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Integrated Fracture Modeling of a Highly Faulted Recumbent Anticline for EOR Simulation of a Heavy Oil Field in Colombia

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Abstract

The impact of fracture network on the reservoir performance can range from very restricted to fully controlling the fluid flow. This impact depends on many factors including but not limited to the type of fracture fill, fracture density, fracture geometry etc.

A case study is presented to demonstrate an approach of integrating data from different sources for building a dual porosity-dual permeability model for EOR simulation. This paper illustrates the workflow for static characterisation of fractured reservoirs.

The described methodology includes the following steps:

1. **A "conventional" static reservoir model which includes lithofacies, porosity, saturation and matrix permeability properties is built first.**
2. **The next step is statistical analysis where fracture sets are identified. For each fracture set, fracture intensity, i.e. number of fractures per unit of distance, is computed and used as the primary variable about fracturing.**
3. **Then geological, structural or lithological factors that can be used to propagate fractures away from the wells are selected and fracture intensities are modeled in 3D space. The integration with the secondary variables is done by co-kriging.**
4. **Finally, fracture properties are computed through discrete fracture modeling.**

Introduction

The La Hocha field is located in the Upper Magdalena Valley, Colombia. The reservoir is the Campanian-Maastrichtian Montserrate Formation, consisting of sandstones, carbonates and shales. The structure is on the low side of the San Jacinto Fault, interpreted as an asymmetric recumbent anticline with its frontal limb overturned. In general the structural behavior shows layers dipping between 45 and 90 degrees. Due the complexity of the structure, there is not seismic image from a 3D survey acquired in the area and the available geological information comes from wells and surface geology. The structural model correspond to a system of deformation associated to detaches in the Villeta Formation, which is being folded and destroyed as the San Jacinto Fault rises its base towards north. Due to the tight folding the reservoir is highly faulted and fractured.

Input data consisted of the previously built structural model, borehole data including well logs, deviation surveys, petrophysical logs, test results and core data.

Petrophysical Study

The wireline logs were interpreted to determine the net pay, effective porosity and water saturation to estimate the original oil in place. The petrophysical analysis also included a detailed lithofacies study which helped to discriminate and characterize the reservoir heterogeneity in order to distinguish the patterns of pore types, occurrences of water saturation, presence of transition zones and mechanical rock properties.

In this analysis, the sand and carbonate facies were defined based on the Vsh (Volume of Shale) and PEF (Photoelectric Factor) curves. The following approach was used: Where the PEF curve is less than three, the lithofacies was assigned as sand facies and the PEF curve is greater than three, the lithofacies was assumed as carbonate facies. The sand facies was further subdivided into Sand 1, Sand 2, Sand 3 respectively based on the Vsh values.

The porosity-permeability and water saturation-height relationships were developed for each lithofacies for different zones in the Monserrate formation.

Statistic Fracture Analysis

Statistic fracture analysis was the second step in the reservoir characterization and modeling workflow. The main objective was to understand and statistically characterize the fracture systems in the La Hocha field. The following reservoir relevant fracture parameters were assessed: fracture set orientations, fracture aperture, fracture porosity, fracture opening mode under the present day stress. At the field-scale, four fundamental fracture systems are observed at La Hocha - two longitudinal and two transverse systems. The two longitudinal systems are approximately parallel to the field’s axis, while the transverse systems are approximately perpendicular to the field’s axis.

A fracture intensity log representing number of fractures per 3 ft (1 m) interval in 17 ft (5 m) floating window was calculated for each of the fracture systems. The intensity log was upscaled arithmetically using the lithofacies log as a weighting parameter. It is clear that different lithologies are fractured differently. Significant variation of rock strength was not expected between the three sandstone lithofacies, so for subsequent fracture modeling, we used only three main lithotypes – sandstone, carbonate and shale. The most brittle rocks are carbonates and fracture intensity in carbonate intervals is the highest.

Matrix reservoir modeling

The interpreted lithofacies, Vsh, PHIE, SW and fracture intensity well logs were imported into the geocellular grid. The lithofacies log was upscaled into the 3D grid using a "most of" method, while Vsh, PHIE, SW and fracture intensity were upscaled arithmetically using the lithofacies log as a weighting parameter.

The matrix reservoir properties modeling workflow included these steps:

1. Lithofacies model containing five lithotypes – good quality sandstone, mediocre quality sandstone, low quality sandstone, carbonate and shale – was created using the Truncated Gaussian simulation.

2. Volume of shale and porosity were distributed using the Gaussian random function simulation and were conditioned by the lithofacies model.
3. Transformation of the porosity model into a matrix permeability model applying the Poro-Perm correlations established from the petrophysics study.
4. Calculation of water saturation grid using the saturation-height function from the petrophysics study
5. NTG ratio was computed applying the petrophysically defined cut-offs to the Vshale, PHIE and SW grids.

Fracture modeling

The first step of fracture modeling was population of the fracture intensity through the model. The following assumptions from the prior statistical fracture study were used:

- Fracture orientation/fracture systems are consistent through the field. The 114/35 fracture system is not observed in the backlimb wells because of the well orientation almost parallel to these fractures, but these fractures are expected to be present.
- Significant fracture parameters variation is not expected between backlimb and forelimb.
- Fractures are assumed to penetrate through the reservoir and die out in the shales above and below the Monserrate formation.
- Partially open fractures are considered open to saturate the model with fractures and provide the engineers with more flexibility during history matching.
- Fracture aperture for the longitudinal fracture systems was arbitrary set to half of the transverse fractures.

Various parameters, so called “fracture drivers”, such as bed curvature, distance to faults etc., were tested for correlation with fracture intensity and fracture aperture. The most statistically and geologically reasonable correlation was established between the fracture intensity and distance to the apex of the La Hocha anticline. The fracture intensity attribute was co-kriged the Distance property for each fracture system and by lithofacies using ordinary kriging. The resulting grids were used to define fracture density in 3D space.

The second step of the fracture modeling process is the fracture 3D network modeling. In our workflow the fracture network model is hybrid and consists of two elements:

– larger and more important fractures are modeled explicitly and can be visualized as discrete fracture patches (discrete fracture model));

- the residual part of the distribution (smaller fractures) is statistically represented as grid properties (implicit fracture model).

Fracture upscaling was done for both explicit and implicit fracture models to obtain representative fracture porosity, fracture permeability, fracture length and sigma factor (connection factor) at the geological model cell scale. Then the entire geomodel was upscaled for simulation. The detailed lithofacies property was upscaled using the “most-of” method. The matrix net-to-gross, matrix porosity, matrix water saturation, fracture porosity and sigma factor properties were upscaled using the "arithmetic average" method with volume weighting to ensure a volumetric equivalence between the geological and simulation models. Matrix permeability was upscaled using the "flow-based" algorithm and fracture permeability as a random property was upscaled using the “geometric average” method.

The dual media reservoir model was history matched and used for EOR simulation and screening. The application of the described methodology at the La Hocha field, Colombia resulted in an adequate modeling of the water encroachment pattern which was critical to plan future development of the field.