Calibration of NMR Permeability Using Cluster Analysis and Cloud Matching*

A. Arora[1], J. Browning[1], S. K. Henderson[1], G. B. Asquith[1], S. Gorell[1], A. Ettehadtavakkol[1]

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[1]Dept. of Petroleum Engineering, Texas Tech University, Lubbock, TX, United States (aamanarora@hotmail.com)

Abstract

Petrophysical characterization of heterogeneous carbonate reservoirs has always been difficult (Akbar 1995). Carbonate rocks can have a variety of pore geometries due to the complexity of their deposition which is further complicated by diagenesis. Understanding the pore structure is crucial to the determination of permeability and the evaluation of a reservoir's flow behavior. While the NMR tool has helped engineers and geologists evaluate the pore size distribution in carbonates, quantitative determination of permeability has remained a challenge. Multiple laboratories and authors (Arns 2007, Wampler 2010, Chen and others 2017) have attempted to calibrate NMR-derived permeability with core data, but such attempts are tedious and require additional inputs and specialized equipment like core computed tomography (CT), capillary pressure and NMR testing of plugs. This paper presents a novel technique of calibrating log NMR data to routine core analysis permeability. Using cluster analysis on hydraulic units from a unified core dataset, regional porosity-permeability correlations are created which are used to develop NMR transforms by cloud matching. The workflow is then used to estimate permeability and hydraulic units for uncalibrated wells in the area. This simple technique requires no additional data or testing and can be optimized using a spreadsheet or code. This paper presents the methodology as demonstrated for the San Andres Formation, a complex carbonate in the Permian Basin.

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Chen, J.-H., S.M. Althaus, M. Delshad, J. Zhang, F. Almalki, Q. Sun, and A. Shawaf, 2017, Optimization of NMR Permeability Transform and Application to Middle East Tight Sands. Society of Petrophysicists and Well-Log Analysts.

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Aghda, S.M., M. Taslimi, and A. Fahimifar, 2018, Adjusting porosity and permeability estimation by nuclear magnetic resonance: A case study from a carbonate reservoir of south of Iran: Journal of Petroleum Exploration and Production Technology, v. 8/4, p. 1113-1127. doi:10.1007/s13202-018-0474-z

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Texas Tech University

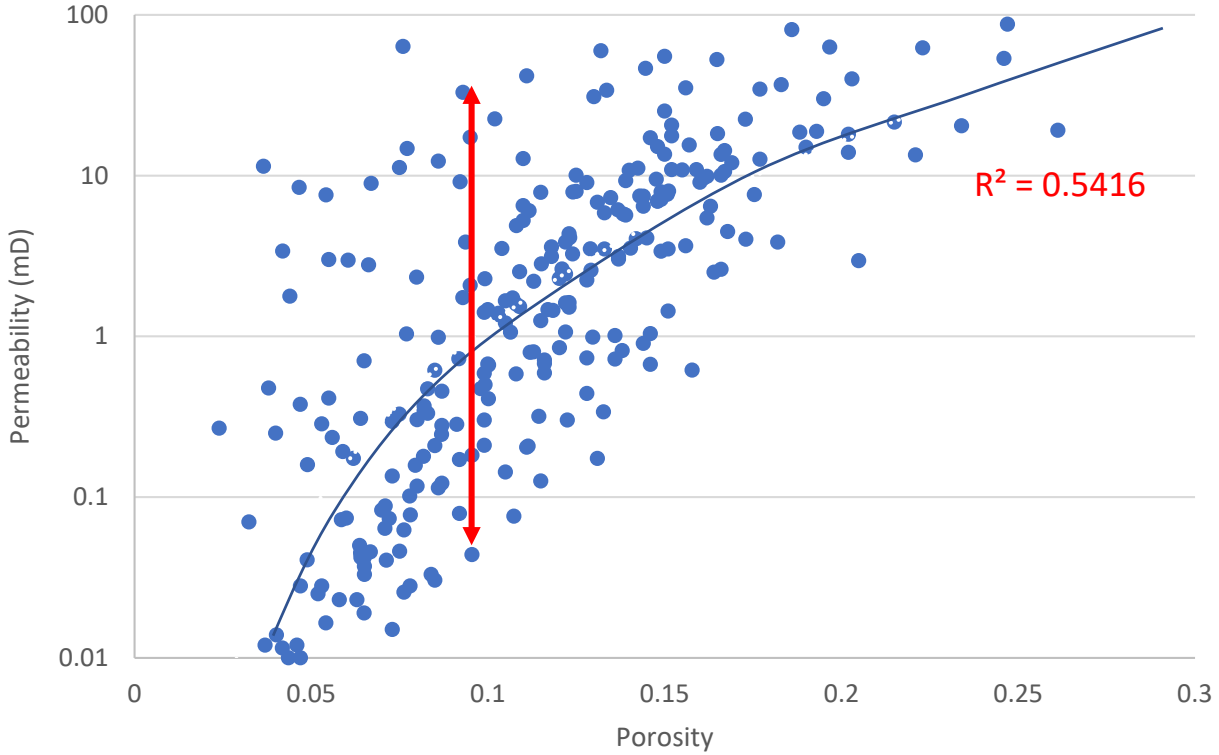
Permeability – Porosity relationships

The simplest approach:

$$k = fn\,(\varphi)$$

This approach is difficult for carbonates.

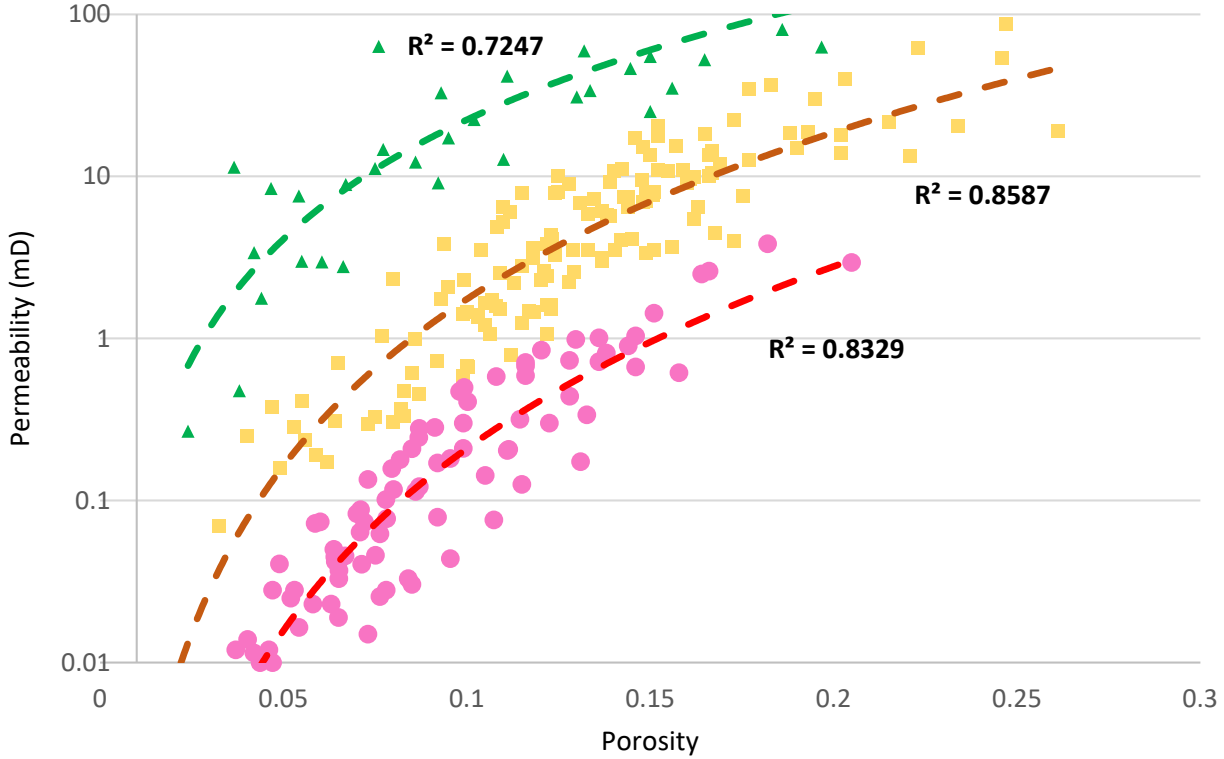
- Weak correlation between porosity and permeability
- High Variability
- Multiple pore types and non-uniform connectivity



Rock Typing Approach

Permeability prediction can be improved by grouping the data into clusters like:

- Facies (whole core)
- Rock types (Special Core Analysis)
- Hydraulic units (Routine Core Analysis)



