CORE SPECIALIST SERVICES

SCA 2020 Webinar Conference

CORE TECHNICAL SERVICES

https://www.core-technical-services.co.uk

September 23, 2020

> Big Data From Core - A New Era in Core Analysis

Craig Lindsay

Craig.Lindsay@core-specialist-services.com

Core Specialist Services

http://www.core-specialist-services.com/

SCA Industrial Relations Liaison

SPWLA European Director

SPE Reservoir Technical Discipline‘s Advisory Committee - Reservoir Technology of the 21ST Century, sub-committee Core Analysis

THE SOCIETY OF CORE ANALYSTS

A chapter of the SPWLA

SOCIETY OF PETROPHYSICISTS AND WELL LOG ANALYSTS

What can be measured?

Data Analysis?

Applications?

A whistle-stop tour!

STATEMENT

Micro & Nano CT, Network Modelling and Digital Rock Physics (DRP / DRA) not covered but the methods described herein would be highly effective for DRP sample selection

History of Core Logging

New techniques in sediment core analysis: an introduction

R. GUY ROTHWELL[1] & FRANK R. RACK[2]
[1] *National Oceanography Centre, Empress Dock, Southampton SO14 3ZH, UK*
(e-mail: rgr@noc.soton.ac.uk)
[2] *Joint Oceanographic Institutions, 1201 New York Avenue, NW, Suite 400,*
Washington, DC 20005, USA

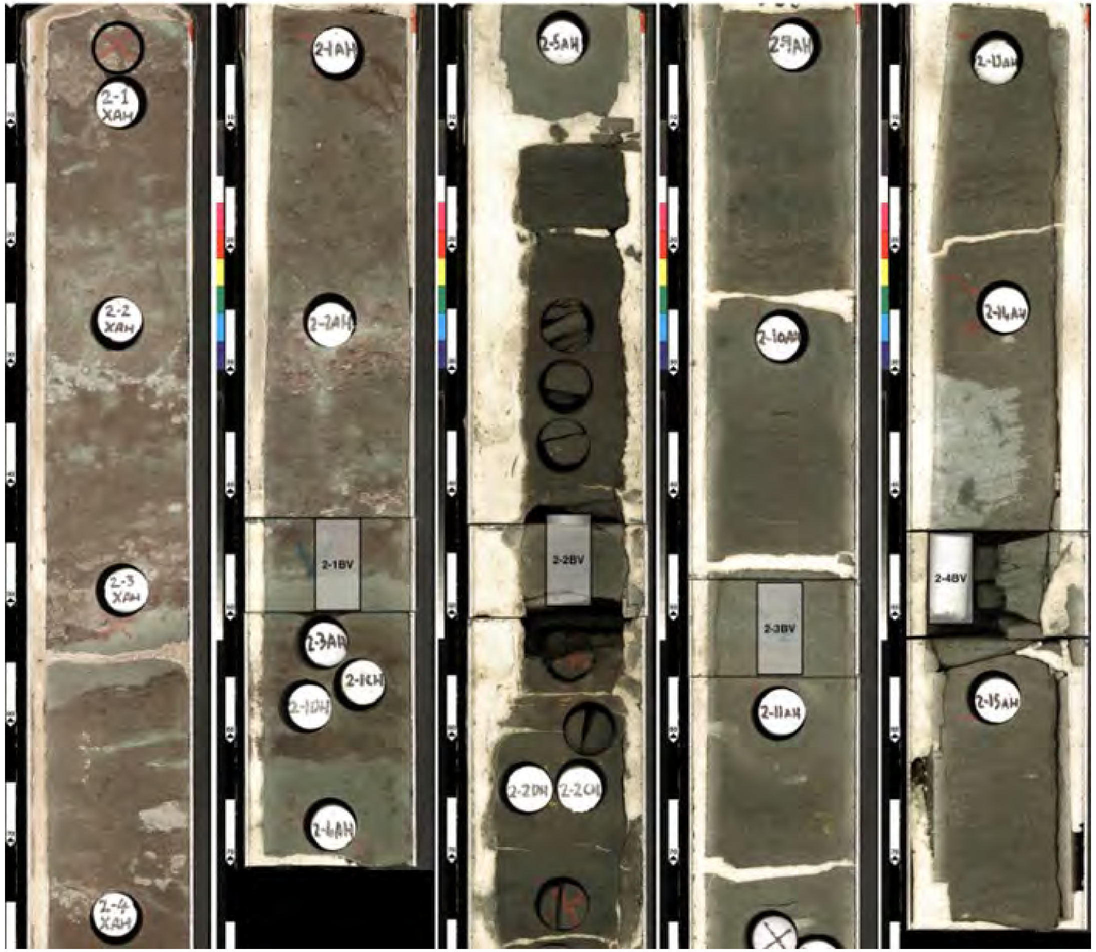
First recorded sediment recovered from the deep sea - 'fine soft blue clay' was sampled in 1773 by Captain John Phipps on HMS Racehorse in 1250m water depth on the southern margin of the Voring Plateau north of Norway.

Advanced core logging methodologies developed starting in the 1980’s (began in 1940’s as per oil industry)

Developed completely independent of oil industry – multi-sensor core loggers have become industry standard

From: ROTHWELL, R.G. 2006. *New Techniques in Sediment Core Analysis*. Geological Society, London, Special Publications, **267**, 1–29. 0305-8719/06/$15.00 © The Geological Society of London 2006.

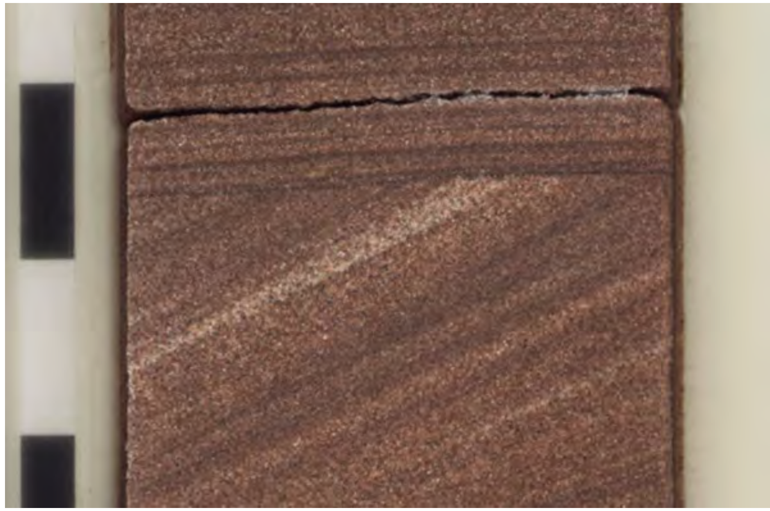
Core analysis standard practice



Industry standard practice for “routine analysis”:

- Cut core plug every 25 cm or 1 ft. – in “reservoir rock”
- May measure “saturation of fluids” in “fresh” state
- Measure porosity, permeability and matrix density in “clean” condition
- OK in “homogeneous” rock (large scale beds)
- Finely bedded formations poorly characterised
- Value in “consistent” practice
- Reservoir model “scale” is >> core plug

Core analysis – capturing heterogeneity?



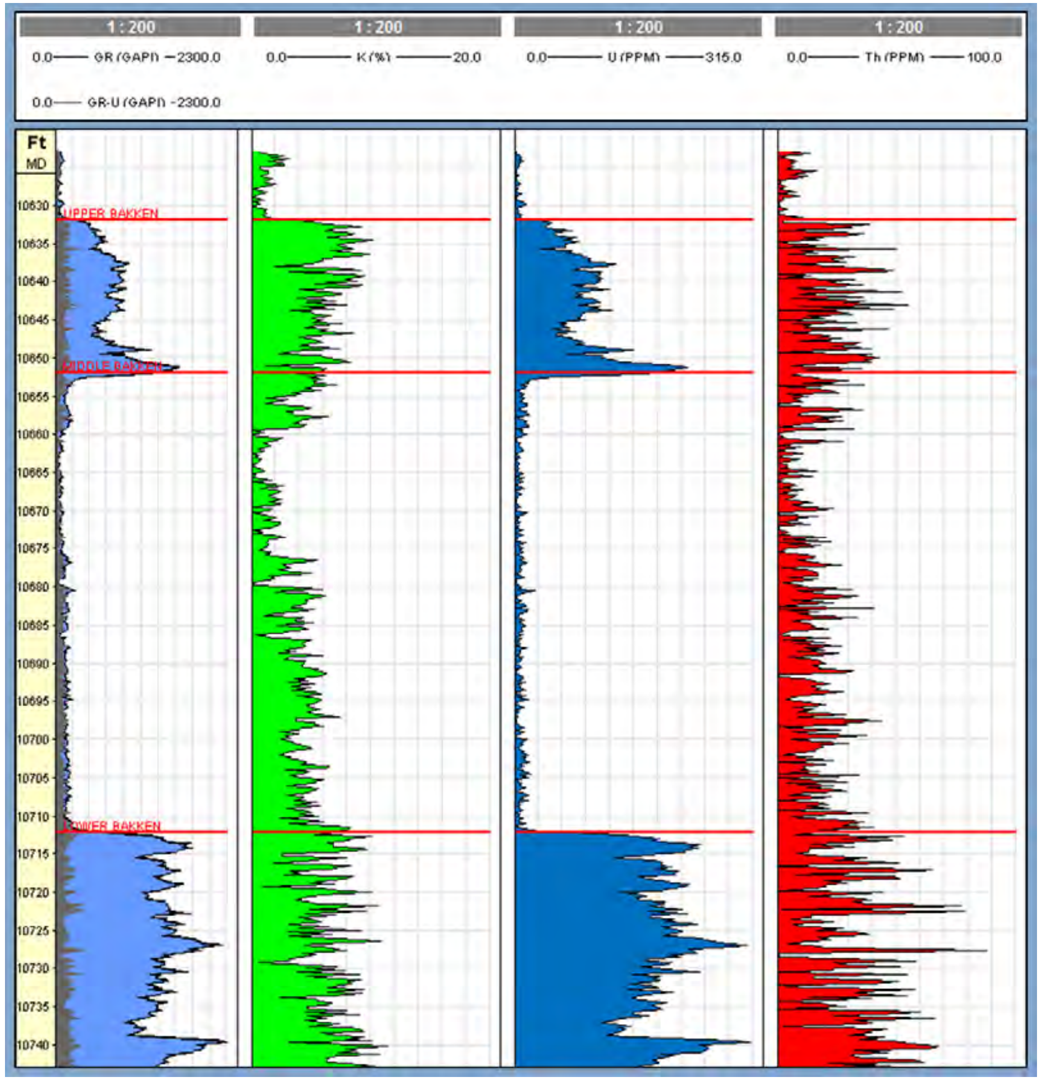
Approaches to heterogeneous rock:

- **Whole core analysis**

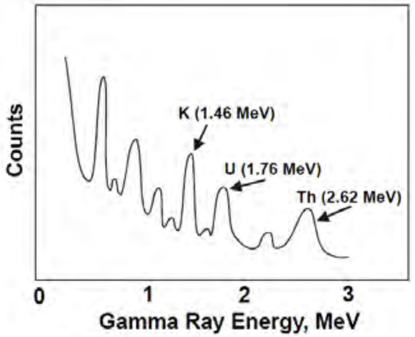
“Continuous” core data = higher resolution than 1 ft or 25 cm?

- **Attempt to “capture” or “characterise” heterogeneity**
- **Core gamma – long established procedure (main application to establish core – log depth shift**
- **Probe permeability**
- **High resolution core imaging**
- **Currently many more options**

Continuous Data - Core Gamma



- First “continuous” core data
- In use since 1940’s
- Core to log depth shifts
- Lithology discrimination
- Spectral core gamma



Permeability – Well Quantified from Plugs?

- Core plug measurements at 1 per ft (25 cm) – may not fully characterise the level of permeability heterogeneity – especially in laminated formations
- Hurst and Rosvoll [1] – proposed method to determine minimum number of measurements (*No*) to determine Arithmetic Mean Permeability +-20%
- Reducing the tolerances – unrealistic number of measurements
- Calculate coefficient of variation,

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

$$No = 100\ Cv^2$$

Hurst A., Rosvoll K.J.*(1991) "Reservoir Characterisation, Permeability variations in sandstones and their relationship to sedimentary structures, (Academic Press),*

Permeability vs. 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:

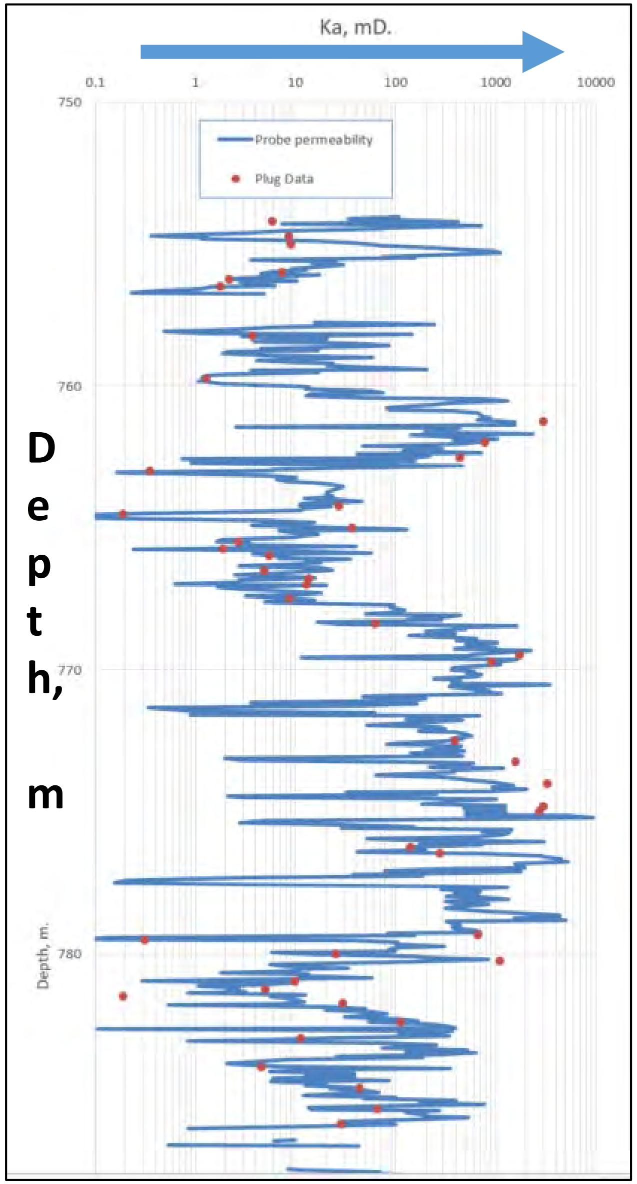
Rotliegend reservoir, Southern North Sea, UK

- 150 plugs acquired (1 per ft.)
- **Cv = 2.5, *No* = 625 Very heterogeneous**
- Plug alone data did not quantify permeability heterogeneity – probe permeability data @ 5 measurements per ft. = **729** points.

*“**Estimating the mean permeability: how many measurements do you need?**”, P. Corbett and J.L. Jensen, First Break, Volume 10, Issue 3, Mar 1992,*

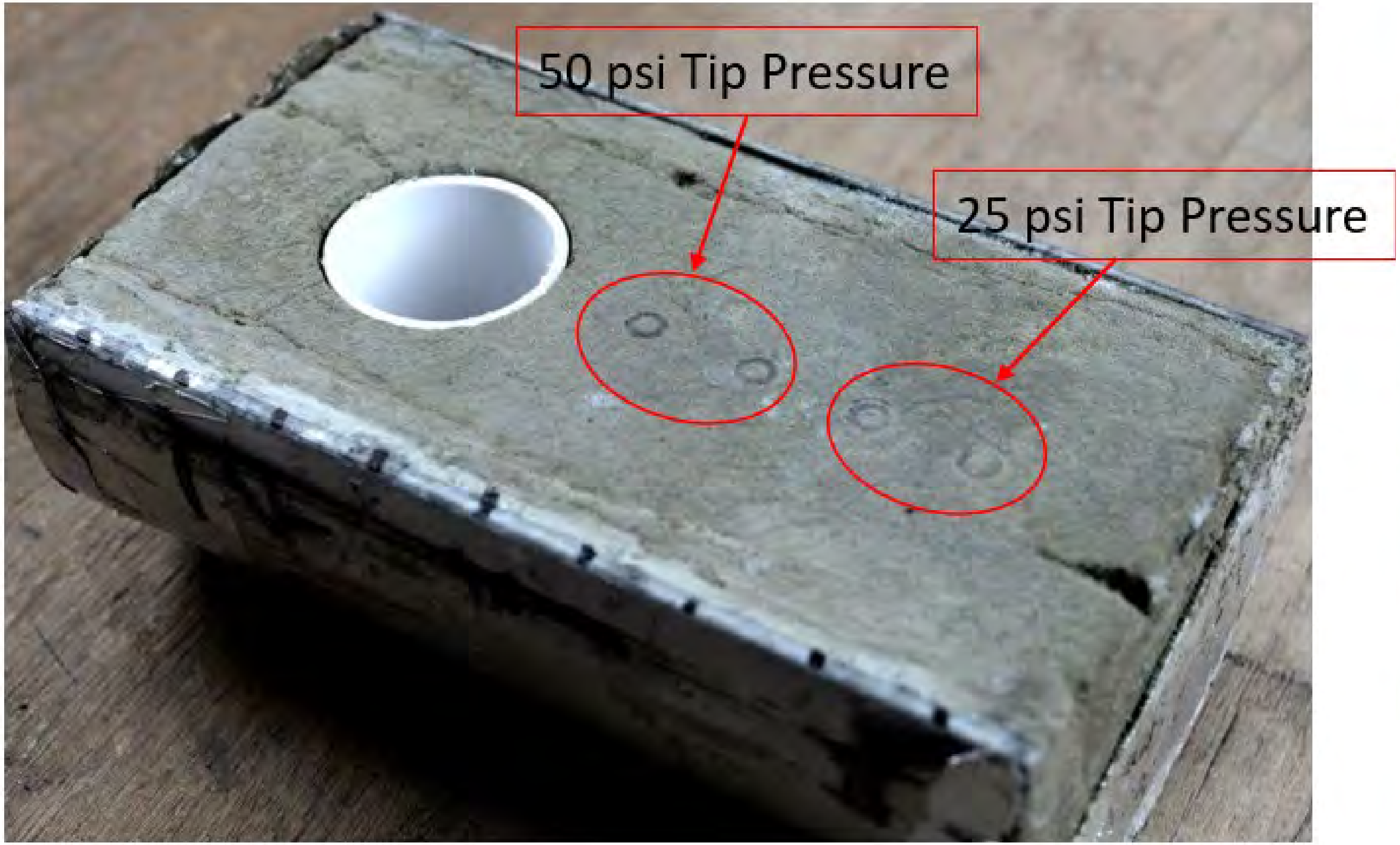
Probe (profile) Permeameter

Ka, mD

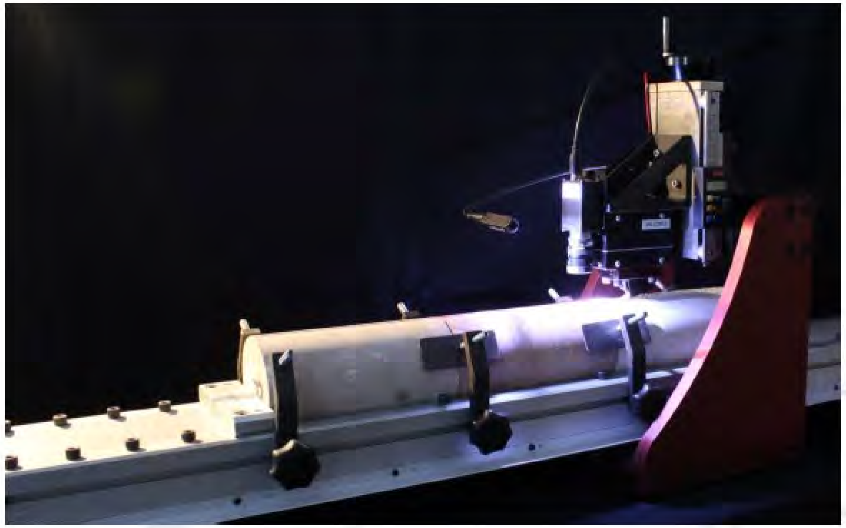


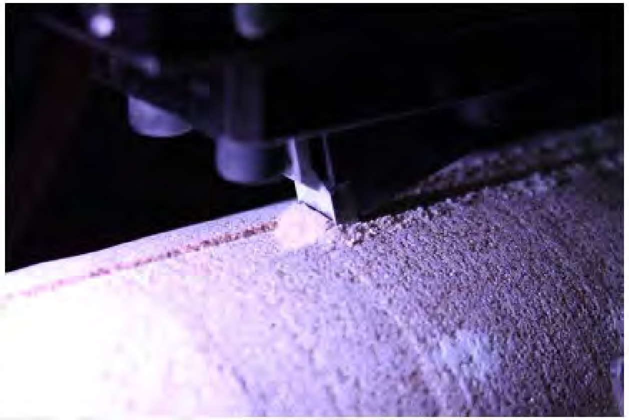
- Common technology since 1980’s
- Requires smooth surface / contact technology
- Semi-Continuous

