

2025 Update to the Utah FORGE Native State Numerical Model

Bozo Vazic, Lynn B. Munday, Ming Yang, Robert K. Podgorney

Energy and Environment Science & Technology, Idaho National Laboratory, Idaho Falls, Idaho, USA

bozo.vazic@inl.gov

Keywords: Enhanced geothermal systems, native state, FORGE

ABSTRACT

In this work we present an updated native state numerical model of the Utah FORGE reservoir, incorporating recent pressure, temperature, and stress data acquired through 2024. The model domain extends 6 km by 6 km laterally and 4.5 km vertically, encompassing the granitic reservoir and overlying sedimentary formations. Mesh refinement has been implemented in the well field region to improve resolution of thermal-hydraulic gradients near injection and production intervals. Temperature calibration incorporates updated thermal gradient measurements from multiple wellbores, with particular attention to convective effects in the fractured granite reservoir. The model demonstrates strong agreement with observed downhole temperature profiles. Pressure boundary conditions have been refined based on recent shut-in pressure measurements and hydraulic monitoring data. In-situ stress parameters have been updated to better represent observed geometrically induced anisotropic stress state and its variation with depth, which is critical for predicting fracture orientation during stimulation operations. Key model parameters including rock thermal conductivity, permeability of both fractures and the surrounding reservoir, and bulk reservoir porosity have been recalibrated using circulation test data from 2024. This updated baseline model provides an improved foundation for simulating enhanced geothermal system development at the Utah FORGE site.

1. INTRODUCTION

The Frontier Observatory for Research in Geothermal Energy (FORGE), funded by the U.S. Department of Energy, is advancing enhanced geothermal system research near Milford, Utah. This multi-phase initiative involved site selection (Phase 1), site characterization (Phase 2), and full implementation and operations (Phase 3). Following the initial native state model developed in Phase 2 (Podgorney et al. 2021) and updated native state model developed in Phase 3 (Liu et al. 2022), an updated three-dimensional coupled multi-field model has been developed using FALCON (Xia et al. 2017, 2021) and MOOSE (Gaston et al. 2012). This model integrates geomechanics, fluid flow, and thermal fields to characterize the native state of the geothermal reservoir and predict changes in deformation, stress, pore pressure, and temperature due to field operations. Calibrated with new subsurface data and measurements from deep wells (e.g., 58-32, 78-32, 16(B)78-32, 16(A)78-32), this updated model incorporates an improved setup for boundary conditions and enhanced predictive accuracy.

2. THERMO-HYDRO-MECHANICAL FIELD EQUATIONS

New native state model is based on coupled temperature, pore pressure, and displacement field equations, which are critical for modeling the complex interactions in porous rocks, particularly in geothermal reservoir conditions where mechanical, thermal, and fluid flow processes are tightly interconnected. The solid field equation, coupled with the fluid and temperature fields, is represented by the stress equilibrium equation for geothermal reservoirs, expressed as follows:

$$\nabla \cdot (\boldsymbol{\sigma} - \alpha p \mathbf{I} - \beta T \mathbf{I}) + \rho \mathbf{g} = 0, \quad (1)$$

where $\boldsymbol{\sigma}$ is the Cauchy stress, p the pore pressure, T the temperature, \mathbf{I} identity tensor, α the Biot's coefficient, β thermal expansion coefficient, ρ density, and \mathbf{g} gravity vector. The fluid flow is simplified by the following equation:

$$\alpha \nabla \cdot \dot{\mathbf{u}} + \frac{1}{M} \dot{p} - \nabla \cdot (\mathbf{k} \cdot \nabla p) = s, \quad (2)$$

where \mathbf{u} is the displacement vector of the solid phase, \mathbf{k} permeability tensor, s fluid flow source, and M Biot's modulus. Lastly, the thermal field equation is expressed as follows:

$$\frac{1}{\gamma} \dot{T} - \nabla \cdot (\boldsymbol{\lambda} \cdot \nabla T - \sum_j h_j \mathbf{F}_j) = h_s, \quad (3)$$

where $\boldsymbol{\lambda}$ is the thermal conductivity tensor, summation over subscript j represents summation over existing phases in the model, h_j is the specific enthalpy for phase j , \mathbf{F}_j advective Darcy flux, and h_s heat source. For a detailed description of the coupled three-field equations that are implemented in the FALCON, see Podgorney et al. (2021).

