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EA Integrated Seismic-Log-Core-Test Fracture Characterization, Barra Velha Formation, Pre-salt of Santos Basin*

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Abstract

Several wells drilled in the Barra Velha Formation, Santos Basin, Brazil, confirmed the presence of fractures mainly through image log and coring. In order to assess the best development plan for the field, forecast productivity and match dynamic data, a DFN model was built based on fracture characterization studies. The DFN model was used to estimate fracture permeability in the reservoir 3D model. This study presents a methodology to model fractures through a robust reservoir characterization. Integration of seismic data, rock core description, logs, and well tests were essential steps for a reliable 3D permeability model of fracture networks.

Introduction

Discontinuities such as faults and fractures are important heterogeneities that must be investigated during characterization process and usually confer to reservoir distinct flow behavior when compared to reservoirs that produce only from matrix. These discontinuities must be considered during reservoir modelling process to assure robustness of production forecast obtained from the geological models and to allow improvement of production development plans.

Located in Santos Basin, Brazil, the Barra Velha Formation is the most important reservoir unit for the Santos Basin Pre-salt oil fields. High permeabilities (>3 Darcy) were verified in well tests performed inside geological features known as carbonatic mounds, mainly due to high fracture intensities and carbonate dissolution. These highly fractured regions were firstly identified through resistive and acoustic image logs. Several subsequent wells brought new information over this fractured reservoir through extensive core data (160m), well tests and good quality well logs confirming large presence of fractures, karstification, and outstanding reservoir productivity.

The main reservoir interval corresponds to lacustrine carbonate successions from the Aptian Barra Velha Formation, localized at an average depth of 5200m. Diverse permo-porosities qualities are found, reflecting the different conditions and environments of tecto-sedimentation. Nonetheless, structural highs and fault zones exhibit the best reservoir conditions, especially within cone-like structures interpreted as carbonate mounds. Geologically the area is inserted in a region of very complex structuration (Dehler et al, 2016; Rigoti, 2015; Magnavita et al., 2010), and syn-sedimentary tectonism have been recognized. During deposition of the Barra Velha Formation, some structural reactivations took place, allowing recognition of several different deformation phases for this reservoir.

Two reservoir types were recognized based mainly on seismic facies, matrix permo-porosity quality, and fracture intensity differences: (1) Carbonate Mound – characterized by chaotic seismic facies, very permeable carbonatic reservoir, formed by association with faults and fractures. (2) Low energy plains – characterized by parallel reflectors seismic facies, with moderate permeabilities (~10-100mD) and rare fracture occurrence. Well A in carbonate mounds and Well D in low energy plains were respectively drilled to identify these differences (Figure 1). These different types of lacustrine reservoirs, especially lacustrine mounds, have morphological similarities with recent analogues such as deposits encountered in Lake Abhe, Ethiopia (Dekov et al. 2014), Pyramid Lake, USA (Benson, 2004) or Lake Bogoria, Kenya (Renaut et al. 2013).

Well tests have identified permeabilities ten times higher than those calculated by logs and core data. It was observed several fracture features in logs of different boreholes, justifying the interpretation of an extensive permeable fracture framework that adds permeability over reservoir matrix.

Objective

To provide a reliable input for double-porosity/double-permeability (2Phi/2K) flow simulation and field production forecast, this study integrates all available data among well logs, cores, well tests, and seismic into the fracture modelling process. The study aims to build a DFN model and grid-based fracture properties to support more accurate flow simulations.

Methodology

To properly match the dynamic data while modelling this type of reservoir, fractures were managed in a separated workflow from matrix. This yielded two groups of grid-based properties (matrix + fractures). This study focus is only on the fracture characterization and fracture modelling processes.

The fracture characterization method initiates by interpreting all fractures features in boreholes acoustic and resistive image logs. The interpretation is used to build fracture intensity logs (P32) for each well and to acquire relevant structural data, used afterwards for conceptual model. The available cores had their structural features classified in types (joints, veins, or shear fractures) and attitudes measured. The cores were also the only source of fracture opening data. To statistically extrapolate measured fracture intensity data from well to further regions, seismic attributes were used, acting as secondary variable for co-kriging in 3D statistical simulation of fracture intensities through the field model. In addition, based on seismic facies and conceptual models, a discrete grid-based 3D property was built to separate reservoir types with distinct fracture behavior. Each of these regions were populated with fracture intensities, fracture orientation data, and opening of closest wells. This method honors data from borehole as an input for the discrete fracture network modelling (DFN) process. After the construction of the DFN, fracture permeabilities were upscaled to reservoir grid using Oda Method (Oda, 1985). For last, it performed an adjustment to flow capacity observed in well tests (Figure 2).

