Technical Report: NMR Physics and Remote Sensing of Reservoirs

Relaxation principles, matrix heterogeneities and passive orbital methodology (RSS-NMR)

SUMMARY

PART I: PHYSICAL FOUNDATIONS AND PROPERTIES OF ROCKS

1. The Fundamental Relaxation Times of Hydrogen

In physics and imaging, hydrogen relaxation times refer to the time required for protons (the nuclei of hydrogen atoms) to return to their thermodynamic equilibrium state after being perturbed by an electromagnetic pulse. This phenomenon is central to NMR (Nuclear Magnetic Resonance) and MRI. Two main time constants characterize the return of magnetization:

- The relaxation time T1 (Longitudinal Relaxation): This is the characteristic time (expressed in seconds) required for the magnetization of hydrogen to recover 63% of its initial equilibrium value after excitation. The protons release the absorbed energy by transferring it to their immediate molecular environment (the lattice).
- The T2 relaxation time (transverse relaxation): This is the characteristic time (expressed in milliseconds) after which the transverse magnetization has decreased to 37% of its maximum value. This phenomenon is due to the interactions between protons (spin-spin interactions) and is always much shorter than T1.

2. The Crucial Distinction: T2 versus T2* (Effective Relaxation)

In practice, the transverse magnetization decreases much more rapidly than the effect of spin-spin interactions alone (T2). This overall phenomenon of accelerated phase shift is quantified by the time constant T2*:

$$1 / T2^{*} = 1 / T2 + 1 / T2 \text{ , inhomogeneous}$$

2.1 DEFINITION

In oil exploration, an **inhomogeneous** or **heterogeneous medium** refers to a reservoir rock whose physical properties (porosity, permeability, saturation) vary from one point to another.

RSS NMR
THE SIMPLE WAY OF EXPLORATION
GEO-NMR.NET
Exploration by satellite

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Unlike a perfectly uniform medium, this structural complexity directly influences the migration and flow of oil and gas.

Main characteristics of an inhomogeneous reservoir

- **Spatial variations:** Petrophysical properties change depending on the location, whether on a microscopic scale (the pores of the rock) or macroscopic scale (the different sedimentary strata).
- **Impact on production:** These variations create preferential pathways for fluids, which can complicate drilling and optimal hydrocarbon extraction.
- **Multiscale modeling:** Reservoir engineers use stochastic modeling tools and multiscale parameterization methods to map this heterogeneity and simulate reservoir behavior.
- **The mechanism:** The loss of coherence of protons is accelerated by inhomogeneities of the main magnetic field (B0), induced in particular by differences in magnetic susceptibility at the interfaces between the solid rock matrix and the fluids.
- **Reversibility:** Unlike true T2, which depends on random molecular collisions, the phase shift due to inhomogeneities is fixed and static. It can be compensated and canceled by applying recentering pulses (Spin Echo sequence).

3. Cut-off Threshold Dynamics: Carbonates vs. Sandstone

The cut-off threshold (T2 cut -off) allows for the hydrodynamic separation of bound water (microporosity, non-productive) from free water (macroporosity, mobile and usable). The observed difference between sandstones (~33 ms) and carbonates (~92 ms) stems directly from the surface relaxation formula:

$$1 / T2 \approx \rho 2 \cdot (S / V)$$

• The lower surface relaxivity ($\rho 2$) of carbonates: Sandstones naturally contain clay minerals and iron oxides with paramagnetic properties that accelerate relaxation (high $\rho 2$). Conversely, pure carbonates (calcite, dolomite) are chemically very clean. Their relaxivity $\rho 2$ is 2 to 3 times weaker, which slows down transverse relaxation and shifts the cutoff threshold to longer times (~92 ms).

4. Critical Mineralogical Impact: Presence of Pyrite (FeS_2)

Pyrite is a conductive and highly paramagnetic metallic iron sulfide. Under the application of the B0 field, the strong magnetic susceptibility anomaly between these grains and fluids generates significant local field gradients (Ginterne), drastically accelerating depolarization by molecular diffusion:

$$1/T2\text{ , measured} = 1/T2\text{, surface} + 1/T2\text{, volume} + (\ \gamma^2 \cdot \text{Ginin}^2 \cdot \text{TE}^2 \cdot D) / 12$$

Major consequences for interpretation:
- Underestimation of pore size: Peaks migrate towards shorter timescales, classifying large, mobile pores as micropores. - Overestimation of bound water (BVI): The irreducible volume is

overestimated at the expense of mobile hydrocarbons. - Signal attenuation: If the phase shift is faster than the minimum echo time (TE), the NMR signal may be completely lost.

PART II: QUANTIFICATION OF PERMEABILITY AND PASSIVE ORBITAL STRATEGY

1. Modeling of Intrinsic Permeability by NMR

NMR evaluates continuous permeability from the complete pore size distribution via two standard equations:

Coates ' model (Free Fluid Model): Based on the ratio of mobile to bound fluids: $KCoates = (\phi / C)^4 \cdot (FFI / BVI)^2$
- The SDR model (Schlumberger Doll Research): Based on the geometric mean of the T2 spectrum: $KSDR = a \cdot \phi^4 \cdot (T2,log)^2$

Limitations and heterogeneities: In complex carbonates (isolated giant pores or ' vugs '), the fluid exhibits a very long T2 without true connectivity. The SDR model then massively overestimates permeability. Modern interpretation requires variable T2 cut - offs and 2D NMR imaging (D-T2 or T1-T2 maps).