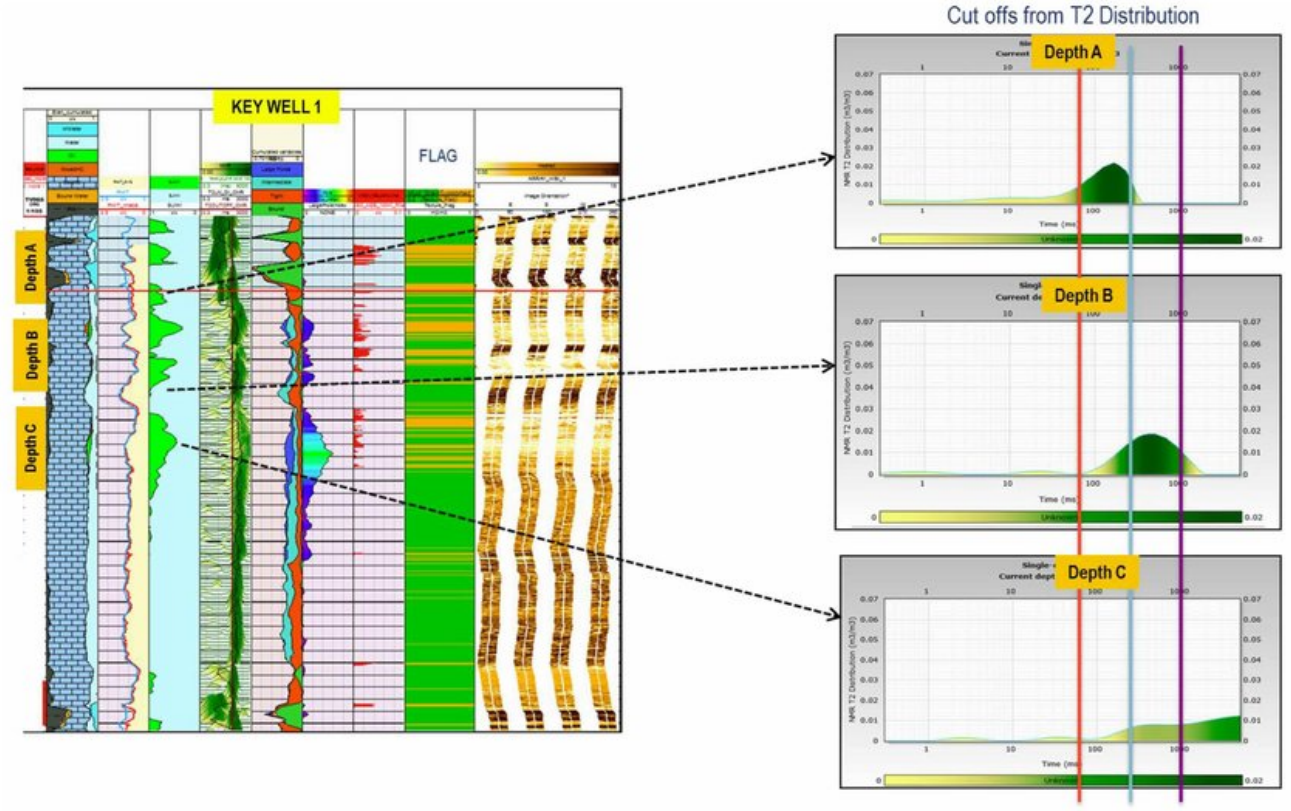
Permeability from NMR log

NMR has the ability to measure the pore size distribution and calculate permeability:

$$k_{SDR} = C \times T_{2gm}^2 \times \emptyset^4$$

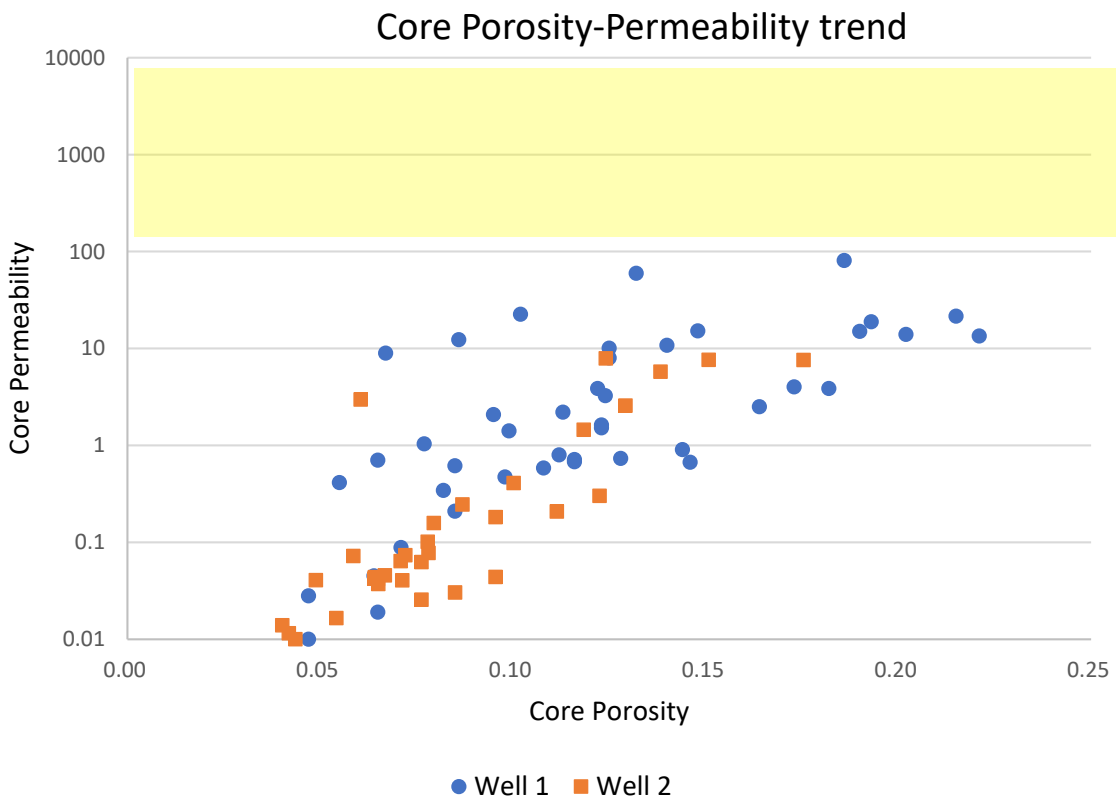
The NMR permeability reported to the operator in default form is purely qualitative.

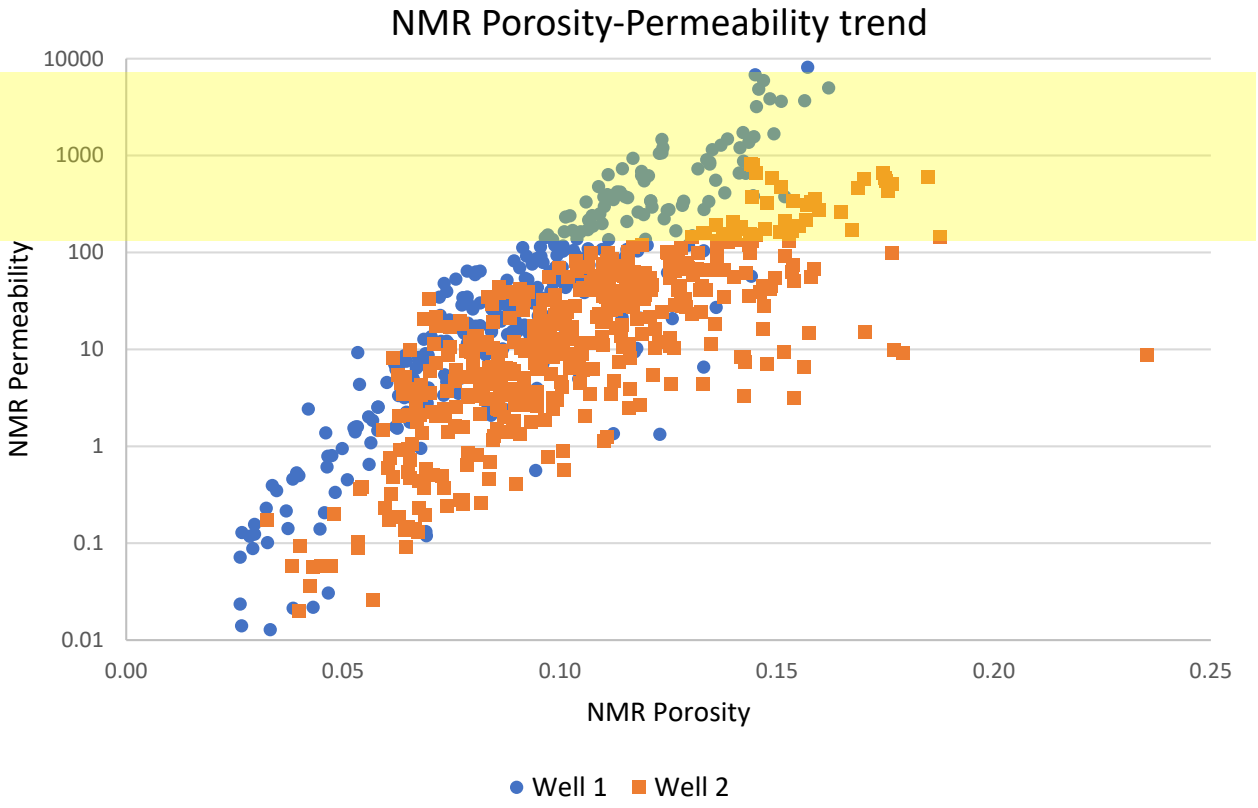
Any quantitative application of permeability from NMR requires local calibration.