Probe Permeameter Core Indent

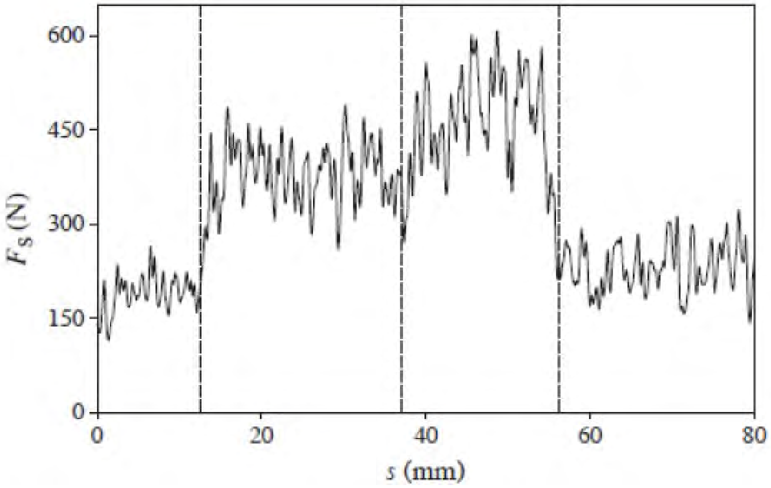


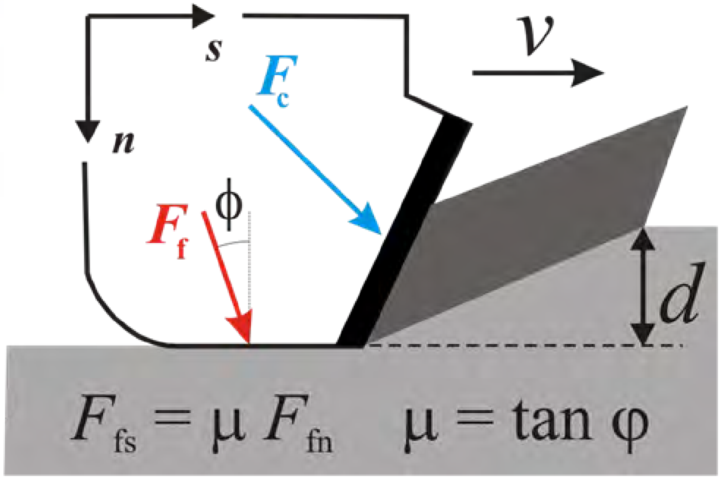
Rock Strength – The Scratch Test





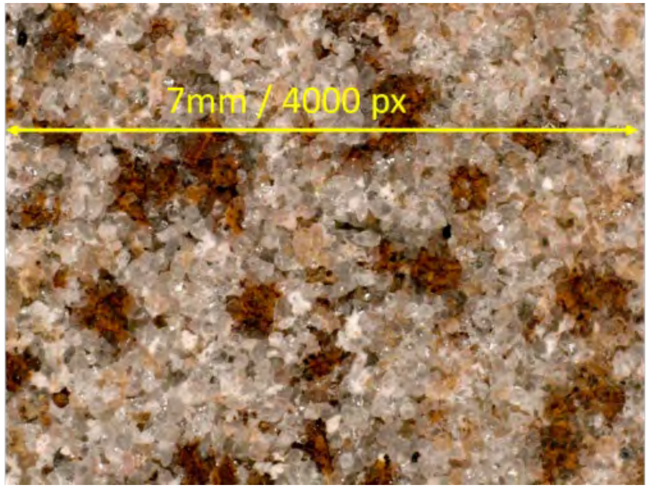
- **Continuous measurement**
- **Unconfined Compressive Strength (UCS)**





High Resolution Core Photography

- VISIBLE LIGHT & UV LIGHT
- 1.8µm PER PIXEL
- MADE ON DRY CUT (NO FLUID DISPLACEMENT)
- EARLY IN THE WORKFLOW

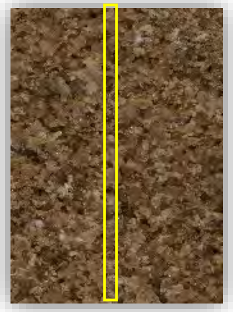


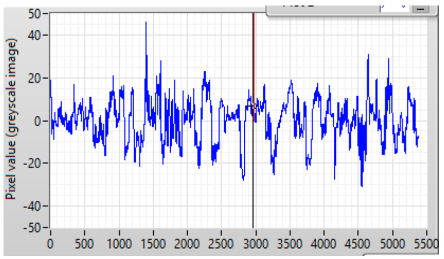
Continuous “thin section” profile

7mm

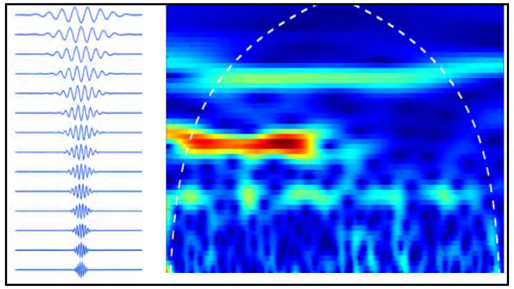
5cm

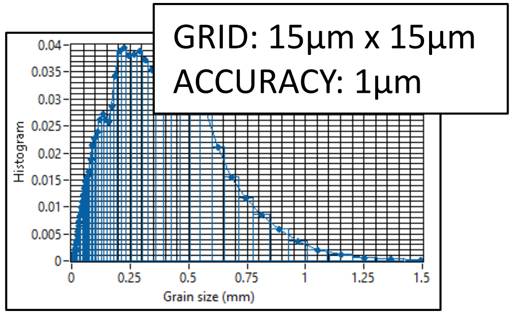
Grain Size Distribution Index Profile

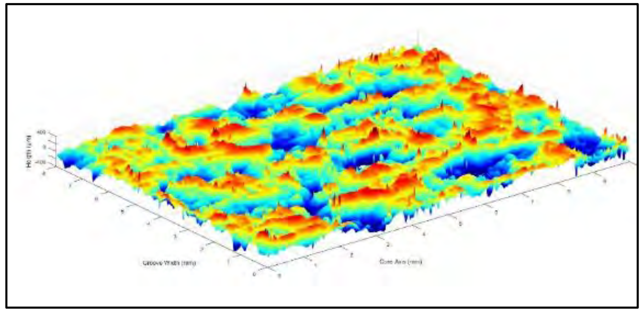


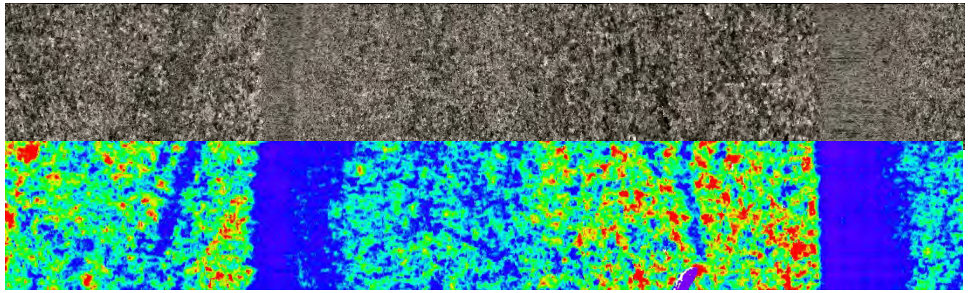


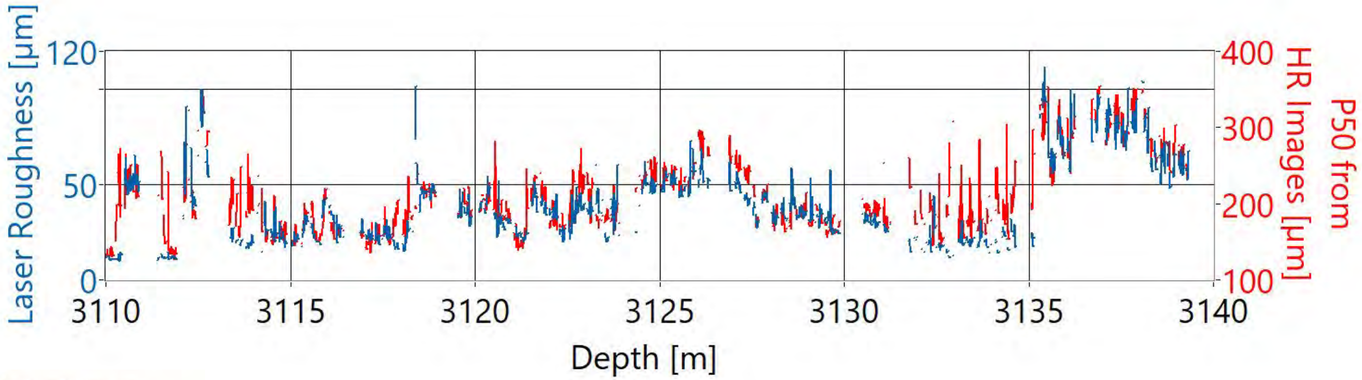
Norm. Pixels BW value

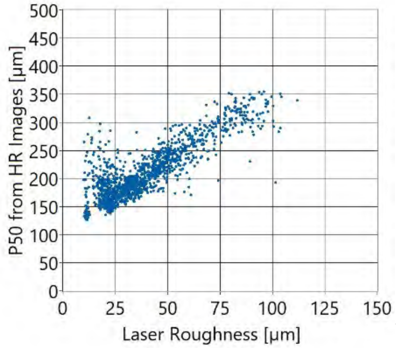


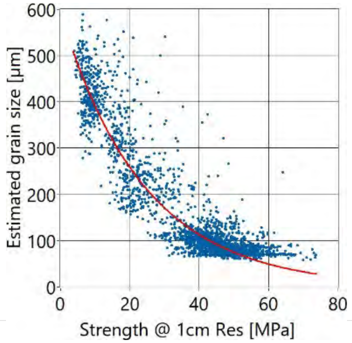












X-Ray CT Scanning of Core

- Method is use since 1980’s
- Core orientation
- Screening prior to sampling
- Single energy (SECT)
- Dual Energy (DECT)

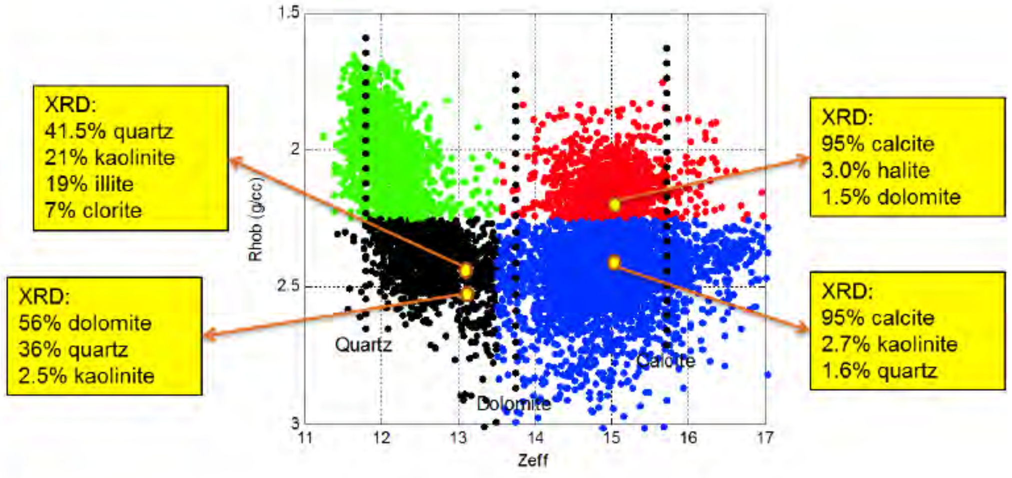
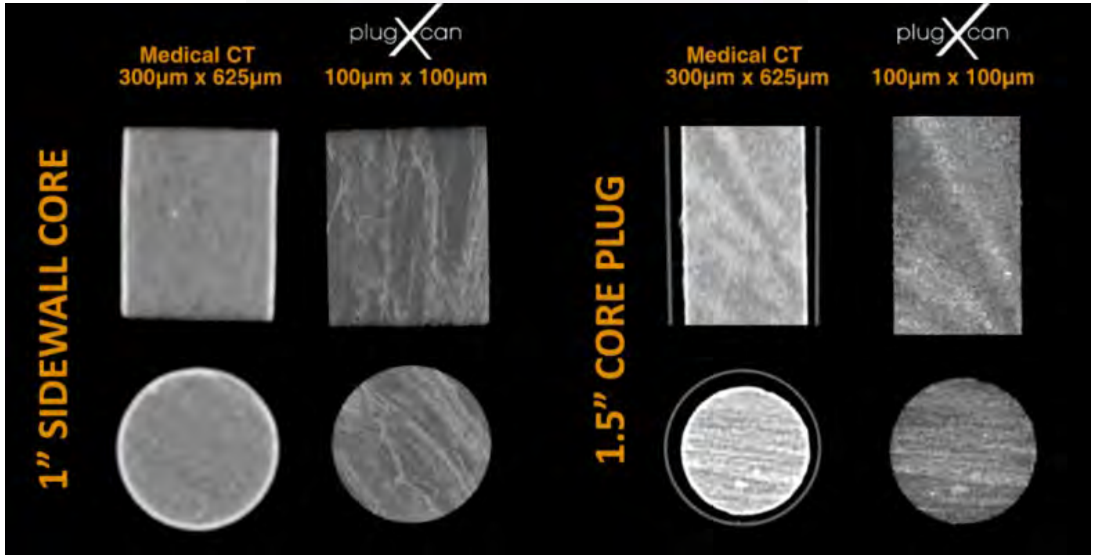


Fig. 17—Integration of XRD with DE CT scanning.

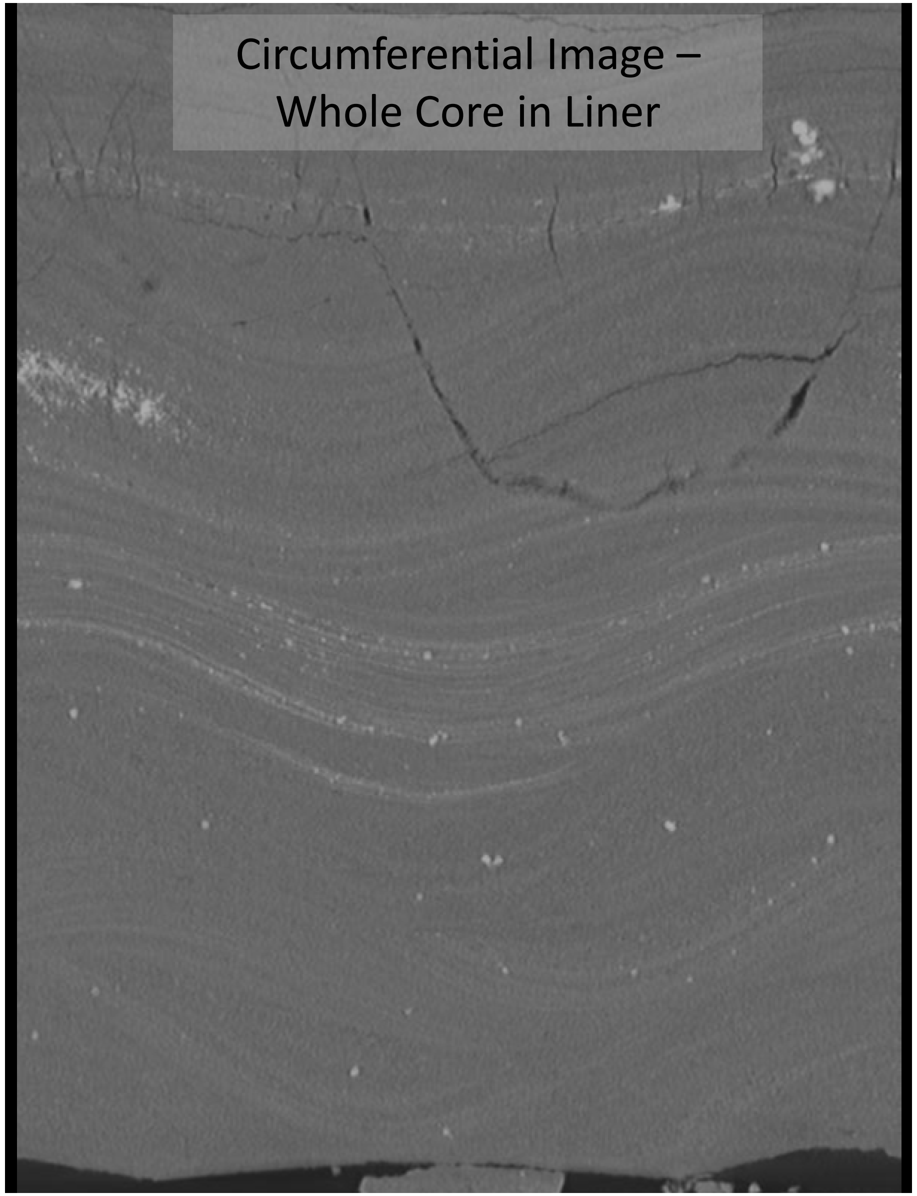
“Advanced Rock Characterization by Dual Energy CT Imaging: A Novel Method in Complex Reservoir Evaluation”, H. Al-Owihan (Kuwait Oil Company) et Al.,   IPTC-17625-MS

High Resolution X-Ray CT Scanning of Core



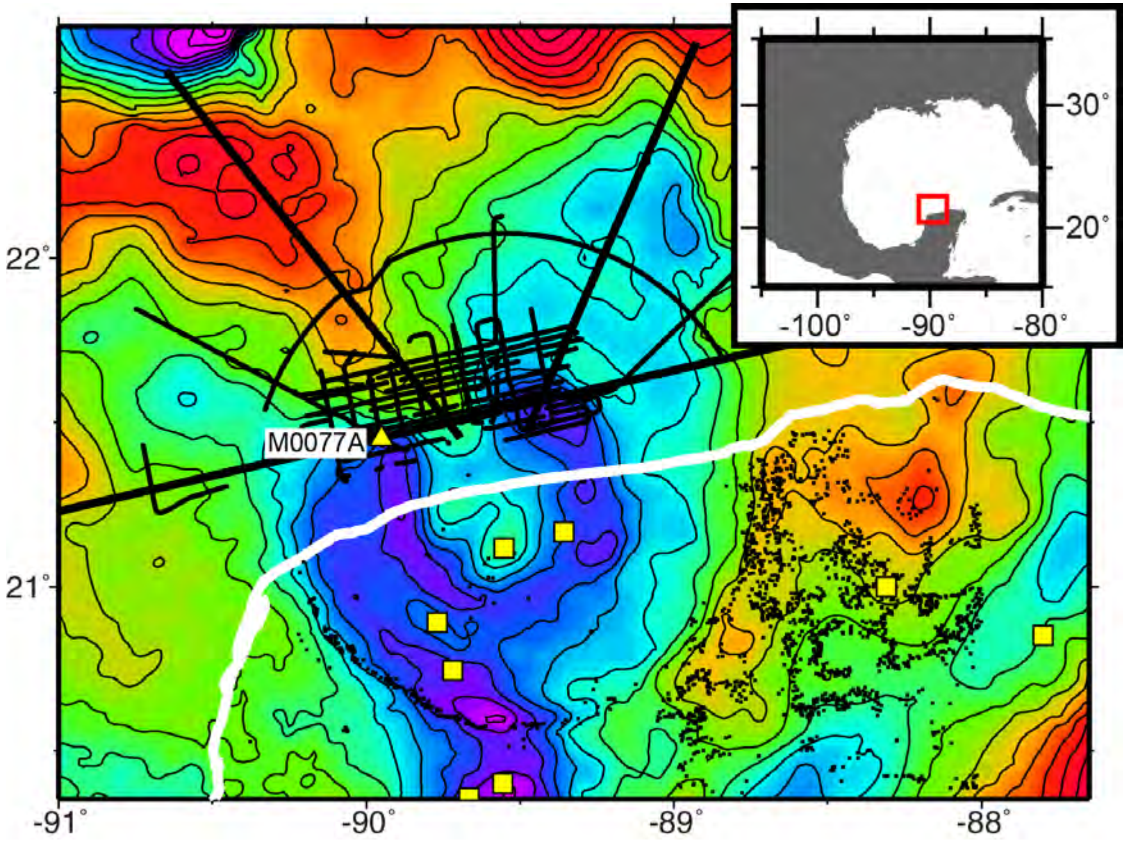
High Resolution X-Ray CT

1 m.



7 c m.

