GEOMECHANICALLY COUPLED SIMULATION OF FLOW IN FRACTURED RESERVOIRS

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Keywords: *Geomechanics, discrete fracture network modeling, reservoir stimulation.*

ABSTRACT

Capturing the necessary and sufficient detail of reservoir hydraulics to accurately evaluate reservoir behavior remains a significant challenge to the exploitation and management of fracture-dominated reservoirs. In low matrix permeability reservoirs, stimulation response is controlled largely by the properties of natural and induced fracture networks, which are in turn controlled by the in situ stresses, the fracture distribution and connectivity and the hydraulic behavior of the fractures. This complex interaction of fracture flow systems with the present-day stress field compounds the problem of developing an effective and efficient simulation to characterize, model and predict fractured reservoir performance.

We discuss here a case study of the integration of geological, geophysical, geomechanical, and reservoir engineering data to characterize the in situ stresses, the natural fracture network and the controls on fracture permeability in geothermal reservoirs. Flow through the individual fractures which form the connected network was explicitly modeled. Fracture stress sensitivity was coupled to the flow simulation through the DFN with dynamic adjustment of aperture to effective normal and shear stresses (after Moos and Barton 2008) and calibrated with microseismic data (positions and times of events) and injection data (rates and pressures). The results highlight the importance of combining all available data, including microseismic, wellbore image, and flow and stimulation test data, to determine reservoir flow behavior and its response to stimulation.

1. INTRODUCTION

1.1 Conceptual Model

Conductivity enhancement of natural fracture networks by stimulation is generally accepted within the geothermal community as the only effective means of creating an Enhanced (Engineered) Geothermal System in an otherwise tight rock. As most fractures are stress-sensitive, their hydraulic conductivities will change with changes in bottom hole flowing and reservoir pressures, causing variations in production profiles between wells. More specifically, fractures can hydraulically open or close due to a decrease (caused by injection) or increase (caused by production) in the effective stress. Flow properties are a function of effective fracture aperture, so it is possible to predict reservoir behavior using a relationship between the mechanical behavior of natural fractures (in response to in situ stress and pore pressure changes) and their hydraulic properties.

Early work by Hossain et al. (2002) demonstrated that it is possible to model the resulting improved reservoir permeability with injection utilizing a hysteretic model for fracture conductivity enhancement by self-propping or dilatant micro-crack formation that occurs when shear slip offsets the walls of previously sealed fractures. Applying this concept, low flow rate injection tests were used to characterize the hydraulic properties of the fractures, their width, stiffness and strength — properties that are often difficult to quantify, leading to large uncertainties in predicted response to stimulation of fractured reservoirs.

1.2 Modeling Shear-Enhanced Permeability

The approach we use here for modeling creation of a connected stimulated network is the observation, validated by numerous studies (e.g., N. Barton, 2007), that fracture conductivity is enhanced when fractures have slipped under a critical state in which the shear stress is sufficient to cause the fracture to fail in shear. Explicitly, we define this condition using a Coulomb failure criterion in which slip occurs when $\tau > \mu\sigma_n$ - So (τ is the shear stress acting on the fracture, μ is the coefficient of sliding friction, σ_n is the effective normal stress and S_o is the Cohesion).

Under natural conditions, relatively few fractures are close to shear failure – in fact, most fractures are nearly completely closed, as σ_n is always greater than zero in situ. Raising the reservoir pressure as occurs during stimulation decreases effective normal stress thereby causing an increase in the number of fractures that are critically stressed and thus can slip. Because fracture walls are rough, slip requires an increase in the crack width which enhances conductivity. As stimulation pressure continues to increase to values above the fracture gradient, Mode I (extensile) cracks will open and, with continued pressure increases, the pre-stimulated shear fractures will also open. When the pressure drops after stimulation is complete, shear fractures remain open (they self-prop), but Mode I cracks will re-close unless proppant or other means are used to maintain their newly created aperture. We compute the effective reservoir permeability both before and after stimulation by summing the contributions to permeability of all of the in situ fractures (see Moos and Barton, 2008).

The underlying principles are that fracture dilation occurs during shear slip, and that there is sufficient connectivity after stimulation to allow each of the fractures to contribute to flow according to their conductivity and density. Although we use other simplifying assumptions e.g. we calculate conductivity using a parallel plate model, calibration using carefully designed injection tests can lead to quantitatively valid predictions for how reservoir flow properties change during stimulation. It is important however to note that the classic cubic relationship between aperture and conductivity is inappropriate when this model is used to compute equivalent continuum properties e.g. for use in a dual porosity dual permeability reservoir simulator. The calibration step also serves another important purpose – that is, it provides data to determine the extent to which shear stimulation provides sufficient benefit to justify its use.