A. Panda (2016)

Variability in NMR Permeability





NMR Permeability - Calibration

NMR permeability calibration can be done by:

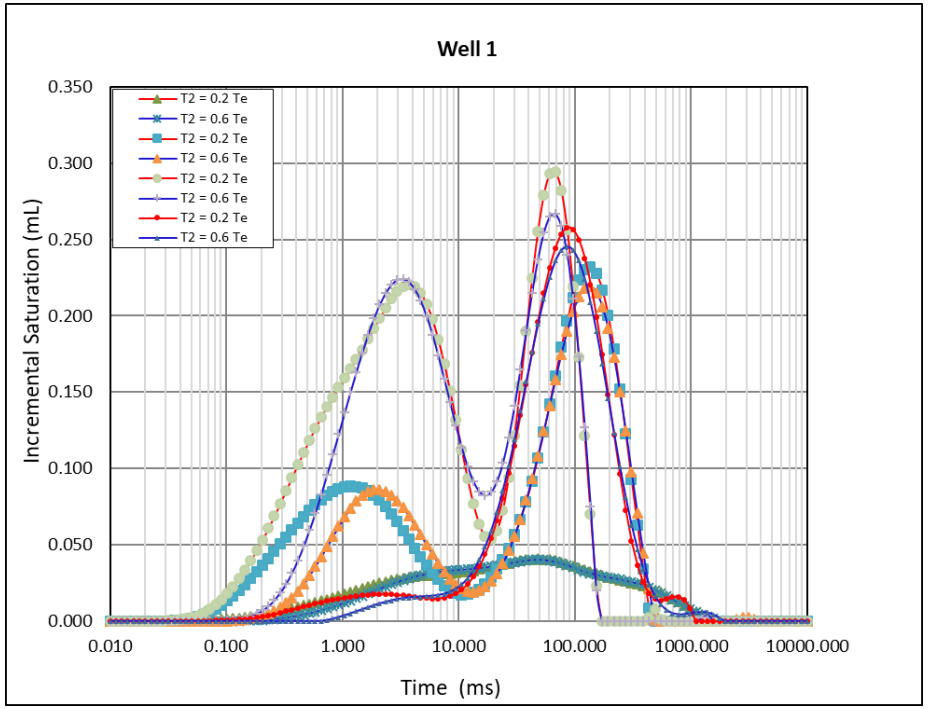
Calculating equation parameters from NMR tests on core plugs

- Core
- Capability/budget

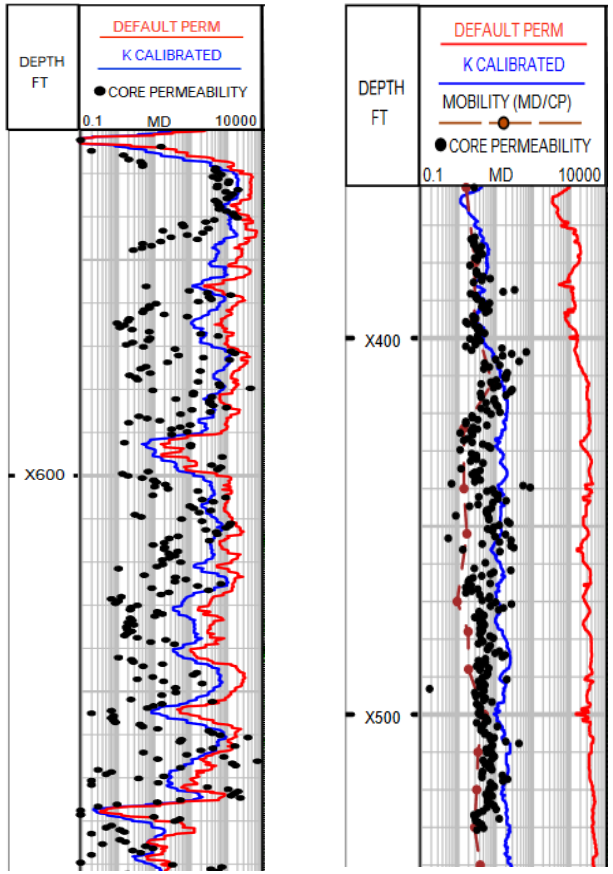
OR

Regression from routine core analysis data

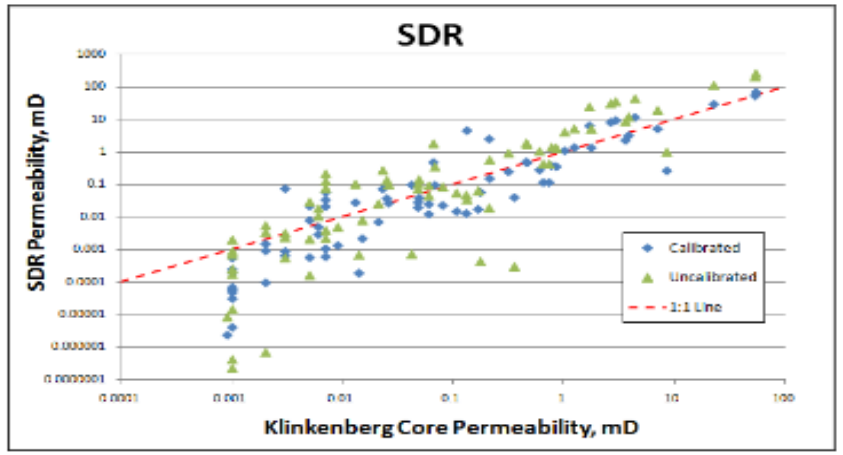
- Depth matching



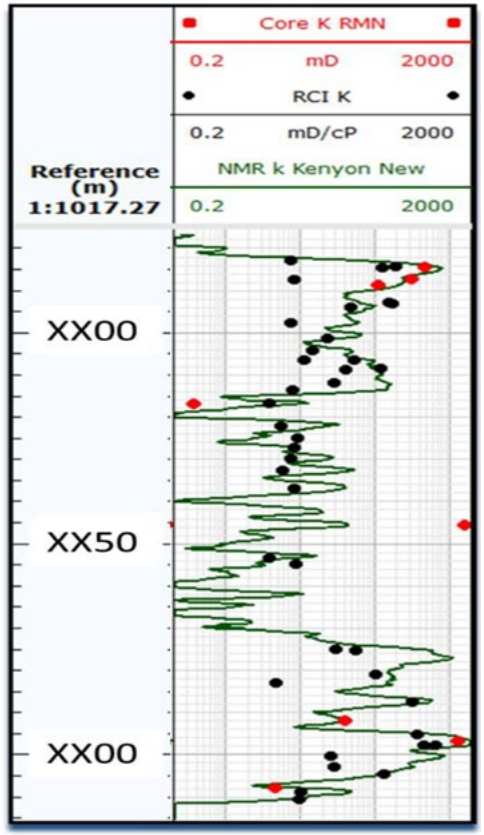
NMR Permeability Calibration – Lit Review



Amabeoku (2001)



J.J. Wampler (2010)



