



Welcome!

The program will begin soon.
You will not hear audio until we begin.



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Multi-Sensor Core Logging – The Future of Core Analysis

Craig Lindsay
Craig.Lindsay@core-specialist-services.com
Core Specialist Services
Society of Core Analysts Industrial Relations Liaison
SPE Reservoir Technical Discipline's Advisory Committee - Reservoir Technology of the 21ST Century,
sub-committee Core Analysis



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What do Core Analysts study?

The properties of geological materials!



WPS TAS SPB TPSC WAG TPV TAB/TPDG TPG WPD

Photos of the rock samples prepared for physical property characterisation. *WPS* sandstone from Raon l'Etape, *TAS* sandstone from Waldhambach, *SPB* sandstone from Saint Pierre Bois, *TPSC* breccia from Albersweiler, *WAG* granite from Saint Pierre Bois, *TPV* hydrothermally altered volcanic rock from Albersweiler, *TAB* hydrothermally altered andesite from Waldhambach, *TPDG* metabasite from Albersweiler, *TPG* metagranite from Albersweiler, *WPD* dolomite from Raon l'Etape

Characterizing the physical properties of rocks from the Paleozoic to Permo-Triassic transition in the Upper Rhine Graben

Alexandra S.L. Kurling¹, Michael J. Healy², Patrick Brand³, H. Albert Gilly⁴, Thierry Bruchési⁵, Catherine Laroque⁶, Christel Deshayes⁷ & Philippe Durlugan⁸

Geothermal Energy • Article number 16 (2019) | [Cite this article](#)

<https://geothermal-energy-journal.springeropen.com/articles/10.1186/s40517-018-0103-6/figures/3>



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This presentation....



- Material is included from a wide range of sources
- Inevitably vendor specific equipment are show
- Vendor specific workflows are illustrated
- Custom ML / AI workflows are illustrated
- There is no intended bias by the author for any specific provider, workflow or analytical method
- Other providers of above may be equally capable and have alternate approaches – there is no malicious intent by their omission
- All sources are referenced / credited where possible
- The intention is to inform / enlighten



THANK YOU TO ALL SOURCES

5

Traditional and Current Instrumentation Routine Core Analysis (RCA, CCA)



Porosity



Permeability



Matrix Density



Porosity &
Permeability



Water saturation



Permeability



Core gamma ray



Mainly specific to conventional oil and gas reservoirs.

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Traditional and Current Instrumentation Special Core Analysis (SCAL)



Mainly specific to conventional oil and gas reservoirs.

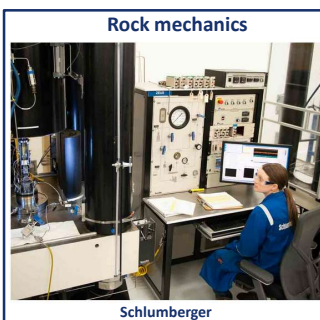
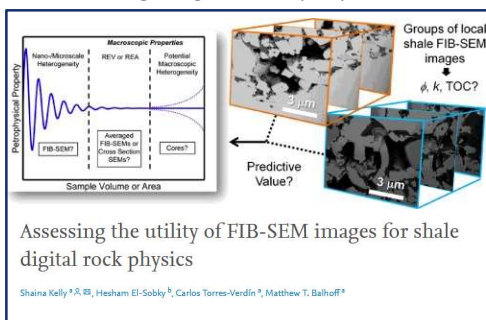
7

Analysis of Unconventional Core (shale, tight gas)



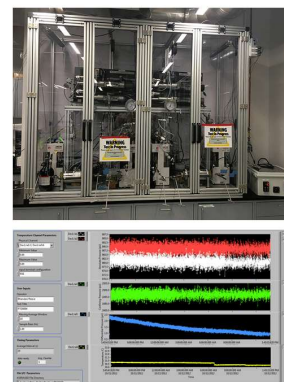
Generally much more problematic;

- Very low permeability and porosity = problematic
- Hydrocarbons not in pores (adsorbed)
- No standard instruments / no agreed standards = data difficult to compare
- Many “conventional” tests difficult or impossible
- Some “heritage” methods still used – retort, GRI (crushed core) = qualitative
- Rock mechanics important - for fracing
- Digital methods more practical (time, cost and feasibility)?
- Core / log integration very important



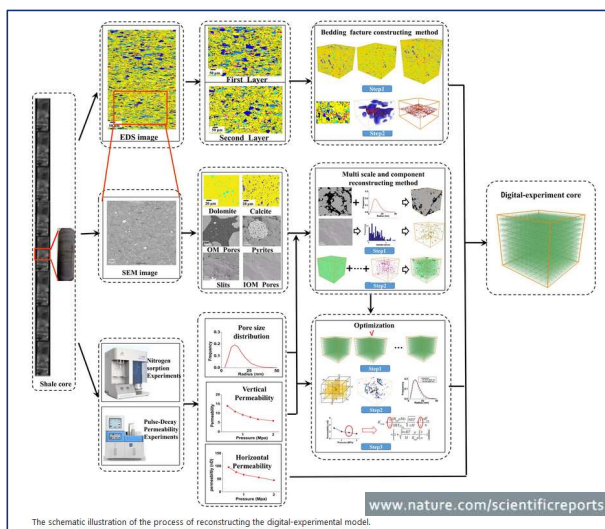
Permeability Measurements

In the GeoMechanics lab we run permeability tests over a wide range of permeability space, from loosely consolidated sands to tight gas shales. We have four distinct systems to measure permeability: a Darcy permeameter, derived through low-pressure triaxial testing, on mudstone samples during CRS testing, and steady state or pulse transient decay permeability on tight gas shales in a biaxial core holder.



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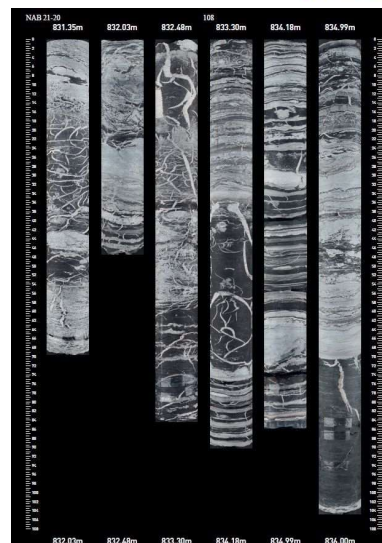
Mudrock digital analysis = Complex & High Tech.



A core-scale reconstructing method for shale

Lili Ji¹, Mian Lin^{1,2}, Gaohui Cao^{1,2} & Wenbin Jiang^{1,2}

www.nature.com/scientificreports

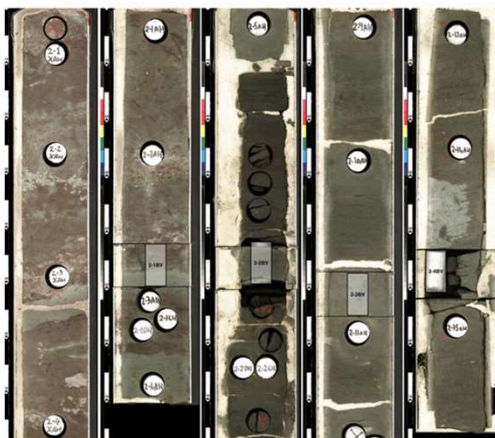


Arbeitsbericht NAB 21-20 Dossier II <https://www.nagra.ch/de>



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Sampling for standard Core Analysis Studies



Industry standard practice for core sampling;

- RCA every 25 cm or 1 ft.
- SCAL several per facies type (guided by RCA)

Standard sampling methods barely scratch the surface in terms of truly representing the core properties & only provide snapshots of core properties

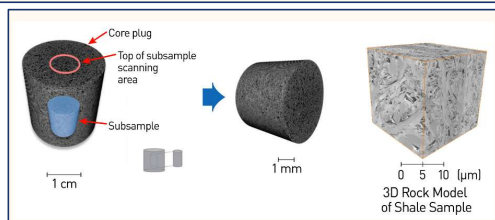
The same applies a wide core based studies such as geomechanics, petrography, geochemistry, formation damage and many more

ONLY standard "continuous" data are core gamma, probe permeability and core imaging.



