PROCEEDINGS, 45th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2020
SGP-TR-216

Reference Native State and Stimulation Models of the Utah FORGE Site

Robert K. Podgorney[1], Aleta Finnila[2], Ahmad Ghassemi[3], John McLennan[4], and Joseph Moore[4]

[1]Idaho National Laboratory, PO Box 1625, MS 2213, Idaho Falls, Idaho, USA 83415

[2]Golder Associates Inc.,18300 NE Union Hill Road, Suite 200, Redmond, WA, USA 98052

[3]University of Oklahoma, Sarkeys Energy Center, 100 East Boyd Street, Norman, OK, USA 73069

[4]Energy & Geoscience Institute, University of Utah, 423 Wakara Way, Salt Lake City, UT USA 84108

robert.podgorney@inl.gov

Keywords: FORGE, reservoir modeling, Milford Utah, discrete fracture, continuum

ABSTRACT

Reservoir models of EGS systems must, by necessity, incorporate detailed descriptions of fractures (or fracture systems) while still encompassing a large enough model domain to minimize potential boundary effects. Here we describe the reservoir modeling efforts for defining the reference discrete and continuum models of the Frontier Observatory for Research in Geothermal Energy (FORGE) site located near Milford Utah, USA. The interconnections between smaller timescale fracturing simulations with longer term operational and reservoir evolution simulations. The modeling efforts also include native state simulations for reservoir pressure, temperature, and stress, and evolve to include transient simulations of potential reservoir development and operational scenarios as well as reservoir optimization evaluation.

1. INTRODUCTION

FORGE is a multi-year initiative funded by the US Department of Energy (DOE) for testing targeted EGS research and development. The site is located inside the southeast margin of the Great Basin near the town of Milford, Utah, and is described in detail in the Phase 2B Report (EGI, 2018) and shown on Figure 1. The current modeling and simulation work includes the development of baseline models using earth, continuum and discrete modeling methods

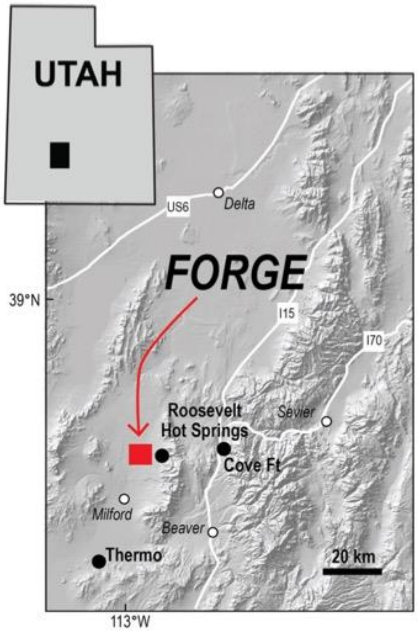


Figure 1: Location of FORGE site near Milford, Utah, USA.

The model region is sized to accommodate the geothermal reservoir intersected by Well 58-32 and future injection and production wells along with their predicted stimulation volumes created during FORGE Phase 3. This results in a region box 2.5 km x 2.5 km x 2.75 km, located approximately between depths of 400 m to 3200 m below the surface (Figure 2). The lithology is divided into two broadly defined units, comprising granitic basement rocks (granitoid) and the overlying basin fill sedimentary deposits. Temperatures in the region are predicted to be between 60°C and 250°C based on measurements in 58-32 with a temperature gradient of 70°C/km (Allis et al., 2019). The model region is rotated 25° from the N-S and E-W global coordinate frame so that the local coordinate frame is aligned with the principal horizontal stress directions as reported in the Phase 2B Final Topical Report (EGI, 2018) with sigma_hmax (σ2) at N25°E and sigma_hmin (σ3) at N115°E (Figure 2). This allows for easier interpretation of tensor values calculated using the local coordinate frame.

