Complete Technical Synthesis: NMR Physics and Reservoir Exploration

Principles of hydrogen relaxation, heterogeneities of rock matrices and passive orbital methodology

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 it takes 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 T1 relaxation time (longitudinal relaxation):
  - Definition: This is the characteristic time (expressed in seconds) required for the hydrogen magnetization to return to 63% of its initial equilibrium value after excitation. It corresponds to the repulsion of the magnetization along the axis of the main magnetic field. - Mechanism: Hydrogen protons release the energy they have absorbed by transferring it to their immediate molecular environment (the lattice). - In MRI: The T1 signal is used to create anatomical contrast. It depends on the tissue: water-rich tissues (such as cerebrospinal fluid) have a long T1 signal, while fatty tissues have a short T1 signal.
- T2 relaxation time (Transverse Relaxation):
  - Definition: This is the characteristic time (expressed in milliseconds) after which the transverse magnetization (perpendicular to the magnetic field) has decreased to 37% of its maximum value. It represents the loss of coherence or the phase shift of the protons relative to each other. - Mechanism: This phenomenon is due to the interactions of the protons with each other (spin-spin interactions). - In MRI: The T2 is always much shorter than the T1. It allows for images where fluids appear very bright (such as edema or cerebrospinal fluid).

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 is measured by the time constant T2*.

$$1 / T2^* = 1 / T2 + 1 / T2_{,\ inhomogeneous}$$

• The mechanism: The loss of proton coherence is accelerated by inhomogeneities in the main magnetic field (B0). These inhomogeneities can be intrinsic to the magnet or induced by differences in magnetic susceptibility at the interfaces of the medium (for example, between the solid rock matrix and the fluids it contains).
• Reversibility: Unlike true T2, which depends on random and irreversible molecular collisions, the phase shift related to inhomogeneities (T2 ,inhomogeneous) is fixed and static. It can be compensated and "canceled" by applying recentering pulses (as in a Spin Echo sequence).

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

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The cut-off threshold (T2 cut-off) is the limiting time constant that allows the hydrodynamic separation of bound water (located in the microporosity, non-productive) from free water (located in the macroporosity, mobile and usable). The major difference observed between sandstones (~33 ms) and carbonates (~92 ms) stems directly from the fundamental equation of surface relaxation:

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

• The lower surface relaxivity ($\rho 2$) of carbonates: Sandstones naturally contain clay minerals as well as traces of iron oxides or heavy metals with paramagnetic properties that strongly accelerate proton relaxation upon contact. Conversely, pure carbonates (calcite, dolomite) are much less free of paramagnetic centers. Their relaxivity $\rho 2$ is 2 to 3 times lower than that of sandstones, which mechanically slows down transverse relaxation and shifts the cutoff time to longer times (~92 ms).

4. Mineralogical Impact of the Crisis: Presence of Pyrite (FeS2)

Pyrite is a conductive and highly paramagnetic metallic iron sulfide. Under the application of the tool's B0 field, the strong disparity in magnetic susceptibility between these metallic grains and the fluids generates significant local field gradients (Ginterne). These micro-gradients drastically accelerate depolarization by molecular diffusion, artificially shortening the measured T2 time.

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

Direct consequences for interpretation:
- Underestimation of pore size: The peaks of the T2 spectrum migrate to the left (short times), mistakenly classifying large mobile pores as micropores. - Overestimation of bound water (BVI): 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 may be completely masked.

PART II: QUANTIFICATION OF PERMEABILITY AND PASSIVE ORBITAL STRATEGY

1. Modeling of Intrinsic Permeability using NMR

NMR calculates continuous permeability from the complete pore size distribution using two reference models:

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

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Limitations in complex structures: In heterogeneous carbonates (isolated giant pores or 'vugs'), the fluid exhibits a very long T2. The SDR model then calculates an immense permeability, which is completely erroneous. Modern interpretation therefore uses variable T2 cut-off points and 2D NMR maps (D-T2 or T1-T2) to isolate the actual connectivity.

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

In large-scale passive observation, the combination of depth searching and hydrogen relaxation allows for the marking of deposits at a distance (up to 7 km). Depth calibration is achieved by varying the Larmor frequency ($\omega_0 = \gamma \cdot B_0$). Once the pulse is cut off, the spectral signature of the returning radio frequency signal serves as a direct physical descriptor.

• Operational Methodology of “Step Zero”:
1. Global Orbital Scan: Passive satellite mapping of a large area without any physical presence on the ground. 2. Anomaly Filtering: Immediate elimination of short T2 zones (dense or clayey matrices of no interest). 3. Fluid Marking: Isolation of long T2 signatures (mobile fluids) and characterization (oil via T1/T2 ≈ 1-2; gas via long T1/short T2 by diffusion). 4. Surgical Focusing (Sweet Spots): Precise delimitation of target areas. Heavy seismic or drilling campaigns are thus concentrated exclusively where the presence and mobility of hydrocarbons are confirmed.

This approach eliminates the need for systematic blind seismic acquisition, drastically reduces costs, has zero environmental impact (discrete/invisible mode) and allows for the rapid reassessment of mature fields without interruption of production.

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