Input Data

Mound regions are intensely fractured reservoirs, showing some dissolved fractures and vuggy intervals. It is possible to observe average values of 0.5 fractures/m and strong orientation for the north-east direction. Some rheological control is observed along reservoir column, as low porosity regions tend to show more fractures than high porosity intervals (Figure 4). In low energy plain regions, fractures were not observed. The absence of fractures in this case was observed both in logs and core.

In terms of core data, it was possible to perform a structural description to identify veins, vuggy fractures, shear fractures, and joints. Some of the cores were azimuth-oriented making possible to acquire fracture orientation data from cores also, confirming orientation previously mapped in image logs and reservoir types previously identified in seismic (Figure 3). The average strike direction for the fractures is around N25°E, although other less often directions occur. Fracture openings measured in cores are averaged around 0,5mm.

A geophysical machine learning study, based on Hampson et al., 2001 technique, was conducted to create a seismic attribute using multi-azimuthal seismic data available for the area. Through multi-attribute prediction using curvature, anisotropy gradient, seismic amplitude, and well fracture data, it was possible to create a 3D fracture intensity attribute, that was used in geological modelling. The attribute had a good fit to well data and also identified different fracture intensity regions.

To avoid non-consistent geological models, a conceptual model for the reservoir structural evolution and fracture occurrence was built. This is an essential part of fracture modelling workflow and is usually the moment where the data is integrated for better understanding of reservoir characteristics and history.

Both formation tests and an extended well test were available. The flow capacity calculated from it was used to calibrate the fracture permeability model. Three formation tests and one extended well tests were used in total.

Fracture Modelling

The first step for the fracture characterization in the field was image log fracture interpretation. From this interpretation, it was possible to build P32 fracture intensity logs, that have been used as the main input data to statistically model fracture intensities through the field. A sequential gaussian simulation (SGS) was performed to build a 3D model of the fracture intensities using image log data interpretation as input. A seismic-based fracture intensity attribute was used as secondary variable in the statistical simulation. Reservoir type regions were inputted in the simulation as a discrete property, to separate fractured from non-fractured regions, assigning to each one of these regions different statistics depending on respective well results.

The SGS generated a 3D fracture intensity model used as input for a DFN (discrete fracture network) modelling process, available in a commercial software. The DFN was built individually for each reservoir type region, in such way that each region would have its own statistical data regarding fracture intensity, orientation, and opening. For all regions, a fracture opening of 0.5mm was initially applied, based on core data. This value was changed a little to match well test permeabilities but worked fine to adjust some wells without any variation. Permeability values were upscaled from the DFN model to grid-based properties using the Oda method (Figure 5).

Conclusion

To properly characterize this fractured reservoir and calibrate fractures permeability values, the study had to integrate all available data. Core data may be used to assess size of fracture openings in the reservoir. The size of the openings measured in the cores yielded permeabilities close to what was verified in well tests and suffered small adjustments to fit the flow capacity. Although some cored fractures may have been uncompressed in their way to the laboratory, the openings from the cores are already a very good approximation to subsurface state.

Seismic attributes were very important to extrapolate the fracture intensity data and to define different reservoir types along the field. It played an important role in assisting fracture intensities estimation far from wells, when used as secondary variable.

Because the most relevant data is well fracture interpretation, it is of major importance to care about image log quality. A good image log interpretation will generate reliable fracture intensity logs, and thus a more accurate fracture porosity and permeability estimations.

At last, fracture permeability models should be calibrated to well test data, to match production history, and avoid anomalous permeabilities as result.

