Applications of 2D-NMR Maps and Geometric Pore Scale Modeling for Petrophysical Evaluation of a Gas Well*

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Abstract

This article presents the petrophysical evaluation of a gas reservoir from the Gulf of San Jorge Basin, Argentina, by means of 2D-NMR maps and a geometric pore scale modeling of the NMR response of the wetting phase. The reservoir contains gas and irreducible water saturation at the top with a sharp transition into the water zone.

The well has been logged with conventional tools, such as Gamma Ray, Neutron, Density and also the MRExplorerSM (MREXSM) to acquire the Nuclear Magnetic Resonance data for determining the irreducible water saturation. Data from Special Core Analysis (SCAL), Scanning Electron Microscopy (SEM), thin sections and capillary pressure tests have also been acquired. The core-log evaluation shows a very good agreement between the laboratory and log field data, especially in terms of irreducible water saturation, porosity and permeability, which was also modeled using the Timur-Coates equation for purposes of field delivery. The 2D-NMR maps, such as T_1-T_2 apparent and Diffusivity-T_2 intrinsic, from both the hydrocarbon and water zone, led to characterizing the clay-bound and capillary-bound water, and the "under-called" porosity due to the low hydrogen index of the gas.

We use a pore scale model that is in a good agreement with experimental data to predict the porosity, permeability, irreducible water saturation and T_2 responses of the wetting phase, including the pendular water effect. A key feature of this model is that it is geometrically determined or precisely defined based on the knowledge of geometry and, hence, the morphology of the pore space at the grain scale. Unlike many other approaches to pore-level modeling, our approach introduces no adjustable parameters and can be used to produce quantitative, a priori predictions of the rock macroscopic behavior.

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APPLICATIONS OF 2D-NMR MAPS AND GEOMETRIC PORE SCALE MODELING FOR PETROPHYSICAL EVALUATION OF A GAS WELL

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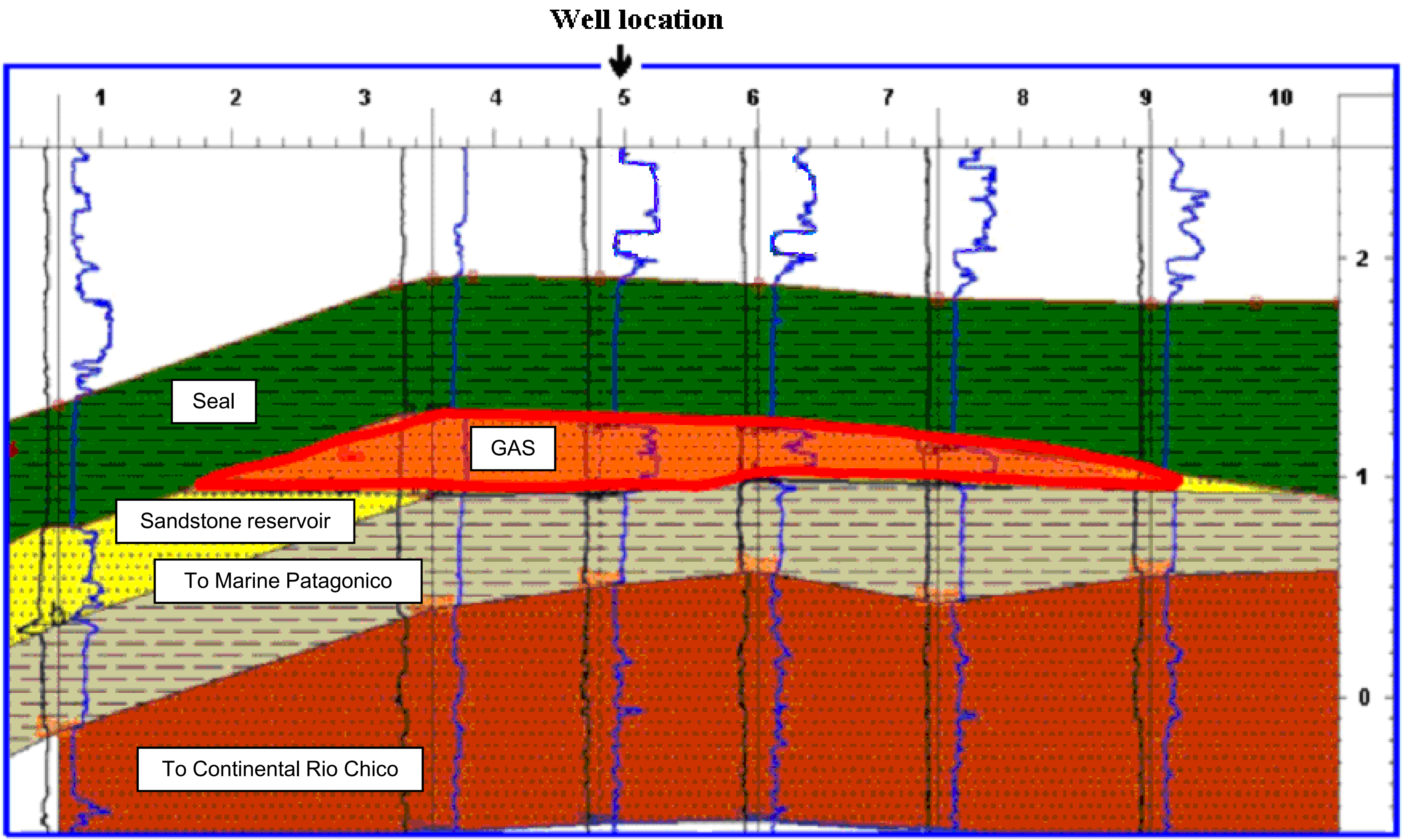
Outline

- Case Study: the Gulf of San Jorge Basin
- NMR Logging
- Pore-Scale Modeling
- Results
- Summary

The Gulf of San Jorge Basin, Argentina

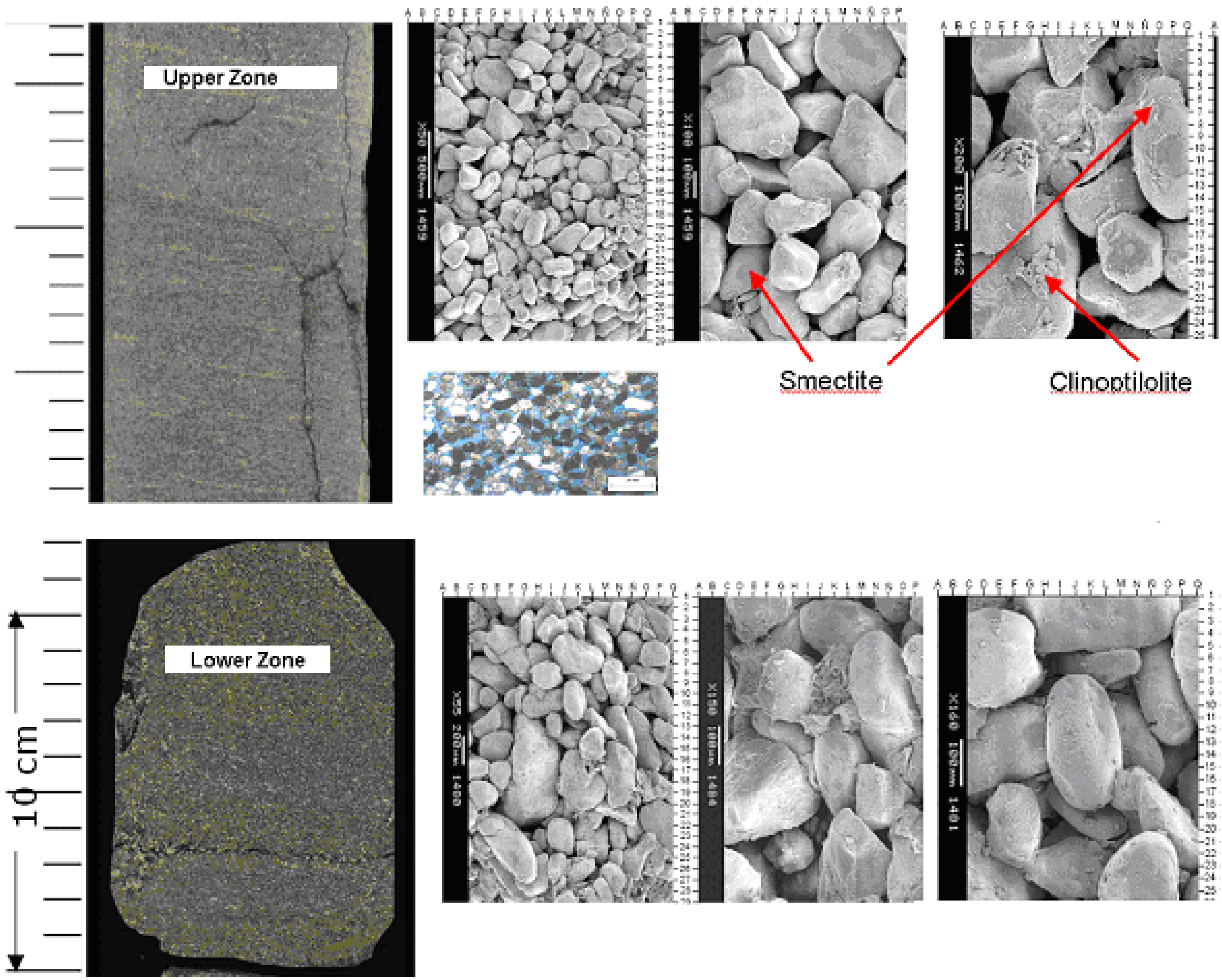
- Located in the heart of Patagonia, and extending from the Atlantic Ocean to the Andean foothills
- Accounts for around one third of the hydrocarbon production in Argentina.
- The origin and subsequent geological evolution of the basin are caused by the rift process responsible for the opening of the Atlantic Ocean in early Jurassic times.
- Accumulation of terrigenous sediments continued well into Early Cretaceous times