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How representative is your digital core analysis sample?

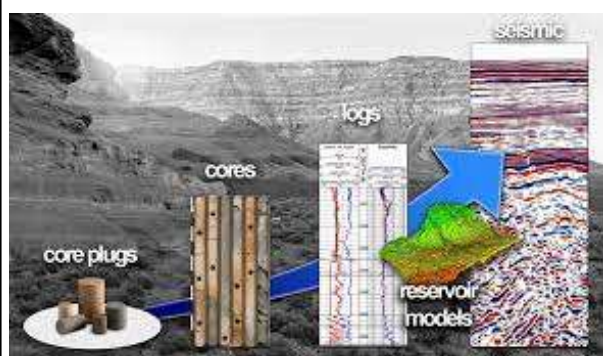


iRock Technologies
<http://www.irocktech.com.cn/en/laboratories/>

Scan type	ROCK SAMPLE SIZE	RESOLUTION RANGE	APPLICATION
3D whole core scan	10 cm to 1 m long 2.5 to 25 cm in diameter	100 μ m to 0.5 mm	Density logging Core plug selection Heterogeneity analysis Fracture analysis Digital core database
3D standard core plug scan	2.5 or 3.8 cm (standard)	12 to 40 μ m	Geological description Heterogeneity study
3D subplug CT scan	1 mm to 2.5 cm	0.5 to 12 μ m	3D detailed scan Microscale pore structure analysis
3D CT nano scan	2 or 200 μ m	1 to 200 nm	3D detailed scan Nanoscale pore structure analysis
3D FIB nano scan	2 or 200 μ m	1 to 200 nm	3D ultrahigh-resolution scan Pore network analysis on extreme samples (shale, tight gas, etc.)
2D nano scan	2.5 cm across or subareas	1 to 250 nm	Large FOV, nm to cm High-resolution image mosaics and analysis
2D mineralogy scan	2.5 cm across or subareas	12 to 50 μ m	Mineral identification and analysis

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The SCALE problem?



- The age old problem of scale
- Core plugs don't capture heterogeneity on a core scale
- Digital core analysis samples probably don't capture heterogeneity on a core plug scale
- We cannot cut and analyze plugs / sub-samples from the entire core – cost / practicality / time
- Selecting relevant / representative samples is critically important (VOI, cost, time)
- A lot of money is spent on high cost / critical value core tests but sampling methodology is critical
- Traditional sampling methods / criteria are not fit for purpose

PRESION SAMPLING FOR ADVANCED STUDIES

NOW POSSIBLE

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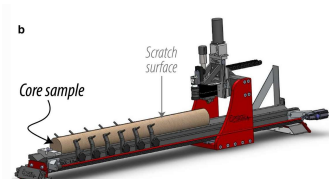
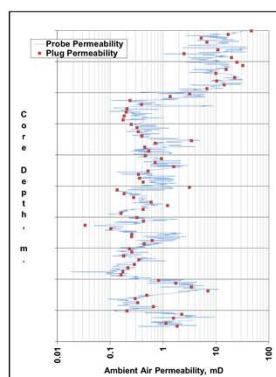
The Solution – continuous core data



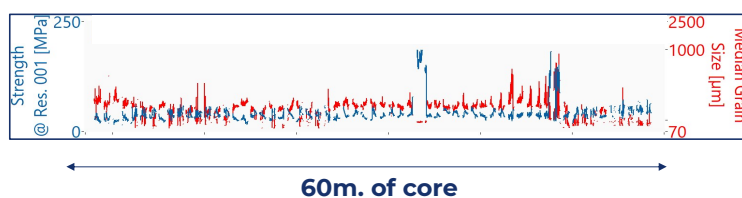
Continuous core data we have traditionally acquired contd.



Profile permeameter

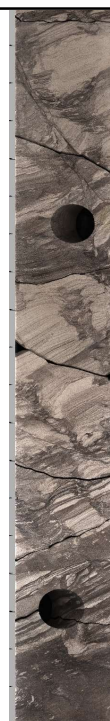


Scratch test (UCS)



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Core imaging then and now



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Permeability – How well is it Quantified from core plugs?



Core plug measurements at 1 per ft. – may not fully characterise the level of permeability heterogeneity – especially in laminated formations

How do we know?

Hurst and Rosvoll – proposed method to determine minimum number of measurements (N_o) to determine Arithmetic Mean Permeability $\pm 20\%$

Reducing the tolerances – unrealistic number of measurements

Calculate coefficient of variation,

$$Cv = \text{Standard Deviation} / \text{Arithmetic Average}$$

$$N_o = 100 Cv^2$$



HURST, A. and ROSVOLL, K.J. (1990) Permeability variations in sandstones and their relationship to sedimentary structures. 2nd International Reservoir Characterisation Technical Conference, Dallas

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Permeability versus Heterogeneity



- Based upon Cv **Corbett and Jensen** proposed heterogeneity classes:

- 0 - < 0.5 Homogeneous
- 0.5 - < 1 Heterogeneous
- > 1 Very heterogeneous

Three examples of applying these principles:

Rotliegend reservoir SNS

- 150 plugs acquired (1 per ft.)
- $Cv = 2.5$, $N_o = 625$ **Very heterogeneous**
- Plug alone data did not quantify permeability heterogeneity – probe permeability data @ 5 measurements per ft = 729 points.



A Comparison of Small-Scale Permeability Measurements Methods for Reservoir Characterisation

Jan 1991

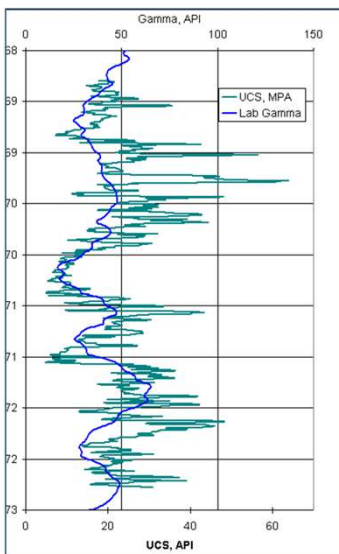
P W M Corbett - J L Jensen

Corbett, P. W. M., and J. L. Jensen, "A Comparison of Small-Scale Permeability Measurements Methods for Reservoir Characterisation," presented at the PSTI Advances in Reservoir Technology Conference, Edinburgh, February 21-22, 1991.

