Integrated Multi-Data Fusion Approach for Discrete Fracture Network Modeling in Deep Carbonate Reservoir

Hui Li[1,2]

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[1]SINOPEC Petroleum Exploration and Production Research Institute, Beijing, China
[2]SINOPEC Key Laboratory for Marine Oil and Gas Reservoir Production, Beijing, China

Abstract

Deep carbonate reservoirs exhibit pronounced multiscale heterogeneity, driven by polyphase fault activation and matrix heterogeneity, which governs the stochastic and hierarchical spatial distribution of fracture networks. The construction of high-fidelity discrete fracture network (DFN) models is critical for deciphering fracture propagation mechanisms and mitigating uncertainties in reservoir characterization under conditions of tectonic overprinting. This study proposes a novel multi-constraint fusion framework integrating geological, geomechanical, petrophysical, and 3D seismic datasets, validated through its application to the Feixianguan Formation carbonate reservoir in the Puguang Gas Field, northeastern Sichuan Basin. It employs a multi-data fusion approach, combining geological, geomechanical, well-based and seismic data constraints for DFN modelling. The geomechanical-based data integrates quantitative predictions of fractures based on the tectonic stress field, considering multi-period faults and different matrix types. The geological based data utilises quantitative predictions based on proximity to faults. The well based data uses image logging in conjunction with array sonic logging to predict fractures. The seismic based data uses several fracture sensitive attributes for fracture prediction. The modelling results indicate that fracture development is influenced by the interaction of fault periods, distance from faults and matrix types. Numerical simulation of gas reservoirs using this integrated model shows a 5% improvement in the historical fit rate, providing further validation of its accuracy.

1. Introduction

Tectonic fractures are fundamental pathways in subsurface systems, governing fluid migration in hydrocarbon reservoirs, groundwater circulation, and geothermal energy accumulation. As products of Earth's dynamic tectonic evolution, these fractures are ubiquitous across sedimentary, metamorphic, and magmatic rock formations, where they enhance reservoir permeability by interconnecting otherwise isolated matrix pores. However, predicting fracture networks remains a persistent challenge due to their complex spatial distributions, which often evade resolution by conventional geophysical and seismic methods.