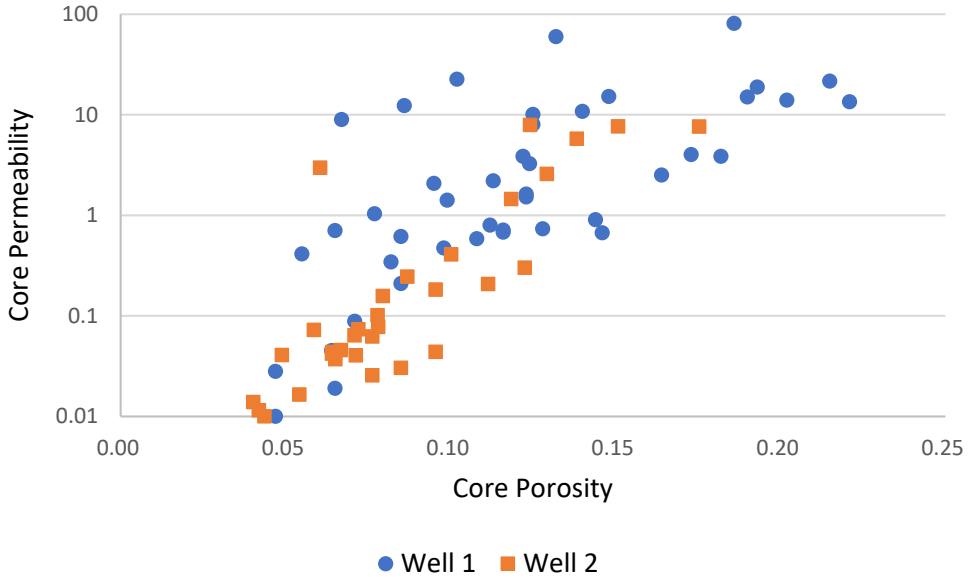
Trevizan (2015)

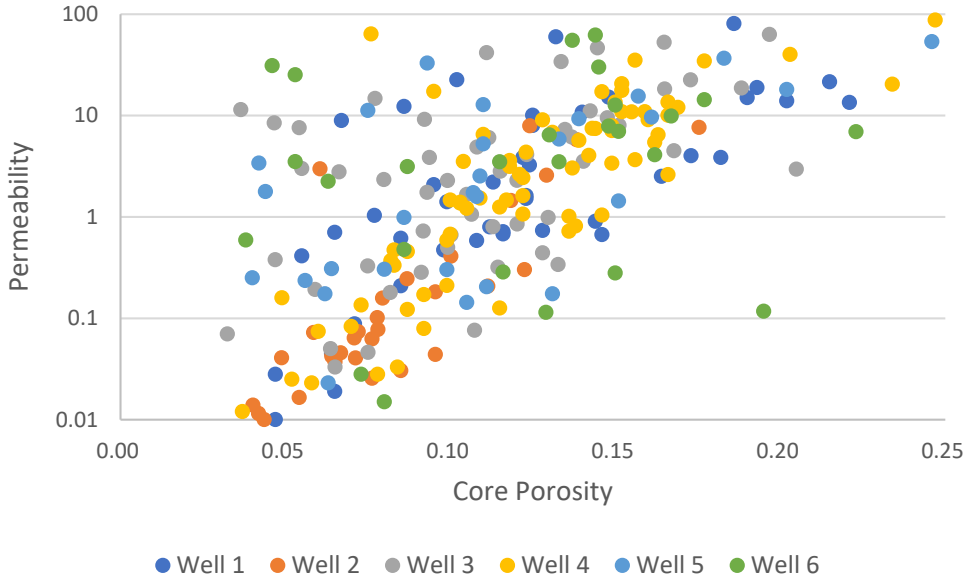
Our Proposed Technique

- Analyze core data and identify characteristic data trends and clusters in the geologic area under study
- Identify similar trends and clusters in the NMR data
- Calibrate NMR permeability by adjusting equation parameters to match the NMR data to core data

  Calibration parameters are determined using an iterative solver which seeks to minimize error between multiple trends simultaneously.

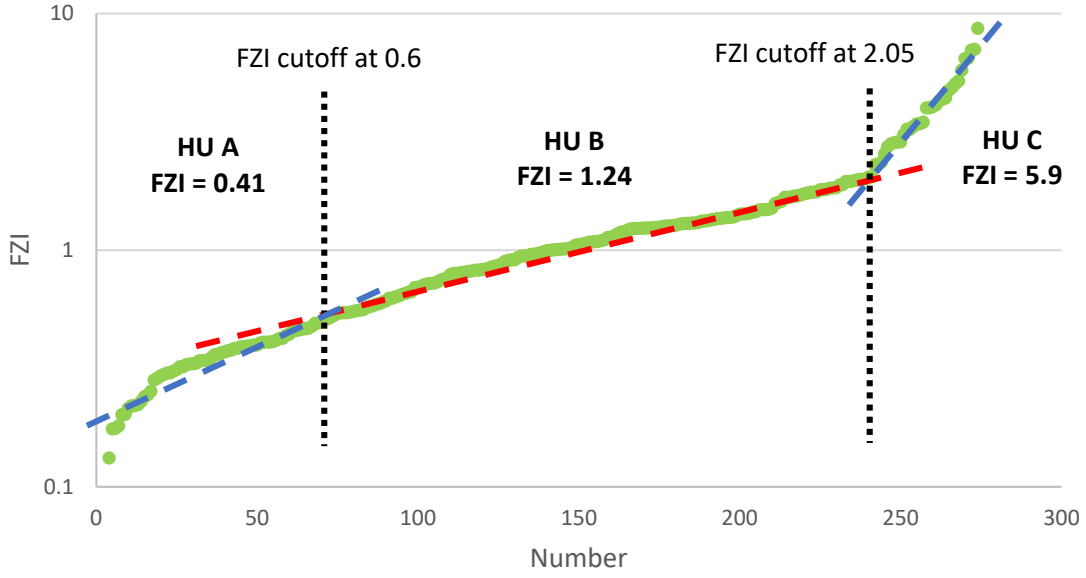
Step 1: Analyze core data and identify characteristic data trends and clusters in the geologic area under study

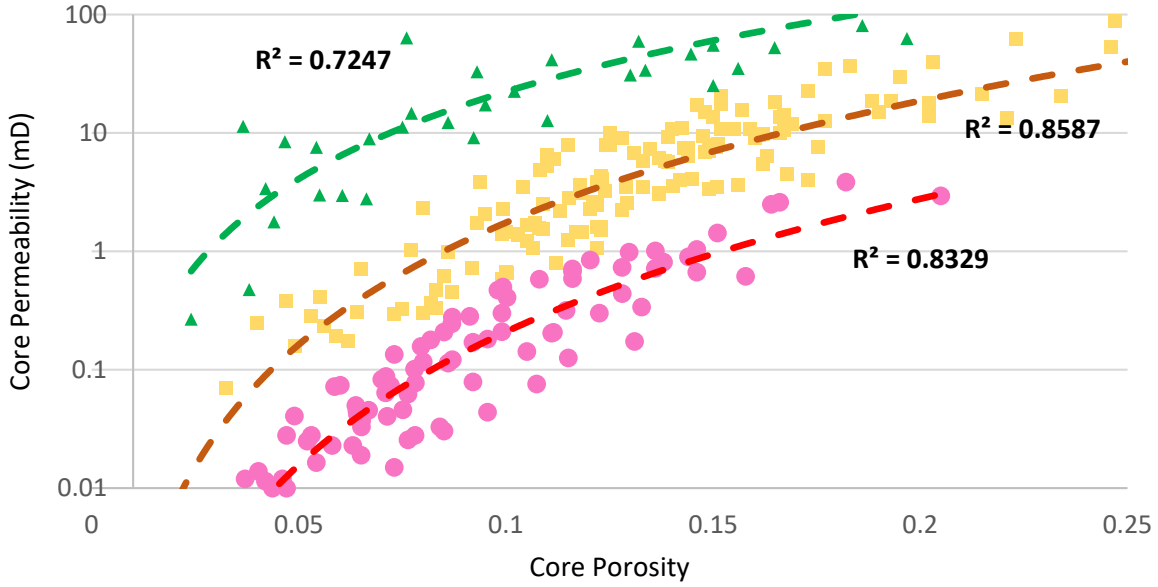




Core data from geologically analogous wells were pooled to analyze the trends and rock types in the area of study.