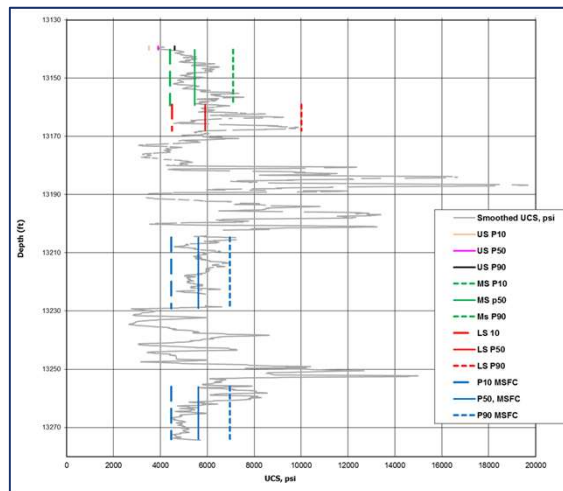
The Rotliegend reservoir in Block 30/24, UK Central North Sea: including the Argyll (renamed Ardmore) and Innes fields
Alan P. Heward, Paul Schofield and Jon G. Gluyas
Petroleum Geoscience, 9, 295-307, 1 October 2003, <https://doi.org/10.1144/1354-079303-578>

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Why continuous core data – basic examples of data correlations



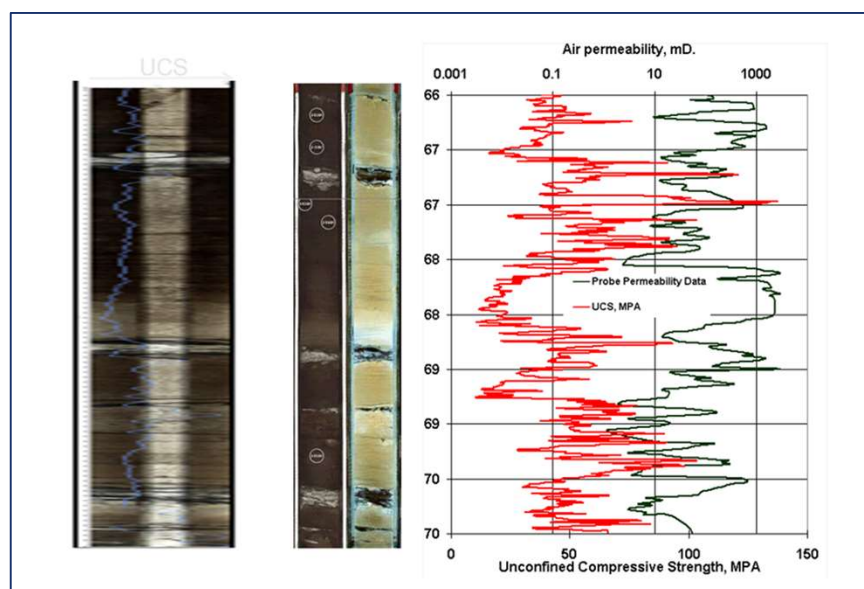
Rock
strength
&
Gamma
Ray?



UCS from scratch test to accurately define sampling points for rock mechanics study

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Why continuous core data – basic examples



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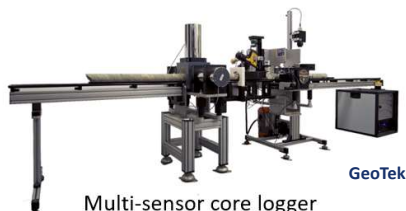
High Resolution Core Characterisation – Multi-Sensor Core Logging (MSCL)



New workflows for new core & New life for old cores



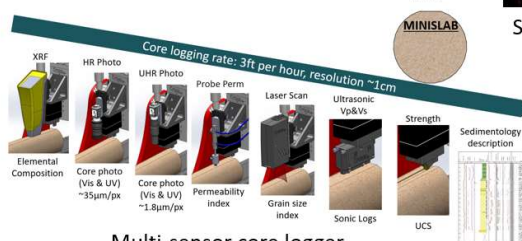
GeoTek



Multi-sensor core logger



Scratch Test
Epslog



Multi-sensor core logger

Epslog



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(Not so) Homogeneous Chalk?

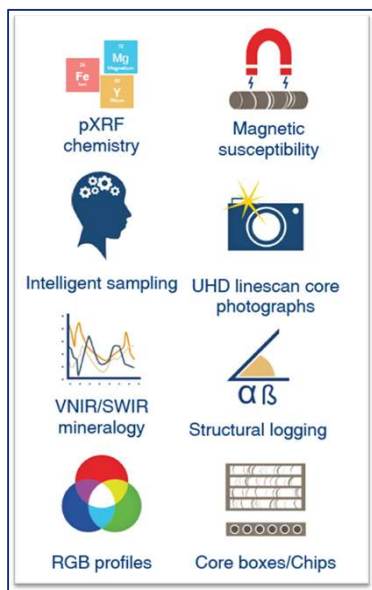


GeoTek

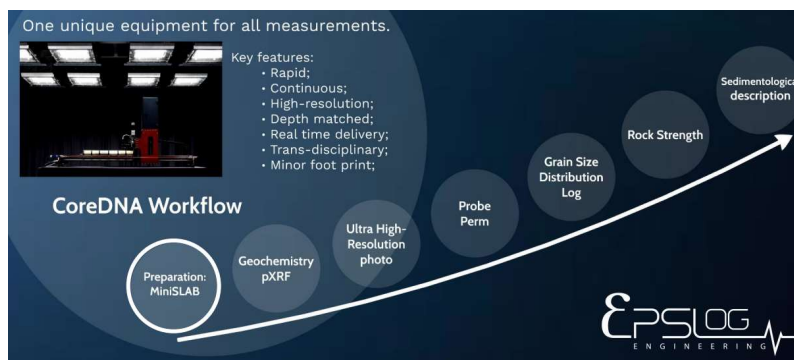


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Example vendor workflows

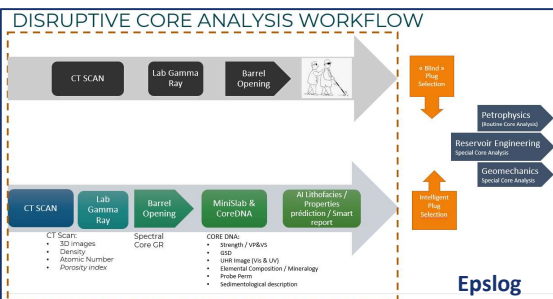
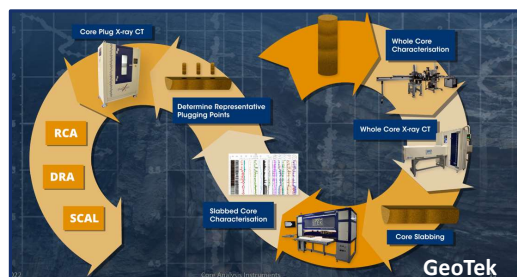


GeoTek



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Example vendor workflows contd.

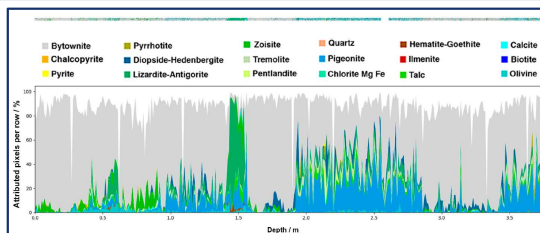


ELEMISSION Inc

Fast, Simple, Efficient:
the true power of laser-induced
spectral analysis:



- ✓ Ultra-fast automated mineralogy
- ✓ Multi-elemental chemical assays
- ✓ Automated lithology
- ✓ Elementary deportation study
- ✓ Mineralogical texture
- ✓ Determination of grain size
- ✓ And more !