Chicxulub Impact Structure



IODP / ICDP Expedition 364 in 2017 recovered 849 m. of core from hole M0077A

Lunar and Planetary Science XLVIII (2017)

X-Ray CT Scanning of Chicxulub Core

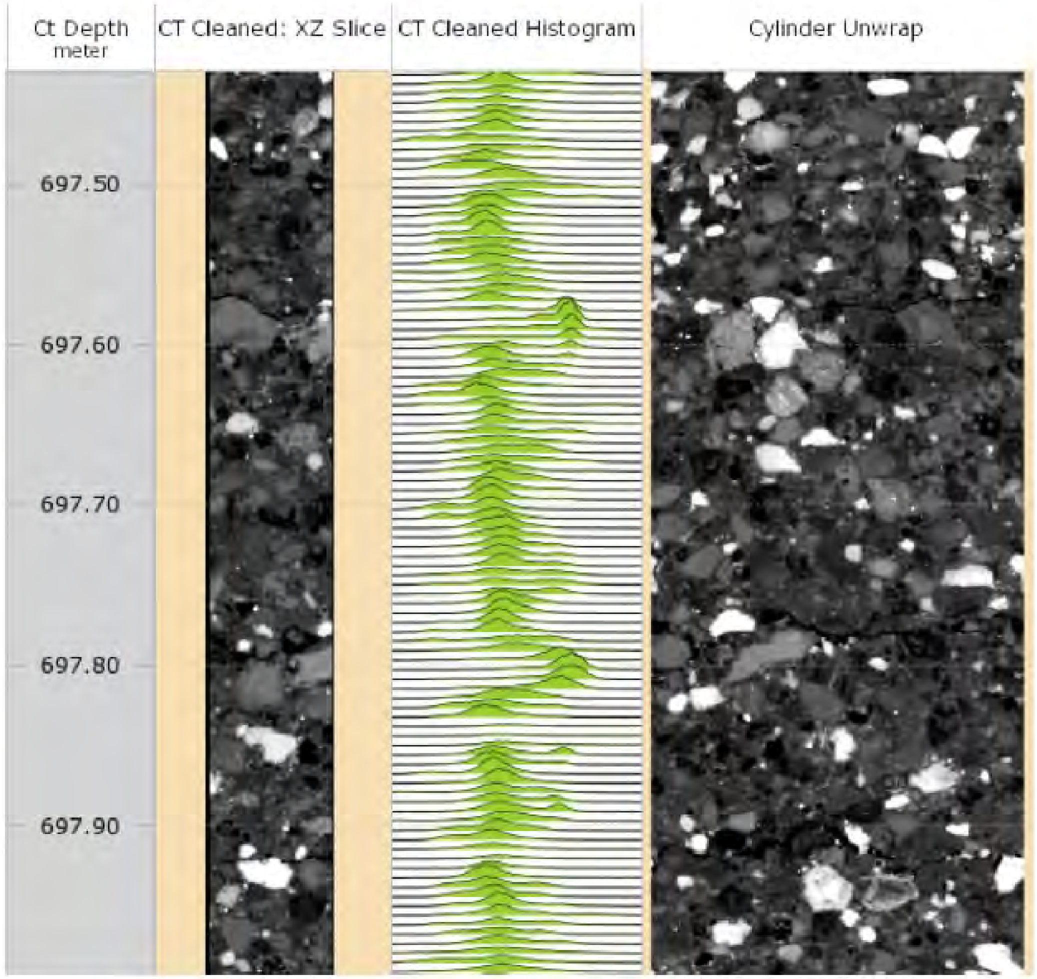
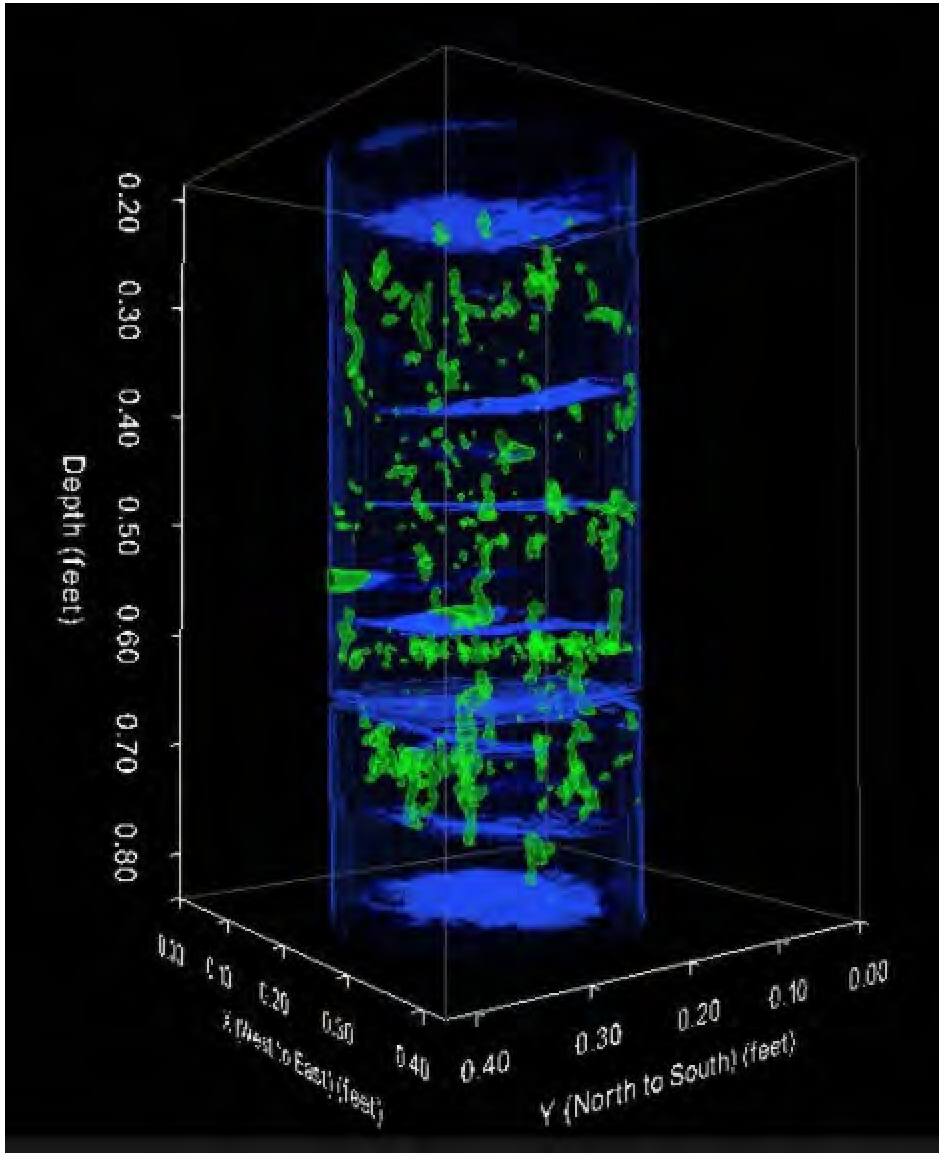


Figure 2: 2D images generated during processing of CT data. The CT histogram provides a visualization of the distribution of CT numbers every 10 slices.

Lunar and Planetary Science XLVIII (2017)



Weatherford Labs

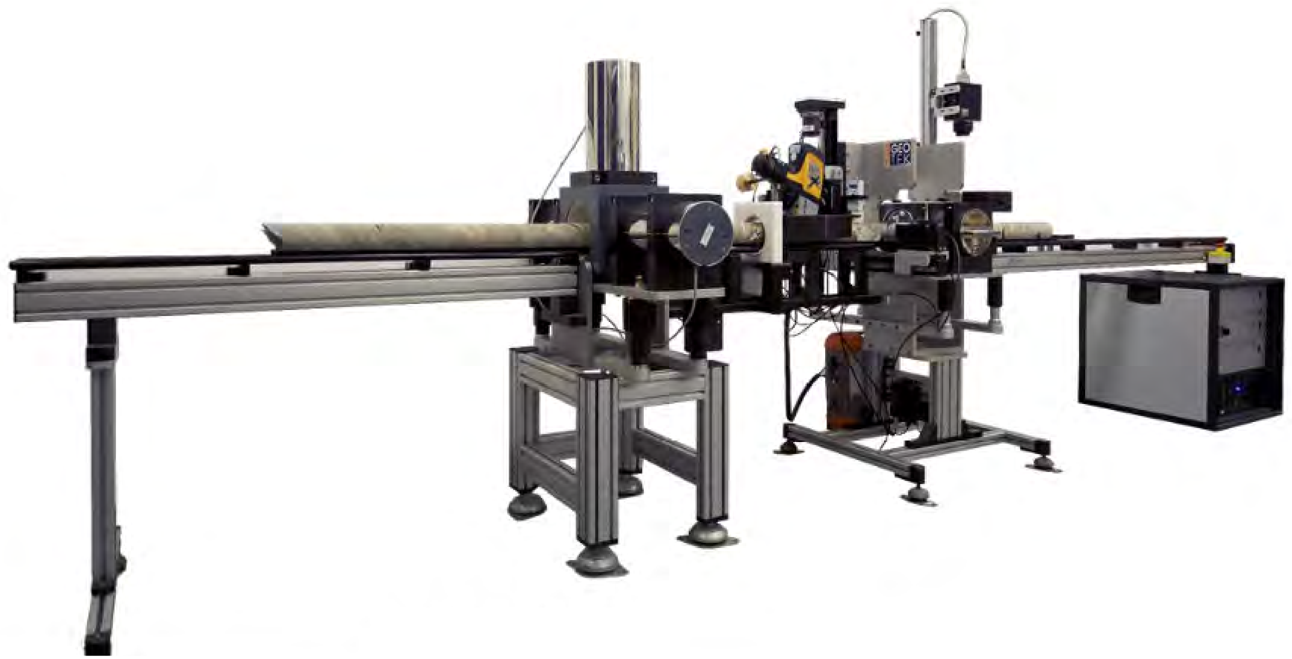
Core Logging not just in Oil & Gas Industry

- Palaeoclimate Studies
- Limnology
- Marine Geology
- Terrestrial Geology
- Petroleum Research
- Unconventional Resources
- Mineral Exploration
- Ice Core Logging
- Repositories

Instrumented core logging is standard practice in other disciplines!

Multi-Sensor Core Logger

- **Automated core logging platform**
- **Cores are pushed passed sensors**
- **Measurement geometry is constant**
- **Multiple sensors (up to 8) can be installed at once**
- **Depth co-registration of data**
- **Data are collected simultaneously**
- **Variable resolution**



Multi-Sensor Core Loggers

One Pass – Multiple High Resolution Data Types

- **CORE DIAMETER MEASUREMENTS**
  Laser micrometers with a resolution of 0.02mm.

- **P-WAVE VELOCITY**
  250-500 kHz piezo-electric ceramic transducers, spring-loaded against the sample. Accurate to about 0.2%, depending on core condition.

- **GAMMA DENSITY (BULK DENSITY)**
  ^{137}Cs gamma source in a lead shield with optional 2.5mm or 5mm collimators. Density resolution of better than 1% depending upon count time.

- **MAGNETIC SUSCEPTIBILITY**
  Bartington loop sensor 60-150mm diameter, or point sensor (on split cores) giving 5% calibration accuracy over two ranges; 1×10^{-6} & 10×10^{-6} cgs.

- **NON-CONTACT RESISTIVITY**
  Non-contact resistivity measurements using a unique double paired coil induction method.

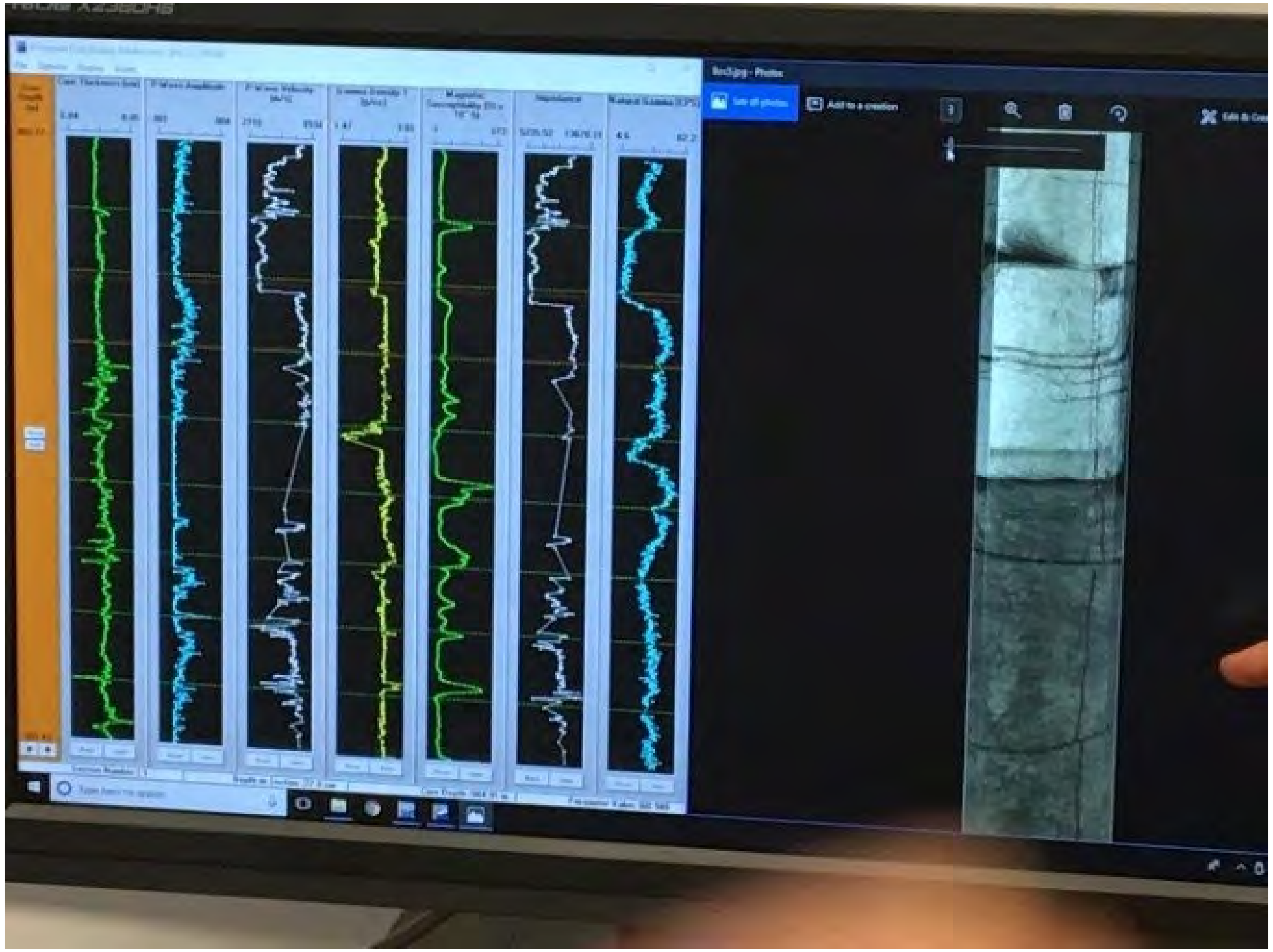
- **GEOSCAN V LINESCAN IMAGING**
  Geoscan V full colour digital linescan imaging system. Produce RGB images and profile data from your cores.

- **COLOUR SPECTROPHOTOMETRY**
  Konica Minolta colour spectrophotometer measuring reflectance in the near UV through the visible and just into the near IR range (wavelengths 360-740nm).

- **NATURAL GAMMA SPECTROMETRY**
  Total natural gamma count or gamma spectra (K, U, Th) from two or more 3″x3″ NaI(Tl) crystals (BGO crystals are available on request).

- **X-RAY FLUORESCENCE SPECTROMETRY**
  Innov-X handheld X-ray fluorescence (XRF) spectrometer which provides elemental analyses.

- **NEAR-INFRARED & VISIBLE SPECTROPHOTOMETRY**
  Near-infrared spectroscopy (= core mineralogy) using the ASDI LabSpec (the integratable equivalent of the TerraSpec) at wavelengths of 350-2500nm.



Geological Core Scanning

- **British Geological Survey** (BGS) new **Core Scanning Facility** at the **National Geological Repository** (NGR) in Keyworth, UK

- £1.4 million to create this new, state-of the art core scanning facility equipped with four high-resolution and automated core scanner systems for core imaging and non-destructive core analysis

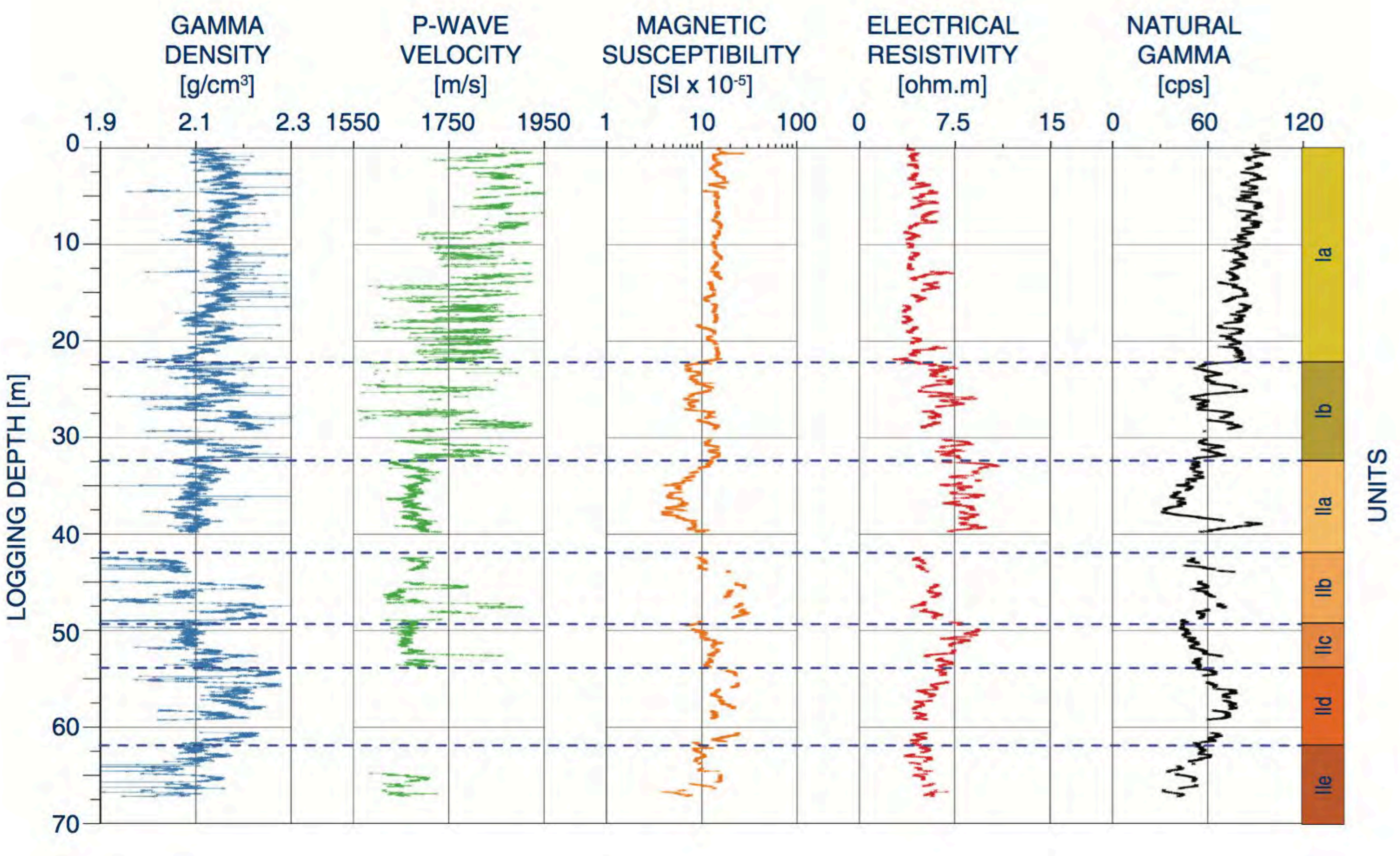
- 600 km of core, plus several million individual core and cuttings samples from over 8,000 offshore hydrocarbon wells and 15,000 onshore wells and boreholes.