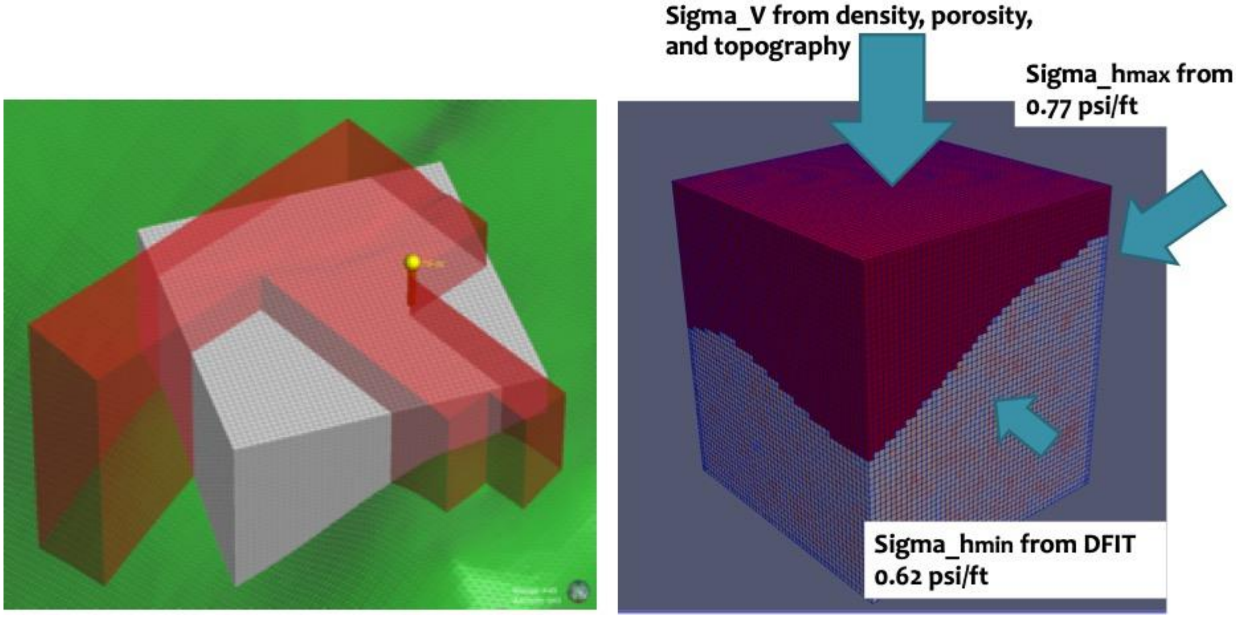
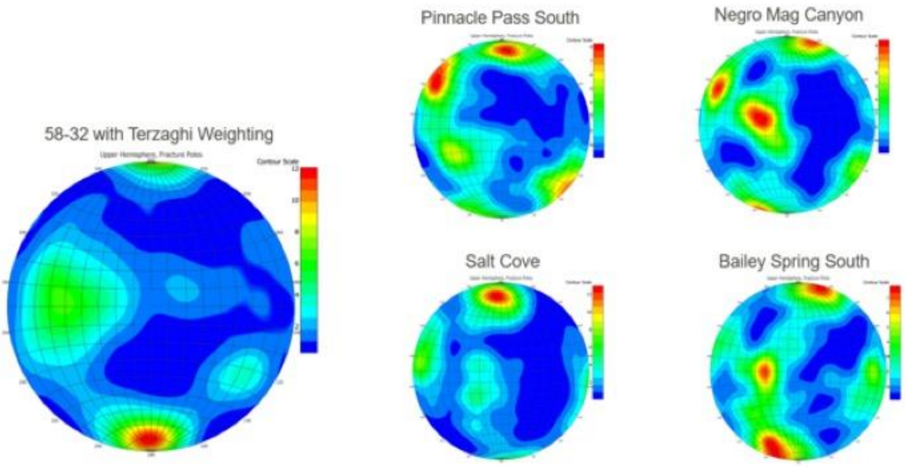


Figure 2: Left: Native state model domain (gray box) shown in relation to the full extents of the FORGE site (red shape) within the earth model domain. Surface shown is the top of the granitoid with the estimated temperature draped over the surface. Right: Numerical model domain shown with grid cells, looking from the southwest toward the northeast. The upper (red colored) portion is the sedimentary materials, while the lower (multicolored) portion is the granitoid. Coloring is relative and based on porosity.

2. REFERENCE DISCRETE FRACTURE MODEL

The FORGE reference DFN model (Finnila et al., 2019) was constructed using FracMan software (Golder Associates, 2019). The DFN incorporates measured surface and well log site data to create planer fractures that communicate as a single hydrological and mechanical system. The reference DFN consists of a deterministic set of fractures intersecting Well 58-32 where fracture locations and orientations are known, plus a stochastic set of fractures away from well control. Fracture apertures, permeabilities, and compressibilities were calibrated using measured bulk rock values once the fractures were generated. Hence, the fracture sizes and intensities were established. Once generated, the DFN is exported for use in the DEM simulations and upscaled to provide properties for continuum modeling simulations. These include 3D properties such as fracture porosity and directional permeability.

Fracture orientations are based on Formation Micro Scanner (FMI) log interpretation of Well 58-32 (EGI, 2018) as shown on the left side of Figure 3. These measured orientations have been weighted to account for the bias introduced by sampling from a vertical well as shown on the right side of Figure 3. The fractures in the DFN were generated by randomly selecting values from the Terzaghi weighted population and so mirror the measured values quite well.