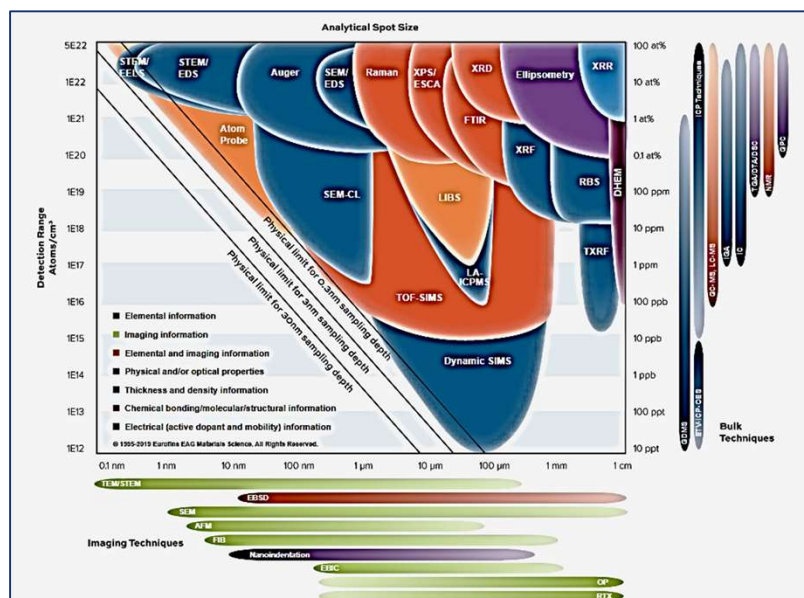


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Mineral Characterisation Technologies

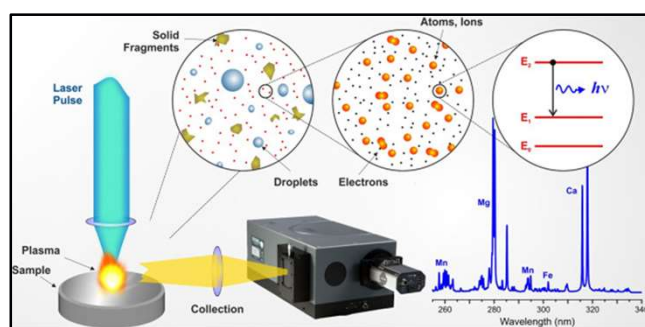


eurofins | EAG Laboratories
<https://www.eag.com/techniques/>

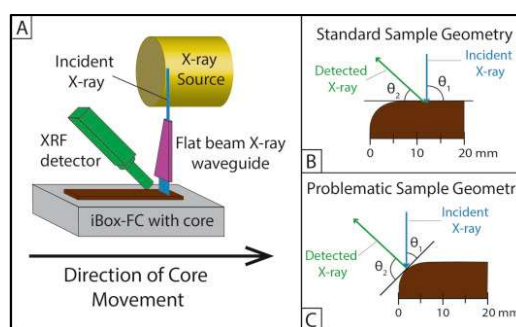


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How do elemental scanning technologies work?



Advances in Laser-Induced Breakdown Spectroscopy analysis for geology: A critical review
 Author links open overlay panel [Cécile Fabre](#)



The iBox-FC: A new containment vessel for Itrax X-ray fluorescence core-scanning of freeze cores

Bradley R.B. Gregory^{1,2}, R. Timothy Patterson¹, Edward G. Reinhardt³, Jennifer M. Galloway⁴

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Miners do it faster ...



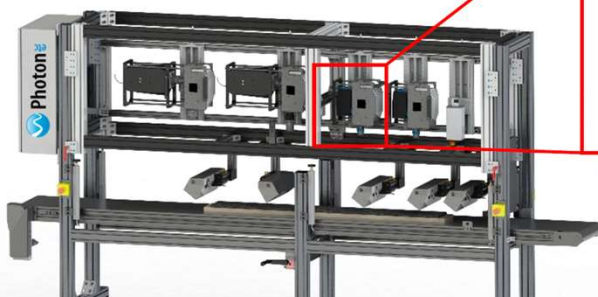
Hyperspectral instruments at CNA

- Line-scan imaging: Image is created by scanning the sample line by line, moving it under the instruments
- **No sample preparation**
- **60 seconds per core box at 1 mm/pixel**

Photon Etc. L-EOS 0.9-2.5
SWIR Hyperspectral camera



Currently at the St John's core storage library



Core box scanning table

Philip Lypaczewski, Ph.D.

Lead Researcher - Hyperspectral Scanning (College of the North Atlantic)



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Miners do it faster ...



Hyperspectral Instruments at CNA

Mobile hyperspectral drill core scanning platform: Photon Etc. nCore system

Hyperspectral at 1mm/pixel (co-registered):

- VNIR (400-1000 nm)
- SWIR1 (1000-1600 nm)
- SWIR2 (1600-2800 nm)
- MWIR (2800-5400 nm)
- LWIR (7500 - 13000 nm)
- 3D profiler (LMI Gocator 2350)
- RGB (0.15 mm/pixel)
- **Room for additional instruments**

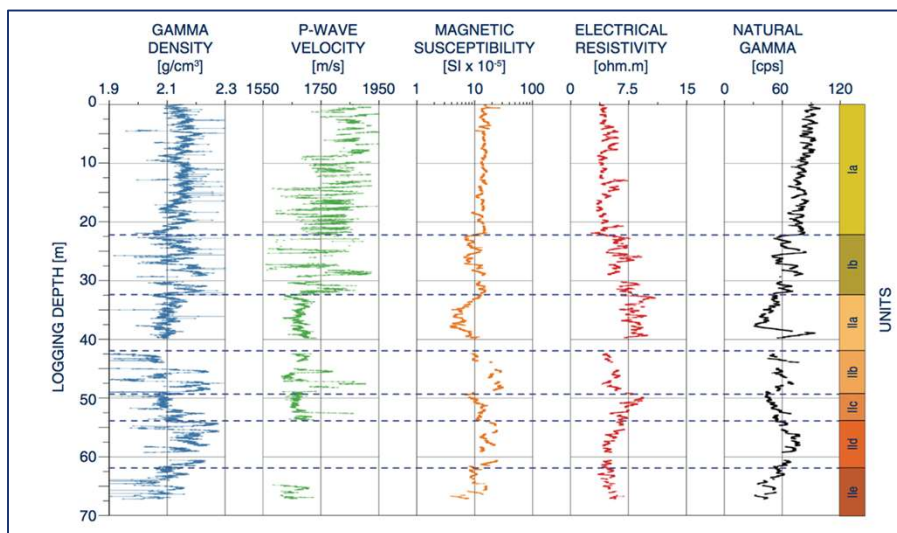
Spatial resolution: **1.0 mm / pixel**

Scanning time: **60 sec round trip** box-in to box-out
= 2000 m / 8 hour shift



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Case Study: ONDRAF/NIRAS Multi-Parameter Stratigraphy