Trap Model



Well location
1
2
3
4
5
6
7
8
9
10
2
1
0
Seal
GAS
Sandstone reservoir
To Marine Patagonico
To Continental Rio Chico

Core Images



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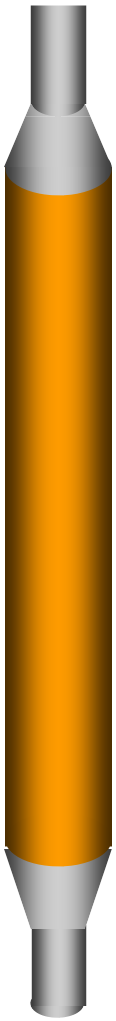
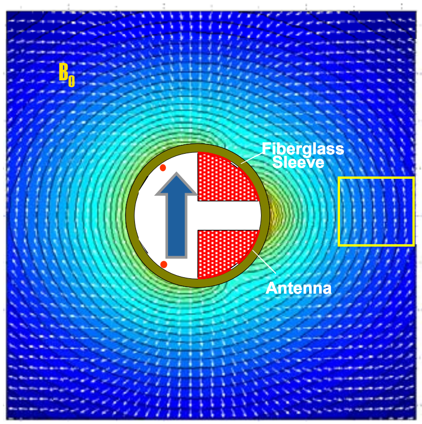
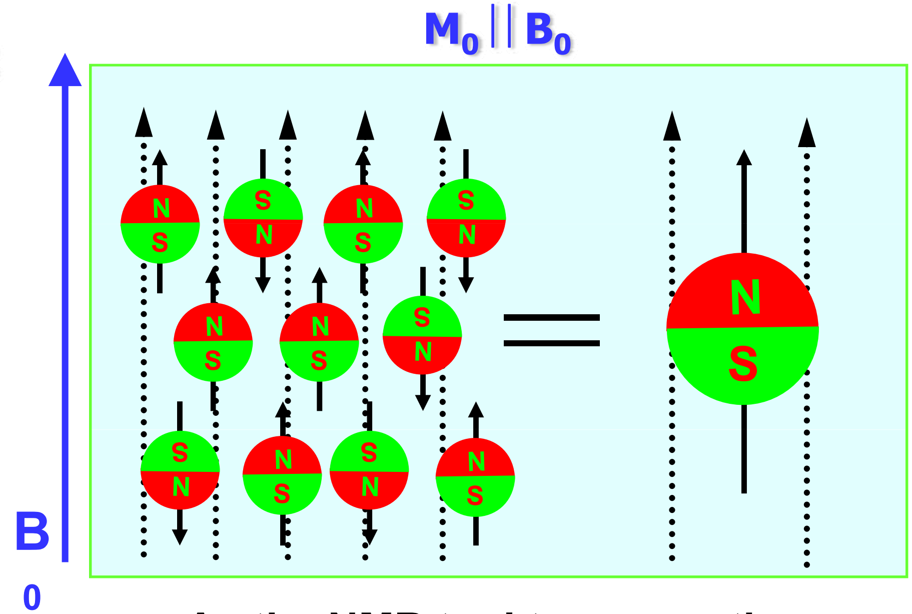
NMR Logging Tool



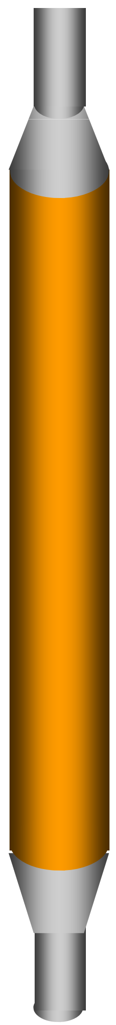
NMR tool (MREX[SM]) contains large permanent magnet with field B_0



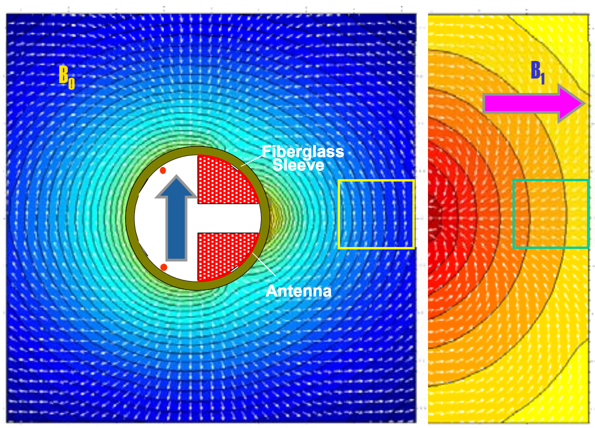


As the NMR tool traverses the wellbore the hydrogen protons of the formation adjacent to the tool are aligned with B_0

