ASSESSING REGIONAL VALIDITY OF NMR CORE CALIBRATION USING SCAN AMSTELLAND-01 & DE BILT-01 GEOTHERMAL EXPLORATION WELLS

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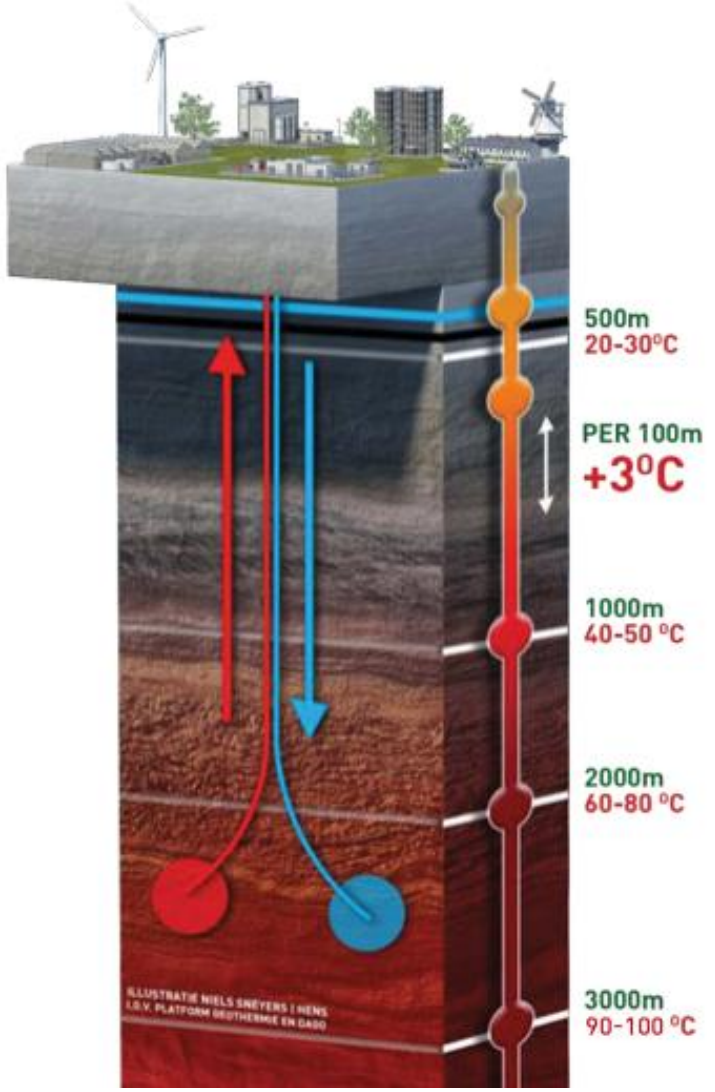
NMR LOGGING FOR GEOTHERMAL PROJECTS

- Geothermal energy in NL:
  - Low enthalpy, saline aquifers
  - Direct use => heat for heat
  - Dominantly matrix permeability systems
- Commercially viable geothermal projects require >100m³ / hour flow rate per well
- Matrix permeability thus critical parameter of the geothermal potential
- Nuclear Magnetic Resonance (**NMR**) logs provide porosity and (empirical) permeability measurement independent from traditional (nuclear) workflows.



WHAT IS NUCLEAR MAGNETIC RESONANCE

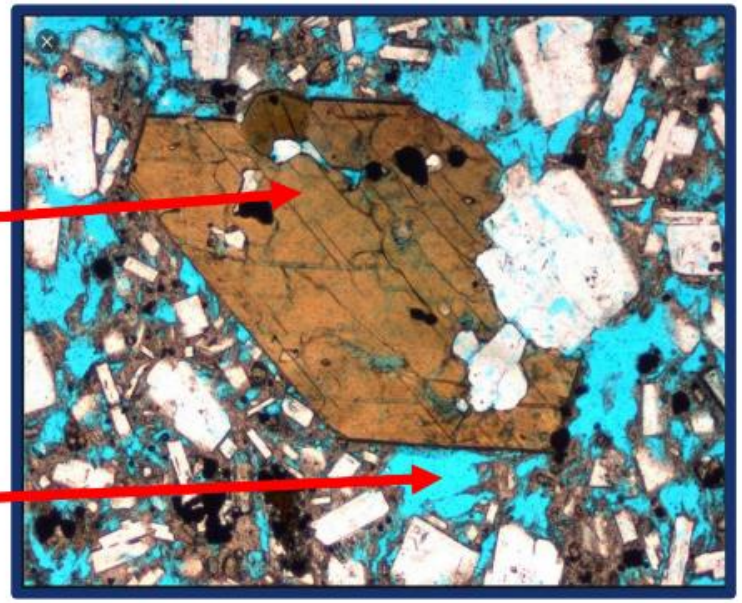
- Measurement Principles
  - Only measures fluid filled porosity
- Solutions and Applications
  - Reservoir storage volume - porosity
  - Quantitative pore fluid volumes

Bone is “Dark”, NOT seen by Magnetic Resonance

Rock matrix is NOT seen by Magnetic Resonance

Fluid rich tissues are visible

Only Fluids in the pore space is measured (blue)



Does not need radio-active source that is common in other porosity measurements such as Neutron / Density

NMR LOGGING FOR GEOTHERMAL PROJECTS

NMR logs measurement provides:
- Total porosity and pore-size distribution measurement
- Standard empirical relationships were used for **qualitative** permeability

Quantitative permeability from NMR requires core-calibration:
1. T2 cut-offs (movable/total bound porosity)
2. Permeability model parameters

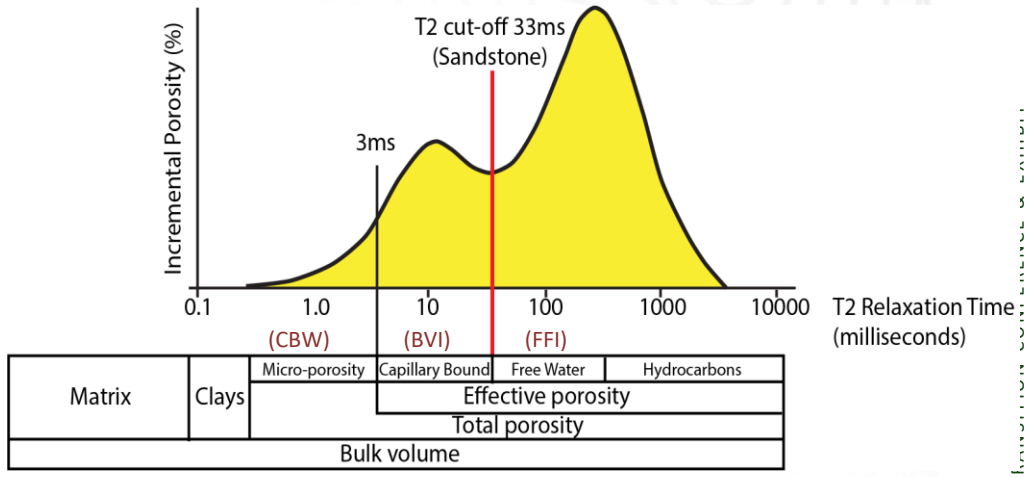
As coring is time-consuming and expensive, it is rarely done in commercial geothermal projects

