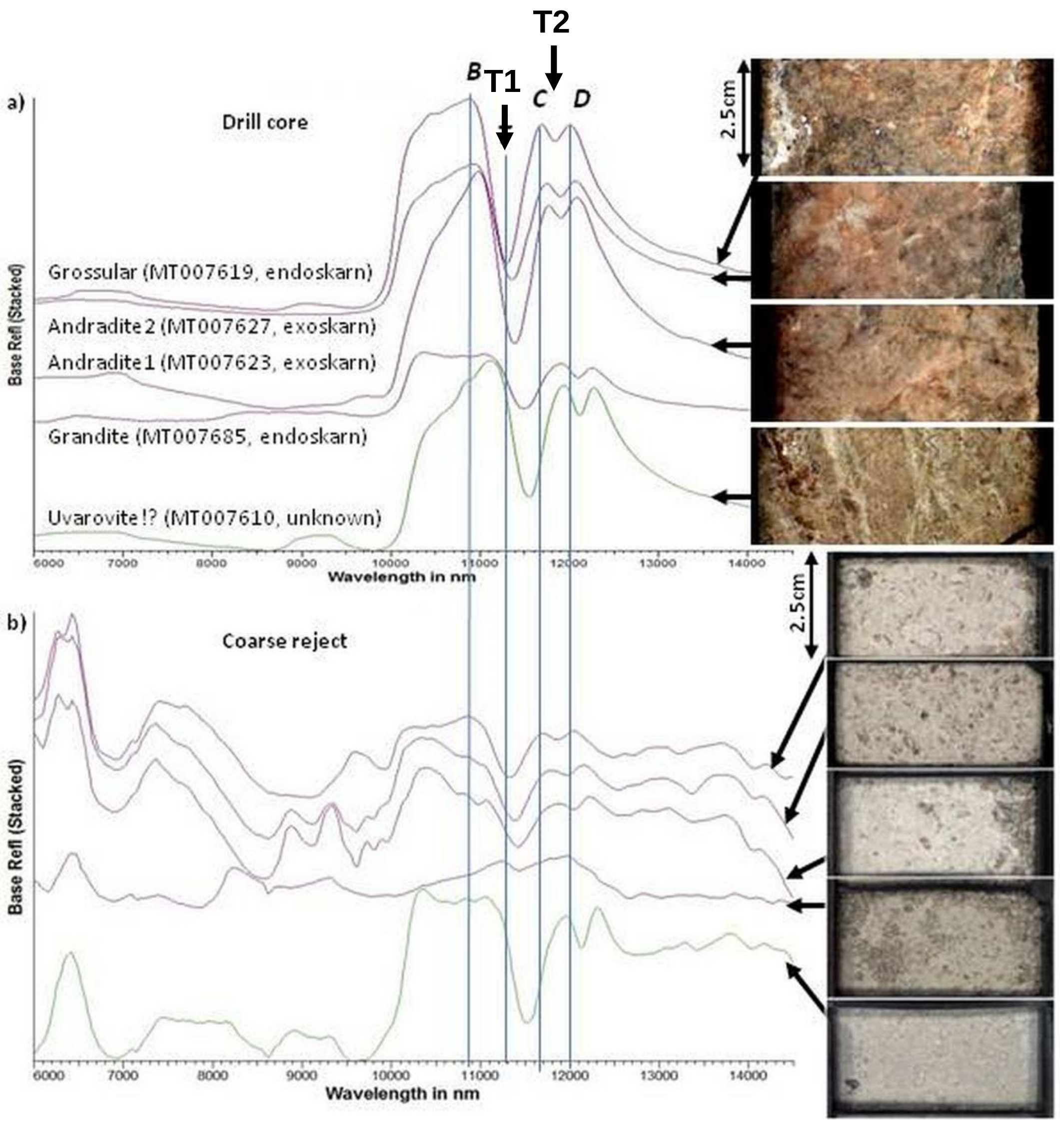
Methods:

- HyLogging data acquired from drill core & blast hole samples
- XRD
- EPMA
- Infrared microscopy