NMR Logging Tool

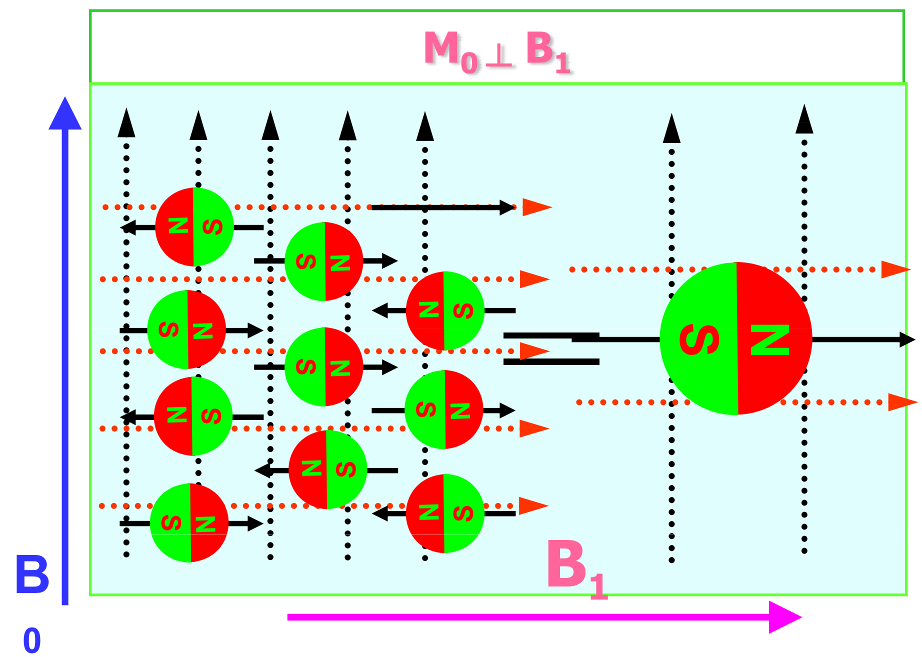


Tool emits radio frequency (RF) pulse with field strength B_1



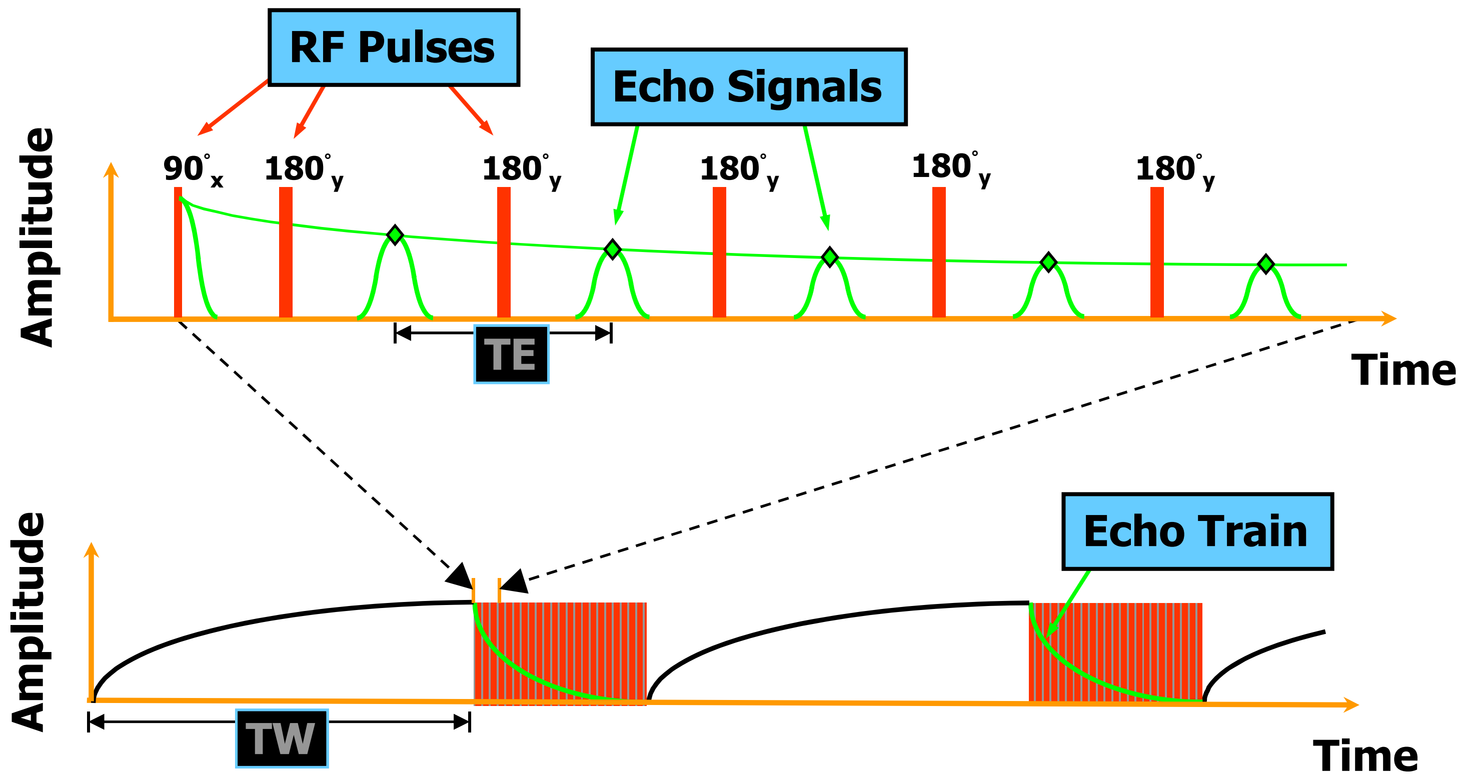
Larmor Frequency

$$\text{freq.} = 4258 \frac{\text{Hz}}{\text{Gauss}} \cdot B_0$$



Spins are tipped 90 degrees by the RF pulse and then begin to precess in the B_0 field

Echo Train

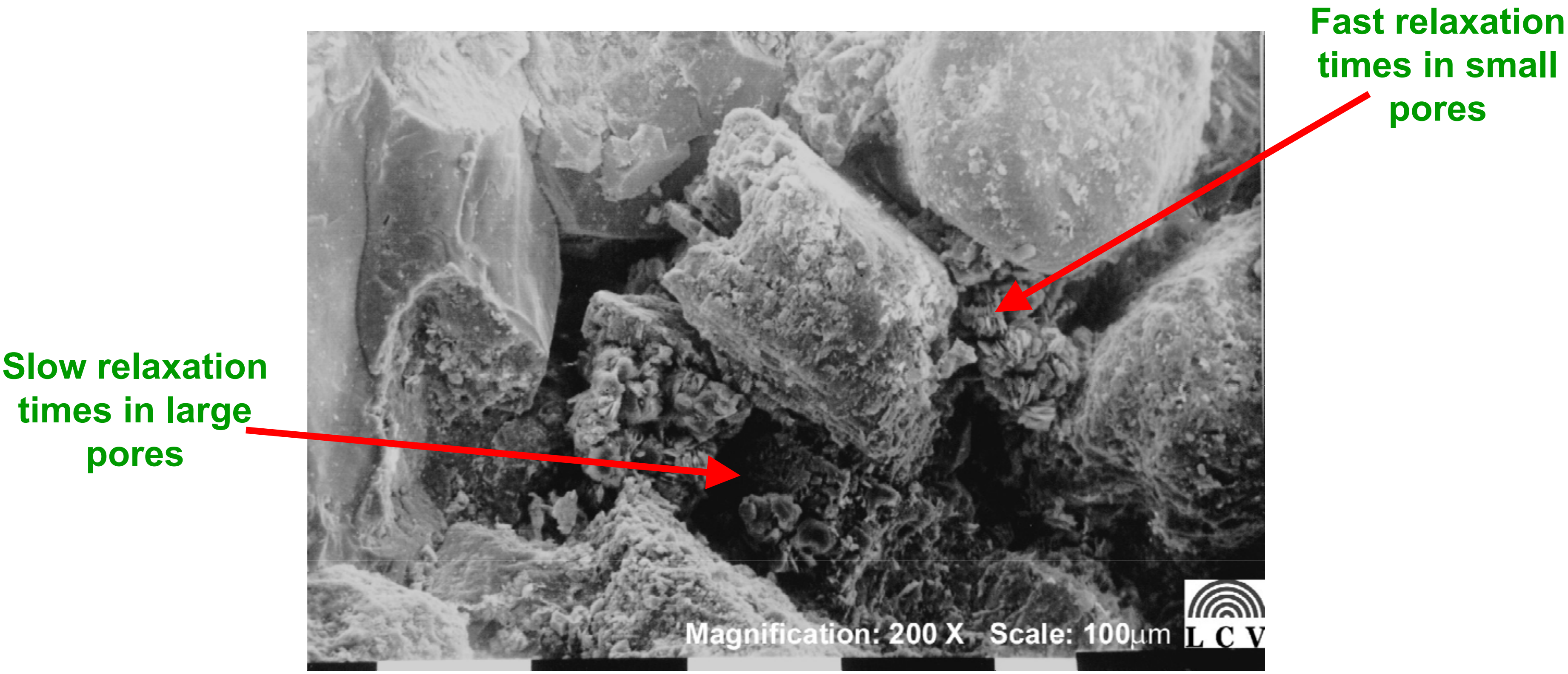


TE : inter-echo spacing time
TW : wait time (≥ 3 x T_1 for full recovery)