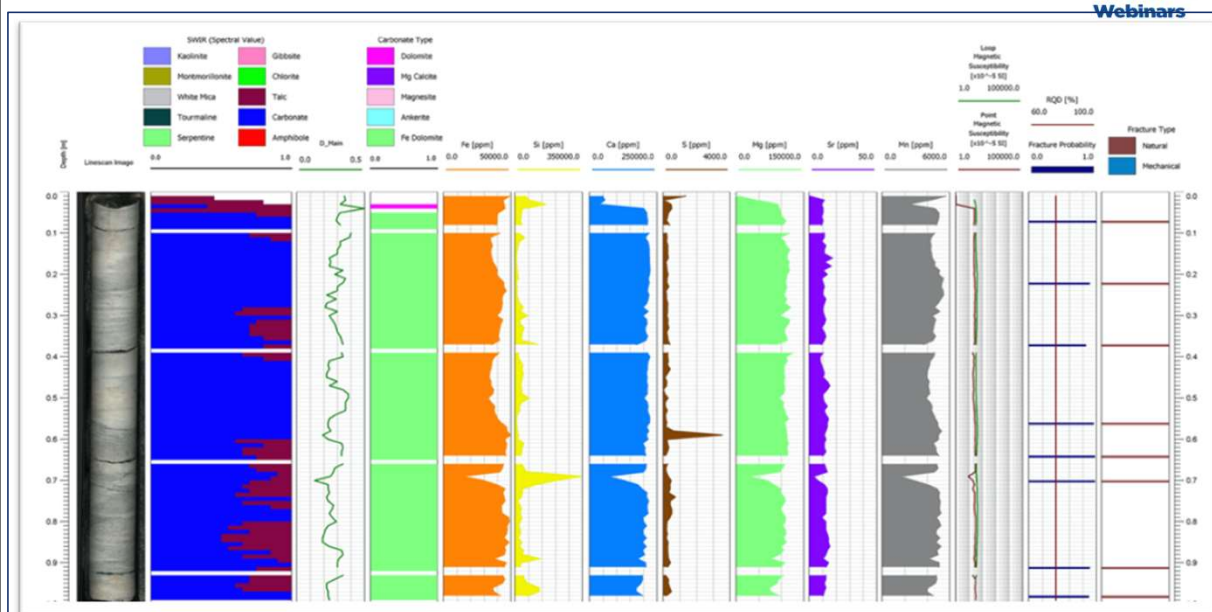
<https://www.ondraf.be>



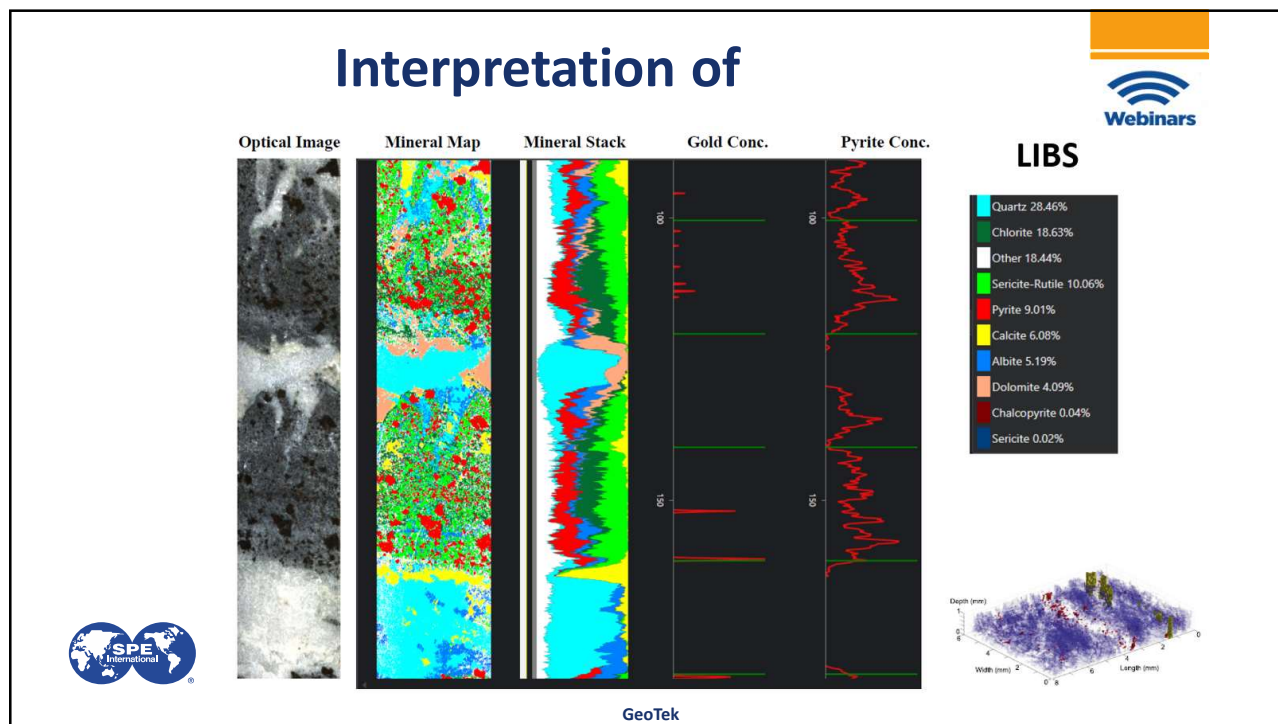
GeoTek

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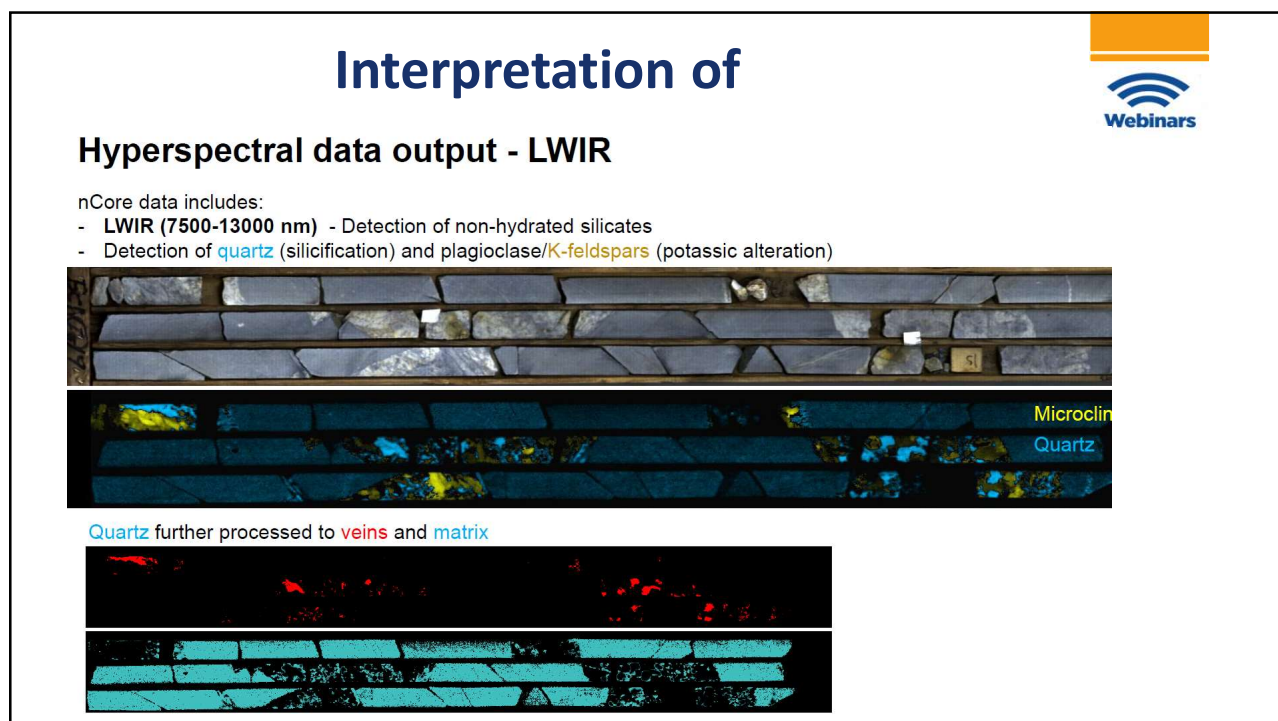
Interpretation of core chemistry & fractures



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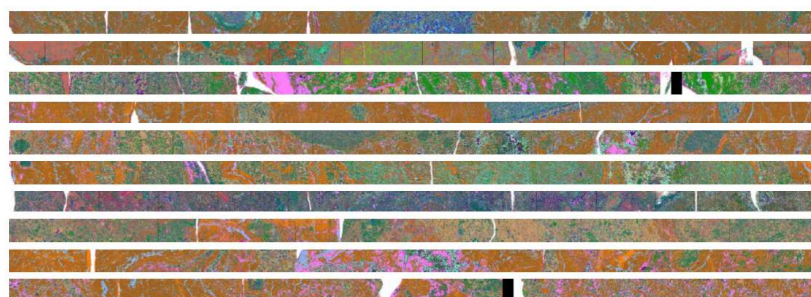


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Interpretation of



QUANTITATIVE AUTOMATED MINERALOGY ON 10 METERS OF CORE



Pyrrhotite	35.8312%
Magnesianhastingsite	10.6586%
Oligoclase	7.9638%
Labradorite	6.7226%
Diopside	5.8009%
Pigeonite	4.7499%
FeOxides	3.9286%
Fluorrichterite	3.7218%
Pentlandite	2.3613%
Biotite	2.0628%
Pyrite	1.8588%
Chalcopyrite	1.1544%
Albite	1.1008%
Actinolite	1.0841%
Muscovite	1.0032%
Epidote	0.9812%
Forsterite	0.4478%
Quartz	0.4330%
Millerite	0.3742%
Ilmenite	0.3498%
Titanite	0.1701%
Estatite	0.1352%
Dolomite	0.1220%
Calcite	0.1126%
Apatite	0.0582%
Rutile	0.0297%
Clinoclase	0.0188%
Sphalerite	0.0003%
Other	6.7643%