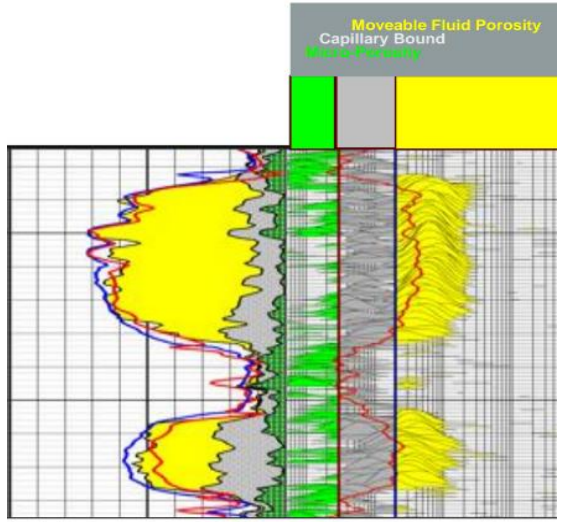
Objective of this study:

- Test whether the calibration from NMR log + core dataset from one exploration borehole is regionally applicable

If successful, NMR log could become an effective and powerful stand-alone tool to determine matrix permeability (distribution) of geothermal reservoirs

T2 cut-offs relate to pore rugosity and are variable per lithology, formation, diagenesis, etc





SCAN AMS-01 & BLT-01 WELLS

SCAN project (Funded by the Ministry of Climate and Green Growth, executed by EBN and TNO) acquires new data in areas with insufficient existing data, in The Netherlands, including:

- Acquisition of new and re-processing of 2D & 3D seismic data
- Drilling of eight data-acquisition boreholes

Amstelland (AMS-01):

- Drilled close to city of Amsterdam in Q4 2023.

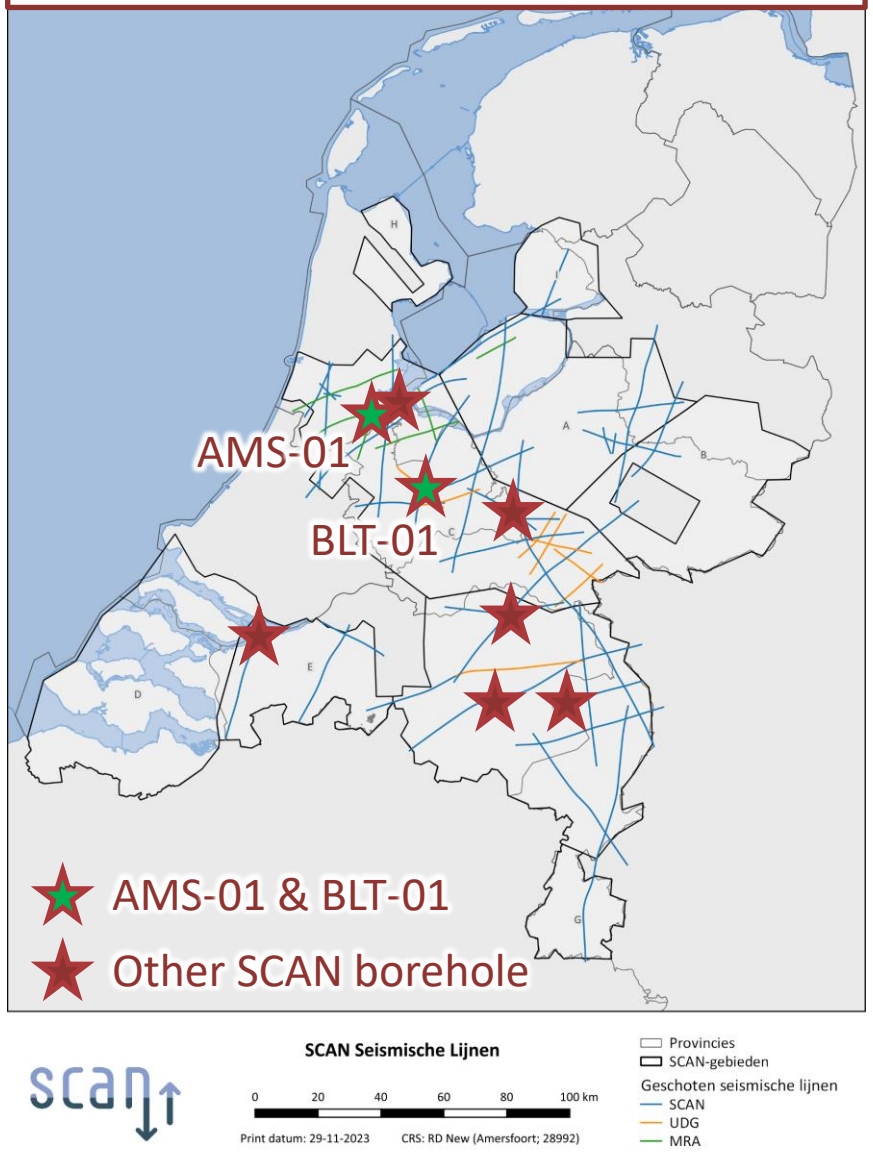
De Bilt (BLT-01):

- Drilled close to city of Utrecht in Q1 2025.

Both wells targeted Permian Rotliegend aeolian sandstone reservoirs

- Proven geothermal reservoir in north of The Netherlands.
- Similar data acquisition allows test case for regional validity of NMR data.