NMR Logging

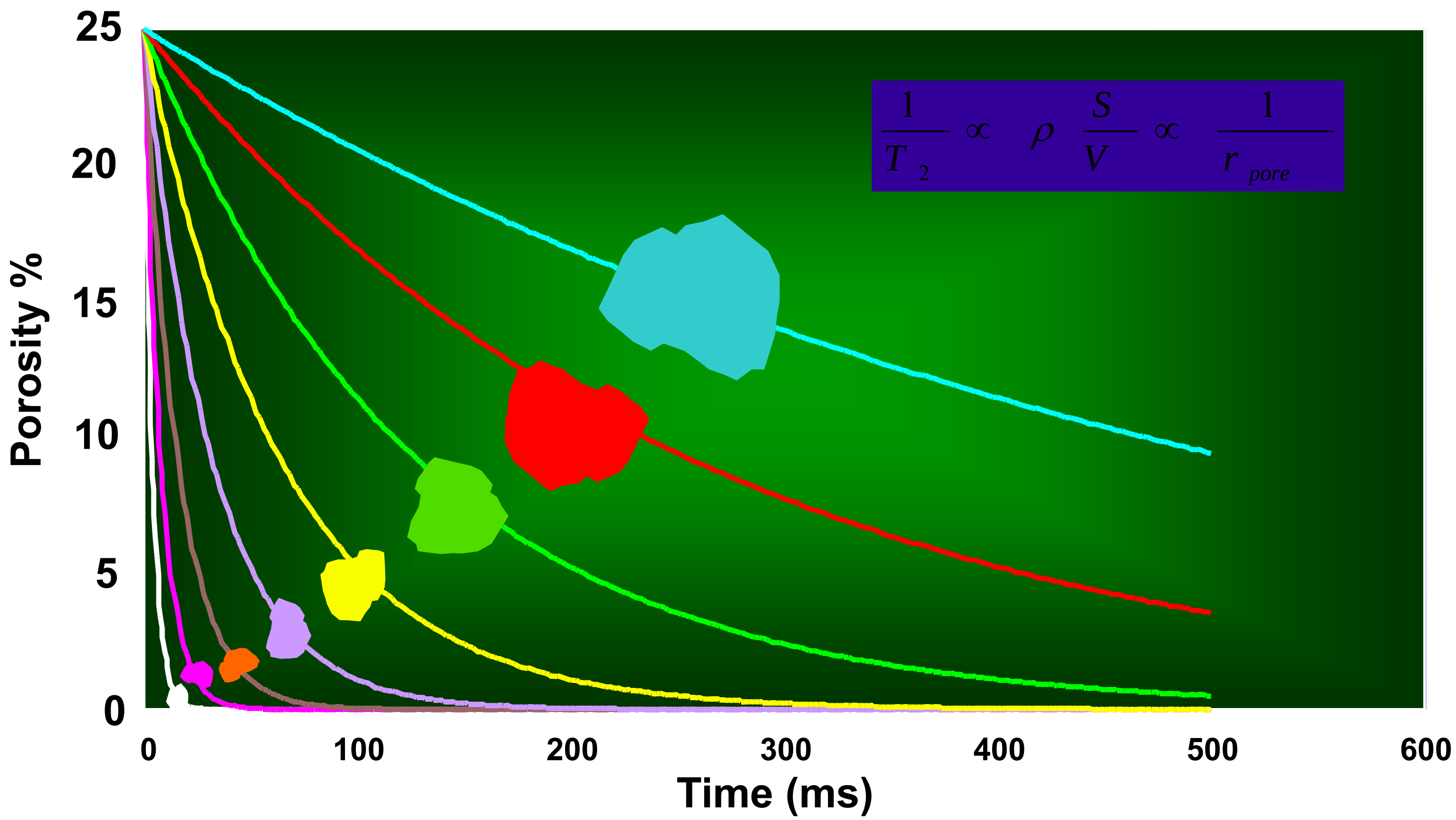
NMR logging measures:

- Quantity of ^1H present in the sample volume: provides lithology-independent porosity
- Relaxation process in the sample



NMR Relaxation – T_2 Decay Rate

T_2 decay rate is inversely proportional to the surface/volume ratio of pores in the rock