2. APPLICATION

The Habanero engineered geothermal system, operated by Geodynamics Ltd., is located in the Cooper Basin in east central Australia and has been the subject of numerous papers; the results described here are from Barton et al., 2013. The target is hot (250°C), water-saturated, naturally fractured granitic (basement) rock. We apply this approach to determine the appropriate parameters required to model and predict the effects of injection, to enable better stimulation design for future wells, and to validate the approach used for that purpose.

2.1 Geomechanical Modeling

The first step, essential to the workflow presented here was to construct a 3D geomechanical reservoir model that includes constraints on stress magnitudes and orientations, and constraints on mechanical rock properties and the fractures themselves. Such a model is essential to understanding reservoir response to stimulation and production in low matrix permeability, fracture-dominated reservoirs.

The geomechanical model for this study was developed using petrophysical, drilling, and wellbore image data along with direct well test measurements and was mapped to a 3D structural grid to facilitate coupled simulation of the fractured reservoir. The horizontal stresses are calculated within the 3-D structural grid based on the local pore pressure and overburden values in combination with modeled effective stress ratios. The resulting static 3-D geomechanical model contains all properties for direct grid-based extraction of the full set of geomechanical parameters required to calculate the mechanical coupling between the stress and natural pre-existing fractures distributed within the reservoir.

Stress modeling results reveal high differential stress within the Habanero Field, where S_{Hmax} is likely to be up to 150 MPa at reservoir depths (Fernández-Ibáñez et al., 2009). The least horizontal stress, S_{hmin}, is intermediate between S_{Hmax} and S_v indicating a reverse faulting stress regime.

2.2 Characterizing the Fracture Network

Fracture sets and orientation are typically inferred from stereographic density plots interpreted from image log analysis (Figure 1a). Developing a fracture conceptual model based only on wellbore image analysis, well tests and tracer tests, requires several assumptions regarding fracture geometries and hydraulic properties that result in significant modeling uncertainties. In this study we interpret in a novel way available microseismic event data to more precisely define fracture geometry, and also use the microseismic data to calibrate the model for the dynamic behavior of the system during stimulation. An example of located microseismic data during the phased stages of the Habanero-1 well stimulation is shown in Figure 2.

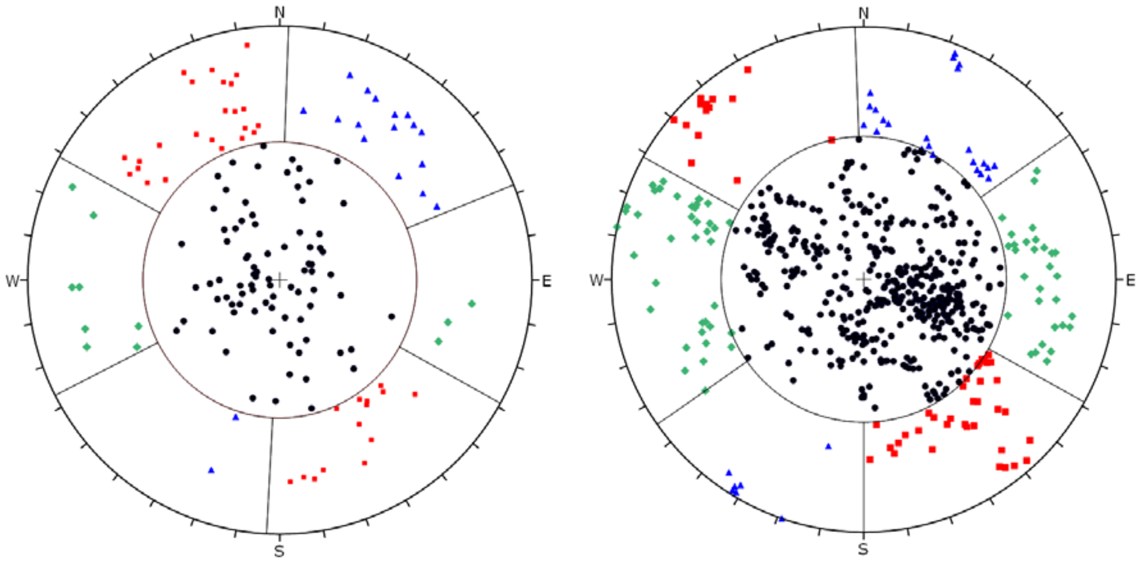


Figure 1: Fracture sets and orientation distributions can be interpreted from stereonets based on (a) image data or microseismic data (b). Equal Angle Wulff net, lower hemisphere projection.