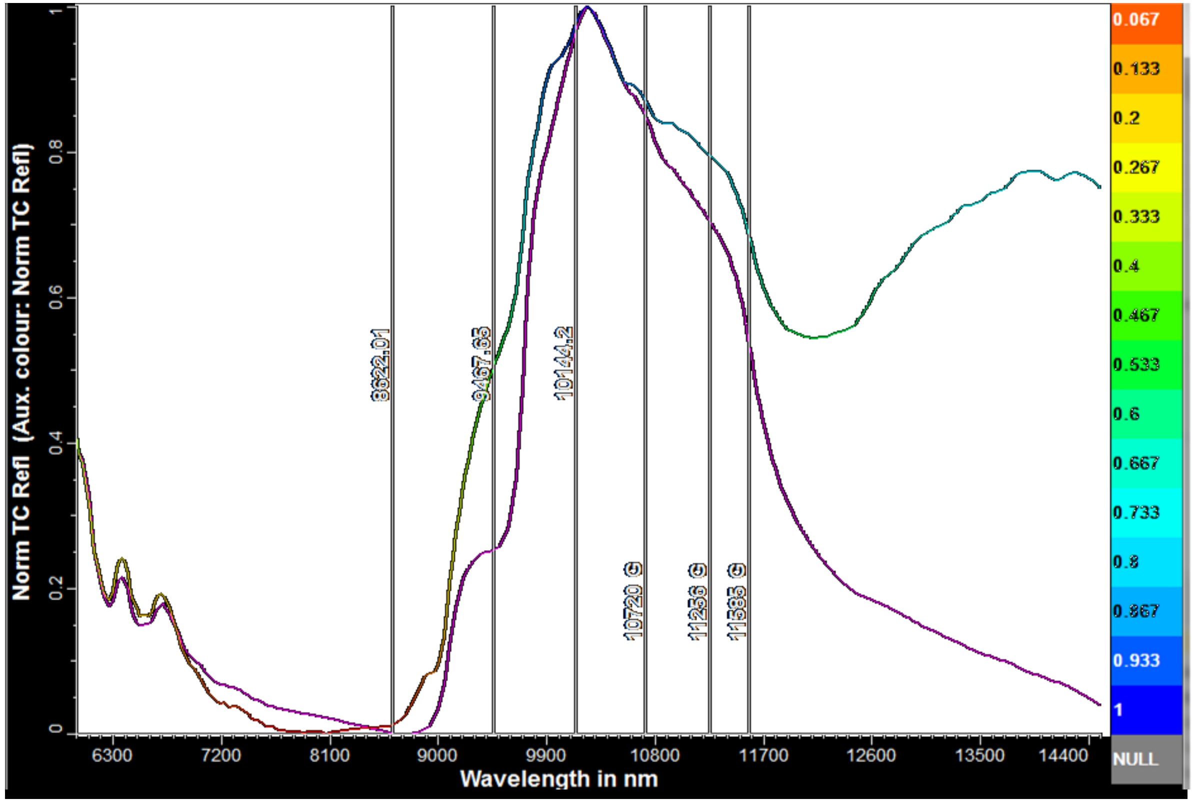
Antamina skarn-hosted Cu-Zn-Mo deposit, Peru

- Quality of results dependant on sample material (i.e. core vs. chips)?
- Dependant on target mineral, though only negligible impact on key minerals (e.g. garnet)

