

Integrated workflow: identification of non-matrix permeability features and their impacts on reservoir management of pre-salt fields

Introduction

Pre-salt carbonate reservoirs are characterized by extreme heterogeneity. Their production behaviour is controlled not only by matrix porosity and permeability but also by non-matrix permeability features such as faults, fractures, connected vugs, karstified intervals, and localized conductive corridors. The early identification of these features is crucial because they may substantially improve well productivity while also accelerating water or gas breakthrough and increasing uncertainty in sweeping efficiency and pressure support.

The study area is characterized by a highly faulted pre-salt carbonate field, where the diagenetic imprint largely controls permeability distribution. Well data have shown that some intervals show significant silicification associated with non-matrix features. The main goal of this work is to present an integrative workflow (Figure 1) that accounts for well logs analysis, elastic inversion results and facies probabilities analysis. The workflow is set to identify areas with high probability of non-matrix permeability features and how those results can be integrated into reservoir management workflows. This study does not claim that inversion can directly image exhaustively non-matrix features, many of which occur below seismic resolution, but rather demonstrates that inversion-derived elastic properties and related products can improve the detection of areas with excess permeability. The final value of the workflow lies in reducing uncertainty for well placement, completion design, geomodelling, and flow-simulation scenario building.

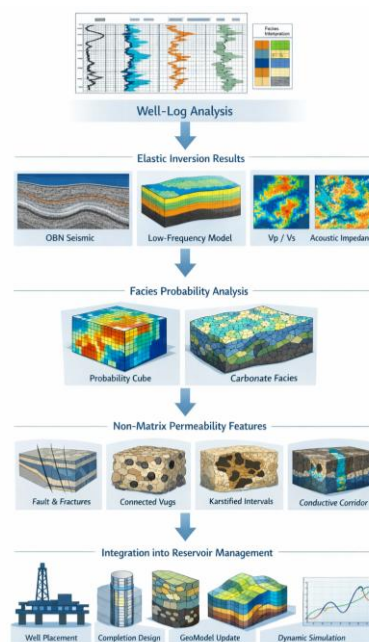


Figure 1: Schematic illustration of the proposed integrative workflow for non-matrix features characterization

Well log analysis

Well log editing was performed with the commercial software Interactive Petrophysics (IP®) prior to any petrophysical interpretation. The density log (RHOB) was quality-controlled against the caliper log to identify washout-affected intervals, where borehole enlargement causes unreliable bulk density readings. The compressional (DT) and shear (DTS) sonic logs were similarly reviewed for cycle-skipping artefacts and noise. Identified spikes were removed from all three curves (Ellis & Singer,

2007). Problematic intervals — primarily washout zones in the RHOB and isolated bad data in the DT and DTS — were replaced with synthetic values derived from established empirical relationships with other available logs. For wells with measured sonic logs, compressional and shear velocities (V_p and V_s) were calculated directly from the edited DT and DTS logs (Mavko et al. 2020). This editing step is critical to ensure that the log-derived petrophysical properties used as input to the elastic inversion workflow are representative of true formation properties rather than borehole conditions (Serra, 1984).

Log based permeability typically estimates matrix permeability of the rock. Drill stem tests (DST) estimate the effective permeability of the tested rock interval. The difference between the DST permeability and the log-derived permeability is therefore an indicator of the tested interval's excess permeability. In the study area, DSTs with higher excess permeability correlate well with intervals showing higher silicification. These intervals also correlate well with non-matrix features identified in image logs.

From the available well data, an association of silicified intervals with major faults seems likely and is one of the underlying assumptions of the method. The working hypothesis is that the faults were a main conduit for fluids that contributed to the silicification of certain intervals. The difference in stiffness between the silicified intervals and the host carbonate rock may have led to the development of weakness surfaces along the borders of these two lithotypes through subsequent tectonic activity. Additionally, tectonic activity would also have enabled the circulation of hydrothermal fluids prone to stimulate carbonate dissolution, thus creating a set of non-matrix features strongly associated with silicification (Fernández-Ibáñez et al. 2022, Mimoun et al. 2022). The association of silicification with non-matrix features is convenient because some logging tools provide an estimate of the rock's mineralogy. We classify as non-matrix any interval with a silica-log volume of 20% or higher. This value generally differentiates well the highly silicified non-matrix prone intervals when comparing image logs with silica log.

