Geomechanics in Volcanics: Implications in Hydraulic Fracturing

Bineet Mund, Ruchika Sharda, Sreedurga Somasundaram, Abhudai Beohar, Ritesh Kumar, Tanzeem Patankar*
Cairn Oil and Gas, Vedanta Limited
bineet.mund@cairnindia.com

Keywords

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Summary

Field development of a tight gas reservoir requires efficient and cost effective hydraulic fracturing. Understanding of the geomechanical properties of the rocks, especially for volcanics in a tectonically stressed structure, is essential for optimum hydro-frac design. This paper summarizes the integrated approach for development of a one-dimensional geomechanical model in Raageshwari Field, Barmer Basin, India. Approximately 125 fracture stages in 20 wells of the field were executed involving 30 million proppants in the formation. This paper attempts to capture the implications of geomechanics in hydraulic fracturing (frac) with learnings and limitations.

Introduction

The Barmer Basin, located in western Rajasthan of India is an intra-cratonic NNW-SSE oriented rift basin. In the southern part of Barmer Basin, Raageshwari Deep Gas (RDG) reservoirs are hosted in a horst block structure (Figure 1 & 2). The Barmer basin formed due to break up of the Indian craton in the Late Cretaceous-Early Paleocene period (Compton et al. 2009). Rifting during the Late Cretaceous (Maastrichtian) resulted in the formation of Raageshwari Deep Volcanic Complex (equivalent to Deccan Volcanism). It is characterized by episodic eruption and deposition of basic and acidic lava flows. Subsequently, deposition of fluvio-lacustrine Fatehgarh formation has led to formation of an erosional unconformity on top of the Volcanics. The Raageshwari Deep Volcanic Complex comprises of two major units; the Prithvi Member (younger) and the Agni Member (older). Prithvi Member is comprised of mostly basic lava flows and the Agni Member contains stacked silicic pyroclastic flows (Felsic) interbedded with basalts. The Prithvi Member is composed of mostly mafic lithology along with diagenetic minerals formed due to hydrothermal alternations. Thickness of the Prithvi Member varies from north to south in the range of 0-600 m, being absent in northern part of the field due to erosion. The base of Agni Member is not yet penetrated through any well; however, encountered thickness of Agni Member in this field goes up to 550 m. The overlying Fatehgarh also varies in thickness from 0 to 200 m, with areas of non-deposition near volcanic highs (Figure 2).

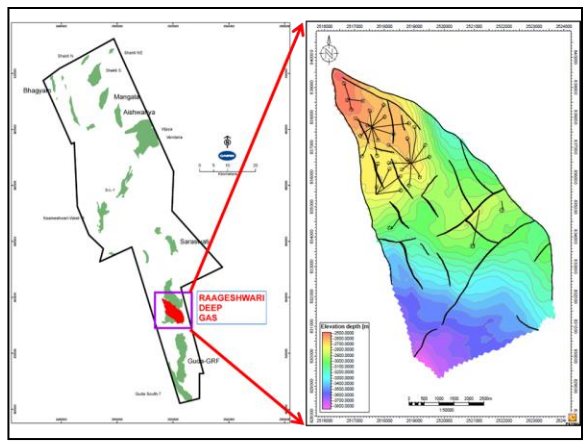

Figure 1: Field Location and structure map of area of interest

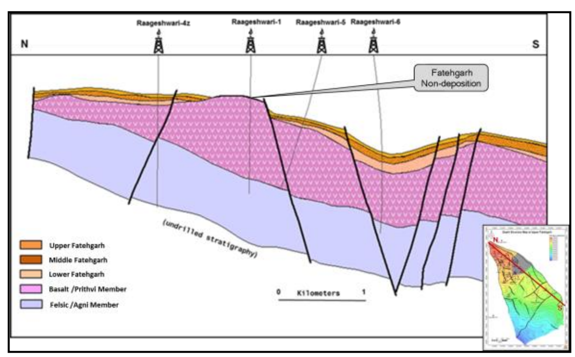

Figure 2: North-South cross-section of Raageshwari Horst Block

Methodology

Basic petrophysical logs were analyzed along with dipole sonic data, rock mechanical tests on core, processed image log data with break out analysis, regional tectonic history, natural fracture evidences and drilling data to create a comprehensive Geomechanical model. Most importantly, the model was calibrated with field test data such as diagnostic fluid injectivity test (DFIT) and step rate test (SRT) / mini frac to reasonably validate the predictability.