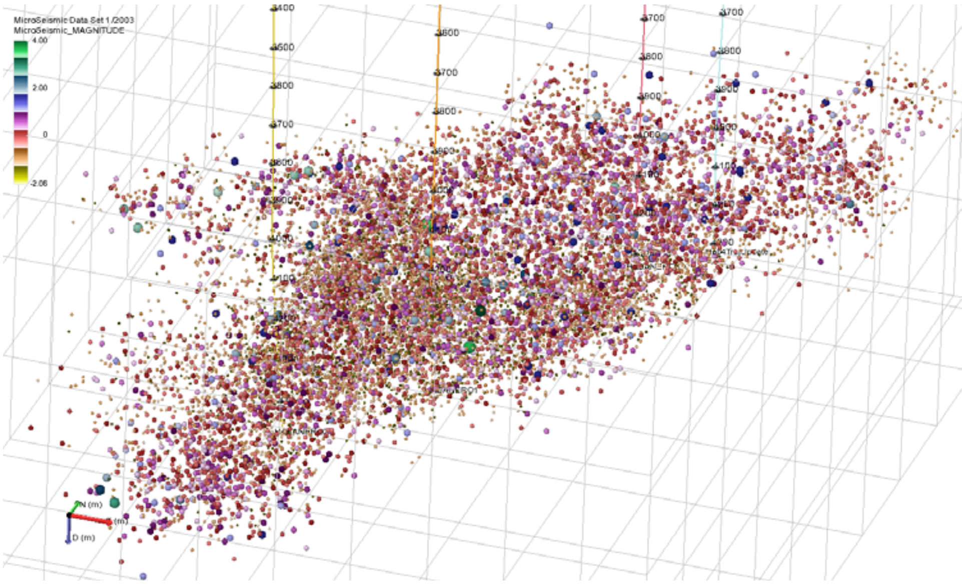


Figure 2: Located microseismic events during phased hydraulic stimulation colored and scaled by moment magnitude.

In this approach we carefully animate the development of the microseismic cloud to infer fractures in the order in which they were stimulated. In this way, a realistic impression of the dynamic stimulation of pressure build-up and consequent fracture stimulation along connected pathways is obtained. Figure 3a shows effective hydraulic apertures inferred where slip events occurred for the main fracture intersecting Habanero-1. Figure 4 shows this fracture along with some of the other fractures detected in this way in the vicinity of the Habanero wells.

It is possible by defining the immediate network around the wellbore to use its properties as the basis for constraining fracture orientations (Figure 1b), size (Figure 3b) and connected fracture intensity. Further, the time at which fractures are stimulated gives an indication of hydraulic diffusivity and by inference hydraulic aperture distribution (see color symbols, Figure 3a). The stimulated fracture area versus cumulative injected volume can be used to calculate a mass balance aperture (fracture volume) which controls the amount of fracture surface that is stimulated for a given injection volume which can be verified by simulating the breakthrough time for tracers.

For this workflow the wellbore image and stimulation test data were used along with microseismic data acquired during the test to determine the reservoir fracture architecture and to provide control points for a realistic inter-connected discrete fracture network. The discrete fracture network (DFN) approach provides a natural framework for describing and modeling of geological structures observed in the wellbore and from seismic, and for simulating their dynamic responses to changes in down-hole and reservoir pressures during injection.