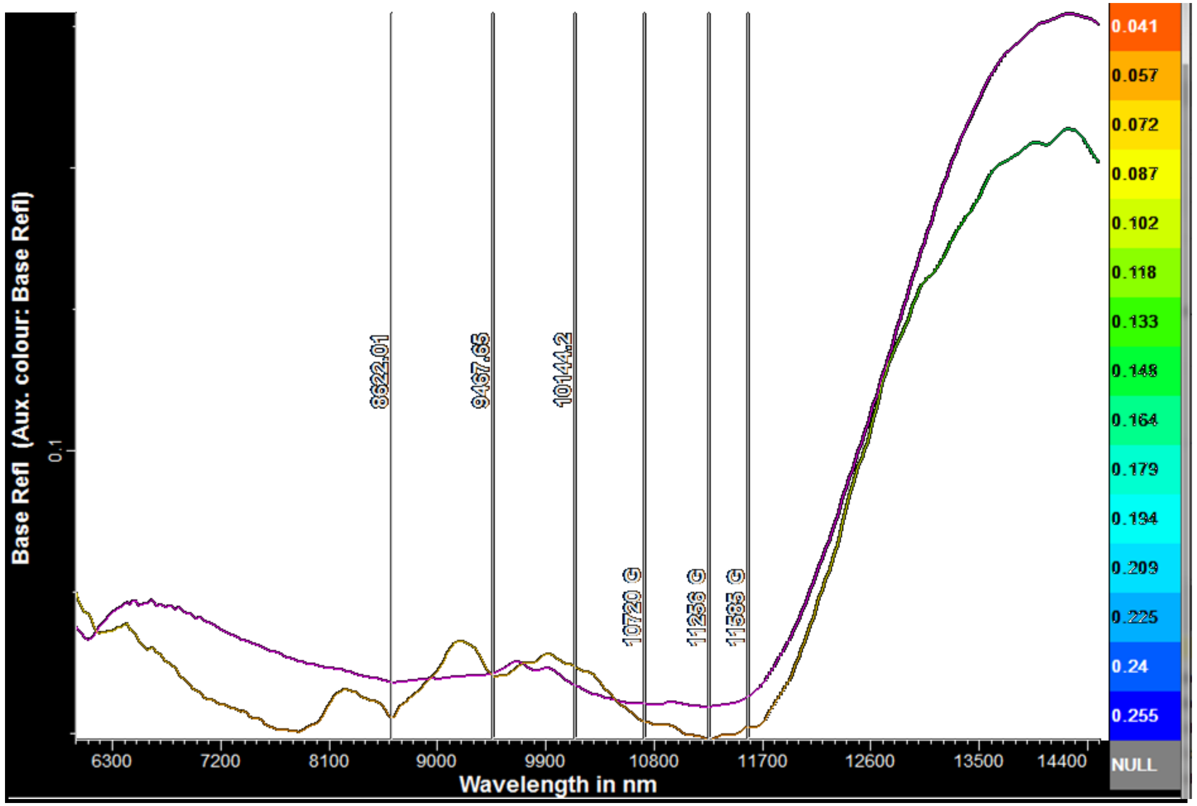


Application: Heavy minerals II

Zircon

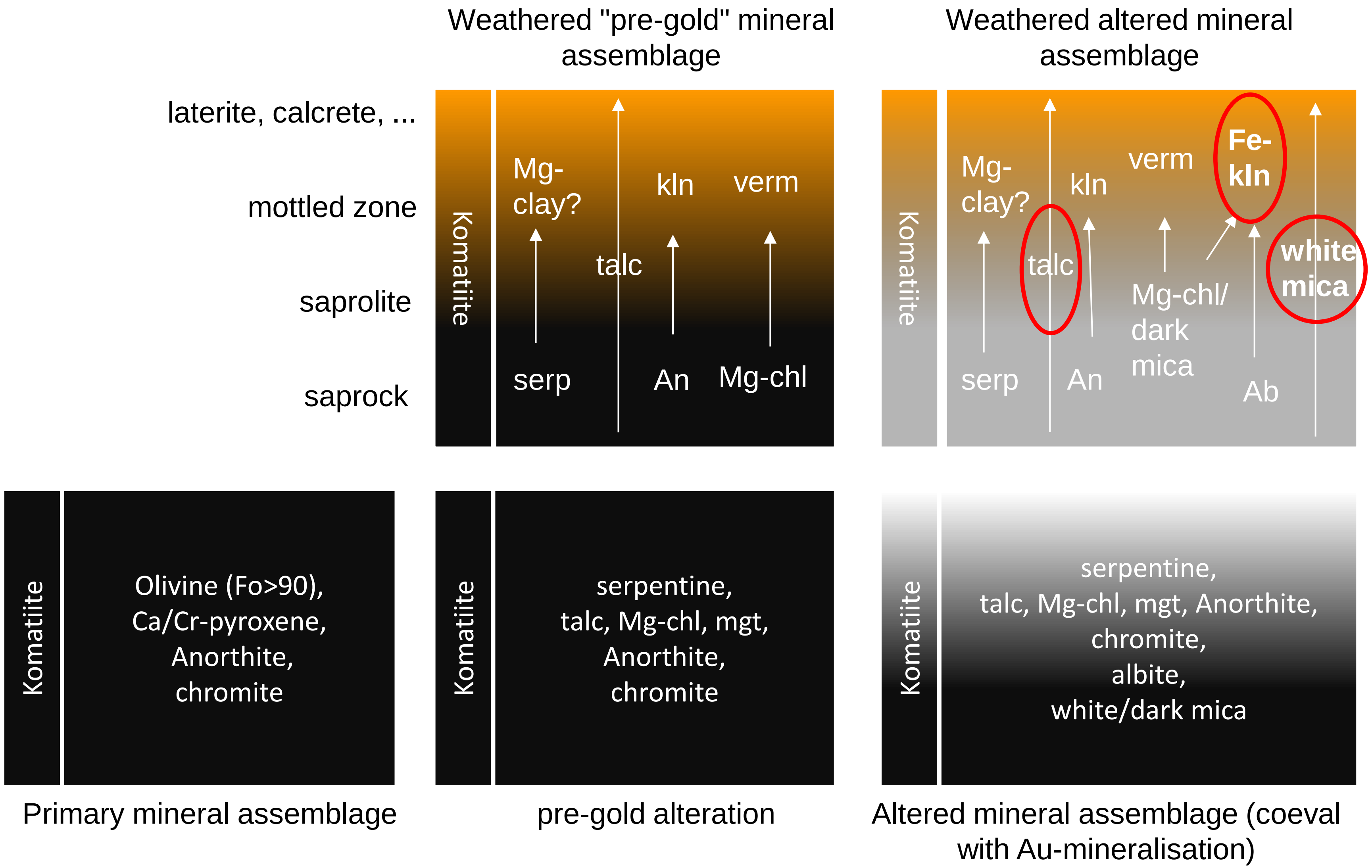


Ilmenite + quartz, rutile, zircon, almandine



HyLogger-TIR spectra; courtesy of Alan Mauger (GSSA NVCL node)