Early Jurassic Earth System & Timescale (JET)

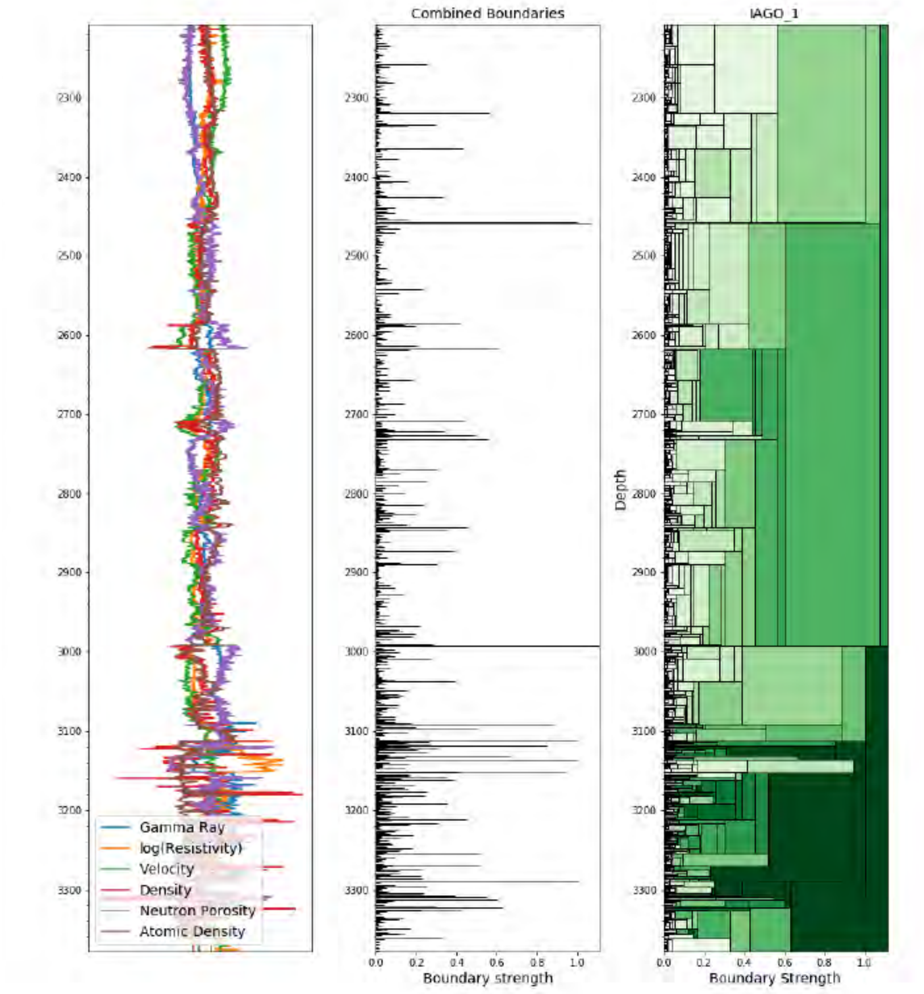
“The …. well will recover approximately **850 m of primarily latest Triassic to Early Jurassic** Strata, including the **Jurassic-Triassic boundary**. This new section is ideal for an integrated astrochronology, chemostratigraphy, biostratigraphy, and magnetostratigraphy which, combined with data being generated from the old Mochas core will become the international standard for these 25 million years of Earth history.”

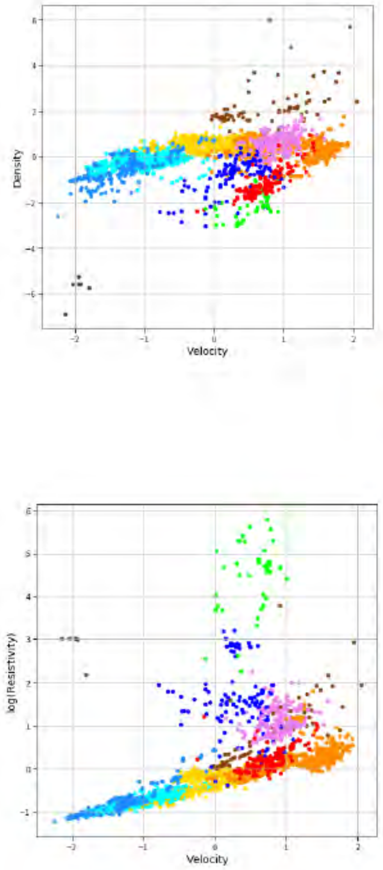
http://blogs.exeter.ac.uk/jet/

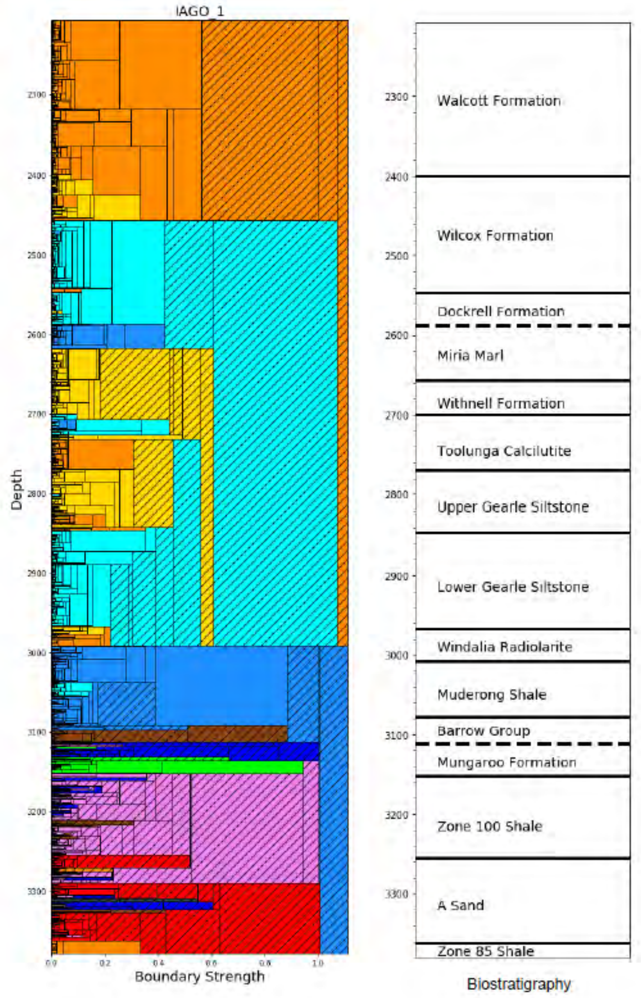
ONDRAF/NIRAS: Multi-Parameter Stratigraphy



Multiscale Automated Boundary Detection



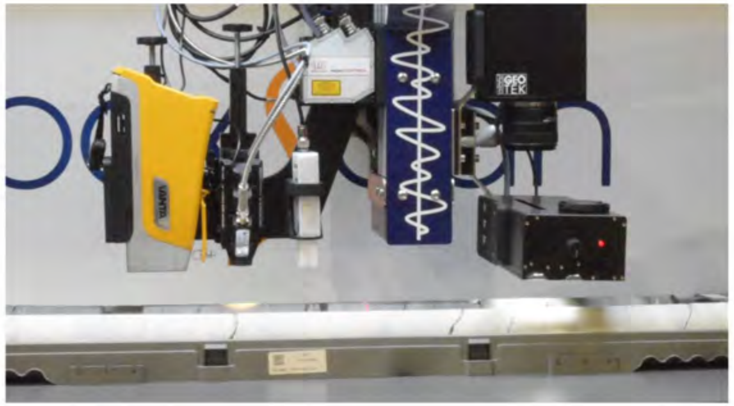


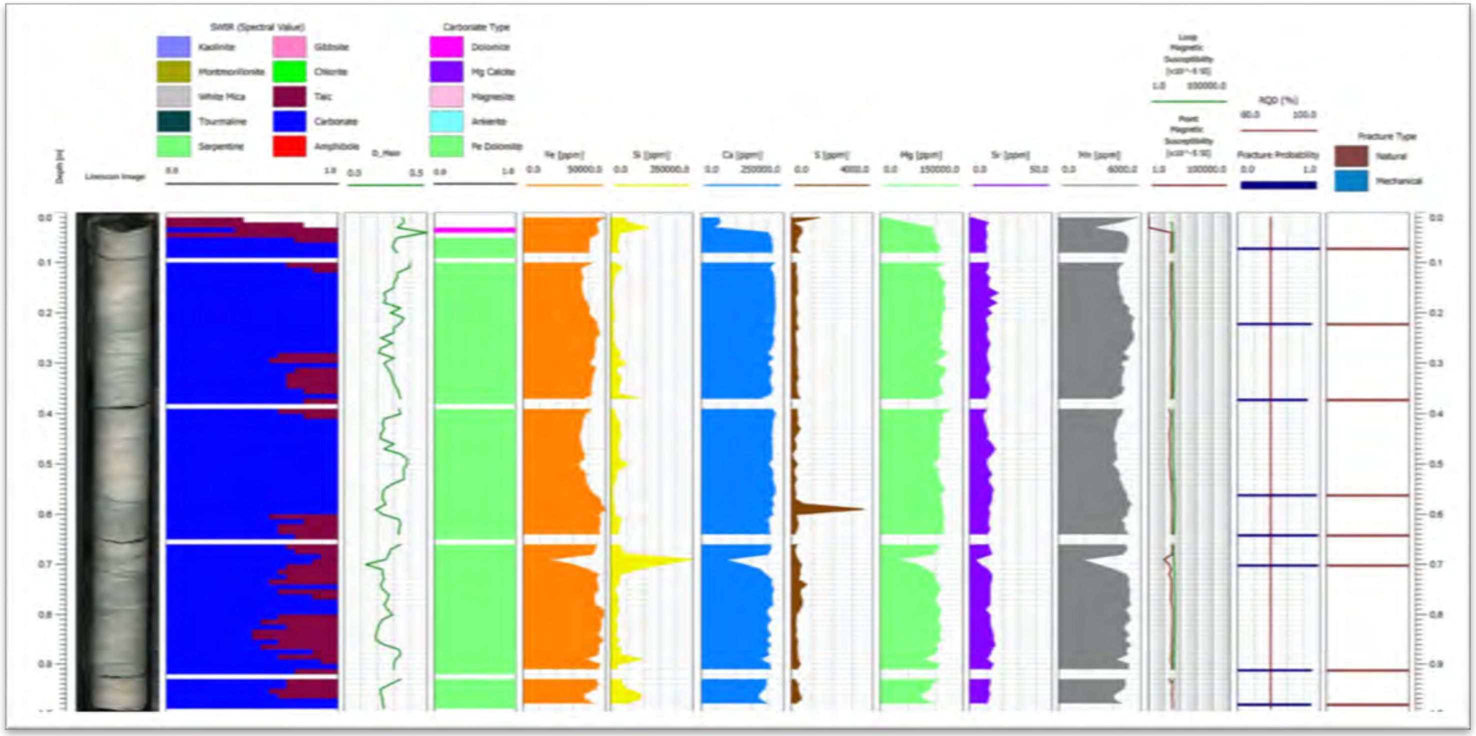


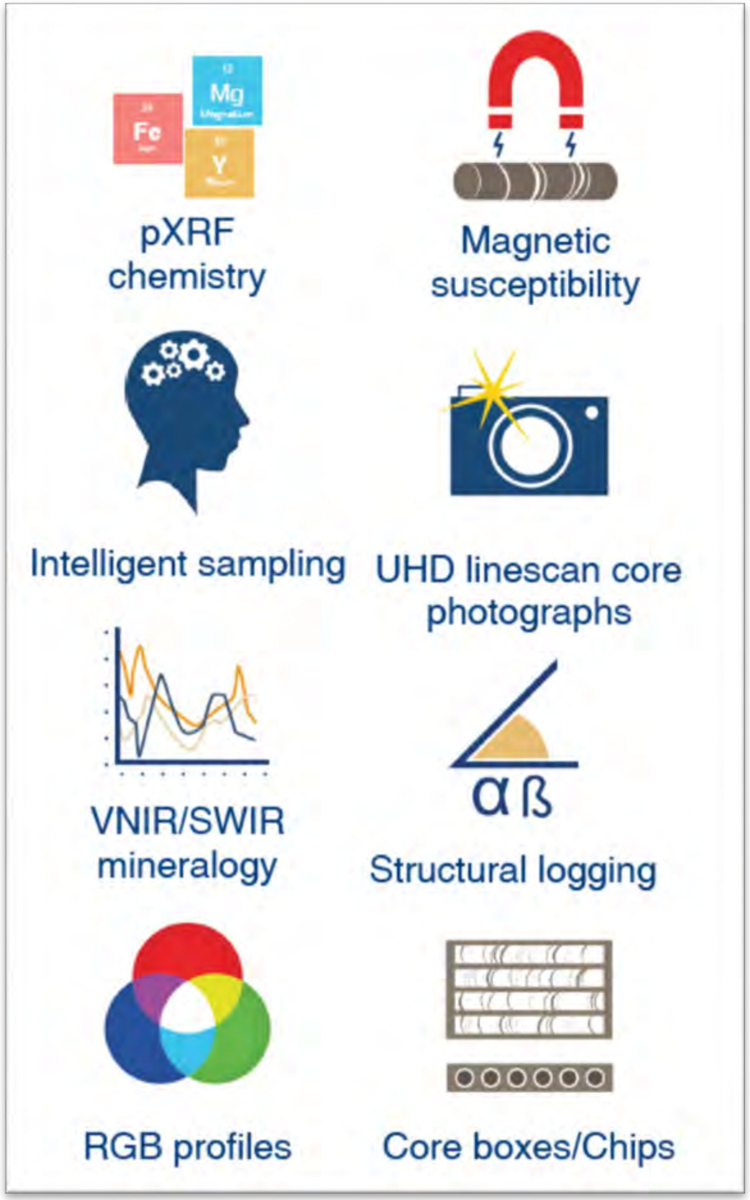
Wavelet tessellation (Hill et al. 2015). Tessellation automatically picks boundaries in depth-attributed numeric data and attributes the area between the boundaries with an average of the data.

Hill E.J., Robertson J., & Uvarova Y., 2015, "*Multiscale hierarchical domaining and compression of drill hole data*". Computers & Geosciences V79, pp. 47-57.

BoxScan system







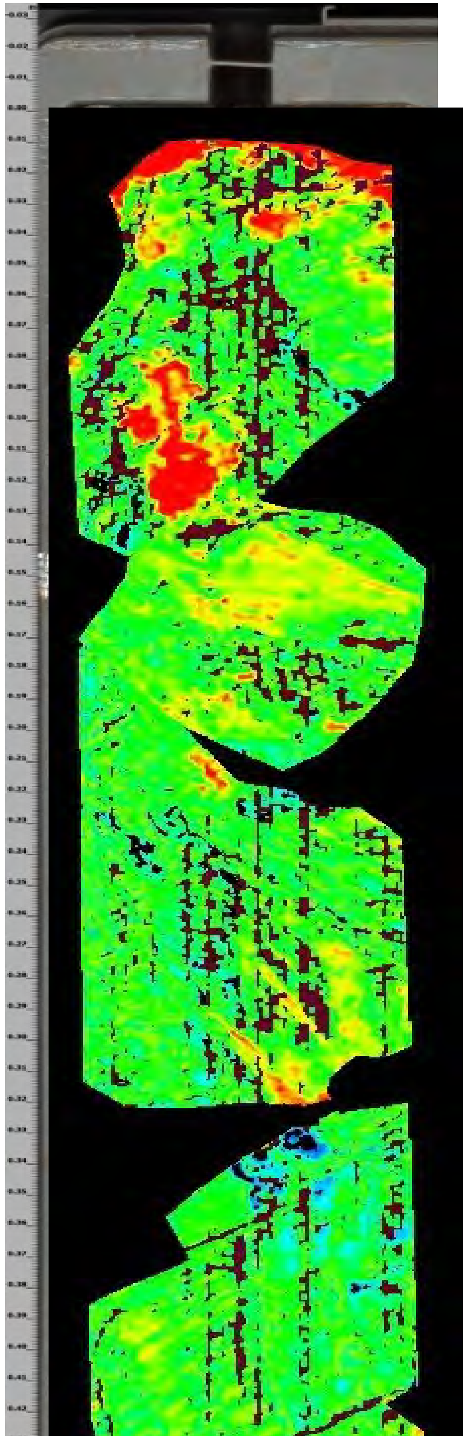
Spectral range from 400 nm to 2500 nm

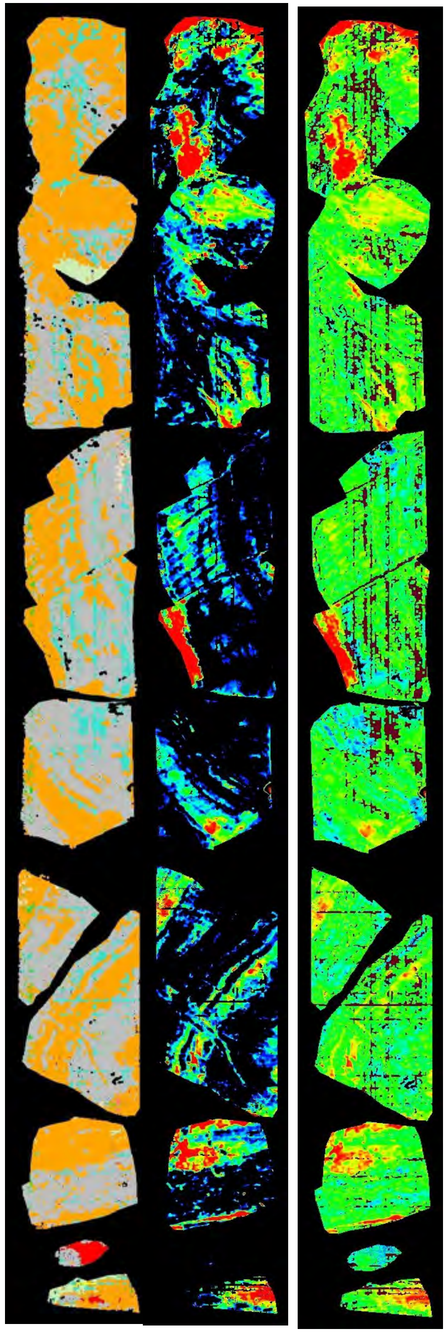
Electronically controlled wavelength separation (down to 2nm)

Continuous coverage high image resolution is (0.5 mm x 0.5 mm)

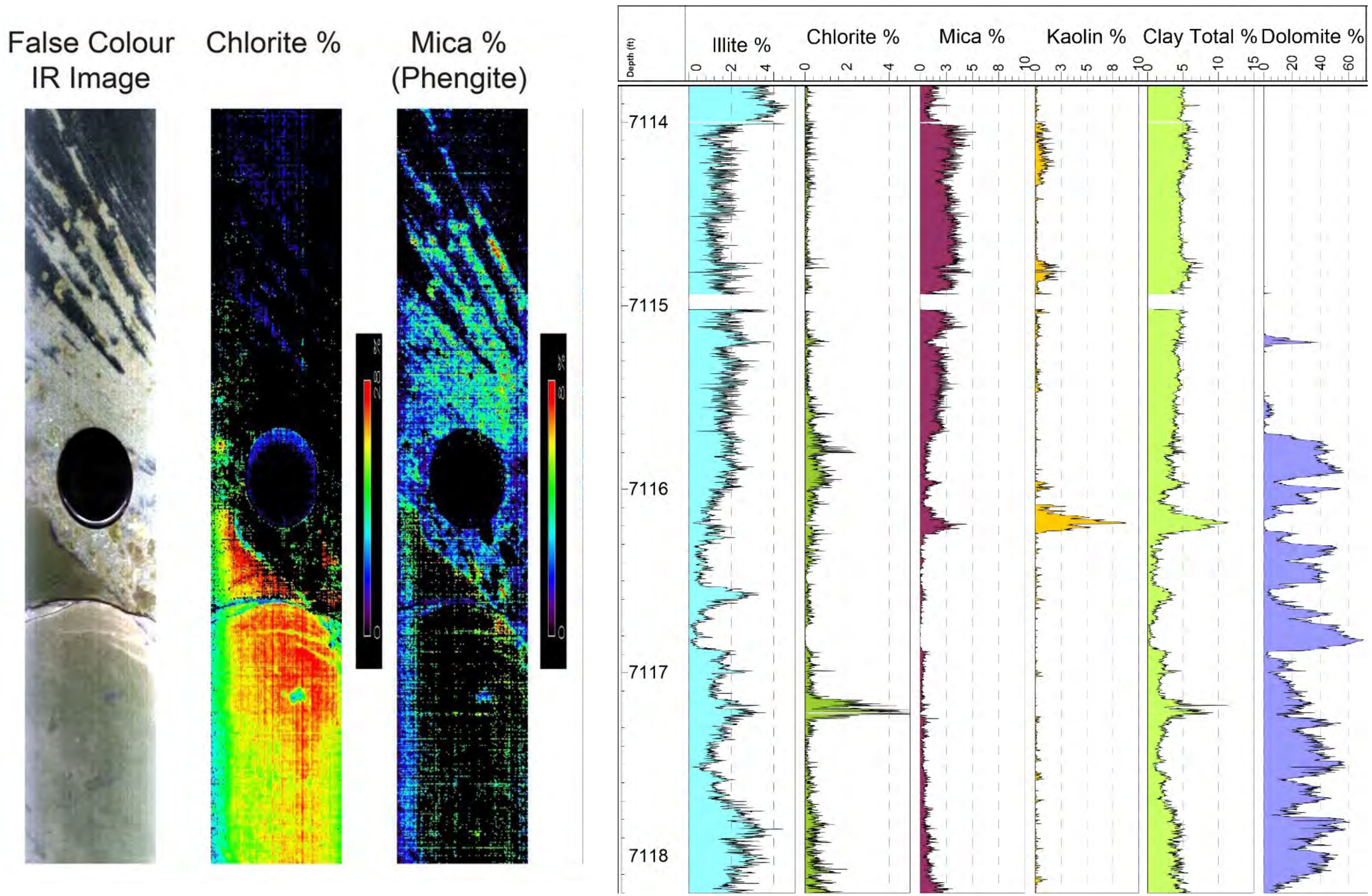
Accurate % data derived for the minerals