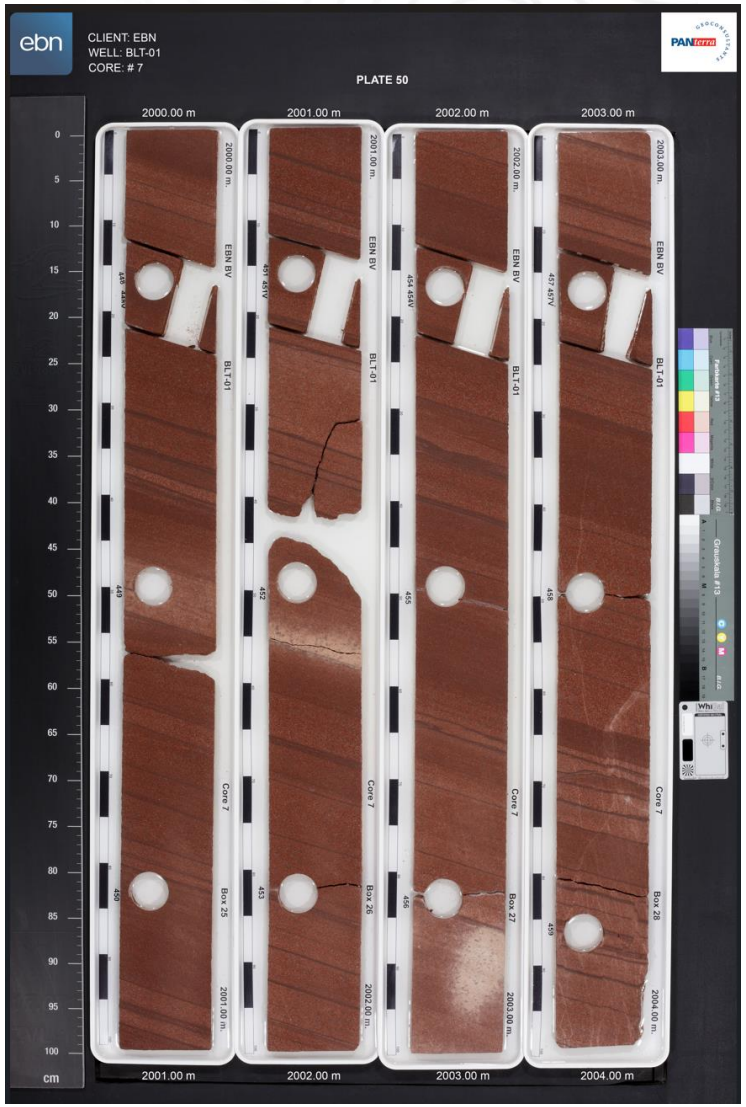
SCAN data-acquisition boreholes



ROTLIEGEND IN AMS-01 & BLT-01

AMS-01 Rotliegend core

BLT-01 Rotliegend core



Approximately 2km depth and 75-80°C

112-118 m thick aeolian sandstone

Extensive data acquisition in both wells:

- Petrophysical logging:
  - *LWD: GR – Resistivity*
  - *WL-Data: (Spectral) Gamma Ray, Image log, Sonic, Density, Neutron, and* ***NMR***
- Extensive coring:
  - *AMS-01: 90m Rotliegend core*
  - *BLT-01: 98m Rotliegend core*
- Extensive core analysis:
  - *Routine and Special core analysis*
  - *MICP, Stressed Porosity, Stressed Brine Permeability*
  - ***NMR experiments*** *(BLT-01 ongoing)*

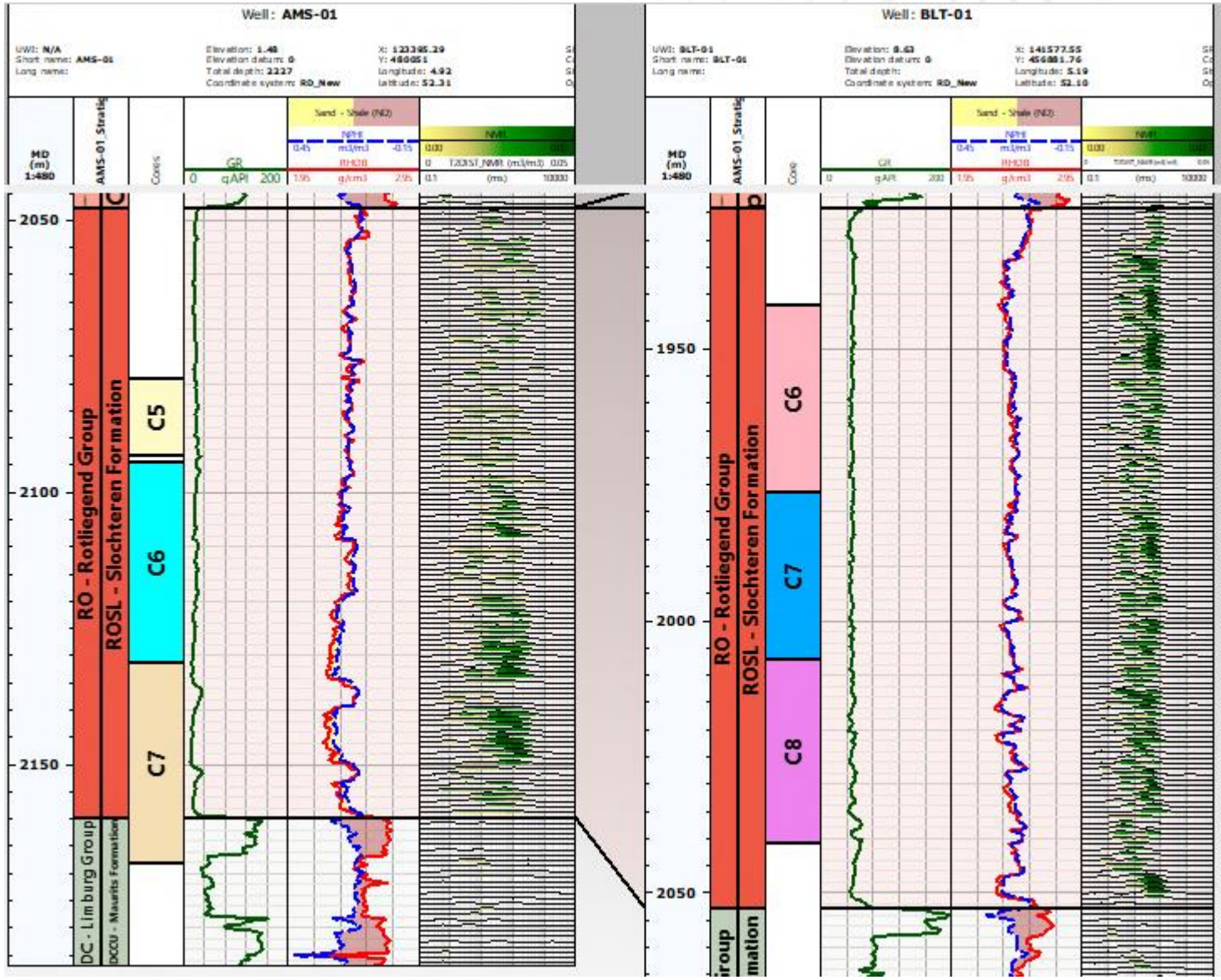
Drilling fluid: WBM in BLT-01; OBM in AMS-01

SCAN NMR LOGGING IN AMS-01 & BLT-01

Rotliegend intervals in both wells are logged with Halliburton MRIL-Prime NMR tool.

8 sec wait time to allow for full water & mud filtrate polarization.