Exploration THROUGH Cover - Archean Au



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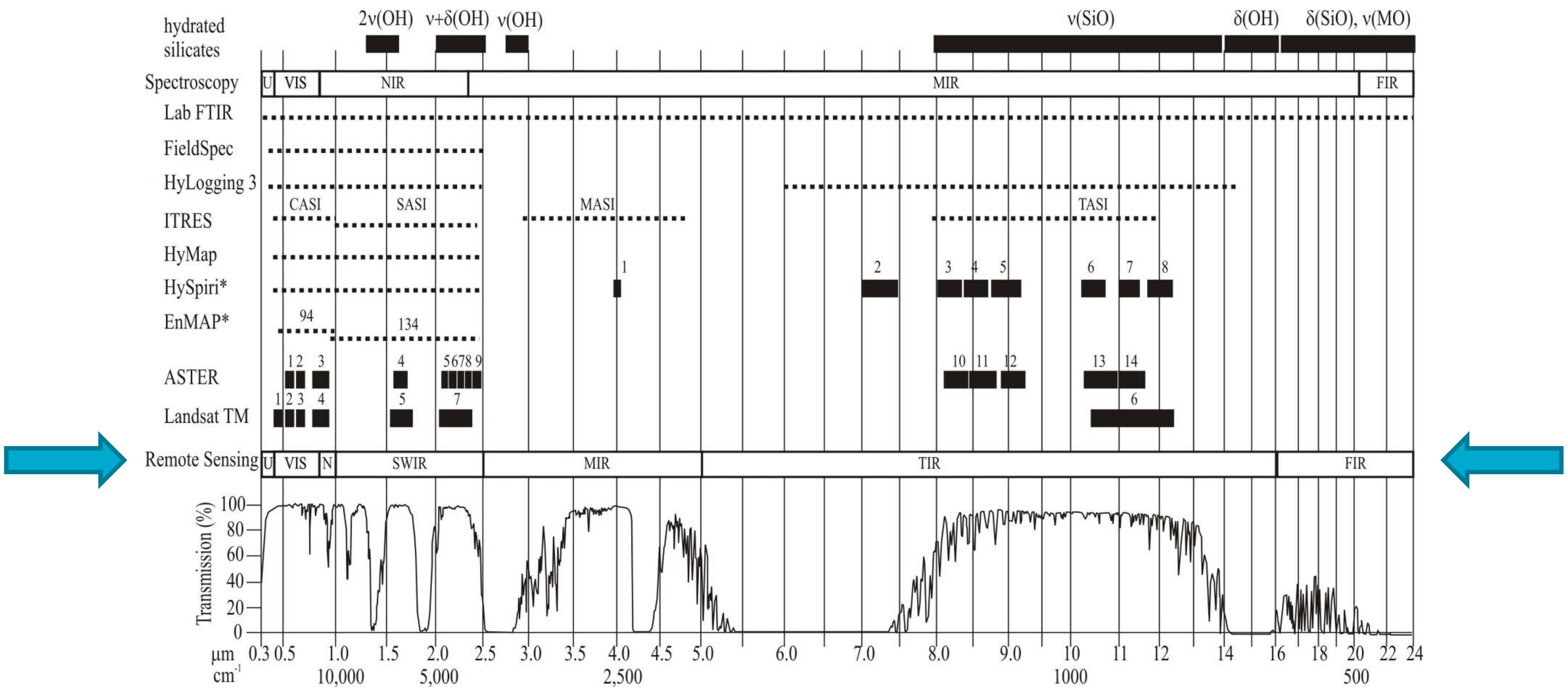
Wavelength nomenclature for this talk

and spectral sensing instruments, active wavelength regions & spectral resolution



Laukamp et al. (2017) Chapter 6. Exploration and discovery. In: Gräfe, et al. (2017) Clays in the Minerals Processing Value Chain. Cambridge University Press

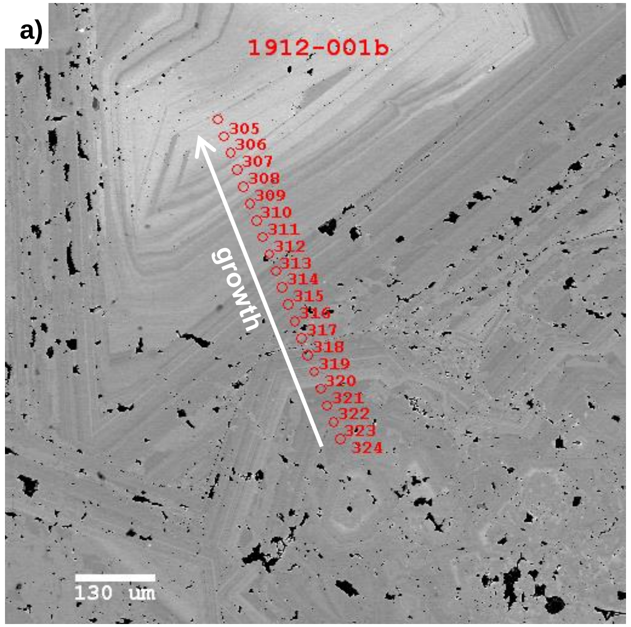
Summary of selected drill core hyperspectral technologies

