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SPECIAL ISSUE:

Discrete Fracture Network (DFN) Modeling in Rock Mechanics: Volume II

Editor's Note

The present ARMA e-Newsletter constitutes the second volume of invited articles on the subject of Discrete Fracture Network (DFN) modeling in rock mechanics.

Volume I, which appeared in the Winter 2017 issue of the ARMA e-Newsletter, contained articles that provide an overview of the nature of DFN models, with appropriate case histories. The articles in Volume II present five examples of DFN applications, solving real-world rock engineering challenges in areas such as geothermal energy (Wei Li et al), oil and gas (LaPointe et al), coals (Busetti et al), mining (Elmoultie), and ground water (Panda). This collection of articles by world-class practitioners should provide the reader with an appreciation of ways in which DFN modeling has enriched rock mechanics practice.

The suggestion to publish a special issue on DFN modeling came to us from ARMA member Amitava Ghosh, who also serves on the ARMA Publications Committee. We owe him our sincere thanks.

Now, we invite you, the readers of this newsletter, to recommend other topics of general interest from the rock mechanics/geomechanics practice, for future special issues of our newsletter. We look forward to hearing from you.

Bezael Haimson

GEOFRAC and its Applications

Submitted by Wei Li, Violeta M. Ivanova, and Herbert H. Einstein (Massachusetts Institute of Technology, Cambridge, Massachusetts, USA), Rita L. Sousa (Masdar Institute of Science and Technology, Masdar City, UAE), and Alessandra Vecchiarelli (Arup New York USA, New York, USA).

Abstract

GEOFRAC is a 3D Discrete Fracture Network (DFN) model developed at MIT. Recent research developments based on GEOFRAC resulted in GEOFRAC-FLOW and GEOFRAC-THERMAL, which simulate the flow and heat transfer in the DFN, respectively. This paper presents the development of GEOFRAC-FLOW and -THERMAL, and summarizes the inputs for the GEOFRAC package. A study on the Fenton Hill Project is used to demonstrate the applications of the GEOFRAC package in simulating the flow and heat transfer in a stimulated hot dry rock reservoir. A case study on the Námafjall geothermal field is used to show how GEOFRAC simulates the flow and heat transfer in a conventional geothermal reservoir. Both of the case studies provide reasonable results for flow rates and temperature in the reservoir.

1. Introduction: Modeling of fracture systems with GEOFRAC

GEOFRAC is a Discrete Fracture Network model developed at MIT based on work by Baecher et al. [1977], Veneziano [1979], Dershowitz [1985], and Ivanova [1995]. Further work by Dershowitz [1985] led to Fracman [Dershowitz, 1989], while Ivanova's [1995] work led to GEOFRAC; the underlying concepts are analogous. GEOFRAC is a three-dimensional (3D), geology-based, geometric-mechanical, hierarchical, stochastic model of natural rock fracture systems [Ivanova et al., 2014] using MATLAB.

The model represents fracture systems as 3D networks of intersecting polygons, generated through spatial geometric algorithms that mimic the mechanical processes of rock fracturing in nature. Specifically:

1. The desired mean fracture size $E[A]$ and fracture intensity P_{32} in a region of volume V are given as inputs. $E[A]$ and P_{32} can be derived from field data; for example, methods for deriving P_{32} are described by Dershowitz and Herda [1992] and for deriving $E[A]$ by Zhang et al. [2002], Mauldon [2000] and Kulatilake [1993].

2. In the primary stochastic process, Poisson planes of intensity μ and a specified orientation distribution are generated in the volume V . The intensity of the Poisson plane process is computed as:

$$\mu = P_{32} \quad (1)$$

The orientation of the fractures can be simulated to follow the distribution observed in the field; for example, Einstein et al. [1979] discussed possible orientation distributions and how to consider possible biases. GEOFRAC defines the orientation distribution with two parameters (m, k) and the mean orientation. The parameter m is the type of distribution, which represents from 1 to 4: uniform distribution for all orientations, uniform distribution for a limited range of orientations, univariate Fisher distribution, and bivariate Fisher distribution, respectively. The parameter k controls the distributions' parameters; for example, in univariate Fisher, a higher k value indicates more concentrated orientations. The mean orientation of the pole of the fractures relative to the volume V is defined as (θ, ϕ) [Ivanova, 1998].

3. In the secondary stochastic process, a Poisson point process with intensity μ is generated on the planes, which are then divided into polygons by a Voronoi tessellation, where the intensity of the point process is computed as:

$$\lambda = \frac{1}{E[A]} \quad (2)$$

The development leading to this simplified expression compared to earlier ones is discussed in Ivanova et al. [2014].

4. In the tertiary stochastic process, polygons are randomly translated and rotated to represent local variations of fracture positions and orientations.

The fracture generation process is illustrated in Figure 1 below:

According to Zhang et al. [2002], natural fracture apertures follow a lognormal distribution based on field data. This is implemented in GEOFRAC by assigning the aperture values following a lognormal distribution to the fracture polygons in the fracture network.

With the help of built-in probability functions in MATLAB, these stochastic processes can be carried out easily. GEOFRAC produces the geometric information, such as the shape, location, orientation and aperture, for all the fractures. Detailed information can be found in Ivanova et al. [2014]. The results of

Primary Process: Generation of Planes	Secondary Process: Division of Planes into Polygons	Tertiary Process: Random Translation	Tertiary Process: Random Rotation
			

Figure 1. Three Fracture Generation Processes (Ivanova et al., 2014)

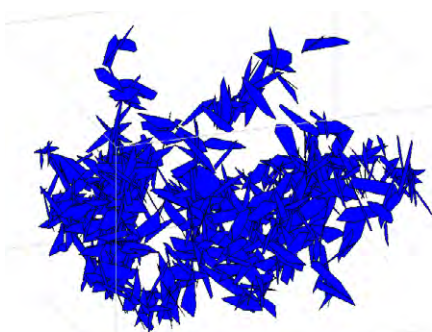


Figure 2. Graphic output generated by GEOFRAC

GEOFRAC are in the form of three-dimensional fracture networks as shown in Figure 2, where each polygon represents a fracture.

Fracture connectivity is important since it governs the behavior (stability, flow) of rock masses. For the purpose of computing interconnected paths, a fracture intersection algorithm was developed, implemented in GEOFRAC, and optimized. The algorithm follows these steps:

1. For every polygon, the radius R_i of the sphere that encloses it is computed.
2. For every pair of non-coplanar polygons, the distance D_{ij} between centers is computed. If R_i and R_j are the radii of two spheres, then the spheres intersect only if $R_i + R_j < D_{ij}$.

3. If two spheres intersect, the intersection, if any, between the polygons is computed. For this step, GEOFRAC implements the algorithms developed by Locsin [2005] to compute intersections between polygons. (See also [Locsin and Einstein, 2012])

Figure 3 shows an example of this process. The fracture intersection algorithm outlined above applies to the computation of fracture area intersections. Its purpose is to eliminate unnecessary computation. If two fracture “spheres” do not intersect, the fracture polygons will not intersect either. (Step 3 takes several calculations, while Step 2 takes only one.)

An additional process, called “clean fracture algorithm”, was implemented in GEOFRAC to determine and retain only those fractures that form an interconnected path [Sousa et al., 2012]. Namely, once all intersections between polygons have been determined, the clean fracture algorithm finds and retains only polygons that intersect either at least two other fractures, or one of the modeling volume boundaries and at least one other fracture. To further optimize the computation, assigning apertures to fractures can be postponed until after the clean fracture algorithm

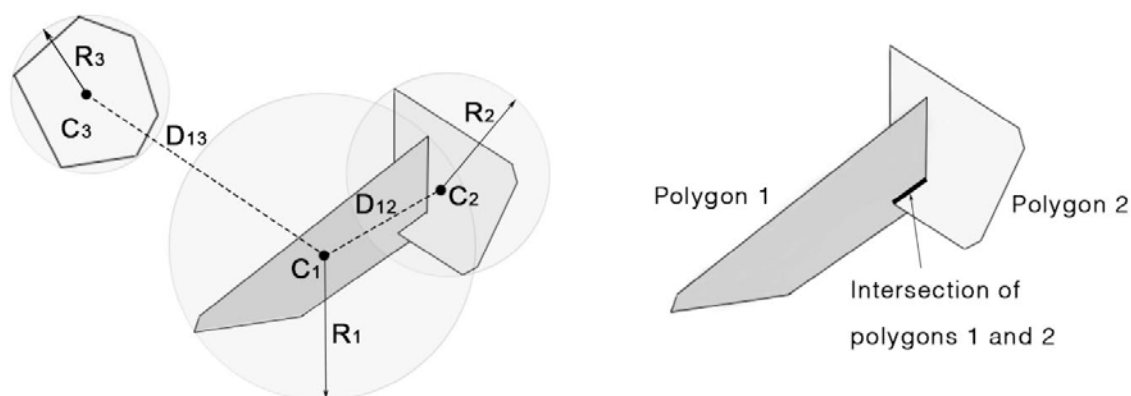


Figure 3. Fracture intersection algorithm: (left image) The spheres enclosing all polygons are computed and the intersections between spheres, if any, are determined. Two spheres intersect if the distance between their centers is smaller than the sum of their radii. The enclosing spheres of polygons 1 and 2 intersect, but neither of them intersects with the enclosing sphere of polygon 3. Therefore, polygons 1 and 2 might be intersecting, but neither of them could be intersecting with polygon 3. C_1 , C_2 , and C_3 are centers of polygons 1, 2, and 3, respectively. R_1 , R_2 , and R_3 are radii of the enclosing spheres of polygon 1, 2, and 3, respectively. D_{12} is the distance between the centers of polygons 1 and 2. D_{13} is the distance between the centers of polygons 1 and 3. (right image) For every pair of intersecting spheres, such as those of polygons 1 and 2, the intersection between the polygons, if any, is determined.

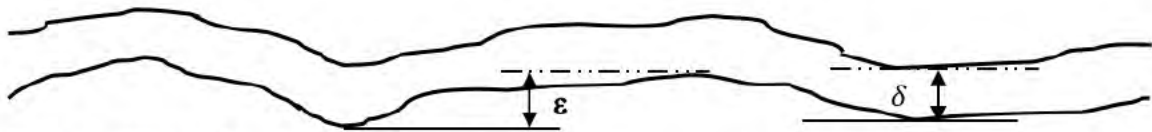


Figure 4. Sketch of fracture surface roughness

is applied. Validation of this fracture model was done by Sousa et al. (2012), who analyzed the connectivity of fracture networks.

2. Development of GEOFRAC-FLOW and GEOFRAC-THERMAL

2.1 GEOFRAC-FLOW

On the basis of GEOFRAC, a DFN flow model was developed by Sousa et al. [2013]. Since GEOFRAC provides geometric information for individual fractures, the flow problem can be solved explicitly. Since fractures are the major flow paths in the rock mass, only the flow in the fracture network is considered. The fluid flow through a single fracture is usually modeled using the cubic (Poiseuille) law [Witherspoon et al., 1980; Zimmerman and Bodvarsson, 1996], which is an analytical solution for laminar flow between two smooth parallel plates. To account for the surface roughness, surface contact, and flow path tortuosity in a natural fracture, a friction factor (f) was introduced by Louis [1969] and modified by Jones et al. [1988]. This semi-empirical quantity is introduced into the cubic law to calculate the flow rate in a single fracture:

$$Q = \frac{w\delta^3\gamma\Delta H}{12f\mu_f\Delta L} \quad (3)$$

where Q is the flow rate in the fracture; w is the width of the fracture provided by GEOFRAC; δ is the fracture aperture; γ is the unit weight of the fluid; f is the friction factor introduced by Louis [1969] and Jones et al. [1988]; μ_f is fluid dynamic viscosity; $\Delta H/\Delta L$ is the hydraulic head gradient in the fracture.

According to Jones et al. [1988], the friction factor can be calculated as:

$$f = 1 + 6\left(\frac{\epsilon}{\delta}\right)^{1.5} \quad (4)$$

where ϵ is the fracture surface roughness and δ is the fracture aperture, as shown in Figure 4.

As shown in equation (3), hydraulic head loss is proportional to the length of the fracture, reciprocal to the width and the aperture cubed. Fluids tend to flow in the direction which has the greatest pressure gradient, and it travels along the paths causing smallest head loss. In the model, paths are chosen as the

shortest connection between the inlet fracture and outlet fracture. These connections can be found by using the Dijkstra's algorithm [Dijkstra, 1959]. After the paths are found, a flow path network is built as shown in Figure 5 below:

To reduce computational cost, the fracture network is simplified by using one branch to equivalently represent the fractures from one node (intersection) to another. The equivalent fracture aperture, length, and width are expressed below.

$$\delta_{eq} = \frac{1}{\sqrt[3]{\sum_{i=1}^n \frac{l_i}{l} \left(\frac{1}{\delta_i^3}\right)}} \quad (5)$$

where l_i and δ_i are the length and aperture of the i^{th} fracture; l is the total length of the series of fractures.

$$l_{eq} = \sum_{i=1}^n l_i \quad (6)$$

$$w_{eq} = \frac{\sum_{i=1}^n w_i l_i}{\sum_{i=1}^n l_i} \quad (7)$$

where w_i is the width of the i^{th} fracture.

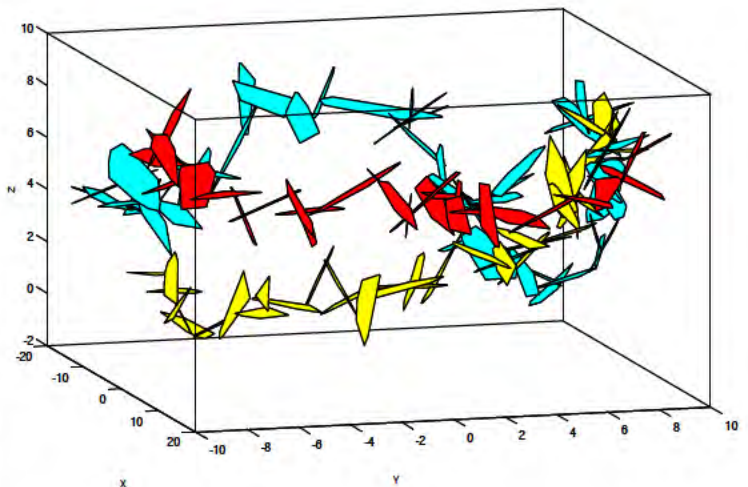


Figure 5. Example of flow network (Sousa, 2012)

With the simplified flow network, the transmissivity between two fracture network nodes can be calculated. The hydraulic heads at the fracture network nodes H_i are formulated into the head vector $\mathbf{H}$. The mass conservation at each node can be formulated into the matrix form of linear equation system:

$$\mathbf{TH} = \Delta \mathbf{V} \quad (8)$$

where $\mathbf{T}$ is the transmissivity matrix; $\mathbf{H}$ is the hydraulic head vector; and $\Delta \mathbf{V}$ is the volume accumulation vector. Except for the nodes at the inlet and outlet, $\Delta \mathbf{V}$ is zero. The linear equation system is solved and then the flow rate in each fracture is calculated. Validation of the flow model has been performed with parametric studies [Vecchiarelli et al., 2013].

2.2 GEOFRAC-THERMAL

Based on the GEOFRAC and GEOFRAC-FLOW, a heat transfer model was developed by Li et al. [2013] to model the heat transfer between the flowing fluid and the fractured rock mass. Based on the assumption of a uniform initial temperature in the rock matrix, the heat transfer model is intended to simulate the early stage of a geothermal reservoir development. In a single fracture, the heat transfer between the flowing fluid and the rock is through heat convection. The uniform wall temperature (UWT) heat convection equation for flow between two parallel plates is used:

$$q_h = h(T_r - T_f) \quad (9)$$

where q_h is the heat flux from the rock to the fluid; h is the heat convection coefficient; T_r is the temperature of the rock and T_f is the bulk temperature of the fluid. The heat convection coefficient h can be calculated as:

$$h = \frac{k_f Nu}{2\delta} \quad (10)$$

where k_f is the thermal conductivity of the fluid; Nu is the Nusselt number, which is the ratio of heat convection flux to heat conduction flux. Nu is related to flow state (laminar or turbulent) and the dimensions of the parallel plates. For laminar flow between two isothermal parallel plates, an analytical solution [Mills, 1995] is available for the Nusselt number as a function of the dimensionless length Z . The dimensionless length is defined as:

$$Z = \frac{k_f L}{2\delta^2 U \rho_f C_{pf}} \quad (11)$$

where L is the distance from the inlet; U is the flow velocity in the fracture; ρ_f is the density of the fluid; and C_{pf} is the heat capacity of the fluid.

The Nusselt number is higher in the thermal entrance region because of the high heat convection rate and asymptotically approaches 7.54 when Z is large. To account for the high heat convection rate in the entrance region, the average Nusselt number (Nu) is used:

$$\overline{Nu} = 7.54 + \frac{0.03}{Z + 0.016Z^{1/3}} \quad (12)$$

As shown in Equation (12), the average Nusselt number is higher when Z is small and it approaches 7.54 when Z approaches infinity.

With the above heat convection model for the heat transfer between the fluid and the rock in a single fracture, GEOFRAC-THERMAL explicitly calculates the fluid temperature in each branch. Assuming that the inflow at each node is well mixed, the temperature of each node can be calculated by weight averaging the temperature of the inflowing branches.

Figure 6 is an example of the results produced by GEOFRAC-FLOW and GEOFRAC-THERMAL. The example simulates the flow and temperature of the fluid in a $10 \times 8 \times 4 \text{ m}^3$ geothermal reservoir. To simplify the graphic output, the fracture branches are represented using lines and the intersections are represented using nodes. The indices are assigned in GEOFRAC before deleting the non-conductive fractures, so the indices of nodes and fractures are not continuous. The output of GEOFRAC-FLOW is the flow rate in each of the fracture branches, which is indicated in blue near the branches. The output of GEOFRAC-THERMAL is the temperature at each of the network nodes, which is indicated in purple near the nodes. The inlet fluid temperature is 70°C , while the rock temperature is 200°C . As shown in Figure 6, because of the high efficiency of heat convection between the rock and fluid, the temperature of the fluid reaches that of the rock at a distance not far from the inlet. This example also shows that GEOFRAC, as a discrete fracture model, calculates the flow rates and temperatures explicitly.

2.3 Summary of GEOFRAC, GEO-FRAC- FLOW and GEOFRAC-THERMAL.

The three models are developed to simulate the fracture network, flow and heat transfer in the geothermal reservoir. For now, the three models are not fully coupled: GEOFRAC-FLOW uses the geometry infor-

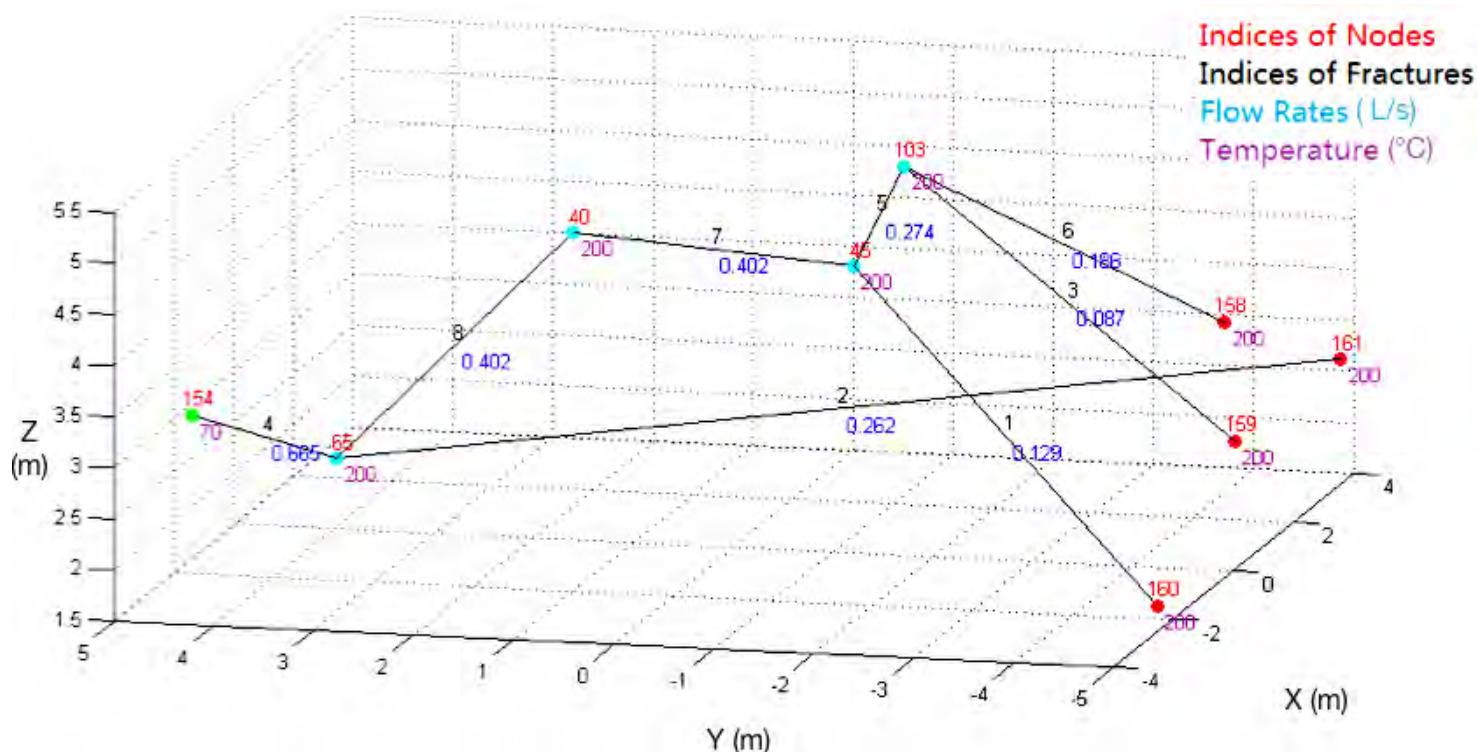


Figure 6. Result produced by GEOFRAC, -FLOW AND -THERMAL.

mation produced by GEOFRAC to calculate the flow in the fracture network; GEOFRAC-THERMAL uses the geometry and flow information to calculate the heat transfer. The results of GEOFRAC-FLOW and -THERMAL will not affect the results of GEOFRAC. The material properties such as viscosity, density, thermal conductivity etc. are assumed to be constant since the reservoir condition is relatively stable. Table 1 summarizes the input of each of the three models.