58-32 with Terzaghi Weighting

Pinnacle Pass South

Negro Mag Canyon

Salt Cove

Bailey Spring South

Figure 3: Contour plots of fracture poles in lower hemisphere, equal area stereonets comparing the weighted FMI data for 58-32 on the left with four outcrop areas located in the nearby mountains on the right.

3. NATIVE STATE THERMAL-HYDRO-MECHANICAL MODEL

The FORGE numerical model domain was sized to accommodate the geothermal reservoir intersected by Well 58-32 and future injection and production wells along with their predicted stimulation volumes created during FORGE Phase 3. The depth to the top of the model domain was chosen so that the entire top of the model consisted for the alluvium materials. This was chosen for two reasons, the first being to be deep as possible in the alluvium to avoid potential shallow lateral flow originating from the east side of the Opal Mound Structure on the southeast side of the domain and the second to facilitate calibration of the vertical stress in the model. A uniform mesh spacing of 50 m was used, which resulted in a total of 137,500 grid cells.

Figure 4 shows the simulated and measured native state pressure, temperature, stress from Well 58-32. Table 1 presents the parameter values for the granitoid materials.

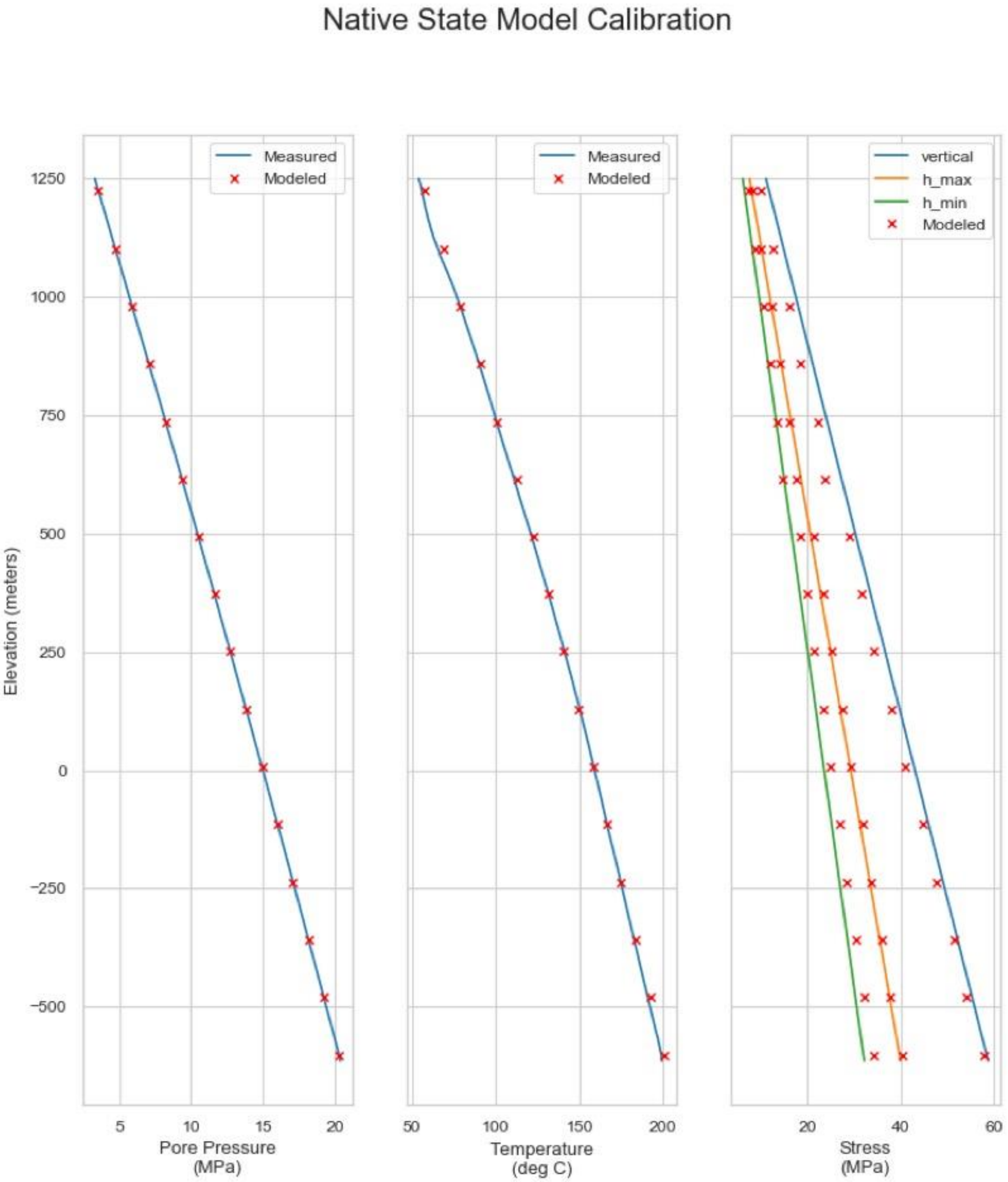
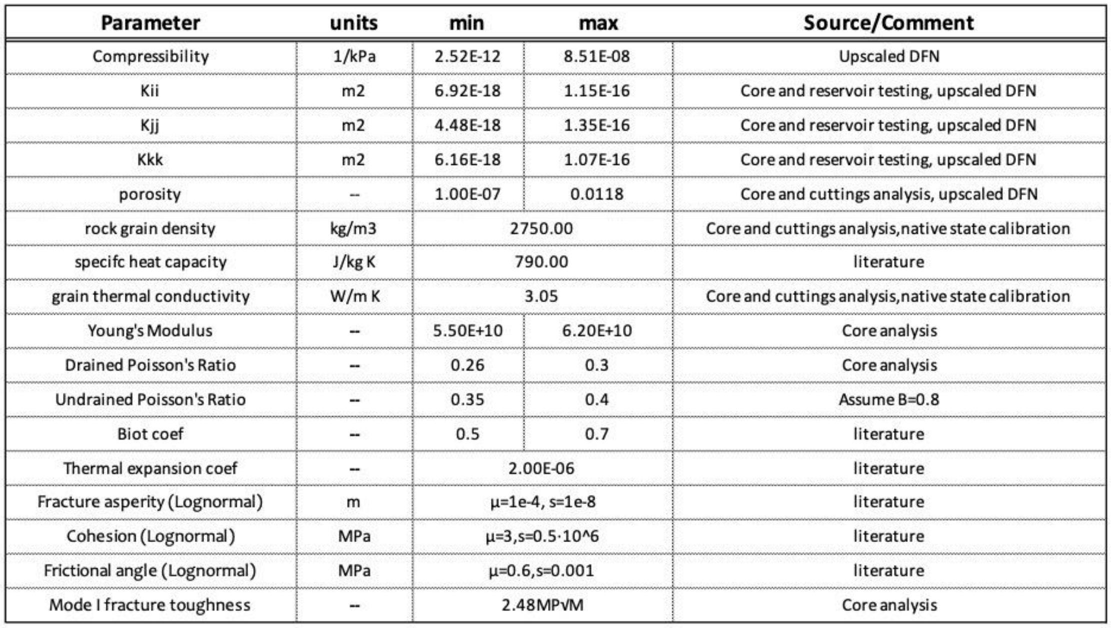


