Permeability Estimation Through Integration of Velocity, Resistivity, and Pore Geometry

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Key Points

- Pore network geometry (size, shape, connectivity) is fundamental for accurate permeability estimation in complex carbonates
- Integration of acoustic velocity which contains insights regarding pore size and complexity through pore stiffness and compressibility and electrical resistivity which contains indications regarding pore connectivity and tortuosity provides a more complete, superior, pore system characterization.
- The most significant improvements in permeability estimation come from combining acoustic, resistivity, and quantitative pore geometry to capture carbonate heterogeneity.

Significance

The limitations of conventional permeability estimation methods in heterogeneous systems provide less than desirable results and require improvements because the implications of better permeability predictions are extensive for:

- **Hydrocarbon Recovery:** Enhanced models optimize well placement, hydraulic fracturing, and waterflooding.
- **Energy Transition:** Accurate forecasts are crucial for Carbon Capture and Storage (CCS) CO_2 injectivity/containment.
- **Environmental Management:** Permeability maps from geophysical data guide groundwater extraction, contamination remediation (e.g., Floridan Aquifer), and mitigate environmental risks by predicting fluid migration and fracture propagation.

The workflow presented here bridges the gap between pore-scale observations and reservoir-scale properties. Future research will focus on developing rock physics templates for carbonates to further advance resource exploration.

Methods and Results

Permeability estimation is critical for subsurface resource management but is notoriously challenging in carbonate reservoirs due to heterogeneous pore systems. Traditional core and log methods often fail to capture the complex interplay between pore geometry, mineralogy, and fluid flow. This work synthesizes research on an integrated approach using acoustic velocity, electrical resistivity, and quantitative pore geometry analysis.

In carbonates, pore geometry—not just porosity—is the primary control on permeability. For example, well-connected, large pores in grainstones create high permeability, while the complex microporosity in mudstones results in low permeability. Traditional models like the Kozeny-Carman equation are often limited by this complexity (Berryman and Blair, 1987). However, digital image analysis now enables the quantification of key geometric parameters. The dominant pore size (DomSize) indicates the size of the main flow pathways, while the perimeter-over-area ratio (PoA) measures complexity. High permeability correlates with large DomSize and low PoA, whereas small DomSize and high PoA signify low permeability (Weger et al., 2009).

Acoustic Velocity and Pore Geometry

Acoustic velocity in porous media is governed by the rock's elastic moduli, which is controlled by mineralogy, porosity, and pore geometry. While the Biot-Gassmann theory models velocity, its assumption of homogeneous pores limits its use for complex carbonates. The Extended Biot Theory (EBT) addresses this by incorporating pore geometry through parameters like the frame flexibility factor (γ_k) (Sun, 1994). Low γ_k values indicate large, well-connected pores that increase stiffness and velocity, while high γ_k reflects isolated pores that reduce them (Sun et al., 2001; Weger et al., 2023).

This link between velocity and pore geometry enables permeability estimation. The velocity deviation (ΔVp) from empirical equations correlates with pore types and permeability: high positive deviations indicate low-permeability zones with isolated pores, while negative deviations signify high-permeability, interconnected systems Anselmetti and Eberli (1993). For example, moldic carbonates with isolated pores exhibit positive deviations (ΔVp>0) due to their stiff rock frames, while rocks with connected microporosity show negative deviations (ΔVp<0).