Systematic parametric studies have been conducted with the models to check their validity, and to help the model user better understand the models. Detailed results can be found in Vecchiarelli et al. [2013] and Li et al. [2014] on GEOFRAC-FLOW and -THERMAL respectively. The case studies described below also include some aspects of parametric studies.

3. Case studies using the GEOFRAC package

3.1 The Fenton Hill project

The project at Fenton Hill was the first attempt anywhere to work with a deep, full-scale hot dry rock (HDR) reservoir [Tester et al., 2006]. The site is located on the edge of the Valles Caldera at the northern end of the Rio Grande rift zone in north-central New Mexico. It was chosen for its heat and rock characteristics, as well as its proximity to the Los Alamos National Laboratory where the project was conceived. The purpose of the project was to develop methods to extract energy economically from HDR systems located in crystalline, granitic/metamorphic basement rock of suitably high temperature. Useful data were

found in the technical report written by Tester and Albright (1979). The plan view of the Fenton Hill site is shown in Figure 7. The injection well (EE-1) is at the top of the map and the production wells (GT) are at the bottom of the map.

According to Tester and Albright, [1979], the main production well is GT-2B, where 90% of the hot fluid is produced. During the injection test, water loss was observed to decrease. One explanation was that the decrease of water loss was caused by saturation of the rock, so it is reasonable to assume that all the water injected is recovered from the production wells. The reservoir can be simplified as a two-well system, which can be modeled by the current GEOFRAC models. Rock temperature was not measured directly. However, the initial water temperature in the well was measured, and was close to that of the rock and could be used as rock temperature.

The horizontal distance between the injection and production wells was about 100m and the estimated effective heat transfer area was 8000m² [Tester and Albright, 1979]. No estimated reservoir volume was reported. The flow rate was in the range of 5–30L/s. The impedance of the reservoir was in the range of 4–21bar-l/s. There were no data on fracture aperture; 0.2mm was assumed as the mean aperture in the simulation done by Tester and Albright [1979].

Using the above-mentioned information, GEOFRAC, GEOFRAC-FLOW and GEOFRAC-THERMAL were applied. Assumptions and estimations are made for

some parameters that are not mentioned in the report by Tester and Albright [1979]. The parameters are summarized in Table 2, for which the definitions can be found in Table 1.

Because of the stochastic processes used in GEOFRAC, the results are not deterministic. To draw reliable conclusions, a moderate number of simulations must be run. In this case study, 20 simulations were run and analyzed below. A statistical analysis has been done by Li [2014] to study the confidence level of averaging the results of 20 simulations. The analysis showed that 20 simulations were enough for drawing reliable conclusions. Figure 8 is a schematic representation of the possible flow paths in one of the simulations. Similar to the convention in the example shown in Figure 6, the flow rates and temperatures are calculated explicitly for the fracture network, as shown in Figure 8.

The mean flow rate of the 20 simulations is 11.3L/s with a standard deviation of 9.05L/s. These values are in line with the flow rate of the production well, which indicates that GEOFRAC can provide results that do not deviate much from the real data. The Reynolds

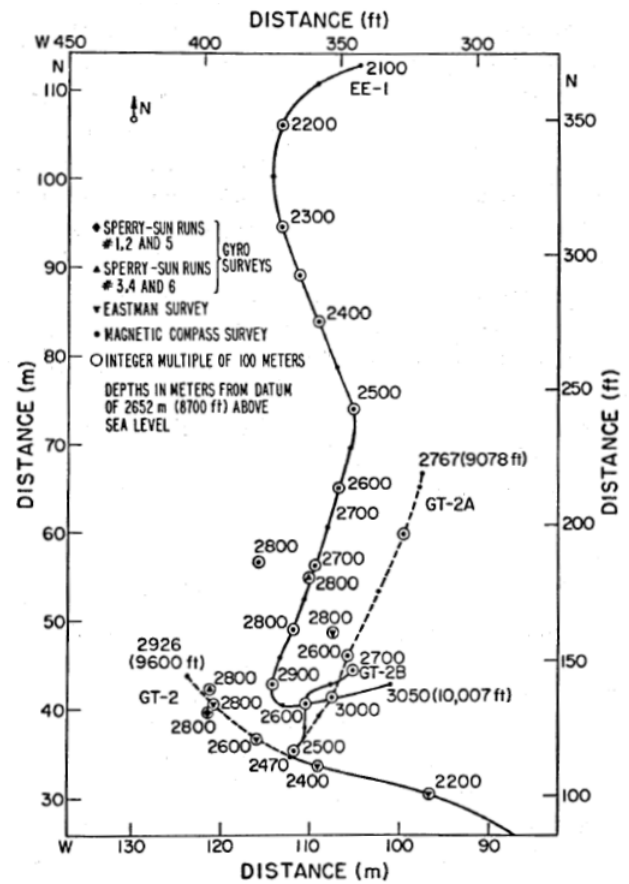


Figure 7. Plan view of the lower section of the GT-2 and EE-1 Wellbores

Table 1. Input parameters of the three models

Model	Inputs	Description
GEOFRAC	X, Y, Z	Reservoir dimensions [m]
	μ	Fracture intensity [m^{-1}]
	$E[A]$	Expected Fracture Area [m^2]
	m, k	Orientation Distribution parameters
	$mPole$	Mean orientation of all fractures
	Rot	Random rotation parameter in the tertiary process
	δ	Fracture aperture [m] (mean value for the stochastic model)
	ε	Fracture roughness [m]
GEOFRAC-FLOW	P_{in}	Inlet pressure [Pa]
	P_{out}	Outlet pressure [Pa]
	μ_f	Fluid dynamic viscosity [Pa·s]
GEOFRAC-THERMAL	k_t	Fluid thermal conductivity [$\text{W}/(\text{m} \cdot ^\circ\text{C})$]
	ρ_f	Fluid density [kg/m^3]
	c_{pf}	Fluid heat capacity [$\text{J}/(\text{kg} \cdot ^\circ\text{C})$]
	T_r	Rock temperature [$^\circ\text{C}$]
	T_{in}	Injection fluid temperature [$^\circ\text{C}$]

number of all the branches is checked to make sure that the assumption of laminar flow in the flow model is satisfied.

Because of the small apertures and large areas of the fractures, the heat transfer between the rock and the flow is very efficient. As shown in Figure 8, the temperature of the water reaches that of the rock at the first node after the injection boundary. One should keep in mind, however, that the thermal model in GEOFRAC assumes a constant rock temperature, so the results can only model the beginning stage of the injection. Still, the results indicate that the large area and small apertures of fractures provide effective heat extraction from the underground.

This case study with GEOFRAC shows that it can be used to model the heat and mass transfer in a geothermal reservoir. However, the constant temperature assumption for the rock limits the capability of this model to simulating only the beginning stage of the injection. While the Fenton Hill case is a HDR (EGS) application, the following case is a hydrothermal application.

Table 2. Summary of the Input Parameter for GEOFRAC Simulation of Fenton Hill Project

X (m)	Y (m)	Z (m)	μ (m^{-1})	$E[A](\text{m}^2)$	m	k	$m\text{Pole}$	rot
40	100	80	0.2	1000	4	20	$[\pi/2, 0]$	0
μ (m)	ε (m)	ΔP (Pa)	μ_c (Pa·s)	k_c (W/m·K)	ρ (kg/m^3)	C_{pc} (J/kg·K)	T_c ($^{\circ}\text{C}$)	T_{in} ($^{\circ}\text{C}$)
0.0002	0.001	1MPa	0.468×10^{-3}	0.6546	983	4185	180	60

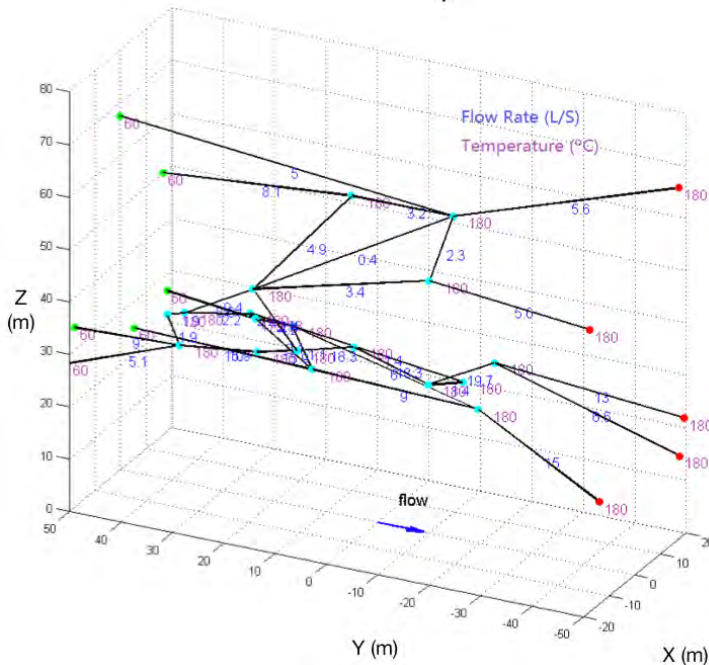


Figure 8. Schematic representation of the possible flow paths obtained in one simulation

3.2 The Námafjall geothermal field

The Námafjall geothermal field is located in north-east Iceland about 5 km northeast of Lake Myvatn, as shown in Figure 9. It is located in the southern half of the Krafla fissure swarm and it is associated with the Krafla volcano. The Krafla geology is characterized by active rifting, forming a graben zone through its center, where volcanic craters, volcanic pyroclastics and lava flows, all of basaltic composition, dominate. The fissure swarm that intersects the Krafla central volcano (100 km long and 5 to 8 km wide) is part of the neo-volcanic zone of axial rifting in North Iceland [Malimo, 2012].

Magma from the Krafla caldera traveled horizontally in the SSW direction along the fissures and fractures all the way down to Námafjall, and it serves as the heat source for the hydrothermal system. There are several fractures and faults in this area, such as the Krummaskard and Grjótagjá, and surface manifesta-

tions are often clearly aligned with the fractures. The geological characteristics of the Námafjall field indicate that the Námafjall ridge is part of the Námafjall-Dalfjall-Leirhnjúkur ridge, and it has an overall length of about 15 km and width of about 1 km [Ragnars et al., 1970].

Deep drillings conducted in this area have provided important information on the sources and composition of geothermal fluids, thermal properties of the fluids and the geology and fracture system of this geothermal area. The data used in the simulations were obtained from the Rivera Ayala [2010], and boreholes and measurements by Landsvirkjun (see e.g., Gudmundsson et al. [2010]).

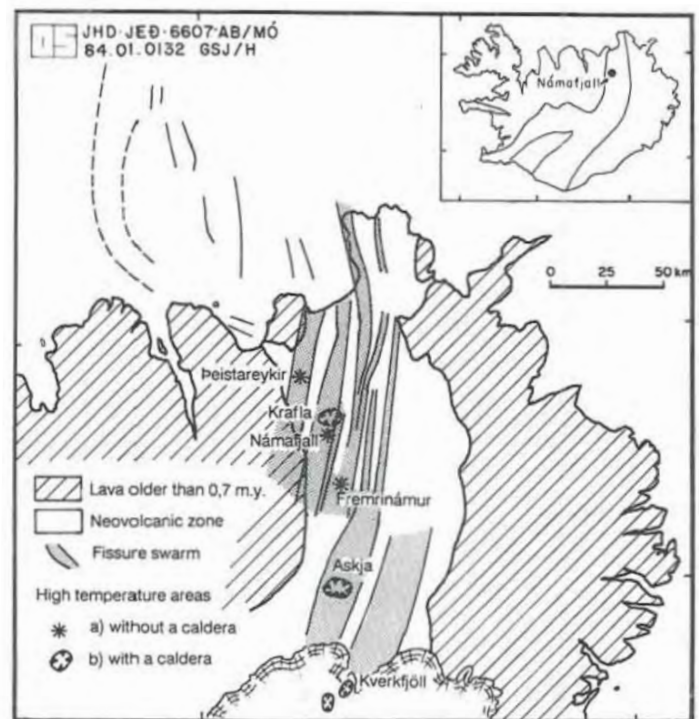


Figure 9. The high temperature areas in North Iceland and location of the Námafjall geothermal reservoir (from Isabirye, 1994)

Table 3. Summary of the Input Parameters for GEOFRAC Simulation of Námafjall geothermal field

X (m)	Y (m)	Z (m)	μ (m^{-1})	$E[A](\text{m}^2)$	m	k	$mPole$	rot
1000	2000	1000	0.02	800,000	4	20	$[\pi/2, 0]$	0
μ (m)	ε (m)	ΔP (Pa)	μ_r (Pa·s)	k_r (W/m·K)	ρ (kg/m^3)	C_{pr} (J/kg·K)	T_r ($^{\circ}\text{C}$)	T_{in} ($^{\circ}\text{C}$)
0.004	0.04	1MPa	0.468×10^{-3}	0.6546	983	4185	250	60

The Námafjall geothermal field is a large reservoir formed by the Krafla caldera. It is about 10 km long and 5-8 km wide. The GEOFRAC simulations (see Vecchiarelli et al. [2014]) are mainly focused on the fractured zone in this field, which is 2000m long, 1000m wide and at the depth from 1000m to 2000m. Given that the flow is mostly from the major faults and fractures, a large expected fracture area $E[A]=800,000 \text{ m}^2$ and mean aperture values (log-normal distribution) are used in the simulation. The parameters are summarized in Table 3, for which the definitions can be found in Table 1.

Figure 10 is a schematic representation of the possible flow paths in one of the simulations. Compared to the case study of the Fenton Hill project, the reservoir is much larger. Since the objective of this case study is to simulate the large-scale fractures and faults, the flow rates in the fractures are higher than those in the Fenton Hill project.

Because of the stochastic processes used in GEOFRAC, the results are not deterministic. To draw reliable conclusions, a moderate number of simula-

tions must be run as before. Again, 20 simulations were run. The average/mean value of the total flow rates was $0.21 \text{ m}^3/\text{s}$ with a standard deviation of $0.14 \text{ m}^3/\text{s}$. These values are in line with the measured production flow [Rivera Ayala, 2010] indicating that GEOFRAC can provide results that do not deviate much from the real data. The Reynolds number of all the branches was checked to make sure that the assumption of laminar flow in the flow model is satisfied.

Similar to the simulation results of the Fenton Hill project, the temperature of the water reaches that of the rock at the first node after the injection boundary. The average energy extraction rate estimated by GEOFRAC is 116,224 KW (see Vecchiarelli et al. [2014]); it is much higher than the capacity of the power plant, which is around 10 MW [Ragnars et al., 1970]. This is quite understandable given that the energy conversion efficiency of a geothermal plant is often around 20%. In addition, the heat transfer model is based on the above-mentioned assumption that the temperature of the rock is constant,

but there is temperature drawdown in the rock. The heat extraction rate cannot be maintained for a long time. Although the results from GEOFRAC overestimate the power of the plant, they provide the upper bound of the power. Future work on the thermal model is needed to produce long-term temperature predictions.

4. Conclusion

This paper presented recent research developments on flow and heat transfer modeling with GEOFRAC, a three-dimensional stochastic discrete fracture network model. Governing equations for flow and heat transfer in a single fracture are presented. Mass and energy conservation equations are

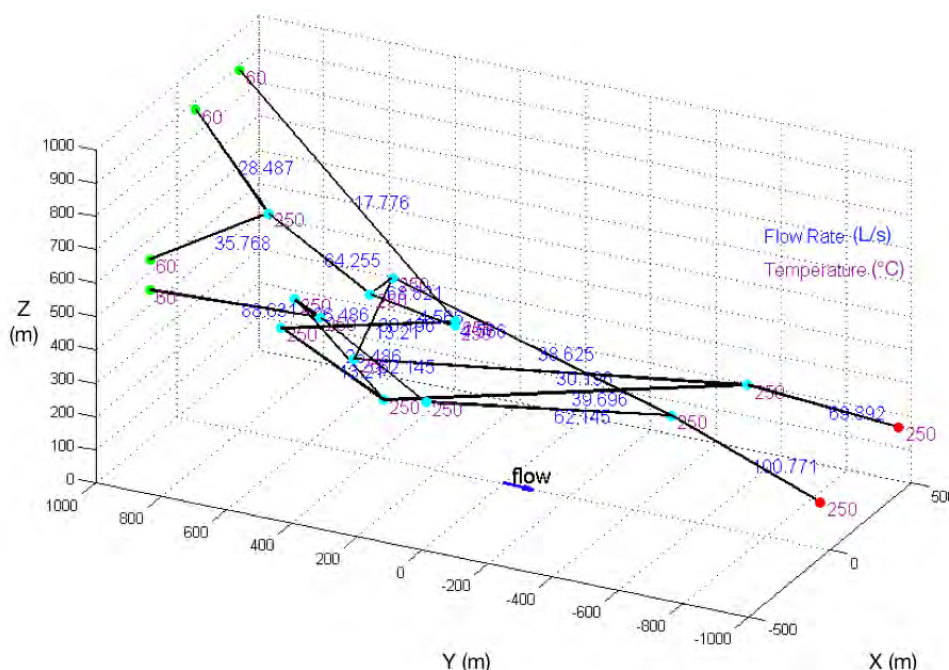


Figure 10. Schematic representation of the possible flow paths obtained in one simulation

used to solve the flow and heat transfer problem in the fracture network. Since GEOFRAC provides the geometric information for every fracture in the modeled volume, the flow rate and temperature for each fracture in the network can be calculated explicitly.

Two case studies have been used to demonstrate the applicability of the GEOFRAC package in modeling the flow and heat transfer in geothermal reservoirs. The case study with the Fenton Hill (HDR/EGS) project demonstrates how the parameters are chosen for GEOFRAC according to the measured data and geological description. Since most of the fluid flows in a few major fractures, relatively simple fracture networks are generated to simulate the flow and heat transfer in the geothermal reservoir. The flow rate and temperature produced by the simulations are in line with the measured data.

The case study with the Námafjall geothermal field, a hydrothermal case, focuses on the fractured zone of the geothermal reservoir. The parameters are chosen for GEOFRAC according to the measured data and geological description so that the major flow conducting faults and fractures can be modeled. The GEOFRAC simulations assume uniform rock temperature, so only the initial stage of the flow and heat transfer is modeled. Yet, the simulations provide reasonable results for flow rates and temperature in the reservoir.

With the discrete fracture network generated by GEOFRAC, the flow and heat transfer in each fracture can be explicitly calculated. The heterogeneity of flow and temperature in the fracture reservoir can be modeled easily with DFN. The current model assumes constant rock temperature, so only the initial stage of a geothermal reservoir can be modeled. However, this provides an upper bound for reference on the temperature and power extraction from the reservoir.

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Effect of Natural Fracture System on Reservoir Stimulation

Submitted by Paul La Pointe, Mark Cottrell, Cliff Knitter and William Dershowitz, Golder Associates Inc., (Redmond, WA)

1. Natural Fractures: Friend or Foe?

Are natural fractures an advantage, a disadvantage, or a side-show in reservoir stimulation for enhanced recovery from unconventional reservoirs? Many shale-gas operators have developed their fields with great success while completely ignoring natural fractures. Instead, they undertake drilling and stimulating according to well development and completion patterns determined solely by lease-hold geometry, or using regional stress orientation.

In many cases, however, operators discover later that this approach results in significant variations in production between wells. Figure 1 presents an example in which an operator used a single, standardized com-

pletion, stimulation and production design at similar depths and landing zones, yet estimated a wide range of ultimate recoveries based on production decline curves. This indicates that it might be possible to “high grade” reservoir development or improve the production from underperforming wells by considering the locally variable geology, and in particular, the natural fractures and in-situ stress.