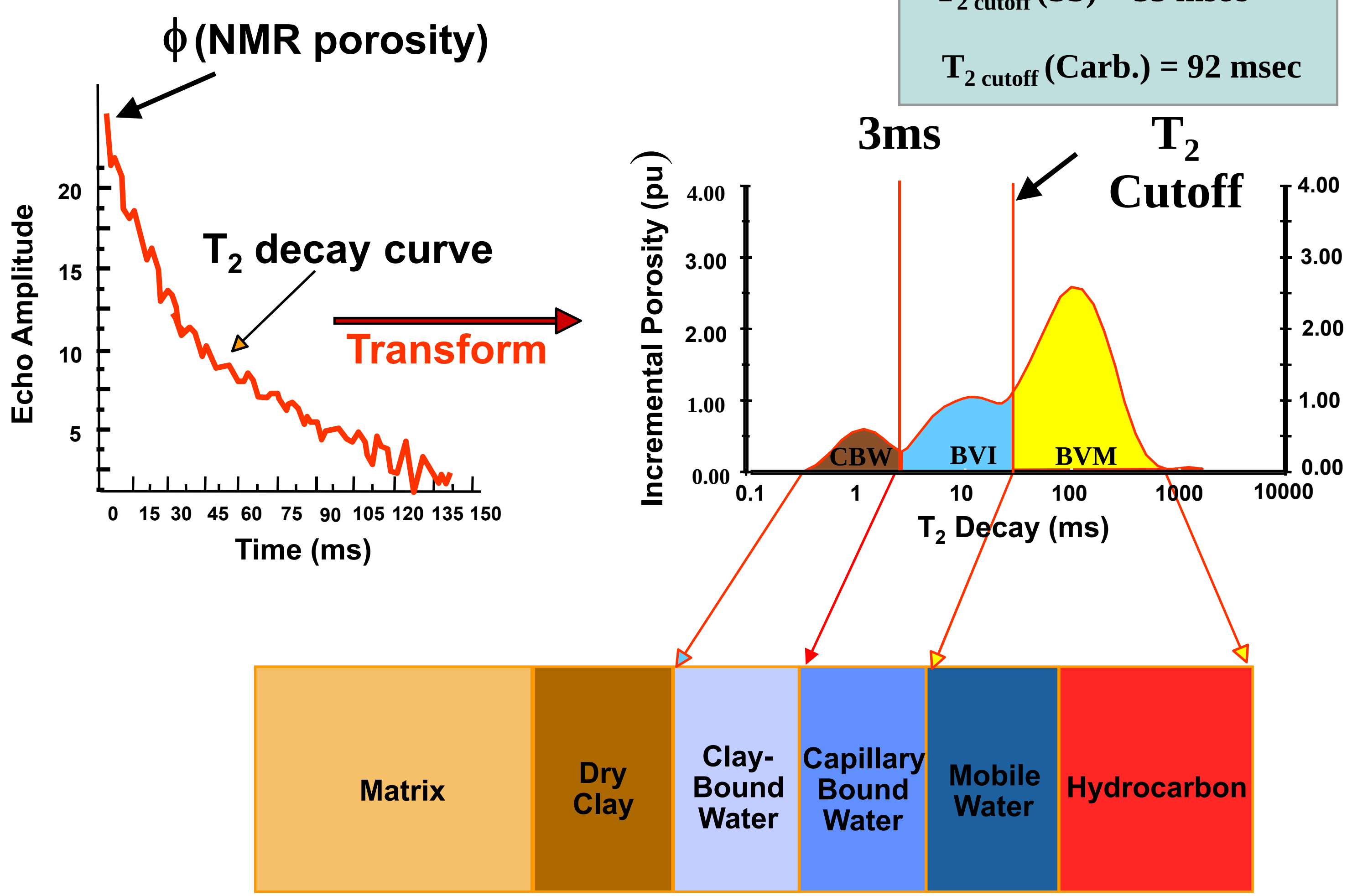


$$\frac{1}{T_2} \propto \rho \frac{S}{V} \propto \frac{1}{r_{pore}}$$

Pore Size Distribution From NMR

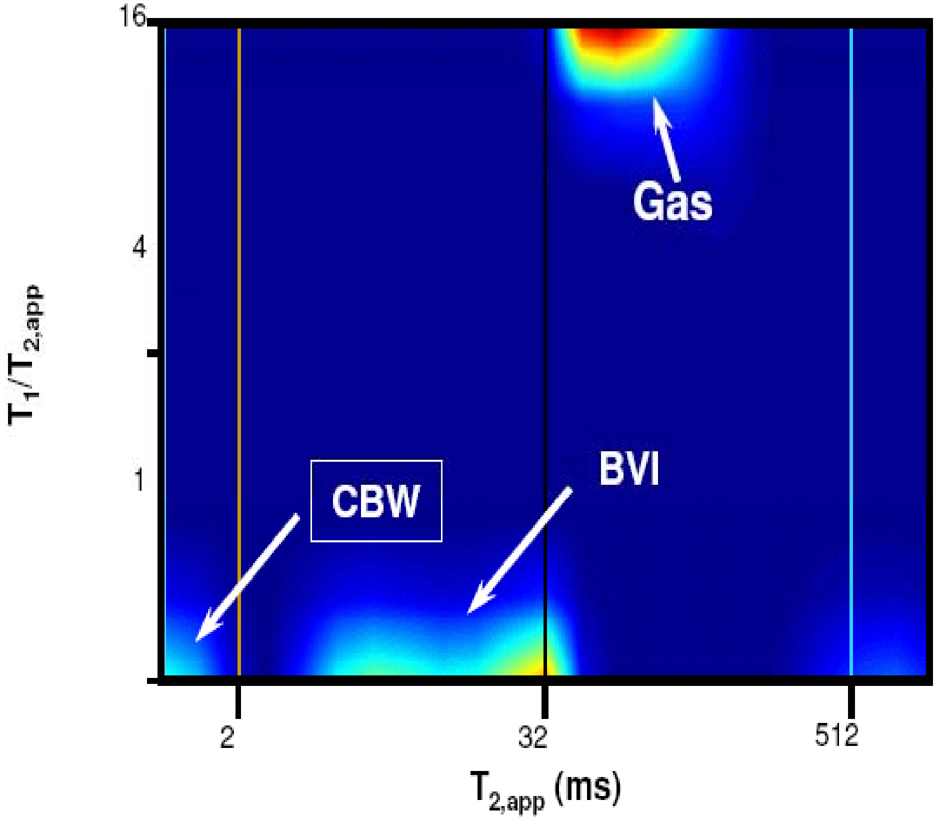
$T_{2\ cutoff}$ (SS) = 33 msec

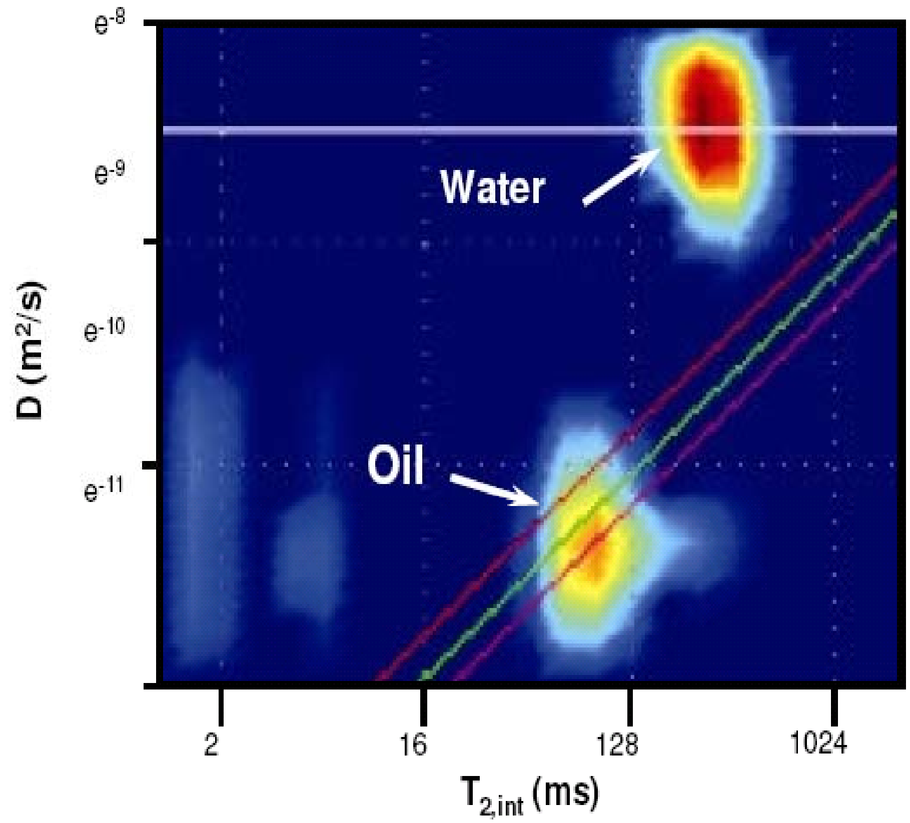
$T_{2\ cutoff}$ (Carb.) = 92 msec



2D NMR

- T_1, T_2, and diffusion data are acquired simultaneously while logging
- 2D NMR plots identify and quantify hydrocarbons





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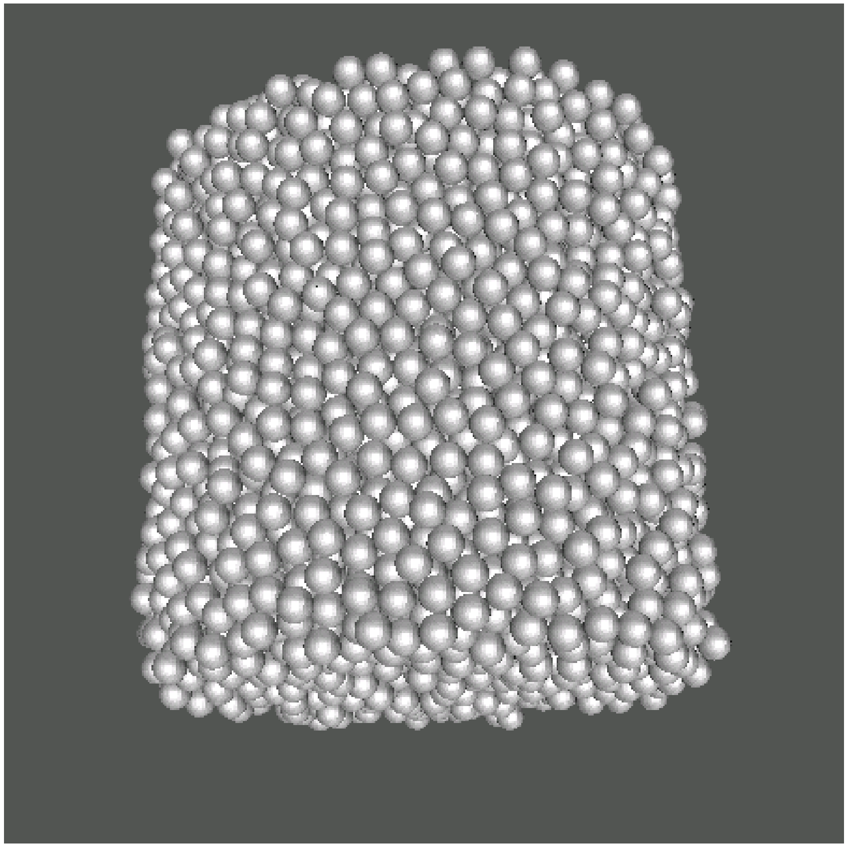
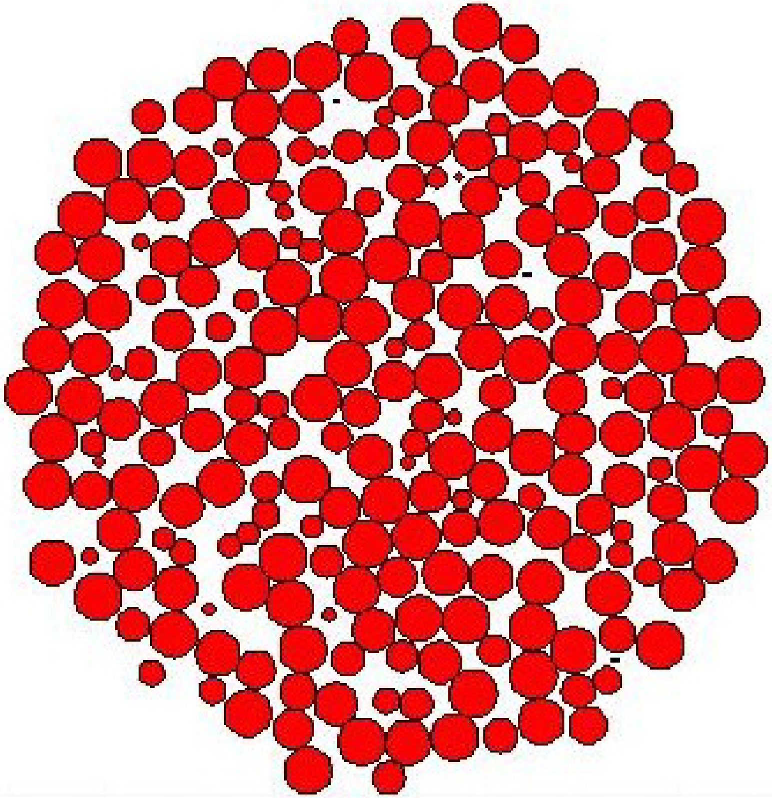
Creating Numerical Model Rocks

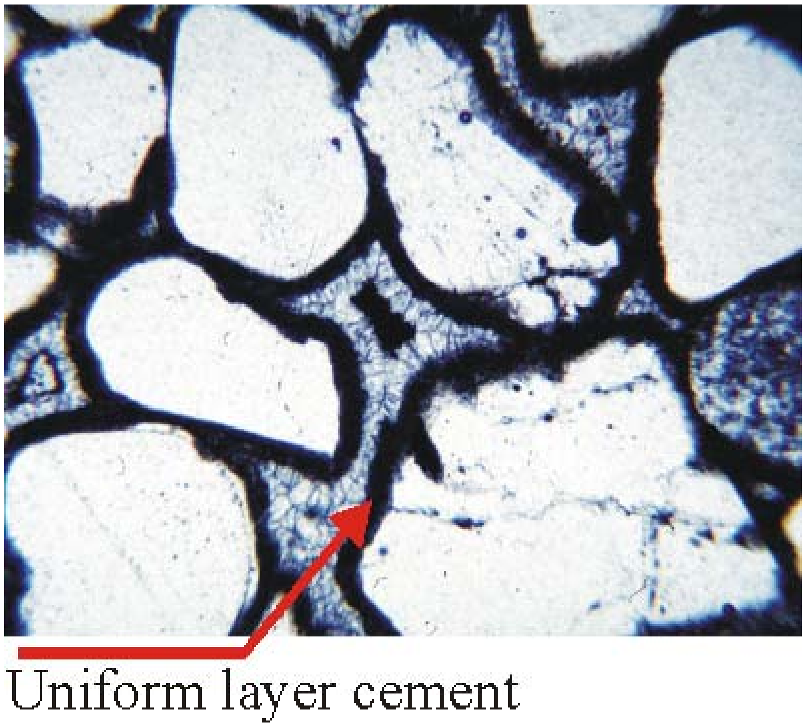
4,000 grains of equal size, $\phi = 36\%$.