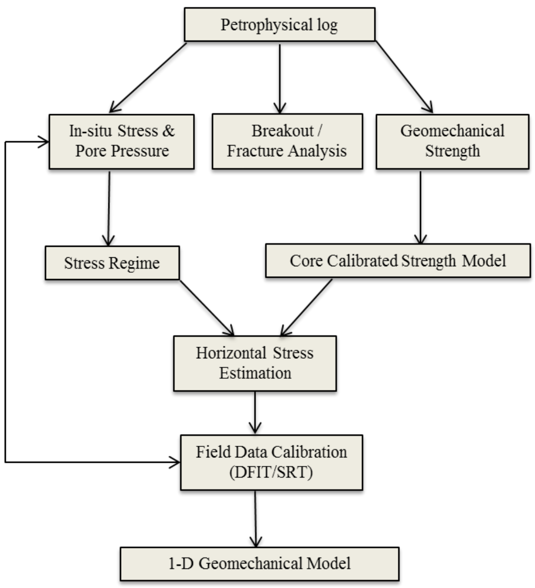

Figure 3: Workflow for 1D-Geomechanical Model

The methodology involved 2 primary steps- 1) Rock Strength estimation and 2) Stress estimation (Figure 3). Dipole sonic data was useful for calculation of rock strength parameters like Poisson's ratio, dynamic Young's Modulus and Compressive Strength etc. Rock mechanical tests were carried out in some of the representative core samples and used for calibration.

Estimation of stress involved assessment of over burden stress, pore pressure, followed by horizontal stress (both maximum and minimum). Wireline bulk density logs (>30 wells) were used for computing over burden gradient (OBG) or vertical stress (Sv). Pore pressure (Pp) was estimated using the sonic log and calibrated to formation pressure from field data. Image log data were used for natural fracture identification, indication of break-outs and drilling induced tensile fractures. Maximum horizontal stress or SHmax (direction and magnitude) was estimated both from break-out angles and tensile fractures. The analysis indicates that the stress regime in the field is closer to strike-slip (SHmax>=Sv).

After the image log review and analysis, minimum horizontal stress (Shmin / Sh) was estimated using Equation 1 (Thiercelin and Plumb, 1994), assuming the formation is isotropic.

$$Sh = \frac{PR}{1-PR}(Sv - \alpha PP) + \alpha PP + \frac{YMs}{1-PR^2}\epsilon_{H_{max}} + \frac{YMs \cdot PR}{1-PR^2}\epsilon_{H_{min}}$$

Where PR is Poisson's ratio, YMs is the static Young's modulus, α is Biot's coefficient, ε_{Hmax} is the maximum horizontal strain, and ε_{Hmin} is the minimum horizontal strain. The first two terms of the equation represent poro-elastic components which can be obtained from sonic data. However, the last two terms of the equation represent tectonic contributions to the stress which need to be field calibrated from Closure Pressure data (CP data).

Geomechanical Model Validation

Hydraulic fracture stage identification, decision on number of perforations, perforation depth, number of Frac stages and finalization of Frac design (proppant size and amount, pumping rate, pumping schedule, etc.) were carried out based on an integrated model combining Petrophysics and Geomechanics (Figure 4). Stress barriers were identified in each stage based on the Geomechanical model. Before the frac job execution, DFIT, SRT / Mini-fracs were carried out to ascertain closure pressure (CP) in the zone of interest. It was found that the model predicted-Shmin was in close agreement with the field data (Figure 5).