The default sandstone T2 cutoffs were used as 3ms (Bound water) and 33ms (Free water) as preliminary interpretation



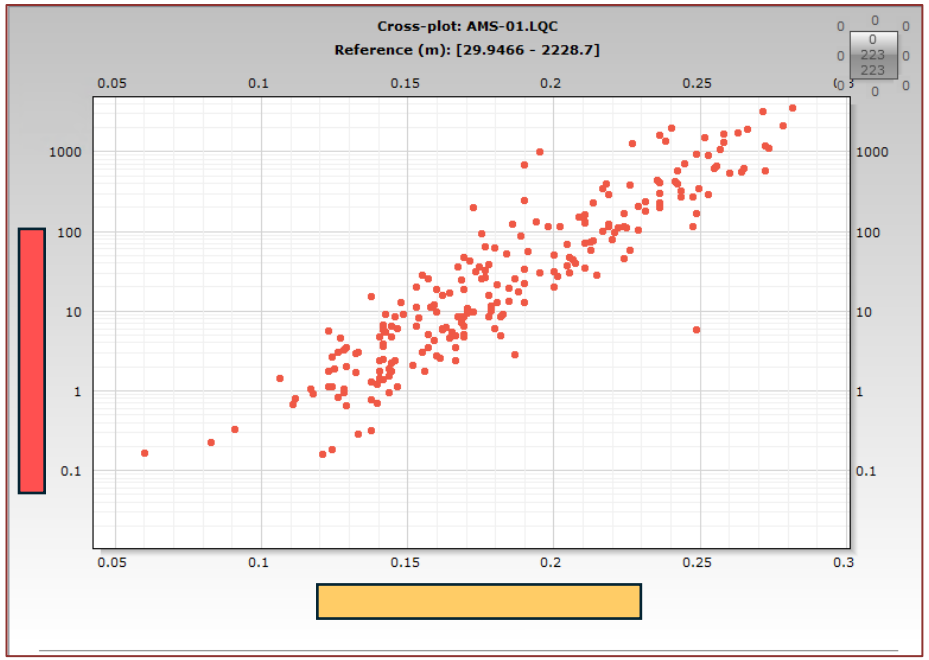
AMS-01 & BLT-01 CORE DATA

Ambient (RCA) core data was corrected to in-situ conditions for each well, using:

- Stressed porosity – 10 plugs
- Stressed brine permeability – 10 plugs

NMR experiments – 15 (AMS-01) & 10 (BLT-01 – ongoing) plugs

AMS-01: 223 core plugs

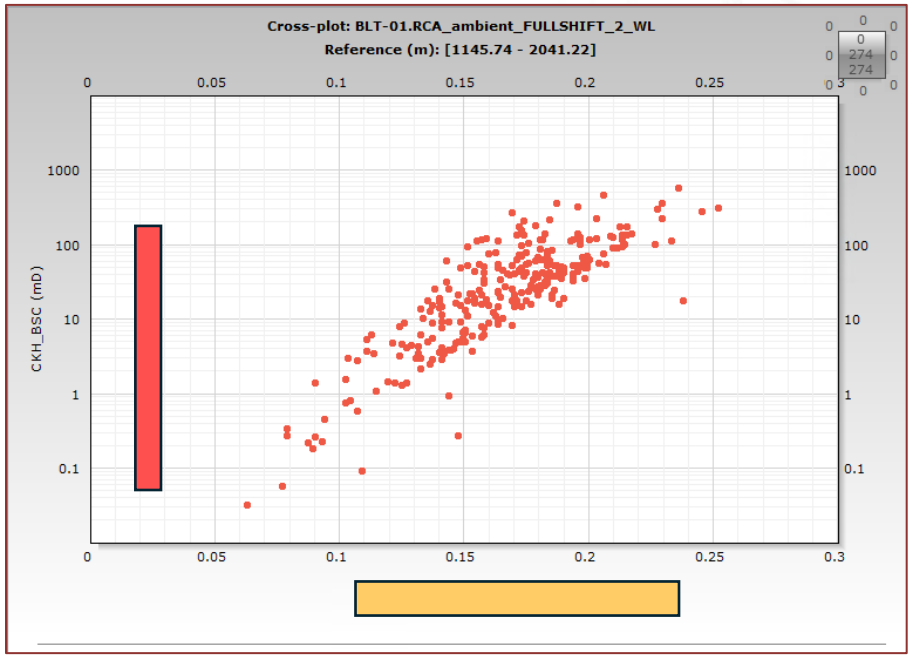


All Rotliegend plugs are hot oven dried (95 °C)

Stress & Brine Corrected Permeability

Stress corrected Core Porosity

BLT-01: 274 core plugs



NMR CORE EXPERIMENTS

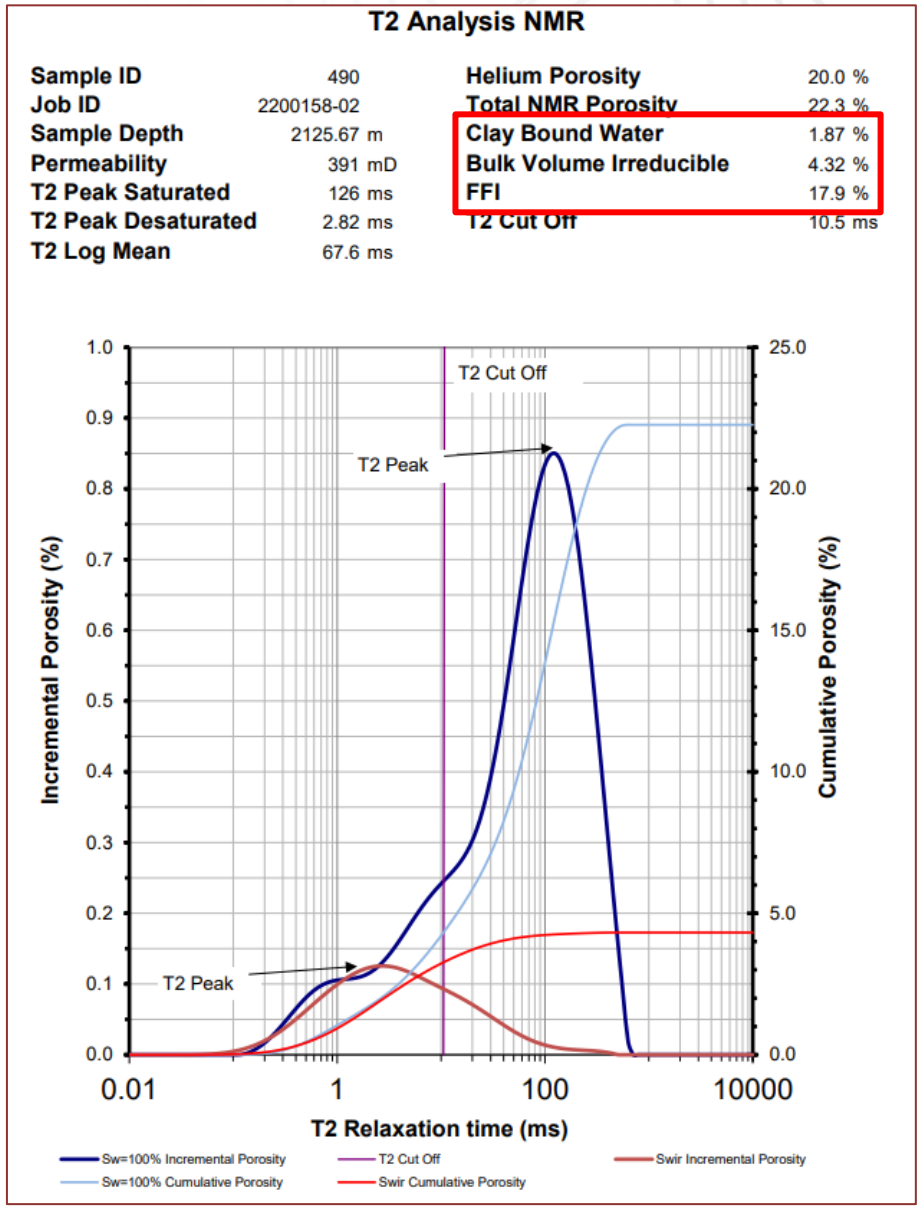
NMR experiments performed on selected core plugs to calibrate NMR log.