Core and Cuttings



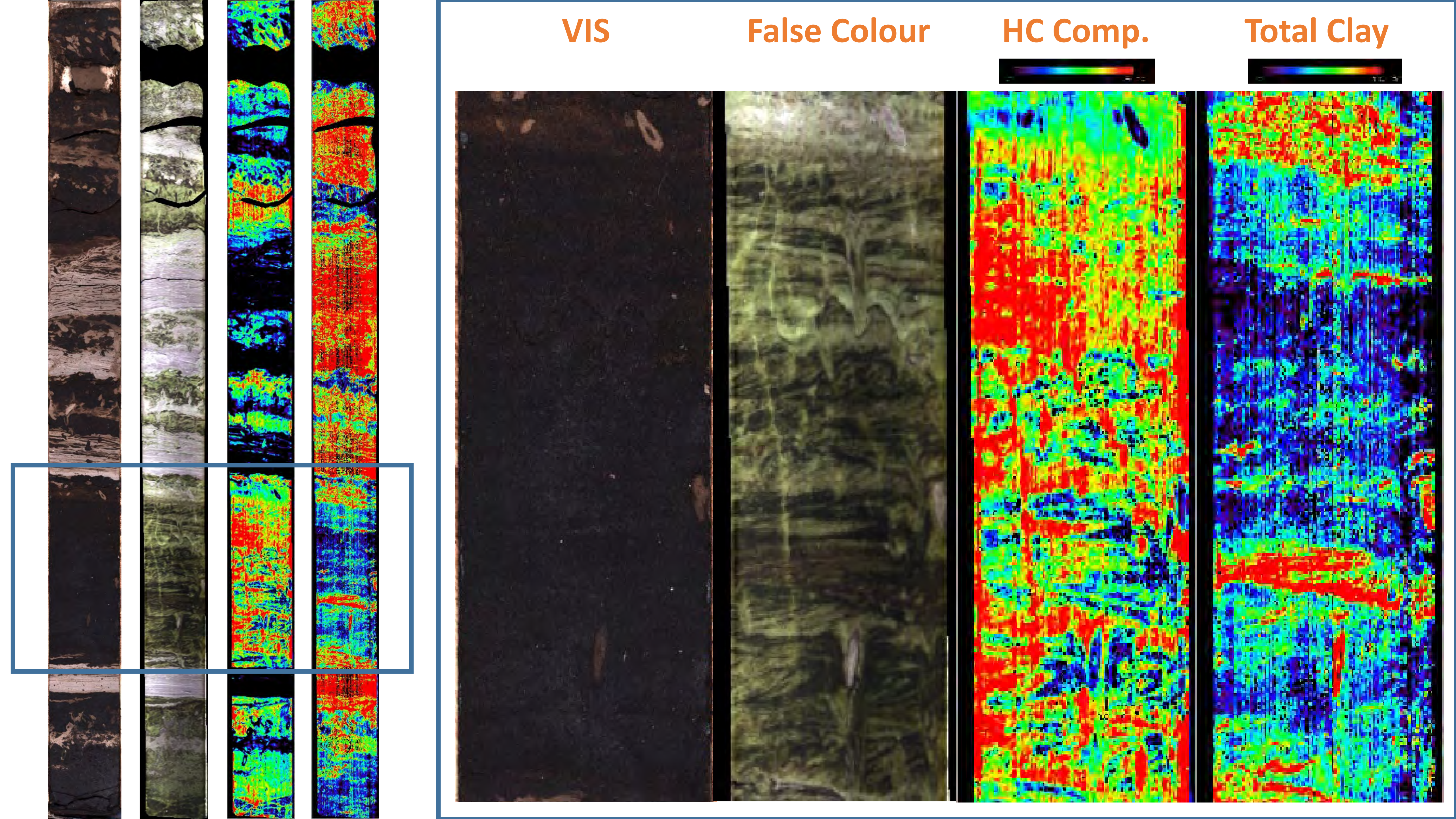


Hyperspectral VNIR/SWIR MSCL Technology

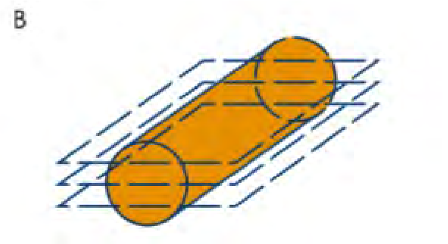


Multi-Sensor Core Scanning with a unique integration of mineralogy, elemental abundance and physical properties

- **Identification of minerals and their polymorphs**
- **Identification of mineral assemblages**
- **Clay crystallinity**
- **Mineral abundances (%) calculated, which are comparable to other analytical methods**

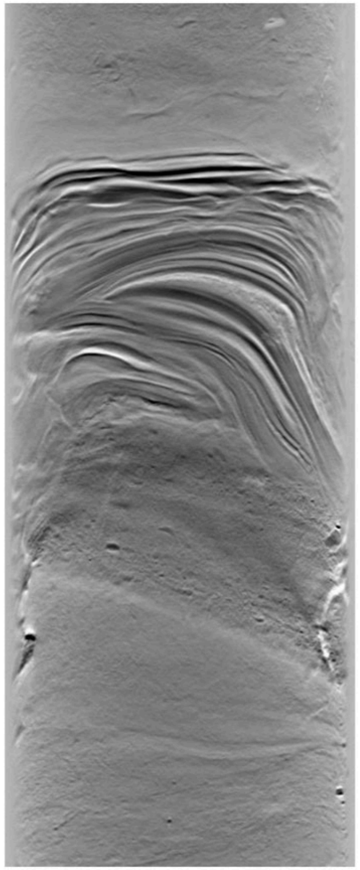

VIS
False Colour
HC Comp.
Total Clay

Laminography



Laminography is an image processing technique used to extract 3D information from 2D scans

- **Reduce** scan time and data storage
- Create multiple laminographs (slabs) at different longitudinal depths from the core
- Laminography is perfect for:
  - **Depth position of dropstones** or shell fragments
  - Create core fly-through videos
  - Create **X-ray slabs of measurement surfaces** rather than averaged images
  - **Visualizing** the geological architecture/features more clearly
  - Creating **circumferential images**



NEW

WORKFLOW

ILLUSTRATION

DISRUPTIVE CORE ANALYSIS WORKFLOW

CT SCAN

Lab Gamma Ray

Barrel Opening

« Blind » Plug Selection

Petrophysics
(Routine Core Analysis)

Reservoir Engineering
Special Core Analysis

Geomechanics
Special Core Analysis

CT SCAN

Lab Gamma Ray

Barrel Opening

MiniSlab & CoreDNA

AI Lithofacies / Properties prediction / Smart report

Intelligent Plug Selection

CT Scan:

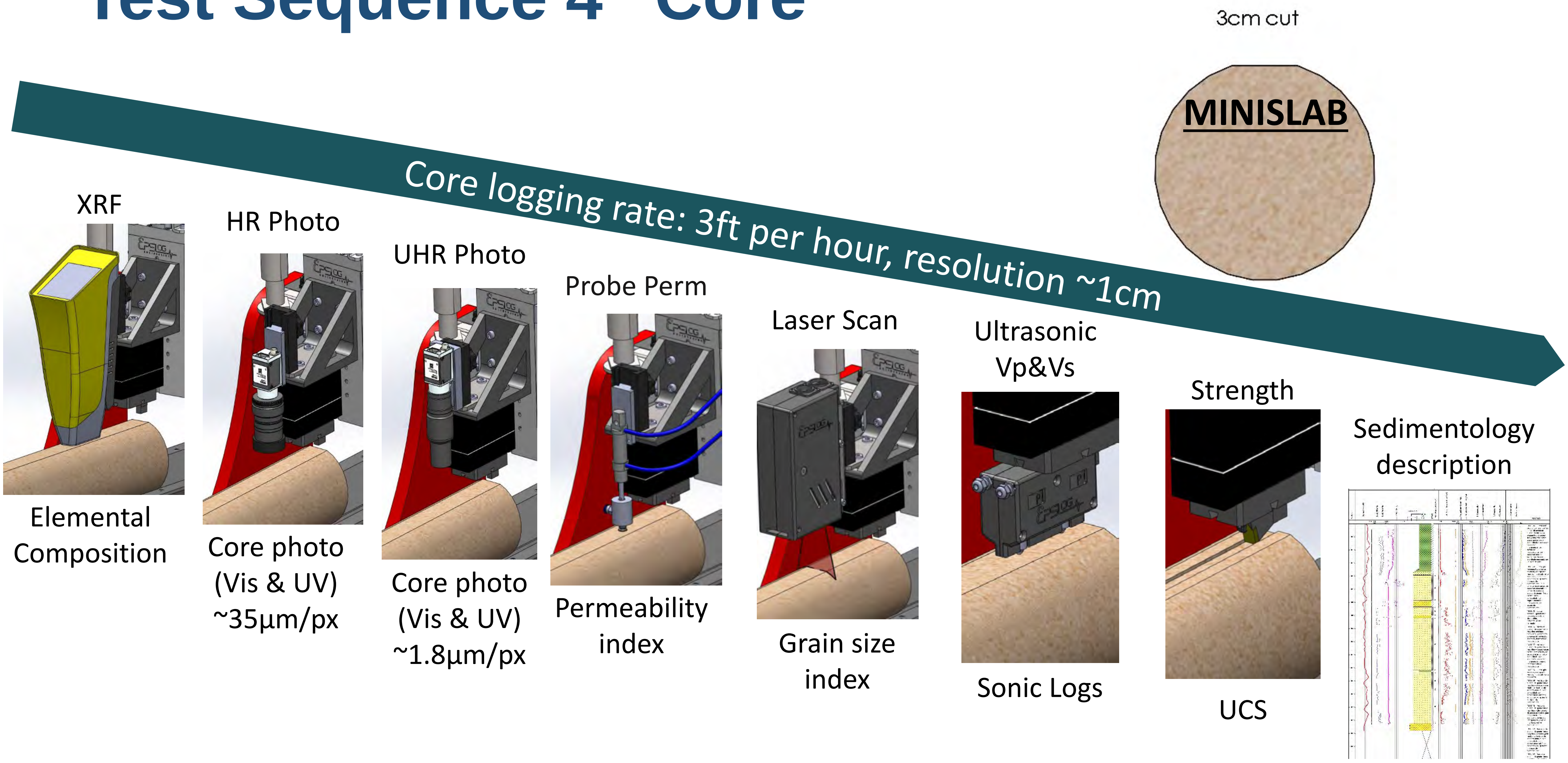
- 3D images
- Density
- Atomic Number
- *Porosity index*

Spectral Core GR

CORE DNA:

- Strength / VP&VS
- GSD
- UHR Image (Vis & UV)
- Elemental Composition / Mineralogy
- Probe Perm
- Sedimentological description

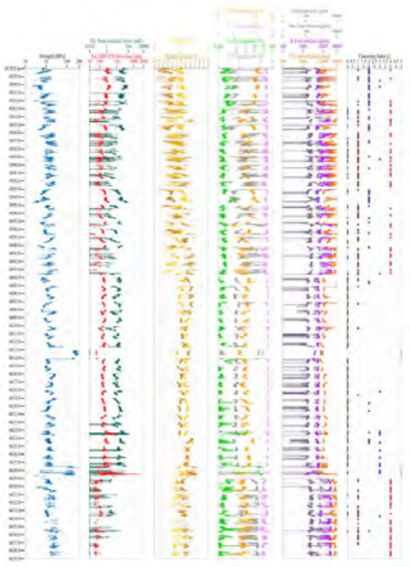
Test Sequence 4” Core

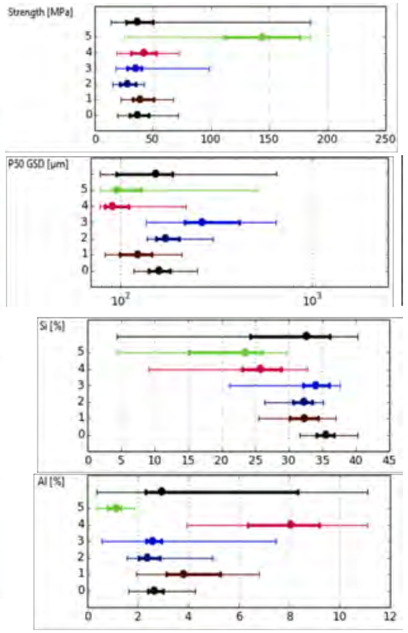


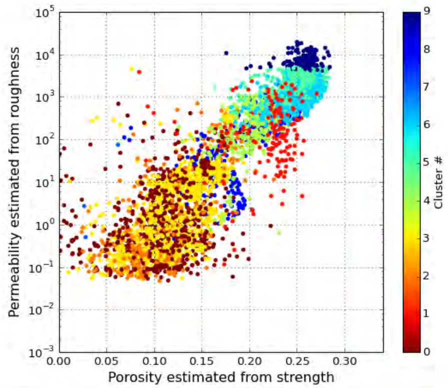
More Knowledge Sooner

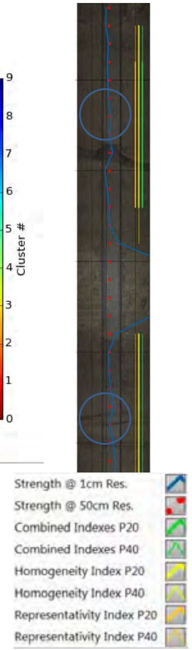
- **MULTI-SENSOR BENCH: ALL DEPTH SYNCRHONIZED** HIGH RESOLUTION SUITES OF MEASUREMENTS (1CM OF ROCK SAMPLE)
- RAPID AND NON DESTRUCTIVE TESTS & ANALYSIS / EARLY IN CORE ANALYSIS WORKFLOW;

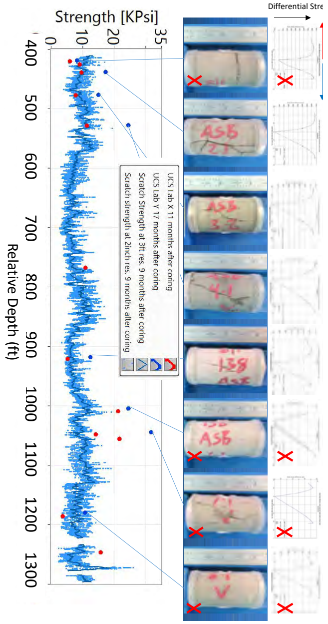
Generation of big data → Facies characterization (properties statistics per facies) → Prediction of reservoir quality indexes → Adaptive Sample Sites selection → Qcing of Test results → Upscaling discrete test results → Establish robust and reliable proxies with wireline logs