3. NATIVE STATE MODEL

3.1 FORGE EGS Geology

The geology of the FORGE site is characterized by a crystalline granitic basement rock (“granitoid” layer) that lies at depths of approximately 1.5 to 4 kilometers, see Figure 1. This granite is relatively impermeable and lacks natural fractures, making it an ideal candidate for enhanced geothermal system (EGS) development, where permeability is artificially created through hydraulic stimulation. The site experiences a high geothermal gradient, with temperatures reaching approximately 175–225°C at target depths, which are optimal for geothermal energy production. Overlying the granite is a sequence of sedimentary and volcanic deposits (“sediment” layer), which serve as an insulating layer, preserving the heat within the granitic reservoir. The finite element model developed in this paper aims to accurately capture the complex contact surface between two separated blocks for sedimentary and granitoid layers.

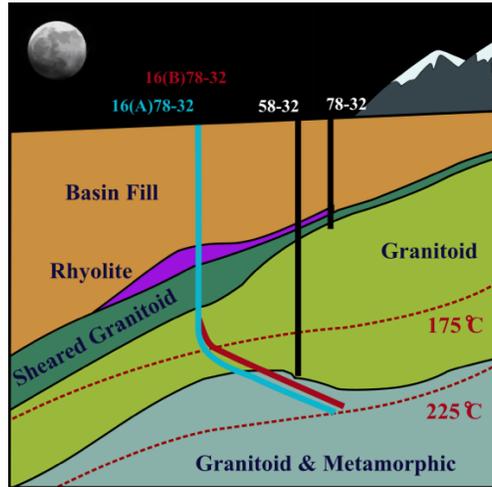


Figure 1: Geological cross section of the FORGE EGS site.

3.2 Mesh Generation

Model domain is defined large enough to enclose a volume of the reservoir intersected by Wells 58-32, 78-32, 16(B)78-32, 16(A)78-32 and a significant subsurface volume below the FORGE EGS site footprint. The model domain of 6.0 km × 6.0 km × 4.5 km is located approximately from 200 m below land surface to the depth of 4500 meters below land surface. A nonuniform mesh with average element size of 40 m was used, with a total of 11 million tetrahedron elements. Finite element mesh of the model is presented in Figure 2. In this mesh, interface across the sedimentary and granitoid layers has been captured.

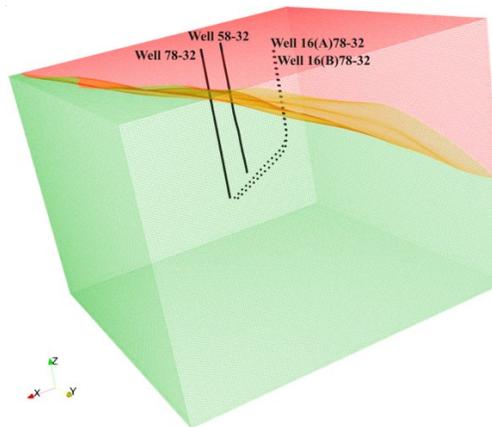


Figure 2: Finite element mesh for FORGE EGS native state model.

3.2 Boundary Conditions

For the native state model to converge with respect to the complex coupled equations that include fluid flow, thermal, and solid mechanics fields, appropriate boundary conditions for each field need to be carefully specified. Boundary conditions for the static model were derived from Phase 3 results, incorporating new data, field tests, and literature. Specifically, boundary conditions for the temperature and pore pressure were obtained from filed measurements from well based data (Podgorney and Allis 2018 and Moore et al. 2020) and FORGE site water table data (Kirby, 2021), respectively. Additionally, horizontal min/max principal stress was obtained from Tounsi (2025) was applied as normal traction on the sides while vertical stress (i.e., normal traction) was defined using overburden and applied to the top

surface. Expect the horizontal min/max principal stress that were applied as a linear function, other boundary conditions were extrapolated as spatially distributed point data via 3-D Leapfrog Geothermal modeling software (Alcaraz et al. 2011). Boundary conditions for three field equations are depicted in Figure 3 summarized below.