Figure 2. Native state model results compared with PT log collected in November 2018. Stress plots are from estimates from Phase 2B testing in the open hole portion of Well 58-32.



Parameter	units	min	max	Source/Comment
Compressibility	1/kPa	2.52E-12	8.51E-08	Upscaled DFN
Kii	m2	6.92E-18	1.15E-16	Core and reservoir testing, upscaled DFN
Kjj	m2	4.48E-18	1.35E-16	Core and reservoir testing, upscaled DFN
Kkk	m2	6.16E-18	1.07E-16	Core and reservoir testing, upscaled DFN
porosity	--	1.00E-07	0.0118	Core and cuttings analysis, upscaled DFN
rock grain density	kg/m3	2750.00		Core and cuttings analysis,native state calibration
specifc heat capacity	J/kg K	790.00		literature
grain thermal conductivity	W/m K	3.05		Core and cuttings analysis,native state calibration
Young's Modulus	--	5.50E+10	6.20E+10	Core analysis
Drained Poisson's Ratio	--	0.26	0.3	Core analysis
Undrained Poisson's Ratio	--	0.35	0.4	Assume B=0.8
Biot coef	--	0.5	0.7	literature
Thermal expansion coef	--	2.00E-06		literature
Fracture asperity (Lognormal)	m	μ=1e-4, s=1e-8		literature
Cohesion (Lognormal)	MPa	μ=3,s=0.5·10^6		literature
Frictional angle (Lognormal)	MPa	μ=0.6,s=0.001		literature
Mode I fracture toughness	--	2.48MP√M		Core analysis

Table 1. Final properties for the granitoid reservoir based on field and laboratory measurements and model calibration.

4. STIMULATION TESTING AND MODELING

The Utah FORGE team chose several well orientations and trajectories to evaluate/interrogate a large portion of the FORGE reservoir, examine the bounds of native state pressure, temperature, and stress, and to examine in a general sense well trajectory in relation to Shmin.