- **AMS-01:** 15 plugs
- **BLT-01:** 10 plugs (currently ongoing)

WL & Lab are different measurements types

Different scale, temperature, pressure, mud & fluid types, magnetic field gradient etc.

Calibration is preformed by matching Free Fluid Index(FFI) & Bulk Volume Irreducible (BVI) from core with FFI & BVI from NMR logs.



AMS-01 NMR POROSITY CORE CALIBRATION

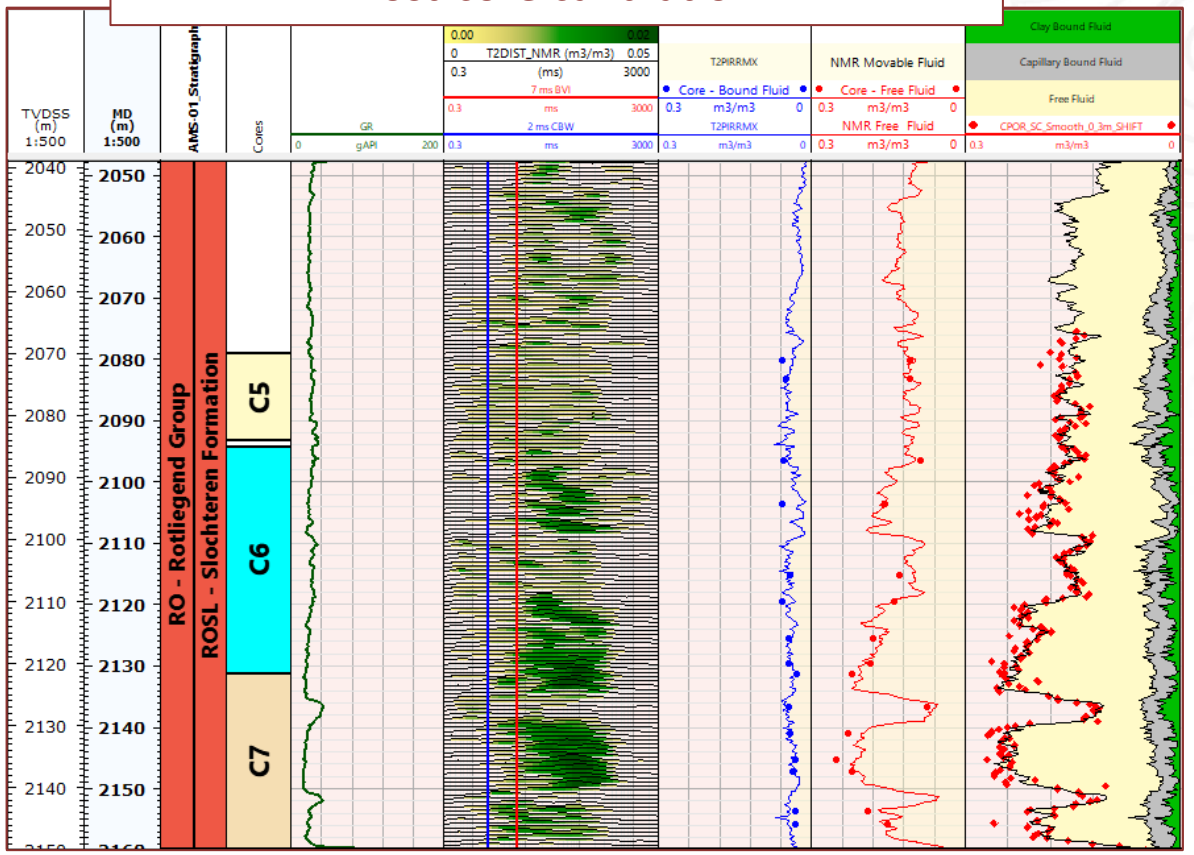
Calibration of NMR logs to NMR core experiments show significant reduction of T2 cutoff times wrt default sandstone values:

- Clay bound water – CBW : **3 ms → 2 ms**
- Capillary bound water – BVI : **33ms → 7 ms**

Calibration results in an increase in Free Fluid volume

Good match between Core porosity & NMR Total porosity.