2. Geological setting

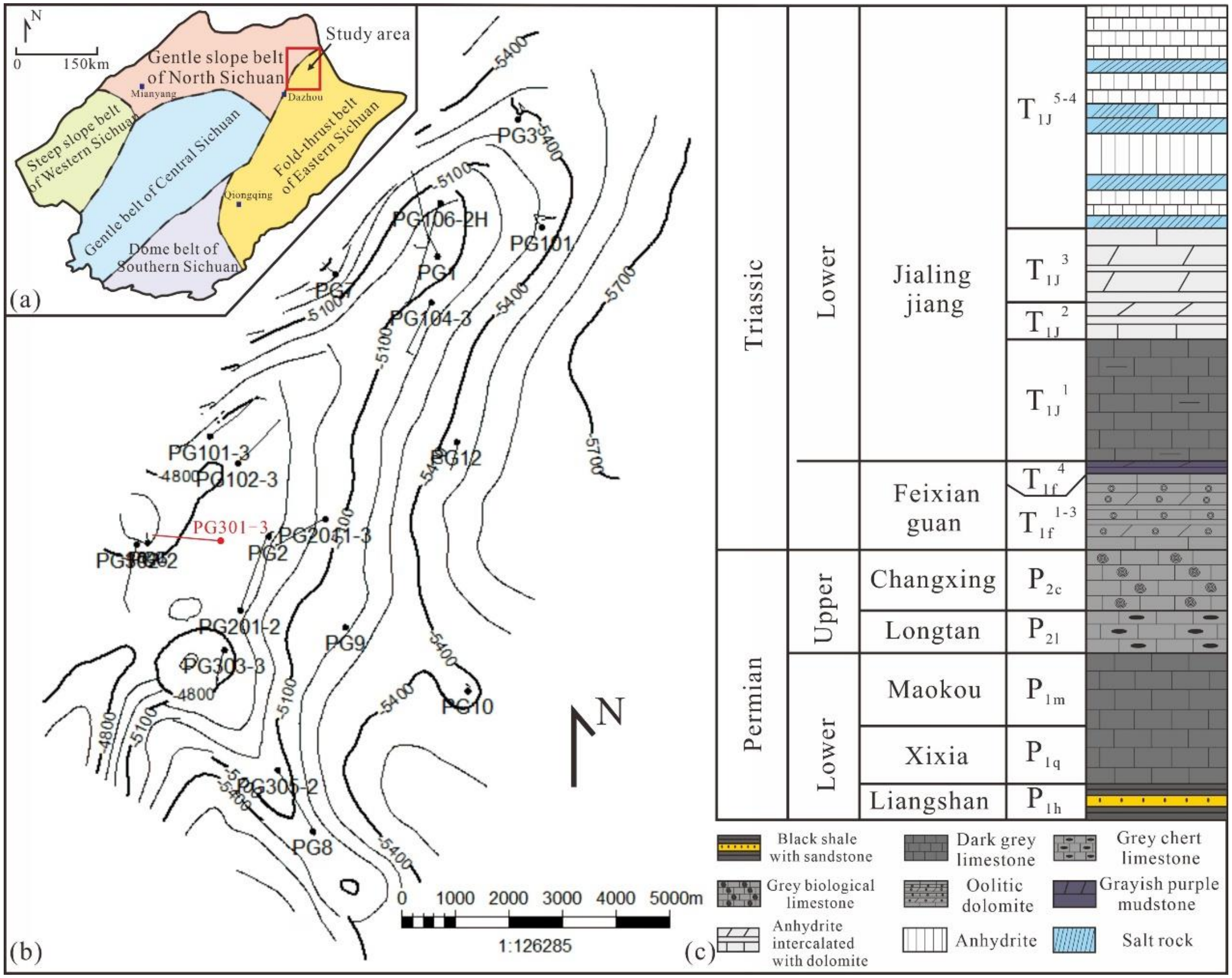

Figure 1. Tectonic setting and stratigraphic distribution of the Puguang gas field. a) Tectonic belt of Sichuan basin. The study area is showed in Figure 1a, located in the northeast of Sichuan Basin, belong to Fold-thrust belt. b) Geological map of the study area showing the structural surface of Feixianguan formation. Black line represents the stratigraphic contour. c) Stratigraphy chart of the study area.

3. Characteristics of natural fracture

Figure 2. Photos of tectonic fractures observed in drilling cores, thin sections and outcrop in the study area. a) High angle fractures with fully filled calcite, PG-2 well. b) Multi-periods fractures intersect with each other, PG104-1 well. c) High angle fracture with unfilled, PG302-1 well. d) scratch on the fracture surface, PG9 well. e) Unfilled microfractures in thin section, PG104-1 well. f) Multi-periods microfracture in thin section, PG104-1 well. g) The first period outcrop fracture filled with calcite. h) The second period outcrop fracture filled with asphalt. i) The third period fracture with unfiled. j) Outcrop multi-period fracture network. k) Outcrop linear tectonic fractures. l) Outcrop full filled linear tectonic fractures.

4. Multi-data fusion approach

Single prediction results often have limitations and uncertainties due to the principles of each method or the quality and resolution of the data. Combining the prediction results of multiple methods and data to form a comprehensive constraint through fusion can improve the modelling accuracy to a greater extent. This method utilizes information entropy to assess the variability of different types of constraints. Higher variability indicates a broader coverage of information within the constraints and greater control over fracture propagation. Conversely, lower information entropy corresponds to higher weights assigned to the constraints. In essence, the entropy weighting method evaluates the weights of constraints by quantifying their influence on controlling fracture propagation through the degree of variation and information entropy.