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A lot of data = A lot of opportunities

Smart Core Analysis

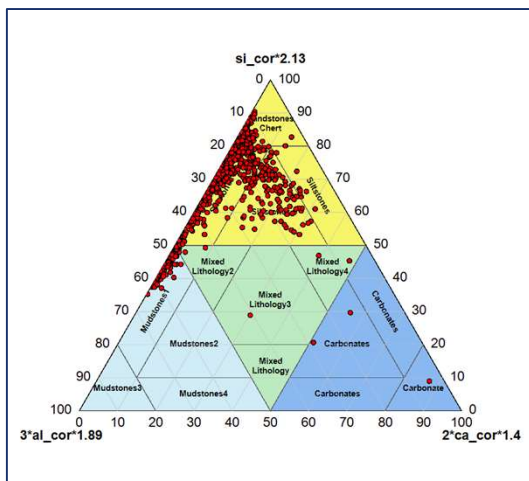
(SCA, SMCA, SACA ...)

“Making Core Analysis Great Again”

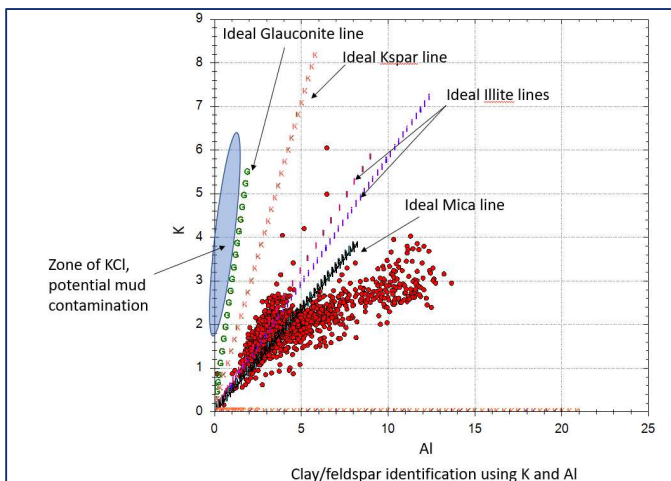


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X-Ray Fluorescence to Mineral Assemblage



<https://www.linkedin.com/in/jenniferkharrazi/>

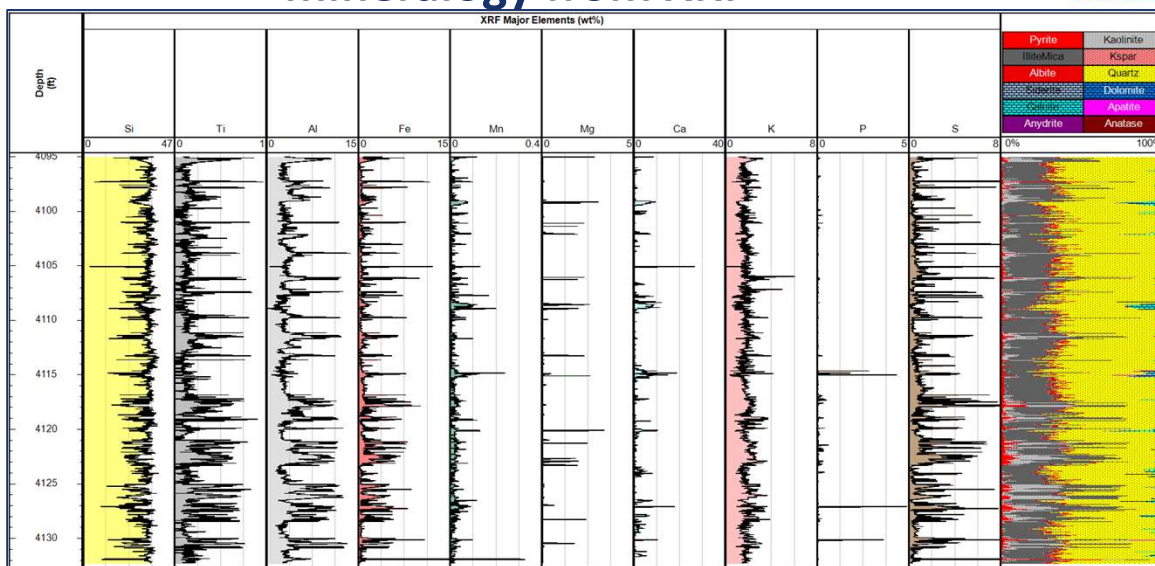


Clay/feldspar identification using K and Al

Stratum Reservoir

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Major elements and calculated mineralogy from XRF



<https://www.linkedin.com/in/jenniferkharrazi/>

Stratum Reservoir

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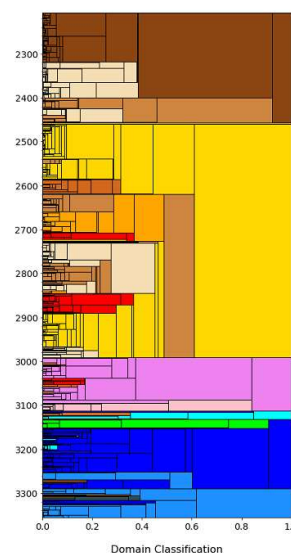
MSCL Data Analysis – Domain Classifications



- Untrained, automated method:
 - **Detect** natural boundaries in data;
 - **Classify** data independantly of boundary information;
 - Combine boundary and classification information, creating hierarchical domains;
- Very few assumptions (data, algorithm, No. clusters).



Hill E J, Robertson J and Uvarova Y (2015). Multiscale hierarchical domaining and compression of drill hole data. Computers & Geosciences, 79, 47-57.
Hill E J, Uvarova Y (2018) Identifying the nature of lithogeochemical boundaries in drill holes. Journal of Geochemical Exploration 184:167-178

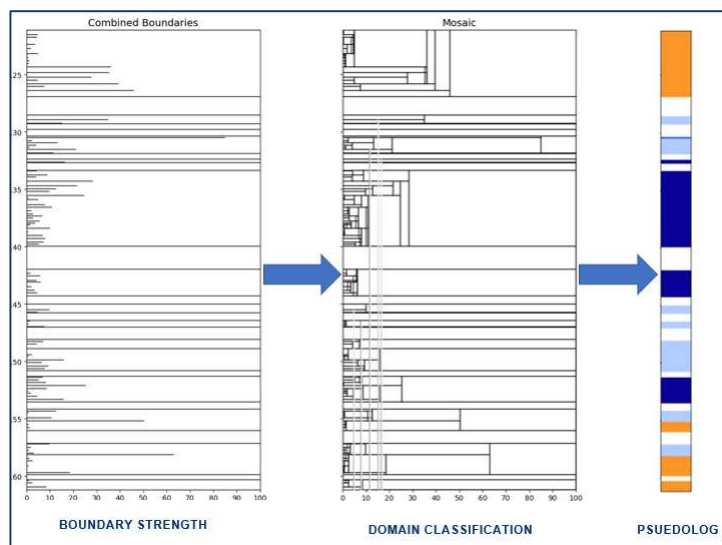


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MSCL Data Analysis – Domain Classifications