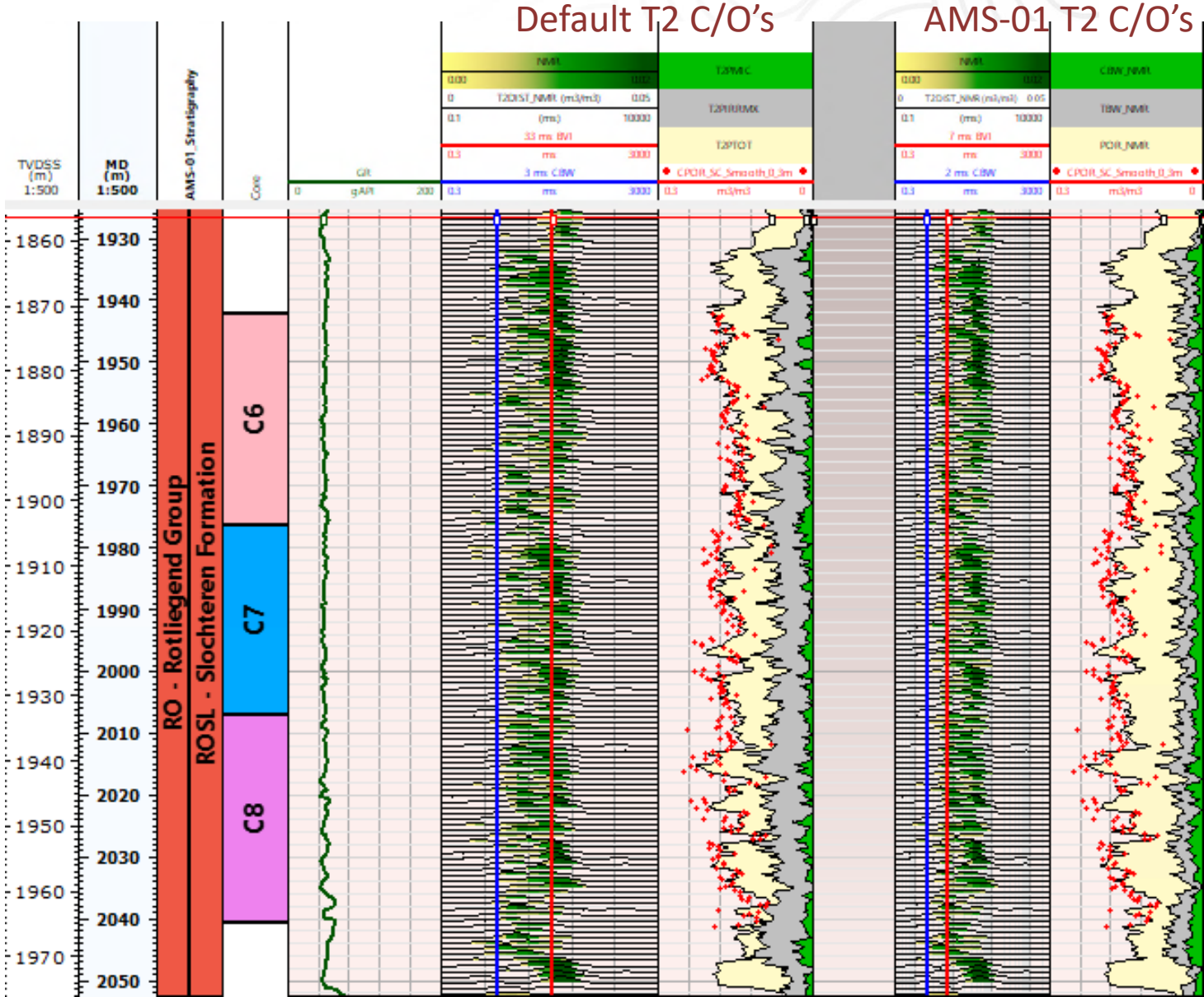
Post-core calibration



NMR LOG POROSITY APPLICATION

BLT-01

- Scatter in core porosity for BLT-01 is larger than for AMS-01.
- Results of both standard and AMS-01 C/O's suggest BLT-01 has lower overall reservoir quality.
- Apply CBW & BVI T2-cutoffs from AMS-01 experiments to BLT-01 logs.
  - *CBW: 3ms → 2 ms*
  - *BVI: 33 ms → 7 ms*
- Compare NMR permeability with stressed brine permeability from core.
  - AMS-01 Calibration

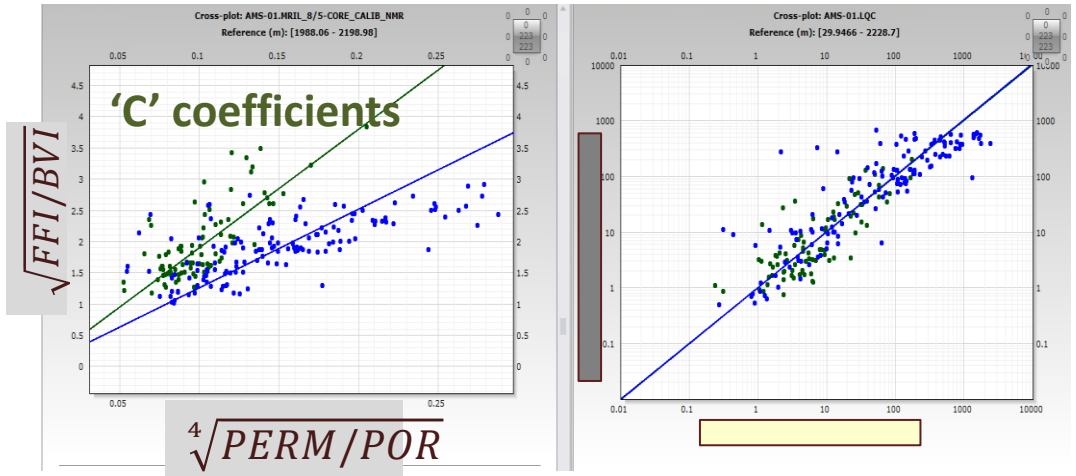


NMR PERMEABILITY CALIBRATION

AMS-01

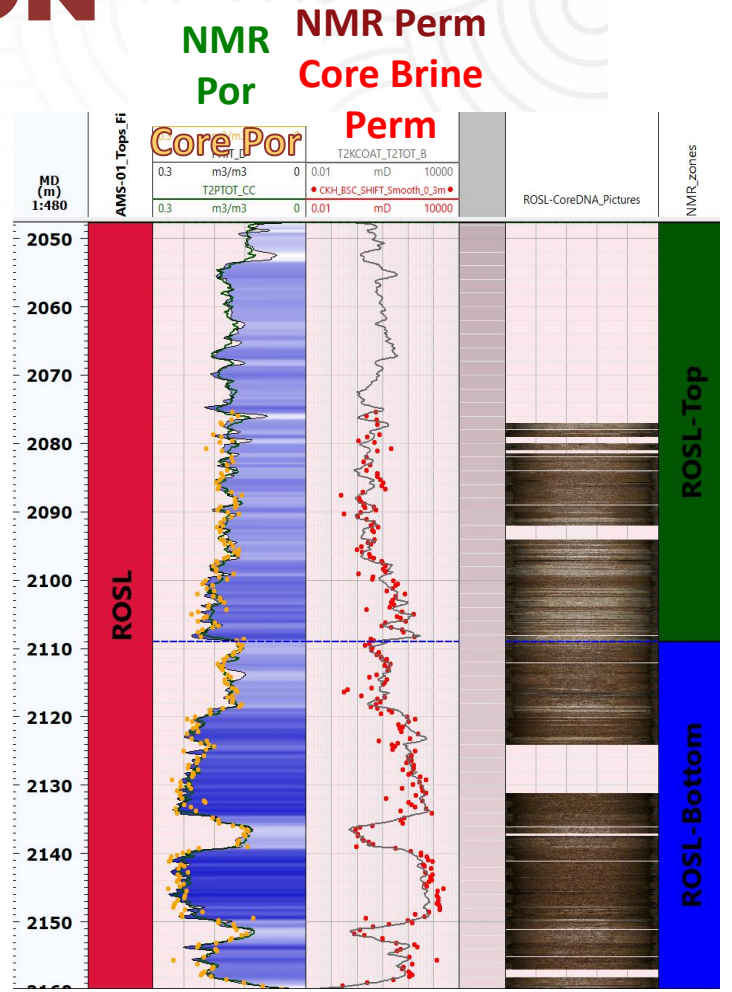
- Timur Coates equation (TC) used to calculate NMR Perm.
  - $PERM_{TC} = \left(\frac{FFI}{BVI}\right)^2 * \left(\frac{\mathrm{POR}}{C}\right)^4$
- Calibrated to **brine permeability** by modifying 'C' parameter.
  - $\sqrt{\left(\frac{FFI}{BVI}\right)} = C * \frac{\sqrt[4]{PERM}}{POR}$ → Using calibrated NMR log & reservoir condition core data

- Rotliegend is divided into 2 zones (Top & Bottom) for this. The core white light picture color shows color difference.