Data normalization:

$$x_{ij}^{0} = \frac{x_{ij}}{x_j^{\max}}, x_j^{\max} = \max\left(x_{ij}\right), i = 1,2,\ldots,n; j = 1,2,\ldots,m$$

$$x_{ij}^{0} = \frac{x_{ij}}{x_j^{\min}}, x_j^{\min} = \min\left(x_{ij}\right), i = 1,2,\ldots,n; j = 1,2,\ldots,m$$

Information entropy:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}, i = 1,2,\ldots,n; j = 1,2,\ldots,m$$

$$E_j = -\frac{1}{\ln(n)} \sum_{i=1}^{1} P_{ij} \ln P_{ij}$$

Weight calculate:

$$F_j = \frac{1 - E_j}{\sum_{j=1}^{m}\left(1 - E_j\right)}$$

Joint evaluation of subjective and objective factors:

$$I_j = \kappa A_j + \left(1 - \kappa\right) B_j, j = 1,2,\ldots,j$$

5. Geophysical fracture prediction

Seismic attributes such as Chaos, Auto Fault Extraction, Qudu, and Variance are identified as preferred fracture-sensitive attributes. And imaging logging directly identifies fracture directly in well scale.

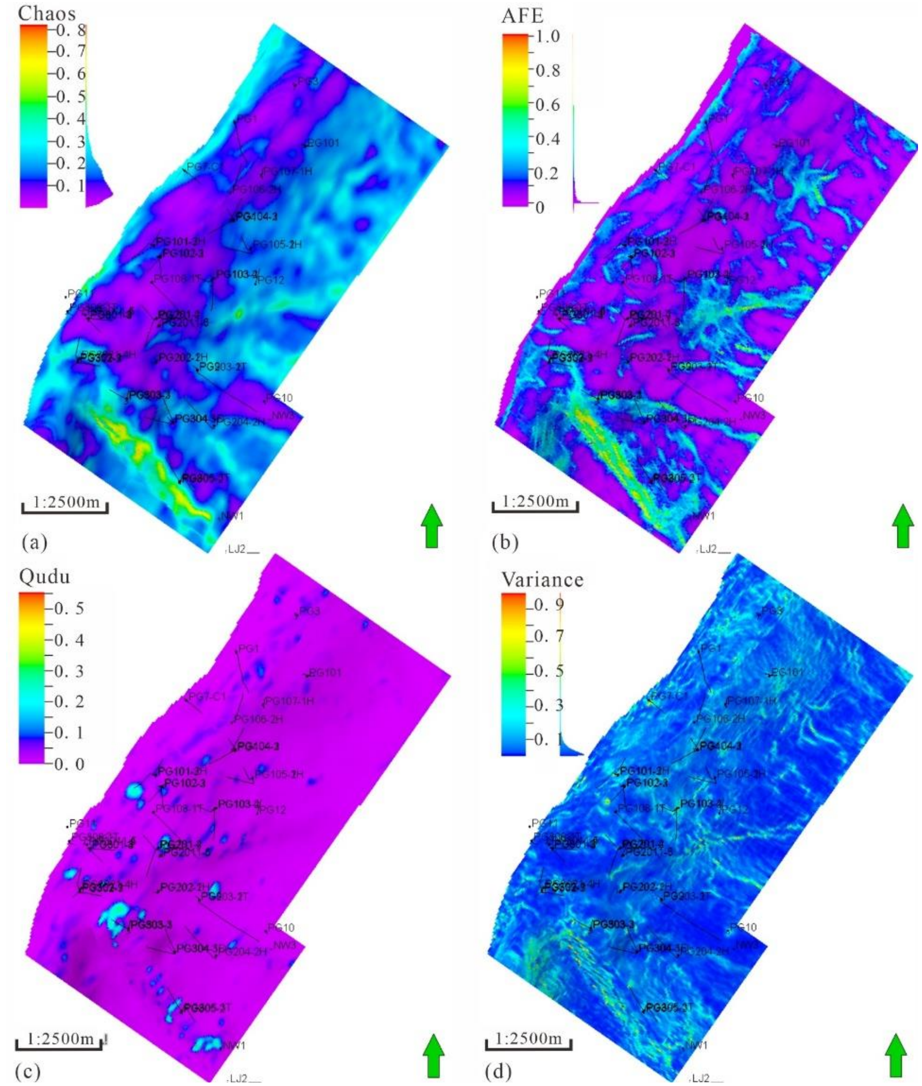

Figure 3. Post-stack seismic fracture sensitivity attributes. a) Chaos seismic attribute; b) AFE seismic attribute; c) Qudu seismic attribute; d) Variance seismic attribute.