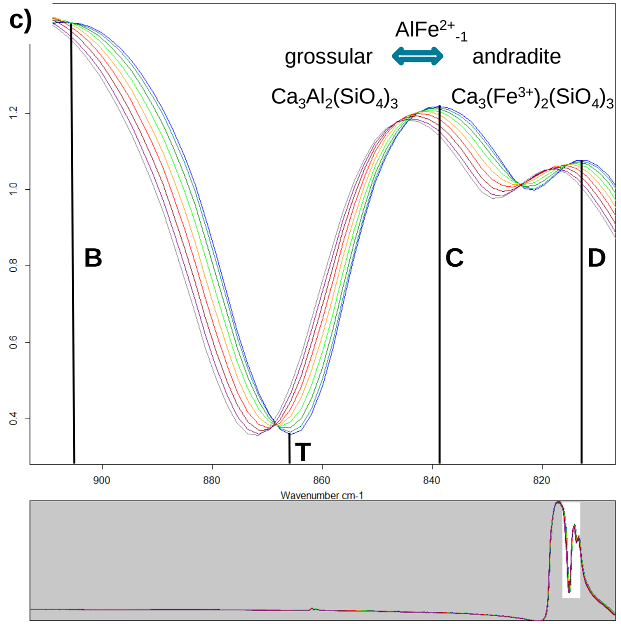
	Imaging				line profiling		
	HCI3 (Corescan)	Fenix (Specim)		Owl (Specim)	HyLogger (Corescan/CSIRO)		
Wavelength range	VNIR/SWIR: 350 to 2500 nm	VNIR: 400 - 1000 nm	SWIR: 970 to 2500 nm	LWIR: 7700 to 12000 nm	VNIR: 380 to 1000 nm	SWIR: 1000 to 2500 nm	TIR: 6000 to 14500 nm
Spectral resolution	ca. 4	3.3 nm	12 nm	100 nm	4 nm	4 nm	25 nm
Spatial resolution	0.5 px^2 (note that images are down sampled 5x5 for interpretation)	0.64 mm	2 mm	1.7 mm	10 mm across track x 14 mm along track @ 4 mm sampling interval 10 mm across track x 18 mm along track @ 8 mm sampling interval		
RGB image resolution	50 µm				0.1 mm		
Scan rates	200 to 1000 m per day	Scan time for single core box: 15 s	Scan time for single core box: 20 s	Scan time for single core box: 17 s	1 metre per minute		
Output data format	All: BIL file format, ENVI/Evince compatible						