Another operator in a different play carried out a detailed field program to investigate and improve its hydraulic fracturing program [1]. As part of this program, the pre- and post-stimulation gas rates were measured in a number of wells, two of which

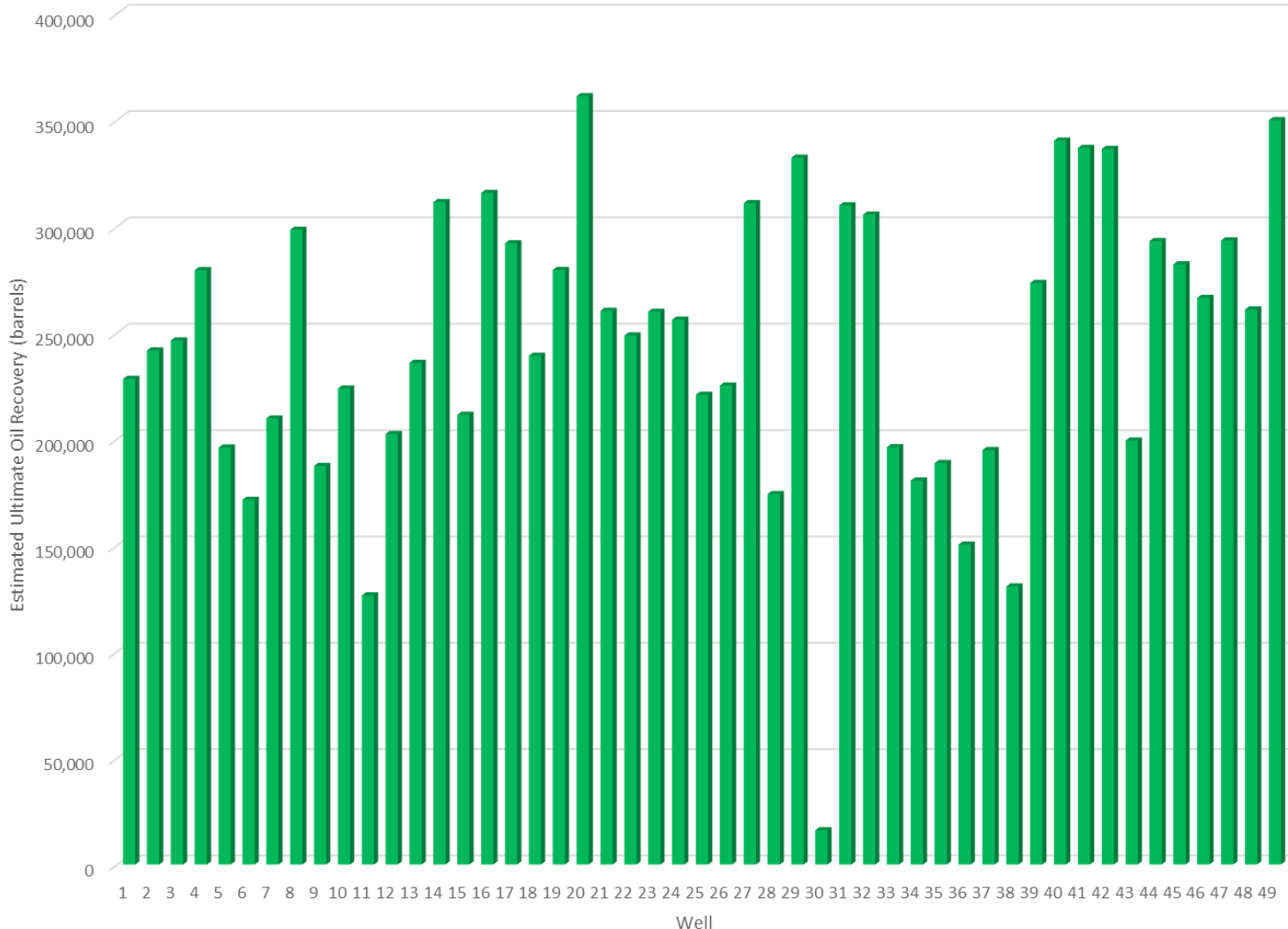


Figure 1. Estimated ultimate oil recovery from 49 wells in an unconventional oil play.

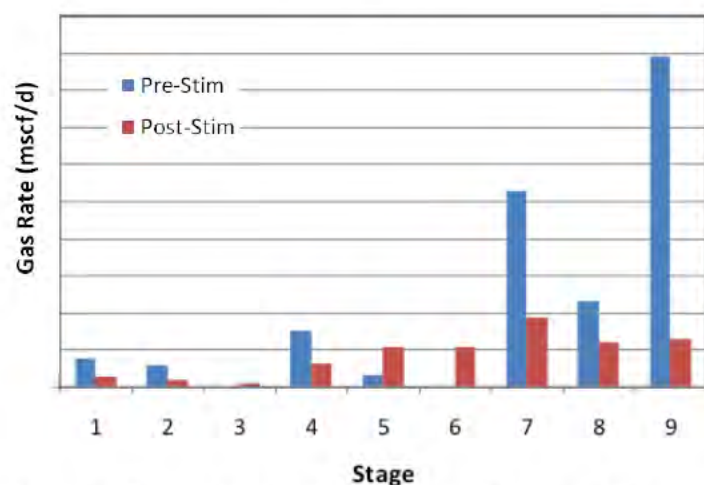
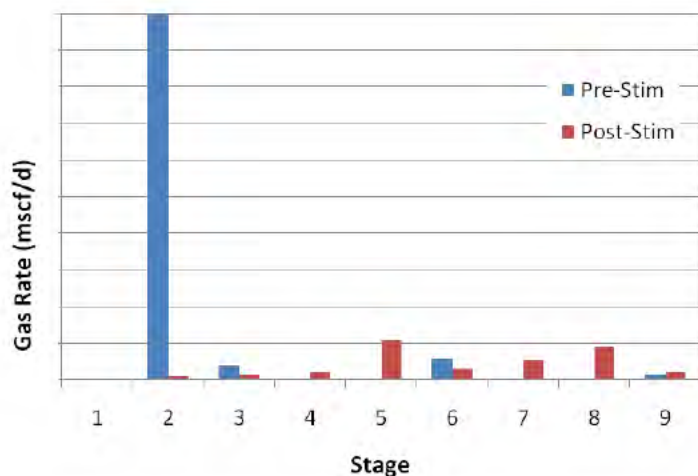


Figure 2. Pre- and post-stimulation gas flow rates by stage for two wells in an unconventional gas play.

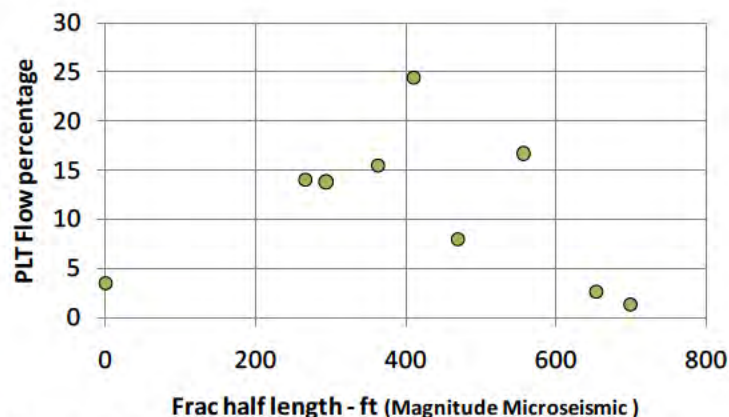


Figure 3. Hydrofracture half-length as inferred from the extent of the microseismicity and the production share from the associated stage.

are shown in Figure 2. In these and in other wells, the pre-stimulation rates for some stages actually *decreased* after hydraulic fracturing. Moreover, the extent of the induced microseismicity during the stimulation process showed little correspondence to the post-stimulation rates (Figure 3).

Analyses using Discrete Fracture Network (DFN) models indicated that geometry and hydromechanical (coupled geomechanical and flow characteristics) properties of the natural fracture system, and the way in which the hydraulic fracture (For this paper, also termed "hydrofracture.") interacted with them, may have played a significant role in the observed rates and recovery in response to these "fracture-neutral" reservoir stimulation programs. In some instances,

Development Decision	Problem Statement
Landing depth	Which stratigraphic interval is it best to target?
Well Spacing	What is the optimal well spacing?
Lateral length	What is the most economical lateral length?
Stage spacing	What is the optimal stage spacing?
Vertical contribution	How much of stratigraphy are we draining (i.e. frac height)?
Timing of wells	In what order should wells get drilled & fraced?
Area differences	How does sub-surface deliverability change?
Completions Optimization	Given deliverability range across the field, does the drilling/completion strategy change?
EUR	What is the influence of natural fractures on the SRV? Where did the proppant go?

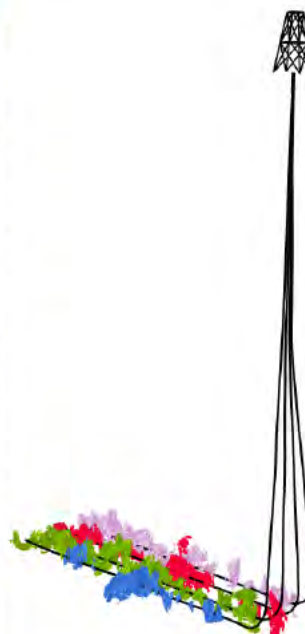


Figure 4. Typical applications of DFN modeling to improve recovery and reduce cost in the development of unconventional oil & gas resources.

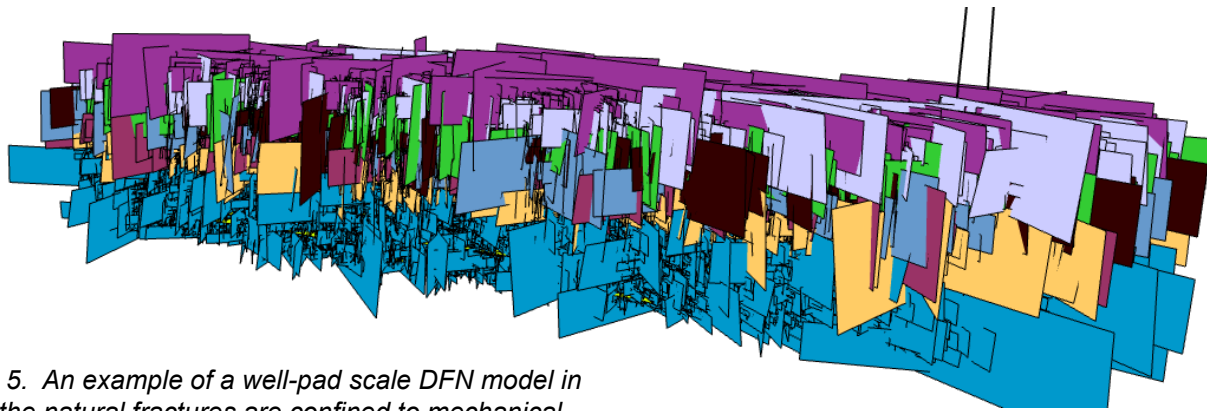


Figure 5. An example of a well-pad scale DFN model in which the natural fractures are confined to mechanical layers.

the hydrofracture interacted with the natural fracture system to increase recovery, while in other cases, the interaction led to a decrease in rates and recovery.

2. Discrete Fracture Network Modeling as a Tool to Optimize Recovery from Unconventional Reservoirs

Fractures can impact unconventional reservoir development in many different areas. Examples of reservoir development decisions that have been addressed through DFN analysis of the interaction of the hydrofracture and natural fractures are shown in Figure 4.

3. What Exactly Is a DFN Model?

A DFN model is an abstraction of the geometry and hydromechanical properties of the natural fracture system in which the natural fractures are represented by convex planar or non-planar polygons (Figure 5). Although not shown in the figure, the hydromechanical properties of the matrix can also be included and modeled within the DFN framework. It is rarely necessary to explicitly include fractures below a certain size, as their contribution to larger scale rock mass response can be represented as an effective property of the matrix.

The development of the DFN model requires specification of the orientation, size, shape, intensity and hydromechanical properties of each fracture. In unconventional reservoirs, borehole image log data is common and can be analyzed to infer the number of fracture sets present, their orientation and possible factors that control the variations in intensity. Core or image logs can also provide some constraints on fracture aperture, although there are many issues that make apertures derived from core or image logs uncertain. Fracture shape and size are also among the more challenging parameters to constrain, since neither can be directly measured. One common method in unconventional reservoirs is to assume that the height of most fractures is confined by the mechanical layer thicknesses, while the lateral ex-

tent is inferred from the analysis of 3D seismic attributes, such as coherence, that may show the lateral extent of larger joints and faults. There are no measurements of the intrinsic fracture permeability, and so this parameter is constrained through later model calibration.

The DFN simulation of the hydraulic fracturing process also requires specification of the stress tensor throughout the model region, as well as various elastic moduli and strength parameters. The elastic moduli (dynamic moduli) are obtained from sonic logs, and may be further calibrated to static values where core has been recovered and tested under triaxial stress conditions in the lab.

In addition, parameters for a frictional sliding law such as Mohr-Coulomb [2] or Barton-Bandis [3] are required in order to simulate the impact of the varying stress field on the fracture aperture and permeability. Often times, there are no lab tests for determining frictional angle and cohesion, and so analog or observational values are employed and adjusted with geological reasonableness during later model calibration. Some vendors have established proprietary correlations between UCS and more commonly measured properties such as Young's Modulus and lithology. If the Barton-Bandis frictional model is employed, JRC may be estimated from core inspection, while JCS can be inferred from UCS and weathering condition of the fracture surfaces, especially if UCS has been measured in the lab from core.

The stress state is typically derived from a series of different sources (Figure 6). A typical workflow has the following steps:

1. Integrate density for vertical stress, S_v
2. Use hydraulic tests (frac/LOT) to determine S_{min}
3. Estimate S_{hmax} from wellbore breakout width (requires S_{hmin} and Compressive Strength)
4. Estimate S_{hmax} from drilling induced tensile fractures (requires S_{hmin})

5. Identify active fault structures in the reservoir to test/calibrate stresses

6. Refine model to account for tectonic stresses

4. Calibration

Calibration is a key part of the workflow to reduce the many uncertainties in the hydromechanical properties assigned to the model, and more importantly, to build confidence in the usefulness of the model for hydraulic fracturing optimization. There are several options in unconventional reservoirs for calibrating and building confidence.

A good way of testing the geometric definition of the natural fracture system is to predict fracture orientations and intensity, and possibly aperture, at a well or wells that were not used for model parametrization. This test can be carried out on a newly drilled well, or on existing wells that were strategically withheld from the model development. The match between model and data can be assessed qualitatively, or more rigorously through standard model evaluation techniques.

There are two other types of data that can be used to calibrate and build confidence in the model: compar-

Vertical Stress

- S_v from integration of wireline measured density

Minimum Principal Stress

- S_{hmin} derived from LOT, XLOT, mini-frac

Max Horizontal Stress

- S_{hmax} derived from modelling and wellbore failure

Stress Orientation

- Borehole breakouts
- Drilling induced fractures

Pore Pressure

- P_p from direct measurement
- Derived from Sonic or Seismic

Figure 6. Sources of data for estimating the in-situ stress field.

ing the pattern of microseismicity in the model to the measured microseismicity; and simulating post-stimulation production if there is sufficient data quality and production time to make a meaningful comparison.

Figure 7 shows the location of measured microseismicity during the hydraulic fracturing of stages along one of the laterals in a four-lateral pad. The colors represent events belonging to a particular stage. Note the extent of the microseismicity and the dif-

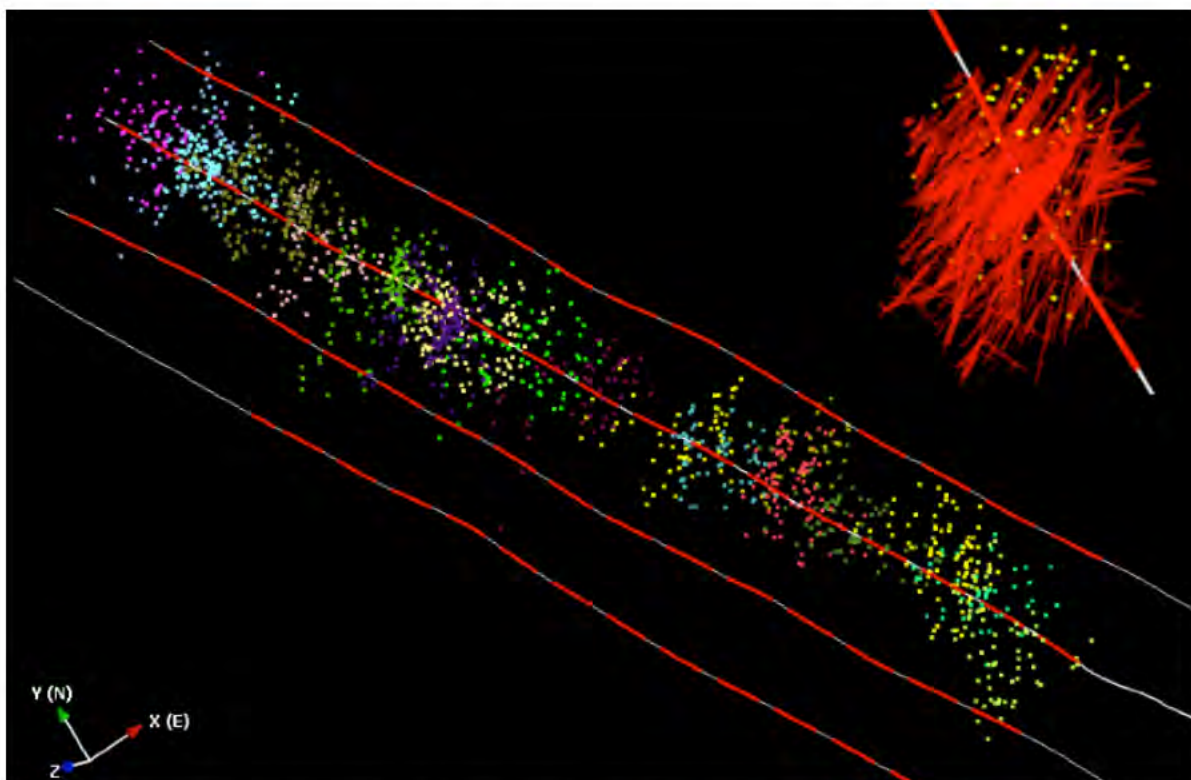
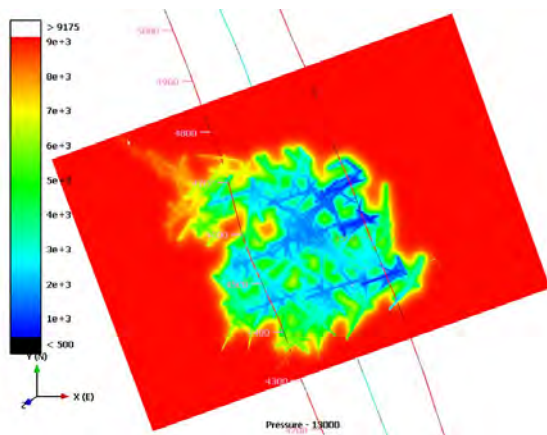


Figure 7. Observed microseismicity along lateral wells. Intervals shaded red are stages. Inset diagram in upper right corner shows a comparison of the measured microseismicity (yellow dots) and the stimulated DFN fracture network (red fractures) for one stage.

Pressure drawdown 542 days



Simulated production drawdown curves

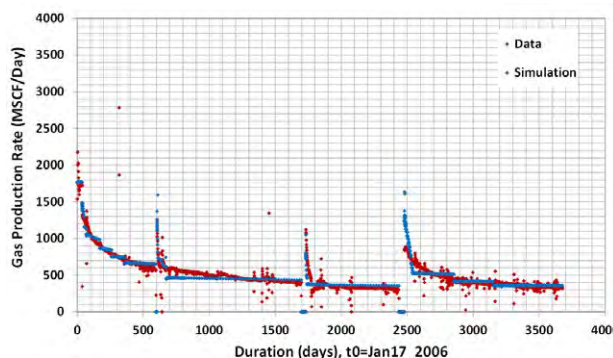


Figure 8. Simulation of pressure drawdown and production using a pad-scale DFN model. Comparison between simulated production history and measured production is very close.

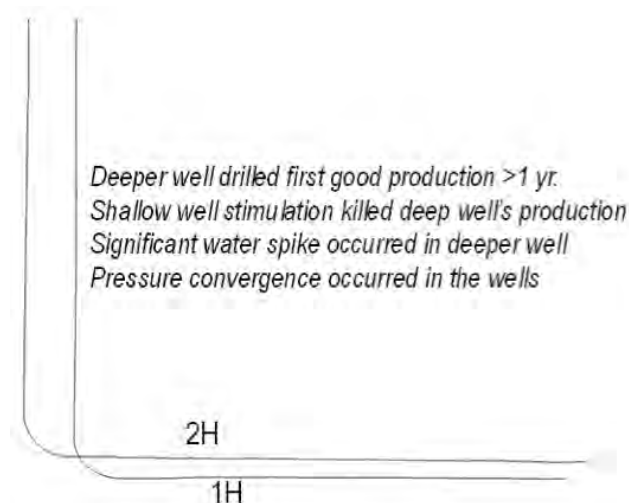


Figure 9. Schematic of stacked lateral well design.

fuse (non-planar) nature of the point clouds.