Numerous simulation cases were performed, with initial simulations focused on reservoir stimulation and later simulations focused on longer-term fluid flow between injection and production well pairs. Reservoir stimulation simulations used higher injection rates and pressures (simulation time of hours to days of stimulation), followed by reservoir operation simulations where longer term behavior can be examined (simulation time up to 10 years of operation).

The stimulation modeling was carried out using two different, but complementary modeling codes, GeoFrac (Cheng and Ghassemi, 2017) and FracMan (Golder, 2019). An initial evaluation of stimulation at 2 through 24 hours of injection, at 2-hour increments, was performed in FracMan as it uses a reduced order set of equations to simulate the stimulation and is computationally efficient enough to perform this large number of simulations. Following this initial stimulation evaluation, the Utah FORGE PMT, and modeling and simulation team, determined to focus on the shortest duration stimulation (2 hours) because the results suggested this period of stimulation would allow for the greatest operational flexibility and site development options going into the future. For stimulation, water was injected at 50 kg/s. The choice of flowrates for these reference stimulation/operational scenarios is important, we chose 50 kg/s because are confident we can inject at this rate (based on the 2C testing in 58-32) and to align with base case assumptions in the GeoVision Study (DOE, 2019). These simulation cases will be the reference for comparison for future scenario testing.

Long-term operation modeling (up to 10 years duration in FALCON) was carried out using FALCON (Podgorney et al., 2011). The FALCON simulations focused on pressure distributions and well hydraulics, heat flow, and evolution of the stress field over time. For these simulations, fluid was injected at 5 kg/s to represent approximately 1/10 the flow that may be expected from the well once complete reservoir stimulation has occurred via multiple fracturing treatments. Flow was injected into a 20m long segment at the toe of the well, with flow being extracted from locations where the stimulated fractures encountered the simulated production well located approximately 100m above the injection well trajectory.

Figure 5 below shows three of the evaluated trajectories, while Figure 6 focuses on the native state conditions along the trajectory shown in red on Figure 5. The remainder of the section will focus on the modeling and simulation of the 3-1a2 Trajectory.

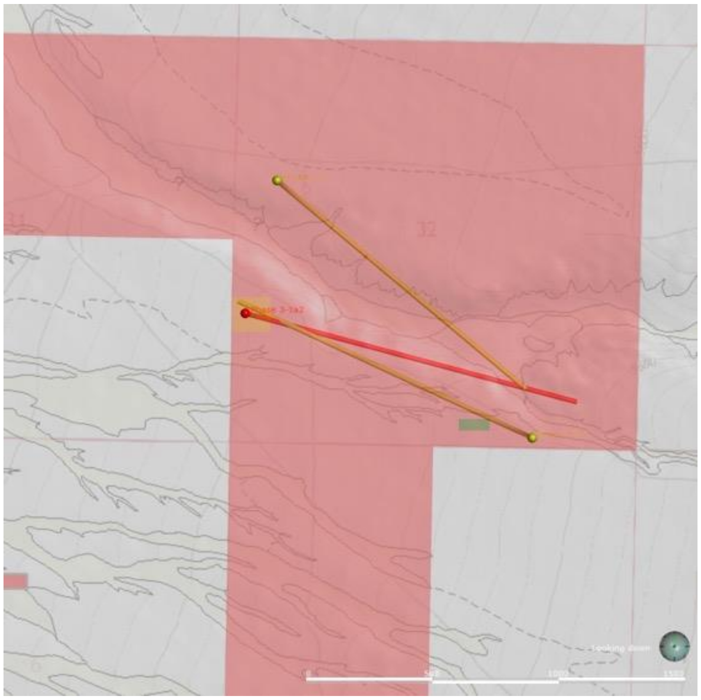


Figure 5. Three potential well trajectories evaluated for the FORGE site. The light red shaded area is the footprint of the FORGE site.