Brine calibrated NMR perm

Stress corrected core brine perm



	ROSL-Top	ROSL-Bottom	Default
'C'	19	12,6	10

BLT-01 NMR WITH AMS-01 CALIBRATION

BLT-01

- Using AMS-01 Timur Coates ‘C’ parameters to calculate BLT-01 NMR Perm and cross check with Core Brine Perm from BLT-01.

- Initially no clear evidence for two ‘*NMR zones*’ in BLT-01.

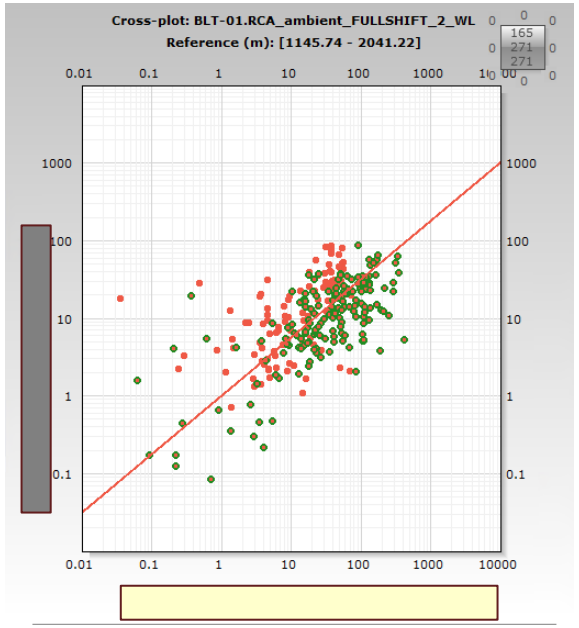
- The AMS-01 ‘bottom’ “C” exponent (12,6) results in the best fit TC perm.

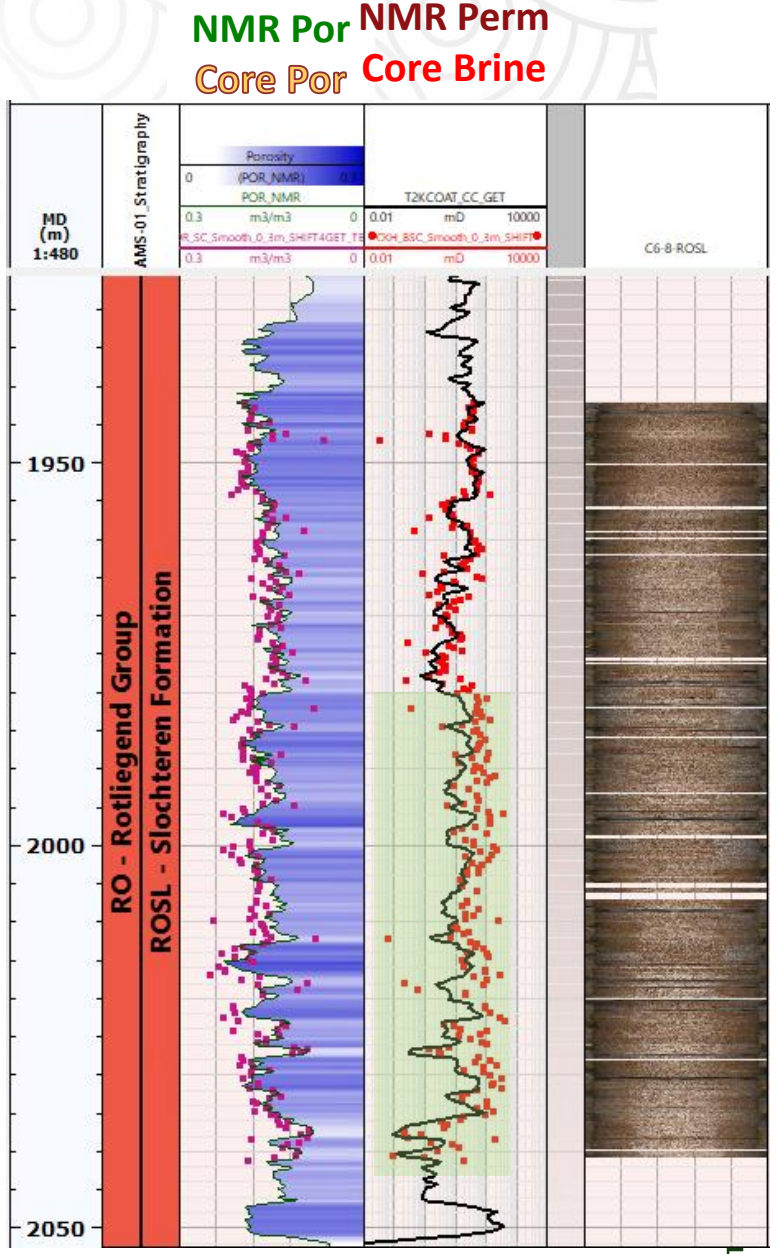
- Upper part of BLT-01 ROSL fits good. However, lower part fit is less good. Possibly two ‘*NMR zones*’?

- Divide BLT-01 in two ‘*NMR zones*’ with top of BLT-01_bottom at 1980m MD and recalibrate.