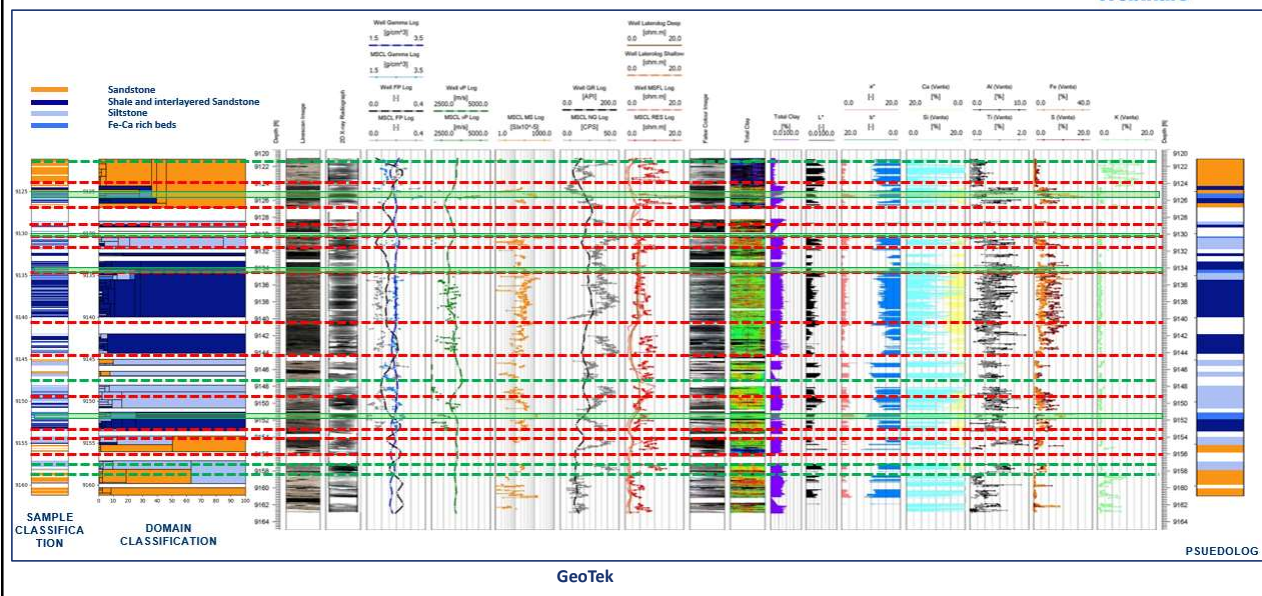


- MSCL data analysed by multiscale boundary detection using Continuous Wavelet Transform;
 - MSCL data used for analysis: **Magnetic susceptibility, electrical resistivity, natural gamma, colour (L*,a*, b*) and XRF (Ca,Si,Al,Ti,Fe,S,K,total counts);**
- Boundaries combined for multiple variables
- Domains created via multivariate tessellation
- MSCL dataset classified via K-means clustering
- Classification applied to mosaic plot
- Pseudolog generated at desired length resolution



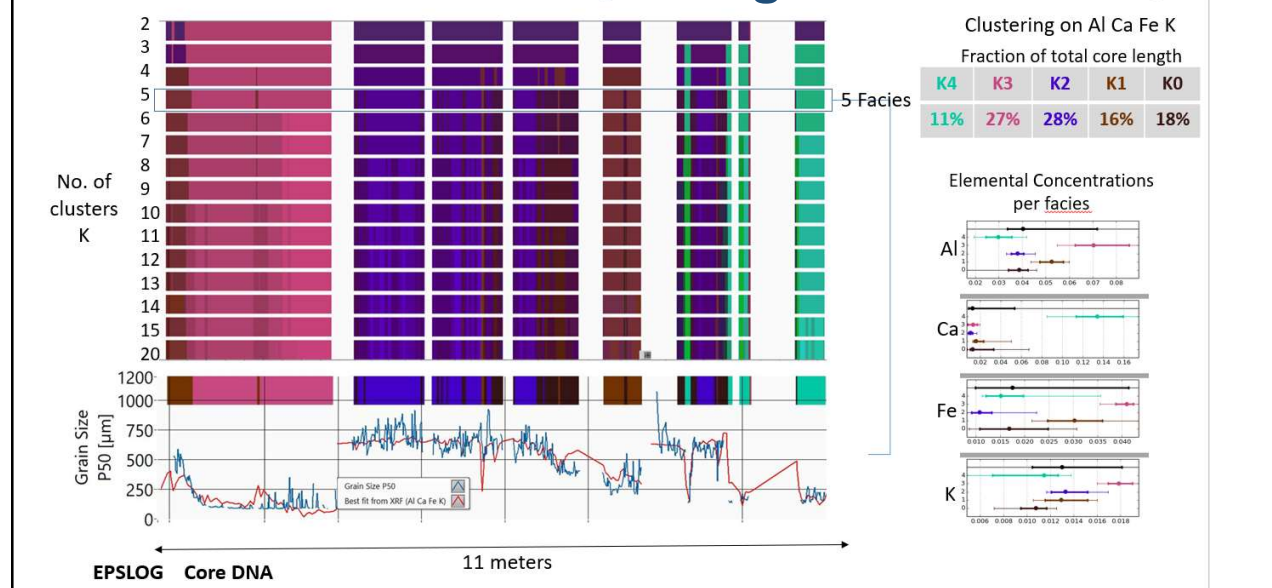
38

Case Study: Rock Core – Well 211-23-8Z (8S1) – FOUR ROCK TYPE ANALYSIS



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Facies Identification: Unsupervised Machine Learning



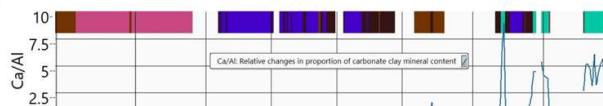
40

Facies Characterisation: Quantitate Values

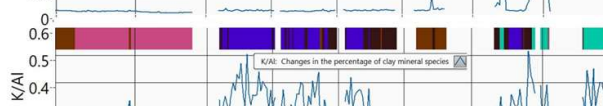


Relative changes:

carbonate/clay



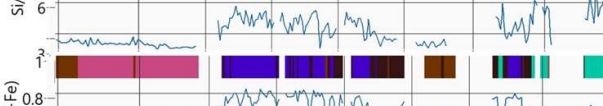
Clay Mineral species



Clay /Quartz



Type of clay minerals

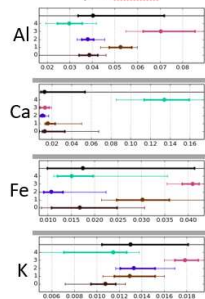


EPSLOG Core DNA

Fraction of total core length

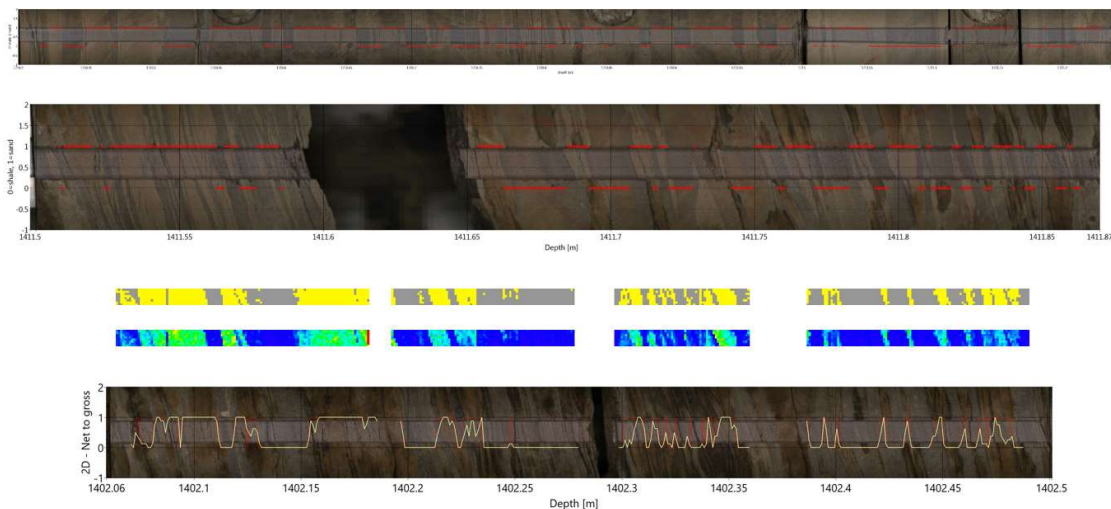
K4	K3	K2	K1	K0
11%	27%	28%	16%	18%

Elemental Concentrations per facies



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Net to Gross



EPSLOG Core DNA

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CoreDNA – EPSLOG Clustering Analysis