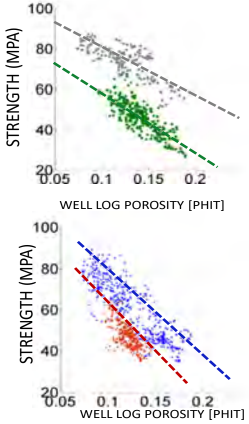




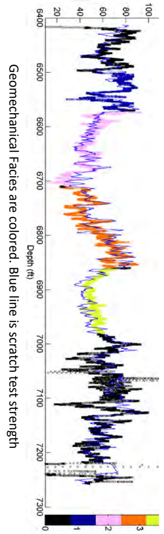




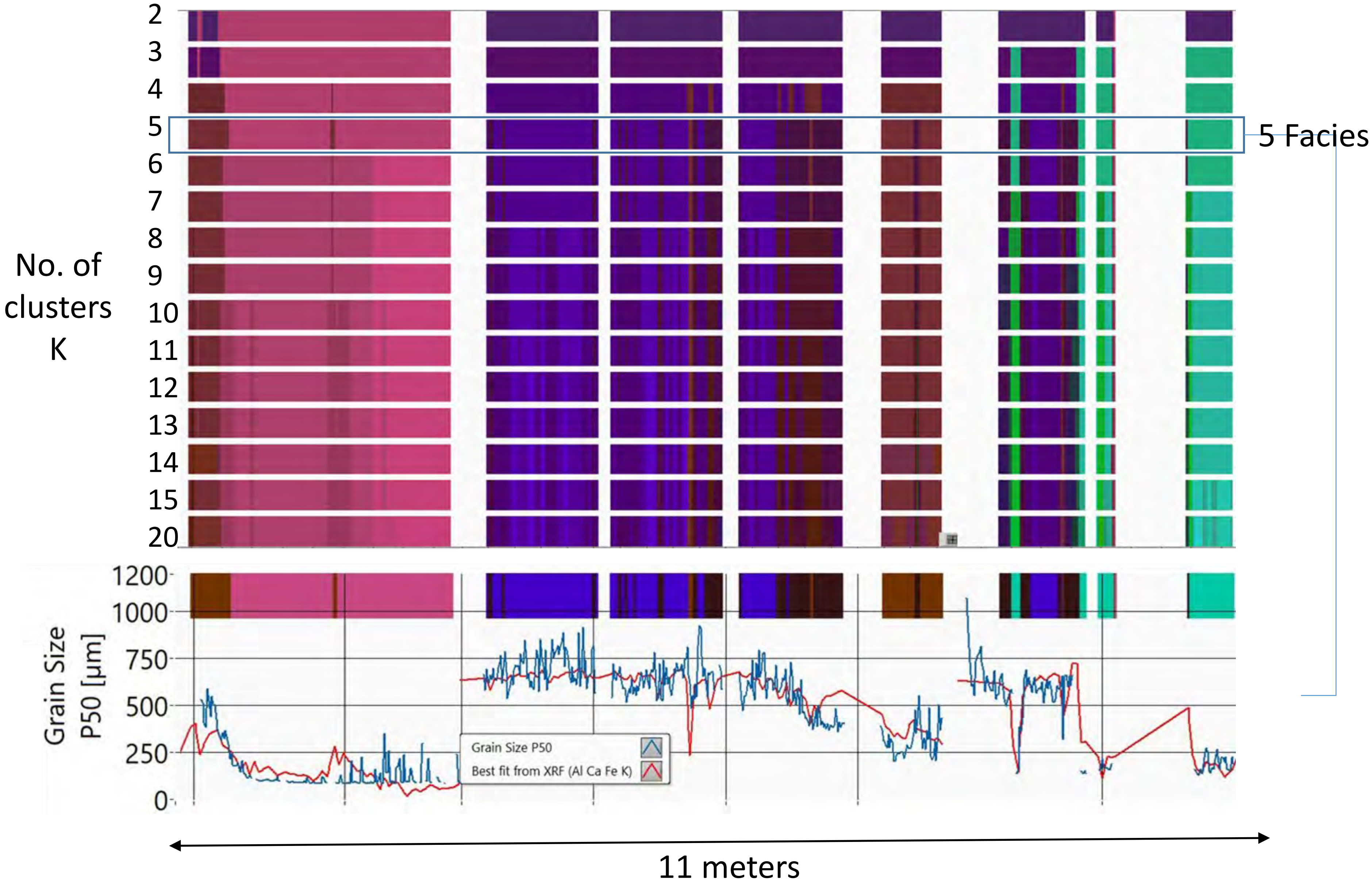




$$UCS(MPa) = c\phi + d\frac{V_p}{V_s} + e$$



Facies Identification: Unsupervised Machine Learning

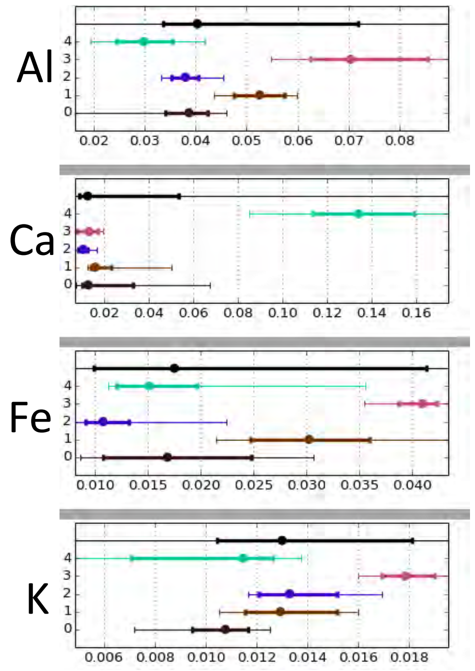


Clustering on Al Ca Fe K

Fraction of total core length

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

Elemental Concentrations per facies



Facies Characterisation: Quantitate Values

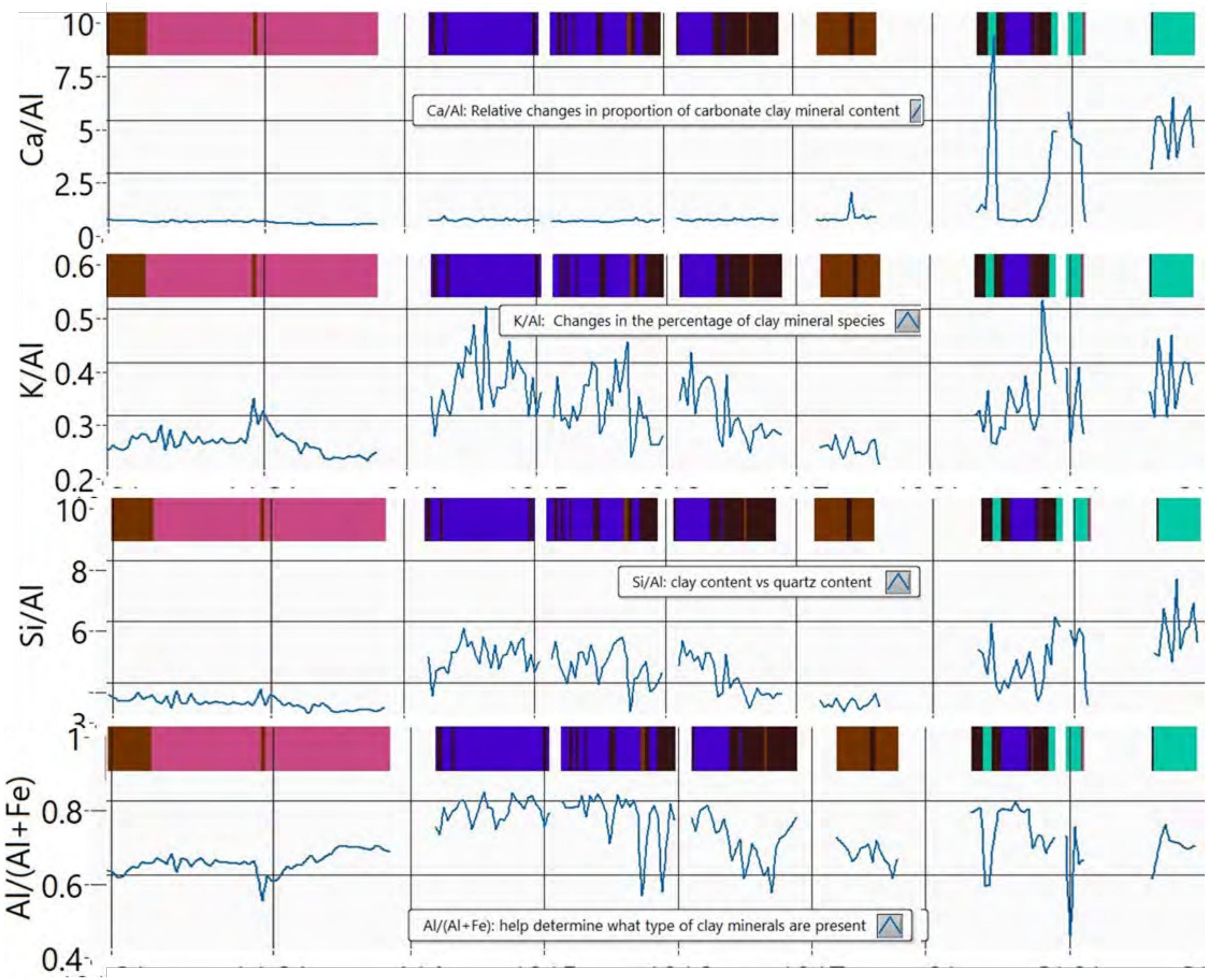
<u>Relative changes:</u>

carbonate/clay

Clay Mineral species

Clay /Quartz

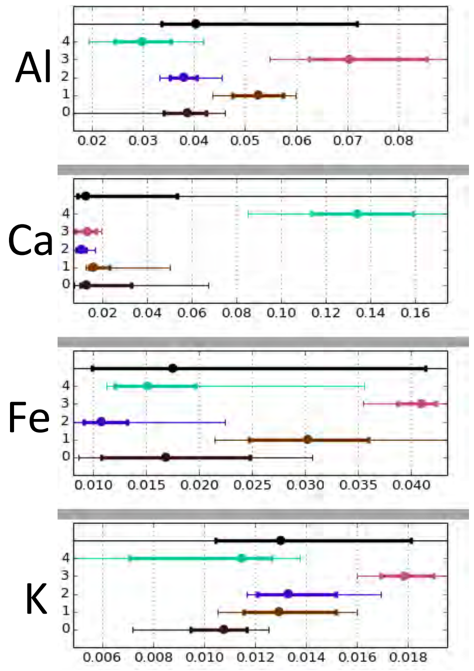
Type of clay minerals



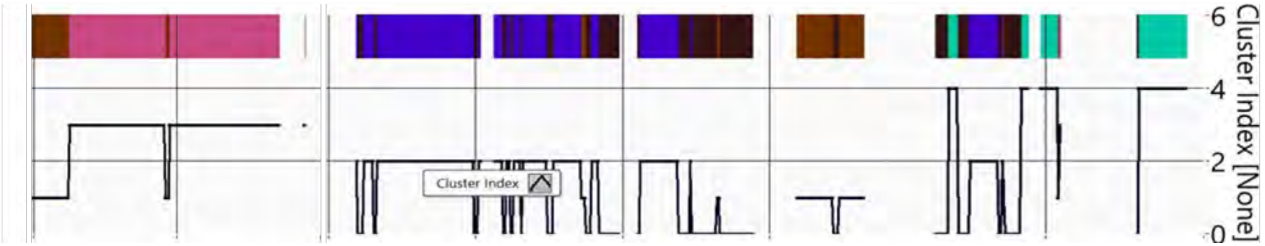
Fraction of total core length

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

Elemental Concentrations per facies

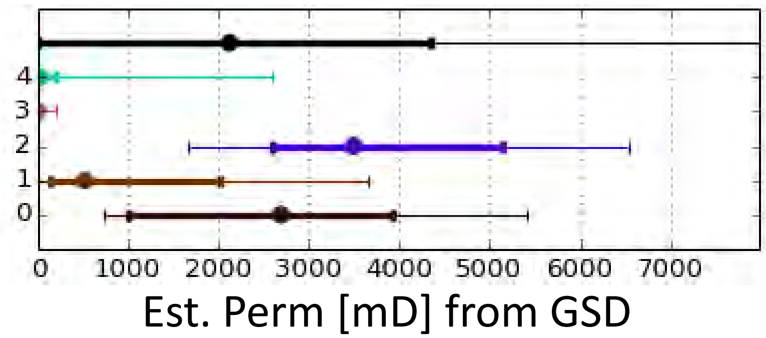


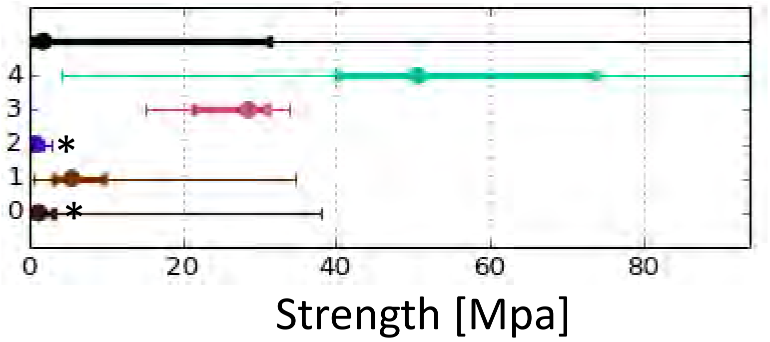
Facies Characterisation: Quantitative Values



Fraction of total core length

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





Low Perm

K3 K4

	Strength [Mpa]	Est. Perm [mD]
P10	23	0.1
P50	29	0.1
P90	60	65

Best Reservoir*

K2 K0

	Strength [Mpa]	Est. Perm [mD]
P10	0.5	1500
P50	1	3300
P90	2	4900

Shaly Sand

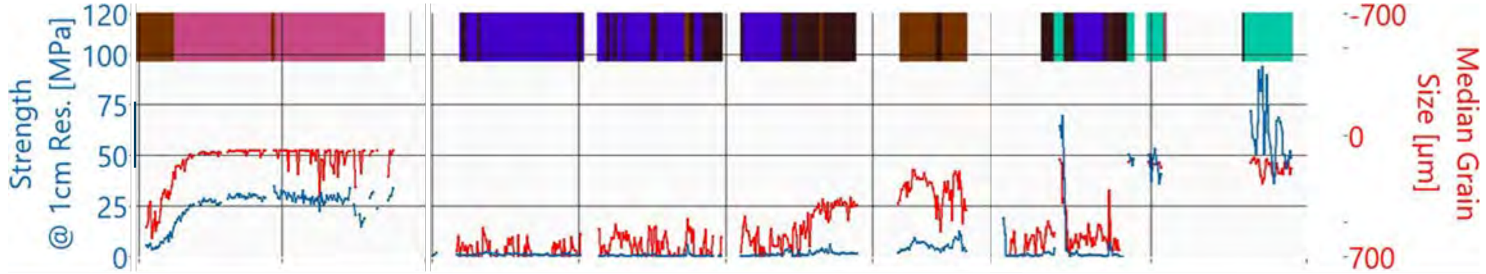
K1

	Strength [Mpa]	Est. Perm [mD]
P10	3	128
P50	6	520
P90	10	2000

Optimized adaptive plugging strategy for each formation

*Risk of sanding from the reservoir (Completion designs adjusted to grain size measured on cores)

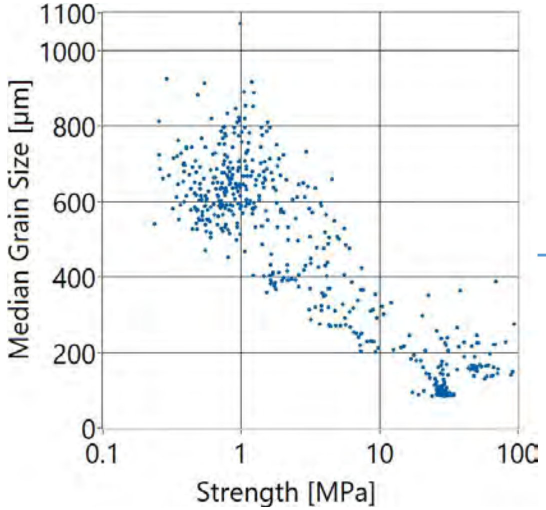
Lithological Interpretation

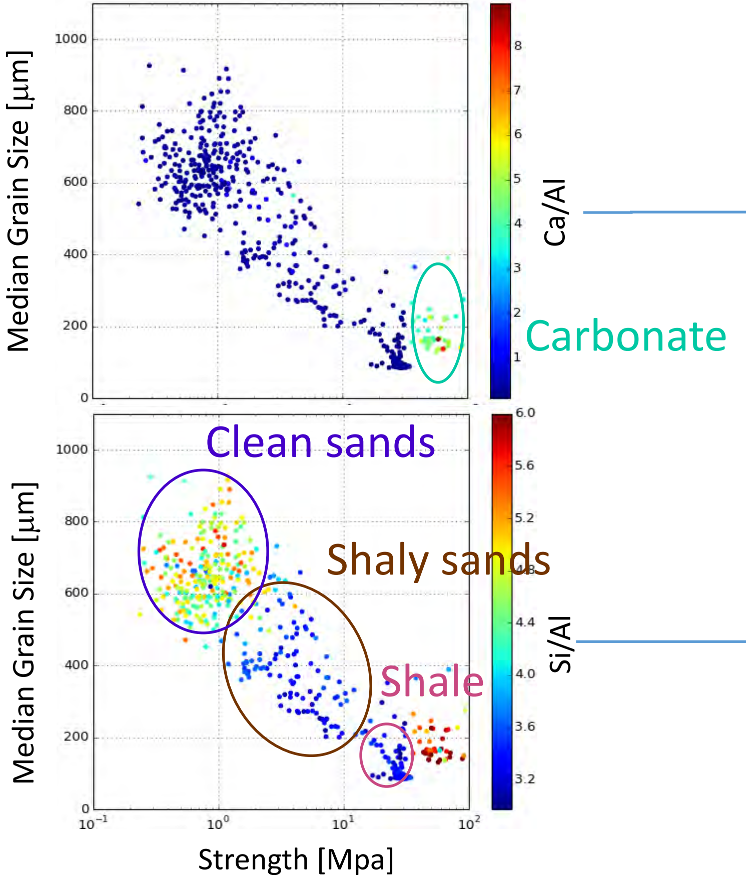


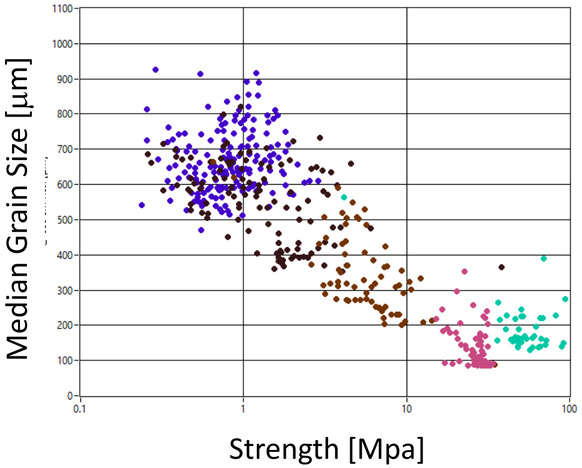
*Inverted axis

Fraction of total core length

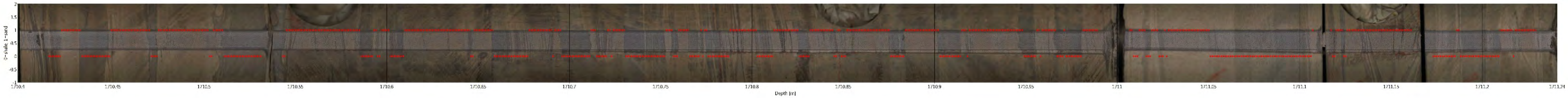
K4	K3	K2	K1	K0
9%	25%	31%	14%	21%

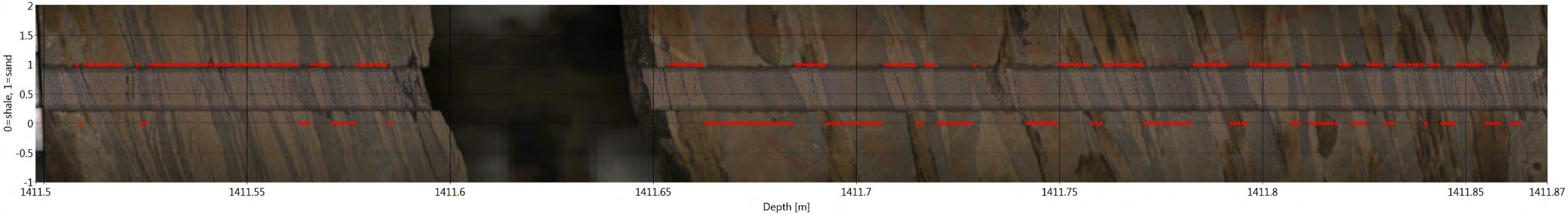


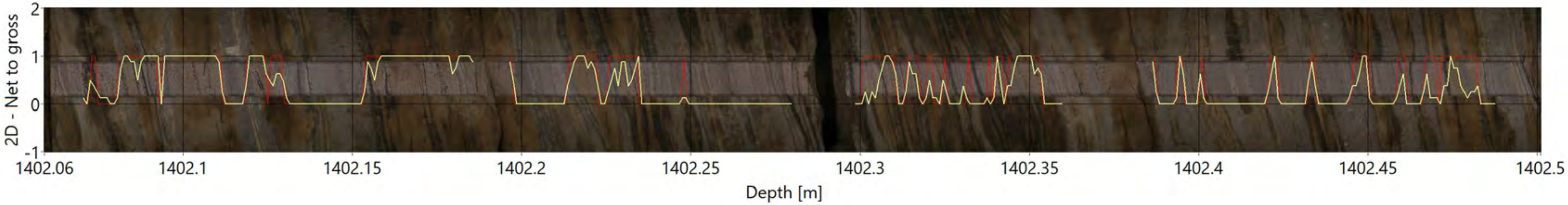




Net to Gross




0=shale, 1=sand
2
1.5
1
0.5
0
-0.5
-1
1411.5
1411.55
1411.6
1411.65
1411.7
1411.75
1411.8
1411.85
1411.87
Depth [m]

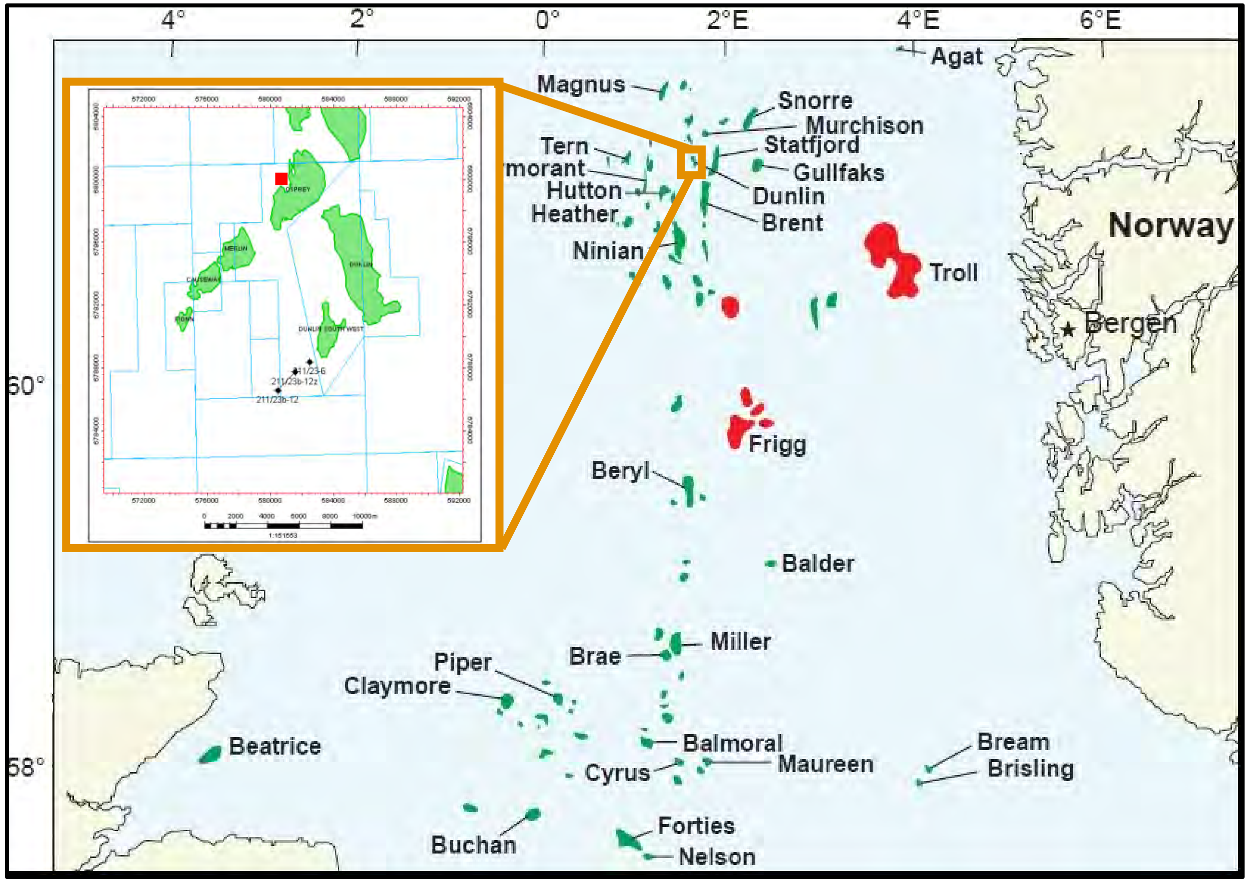

2D - Net to gross
2
1
0
-1
1402.06
1402.1
1402.15
1402.2
1402.25
1402.3
1402.35
1402.4
1402.45
1402.5
Depth [m]

MSCL CASE STUDY

FACIES PREDICTION

Case Study: Rock Core 211/23-8Z (8S1) Well Log and MSCL Data

https://ndr.ogauthority.co.uk/dp/controller/PLEASE_LOGIN_PAGE



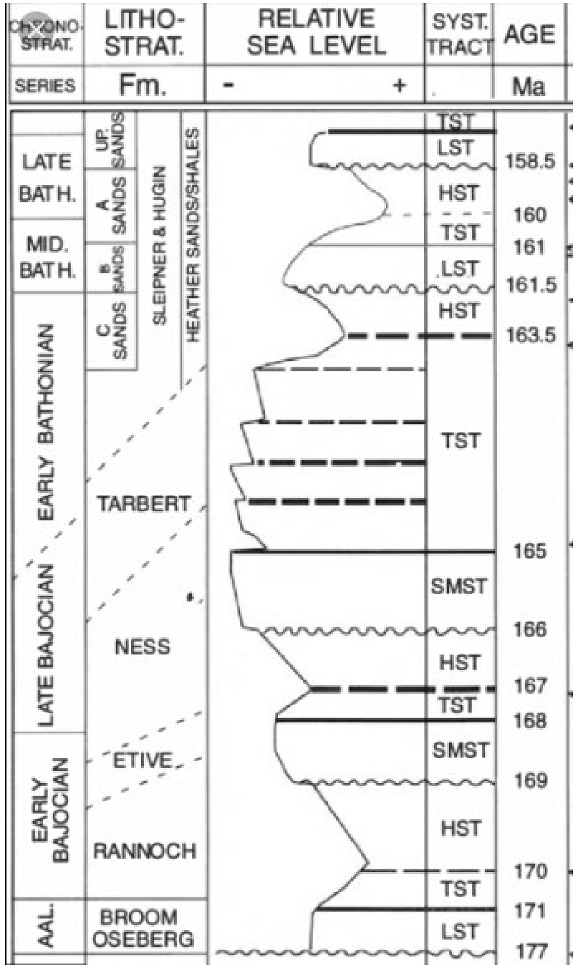
- Approximately 40’ (between 9121’ – 9163’) slabbed core drilled in 1985 from borehole 211-23-8Z(8S1) from the UKCS Osprey/Dunlin field;
- Extensive set of well log and core analysis data was available from the UK’s Oil and Gas Authority, National Data Repository (NDR) (open access);
- The core was logged and imaged using the following techniques: **Multi-Sensor Core Logger**, **Rotating X-ray CT (RXCT)**, and **SpecCam 4 VNIR/SWIR Hyperspectral Camera**. These data are combined with the existing well core data (core and log);
- Approximately 80,000 data points were interrogated using multivariate wavelet analysis to interpret facies or domains and a rock type pseudo-log