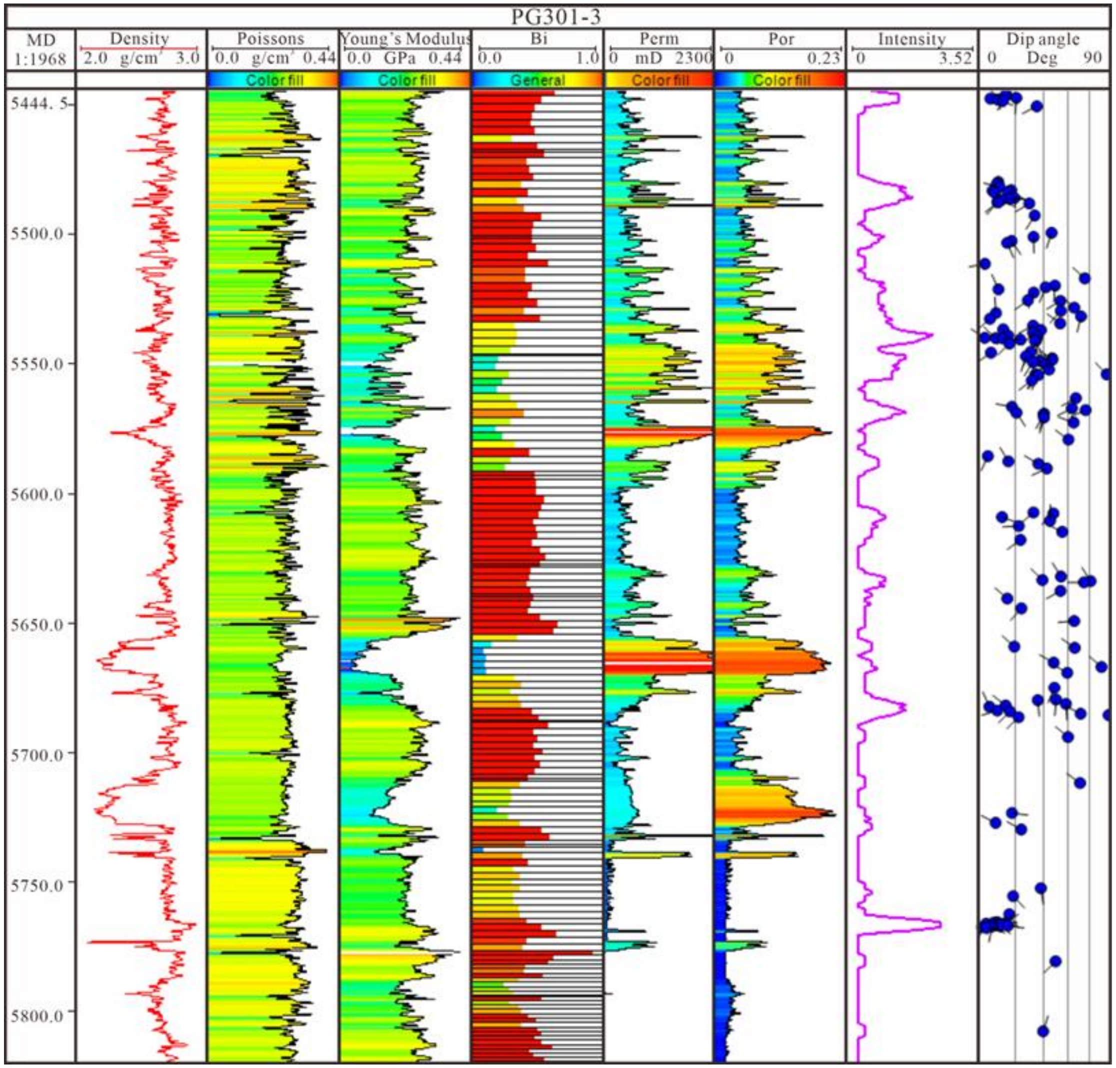

Figure 4. Fracture well log interpretation of well PG301-3 utilizing image log, array acoustic log, and other conventional log. The fracture density curve, brittleness index, porosity and permeability are used to explain the degree of fracture development.