Microseismicity can also be simulated in the DFN model, in which fractures where the shear stress has exceeded the frictional resistance to slippage are identified and tagged with a dot at their centroid to indicate a potential microseismic event. An inset in the upper right-hand corner of the figure shows the results for one stage. The yellow dots are the measured microseismicity, and the red fractures are those fractures in the DFN model where the shear stresses exceeded the frictional stresses and rock strength resisting slippage, showing good correspondence between the DFN model and field results. The results of this DFN model illustrate that the natural fracture system is significantly interacting with the induced hydrofracture.

Another way to further calibrate and build confidence in the DFN model is to simulate post-stimulation production. Production occurs at variable rates, and so

it is convenient to rate-normalize the production history through deconvolution so that the resulting production history mimics a constant production rate history. This is computationally easier to simulate and makes the impact of the natural fracture system and matrix more clear by minimizing the impacts of rate variability. Figure 8 shows an example of post-stimulation production simulation for a three-well pad. The production obtained from the model closely matches the measured production. The pressure snapshot at 542 days shows that a lot of the region between the three laterals has been potentially drained, indicating the greater spacing between laterals may lead to increased recovery.

5. Optimizing Landing Zones

An operator in the Permian Basin found in a two-well stacked-lateral design (see Figure 9) that the interference of the upper lateral with the lower one significantly reduced the economic viability of the well pad. The design was intended to increase production but had the opposite effect. The operator needed to understand what caused the problem and how it could be avoided.

A DFN model was created for the well pad and surrounding region, calibrated and evaluated to build confidence in the model. At this point, a series of targeted simulations were carried out. Figure 10 shows the maximum horizontal stresses after stimulation around the lower lateral that was hydraulically fractured first. Figure 11 shows the maximum horizontal stresses after the subsequent stimulation of the upper lateral. Note the differences in appearance between the two results.

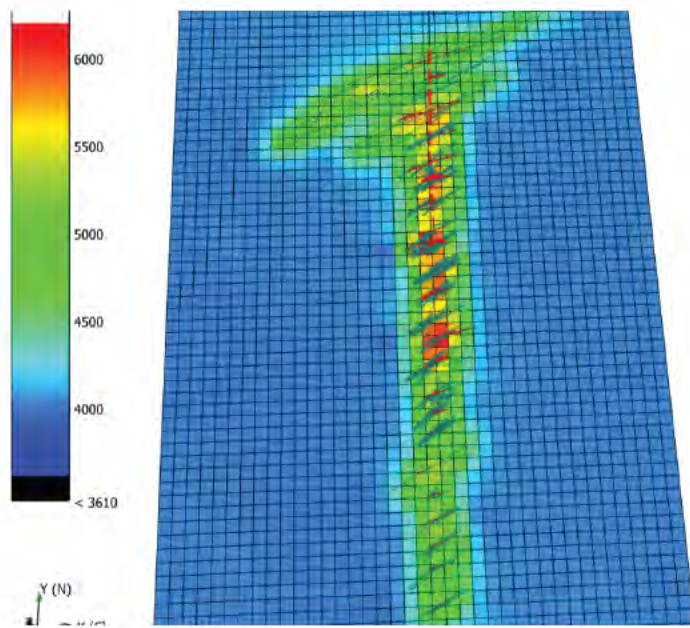


Figure 10. Stresses around the lower lateral, hydrofractures and the natural fracture system connected to the hydrofractures after the stimulation.

6. Optimizing Stimulation Design

Figure 12 shows how the stress perturbation associated with the stimulation of the upper lateral impacted the stresses around the lower lateral. The DFN modeling showed that the stimulation of the deeper well formed a stress shadow (lower stress region) that extended upward toward the landing horizon for the upper well. Stimulation of the upper well took advantage of the lower stress region, resulting in interference between the two wells.

In a different unconventional play, the operator wanted to improve recovery if possible by using a different stage spacing and length, number of perforation clusters, pumping rates, lateral length and lateral spacing. The combination of factors resulted in over 30 cases. It would have been prohibitively expensive to test all of the alternatives in the field, so the cases were first screened using DFN models. Figure 13 shows pressure snapshots for two of the alternative cases (Cases 2 and 4) after 1500 days of production post-stimulation for two different lateral spacings.

The figure shows that the amount of drainage is a function of both the lateral spacing (330 ft vs. 500 ft), and the differences between the stimulation operational parameters represented by each case. For Case 4, the 500 ft spacing may be failing to adequately drain some of the matrix between the laterals, suggesting that a spacing on the order of 330 ft may be preferable to a 500 ft spacing for this case. Alternatively, there appears to be interference among the three laterals for Case 2 at the 330 ft spacing, and

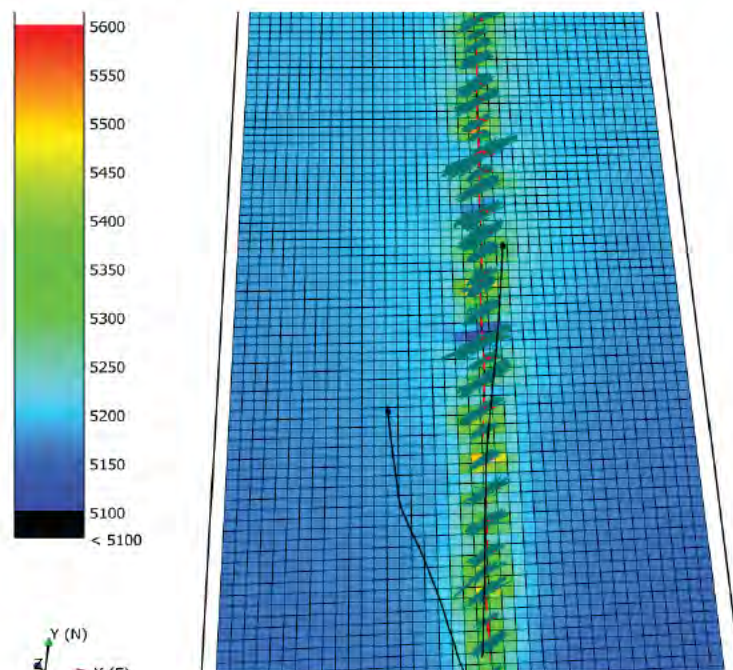


Figure 11. Stresses around the upper lateral, hydrofractures and the natural fracture system connected to the hydrofractures after the stimulation.

more extensive drainage for a 500 ft spacing.

Figure 14 illustrates how the DFN simulations were used to identify optimal spacing for the cases, and how the optimal spacing for one case may not be optimal for another.

Figure 15 summarizes the calculated EUR for 12 of the cases and three fracture model and geomechanical scenarios.

Each one of the three colored histogram bars in the graph corresponds to an alternative conceptual scenario for parameterizing the DFN model. One of the useful aspects of DFN modeling is that it makes it possible to better understand the sensitivity of model results to individual parameters and to assess whether the attendant uncertainty in these parameters materially impacts any design conclusions. In the instance shown in the graph, the conceptual uncertainty regarding the alternative fracture and geomechanical models is much less than the alternative hydraulic fracturing designs.

7. Refracturing

Low oil and gas prices have caused some operators to consider re-fracturing existing wells rather than drilling and completing new wells. However, the stress surrounding a stimulated and produced well can be quite complex (Figure 16), as can the drainage. "Engineered" completions are becoming more common, in which the completions engineer does not apply a uniform pattern of stage designs, but tailors

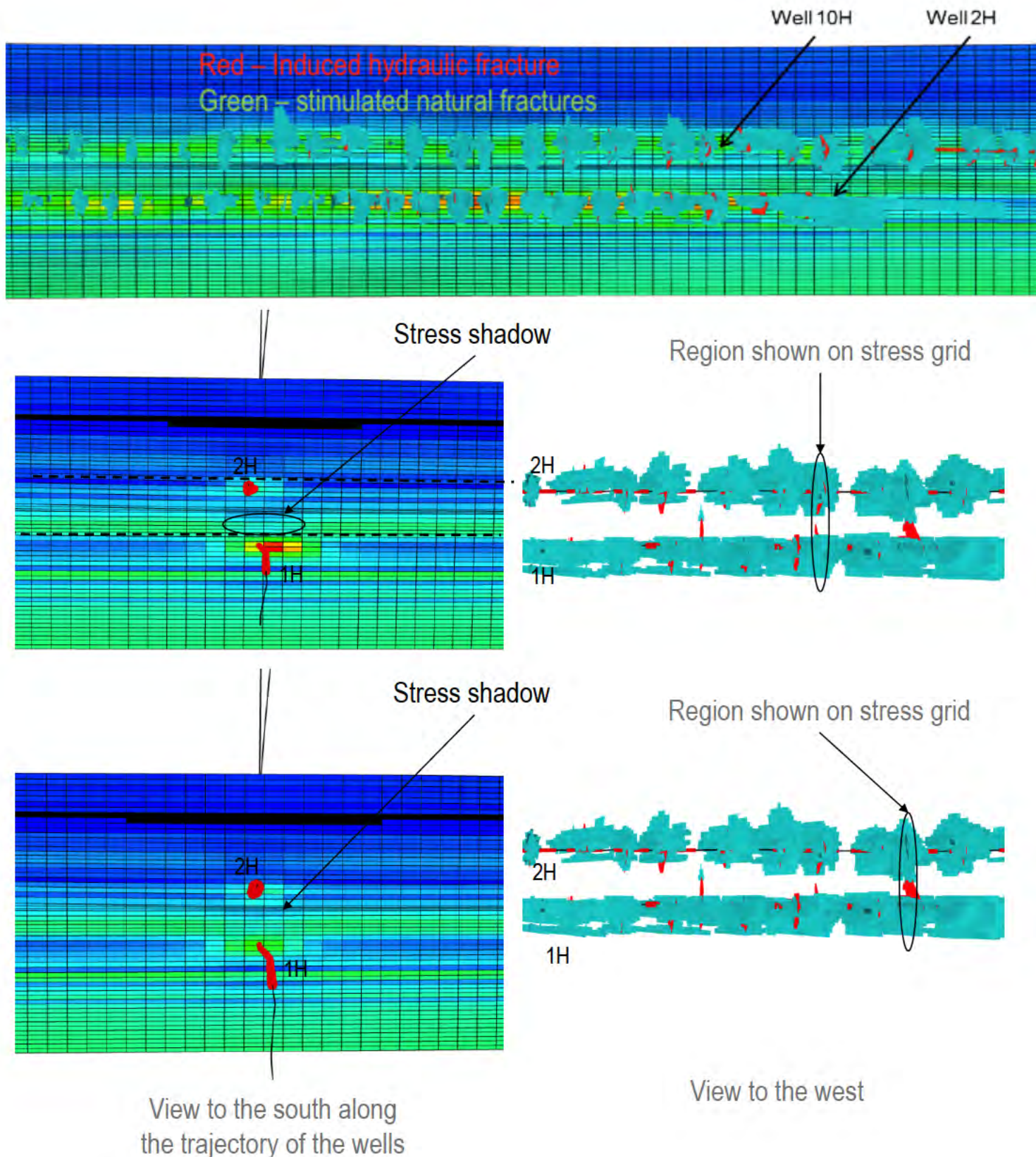
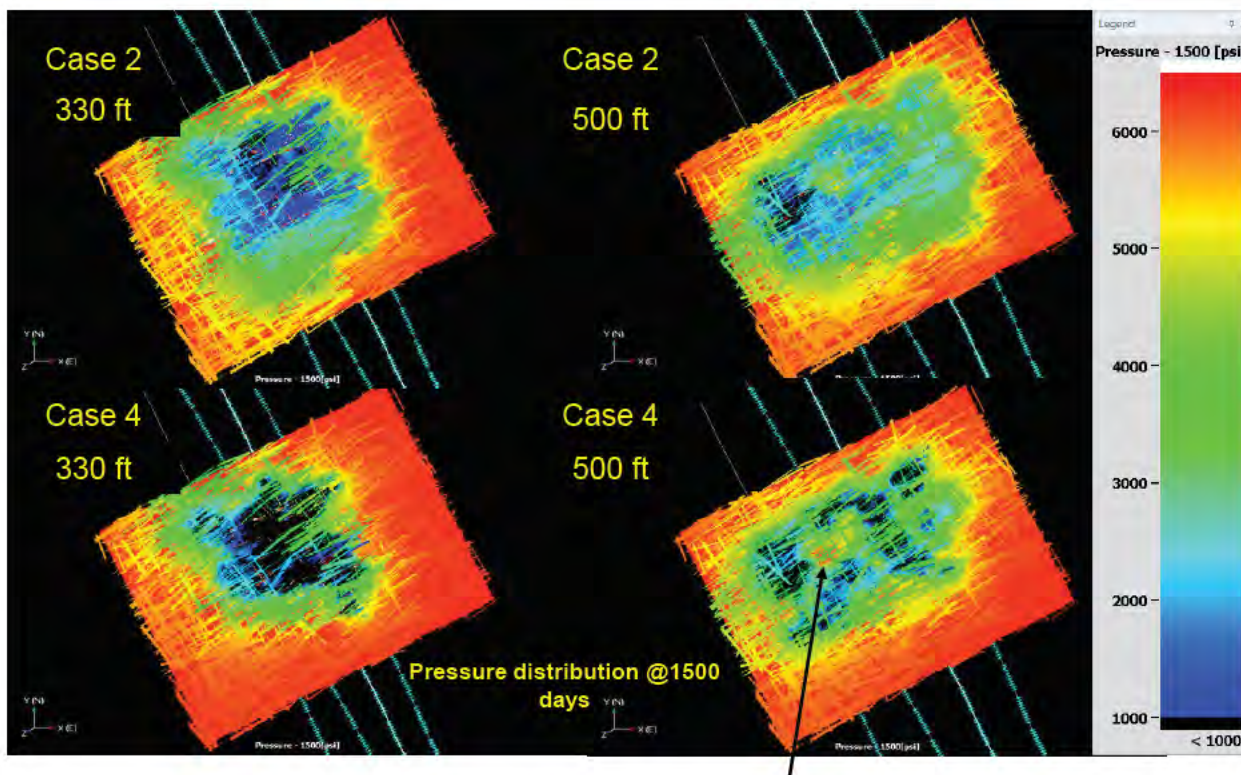


Figure 12. Cross-sectional views of maximum horizontal stress after both laterals had been hydrofractured.

the stage locations, lengths, number of clusters and other design parameters to the geological conditions in order to maximize recovery, reduce costs or both. DFN modeling can provide useful information to the completions engineer to design the fracturing or the re-fracturing process.

Figure 17 shows the effect of the perturbation of the stress field by an initial well. The stimulations overlapped, resulting in “frac-bashing” and loss of production from the initial well. The stress shadows resulted in a smaller stimulated rock volume and reduced production in the adjacent, later-stimulated well.



A 500 ft spacing leaves unproduced "gaps" between laterals in Case 4

Figure 13. DFN simulation of alternative stimulation design and lateral spacing, showing pressure distribution after 1500 days.

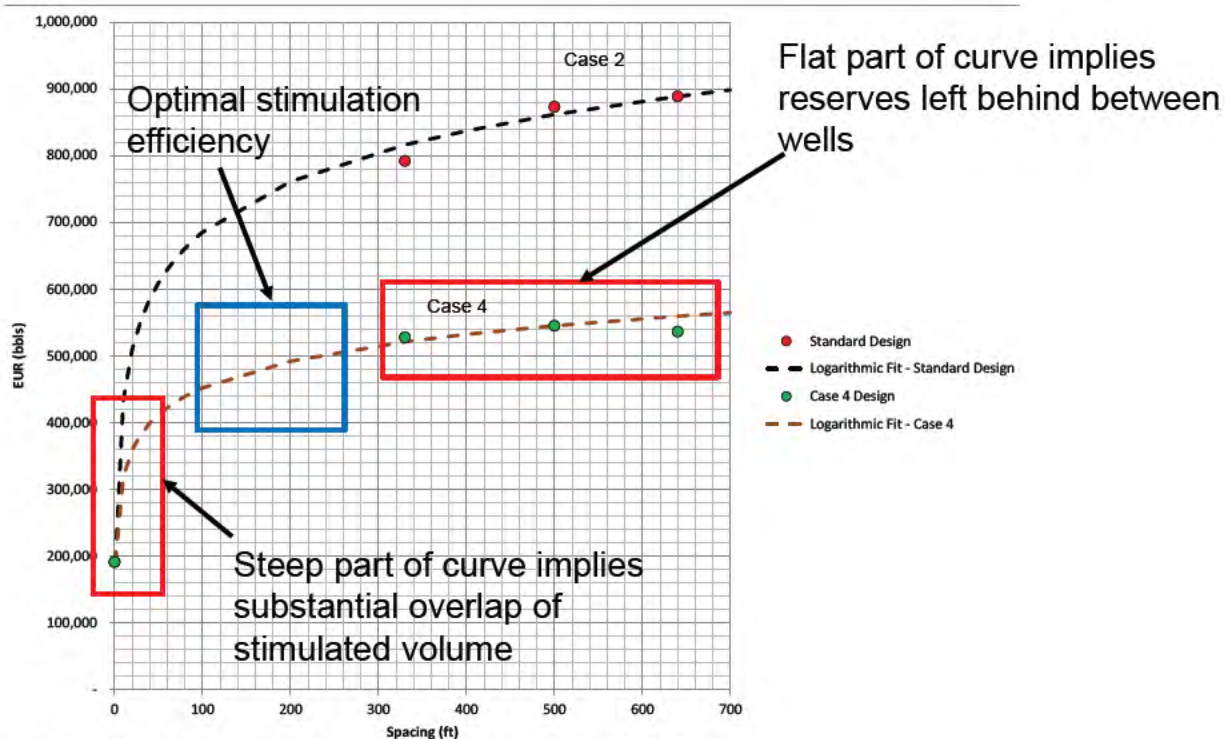


Figure 14. Optimization of lateral spacing through DFN modeling.

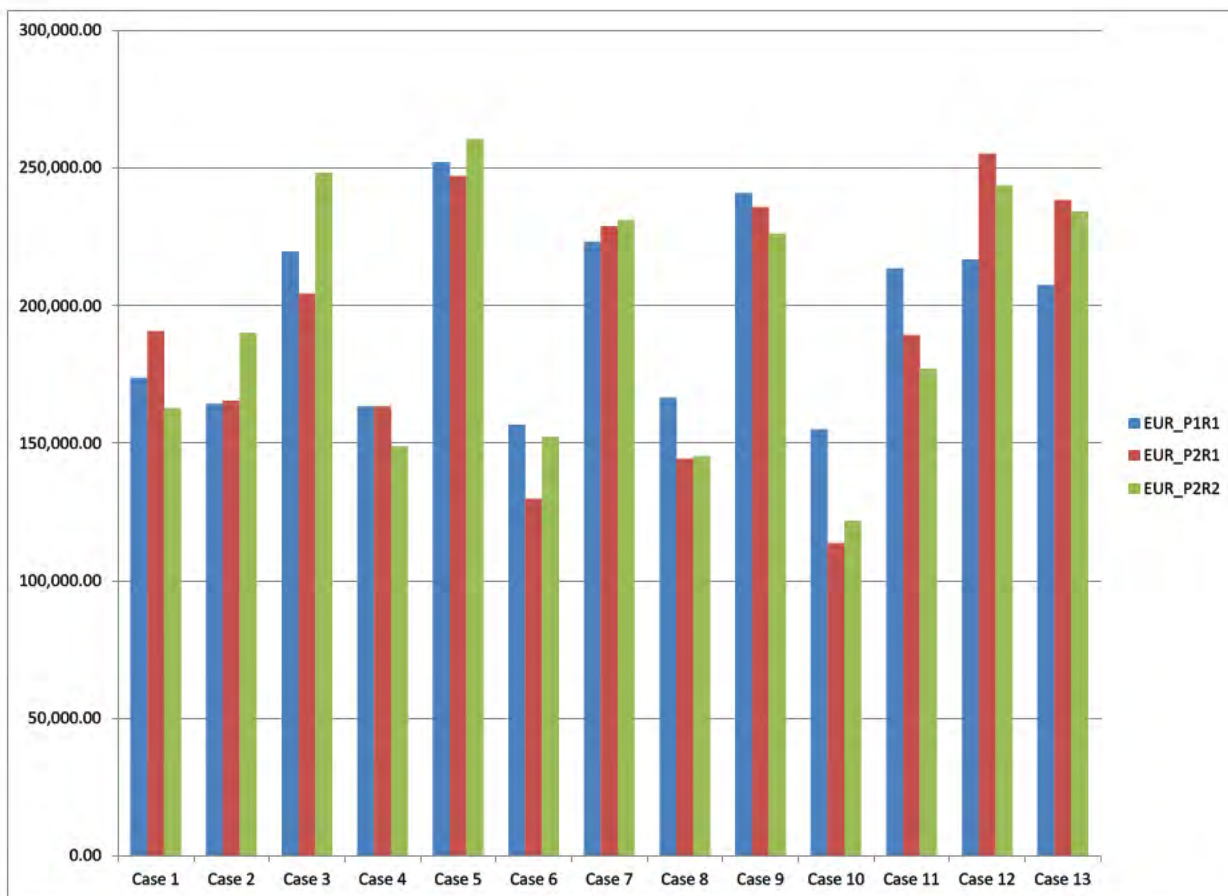


Figure 15. Comparison of EUR predicted through DFN simulation for 12 alternative hydrofracture design cases and three conceptual scenarios for the fracture and geomechanics model.