AlFe^{2+}$_{-1}$ in ugrandite series

Antamina skarn-hosted Cu-Zn-Mo deposit, Peru

EPMA and infrared microscopy

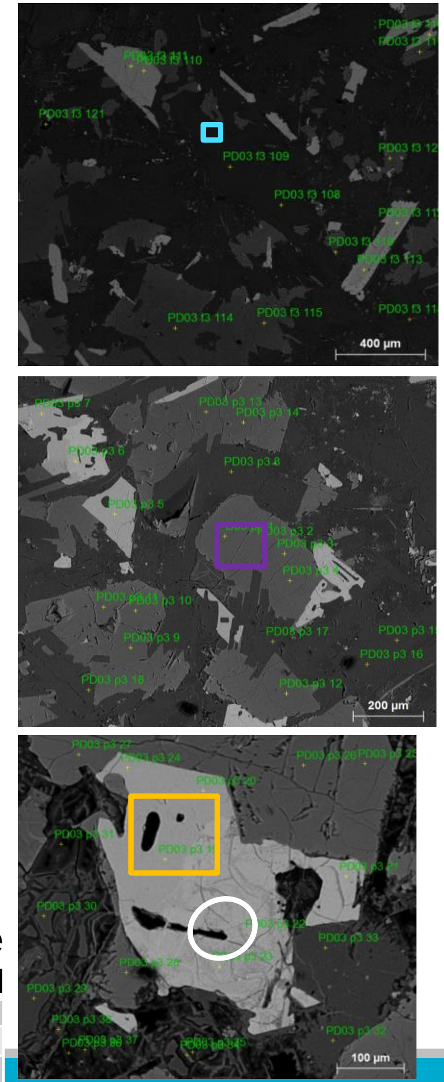




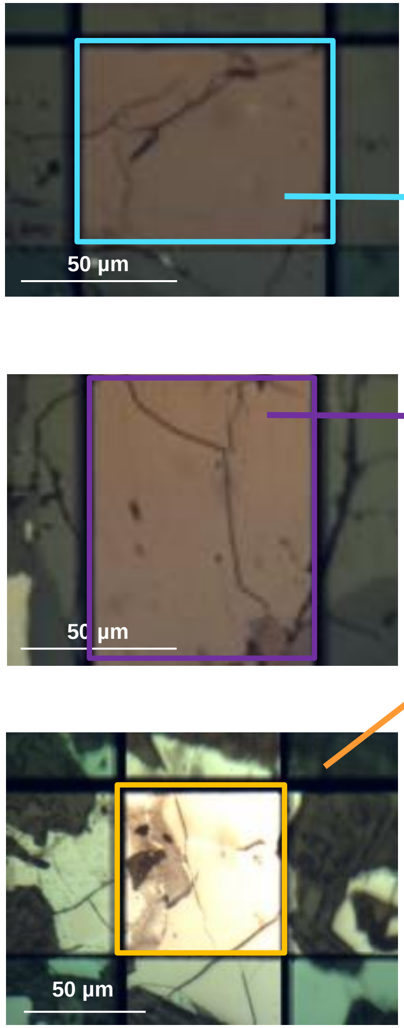
sulphide mineralisaton associated with compositional change of garnet from grossular to andradite

Application: Heavy minerals I

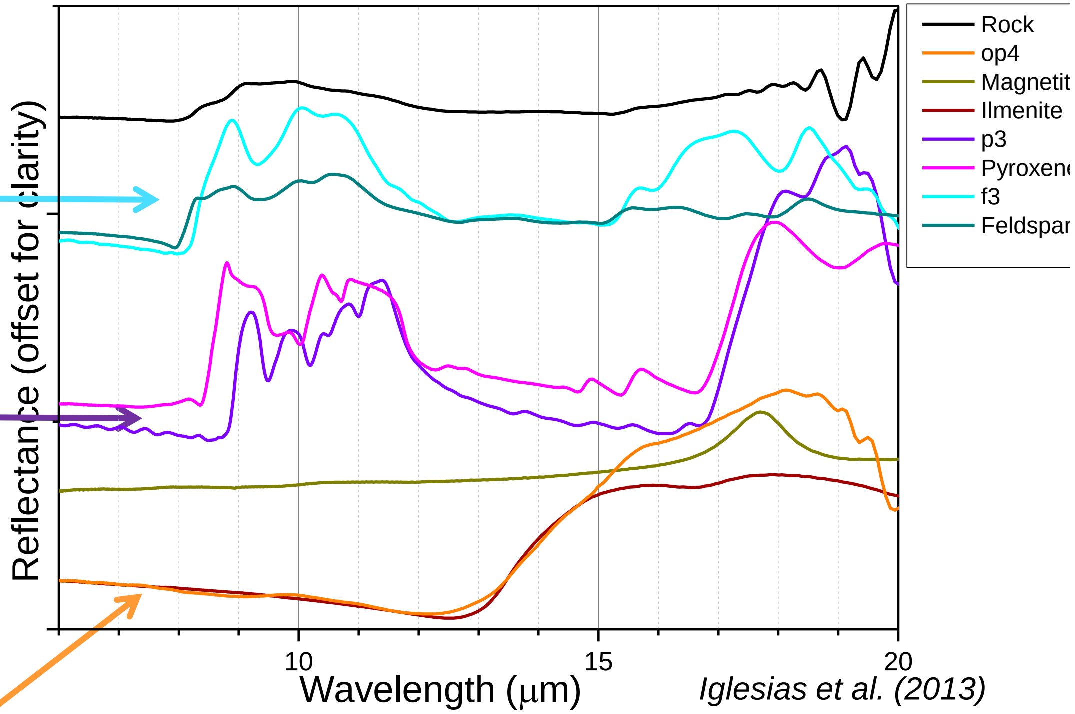
SEM



Hyperion



Thermal Infrared Data



Iglesias et al. (2013)

Ilmenite

OP4	Wt %
FeO	45.53
TiO2	54.47

Titanomagnetite

OP4	Wt %
FeO	63.95
TiO2	33.48
MnO	2.57