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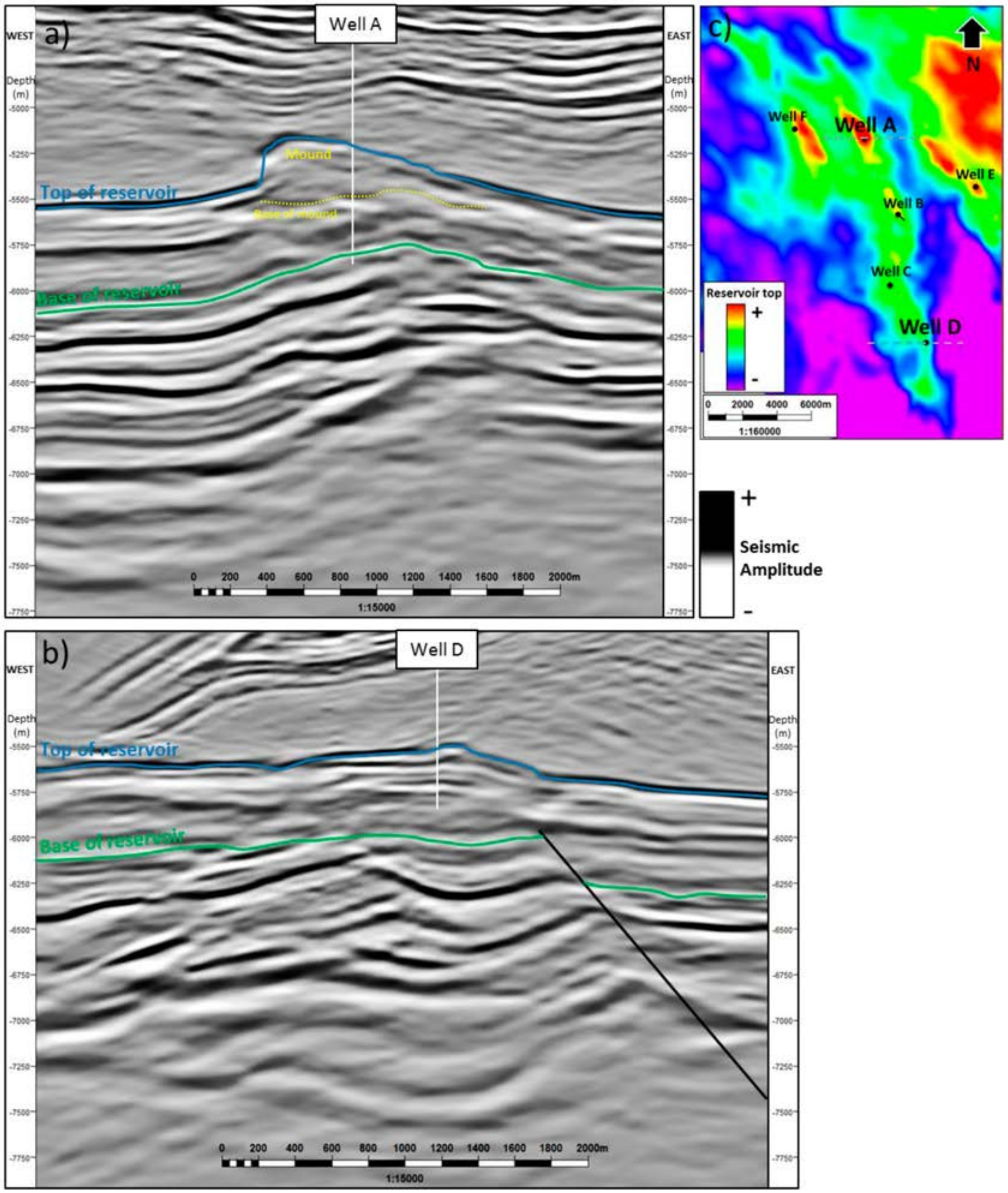


Figure 1. Seismic section crossing wells A and D. A) Seismic section through well A showing carbonate mound reservoir type characterized by chaotic seismic facies. B) Seismic section through well D showing low energy plain reservoir type, characterized by parallel reflectors seismic facies. C) Reservoir top map showing well and section locations.