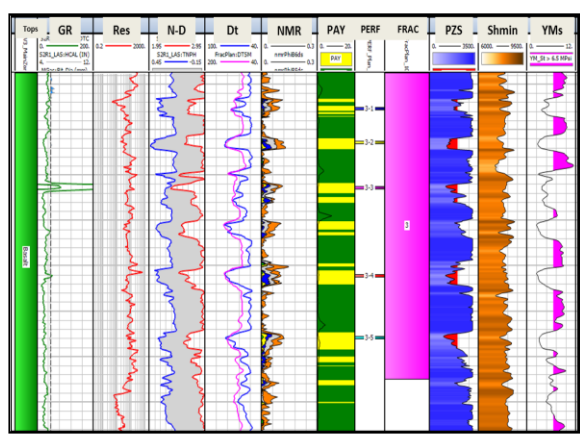

Figure 4: Integrated Model for Frac Optimization

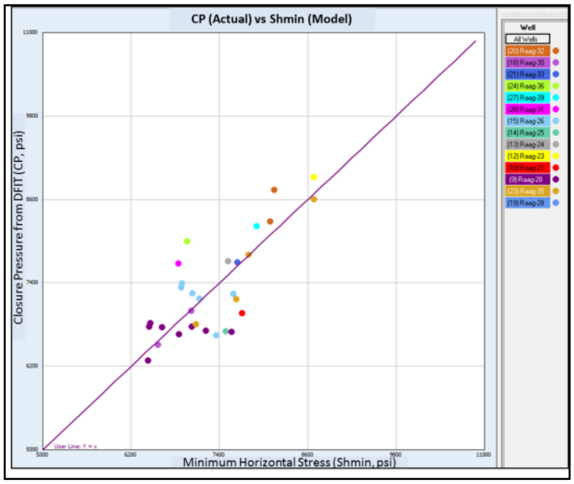

Figure 5: Comparison of predicted Shmin with CP from DFIT

Impact on Hydraulic-Fracturing

Geomechanical property estimation in Volcanics of this field revealed the inherent heterogeneity in rock strength of the reservoir. It was observed that the Young's Modulus (YMs) played a crucial role in fracture propagation and placement. Distinct difference was observed in computed YMs in between Fatehgarh clastics (Narrow range) and Volcanics (Wide range), as illustrated in Figure 6 & 7. In Volcanics, YMs ranged from 2 – 10 Mpsi (majority of points stayed in between 3 to 7 Mpsi).

In contrast to unconventional shale plays, volcanics are brittle by nature. Swelling clays hampering frac propagation is not an issue in this field. However, huge strength variation in the rocks impacts fracture geometry. Very high Young's Modulus (high strength rocks) results in lowering of fracture width and hence hinders frac propagation. Rocks with low YMs, when sandwiched between rocks with very high YMs, upon fraccing, develop a contained fracture growth. Alteration of porous zones (vesicular intervals at top of lava) and non-porous zones (lava bottom or interior) are quite common in basalts. Contained frac growth normally affects net pressure accumulation in a frac stage which was observed as an increased instantaneous-shut-in pressure (ISIP). Figure 8 illustrates picking of closure pressure and ISIP from an injection fall-off test (post DFIT/SRT/Mini-frac). Net pressure (NP) can be calculated from the picked ISIP and CP in an injection test.