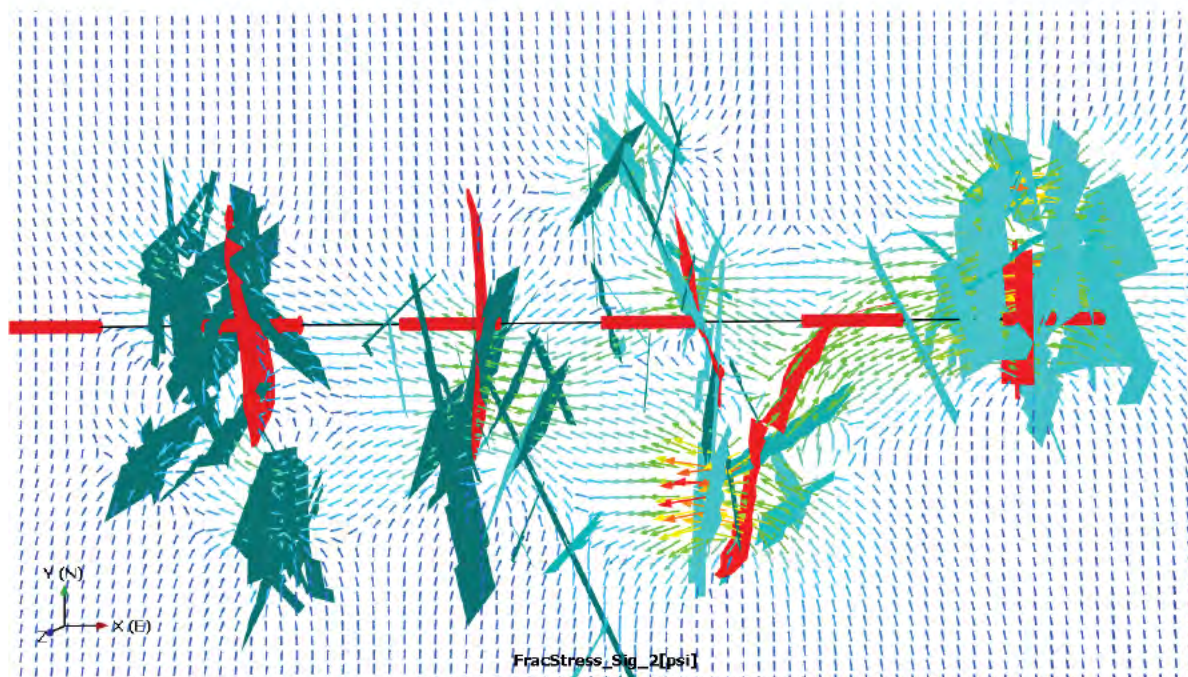


Figure 16. Stress re-distribution after stimulation.

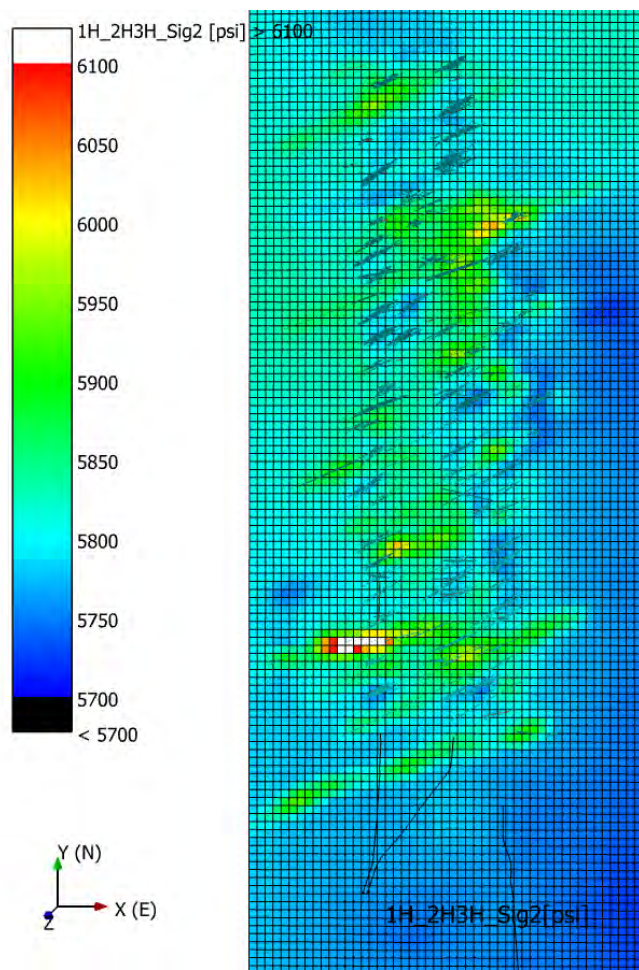


Figure 17. "Frac-Bashing" due to overlapping stimulations.

Acknowledgments

We would like to thank ARMA for publishing this special *Newsletter* on DFN modeling. All DFN models and associated simulations shown in this article were created with Golder Associates' *FracMan* discrete fracture network modeling software (www.fracman.com).

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Geomechanical and Discrete Fracture Network Modeling of Coals in the Surat Basin, Australia

Submitted by Seth Buseti and Bob Krantz (Conoco Phillips, Houston, TX), and Thomas Flottmann (Origin Energy, Brisbane, Queensland, Australia)

Introduction

System permeability in the Jurassic Walloons tight coal seams, Surat Basin, Queensland, Australia (Figure 1), has been linked to abundant natural fractures that formed during tectonic deformation. Our previous studies have identified that the distribution of the natural fracture systems and the *in-situ* state of stress vary across the field, depending on the local geologic setting as it sits in the regional structural framework (Brooke-Barnett et al., 2015). Production data indicate that sustained permeability enhancement occurs locally where the natural fracture sets remain open during depletion, suggesting that both fracture intensity and orientation are key drivers. To predict relative fracture contribution around the field, we combined seismic structural interpretation, forward geomechanical modeling, and discrete fracture network (DFN) modeling, then conditioned the results to wellbore image log data. We then upscaled the fracture model to a geocellular grid for integration with other fieldwide geologic and production data.

Geologic Setting

The study area is in the Walloons field, southeast Queensland, Australia (Figure 1). Hydrocarbon resources in the region are found in the Jurassic-Cre-

taceous Surat basin and underlying Permian Bowen basin that together contain up to 10 km of terrestrial and shallow marine units including gas-bearing interbedded coal seams (Shaw et al., 1999). The main producing intervals are in pervasively fractured coal seams of the Jurassic Walloon subgroup. Individual seams are 0.1 to 1m thick on average, and are at present-day depths of around 300 m – 1000 m. The units are gently deformed by subtle folds and minor faults that result from reactivation of more dramatic underlying inversion structures in the Bowen Basin. The deeper inversion structures were formed during multiple episodes of tectonic contraction associated with the Permian-Triassic thrust system of the New England Orogen (Korsch, 2004).

Structural Interpretation

Three scales of faults were interpreted from 2D and 3D seismic that contribute to the overlying Jurassic structure and fractures (Figures 2 and 3). Deep regional thrust faults and associated folds exist below the Triassic unconformity and connect to lower sub-Permian detachments. These major faults extend hundreds of km. in length and form the overall structural framework for the Surat Basin. Seismic images reveal that many of the subtle folds in the Jurassic interval are directly linked to reactivation of these

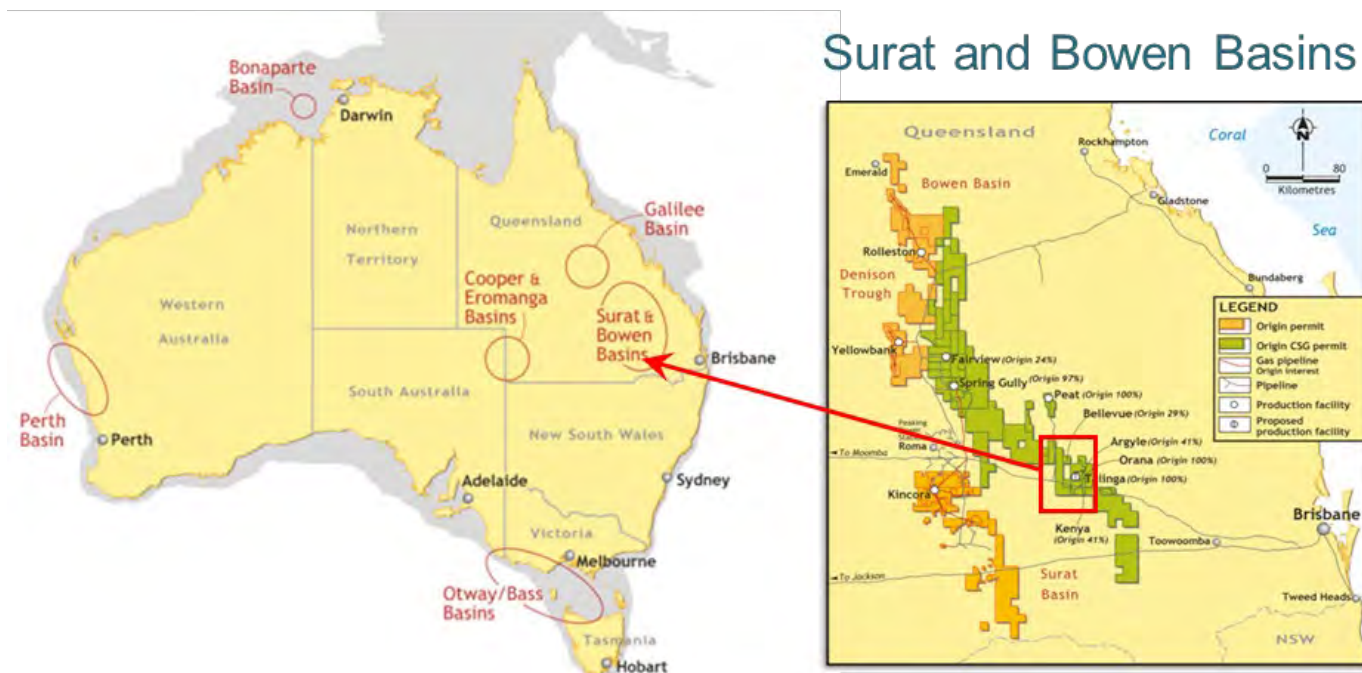


Figure 1. Field location for the Surat Basin study.

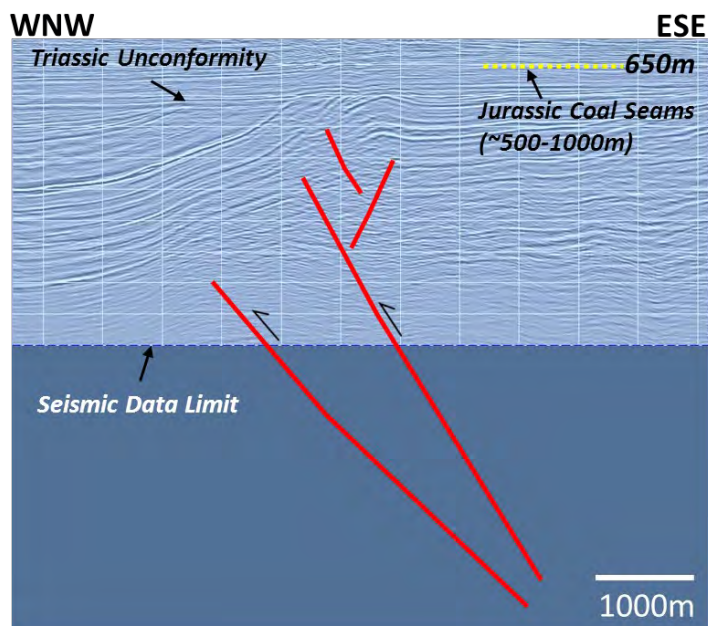


Figure 2. Typical interpreted seismic cross section. Note that regional scale deep faults have been interpreted below the seismic data limit in order to better represent the structure at depth.

deep faults, evidenced by deformation of the regional unconformity. Intermediate scale faults are imaged by amplitude offsets of tens of meters or more and link the lower and upper structures. Shallow faults that penetrate the Jurassic reservoir units are subtle in seismic, and sometimes can only be distinguished by seismic attributes such as coherence. They follow trends associated with the deep and intermediate faults. At each level of faulting, several stratigraphic horizons were interpreted for hanging-wall and footwall cut-offs to estimate fault throw distribution (Figure 3).

Geomechanical Forward Modeling

Forward elastic dislocation models were generated using the T7/Traptester software (Badleys Geoscience Ltd.) (Figure 4). Key inputs into the model are fault geometry and throw distribution, boundary strain (type, magnitude, and orientation), as well as rock stiffness and depth of burial. We used an iterative modeling approach with paleo-strain orientation and magnitude as the main constraints to calibrate the model to actual horizon topography (present day deformed geometry). The result of the model is a full field array of displacement vectors, deformed grids, and strain and stress calculated on the grids and seismic interpreted horizons, specifically the upper and lower Walloons horizons. We used the T7 fracture prediction tool to generate a fieldwide pattern of discrete natural fractures (visualized as grid-centered discs) with unique type (normal, reverse, strike-slip) and orientation that varies by location as determined by the local principal stress directions (Figure 4).

Calibrating the Full Field DFN Model to Wellbore Data

Image log fracture data were available for five wells within the seismic coverage (Figure 5, left blue rose plots). The overall trend of fractures is north-west-southeast (Figure 5, middle-right red rose plot), though the trend varies locally by structural position. We used the results of the forward geomechanical model to populate a geocellular model in the DFN software FracMan (Golder Associates) with cellular attributes for fracture orientation and type, as well as stress calculations. For each cell, stochastic fracture sets were generated, using the T7 orientations as the basis, then adding appropriate orientation dispersion factors to each fracture set for the different structural

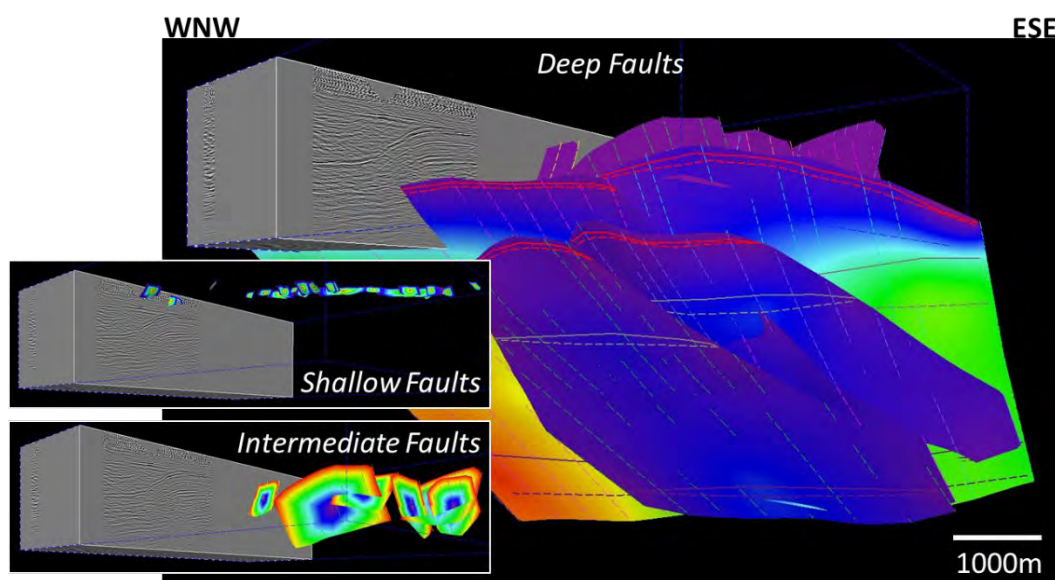


Figure 3. 3D Faults at deep, intermediate, and shallow levels. Colors indicate throw distribution (blue = highest throw).

domains to create a locally conditioned DFN (Figure 5, left map and middle-right purple rose plot). For this model, fracture size is arbitrary (the actual coal fractures are very small) and is only used for visualization purposes. Fracture intensity/spacing was scaled to the computed maximum Coulomb shear stress (MCSS) with a relative weighting of deep fault perturbation > intermediate > shallow. This weighting was determined

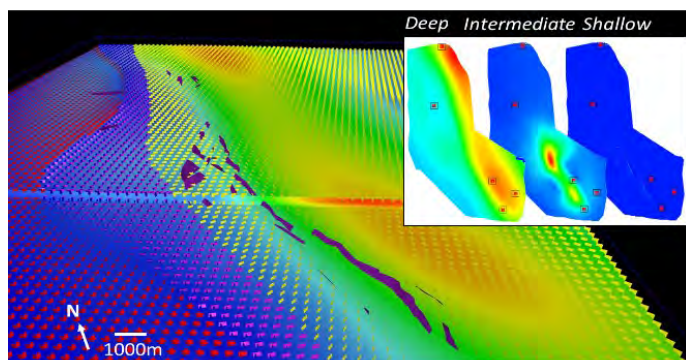


Figure 4. Results of elastic dislocation forward model for the seismic volume. Color contours indicate maximum coulomb shear stress. Small planes indicate the predicted natural fracture orientation. Top-right inset: MCSS results for deep, intermediate, and shallow fault perturbation models; the small squares indicate the locations of wells with image logs.

by comparing wellbore fracture intensity from the image logs against MCSS for each of the geomechanical grids. The resulting field wide fracture model is shown on the right map of Figure 5.

Upscaled Fracture Model

The average present-day stress tensor was applied to the field wide DFN (Figure 5, right) and shear and normal stress were solved for each discrete fracture. Figure 6 shows the upscaled attribute models, in each case normalized for value ranges of 0 to 1. The left map is the normalized fracture intensity map, where red colors indicate the most intense fracturing. The middle is the resolved fracture dilation attribute, where red indicates the areas predicted to have open natural fractures (note color scale is opposite of Figure 5). The right plot shows a convolved fracture effectiveness multiplier, which combines the intensity and dilation attributes into a single normalized parameter. The predicted fracture attributes show positive visual correlation to field permeability maps from well production data for dozens of wells, suggesting the DFN approach has merit as a helpful predictor of performance, and at this coarse level is suitable for screening. With future refinement of the structural inputs and production data we expect even more utility from the model.

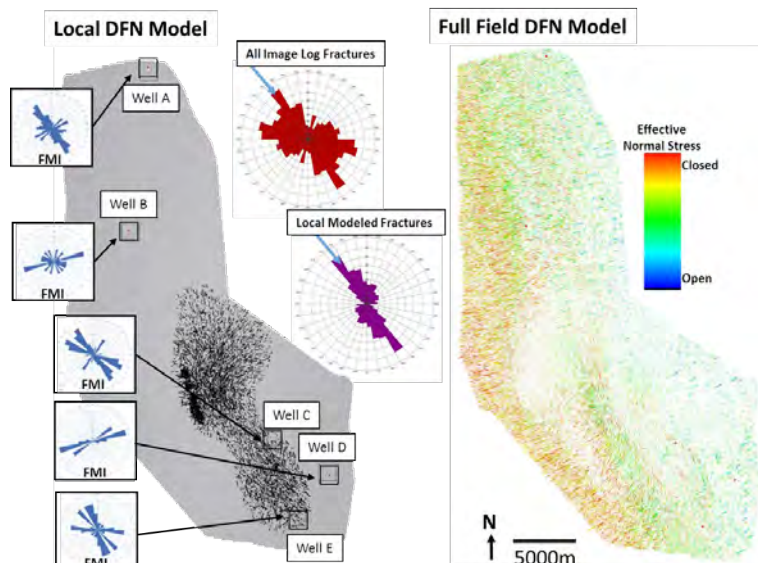


Figure 5. Map views of local and full field DFN models. The small boxes (left) indicate the five wells in the area with FMI image log data.