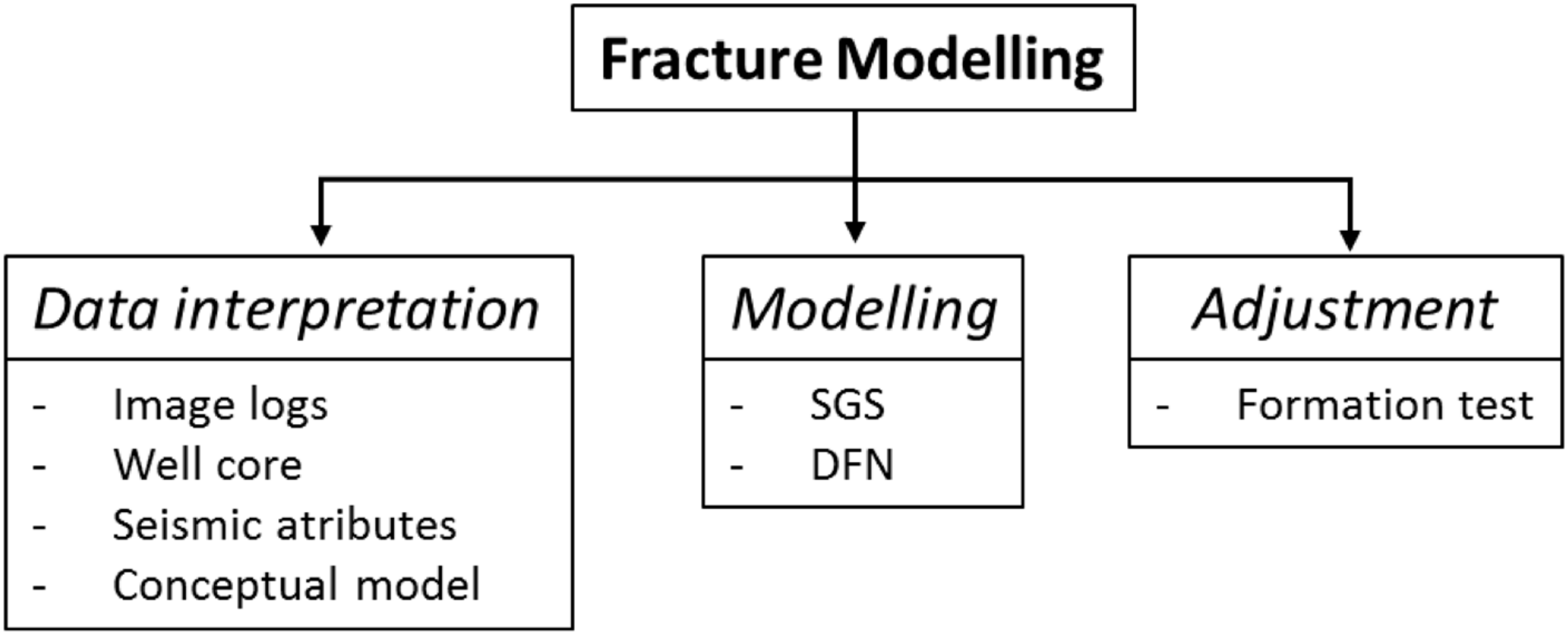
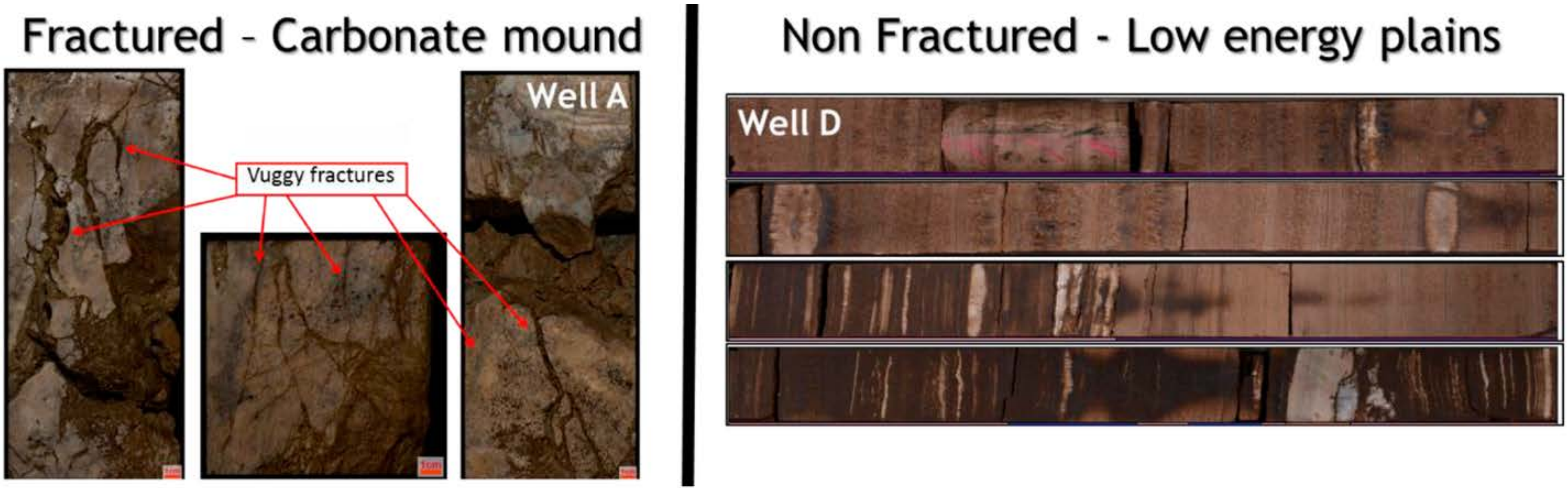


Figure 2. Methodology for integrated fracture model. Data interpretation part should cover all available data of image log interpretations, well core descriptions, seismic attributes, and the geological conceptual model. The modelling part is based on sequential gaussian simulation (SGS) of fracture intensities and discrete fracture networks (DFN). For conclusion, formation tests are used for permeability adjustment of model.