6. Geomechanical fracture prediction

Finite element method is used to predict the spatial distribution of fracture density during the three period: the late Yanshanian period, early Himalayan period and late Himalayan period.

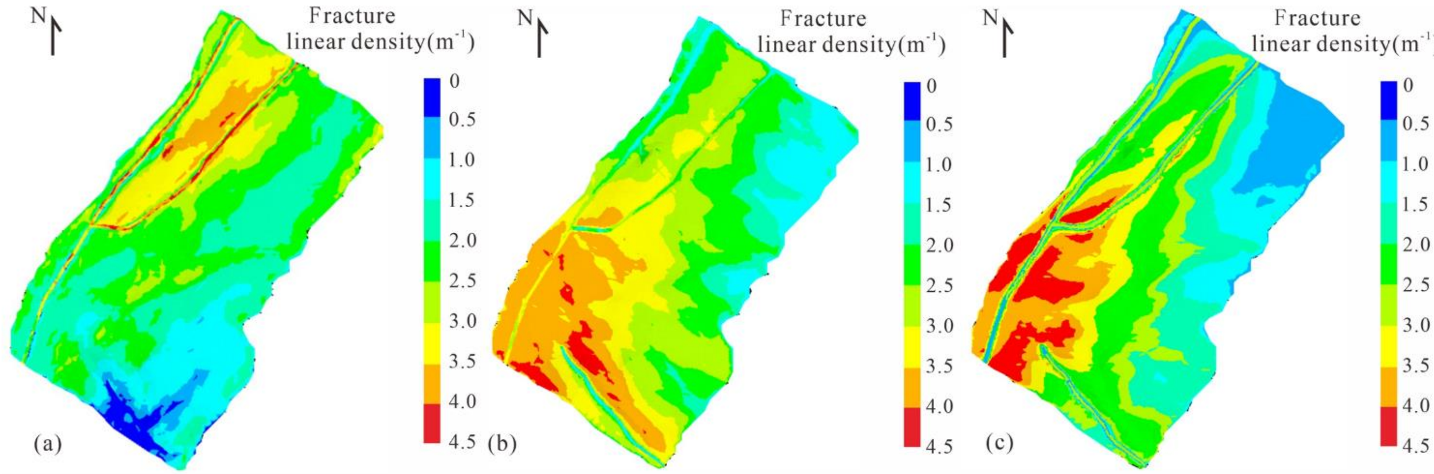

Figure 5. Numerical simulation result of multi-period tectonic stress field. (a) The predicted distribution of fractures in the late Yanshanian period. (b) The predicted distribution of fractures in the early Himalayan period. (c) The predicted distribution of fractures in the late Himalayan period.