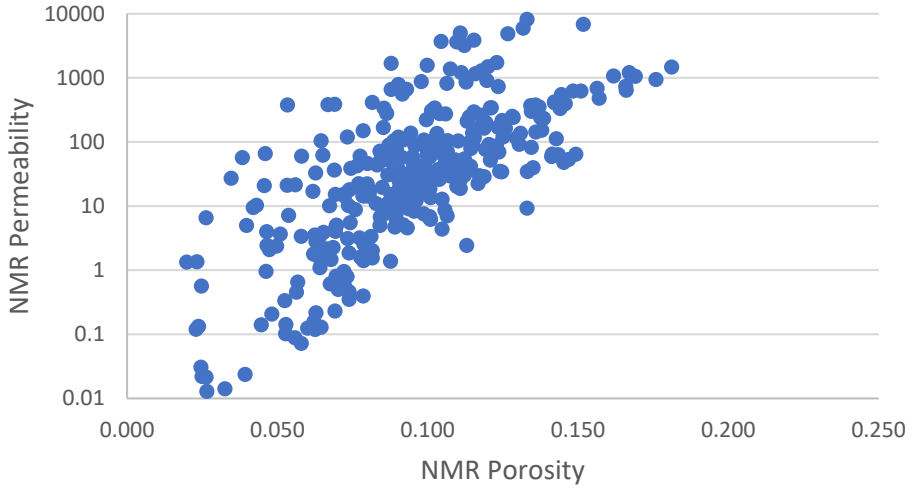
Step 1: Analyze core data and identify characteristic data trends and clusters in the geologic area under study

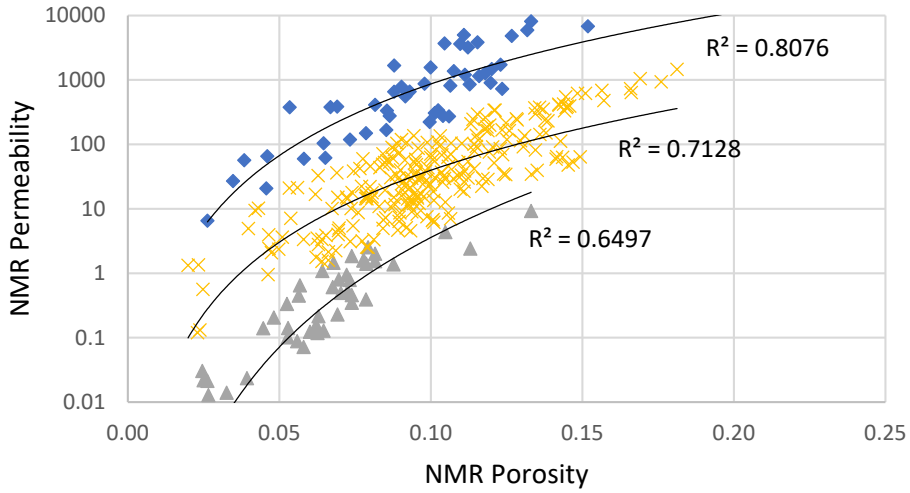


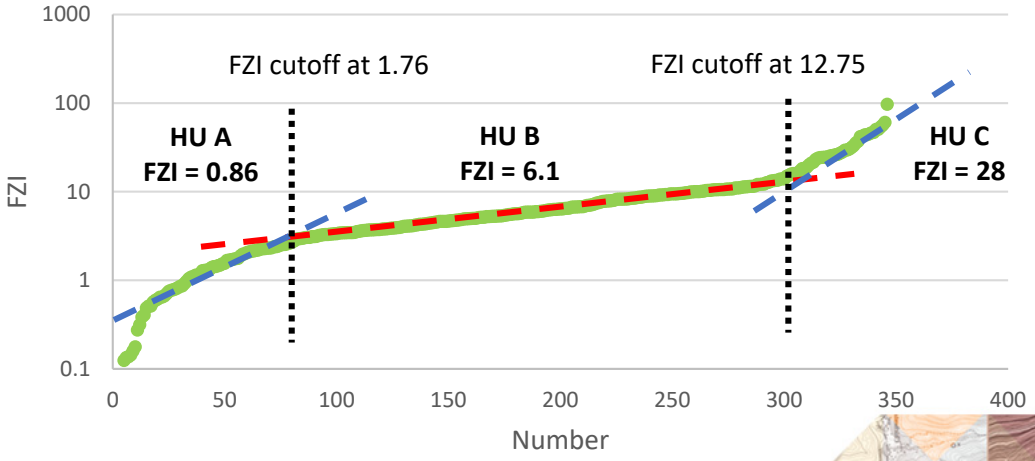


The pooled core data from 6 wells was divided into 3 hydraulic units using Amaefule's Flow Zone Indicator (FZI) approach. Cut-off values of FZI were determined from a Lorenz plot

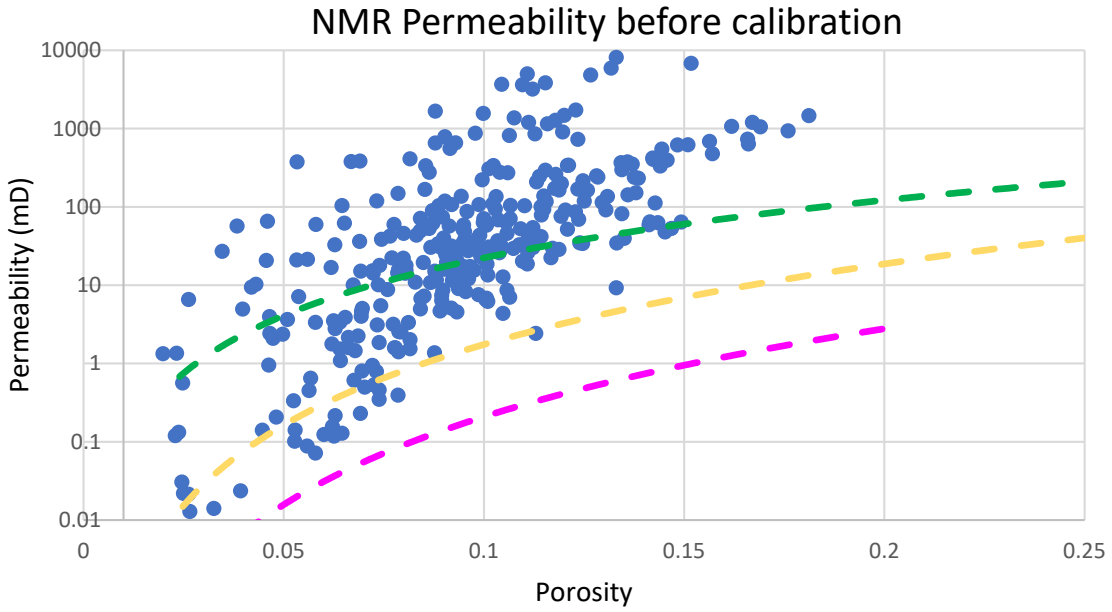
Step 2: Identify similar trends and clusters in the NMR data

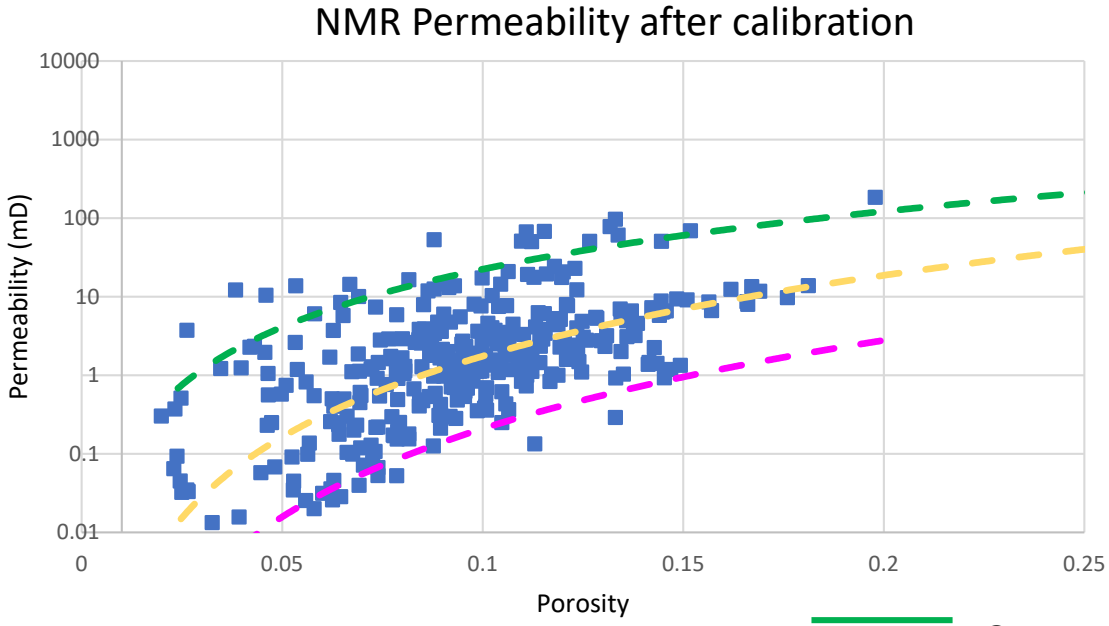






Step 3: Calibrate NMR permeability by adjusting equation parameters (shown in **red**) to match the NMR data to core data





$$k_{SDR} = \mathbf{4.6} \times T_{2gm}^{\mathbf{2}} \times \emptyset^{\mathbf{4}} \rightarrow k_{SDR} = \mathbf{0.005} \times T_{2gm}^{\mathbf{1.7}} \times \emptyset^{\mathbf{1.7}}$$