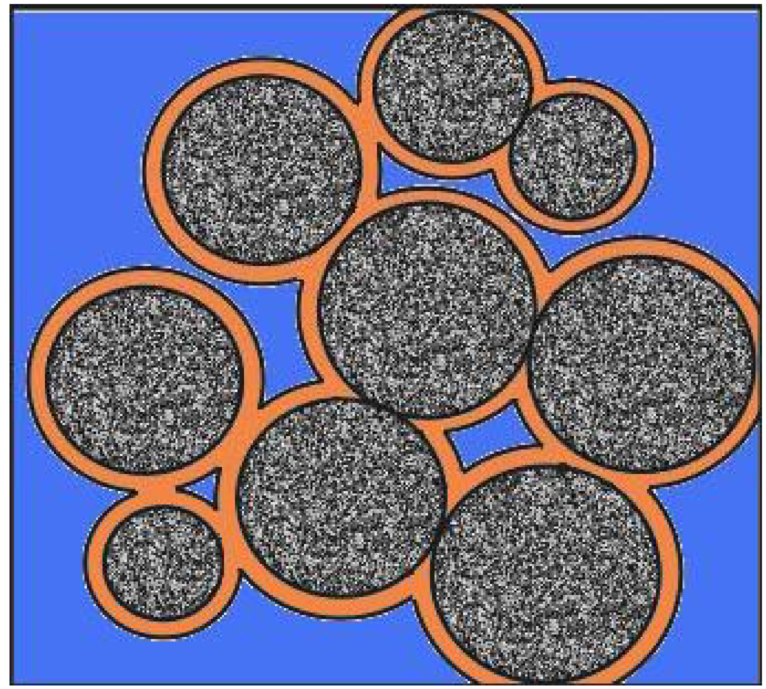




Cross-section

Model Isopachous Cement

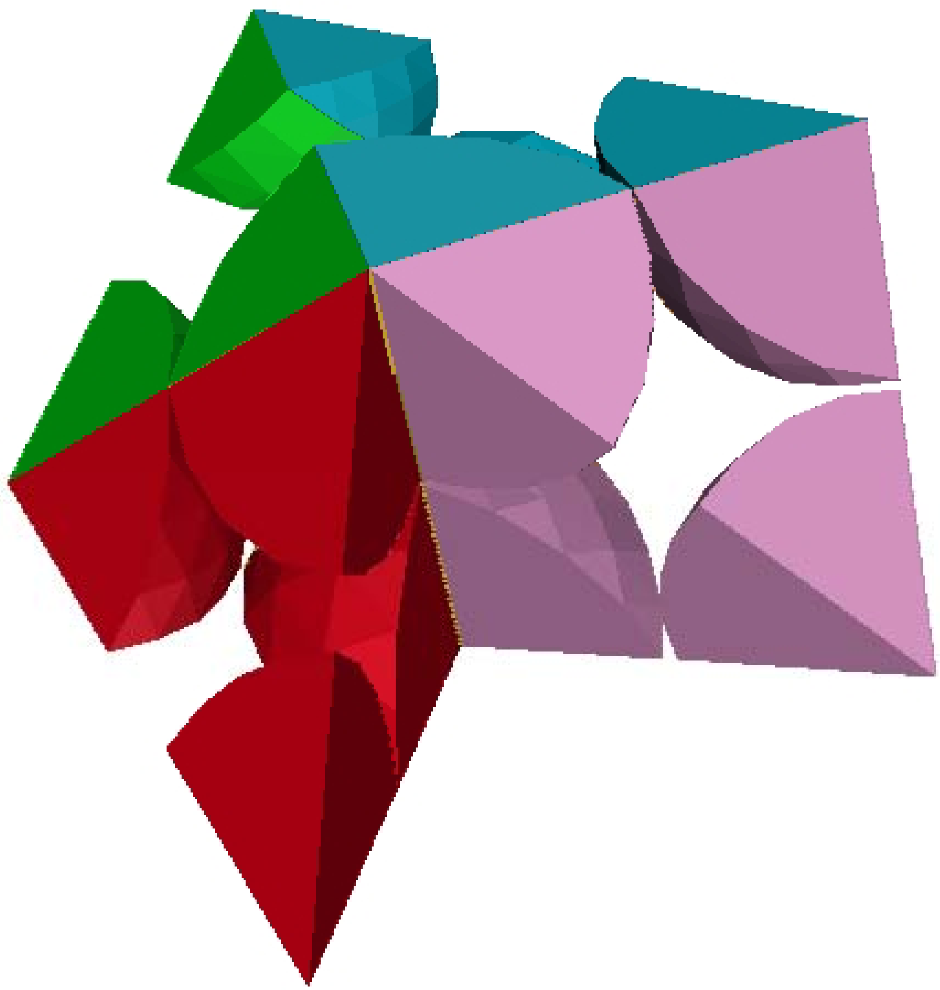




Sandstone containing isopachous (uniform layer) cement

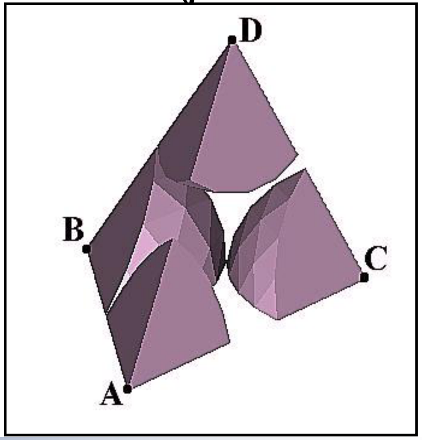
Model cemented porous media

Network Model

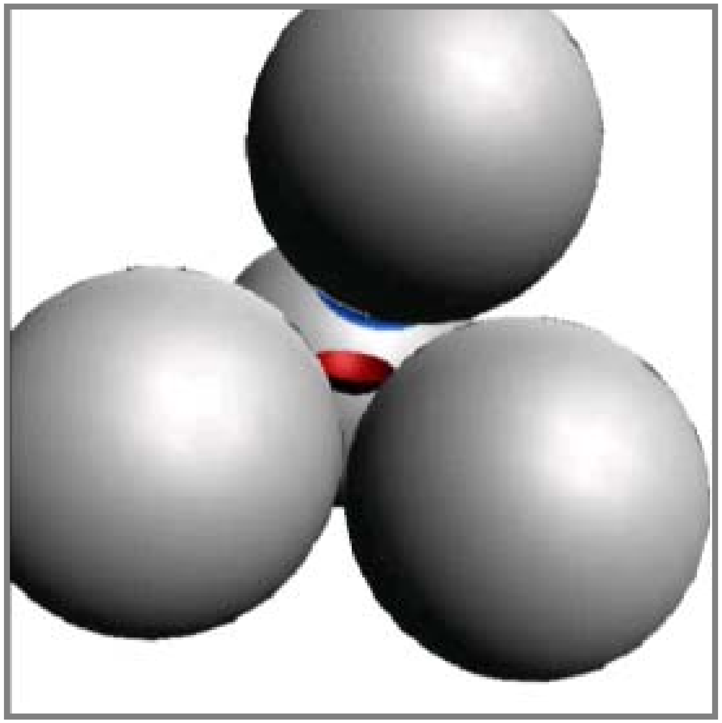


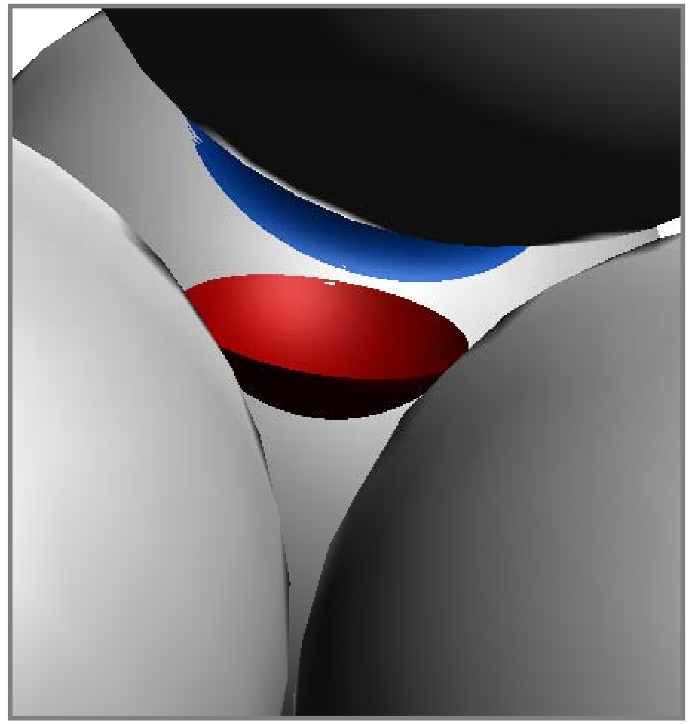
- Subdivide pore space into modified *Delaunay cells*:
  - Join four nearest neighboring grains to form tetrahedra;
  - Merge flat tetrahedra to form larger pores.
- Result is a network:
  - Cells ↔ Sites (*pore bodies*)
  - Faces ↔ Bonds (*pore throats*)

Delaunay cell



Possible Fluid Configurations





Wetting phase exists in the form of *pendular rings* between solid grains and *menisci* between tetrahedral pores.