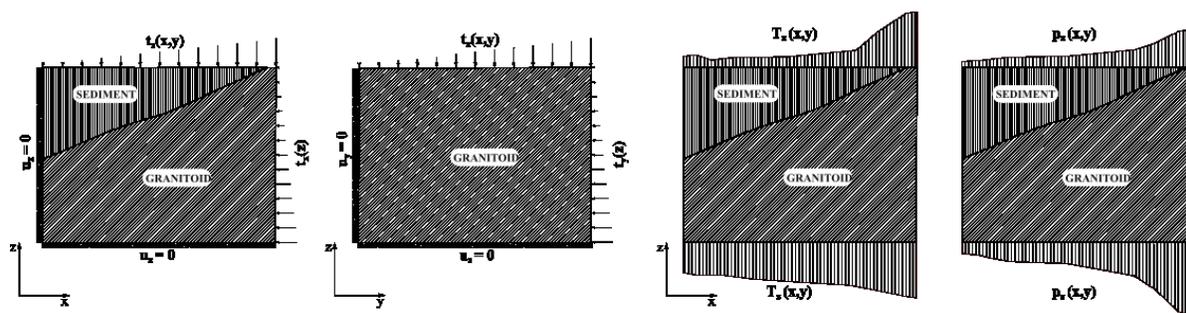


Figure 3: THM boundary conditions

1. Boundary conditions for the fluid flow field equations
 - a. Pore pressure calculated from water table applied as Dirichlet boundary condition on the top and bottom surface.
 - b. No flow Neumann boundary condition applied to all sides.
2. Boundary conditions for thermal field equation
 - a. Temperature extrapolated via Leapfrog Geothermal software and applied as a Dirichlet boundary condition on top and bottom surface.
 - b. No heat flux Neumann boundary condition applied to all sides
3. Boundary conditions for solid mechanics field equations
 - a. Fixed boundary condition applied in x,y, and z direction on surfaces with negative x,y, and z normal direction, respectively.
 - b. Neumann boundary conditions as normal tractions applied on surfaces with positive z,y, and z normal direction
 - c. Body force due to gravity.

By applying these boundary conditions and gravity (body force), the solution from this native static model will provide initial conditions including pore pressure, temperature, and stress for further transient analysis where fluids are injected through wellbores.

3.3 Material and Phase Properties

Reservoir properties for the native state model were primarily sourced from characterization data. When a range of values was available, the mean or median was used and adjusted during model calibration. Uniform material properties were applied within the alluvium and granitoid. Table 1 summarizes the reference values used for FORGE's current stat (McLennan et al. 2018, Moore et al. 2018, Podgomey et al. 2021).

Table 1: Model Material Properties and Parameters.

Parameter	Units	Values	
		Sediment Layer	Granitoid Layer
Permeability	m ²	10 ⁻¹⁴	5*10 ⁻¹⁷
Porosity	-	0.12	2*10 ⁻⁰⁴
Rock grain density	kg/m ³	2500	2750
Specific heat capacity	K/kgK	830	790
Grain thermal conductivity	W/mK	2.0	3.05
Young's Modulus	Pa	3.0*10 ¹⁰	6.2*10 ¹⁰
Drained Poisson's Ratio	-	0.3	0.3
Biot coefficient	-	0.47	0.47
Thermal expansion coefficient	-	6.0*10 ⁻⁰⁶	6.0*10 ⁻⁰⁶

3.4 Calibration and simulation results

The simulation results for the FORGE EGS native state model are summarized as follows. Figure 4 displays contour plots for pore pressure, temperature, Von Mises stress hydrostatic pressure, vertical normal stress, and shear stress in the X-Y plane. Field variables exhibit linear distributions vertically, with minima at the surface and maxima at the base but show significant horizontal variations. The applied shear traction, combined with normal pressure boundary conditions, causes notable stress variations at the sediment-granitoid interface, with shear stress spatially \ll 10% of the vertical normal stress.