Elastic seismic inversion

Elastic inversion was performed using Ocean Bottom Nodes (OBN) seismic, well-log, and velocity data. A major challenge in the OBN workflow was the construction of a reliable low-frequency model, as simple inter-well interpolation was inadequate. This limitation was addressed by integrating well data with seismic velocity (Pendrel 2015), which was calibrated to the wells, transformed into S-velocity and density, and subsequently recalibrated to derive the final elastic properties (Figure 2). Constrained by well control, this workflow improved the robustness, stability, and geological consistency of the inversion results, yielding a more reliable V_p/V_s estimate.

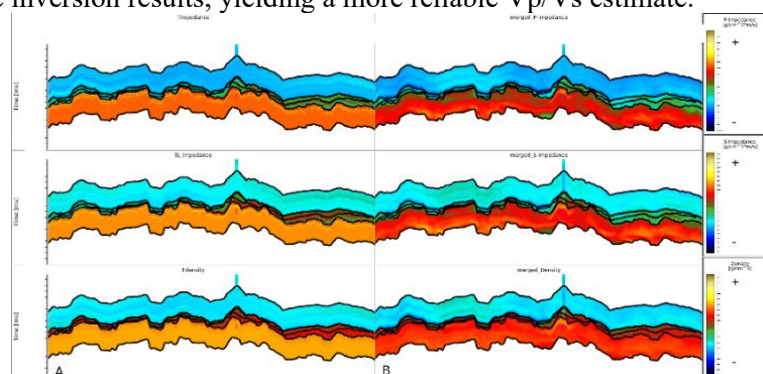


Figure 2: Difference between Low Frequency Models. A) simple inter-well interpolation; B) using P-Wave velocity volume as a constraint

A deterministic Constrained Sparse Spike inversion was subsequently applied. Quality control, based on comparisons with well logs, cross plots, and maps, demonstrated consistent and robust results,

supporting improved field characterisation. The inverted outputs, namely P-impedance, S-impedance, and V_p/V_s , were used to enhance the discrimination between matrix and non-matrix intervals.

Facies analysis

Following the classification of wells according to matrix- and non-matrix-dominated behavior, facies probabilities were calculated. The methodology derives facies probabilities from deterministic inversion results and generates probability volumes that incorporate estimated uncertainties associated with facies property overlap, seismic resolution, and noise. Based on Bayesian probability theory, it quantifies the likelihood of a given facies being present at each seismic location. Figure 3 illustrates the probability density function (PDF) used to generate the matrix and non-matrix probability volumes. As the PDFs are highly sensitive, close integration between geological and geophysical interpretation is essential for obtaining robust results.

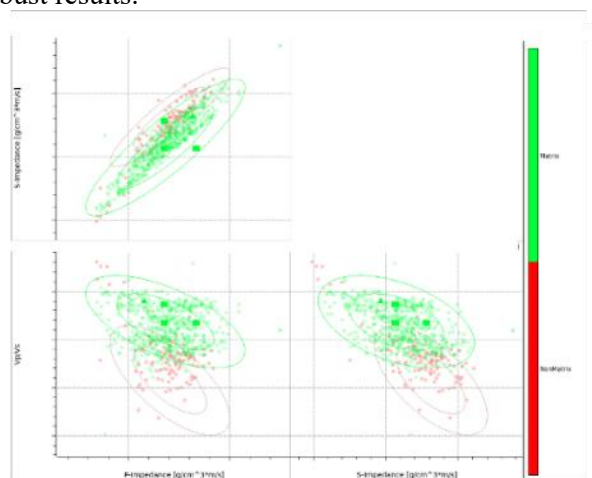


Figure 3: PDFs between P-impedance, S-impedance, V_p/V_s and Matrix and Non-Matrix facies.