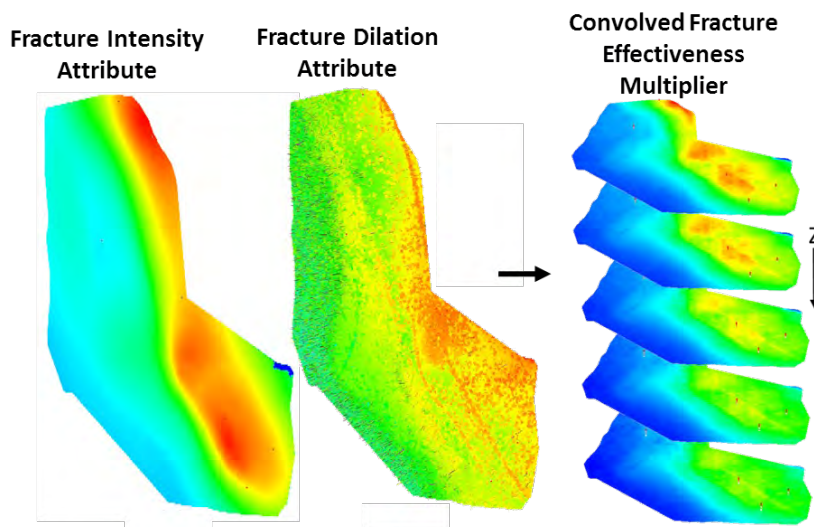


Figure 6. Upscaled full field fracture attribute models, units are shown as scalar multipliers (0-1). The overall fracture effectiveness model (right) is displayed at several depths within the Walloons interval.

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DFN-based Analysis for Mining: Example Applications and Recommendations

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1. Summary

The mining industry is increasingly utilizing formal risk analysis, often based on probabilistic modeling of processes such as mine scheduling, system reliability, comminution, ground control and slope design. Probabilistic analyses often involve the use of multiple realization techniques such as Monte Carlo methods to propagate the uncertainties of input parameters into the resulting analyses. For conceptualisation, modeling and analysis of rock mass in mining processes, there is an increasing use of discrete fracture network (DFN) based approaches which allow explicit representation of rock mass discontinuities. We briefly present some examples of DFN-based analyses for mining problems. This is followed by a discussion of the complicating factors associated with interpretation and communication of the analyses.

2. Recent Applications of DFN in mining

Many researchers and industry practitioners have been actively pursuing methods to better employ DFN approaches in the mining and quarrying industries. In 2014, the First International Conference on Discrete Fracture Network Engineering showcased many examples, including the keynote delivered by Loren Lorig on this very subject (Lorig, 2014), slope design and optimization of bench face angles for surface mining (Weir & Fowler, 2014; Mathis, 2014; Havaej, Coggan, & Stead, 2014), geomechanics modeling of excavation stability in an underground quarry (Salvini, et al., 2014), quantification of rock mass preconditioning for caving operations (Brzovic, Rogers, Webb, Alvarez, & Schachter, 2014), discrete element modeling for longwall top coal caving (Gao & Stead, 2014), analysis of fluid flow into mine workings (Ciszyk, Maxwell, & Eso, 2014) and stability analysis of an ore pass (Esmaili & Hadjigeorgiou, 2014) to name a few. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has been active in this field for many years. Most recently, there has been considerable work applied to both Australian and International coal (including projects with the Australian Coal Association Research Programme) and hard rock (including projects with the Large Open Pit Slope Stability Project) mining. Some examples specific to

surface mining are briefly discussed below.

A stability isoplethogram (Windsor & Thompson, 1996) is a means of interrogating the stability characteristics of the internal rock mass for multiple proposed excavation geometries. A sensitivity analysis is performed whereby the orientation of the proposed excavation geometry is altered in both dip and dip direction and the stability is assessed. Results are then plotted on a 2D contour plot that supports identification of more optimal excavation orientations. A recently developed algorithm uses DFN based Monte Carlo simulation and an optimized stability analysis for calculation of the isoplethogram (Elmoultie, Krähenbühl, & Soliman, 2016). Figure 1 presents the results of applying this technique for estimation of failure volumes for an open cut mine located in Queensland, Australia. The geology of the open pit site consists of four major lithological units of a general dip of approximately 65° to the west. The horizontal and vertical axes represent the dip directions and dips, respectively, of potential excavation (planar) surfaces. The analysis is based on one hundred 3-dimensional DFN realizations followed by rigid block limit equilibrium stability analyses. Blue regions in the isoplethogram indicate slope orientations displaying a local minimum in predicted failure volumes and therefore this chart can be used for assessing various potential slope designs.

Utilization of geophysical logging in addition to borehole and exposure mapping provides further constraints on the DFN generation. The Detailed Strength Method has been developed by CSIRO to utilize high resolution geophysical logs for discrete representation of geological contacts in geomechanics modeling (Poulsen, Adhikary, & Balusu, 2016). This method has been applied for analysis of slope stability of a deep open pit coal mine in a sedimentary geology (Figure 2). A full composite of the geological log is made to the resolution of the numerical mesh. The dominant strata type is identified in each composite interval as coal, claystone, shale or sandstone-dominated resulting in multiple (76 in this case) individual geological units. Each composite unit has strength

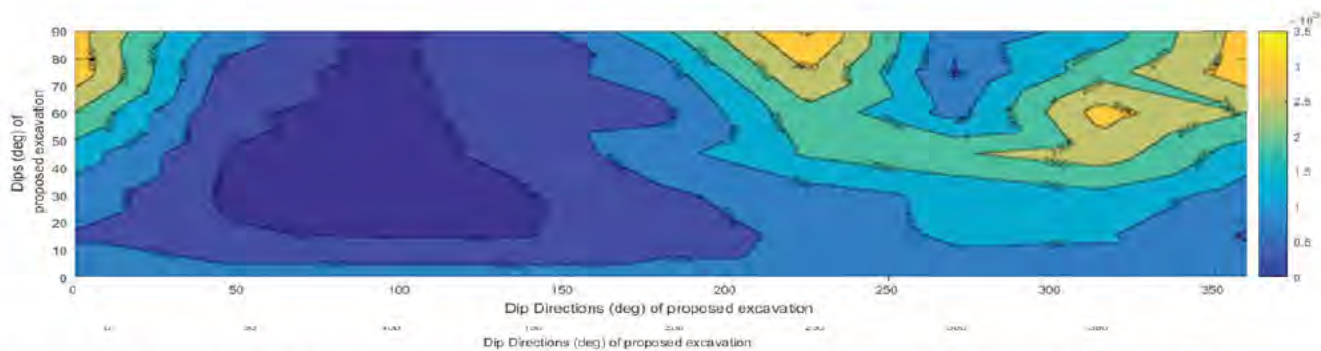


Figure 1. Failed volume excavation isoplethogram (in m^3) for a section of an open pit slope. (Taken from Elmoultie, Krähenbühl, & Soliman, 2016).

and stiffness properties assigned based on the geological and geotechnical logs and dominant geophysical response for the interval. Compared to models with a simpler description of the rock mass, this model predicts that the mass of rock at failure becomes increasingly shallow and localized and is displaced near horizontally out of the pit slope, in agreement with field observations.

CSIRO has collaborated with the 3SR Laboratory, Grenoble, to investigate the efficacy of coupling of topographic data, structural mapping, DFN generation and discrete element method (DEM) modeling for 3D geomechanical analysis of slope stability. High resolution photogrammetric survey data and DFN-DEM modeling has been used to assess the suitability of alternative rock mass models for a composite type failure in an open cut coal mine (Bonilla-Sierra, Elmoultie, Donzé, & Scholtès, 2016). As shown in Figure 3, photogrammetric measurements of the failed rock bridge were possible and can, in principle, be used to test the validity of the proposed rock mass models based on 3D morphological analysis of numerically predicted failure surfaces. A constraint in this approach is the resolution of the discretization used in the numerical modeling.

Most recently, CSIRO has collaborated with the University of Queensland's Sustainable Minerals Institute (SMI) to couple the DFN approach with blast energy and fragmentation simulation for optimization of drill and blast operations in open cut mining operations. The algorithm integrates timeweighted blast energy simulation (Kleine, 1988; Onederra & Chitombo, 2007), blast fragmentation prediction (Sarma, 1994), and estimation of the in-situ block size distribution (Elmoultie & Poropat, 2012). For the assessment of blast design efficiency and identification of potential hazards such as face-bursts, a multi-criteria approach has been implemented in a software program (Dean, et al., 2015).

This approach is often used in the geosciences for

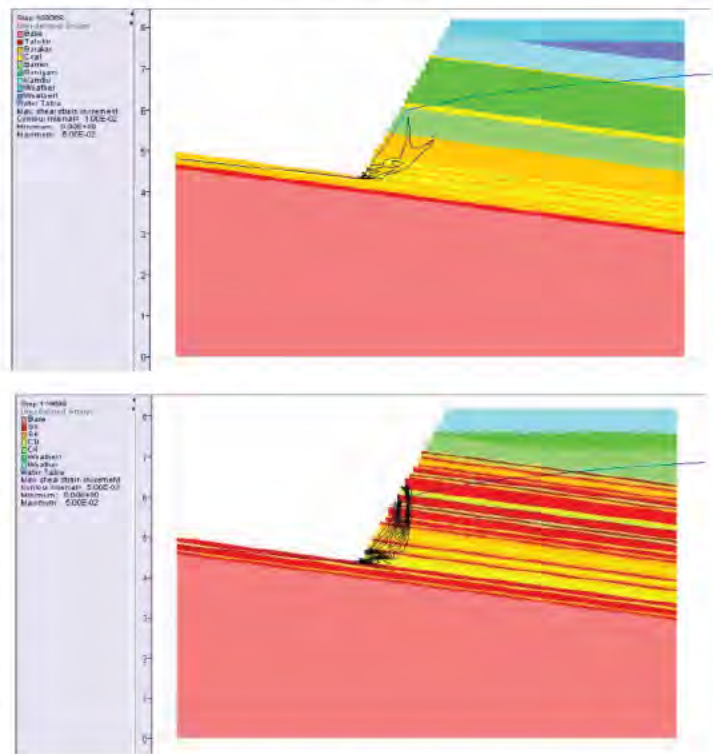


Figure 2. Comparison of the formation model (top) with the detailed model (bottom) for a theoretical pit of 390m depth with 60° face angle. Predicted shear strain contours shown to a maximum of 0.05. (Taken from Poulsen, Adhikary, & Balusu, 2016).

the characterization of complex, multidimensional problems. Choice of weighting for the individual criteria relies on qualitative, site based judgements. The software allows the practitioner to take into account several criteria, including face burden (3D analysis of the location of bench face relative to the front row of the blast pattern), predicted energy intensity (a function of face burden and calculated based on the predicted 3D distribution of blast energy), structural connectivity (an analysis of the connectivity between discontinuities and the blast pattern), fracture intensity (in this analysis, the P21 metric calculated on the bench face has been used) and a normalized index relying on expert judgement to classify the overall properties of the geotechnical domain. Several crite-

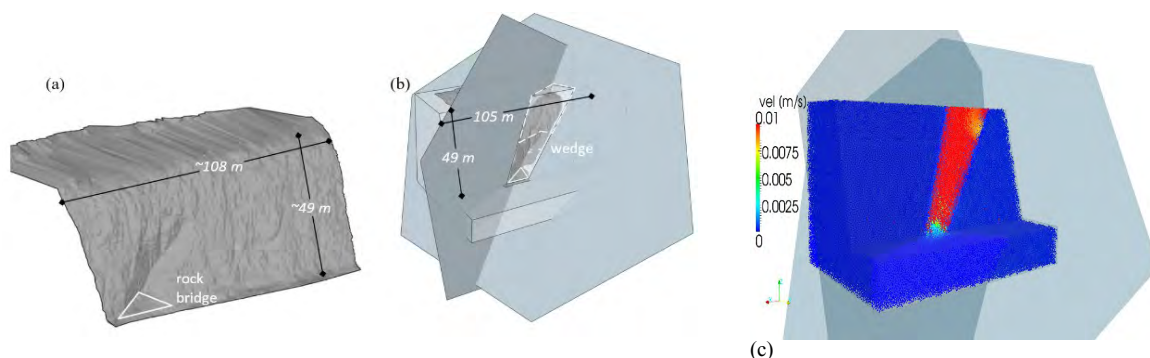


Figure 3. 3D geometric model and associated DFN used for the numerical simulations. (a) The surface of the wall surveyed photogrammetrically and (b) the DFN and the volume used for simulations, merged with the surface of the wall, showing the constrained wedge. The idealized rock bridge is highlighted with the white triangle. (c) The results of one of the DEM simulations indicating failure of the rock bridge and movement of the resulting wedge. (Taken from Bonilla-Sier, Elmoutie, Donzé, & Scholtès, 2016).

ria and the final multi-criteria result are shown in Figure 4. This software will now be trialled by engineers at several Australian coal mines to assess its efficacy in supporting optimization of blast pattern design.

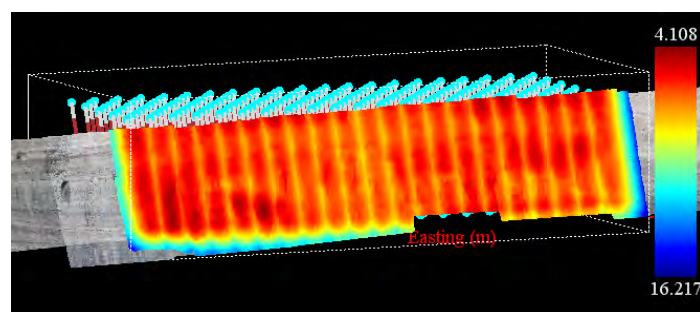
3. Recommendations on the use and interpretation of DFN based analysis

The DFN approach clearly supports a number of powerful engineering techniques, ranging from problem conceptualization to empirical and numerical modeling and analysis. However, as with all rock mass modeling, the ability to capture the salient properties of the rock mass under investigation is difficult given constraints on knowledge of the rock mass (epistemic uncertainty), inherent randomness of the rock mass -- particularly discontinuities (aleatoric or stochastic uncertainty), the size of the volume of interest (bench scale, inter-ramp or full slope) and the spatial resolution required (computational limitations). Several factors need careful consideration for an engineering analysis based on the DFN approach to be both robust and of value for interpretation.

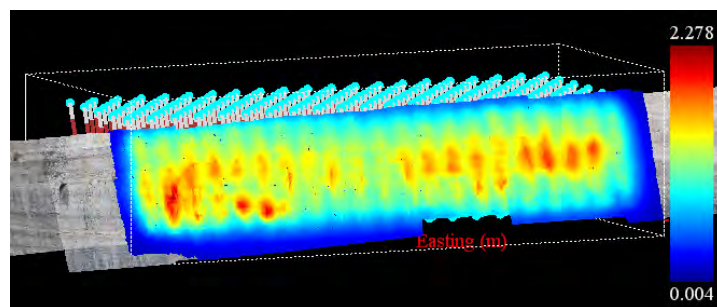
3.1 Modeling objectives

As with all modeling and simulation, the purpose of DFN-based analysis needs to be carefully defined and understood within the limitations of the scientific method (Vick, 2002), including appreciation for lack of model uniqueness. Improved conceptualization of the problem may be attainable from relatively crude representations of the rock mass discontinuities depending on the complexity of the phenomena being studied.

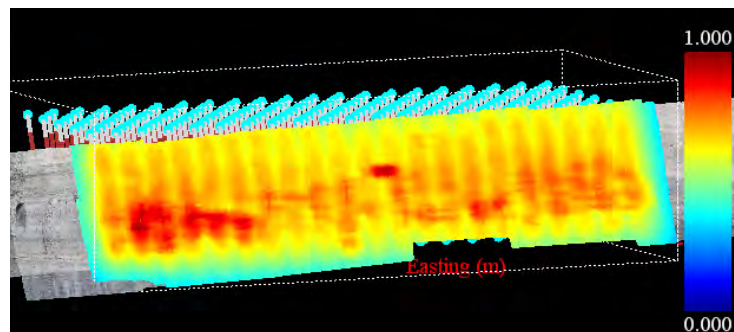
Figure 5 outlines the changing *minimum* requirements on a DFN-based analysis of slope stability as a function of the modeling objective. For this discussion, we focus purely on the structural properties of the in-situ discontinuities and assume that the phys-



(a)



(b)



(c)

Figure 4. Results of the individual criteria of (a) face burden, (b) energy intensity, and (c) multi-criteria analysis. Red indicates higher values. Details are described in the text.

ics for complex processes (fracture propagation and rock mass failure mechanisms) is adequately represented by the empirical or numerical modeling subsequently being applied. Sensitivity analyses are almost mandatory even at the conceptualization stage to gain an appreciation for both the reliability of the calculated results as well as complexity of the problem (Hoek, 2009). Forecasting, and especially prediction, are problematic due to the aforementioned constraints. We will revisit this in the section 'Outliers'.

3.2 Data acquisition

Sampling biases associated with borehole and exposure mapping of discontinuities are an ever-present problem. Discontinuity size or persistence is regularly under-estimated, sometimes severely, with analysis of fracture network connectivity, compartmentalization and in-situ block size distribution being highly sensitive to this. For mining slopes, orientation bias can result in particularly poor sampling of release surfaces which are sub-parallel to the newly exposed bench faces. Although digital technologies are increasingly being used worldwide for acquisition of structural data (photogrammetry and laser scanning, terrestrial and aerial platforms), these sampling bias issues remain. Further, the growing use of algorithms for automated mapping of discontinuities tends to discourage careful consideration of bias issues and therefore may exacerbate this problem. Validation that the behavior of DFN-based models concur with field observations is therefore vital. For sedimentary geologies, further issues include estimation of persistence parallel to bedding and representation of release surfaces along this bedding. Stochastic rep-

resentation of such release surfaces can be accomplished provided that accurate sampling has been undertaken (Elmoultie M. , Krähenbühl, Poropat, & Kelso, 2014).

3.3 Uncertainty

The inherent assumption present in most geological and geotechnical analyses is that it is reasonable to assume that the majority of joints being considered can be delineated into distinct sets with each set comprising discontinuities having statistically similar orientation characteristics. However, within any rock mass there is always a proportion of discontinuities which cannot be reasonably assigned in a standard clustering analysis. These discontinuities can be referred to as either isotropic, random or background (Priest, 1993). The influence of the isotropic component of rock mass discontinuities has been analyzed using DFN (Elmoultie, Poropat, & Meyers, 2012) and it is evident that neglect of this component can introduce large errors in estimation of in-situ block size distributions and stability analyses. Figure 6 shows an example stereonet for a rock mass containing a large proportion of isotropic structures.

3.4 Outliers

If the event of interest, such as frequency of occurrence of bench scale failures for a particular failure mode, is statistically unlikely (either because of actual likelihood of occurrence or because data sampling precludes the accurate quantification of occurrence in statistical simulations) then there are significant limitations associated with derivation of failure probabilities through simulation. In practice, particularly for 3D analyses, limited numbers of DFN realizations

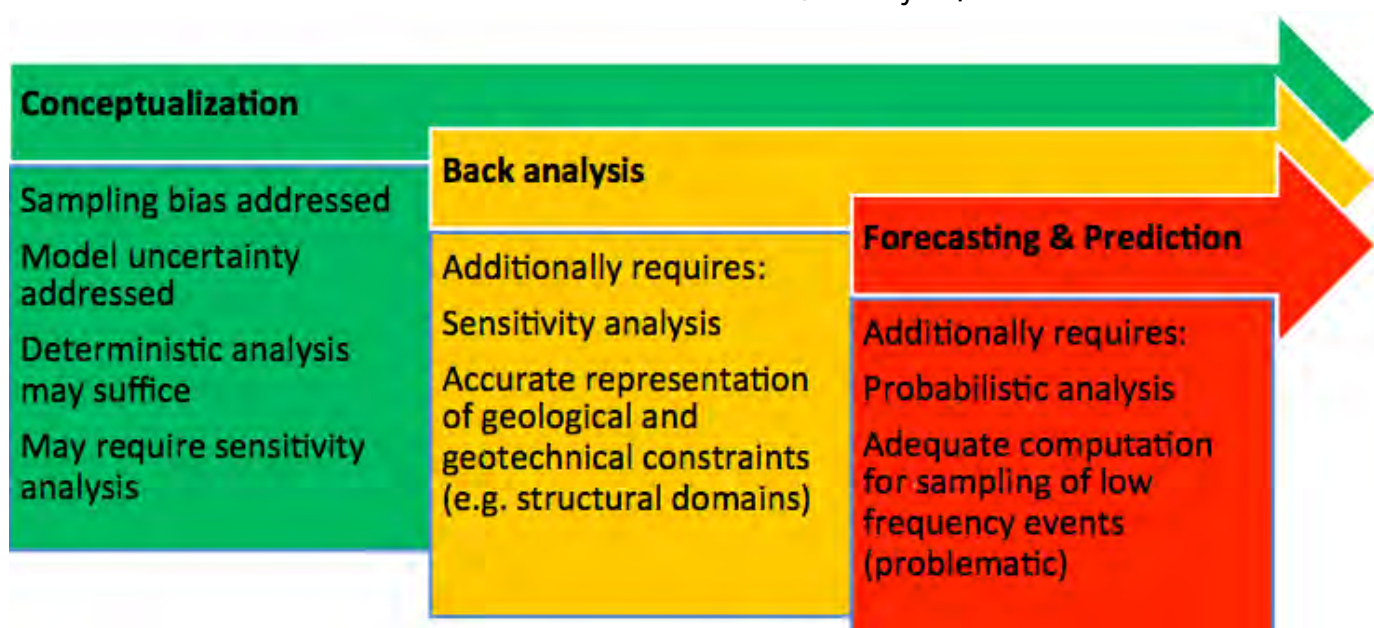


Figure 5. Various demands on the DFN analysis as a function of modeling objective, focussing on representation of in-situ discontinuities for a slope stability analysis.