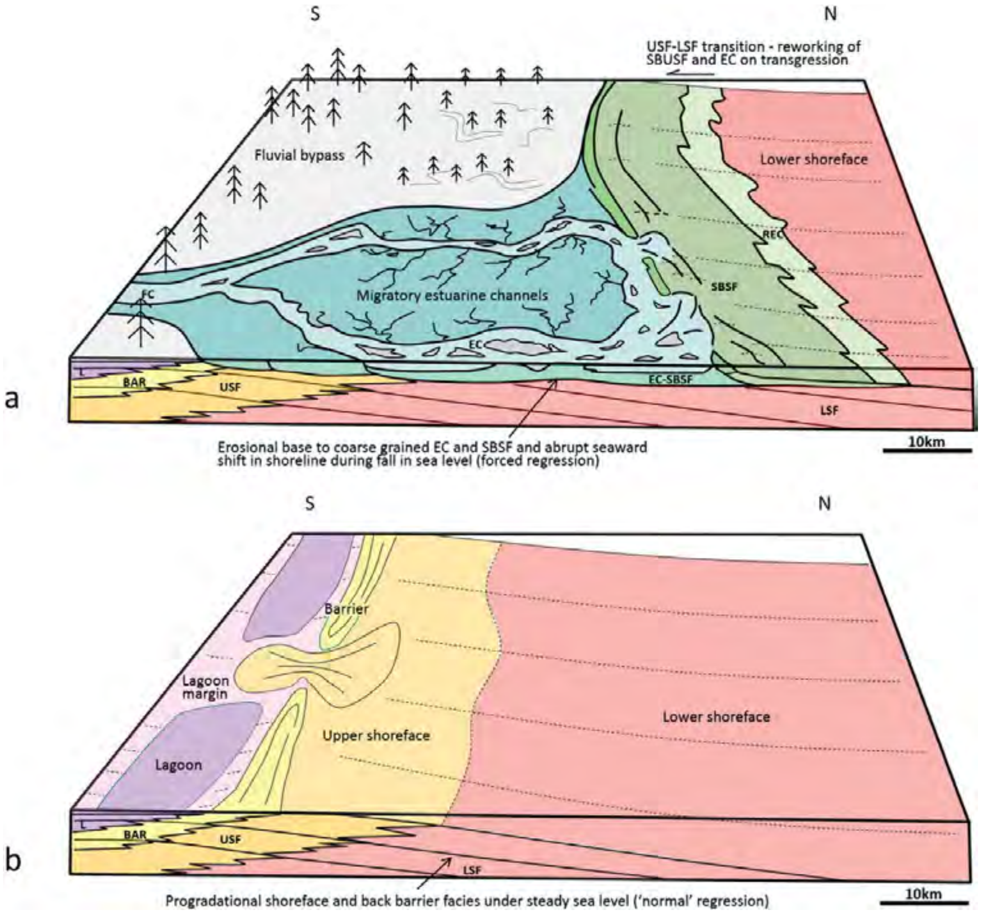
Case Study: 211/23-8Z (8S1) Dunlin/Osprey Field

CORE	1	8927 - 8968
CORE	2	8968 - 9006.8
CORE	3	9007 - 9067
CORE	4	9067 - 9127
CORE	5	9127 - 9166
CORE	6	9171 - 9230
CORE	7	9231 - 9291

Total of 357.8 ft

Brent sequence cored from Heather through to Etive

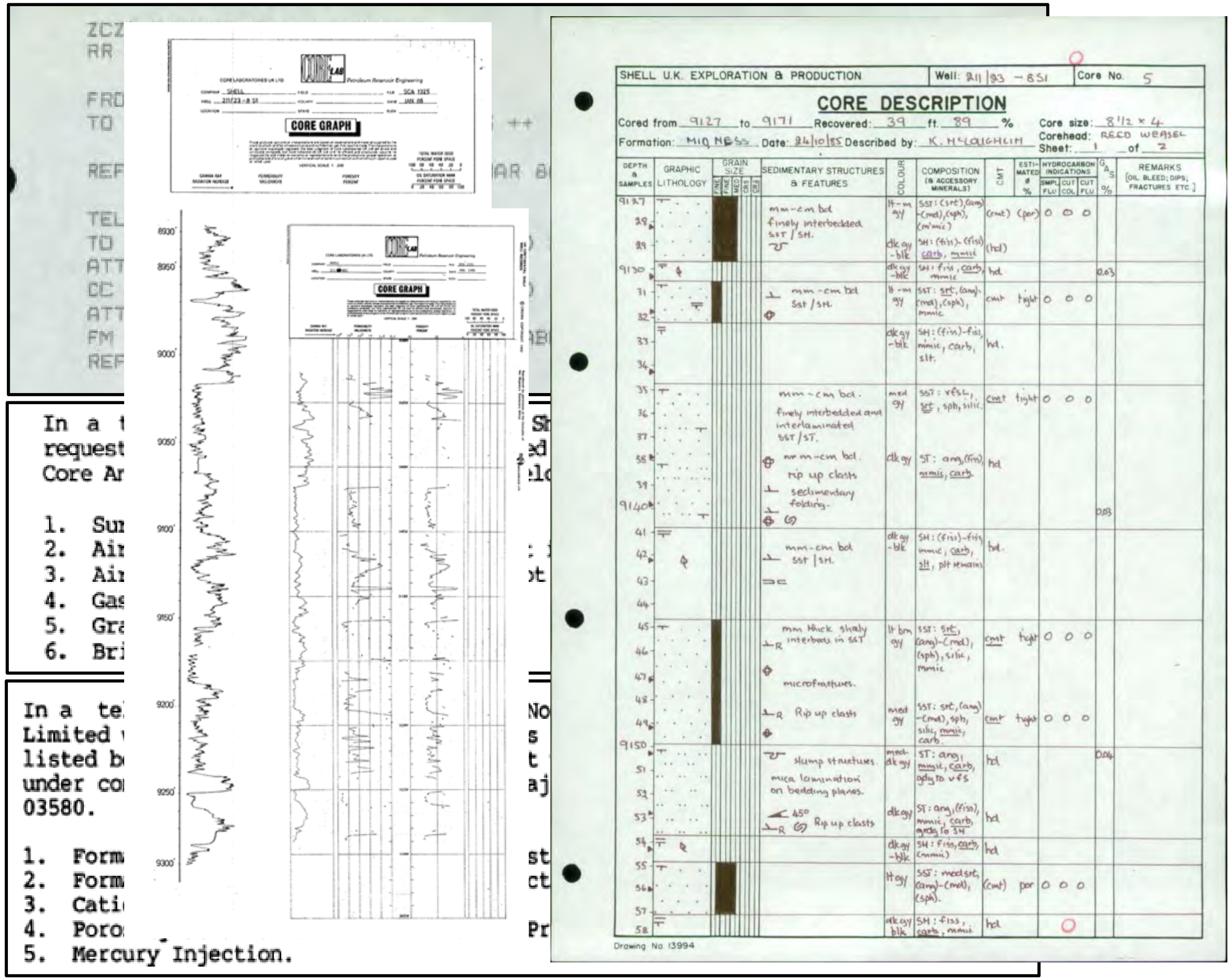




Described by: K. McLOUGHLIN Corehead: RECD WEASEL
Sheet: 1 of 2

211/23-8Z (8S1) - Sediments

211-23-8Z (8S1) - Vintage Core Analyst?



4th April, 1986.

CORE LABORATORIES UK LTD

DIRECTORS
W. R. AUFRICHT (U.S.A.)
Wm. A. ROBBINS, JR. (U.S.A.)
TED J. GRIFFIN, JR. (MANAGING)

Shell U.K. Exploration and Production,
1, Altens Farm Road,
Nigg,
ABERDEEN.

For the attention of Mr. G. G. Bakker.

Subject : Core Analysis Study,
Well : 211/23-8SI
File : SCA 1325

Dear Sir,

In a telex dated 6th November 1985, Shell U.K. Exploration and Production requested Core Laboratories U.K. Limited to perform a series of Conventional Core Analysis measurements, as listed below, on samples from the subject well.

1. Surface Core Gamma
2. Air Permeability (Horizontal at foot intervals)
3. Air Permeability (Vertical at 20 foot intervals)
4. Gas Expansion Porosity (every foot)
5. Grain Density (every foot)
6. Brinell Hardness

The results of these measurements are presented herein as a Final Report and serves to confirm all data previously submitted in preliminary form. A table of contents immediately follows this letter.

This report replaces the copy issued on 27th January 1986, following the rectification of the sample numbering problem which occurred in Core No. 6, as discussed N. O'Neil/C. Lindsay. Thus the data for this core is now in the correct order.

Please accept our apologies for any inconvenience this may have caused you whilst evaluating the data from this well.

The Brinell Hardness Data is reported in two formats as described in the procedures section. We hope this may be of use to yourselves when evaluating data for Brinell Hardness from different laboratories.

It has been a pleasure working with Shell U.K. Exploration and Production on this study. Should you have any questions, please do not hesitate to contact us.

Yours faithfully,
CORE LABORATORIES U.K. LIMITED

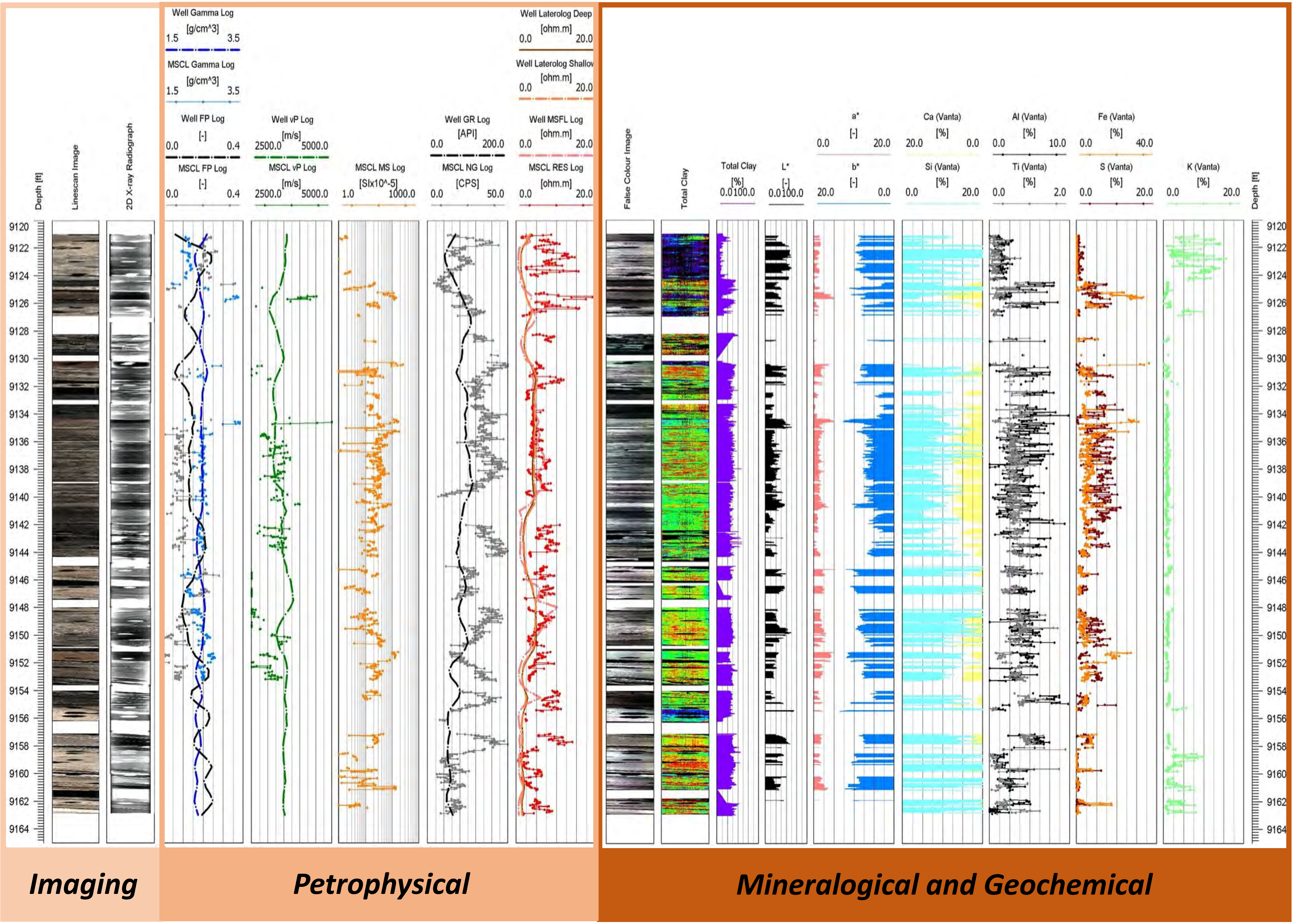
C.M. Lindsay

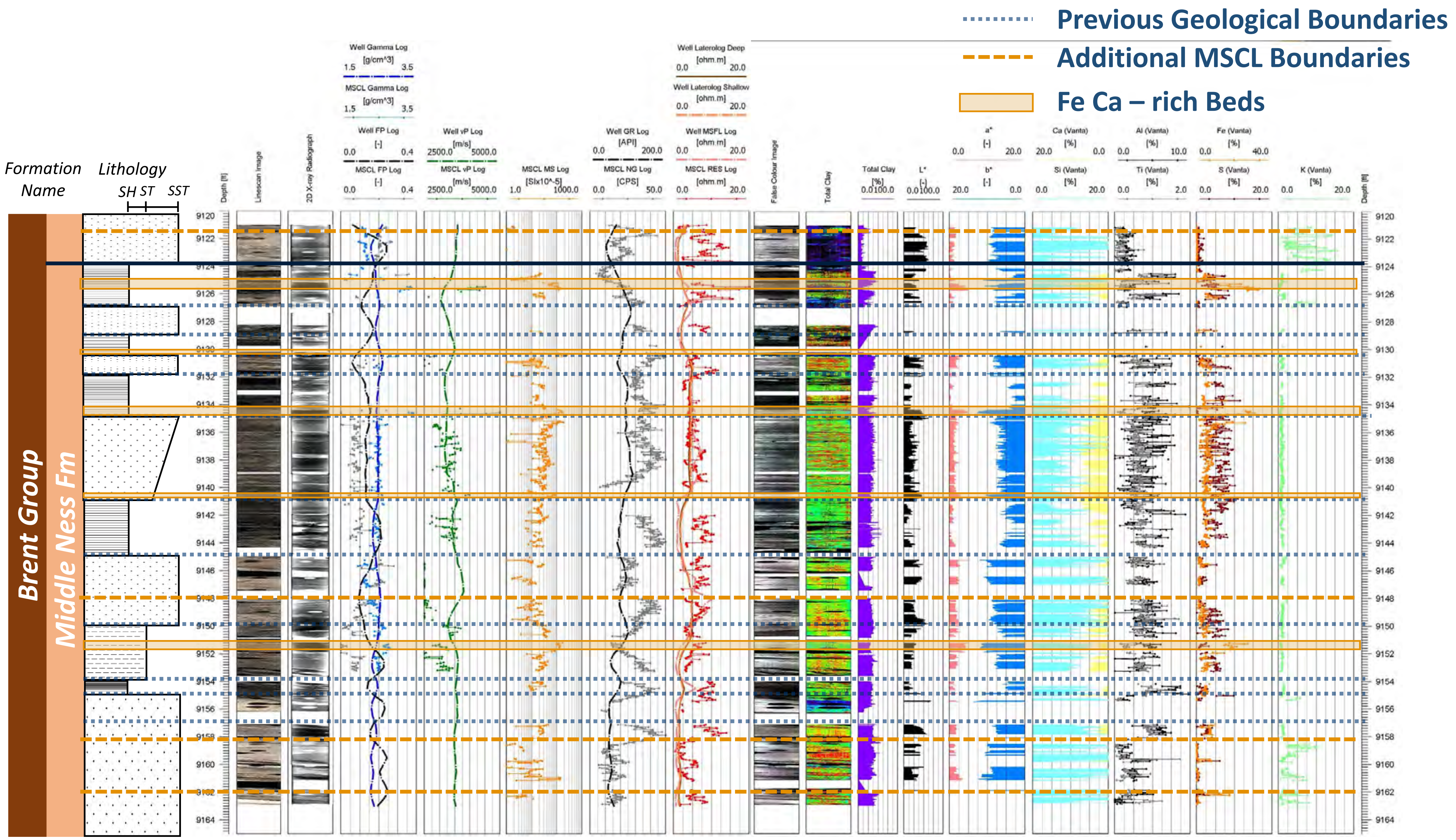
Craig Lindsay,
Core Analysis Department.

REGISTERED OFFICE: 75 GREENFIELD ROAD, LONDON E1 1EJ REGISTRATION NUMBER 1331818 VAT NUMBER 219 8700 49

MSCL Multi-Parameter Stratigraphy

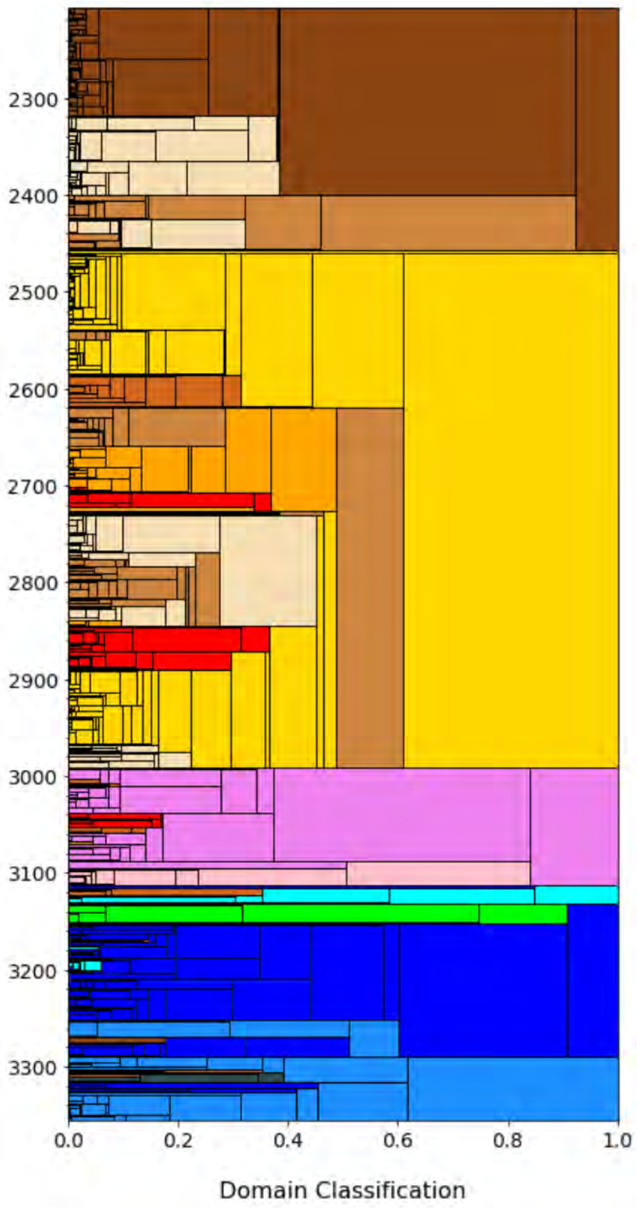
- Data acquired over 2 to 3 days
- Depth co-registered imaging, petrophysical, mineralogical, and geochemical data
- Good correlation between well log and core log




Previous Geological Boundaries
Additional MSCL Boundaries
Fe Ca – rich Beds
Formation Name
Lithology
SH ST SST
Brent Group
Middle Ness Fm
Depth [ft]
Linescan Image
2D X-ray Radiograph
Well Gamma Log [g/cm^3] 1.5 3.5
MSCL Gamma Log [g/cm^3] 1.5 3.5
Well FP Log [-] 0.0 0.4
MSCL FP Log [-] 0.0 0.4
Well vP Log [m/s] 2500.0 5000.0
MSCL vP Log [m/s] 2500.0 5000.0
MSCL MS Log [SIx10^-5] 1.0 1000.0
Well GR Log [API] 0.0 200.0
MSCL NG Log [CPS] 0.0 50.0
Well Laterolog Deep [ohm.m] 0.0 20.0
Well Laterolog Shallow [ohm.m] 0.0 20.0
Well MSFL Log [ohm.m] 0.0 20.0
MSCL RES Log [ohm.m] 0.0 20.0
False Colour Image
Total Clay
Total Clay [%] 0.0 100.0
L* [-] 0.0 100.0
a* [-] 0.0 20.0
b* [-] 20.0 0.0
Ca (Vanta) [%] 20.0 0.0
Si (Vanta) [%] 0.0 20.0
Al (Vanta) [%] 0.0 10.0
Ti (Vanta) [%] 0.0 2.0
Fe (Vanta) [%] 0.0 40.0
S (Vanta) [%] 0.0 20.0
K (Vanta) [%] 0.0 20.0
9120
9122
9124
9126
9128
9130
9132
9134
9136
9138
9140
9142
9144
9146
9148
9150
9152
9154
9156
9158
9160
9162
9164

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).