Fractured – Carbonate mound

Non Fractured - Low energy plains

Figure 3. Core data showing different reservoir types. On the left, carbonate mound with vuggy fractures. On the right, non-fractured low energy plains.

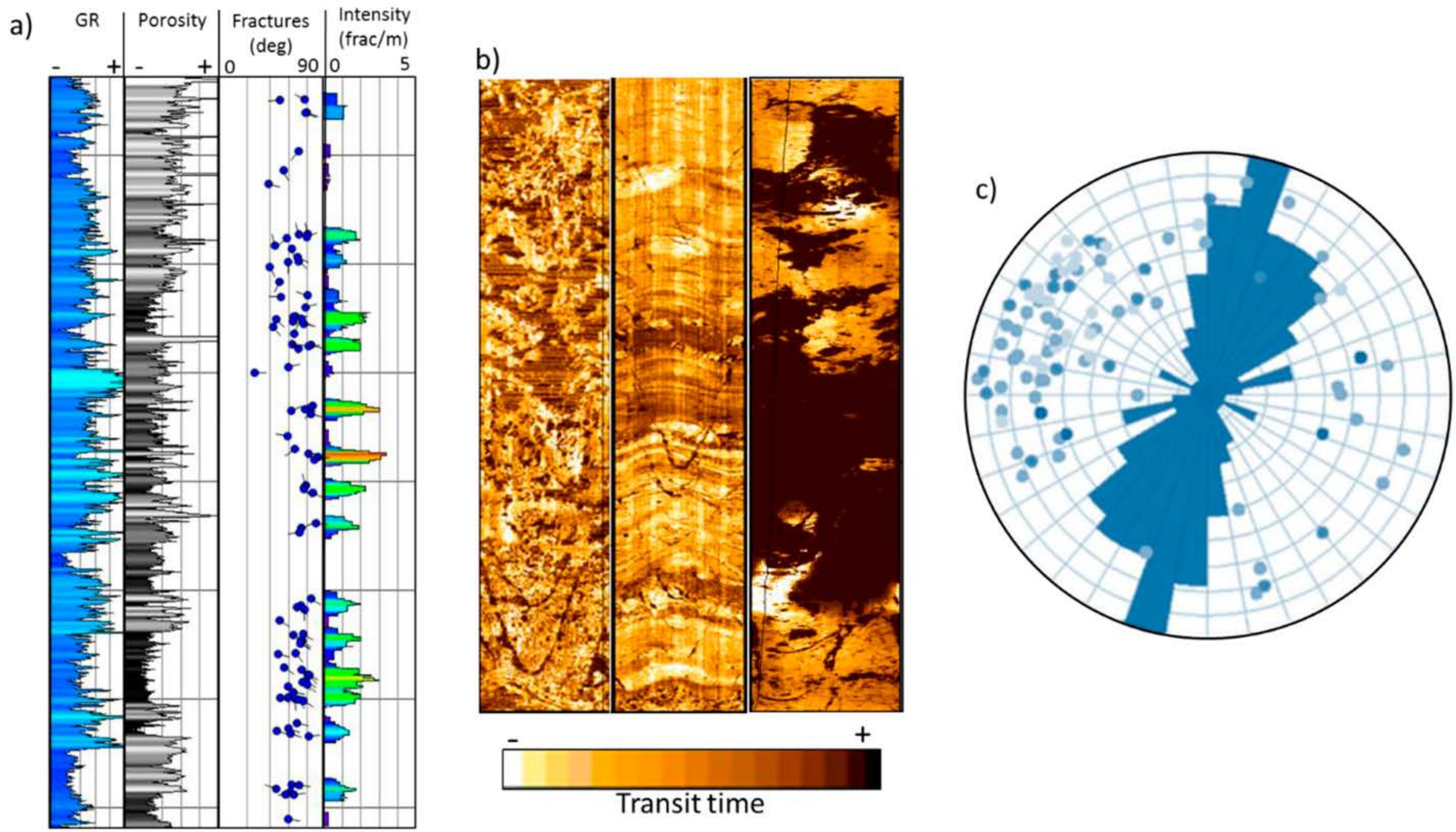


Figure 4. Well A fracture data from mound region. A) Well log data and fracture interpretation; B) Acoustic image logs showing fracture and dissolution features (white: low transit time; black: high transit time); C) Image log fracture rose-diagram.