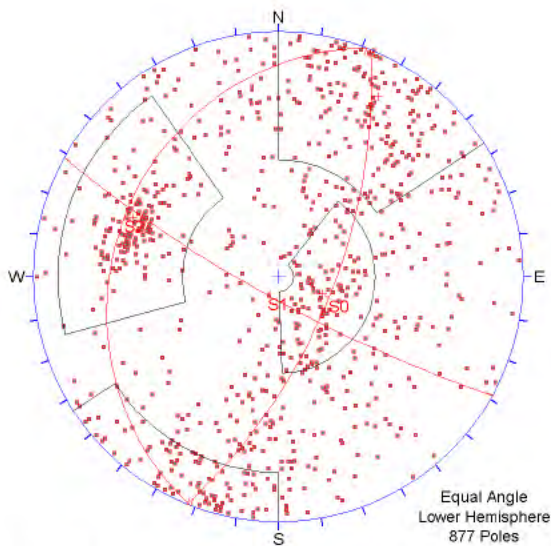


Figure 6. Stereonet showing structural data for the rock mass shown. Approximately 38% of poles belong to the isotropic set. (Taken from Elmoultie, Poropat, & Meyers, 2012).

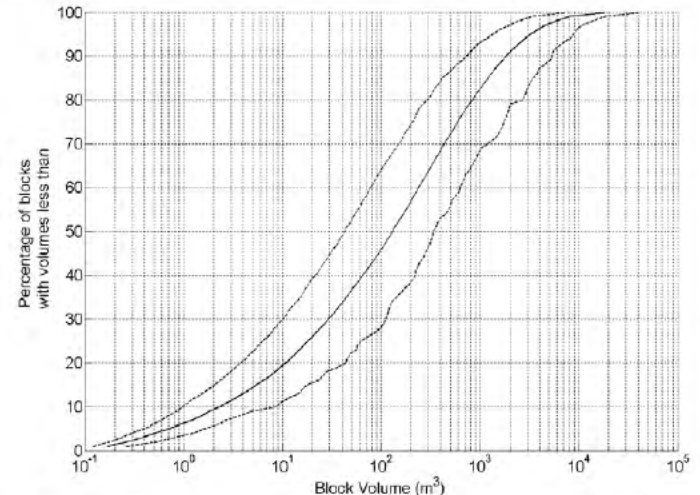
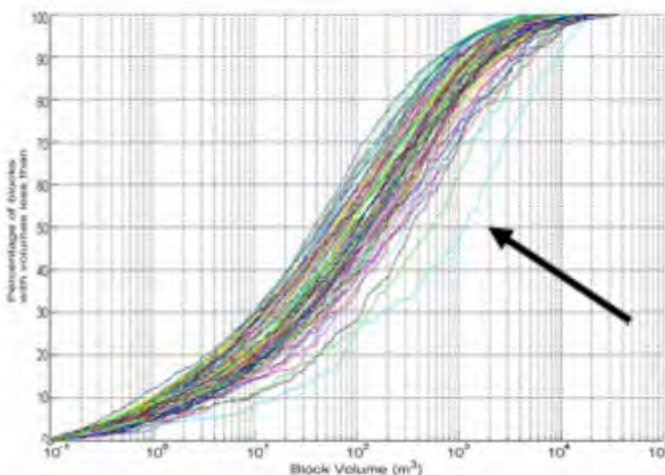


Figure 7. Example of a Monte Carlo simulation of in-situ block size distribution estimated using DFN. Raw curves for 100 simulations are on the left and 95% confidence curves on the right. They raise the question: What frequency and how significant is the 'outlier' curve highlighted with the arrow on the left figure?

are interrogated due to computational constraints. Although this constraint is relaxed through the increasing adoption of efficient sampling schemes (e.g. Latin Hypercube) and distributed computing facilities, practical constraints mean that 3-dimensional DFN analyses are still limited to the thousands of realizations per model scenario. This is likely insufficient to simulate low likelihood events (perhaps of high consequence) in sufficient numbers to accurately estimate frequencies of occurrence (Figure 7).

Consider the interaction of a mappable discontinuity network (i.e., structures sampled via daylighting on exposures or boreholes (labelled as sets S) with poorly sampled or unsampled structure sets (labelled as sets U). These unsampled sets only become evident after failure, so the probability of occurrence of U is unknown or poorly quantified.

Several analysis modes can be performed in order to understand this interaction, each requiring a different interpretation, and these are shown in Figure 8. Mode A uses deterministic representation of all structures and is only suitable for analysis of potential failure mechanisms, not determination of frequency of occurrence. Modes B and C support frequency estimation for the conditional and unconditional presence of U respectively. However, note that in practice, the outcomes of a mode C analysis are always questionable due to the poor knowledge of U .

Figure 9 shows one approach to dealing with this difficulty as applied to the analysis of bench scale failures in an open pit mine. The potential presence of release surfaces sub-parallel to the bench faces (poorly sampled) to influence failure modes in various sections of an open pit is being analyzed. A con-

A	B	C
• Sets S included deterministically • Sets U included deterministically • No frequency of occurrence can be derived	• Sets S included deterministically & stochastically • Sets U included deterministically • Frequency of occurrence given activation of sets U can be derived	• Sets S included deterministically & stochastically • Set U included stochastically • Frequency of occurrence can be derived (in principle)

Figure 8. Three different methods of accounting for the activation of the poorly sampled discontinuity sets (U) with sampled sets (S)

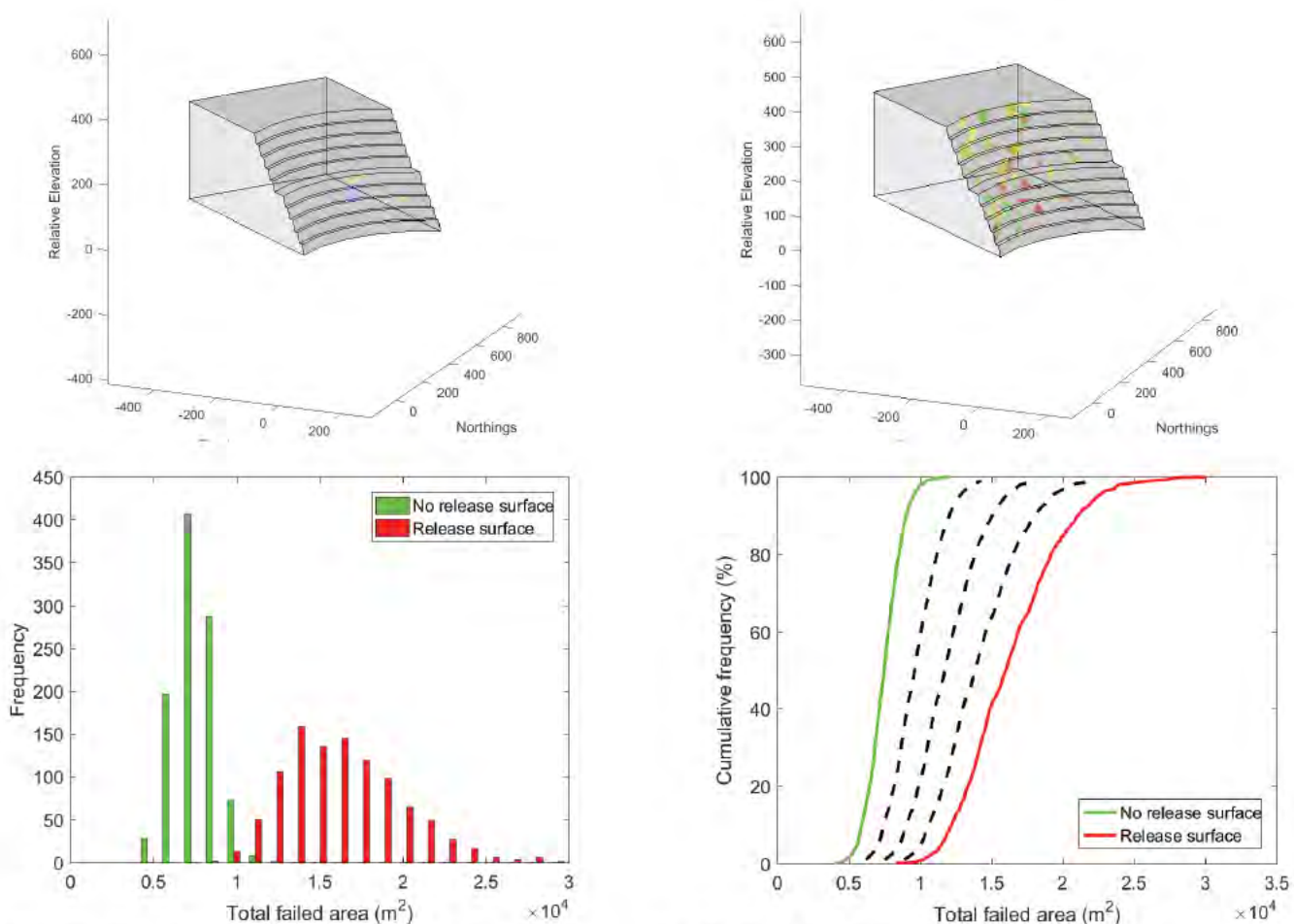


Figure 9. (top) Single realizations of two modeling scenarios. On the left, a base case scenario where the poorly sampled set is ignored and on the right, it is included deterministically (Mode B). The frequencies of potential failure zones (indicated by yellow and red zones) predicted in each analysis differ significantly as expected. (bottom) Comparison of total area of failed bench face with and without the presence of tensile release surface for 1000 simulations. The left figure shows the histograms and the right shows the cumulative frequency curves (solid curves). These solid curves define the range of possibilities for this particular failure mode and the dashed curves represent the 25%, 50% and 75% interpolations between these extremes.

servative analysis is performed where their presence is assumed to be equally likely at all locations (deterministically, mode B). These simulations predict a much greater frequency of occurrence for failures compared to a base case analysis which does not account for this release surface (Figure 9, top left). Estimation of total area of bench face affected by failure is calculated based on 1000 simulations for each of these two scenarios, which can be viewed as 0% probability and 100% probability that the release surface failure mode exists. Scenarios in between these extremes can then be considered using interpolation (in this case, shown for 25%, 50% and 75% probability) and applying expert knowledge of the site conditions to determine which case is appropriate for design purposes. Justification for such judgements should be communicated clearly in all reporting.

3.5 Communication of uncertainty

Finally, communication of analysis interpretation and, in particular, uncertainty quantification is discussed. Intuitive communication of uncertainty is a challenge in most science and engineering disciplines. A recent IEEE conference on Big Data and Visualisation included a paper specifically on this topic titled *Communicating Statistical Uncertainty to Non-Expert Audiences* (Roberts & Gough, 2016). One can argue that with respect to modeling and simulation in general, let alone the DFN based variants, the readership of a geotechnical report will consist mainly of *non-experts*. Further, it has also been recognized that *overconfidence bias*, or cognitive under-estimation of uncertainty, is of particular relevance in geotechnical engineering (Vick, Degrees of Belief: Subjective probability and engineering judgement, 2002). Analysis utilizing DFN approaches necessarily involves a degree of knowledge of the strengths and limitations of statistical methods and these should be clearly communicated.

For slope stability analysis, there are particular misconceptions that need to be addressed. The aforementioned issues regarding outlier analysis using simulation based methods to estimate frequency of low likelihood events means that usage of the term *probability of failure* should be heavily qualified in all reporting, particularly to mine or operations management who will likely not have the context to appreciate the limitations of the simulations being performed. This takes on added importance when the complexity of the slope failure mechanism being investigated is over-simplified (or not represented at all) by the stability analysis. In such scenarios, interpretation of the frequency of occurrence of failures

observed in simulation may bear no relationship to the field investigations. In general, when incorporating such results in a risk analysis framework, it is wise to note the recommendations of experts that the more feasible goal is prioritization (rather than quantification) of failure mode likelihoods (Vick, 2014).

Acknowledgments

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The Challenge of Modeling Groundwater Flow in Fractured Bedrock Aquifers

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Abstract:

Investigating and modeling fluid flow in fractured bedrock aquifers is a challenge. Two fundamental approaches are found in the literature for modeling fluid flow through fractured bedrock: (1) equivalent continuum/porous media approach and (2) discrete fracture flow (DFN) approach. In general, the formulation of a hydrogeological simulation model in fractured rock aquifer is an iterative process. The process of building a conceptual hydrogeological model integrates various disciplines with the help of expertise of geologists, geophysicists, and hydrogeologists. The conceptual model is a hypothesis describing the main features of the geology, hydrological setting and relationship between the fluid flow and fracture network.

The steps in building a conceptual model of the flow system through a fractured rock depend on the identification of the most conductive and connected fractures within the fracture system. The geometrical properties (orientation, length and density, etc.) of individual fracture sets play an important role in developing discrete fracture networks. The fracture network at the 2D or 3D level is generated using joint data obtained from 2D or 1D exposures. Using numerical modeling (finite element method), the fluid flow is simulated through those networks applying appropriate hydraulic boundary conditions.

A DFN model was developed and applied to estimate the groundwater supply for a transportation project in the fractured granitic rock for a highway upgrading project. The available information on fractures from surface and boreholes was used to infer the geometric parameters needed to build a fracture network model for the fractured granitic rock aquifer. The observed response from pumping tests was used to calibrate the hydraulic properties and hydraulic boundary conditions for the numerical model. The actual drawdowns at various observation wells were compared to the results of the numerical model to assess the model validity. The case study demonstrates how this conceptual discrete fracture flow model improves the understanding of the groundwater flow through fractured bedrock, especially in low permeability rock mass.

1. Introduction

The fluid flow through a granitic rock mass takes place through the fracture network, as the rock matrix is highly impermeable. The fluid flow through such a jointed rock is governed by the connectivity among the joints and their hydraulic properties. The connectivity depends on the number of joint sets, joint orientation, joint spacing, joint size, joint aperture and joint location. Two fundamental approaches are found in the literature for modeling of fluid flow through jointed rocks: (1) an equivalent continuum flow approach; and (2) a discrete fracture flow or DFN approach. The equivalent continuum/porous media approach assumes that the combined effect of fractures and matrix can be represented by an equivalent continuum represented mathematically by a symmetric hydraulic conductivity tensor at the scale of interest. On the other hand, the discrete fracture flow approach recognizes that fractures in matrix rock are distributed as discrete features, and may have significantly different hydraulic properties poorly captured by a symmetric conductivity tensor at the scale of interest.

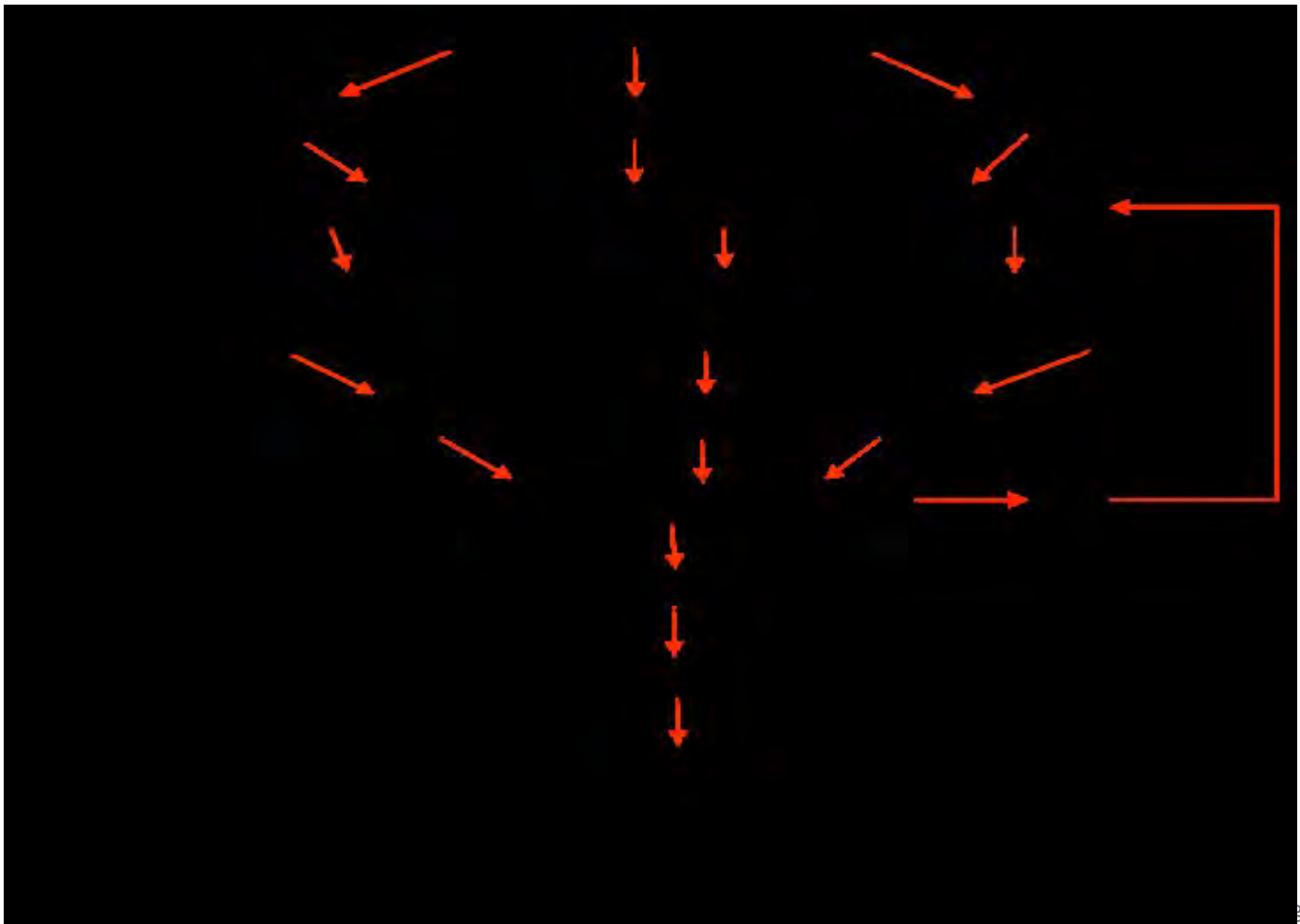
In a conventional equivalent continuum model, the heterogeneity of the fractured rock is discretized into structured or unstructured grids, with uniform material properties within each cell. Individual fractures are not explicitly treated in the model except when they exist on a scale large enough to be considered a separate hydrological unit (e.g., an areally extensive shear zone). The properties in each cell are constant and consist of values for transmissivity, permeability, storativity, effective porosity and others that express the volume-averaged behavior of many fractures. Conventional forms of the ground water flow equation, which were developed originally for granular porous media, can then be adopted. The use of continuum approximations in a deterministic framework has been the common practice.

Theis (1935) developed an equation to calculate the radial flow under constant pumping rate for a hypothetical aquifer that is uniform, isotropic and infinite. Average values of S (storage coefficient) and T (transmissivity) can be obtained in the vicinity of a pumped well by measuring drawdown in one or more obser-

vation wells. Under the porous media assumption, the S and T parameters can be obtained from drawdown data using the Theis type curves. Cooper-Jacob's method (Cooper-Jacob, 1946) further simplified the Theis equation so that a plot of drawdowns versus the logarithm of time (t) forms a straight line. The transmissivity is obtained from the slope of this straight line and the storativity is obtained from the time-drawdown curve in the observational well. Data from the recovery test may be used to calculate the transmissivity in the same manner as the pumping drawdown data, thereby providing an independent check on pumping test results. The recovery drawdown data known as residual drawdown is plotted versus the logarithm of time ratio (t/t') where t is the total time since pumping started and t' is the time since pumping ended. The residual drawdown plot cannot be used for determining the storage coefficient even though that plot is valid for calculating the transmissivity.

The equivalent continuum approach is based on the REV (representative elementary volume) concept.

The REV of a statistically homogeneous rock mass is defined as the minimum block size or volume beyond which any sub mass behaves essentially like the whole mass with respect to the combined effect of the rock matrix and fractures. Hence, any jointed rock media having properties similar to the REV may be modeled as porous media at a block size greater than or equal to the REV size. The hydraulic parameters for the porous media approach are predicted from the field tests only. For some sites it may not be possible to obtain REV behavior at any scale. For such sites, the porous media assumption approach is clearly not suitable. Conceptually, discrete fracture flow models have the capability of finding hydraulic parameters at any scale. The flow behavior through low permeable jointed rock conforms more closely with the discrete fracture flow approach. In the past, several authors (Schwartz et al. 1983; Long and Witherspoon 1985; Oda et al. 1985; Cacus et al. 1990; Panda and Kulatilake, 1999 (a & b)) have studied the effect of joint geometry parameters on the flow behavior of jointed rocks based on the discrete fracture flow approach.