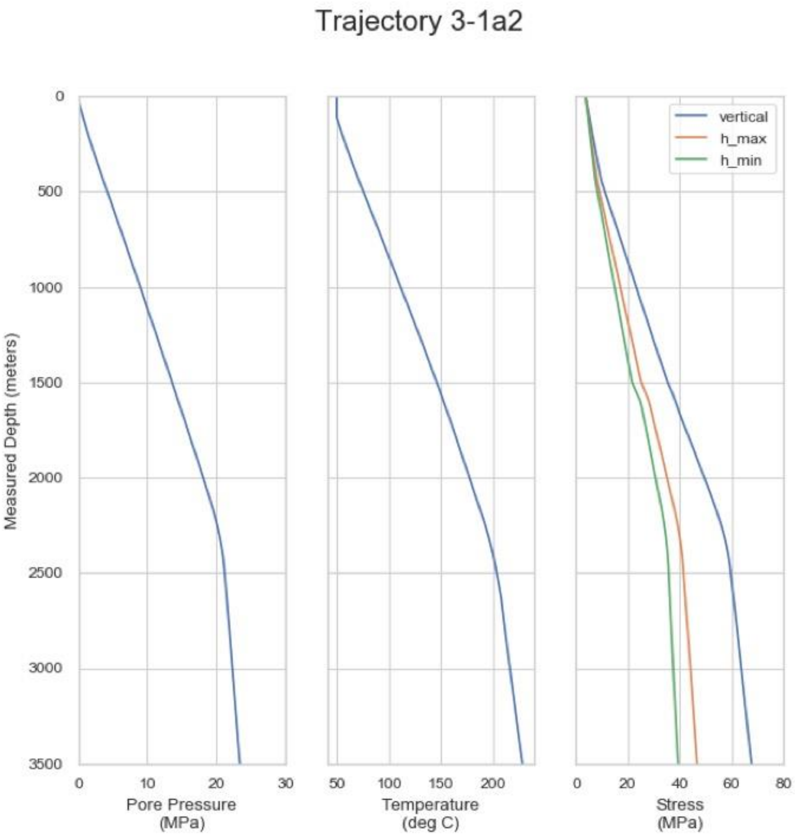


Figure 6. Predicted native state conditions along Trajectory 3-1a2 from land surface to the toe.

The bottom 20 m of the toe was stimulated in a series of simulations ranging in times from 2 to 24 hours. The extent of all three types of fractures stimulated in the model, the single induced tensile fracture, inflated natural fractures, and fractures failing in shear, are shown in Figure 7. As a rough estimate of how the fracture permeability changes, their initial permeability which was based on their size is increased by a factor of 100. The DFN after the 2-hour stimulation was then upscaled to calculate equivalent continuum fracture porosity and directional permeability on a 10m scale. These properties are then used as inputs to the FALCON THM simulations.

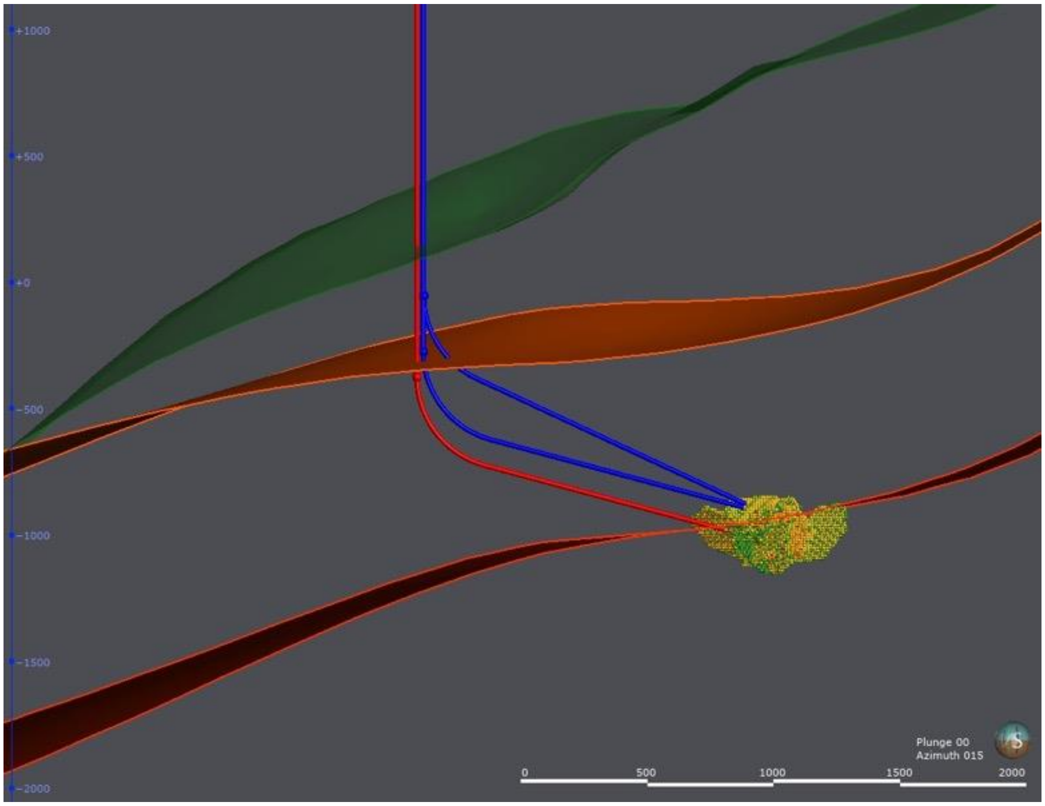


Figure 7. Side view of stimulating Trajectory 3-1a2 (red trace) for 2 hours. The green surface is the top of the granitoid rocks at the site, the orange surface is the modeled native state 175C isotherm, and the dark red-blackish surface is the modeled 225C isotherm. Potential production wells shown with the blue traces.