$$NP = ISIP - CP \qquad \text{(Equation 2)}$$

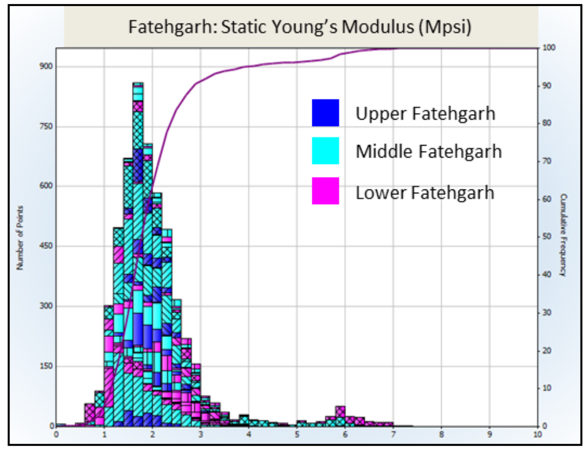

Figure 6: Static Young's Modulus Histogram for Fatehgarh

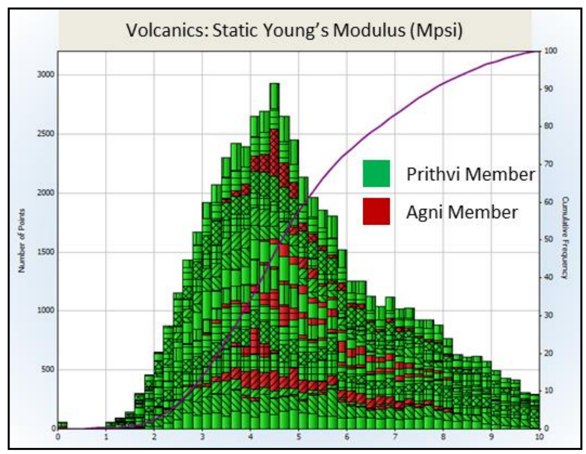

Figure 7: Static Young's Modulus Histogram for Volcanics

Comparison of ISIP and CP from several DFITs resulted in an increased net pressure accumulation in few of tests (Figure 9). Increased NP may result in very high treating pressure during frac. Post frac ISIP turned out to be higher than pre-frac ISIP (DFIT/SRT) in many stages.

During RDG frac campaign, more than 90% of the frac jobs were carried out successfully; however, in few of the stages (marked in Figure 9) very high treating pressures were encountered and resulted in pressured-out cases or early flush.

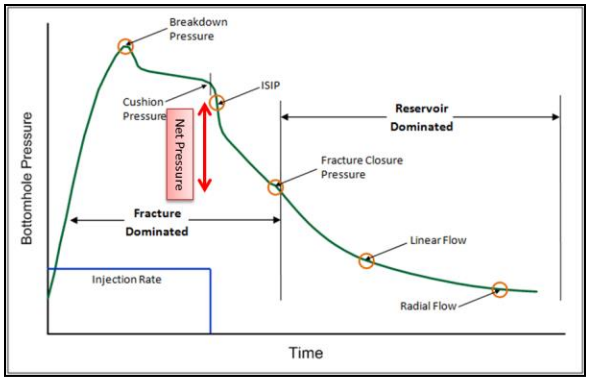

Figure 8: Cartoon illustrating CP, ISIP & NP from an injection fall-off test

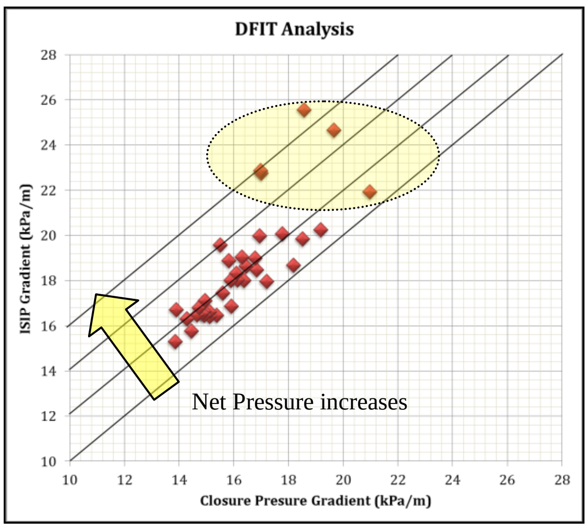

Figure 9: CP and ISIP plot from DFIT showing area of increasing net pressure and highlighted region where frac issues were encountered

Post frac ISIP is influenced by higher closure pressure, net pressure accumulation during frac, treating fluid type, etc. Higher ISIP and CP are expected in the areas where tectonic disturbances and structural elements like faults are predominant. Necessary data acquisition and calibration are essential to account for local variations in stresses. Any Geomechanical model is subject to limitations posed by intrinsic assumptions and data constraints regarding the stress history of a region. Hence, perfect match with field data is not always possible.

Conclusions

This study on Raageshwari field helped in achieving a successful hydro-frac campaign and increased production from the field. It highlighted on the heterogeneity of geomechanical properties, in-situ stresses and their effective application in realizing hydro-frac objectives. Post frac analysis of each stage calls for continuous update and improvement of the model addressing local variation in in-situ stresses and variation in geomechanical properties. This example from Barmer Basin can be helpful in developing a tight volcanic reservoir elsewhere.

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