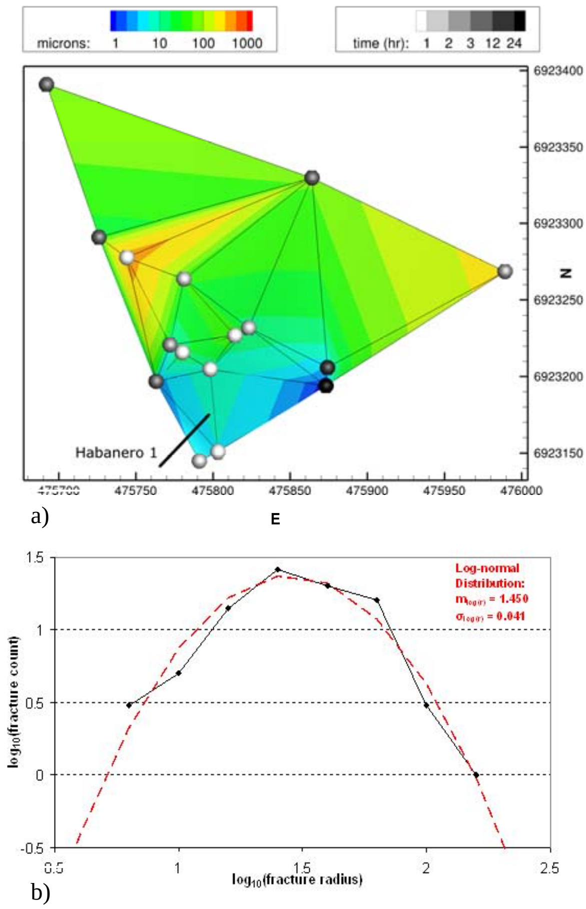


Figure 3: a) Effective hydraulic apertures inferred where slip events occurred on a fracture intersecting Habanero 1 at an elevation of 4135m. b) Water conducting fracture size distribution interpreted from microseismic events. Fracture aperture scale is microns and radius scale is meters.

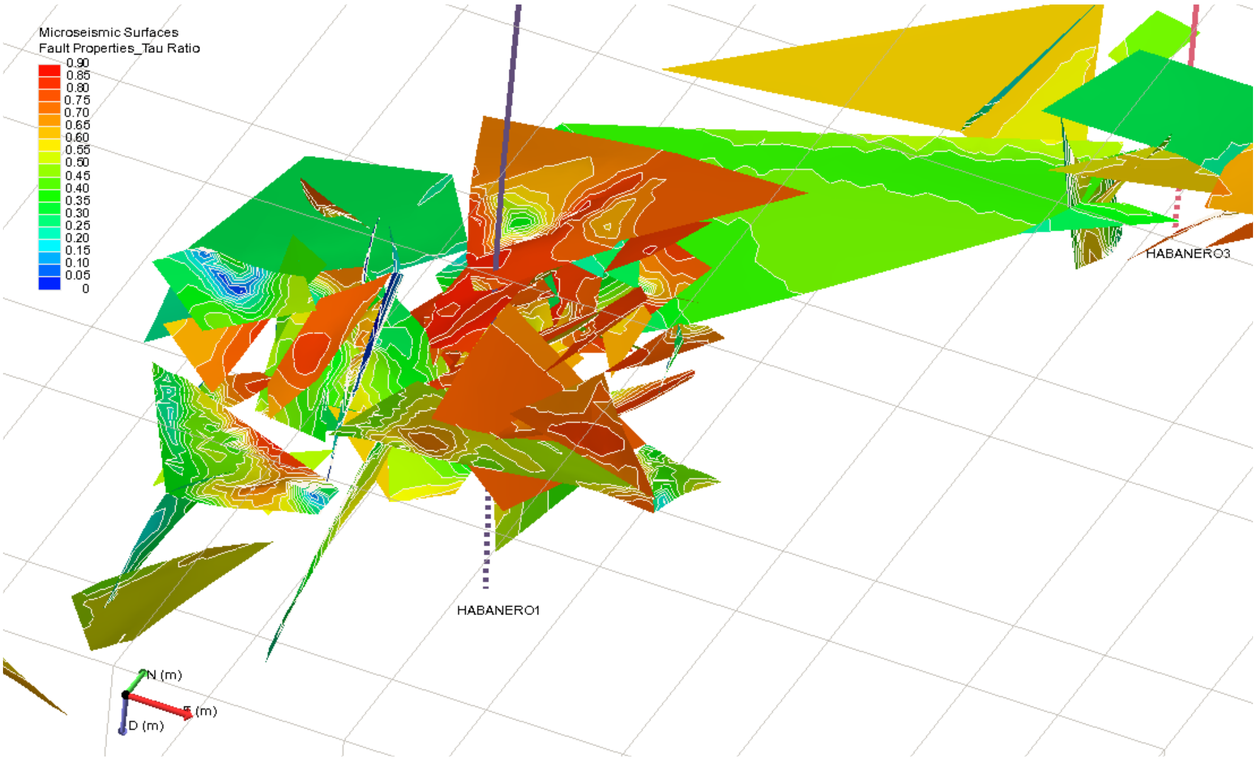


Figure 4: Part of the inferred network of fractures local to Habanero 1 viewed from the southeast, and determined through analysis of microseismic events. Color indicates proximity of the fractures to frictional failure.