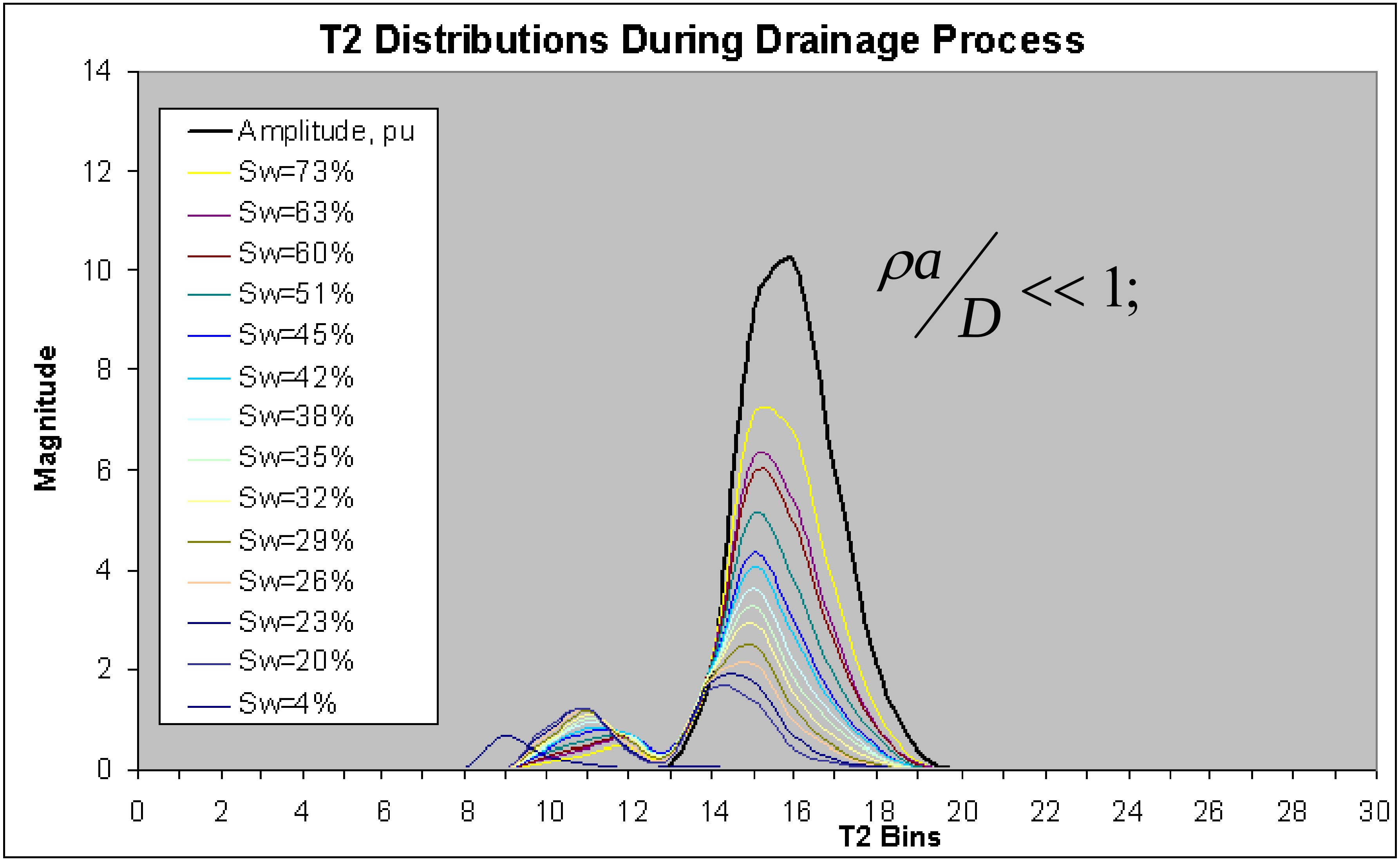
Model of NMR Response

- Brownstein and Tarr (1979) model is commonly used:
  - Diffusion equation for total magnetization with surface-like sinks;
  - Isolated spherical pores;
  - Fast diffusion limit: $\rho a / D << 1;$
  - Single exponential decay of a pore:

$$M(t) = M_0(t) \exp\left(-t / T_2 \right),$$

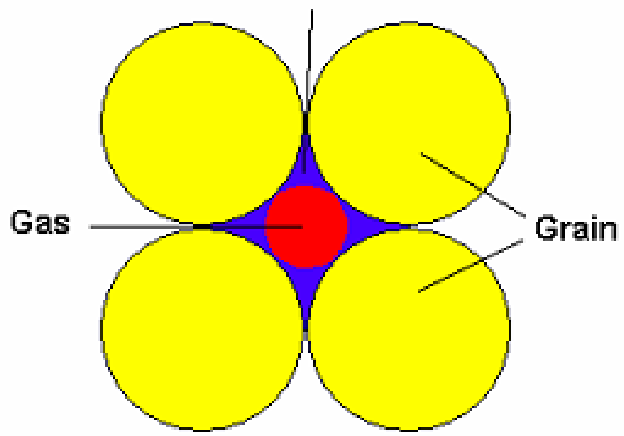
$$\frac{1}{T_2} = \rho \frac{S}{V}.$$

T_2 Distribution from Pore Scale Model

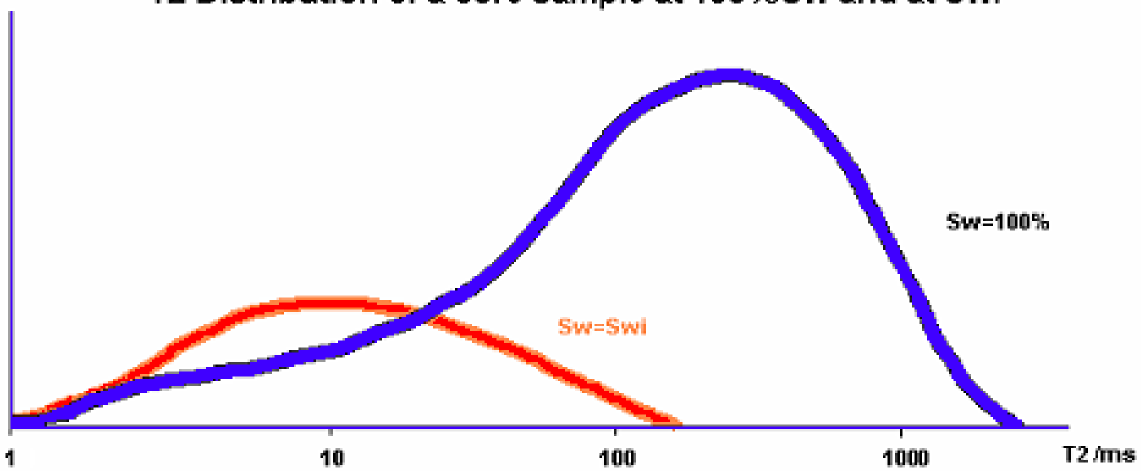


$$\rho a / D \ll 1;$$

Pendular Water



T2 Distribution of a core sample at 100%Sw and at Swi



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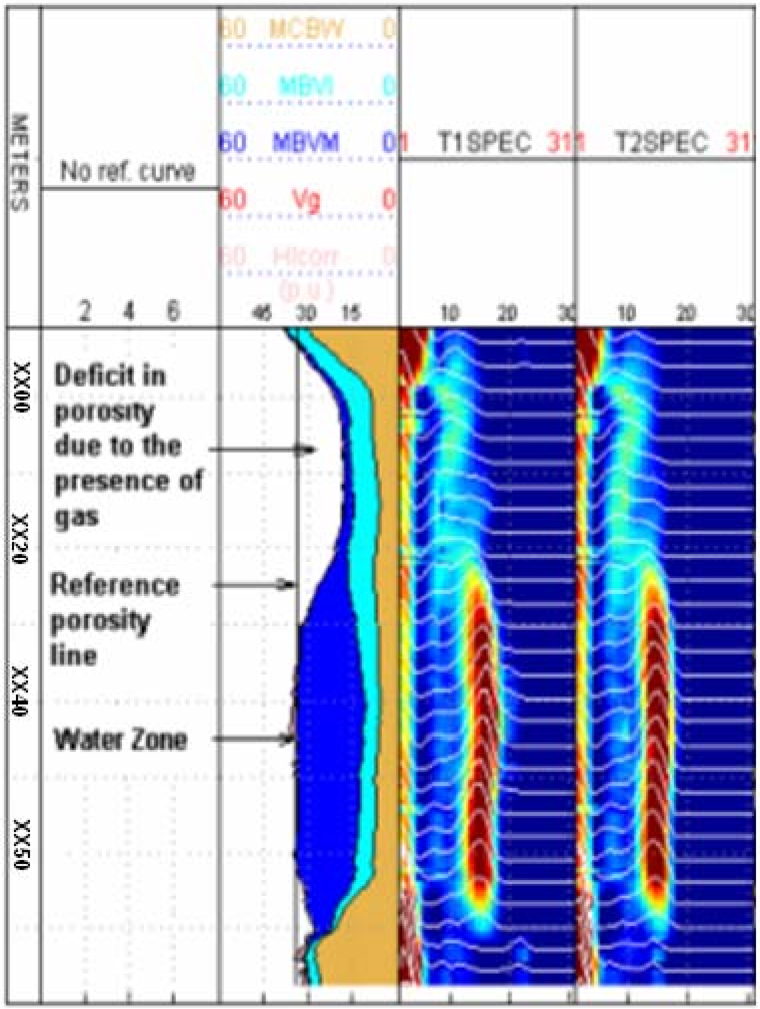
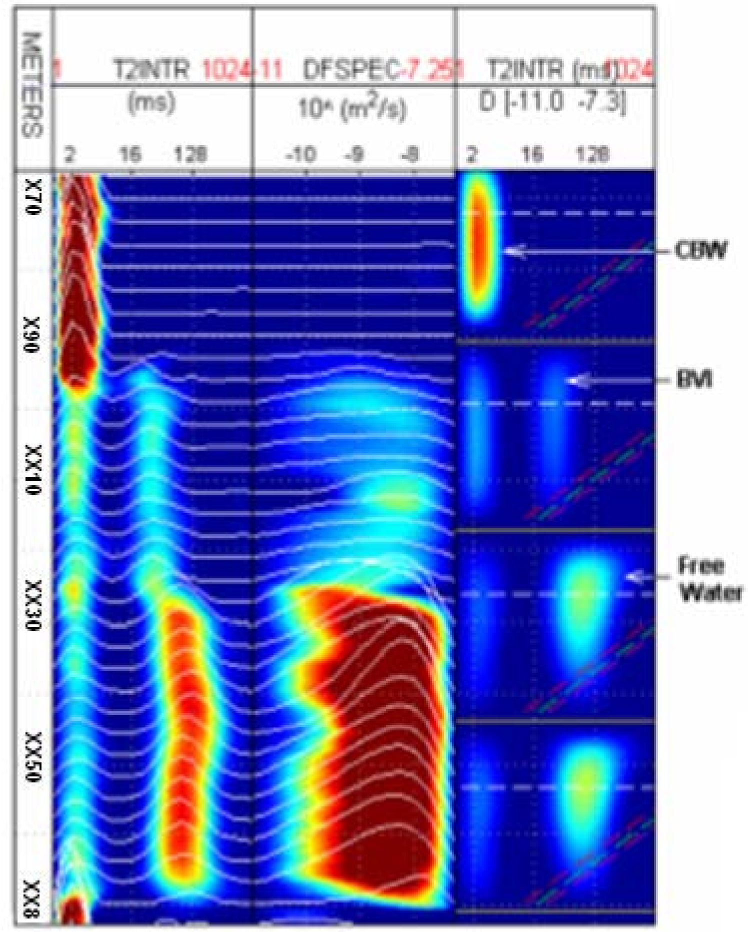
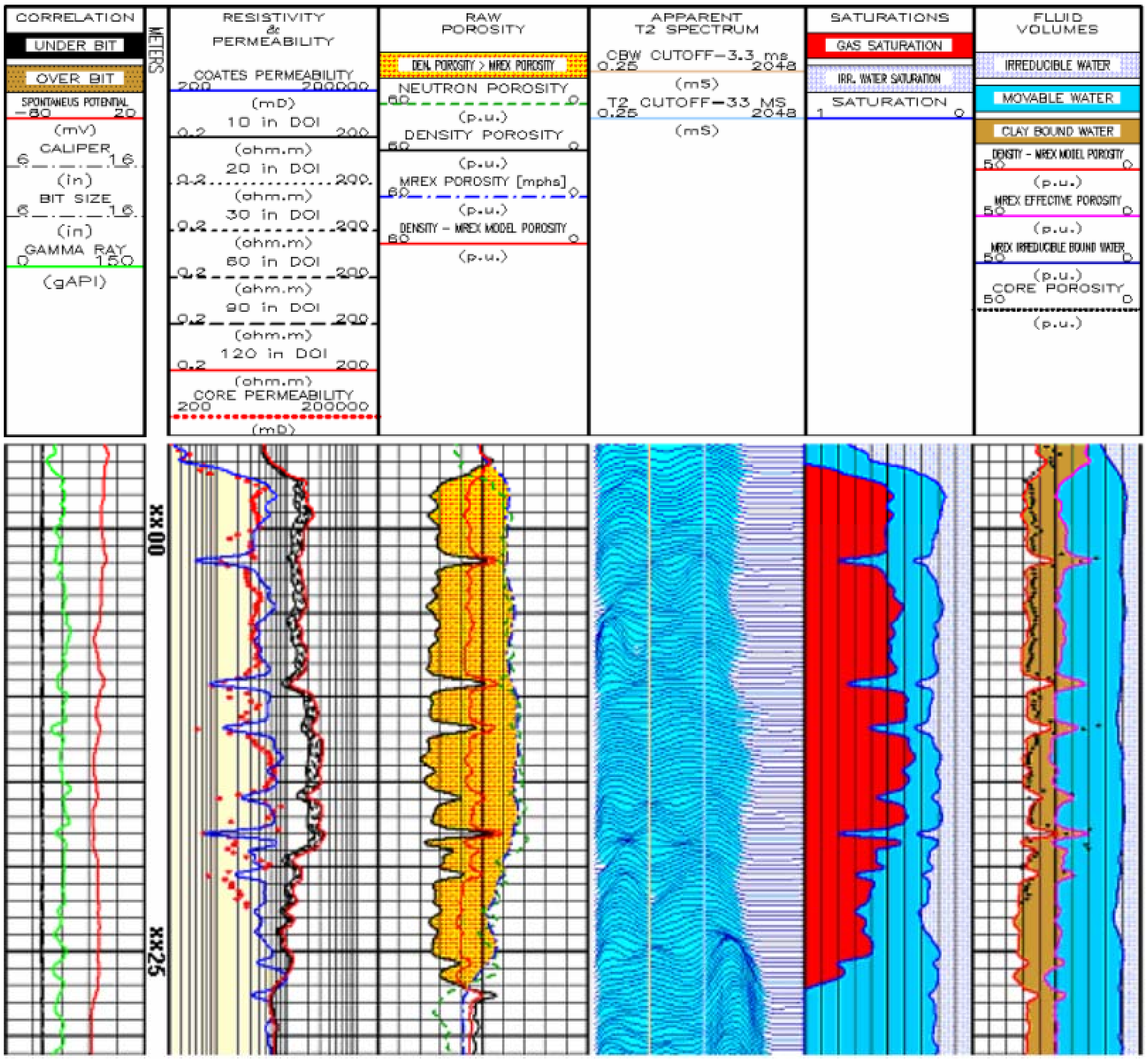
Layer Evaluation





Final Petrophysical Evaluation



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Summary

- NMR logging is an important reservoir characterization tool for both rock and fluid typing purposes;
- 2D NMR allows for determination of the fluid type using diffusivity and relaxation time contrasts;
- Pore-scale modeling further characterizes the NMR behavior of the wetting phase different saturation levels;
- Integrated interpretation of logging data, including NMR and pore-scale modeling techniques, provides detailed petrophysical evaluation of a gas well.

Reference

Brownstein, K.R., and C.E. Tarr, 1979, Importance of classical diffusion in NMR studies of water in biological cells: Physical Review A, v. 19/6, p. 2446-2453.