Application: Well 1

Data Set:

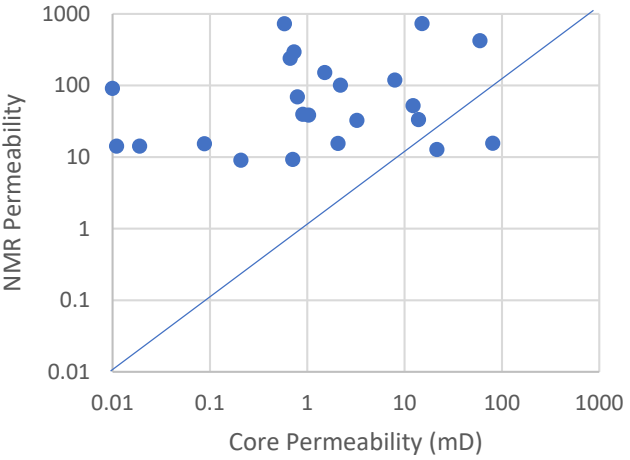
- NMR Log
- Core Gamma,
- Routine Core Analysis,
- Core NMR Measurement on 3 plugs

Calibration Techniques:

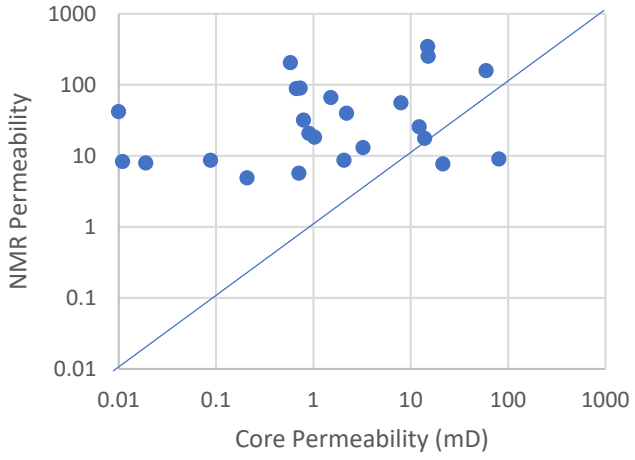
- Use parameters from core NMR
- Regression with depth matched RCA permeability
- The proposed technique