7. Geological fracture prediction

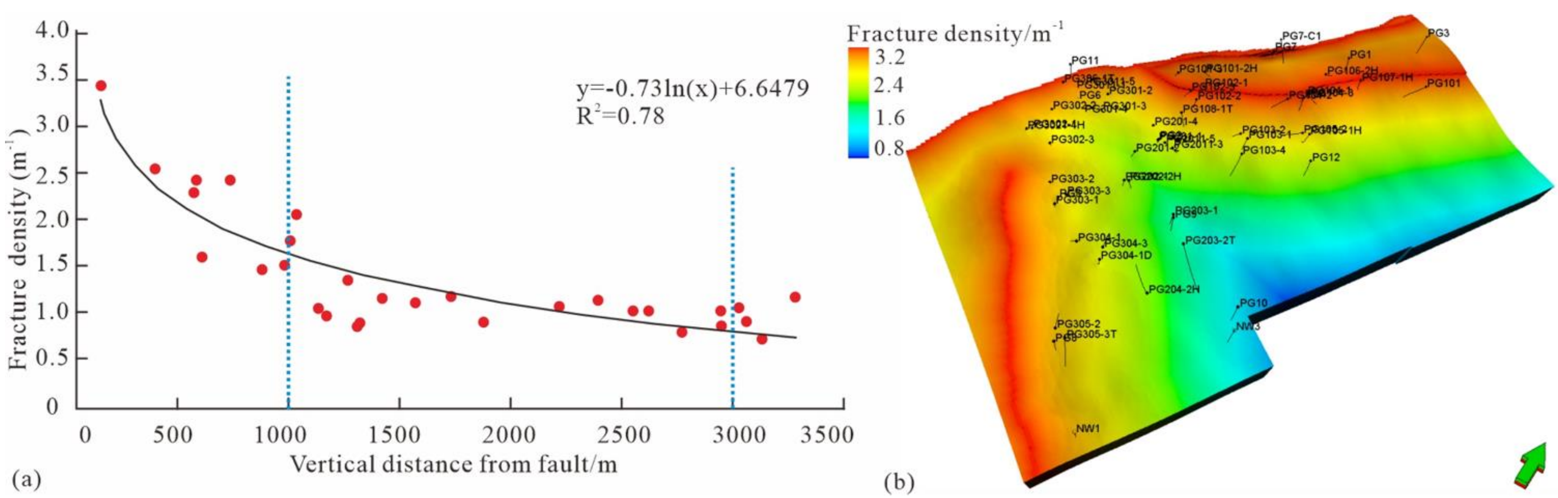

Figure 6. Geological constraint volume. a) Relationship between fracture density and vertical distance from faults. b) Constraint model of distance from faults.

8. Fusion density volume

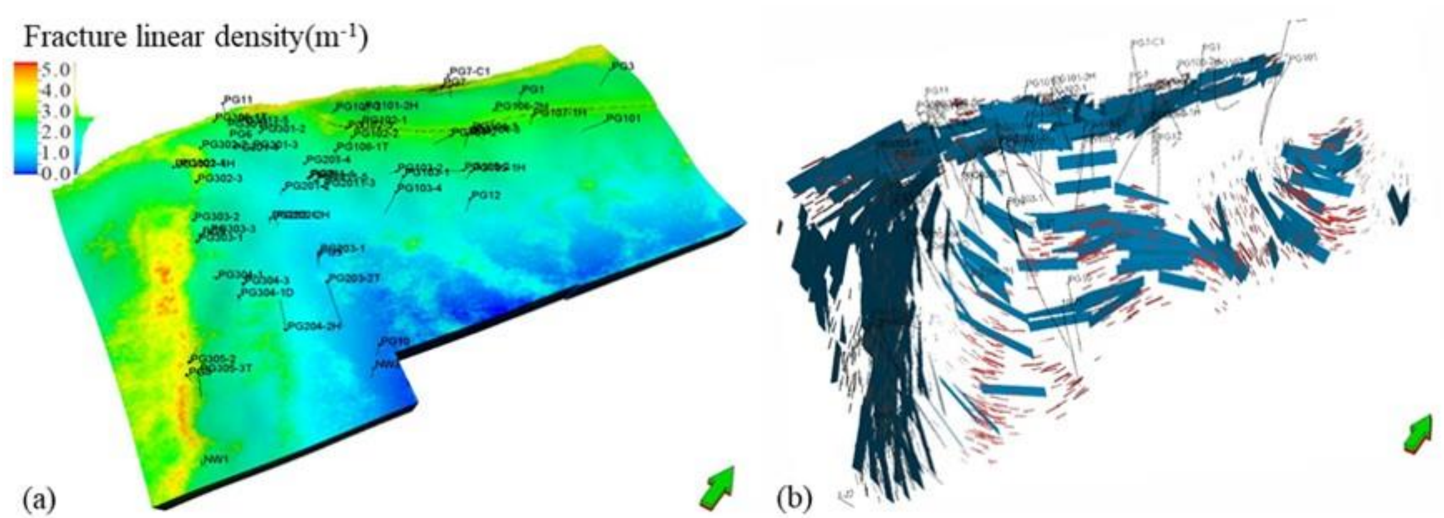

Figure 7. a) Multi data driven fusion fracture density volume. b) Discrete fracture network model.

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