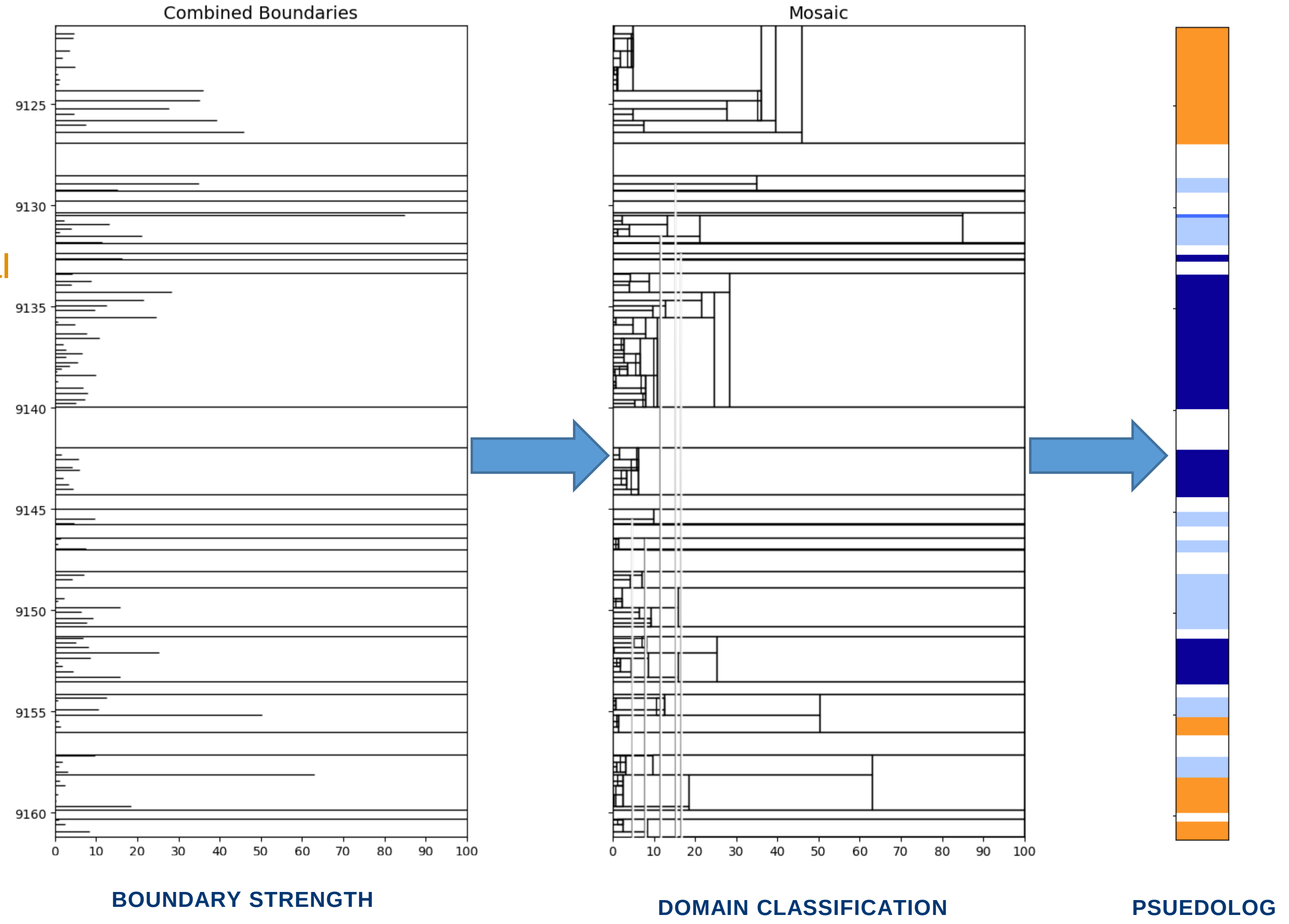


DATA MOSAIC CSIRO

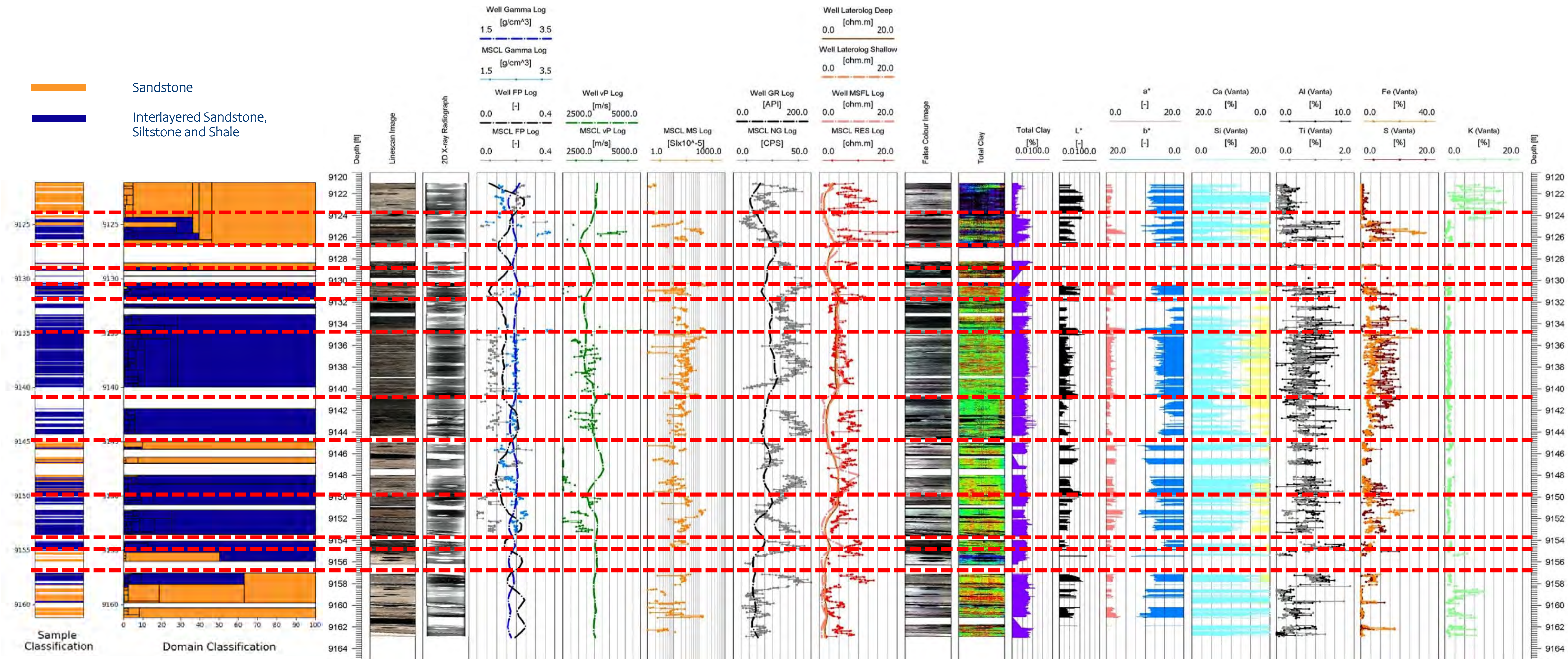
Hill E J, Robertson J and Uvarova Y (2015). Multiscale hierarchical domaining and compression of drill hole data. Computers & Geosciences, 79, 47-57.
Hill E J, Uvarova Y (2018) Identifying the nature of lithogeochemical boundaries in drill holes. Journal of Geochemical Exploration 184:167–178

211/23-8Z (8S1)
Classification Domain Workflow

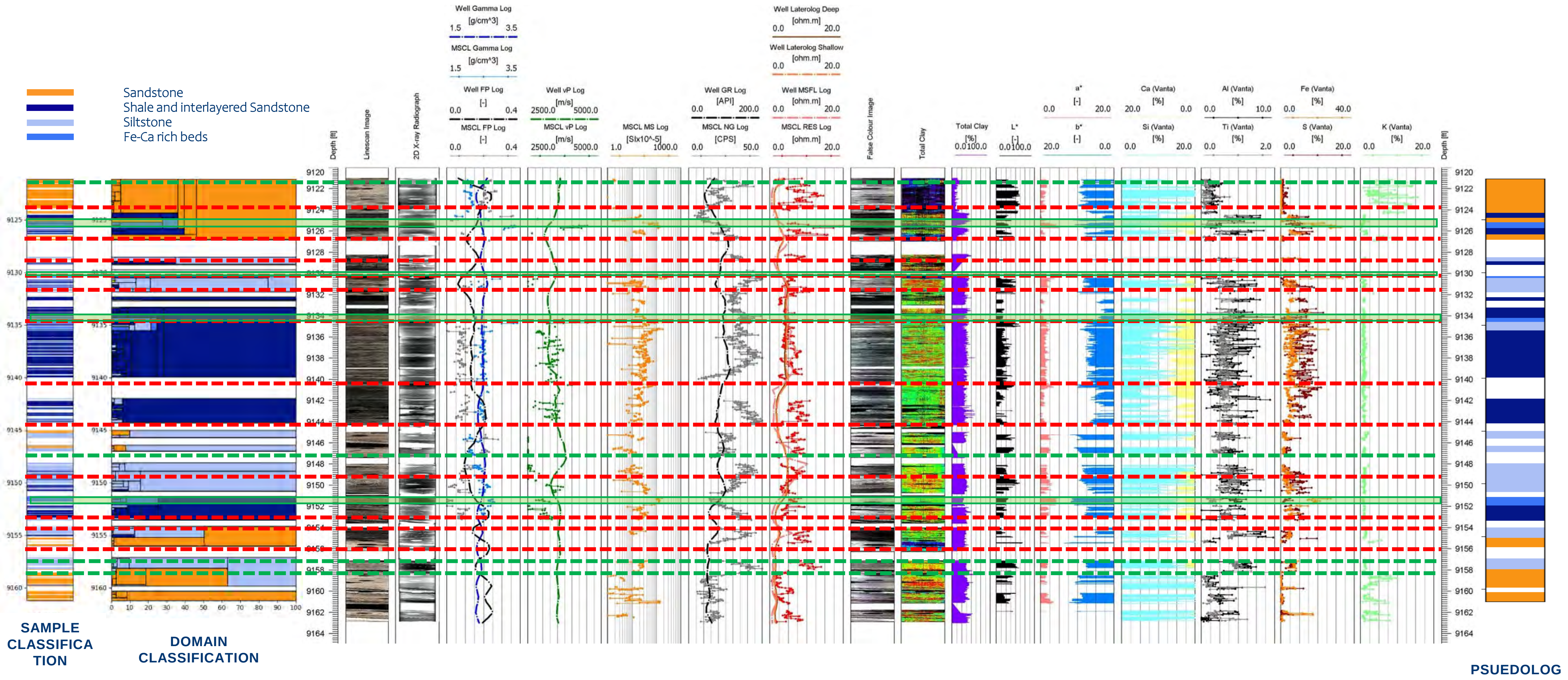
- MSCL data analysed by multiscale boundary detection using Continuous Wavelet Transform;
  - MSCL data used for analysis: **Magnetic susceptibility, electrical resistivity, natural gamma, colour (L*,a*, b*) and XRF (Ca,Si,Al,Ti,Fe,S,K,total counts);**
- Boundaries combined for multiple variables
- Domains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



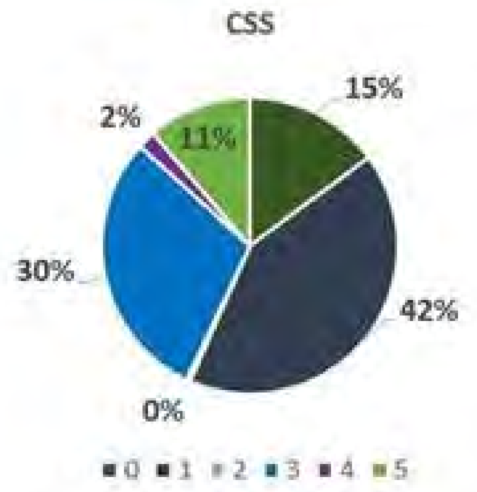
211-23-8Z (8S1)
Two Rock Type Solution

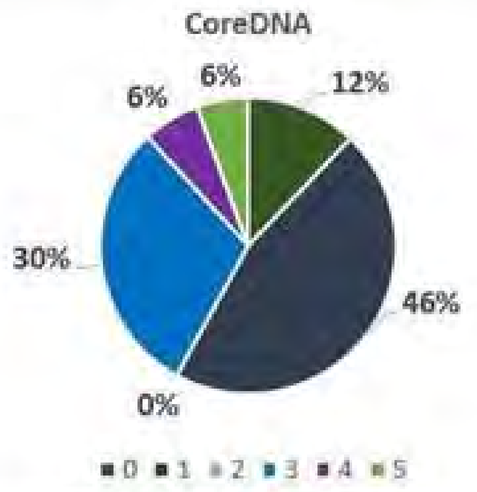


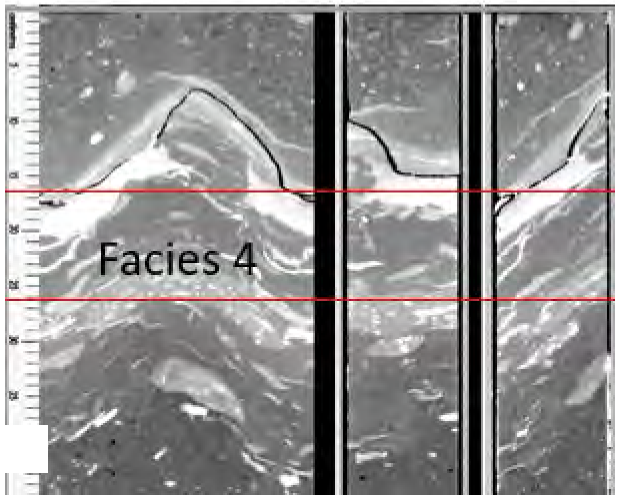
211-23-8Z (8S1)
Four Rock Type Solution



Man + Machine = Value^2







From Core Logging 1 meter;

- 50 pXRF points for atoms above Mg.
- 500 000 x 3500 pixels
- 3D topography images: 66 000 x 66 pixels
- Strength: 100
- Vp & Vs: 2*25

Facies Discussions:

Facies 0: 12%: Shaly Fine Sand. Low Si/Al ratio

Facies 1: 43%: Medium Sand. HIgh Si/Al ratio, Low Ca

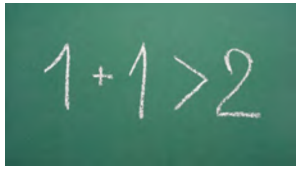
Facies 2: 5%: Clay. Very low Si/Al ratio, Low Ca, High Al, High S

Facies 3: 28%: Coarse to very coarse Sand. High Si/Al ratio, Low Ca, Low Al

Facies 4: 6%: Medium to coarse Sand. Low Si/Al ratio, large S

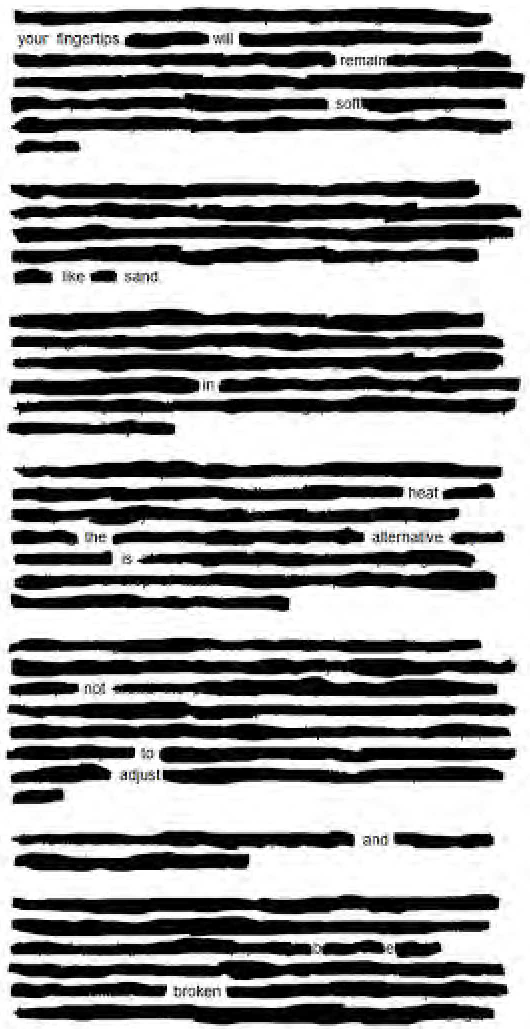
Facies 5: 5%: Hardest. Fine Sand with large Ca. High Si/Al ratio

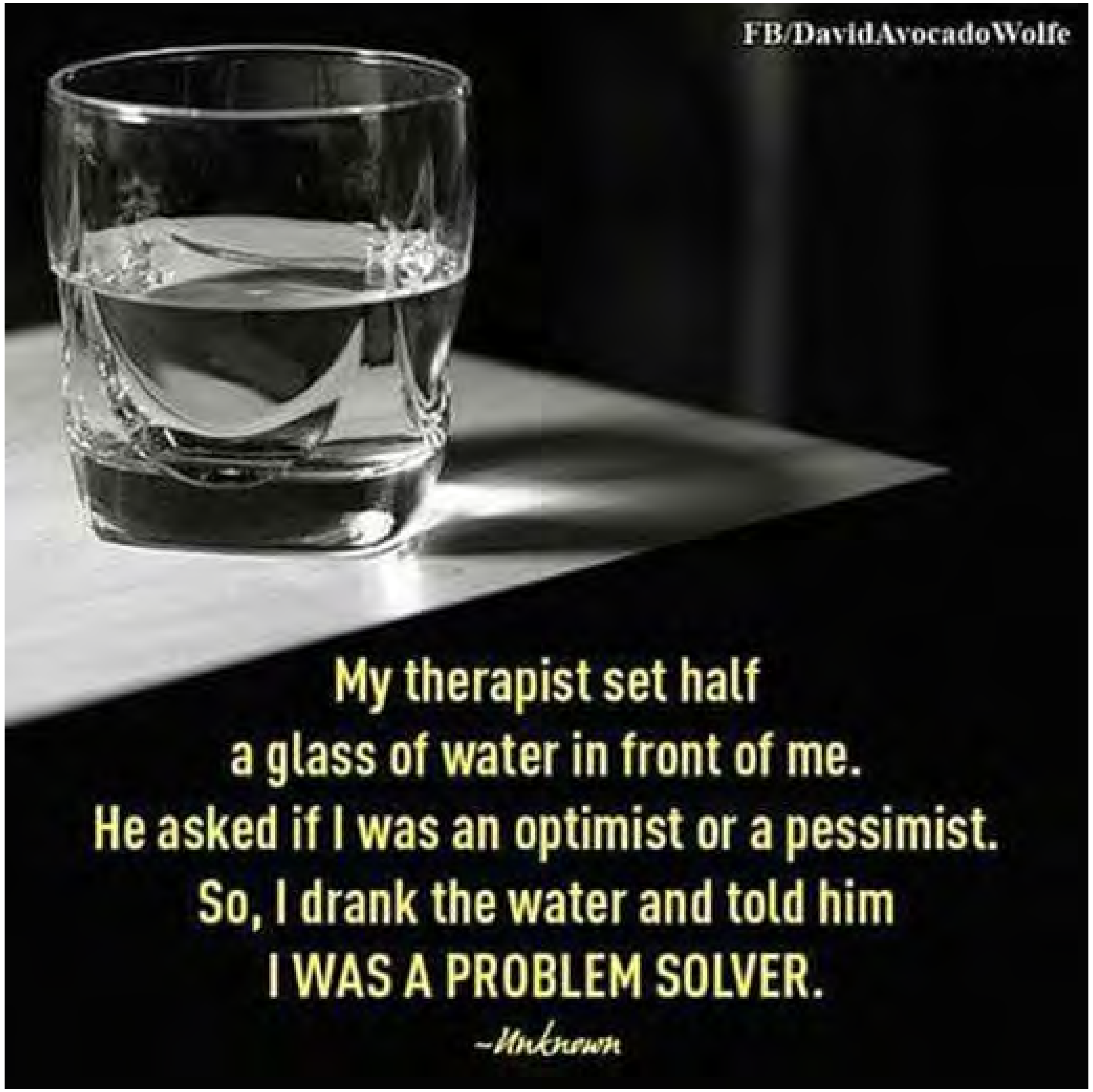
I did an OK job at selecting sampling points BUT I had no ability to identify actual facies!



Multi-sensor core logging?

- **We have Routine Core Analysis (RCA or CCA)**
- **Special Core Analysis (SCAL)**
- **Digital Rock Analysis (DRA or DRP)**
- **Now we have Smart Core Analysis (SCA!)**





Core Analyst **Sw = 50%**