Comparison of Results: Well 1

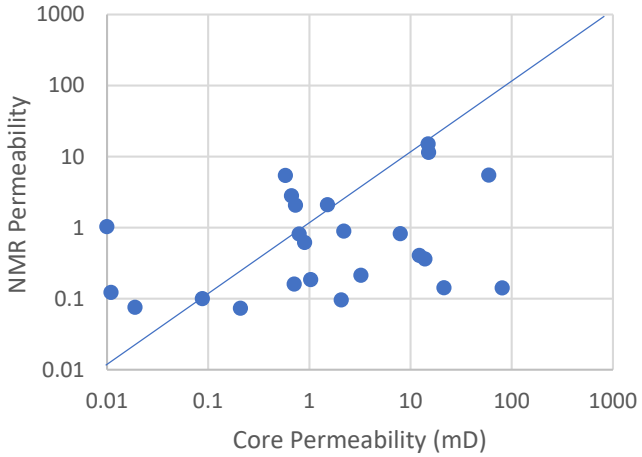
Uncalibrated NMR Permeability



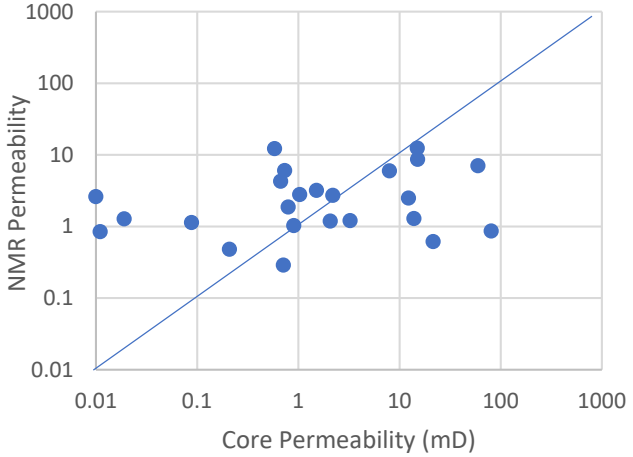
Calibrated NMR with Core NMR parameters

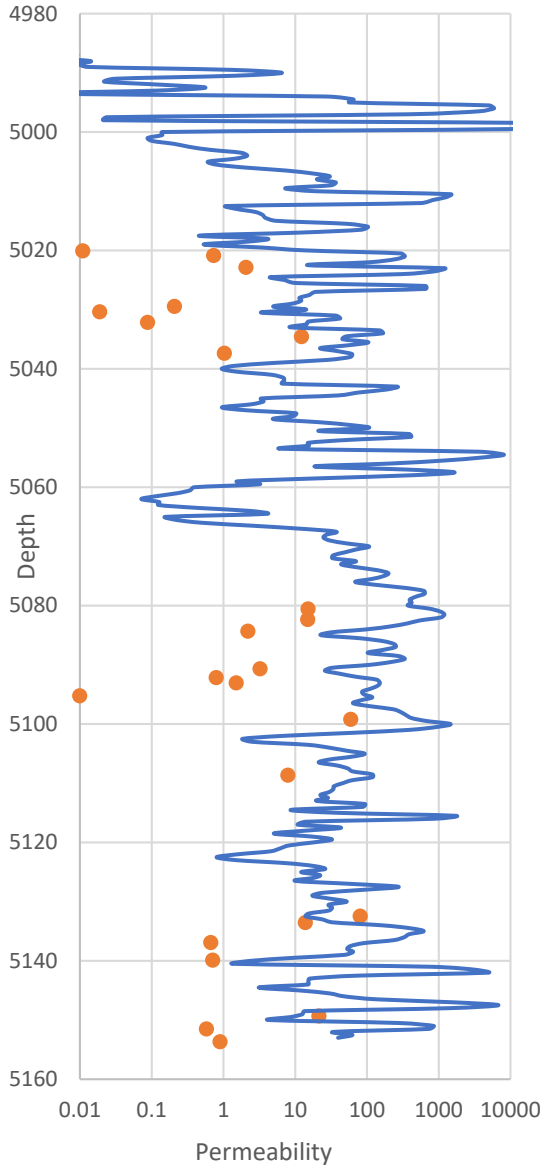


Calibrated NMR with RCA

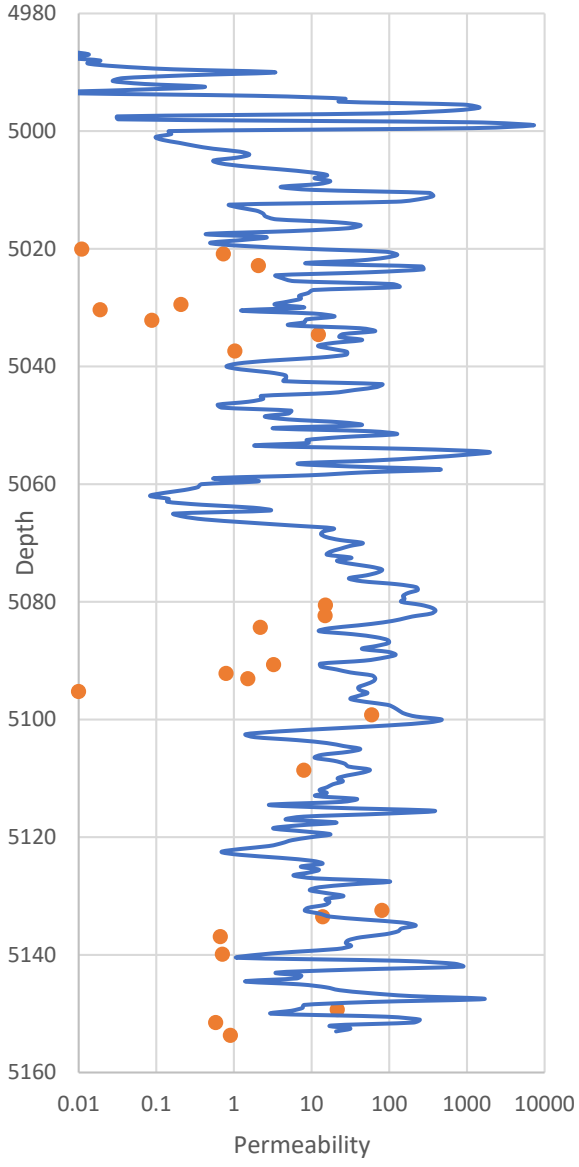


Calibrated NMR with proposed technique

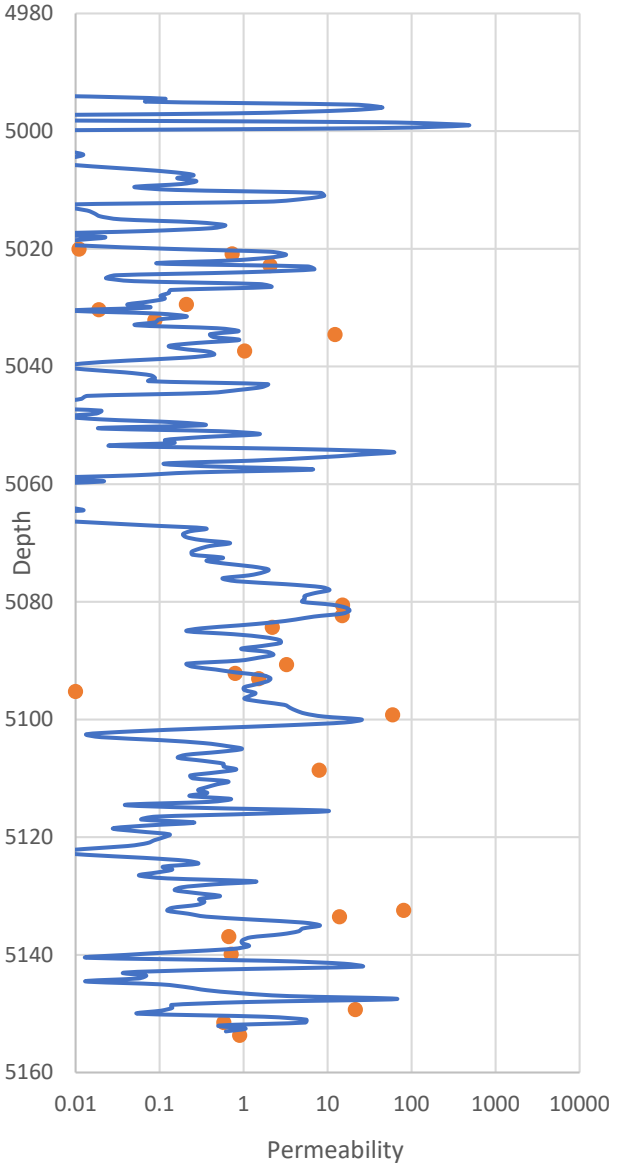




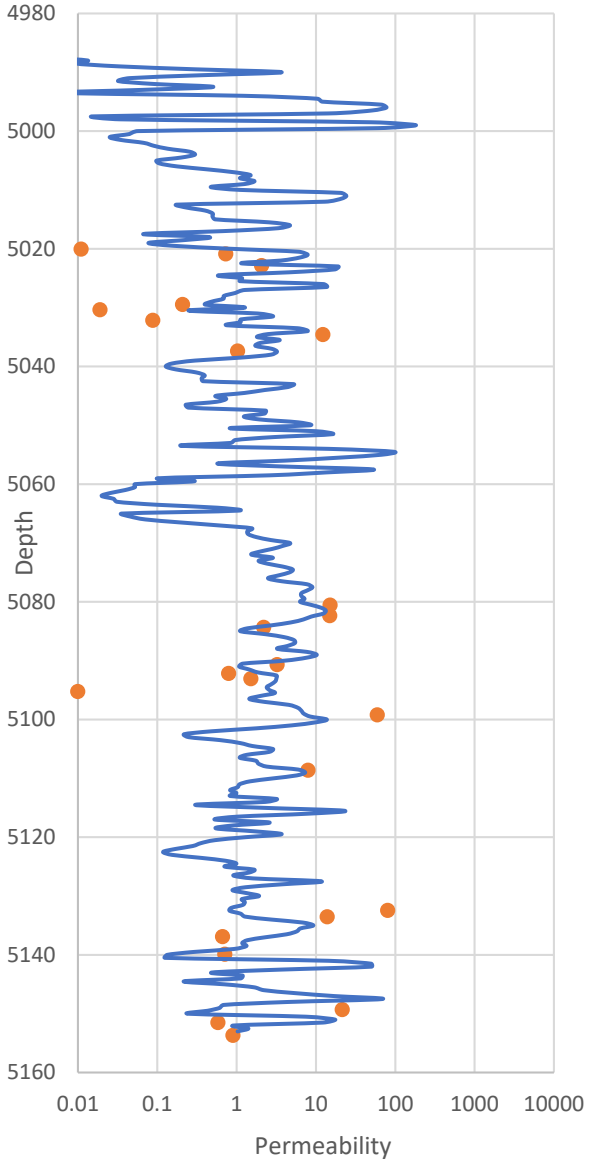
Uncalibrated NMR Permeability



Calibrated NMR with Core NMR parameters



Calibrated NMR with regression with RCA



Calibrated NMR with proposed technique

Application: Well 2

Data Available:

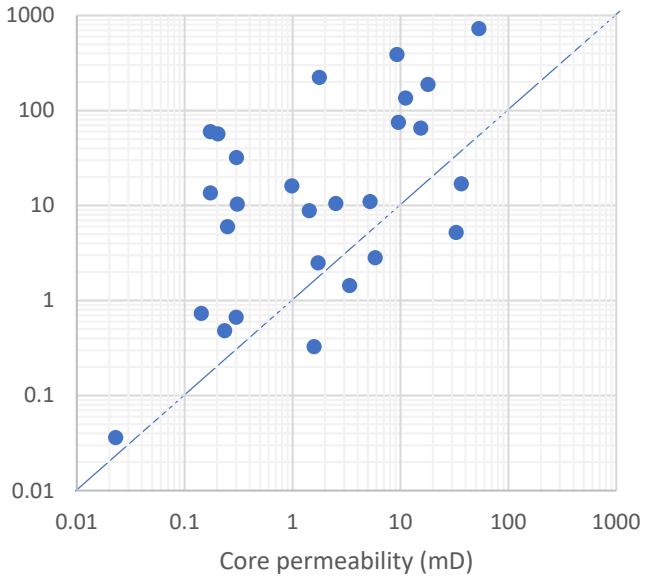
- NMR Log
- ~~Core Gamma~~,
- ~~Routine Core Analysis~~,
- ~~Core NMR Measurement~~

Calibration Techniques Available:

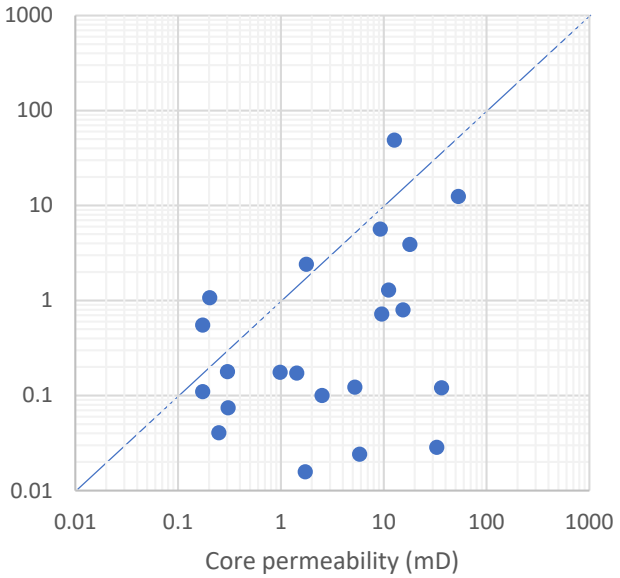
- Use of calibration parameters from offset well 1
- The proposed technique