The impact of non-matrix permeability features on pre-salt fields reservoir management

Gas breakthrough is one of the major risks for the reservoir management of pre-salt carbonate reservoirs. Reservoir heterogeneity due to non-matrix features drives gas movement by creating preferential flow paths that accelerate gas migration and recirculation. Therefore, breakthrough timing and sweep efficiency are highly sensitive to heterogeneity and non-matrix features. The strong well productivity, observed in these types of reservoirs, drives higher gas production and re-injection, which accelerates gas recirculation through highly connected flow corridors created by the non-matrix permeability features.

One example of the impact of considering the excess permeability layers driven by non-matrix features is their effect on the production forecast. Dynamic modelling demonstrates that accounting for these excess permeability features significantly alters production forecasts, primarily due to enhanced injector–producer connectivity and potential gas channelling, especially near faulted zones. Considering excess permeability layers in dynamic models has a strong impact in the response of the reservoir production forecast over time. This is mainly due to the high connectivity observed between gas injectors and oil producer wells, and may be amplified by the location of wells close to faults favouring gas channelling.

In this type of field gas breakthrough risk must be a priority to be monitored and mitigated. It is important to proactively address early gas breakthrough risks through targeted mitigation measures and enhanced modelling, strengthening operational resilience and value delivery (Kumar et al., 2026). Experience shows that balanced production/injection rates allow controlling GOR in the short-term. However, rate balancing alone is insufficient for long-term control, making integrated subsurface

understanding and flexible operational design essential to optimize recovery and manage gas breakthrough risks. Ways to accommodate the unknowns and provide greater flexibility include installing intelligent completions in gas injectors and oil producers, adopting a water-alternating-gas (WAG) strategy, having relief gas wells strategically located away from oil producing hubs and manage balanced production/injection rates.

Conclusions

This study highlights that the identification of non-matrix permeability features in pre-salt carbonate reservoirs is most effective when approached through an integrated multidisciplinary workflow. By combining seismic interpretation, inversion, structural attributes, rock physics, borehole observations, drilling indicators, well tests, and production data, it becomes possible to better constrain the spatial distribution of domains associated with excess permeability and enhanced connectivity. Empirical evidence shows that silica is associated with non-matrix features. Given the correlation between seismic inversion attributes and silica, seismic inversion provides valuable support by enhancing the prediction of these non-matrix features. The resulting reduction in uncertainty has clear implications for reservoir management, contributing to a better assessment of breakthrough and sweep risks, well placement, optimized completion and injection strategies, and more focused surveillance. In complex pre-salt settings, the greatest value lies in the integration of complementary datasets and disciplines, with seismic inversion acting as an important component of a broader reservoir-management strategy.

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References

- Pendrel, J. V. [2015] Low frequency Models for inversions-is simple better? GeoConvention 2015
- Fernández-Ibáñez, F., Jones, G. D., Mimoun, J. G., Bowen, M. G., Simo, J. A., Marcon, V., & Esch, W. L., [2022] Excess permeability in the Brazil Pre-Salt: Non-matrix types, concepts and diagnostic indicators
- Mimoun, J. G., & Fernández-Ibáñez, F., [2022] Carbonate Excess Permeability in Pressure Transient Analysis: A Catalog of Diagnostic Signatures from the Brazil Pre-Salt
- Ellis, D.V. & Singer, J.M. [2007]. Well Logging for Earth Scientists, Springer
- Kumar, R. & Sha, Foo & Asykin, Nurul & Salleh, Zaimi & Othman, Mohamad. [2016]. Improvement in Oil Recovery Through Pro-Active Reservoir Management for a High Value Asset – A Case Study. 10.4043/26472-MS
- Mavko, G., Mukerji, T. & Dvorkin, J. [2009]. The Rock Physics Handbook, Cambridge
- Serra, O [1984]. Fundamentals of Well-Log Interpretation, Elsevier
- Pendrel, J. V.[2014]. Low-frequency models for seismic inversions: Strategies for success.