2.3 Model Calibration and Simulation

A pre-injection test was appropriately conducted using a series of successively larger injection rates none of which exceeded the minimum stress, followed by two periods of continued injection at lower rates. Model parameters were constrained by fitting this data. The initial, low flow rate injectivity test data recorded in the Habanero-1 well are shown in Figure 5a as pressure versus flow rate. The lower plot of Figure 5b shows the cumulative number of fractures that have slipped versus increasing pressure. As injection proceeds from an initial low rate to higher rate, well-oriented fractures tend to slip; at higher pressures, less-well oriented fractures will also slip. The shape of the measured pressure versus flow rate curve (symbols) is forward modeled (solid line) by varying the parameters of the relationship between equivalent aperture and effective normal stress and the frictional properties following Moos and Barton, 2008:

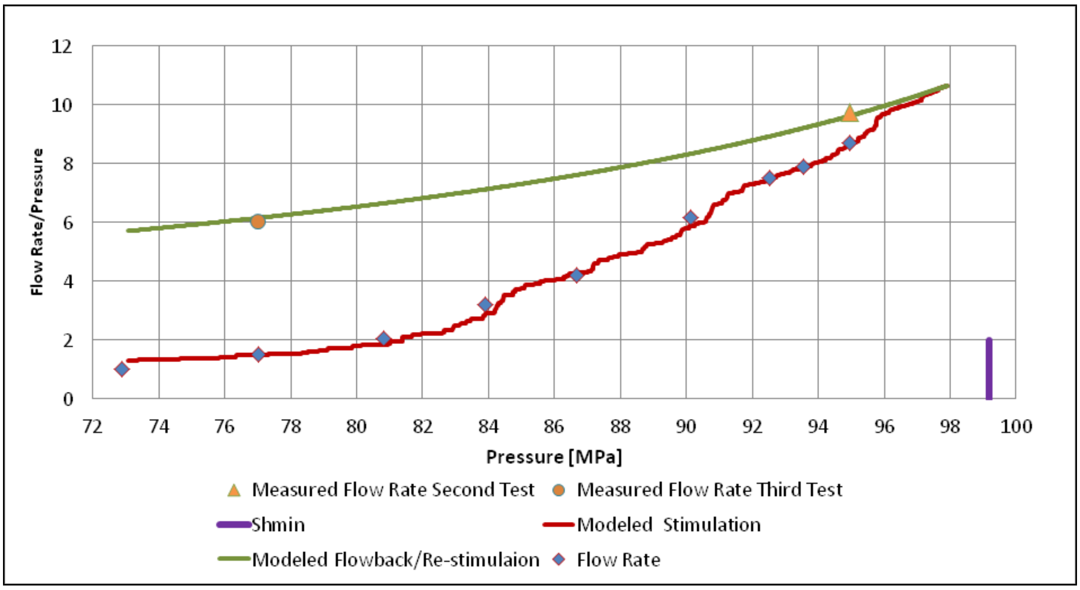
$$a = \frac{A}{1 + 9\,\frac{\sigma'_n}{B}} a_0 \qquad (1)$$

where a is equivalent aperture, σ_n the effective normal stress, $a_0 \cdot A$ and $a_0 \cdot A_{slip}$ are the pre- and post-slip apertures, B and B_{slip} the pre-and post-slip 90% closure stresses. The aperture-stress coupling model parameters used to fit the data are provided in Table 1.