For the long-term operational simulation, fluid at 100^{o}C was injected into a 20m long segment consisting of 3 computational nodes that represented the toe of the trajectory under consideration. Fluid was initially injected at reservoir temperature and was linearly reduced to 100^{o}C over the first 5 days of simulation to approximate the well coming into thermal equilibrium with the injected fluid and reservoir. Fluid production from the extraction wells was simulated using the method proposed by Peaceman (1983), where a reference bottomhole pressure was specified and outflow is calculated as a function of the permeability and pressure differential.

Figure 8 shows time series of the modeled pressure and stress in the model grid cell containing the injection interval for Trajectory 3-1a2. The total modeled pressure increase required to inject the 5 kg/s is approximately 15.2 MPa, which slowly increased over the full 10-year simulation duration. All components of the effective stress were largely unaffected near the injection interval.

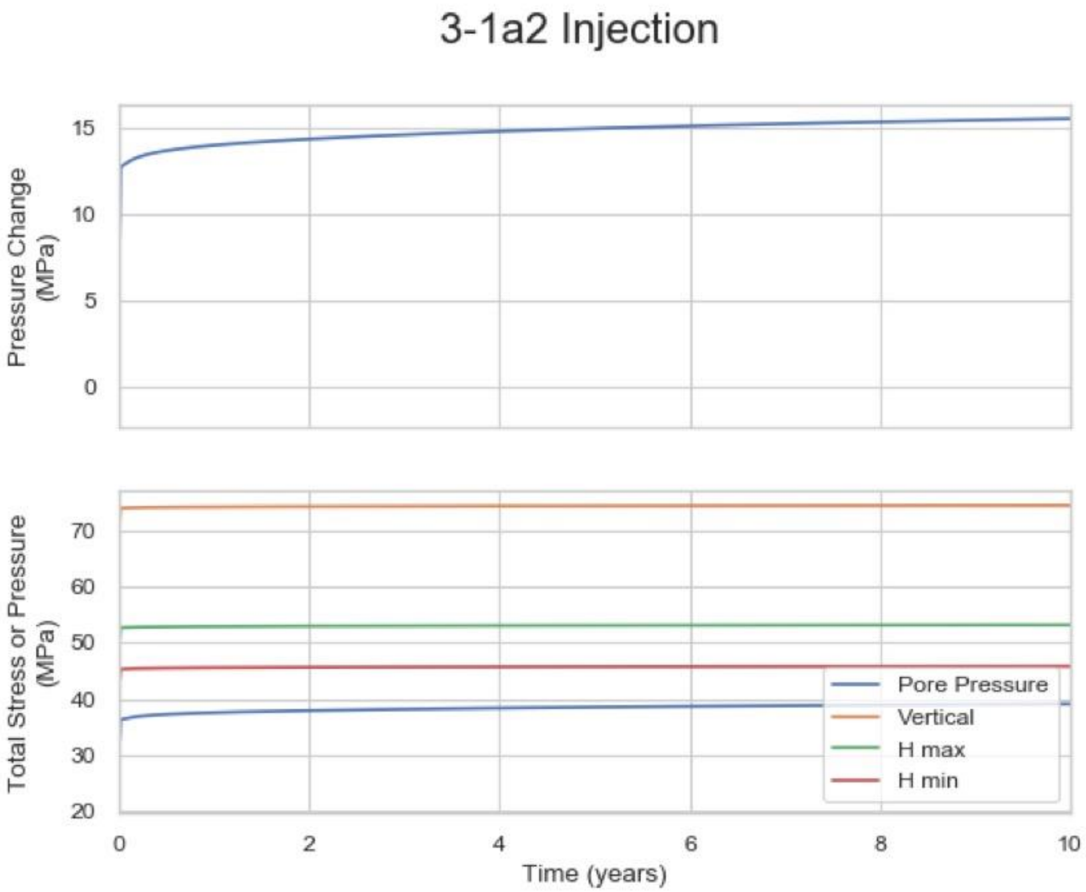


Figure 8. Pressure increase (top) and changes in total pressure and effective stress (bottom) resulting from injection into the toe section of 3-1a2.