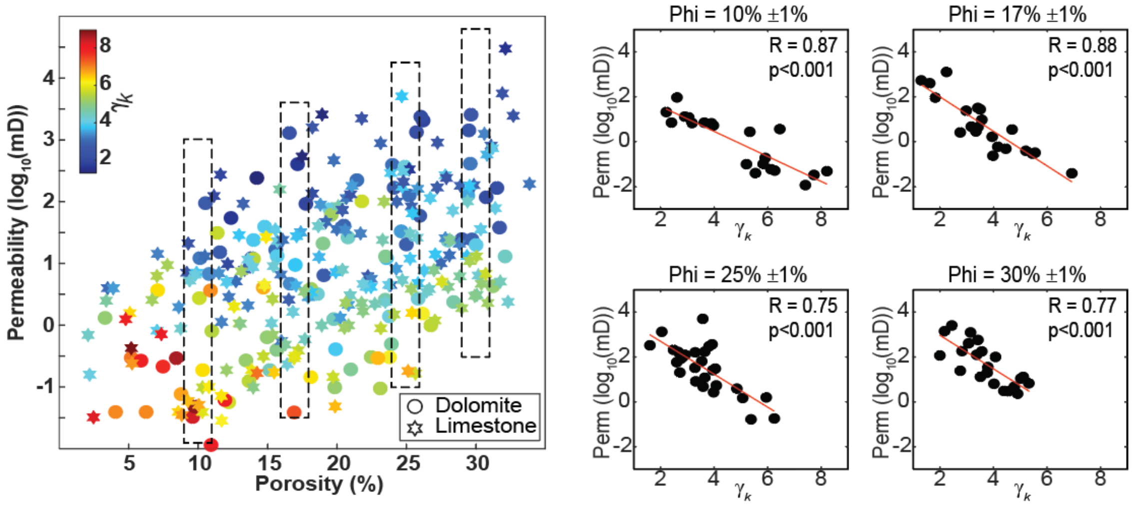

Figure 1: (left) Permeability vs. porosity of limestone and dolostone samples showing substantial variability of permeability at any given porosity and no well-defined correlation exists. Superimposed in color are the EBT parameter γ_k. Higher values of γ_k, represent smaller pores and a more complex pore system. (right) Correlations between permeability and γ_k within small ranges of porosity (dashed boxes on the left) illustrate that low permeability and γ_k are inversely correlated.

A notable exception to the permeability-velocity relationship occurs in oomoldic carbonates. These rocks contain large, spherical pores (ooid molds) that enhance acoustic velocity by reducing pore compressibility, mimicking the response of low-porosity, high-stiffness rocks. However, if the molds are unconnected, permeability remains low despite high velocity. (Lucia, 1995) classifies such systems as "separate-vug porosity," emphasizing the need to differentiate effective (connected) and ineffective (isolated) porosity in permeability models. For example, in the Cretaceous Shuaiba Formation, oomoldic grainstones with 25% porosity exhibited velocities comparable to low-porosity mudstones, yet permeabilities <10 mD due to poor pore connectivity (Smith et al., 2003). This paradox highlights the importance of complementary datasets, such as electrical resistivity or NMR logs, to identify non-producing zones with high velocity but low permeability.

Electrical Resistivity and Pore Geometry

Laboratory measurements of electrical resistivity in rock samples are crucial for interpreting reservoir properties and geophysical data. These measurements are influenced by various factors, including temperature, pressure, and wettability (Akbar et al., 1995; Wei and LIle, 1991).

Archie's law (F = φ^-m) is fundamental, relating the formation factor to porosity and the cementation exponent (m), which quantifies pore tortuosity. In carbonates, m varies significantly (1.7–4.0) with pore type: low values (1.8–2.2) indicate well-connected interparticle pores, while high values (2.5–4.0) reflect isolated vugs or microporosity (Verwer et al., 2011).

Digital Image Analysis (DIA) parameters strongly correlate with resistivity. A high perimeter-over-area ratio (PoA), signifying complex pores, often leads to larger number of connections and lower resistivity due to enhanced ionic pathways. Microporosity presents a key complexity; it creates low resistivity but contributes little to permeability if the pores are disconnected (Ehrenberg et al., 2006; Verwer et al., 2011).

Resistivity-derived permeability models, like those incorporating m and separate-vug porosity, can achieve good accuracy. However, their effectiveness relies on robust pore-type classification (Ramakrishnan et al., 1998; Smith et al., 2003). Recent advances show that integrating m with DIA parameters like PoA significantly improves permeability predictions by directly quantifying pore geometry, highlighting the power of combining electrical and geometric data for reservoir characterization (Weger et al., 2009; Weger et al., 2023).

Integrating Acoustic and Resistivity Data

Combining acoustic and resistivity data leverages their complementary sensitivities: velocity reflects pore stiffness, while resistivity highlights connectivity. Acoustic based estimation frameworks, such as those developed by Sun (2001) and Weger et al. (2023) solve for pore geometry parameters (f_k, γ_k) that directly correlate to pore geometry. For example, Dou et al. (2011) used EBT-derived γ_k and Archie's m to map permeability trends in a Permian Basin reservoir, achieving a correlation coefficient of r=0.85 with core data.

Machine learning algorithms trained on multi-physics datasets (acoustic, resistivity, DIA) show promise in predicting permeability. For instance, Al Khalifah et al. (2020) used neural networks incorporating Vp, Rt, and PoA to predict permeability in a Saudi Arabian carbonate field, achieving R^2=0.85.

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