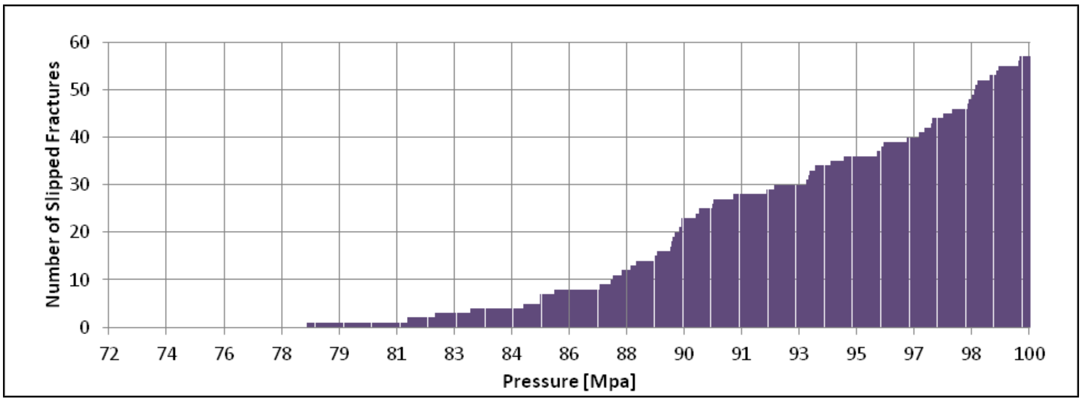
These fracture flow properties, stresses and the deterministic fracture data discussed above were used to explicitly model flow and transport through individual fractures which form the connected discrete fracture network (DFN). The modeling software, ConnectFlow, applied in this study is an efficient finite-element DFN method that uses a stochastic approach to generate networks of planar fractures that have the same statistical properties as those that are interpreted from field data.

Table 1: Aperture-stress coupling parameters determined for the Habanero EGS field.

Parameter	Mean	Standard Deviation
Model Depth [m]	4,267	
S_{Hmax} [MPa]	150.9	10%
S_{hmin} [MPa]	124.4	10%
S_v [MPa]	97.9	5%
P_p [MPa]	73.1	5%
S_{Hmax} Azimuth [deg]	80	±10°
Cohesion [MPa]	1.72	5%
Sliding Friction	0.6	10%
a_0	0.8	10%
A	0.1	10%
A_{slip}	0.25	10%
B	58.6	10%
B_{slip}	172.4	10%



a)



b)

Figure 5: Aperture-stress coupling calibration from Habanero-1 stimulations. a) Flow rate versus pressure for modeled (solid line) and measured (symbols) injection and number of fractures slipped with pressure (b).

Fracture stress sensitivity is internally coupled to the flow simulation through the DFN with dynamic adjustment of aperture to effective normal and shear stresses and calibrated with microseismic data (positions and times of events) and injection data (rates and pressures).

Figure 6 shows the stress-aperture coupled simulated and measured well pressures during the first four hours of Habanero-1stimulation. This plot corresponds to the pressure versus flow rate shown in Figure 5.

The result of modeled and measured stimulations over about one month of phased stimulation using this approach are fully discussed in Barton et al., 2013. Additional measurements, including tracer breakthrough data, were also well matched by the resulting parameters, which provided validation of the technique and confirmed the benefit of stimulation in this reverse faulting environment.

2. CONCLUSION

In this case study we illustrate how microseismic monitoring during hydraulic stimulation provides a means to constrain both static properties (size, intensity, connectivity) and dynamic properties (hydraulic and mass balance apertures, geomechanical and compliance models) when used in combination with standard fracture interpretation and production logging. In predictive mode, the simulations can be used to estimate likely pressure evolution, as well as extent, geometry and volume of hydro-shearing resulting from the stimulation.

ACKNOWLEDGEMENTS

The authors wish to thank GeoDynamics Limited for the use of their complete set of data from the Habanero Field and for their generous time assisting in its delivery and interpretation.

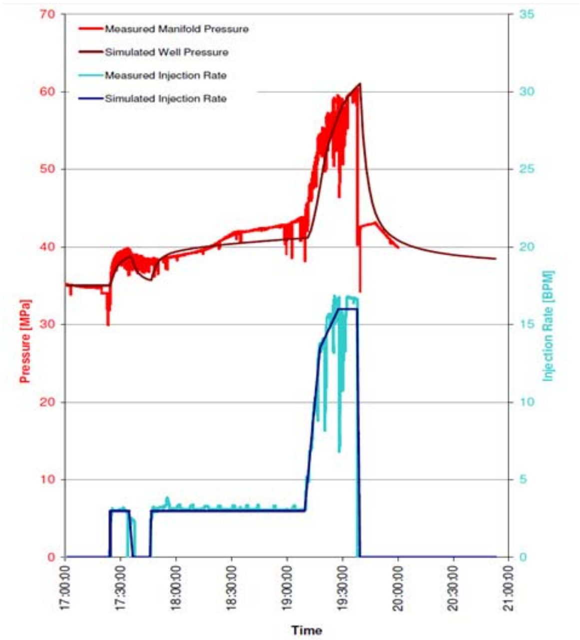


Figure 6: Measured and simulated well pressures during the first four hours of Habanero-1 stimulation.

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