Brine calibrated NMR perm

Stressed corrected core brine perm

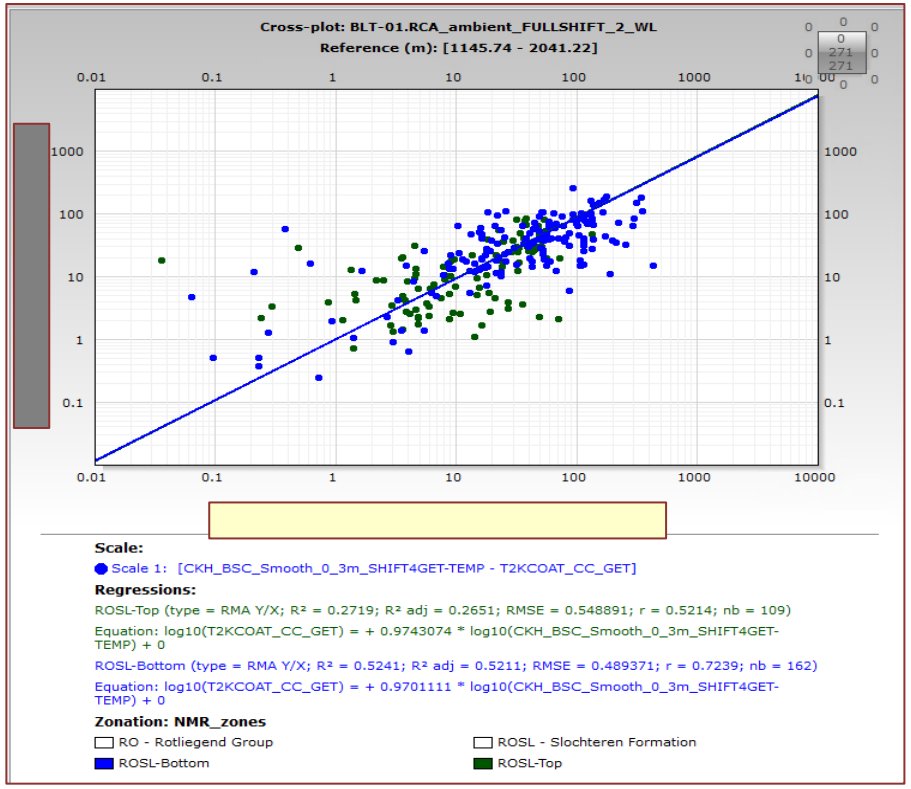




	ROSL	Default
‘C’	12,6	10

BLT-01 NMR LOG – MODIFIED CALIBRATION

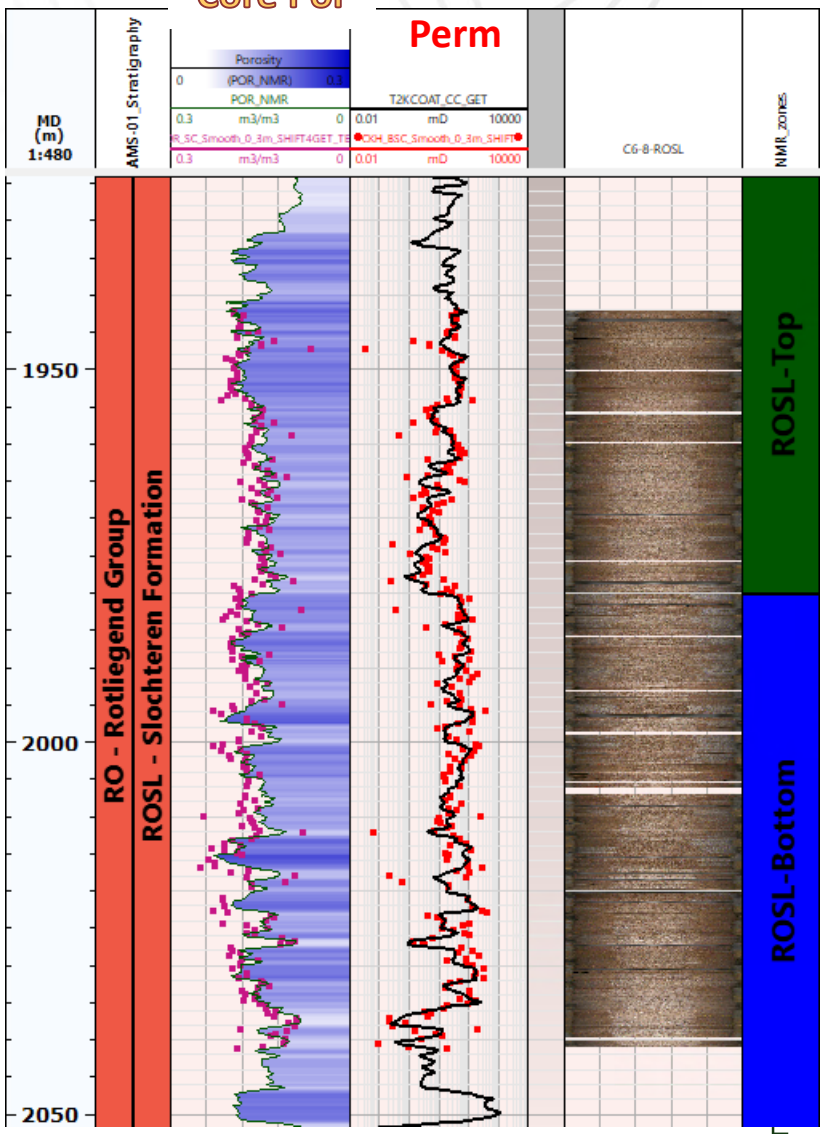
Modify “C” parameter for BLT-01 Bottom zone to NMR Permeability.



BLT-01_Bottom:
C= 9,6 → results in same fit as BLT-01 Top.

Brine calibrated NMR perm

Stressed corrected core brine perm



	ROSL-Top	ROSL-Bottom	Default
‘C’	12,6	9,6	10

DISCUSSION & CONCLUSIONS

Arithmetic average NMR based permeability of ROSL			AMS-01	BLT-01
NMR log	Uncalibrated	CBW & BVI C/O's: **3 & 33 ms** Default TC equation	39 mD	12 mD
	T2 calibration	CBW & BVI C/O's: **2 & 7 ms** Default TC equation	291 mD	54 mD
	Timur-Coates calibration	Timur Coates **calibrated** "C" parameters	82 mD	46 mD

- Initial indications suggest that NMR calibration from AMS-01 can considered partly valid for BLT-01 (T2 C/O's).
  - Significant increase of free fluids (and perm) compared to standard T2 parameters.
  - Similar average perm of BLT-01 with AMS-01 T2 C/O's using standard Timur-Coates parameters and fitted 'C' parameters.
  - Calibrated 'C' parameter from Timur-Coates does not appear to be transferrable. Variation in this parameter and resulting permeability suggest complex relationships via poorly understood mechanisms.
  - Match with well test perm appears to be good (~40 mD), recommend the talk of **Sanchita Ganguly** on **Thursday (17:10)** for more details on BLT-01 reservoir.
- Core calibration results from BLT-01 are a work in progress. Can shed more light on this issue.
- Some outstanding questions:
  - Does the 'C' parameter needs so much attention for calibration per zone, or is the T2 cutoff the main controlling factor for both Free fluid volume and permeability
  - Rotliegend in AMS-01 was drilled with OBM. This resulted in OBM filtrate invasion. What is the effect on NMR logging? And does this void the regional calibration?
- Further studies are currently being carried out by SCAN to further enhance this methodology for a more robust outcome.

WANT TO HEAR MORE SCAN RESULTS?

Tuesday	16:30-16:50	Marc Hettema	Minimum stress testing XLOT in seals of Geothermal SCAN wells: Methodology and models
Thursday	15:50-16:10	Sven McCarthy	The role of sedimentology in heterogeneous shallow geothermal reservoirs - The Brussels Sand Member
	17:10-17:30	Sanchita Ganguly	**Integrated Approach To Characterize Geothermal Reservoir Flow Potential: An Example From De Bilt-01**
Friday	09:00-16:00	PanTerra	Core Workshop for CCS and Geothermal: Geological Risk Assessment for Geothermal and CCS on Core Material