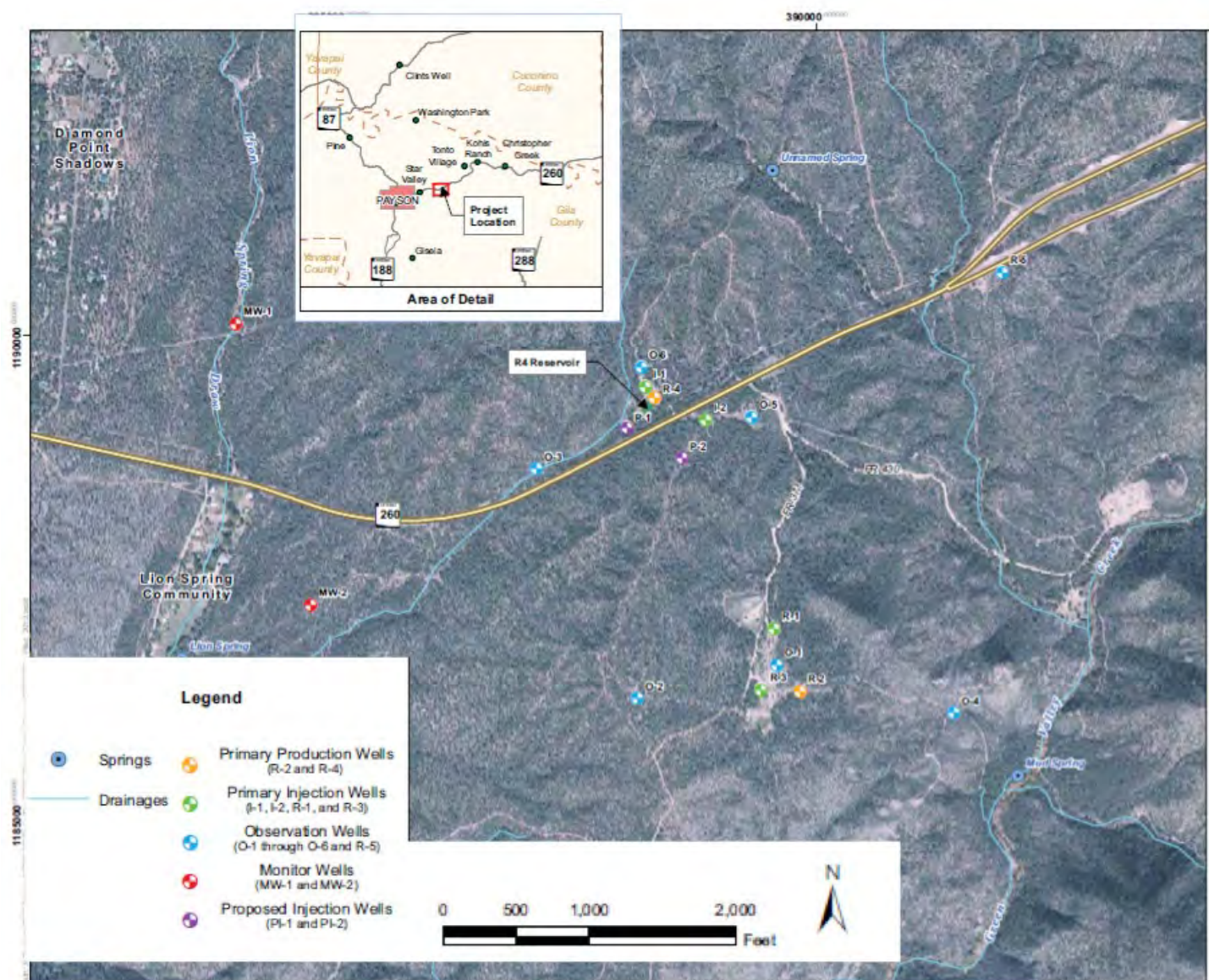


Figure 2. Location of wells, creeks and springs at RV site.

2. Methodology

Figure 1 outlines the general approach to developing a DFN model for fracture flow simulation. The discontinuity/fracture data may be obtained from boreholes (core and optical televiewer), scanlines, lineament mapping and two-dimensional (2-D) exposures, such as rock outcrops in the surfaces and tunnel walls. The subsurface lithology can be interpreted from surface geophysical data (seismic and resistivity) and borehole geophysical data (acoustic televiewer, guard electrical conductivity, induction resistivity, neutron, gamma density, temperature, caliper, etc.). Conventional short term, step discharge, or constant rate aquifer tests are performed on the pumping wells to calibrate the hydraulic properties of the DFN model. The DFN mode for the aquifer may be divided into different statistical homogenous regions based upon the fracture pattern characteristics or flow behavior.

3. Case Study

The groundwater resources along the highway corridor (State Route 260 from Payson to Heber) were investigated within areas of the Tonto National Forest to identify viable water sources for the 20 mile-long construction project for the Arizona Department of Transportation (ADOT). A groundwater-based solution in the project area required finding a suitable subsurface aquifer with a sufficient supply of water. This solution had to be implemented without significant negative impacts to the forest resources, including natural streams and springs, and nearby existing wells. The alternative to groundwater was hauling the surface water from the reservoir situated 65 miles from the construction site -- resulting in an additional cost of more than \$20 million. Detailed geological, geophysical and hydrological evaluations were

performed (AGRA, 1998) to assess groundwater resources for the construction water supply. Five locations along the highway corridor were initially targeted as potential well sites. Based on this initial evaluation, three target sites were selected for further investigation, but only the RV Site (Figure 2) was selected for detailed investigation work; very low yield (1 to 5 gpm) wells were found in the other two sites. Five exploration wells (R-1 through R-5) were drilled at the RV Site, and aquifer tests were performed to estimate the long-term yields of the wells. One of the wells (R-5) showed a yield of about 25 gpm, three of the wells (R-1, R-2 & R-3) had a yield of about 60 gpm, and one of the wells (R-4) exhibited a yield of about 190 gpm.

Six observation wells (O-1 through O-6) were drilled at the site for monitoring during pumping and long term monitoring. Intensive downhole geophysical logging was performed to characterize the aquifer materials and the fracture network. In particular, guard electrode electrical logs were used to measure formation resistivity and to infer values of formation porosity and permeability. The initial ground water level plot (3D) for the RV site well field is presented in Figure 3. Borehole acoustic televiewer logs were used to measure the thickness and orientation and density of the large connected fractures. Drill cuttings from each of the wells were visually examined and comprehensive geologic logs were prepared for each well drilled during the evaluation. A geologic reconnaissance of granitic outcrops in the project area was performed to inspect and characterize the condition of the fractures exposed at the ground surface. Short-term, step-discharge or constant-rate aquifer tests were performed on each of the proposed production and injection wells to estimate the specific capacity and yields of the wells. Four longer aquifer tests (ranging from 24 hours to 38 days) were performed to evaluate the long-term, sustainable yield of the well field and the potential impacts that could result from the withdrawal of a large volume of water from the well field. The water levels in the wells have been monitored on an ongoing basis to evaluate natural fluctuations and to estimate recharge into the well field.

The groundwater flow in the RV well field occurred through fractures. Anisotropic flow behavior was observed during the initial 24 hour tests, leading to the decision that a discrete fracture flow approach would be more appropriate for modeling the aquifer at the RV well field. A discrete fracture network was

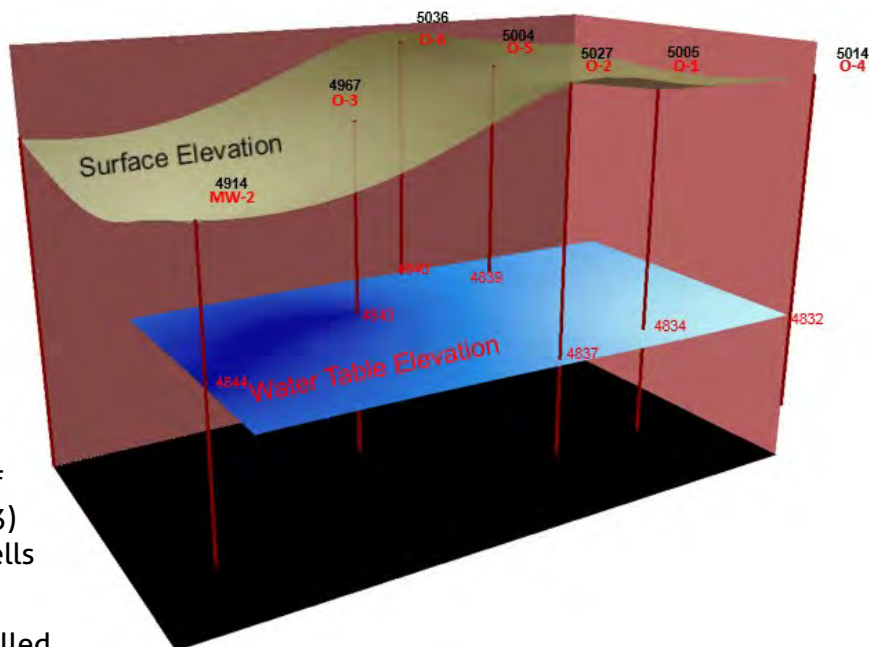


Figure 3. Visualization of the surface and water level elevations in feet at RV site well field.

developed to numerically simulate the flow through fractures in the granitic rock at RV site well field (Kulatilake et. al. 1998). The equivalent discrete fracture network geometry in 2D used in the fracture flow model is presented in Figure 4. Different zones of the modeled area were assigned different fracture transmissivities based on the data generated during the 24-hour aquifer tests. The values for the parameters calculated from the 24-hour aquifer test were used in the 38-day aquifer tests to validate the aquifer parameter. The simulated results from the computer model matched the observed pumping test results (drawdown) at pumping wells and observation wells (Panda and Kulatilake, 2009). The computer model predicted that the water levels in the well field would decline by up to 20 feet after one year of pumping and by up to 100 feet during the life of the project. Water level declines of this magnitude would have the potential of impacting existing wells in the communities and nearby springs and creeks. Withdrawal of construction water from the well field was not considered a viable option without the performance of monitoring to measure impacts, and the establishment of threshold levels for determining when withdrawals should be stopped. It was also shown that the fractured rock aquifer was of limited extent and essentially disconnected from a regional groundwater regime. Natural water flow into the aquifer from either the ground surface or from the aquifer boundaries would not be sufficient or rapid enough to help with recharge.

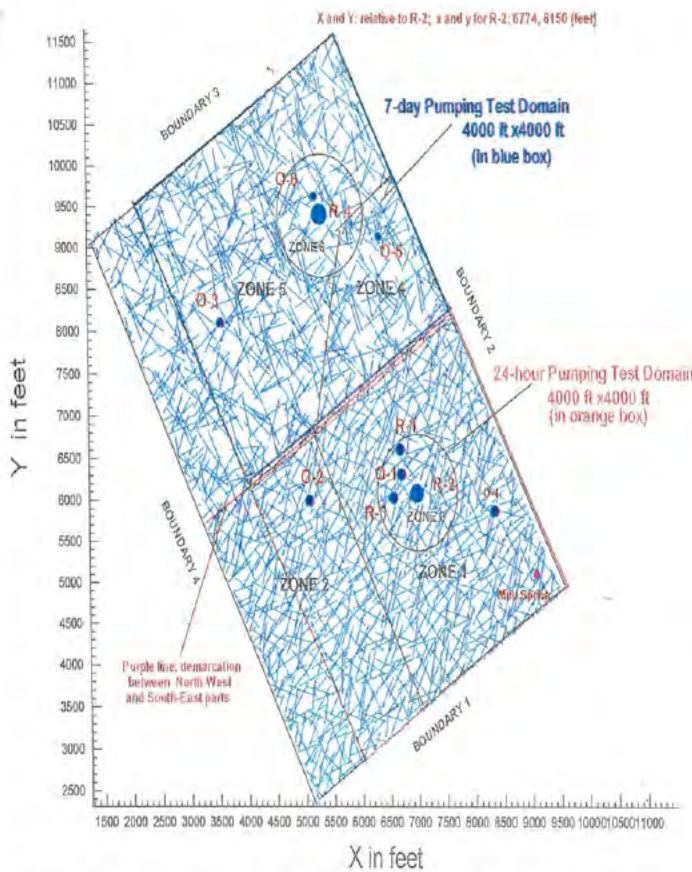


Figure 4. Two dimensional (2D) discrete fracture network model for the well field

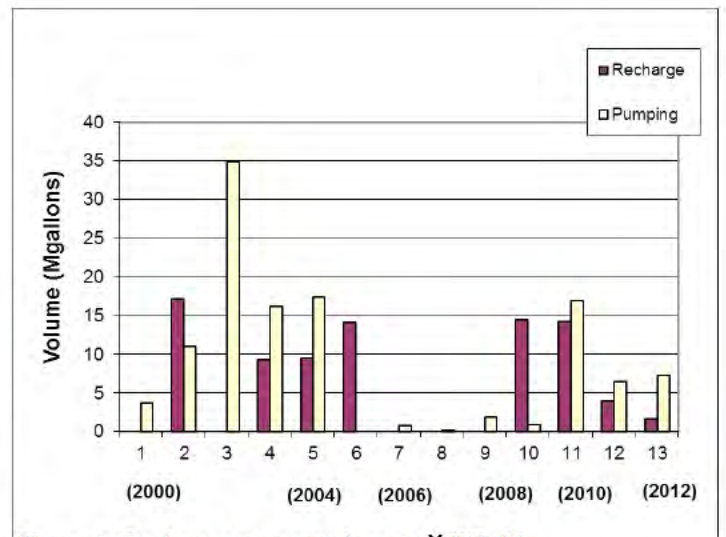


Figure 5. Recharge vs. pumping at well field

Surface water from nearby Tonto Creek was available to supplement water from the RV site well field. Hence, the construction of an underground water storage and recovery system at the RV site was developed for the sustainable use of the groundwater resources at the RV site. Withdrawal of water from Tonto Creek was limited to periods of high flow, when withdrawals would have minimal impact on

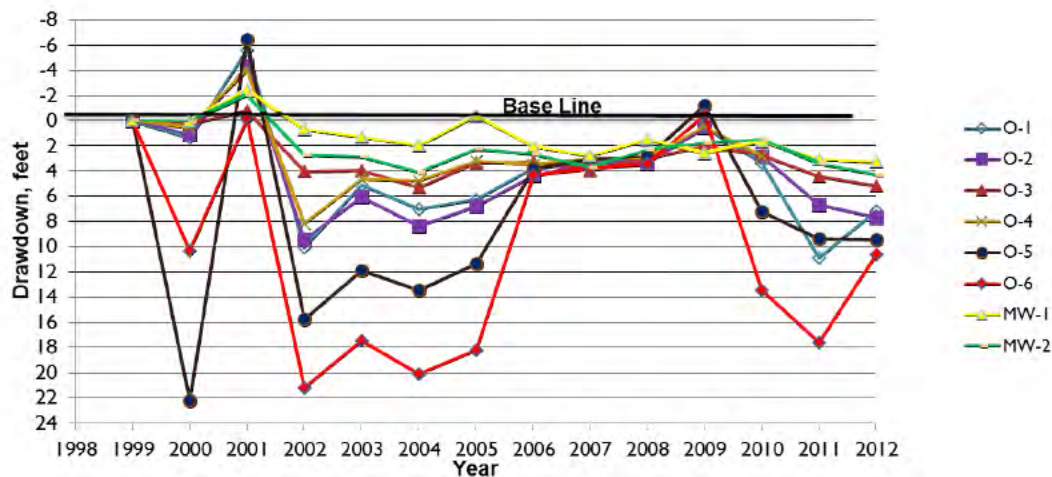


Figure 6. Monitoring of water level at observation and monitoring wells

Comparison of Drawdown due to Pumping in 2002
Modeled- 21 mgallons,
Observed- 26 mgallons

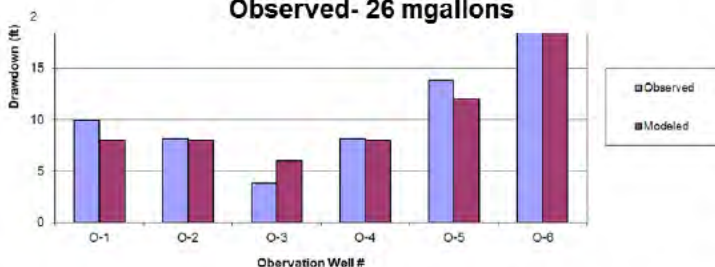


Figure 7. Predicted drawdown vs. observed drawdown

the creek system. It was very important to observe that the flow at Mud Spring had ceased 5 days after the start of the 38 day pump test program. A total of 18.4 million gallons was removed during the simulated withdrawal. Mud Spring did not flow for two years until a total of 18 million gallons was returned to the aquifer during the first year of recharge -- when aquifer water levels returned to pre-test levels, and Mud Spring again flowed.

The construction water supply from the RV site aquifer was successful for 12 years using the artificial recharge program based on the result of discrete fracture flow model. Recharge and pumping data for the well field through the year 2012 is presented in Figure 5. The monitoring data for the years up to 2012 is presented in Figure 6. The monitoring well data validated the assumption of discrete fracture flow as opposed to continuum flow for the RV site well field. It clearly demonstrated that there was very little natural recharge to site, that the water level declined with pumping, and was recovered with recharge.

The observation well data for 2002 was used to compare the observed data with the model data as there was no recharge in 2002. The observed drawdown data matches well with the modeled data at each observation well as shown in Figure 7.

4. Conclusion

The discrete fracture network flow model was used to develop the groundwater flow model in a fractured rock aquifer. The groundwater resource evaluation was accurately predicted through a discrete fracture flow model. The discrete fracture flow model predicted that the drawdown due to groundwater pumping required to meet the demand of construction water would be significant and it would impact the creek, springs and nearby wells.

An innovative artificial recharge program was developed to reduce the impact of the groundwater drawdown at the RV site well field. The project was successful as adequate groundwater supply was available at the RV site to meet the demand for construction water for 12 years with the help of an artificial recharge program. There was minimal drawdown in the well field and the impact to the creek and springs was also minimal. The success of the project has demonstrated that, in areas with suitable geologic conditions for fractured rock aquifers, such aquifers can be used as storage reservoirs for water that is only seasonally available. However, if such aquifers are tapped and not recharged, then the groundwater is essentially mined. Sustainability requires an active recharge component to assure that the resource will continue to be available.

The design of an underground water recharge program should be clearly based on the appropriate groundwater flow model based on discrete fracture network model. The long-term recharge and pumping should be designed based on the adequate hydrogeological characterization of the fracture rock aquifer and development of a conceptual discrete fracture network

model. With the advance of high-level computational system, the conceptual discrete fracture flow model can be developed using appropriate field data that can realistically model the fluid flow through fractured rock. Such conceptual models can effectively simulate the fluid flow through fractured rock, which can be useful for many applications to hard rock mining for dewatering, evaluation of groundwater resources, development of pit hydrologic sink model, and contaminant flow transportation.

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ARMA News Briefs

■ **San Francisco 2017 Symposium** ARMA expects over 500 technical papers to be presented at its 51st U.S. Rock Mechanics/Geomechanics Symposium to be held in San Francisco, California, USA on 25-28 June 2017. In addition, five keynote talks will be given by Francois Cornet (9th Annual MTS Lecture), Derek Elsworth, David Yale, Erik Westman, and Maria-Katerina Nikolinakou. Two short courses will be offered on Shale Gas Geo-Engineering by Maurice Dusseault and 2D and 3D Modeling of Rock Fracturing Processes in Geomechanics by Andrea Lisjak and Aly Abdelaziz. Three workshops will be offered on Emerging Advances in Geomechanics, Hydraulic Fracturing, and How Laboratory Geomechanics Testing Adds Value to Exploration and Production. Technical tours, an exhibition hall, and special events round out an exciting program. Early registration is available until 25 May 2017. Registration and further information can be found at www.armasyposium.org.

■ **ARMA Board Elects Officers** At its recent meeting in Charleston, SC, the Board of Directors elected the following officers for 2017-2019: Laura Pyrak-Nolte, President; Joe Morris, Vice President; Maria Nikolinakou, Treasurer; and Kate Baker, Secretary. The new officers will take their new positions on 25 June 2017.

■ **Unconventional Resources Technology Conference (URTeC)** ARMA is pleased to be a supporting organization for the upcoming URTeC conference to take place in Austin, Texas, USA on 24-26 July 2017. URTeC is an integrated science and technology event for unconventional play development. ARMA is developing an agenda for two sessions at URTeC on theory and practice, and simulations. More information can be found at <http://urtec.org/2017>.

■ **DFNE 2018 Conference** ARMA is sponsoring the Second International Discrete Fracture Network Engineering Conference to be held on 20-22 June 2018 in Seattle, Washington, USA. The conference will be held in conjunction with ARMA's 52nd U.S. Rock Mechanics / Geomechanics Symposium scheduled for 17-20 June 2018 at the Westin Seattle Hotel. The conference will examine DFN theory and fundamentals; oil, gas and geothermal energy; DFN approaches for underground and surface mining; and DFN approaches for infrastructure/geohazards. For further information see: www.dfne2018.com.