Comparison of Results: Well 2

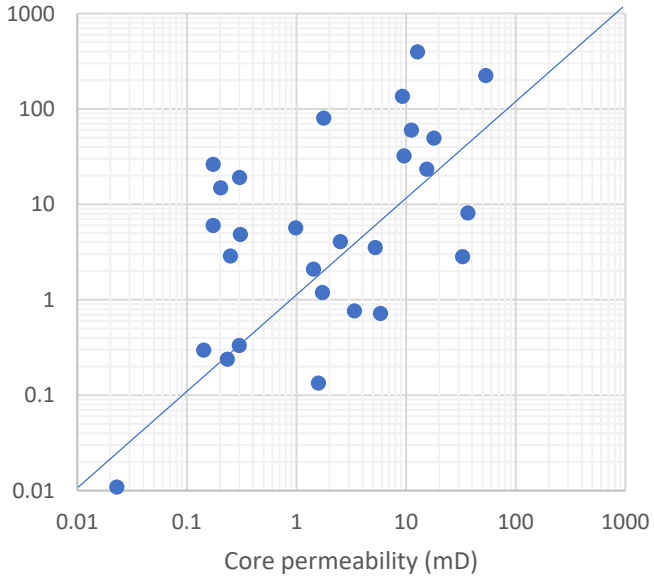
Uncalibrated NMR Permeability

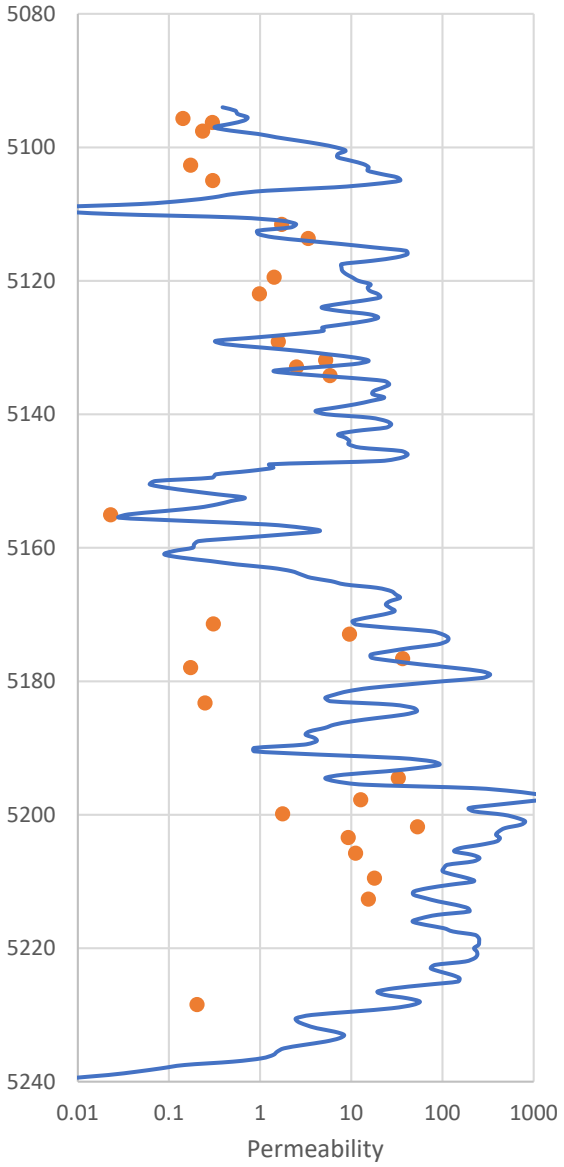


Calibrated NMR with Well-1 parameters

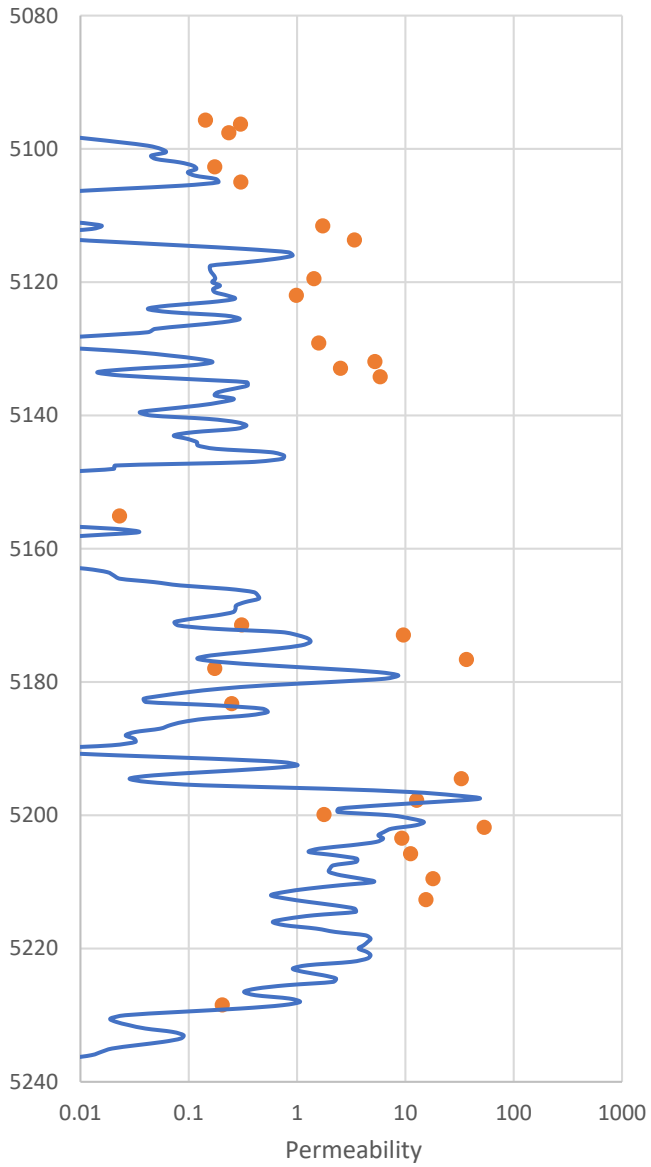


Calibrated NMR with proposed technique

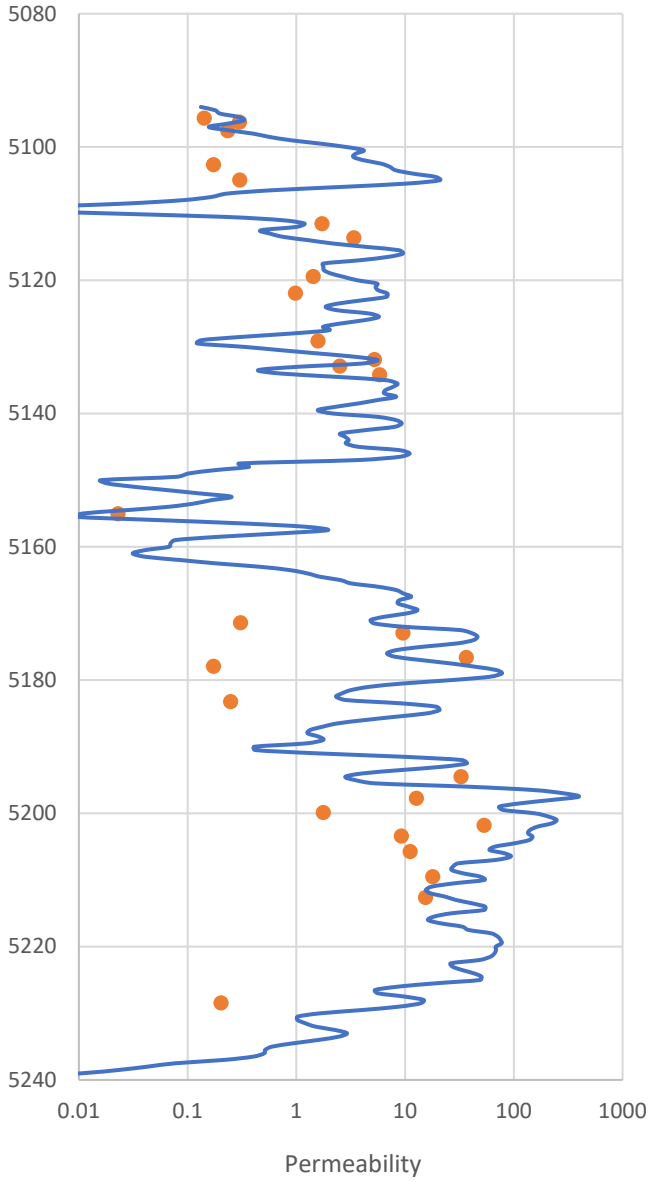




Uncalibrated NMR Permeability



Calibrated NMR with Well-1 parameters



Calibrated NMR with proposed technique

Advantages:

1. Does not require NMR measurements on plugs
   - Cost restrictions
   - Legacy core data
2. Can be used when core data is unreliable
   - Depth uncertainty
   - Biased depth selection on the plugs
3. Can be applied to calibrate wells that do NOT have cores
   - Calibration is to data or rock properties of the geologic area
4. Calibration can be performed using a spreadsheet or simple coding

Limitations:

1. Required good RCA dataset
   - Multiple wells
   - Identification of all rock types or trends
2. The core data pooled should be geologically similar
   - Geology and rock properties can vary considerably depending on the depositional environment
3. Solutions can be non-unique based on seeding parameters during regression/adjustment

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