2. Global Orbital Remote Sensing (Passive RSS-NMR Surveying)

The integration of RSS-NMR technology allows for the combination of deep exploration and remote analysis of hydrogen relaxation (up to 7 km). Targeting is based on the Larmor frequency variation, and the returning radio frequency signal serves as a direct physical signature.

The operational methodology of "Stage Zero" is as follows:
1. Global Orbital Scan: Passive satellite mapping of a large area without any ground presence or impact. 2. Anomaly Filtering: Elimination of short T2 zones (dense or clayey matrices). 3. Fluid Marking: Isolation and characterization of long-term fluids (light oil via $T1/T2 \approx 1\text{-}2$; gas via long T1/short T2). 4. Surgical Focusing (Sweet Spots): Precise delimitation of target areas to concentrate heavy seismic activity or drilling exclusively on confirmed potentials.

This approach eliminates the need for systematic and destructive seismic acquisition over an entire block, guarantees absolute discretion (passive mode) and optimizes the rapid reassessment of satellite reservoirs in mature fields.

cut -off threshold of T2 longer in carbonates (~92 ms) than in sandstones (~33 ms)?

The cut-off threshold (T2 cut -off) is the limiting time constant that allows the hydrodynamic separation of bound water (located in the microporosity, unproductable) from free water (located in the macroporosity, mobile and usable). The major difference observed between sandstones (

siliciclatic) and carbonates (limestones, dolomites) stems directly from the fundamental equation of surface relaxation:

$$1 / T_2 \approx \rho_2 \cdot (S / V)$$

Where ρ2 is the surface relaxivity of the solid mineral, $_{S\ \text{the}}$ *pore area and V its volume.*

• The $_{\text{lower}}$ surface relaxivity (ρ2) of carbonates: Sandstones intrinsically contain clay minerals as well as traces of iron oxides or other heavy metals. These elements possess paramagnetic properties that strongly accelerate the relaxation of protons upon contact (high ρ2). Conversely, pure carbonates (calcite, dolomite) are chemically much "cleaner" and free of paramagnetic centers. Their surface relaxivity ρ2 is therefore 2 to 3 times lower than that of sandstones.

• The mathematical impact on the T2 spectrum : Since the relaxivity ρ2 is lower in calcite; protons in fluids take longer to relax mechanically for an identical pore geometry (S/V). Thus, water retained by capillary action in the microporosity of a carbonate will exhibit an extended T2 (up to ~92 ms) before it can be considered a free fluid, requiring the cutoff point to be shifted towards longer times.

4. The impact of pyrite on the NMR analysis of reservoirs

Pyrite (FeS2) is a conductive and highly paramagnetic, even ferromagnetic, metallic iron sulfide. While its effect on electrical resistivity logs is documented, it critically disrupts NMR measurements via two distinct mechanisms:

• Generation of strong local magnetic field gradients: Under the application of the tool's main magnetic field (B0), the pyrite grains become intensely magnetized. The significant disparity in magnetic susceptibility between these metallic grains and the surrounding fluids generates substantial local field gradients (Ginterne). These micro-local gradients drastically accelerate depolarization by molecular diffusion, artificially shortening the measured T2 time:

$$1/T^2{}_{,\ \text{measured}} = 1/T^2{}_{,\ \text{surface area}} + 1/T^2{}_{,\ \text{volume}} + (\gamma^2 \cdot {}_{\text{internal}}\ G^2 \cdot TE^2 \cdot D) / 12$$

petrophysical interpretation :
- Underestimation of pore size: The peaks of the T2 spectrum are artificially shifted to the left (short times). A large producible pore may be mistakenly classified as a micropore.
- Overestimation of bound water (BVI): As the signal shifts below the historical cutoff , the volume of irreducible water is overestimated at the expense of mobile hydrocarbons.
- Signal attenuation: If the phase shift is faster than the minimum echo time (TE) of the probe, the NMR signal of a pyritic zone may be completely masked.

5. Evaluation of intrinsic permeability by NMR

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NMR offers the unique advantage of calculating continuous permeability from the complete pore size distribution, rather than relying on overall empirical porosity/permeability correlations. Two reference formulations dominate the industry:

Coates model (Free Fluid Model)
Preferred in sandstones and simple intergranular structures, it is based on the ratio between the mobile fluid and the bound fluid:

$K_{\text{Coates}} = (\phi / C)^4 \cdot (\text{FFI} / \text{BVI})^2$

Where ϕ is the total porosity, FFI (Free Fluid Index) the area beyond the cut -off, BVI (Bound Volume Irreducible) the area below the cut -off, and C a local calibration constant.

B. The SDR (Schlumberger Doll Research) model
, based on the geometric mean of the T2 spectrum (T2 ,log), proves to be particularly sensitive to the presence of interconnected macropores:

$K_{\text{SDR}} = a \cdot \phi^4 \cdot (T_{2,\log})^2$

Where 'a' is a coefficient related to the type of rock matrix.

6. Limits and solutions for complex structures (Carbonates)

In heterogeneous carbonates (dual porosity: microporous matrix + isolated vugs or fractures), these standard models bias the analysis. A large, unconnected pore (vug) will exhibit a very long T2; the SDR model will then calculate a completely erroneous giant permeability, ignoring the impermeability of the surrounding matrix.

To circumvent this, modern interpretation incorporates variable T2 cut - offs as well as two-dimensional NMR imaging (D-T2 or T1-T2 maps) to decouple the geometric size of the pores from their actual fluid connectivity.

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