6. SUMMARY AND CONCLUSIONS

Geologic characterization activities, combined with historical information, culminated in a conceptual model of the site which is dominated by thermal conduction in a large granitoid body with a top surface that dips generally to the west. The granitoid reservoir is overlain by younger sedimentary materials that host a non-potable groundwater resource. A reference earth model was constructed based on the geologic conceptual model that will be used to assess all future changes in geologic understanding at the site.

A detailed native state Thermal-Hydraulic-Mechanical model of the region of the site where stimulation and operations are expected to occur was created based upon the reference earth model. The modeled boundary conditions were mapped directly from geologic, geographic, and hydrogeologic conditions measured at the site, and were modified along with select reservoir properties to come to a calibrated steady-state solution. A reference set of reservoir flow, heat transport, DFN, and mechanical properties were developed from the calibration exercise, and used by the team for follow-on modeling to ensure comparability of results.

Stimulation potential of the reservoir has been baselined for numerous potential well trajectories using multiple numerical methods. The well trajectories were chosen so that the spatial variability in reservoir pressure, temperature, and stress, and the resultant effect on predicted stimulation, could be assessed. All simulation methods suggest stimulation can be successfully carried out at any of the trajectories via a combination of fracture dilation, shear failure, and tensile failure. The western portion of the reservoir generally exhibited greater vertical growth, likely due to the lower overall stress as one moves westward in the study area. The predicted stimulation response at early times was generally isotropic and may limit the number of stimulation stages along any given lateral, with later times showing a greater vertical growth. More detailed results were presented by Finnila and Podgorney (2020).

Long-term simulation of reservoir operations suggested that all trajectories examined would support flow through testing of durations lasting up to 2 years without significant thermal breakthrough or pressures that would cause additional fracture growth at the site. Predicted fluid recovery was in excess of ~95% for both cases tested. Based on the stimulation and long-term flow modeling results from both trajectories, a west to east trajectory will likely allow greater flexibility for stimulation and thermal response studies.

ACKNOWLEDGEMENTS

Funding for this work was provided by the U.S. DOE under grant DE-EE0007080 “Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site”. We thank the many stakeholders who are supporting this project, including U.S. DOE Geothermal Technologies Office, Smithfield (Murphy Brown LLC), Utah School and Institutional Trust Lands Administration, and Beaver County as well as the Utah Governor’s Office of Energy Development. Selected output for this paper was generated using Leapfrog Software. Copyright © Sequeent Limited.

REFERENCES

Allis, R.G., Gwynn, M., Hardwick, C., Hurlbut, W., Kirby, S., and Moore, J., 2019. Thermal characteristics of the Roosevelt Hot Springs system, with focus on the FORGE EGS site, Milford, Utah. Utah Geological Survey Miscellaneous Publication

Cheng, Q., Ghassemi, A. 2017. Numerical Modeling of Fluid Flow, Heat Transfer and Induced Microseismicity in Three Dimensional Fracture Networks. 51st U.S. Rock Mechanics-Geomechanics Sym. San Francisco, CA.

Energy and Geoscience Institute at the University of Utah, 2018, Roosevelt Hot Springs, Utah FORGE Well 58-32 Schlumberger FMI Logs DLIS and XML files [data set]. Retrieved from http://gdr.openei.org/submissions/1076.

Finnila, A., B. Forbes, and R. Podgorney, 2019. Building and Utilizing a Discrete Fracture Network Model of the FORGE Utah Site ROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 11-13, 2019

Finnila, A. and R. Podgorney, 2020. Exploring Hydraulic Fracture Stimulation Patterns in the FORGE Reservoir Using Multiple Stochastic DFN Realizations and Variable Stress Conditions, ROCEEDINGS, 44rd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 10-12, 2020

Golder Associates, 2019, FracMan® Reservoir Edition, version 7.8 Discrete Fracture Network Simulator.

Peaceman, D. W. 1983, Interpretation of well-block pressures in numerical reservoir simulation with nonsquare grid blocks and anisotropic permeability. SPE J., 23:531–543

Podgorney,R., H. Huang, C. Lu, D. Gaston, C. Permann, L. Guo, D. Andrs, 2011, FALCON: a Physics-based, Massively Parallel, Fully-coupled, Finite Element Model for Simultaneously Solving Multiphase Fluid Flow, Heat Transport, and Rock Deformation for Geothermal Reservoir Simulation, Idaho National Laboratory Report, Idaho National Laboratory, Report INL/EXT-11e23351.

U.S. Department of Energy (DOE). 2019. GeoVision: Harnessing the Heat Beneath Our Feet. Washington D.C.: U.S. Department of Energy. DOE/EE-1306.