CoreDNA

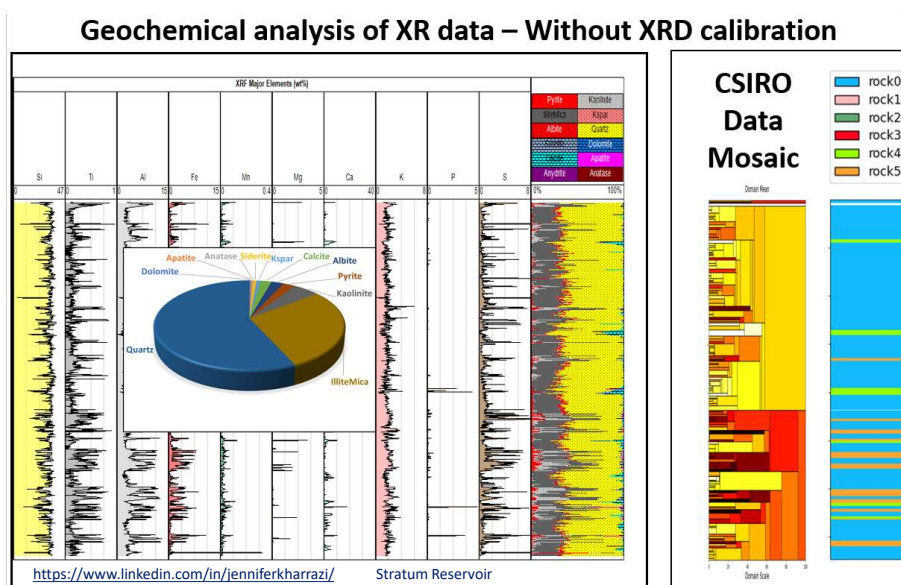
46% 30% 6% 6% 0%

0 1 2 3 4 5

CSIRO Data Mosaic

Rock 0 82% 11% 7% Rock 4 Rock 5

Comparative Interpretation- Example 2



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Virtual Core Table

Kyle

Simulating lunar water

Laser-Induced Breakdown Spectroscopy for the Identification and Quantification of Water Ice and Platinum Group Elements in Lunar Regolith Simulants

Frédéric Diotte¹, Myriam Lemelin¹, François R. Doucet²
¹ Université de Sherbrooke, ² ELEMISION Inc.

Canadian Space Agency, Agence spatiale canadienne, Québec, CSRS NSERC

1. Introduction

Up to 96% of lunar water ice deposits could have been delivered to the lunar surface between 4.25 and 3.75 Ga, with a high contribution coming from impactors (Cannon *et al.*, 2020). Chondrites are also a major source of highly siderophile elements (HSE) as they were found to be 3000 to 5000 times more enriched in HSE than primitive lunar rocks (McDonough *et al.*, 2020). Relative abundances of HSE could thus be used as indicators to estimate the influx and types of impactors which delivered them to the Moon (Doran *et al.*, 2004; Day *et al.*, 2016). An in situ instrument having the capability to quantify HSE within the regolith would help contextualize detections of volatiles and provide metrics to allow determining their geologic origin.

The aim of this project is to evaluate the capabilities of the Coriolis, an imaging LIBS instrument developed by Montreal based company ELEMISION, to study the composition of lunar regolith simulants. Limits of detection (LOD) will be calculated for volatiles and platinum group elements within lunar regolith simulants at low pressure and temperature. We also investigate the benefits of imagery to discriminate between samples containing water ice in different forms (micrometric particles and bulk dirty ice).

2. Methods

Lunar regolith simulants (Exolith Lab's Lunar Highlands Simulant) were mixed with snow and liquid water before freezing (-80°C). Liquid nitrogen was used to limit the metamorphism of snow crystals during preparation. In total, 60 standards were made, with H₂O concentrations varying between 0.5 and 40 wt. %. LIBS measurements were acquired using ELEMISION's Coriolis with a stepsize of 50 μm. LIBS hyperspectral cubes of emission were acquired for each sample, with a size of 200 × 200 px. The figure to the right shows the distribution of intensity of hydrogen emission (656.48 nm) on a sample containing 30 wt. % snow.

No preprocessing other than dark subtraction was conducted on those measurements. Average spectra of emission for each standard were computed, and were used to perform a linear calibration model. Different images were also generated by normalizing the signal using reference intensity peaks. Ratios can help reduce the dispersion of LIBS intensity, leading to higher accuracy of predictions (Rapin *et al.*, 2017). The experimental ratios were H₂ (656.48 nm) / Si (251.66 nm) and H₂ / O (777.3 nm).

3. Results

The mean intensity of hydrogen (656.48 nm; n=40000) in icy simulants increases linearly below 10 wt. % (with a R² of 0.91), and decreases at higher concentrations. Such a loss of intensity is expected, as pure water ice has a small absorption coefficient at 1024 nm, leading to a less energetic laser-induced plasma within a water-saturated medium (Aep *et al.*, 2004).

For low water ice concentrations (< 15 wt. %), samples containing snow and bulk ice result in a similar H₂ / [H₂O] relationship. Photothermic effect induced by the laser seems to cause the melt of the sample after a few impingements, which could minimize any difference between LIBS measurements of snow and bulk ice samples. Therefore, measurements conducted at very low temperature could compensate this effect.

Patchy features are observed within the spatial distribution of intensities for both types of icy lunar simulants. Those features have sizes increasing with water concentration (up to a few millimeters). Those agglutinates are characterized by significantly stronger intensities over the whole spectrum of emission. They could represent clumps of particles formed due to the higher cohesion between wet particles. Laser-matter interaction is stronger in those agglutinates, resulting in overall higher intensities. The formation of those agglutinates could be due to subtle variations during sample preparation and mixing. This also seems to be a major contributor to the residuals of the linear regression. A lower dispersion of H₂ intensities is obtained when a linear regression is only applied to those agglutinates, defined as pixels with low H₂ (656.48 nm) / Si (251.66 nm) ratio (<1). Resulting R² is then 0.96.

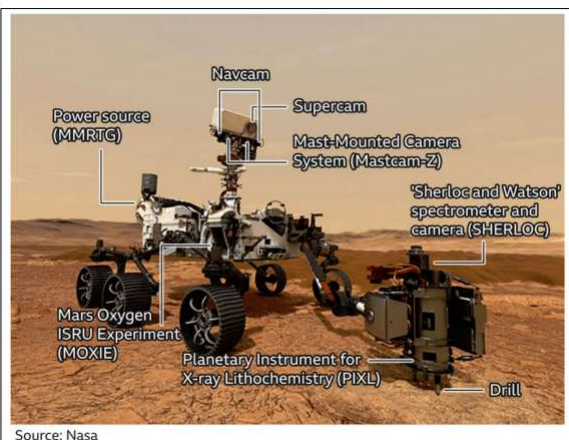
4. Future work

- Further LIBS measurements will be carried out using lunar simulants mixed with HSEs in an interaction chamber at 3.33x10⁻³ Pa and 70K.
- Limits of detection will be calculated for HSEs and water ice.
- Various regression models (PCR, PLS, LMM) will be compared to determine which quantitative analysis method provides the highest precision.

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Thank You - Questions



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