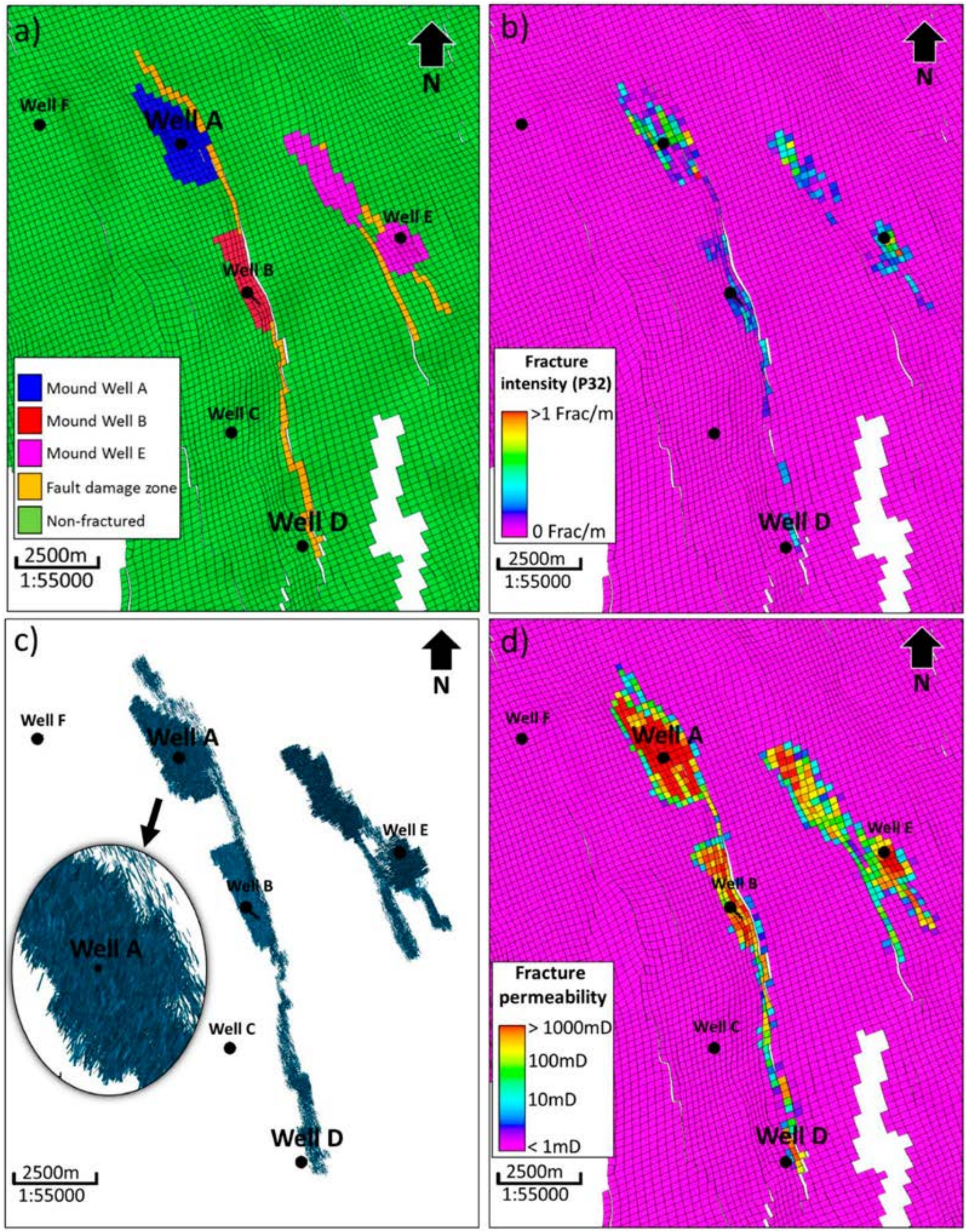


Figure 5. Grid based fracture properties and DFN. A) Discrete reservoir type regions. B) P32 fracture intensity. C) Discrete fracture network (DFN). D) Fracture permeability upscaled with Oda method.