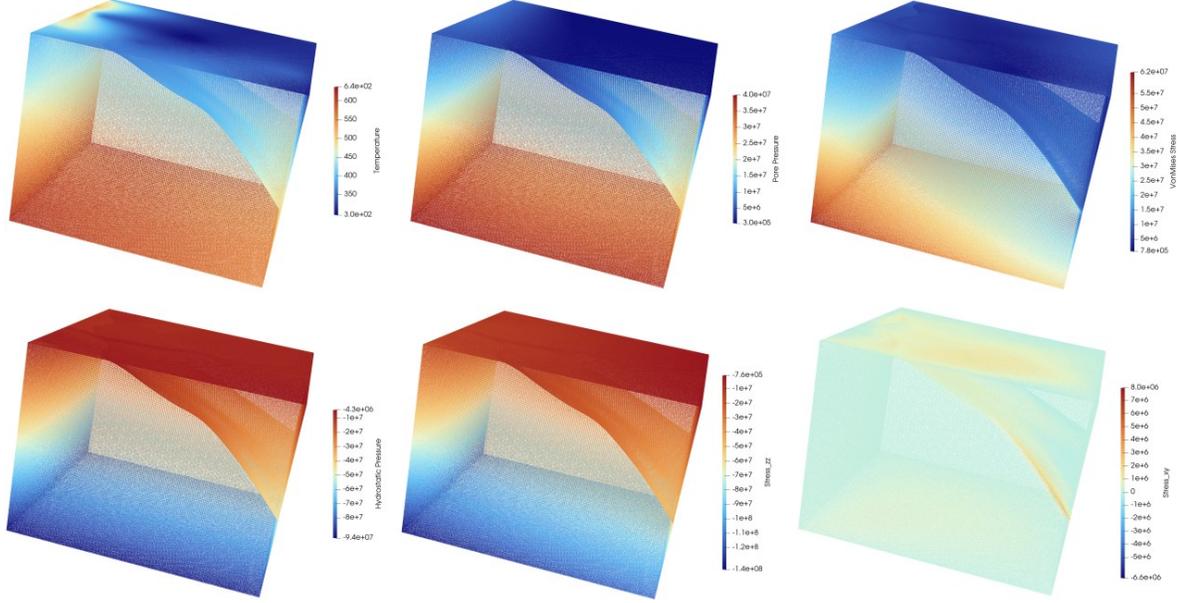


Figure 4: Calibrated native state model contour plots. From top left to bottom right; pore pressure, temperature, Von Mises stress hydrostatic pressure, vertical normal stress, and shear stress in the X-Y plane.

The native steady-state model results are derived from a series of calibrations using MOOSE optimization module (Prince et al. 2024). This process adjusts key parameters to align the predicted field variables with field measurements along wellbores. The optimization procedure involves iteratively minimizing the difference between model predictions and observed data by systematically refining parameter values to achieve the best fit. Calibration is carried on comparisons between the measured variables of the pore pressure, temperature, and field stresses and the corresponding variables predicted from the model. The pore pressure, and temperature were measured from Wells 58-32, 78-32, 16(B)78-32, 16(A)78-32. Minimized objective function for pressure and temperature is defined as follows:

$$\mathcal{L} = \min_{sT, sP} \frac{1}{2n} \sum_{i=1}^n \left[\left(T_i(sT, x, y, z) - \hat{T}_i(x, y, z) \right)^2 + \left(p_i(sP, x, y, z) - \hat{p}_i(x, y, z) \right)^2 \right], \quad (4)$$

where sT and sP are scaling factors applied to temperature and pressure boundary conditions, n is the number of data points, T and p are temperature and pressure from the simulation, and \hat{T} and \hat{p} are temperature and pressure obtained from the well measurements. Furthermore, orientation of the maximum total horizontal stress was inferred from the Well 58-32 Formation Microscanner Image (FMI) log (Moore et al. 2020) and thus stress calibration was done using data for Well 58-32. Similarly to the objective function in the Equation 4, minimized objective function for the stress is defined as follows:

$$\Delta \sigma_i = \sigma_i(s_x, s_y, s_z, x, y, z) - \hat{\sigma}_i, \quad (5)$$

$$\mathcal{L} = \min_{s_x, s_y, s_z} \frac{1}{2n} \sum_{i=1}^n [(\Delta \sigma_i)^2],$$

where s_x , s_y , and s_z are scaling factors applied to traction boundary conditions, n is the number of data points, σ is Cauchy stress tensor from the simulation, and $\hat{\sigma}$ is the principal stress tensor obtained from the well measurements. Figures 5 and 6 present calibration of temperature and pore pressure, where we can see a relatively good match to the measurements. Figure 7 shows stress calibration to the Well 58-32 data where this comparison is qualitative as we are comparing normal stresses to principal stresses. This comparison is valid because principal stress angles obtained from the model are approximately 10 degrees. Additionally, in Figure 7 we show the spread of the measured horizontal minimal principal stress for Zone 1 obtained from Table 1 in Moore et al. 2018.

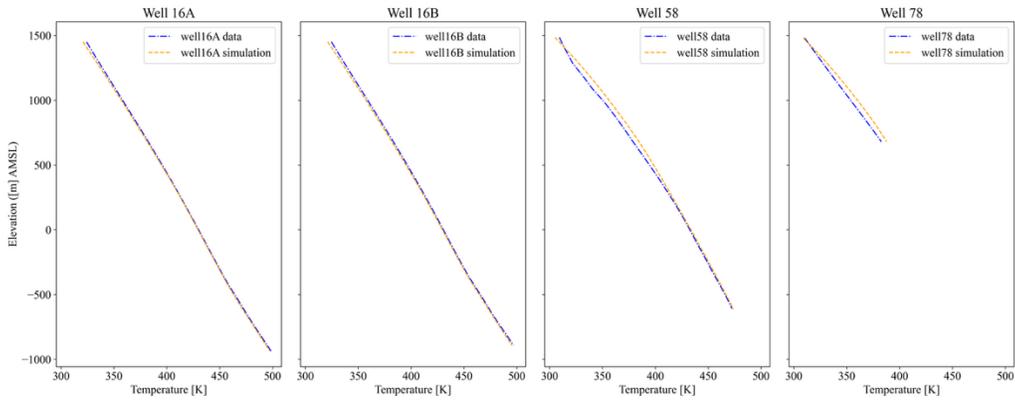


Figure 5: Model calibration regarding temperature.

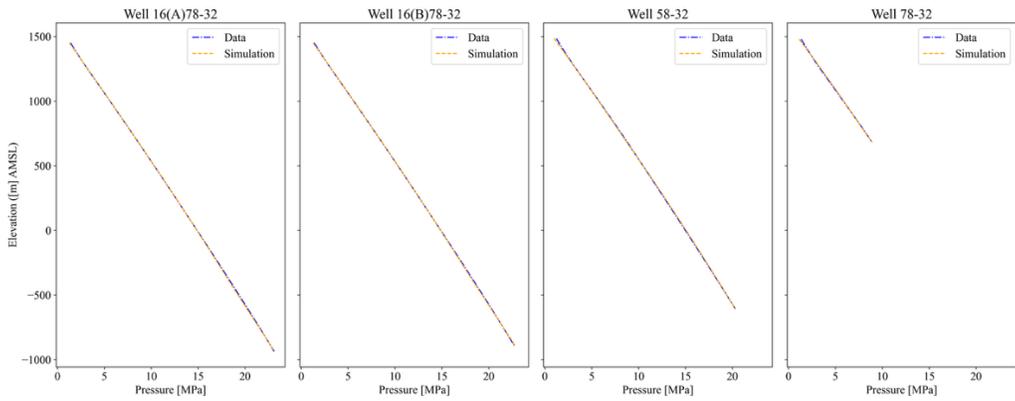


Figure 6: Model calibration regarding pore pressure.

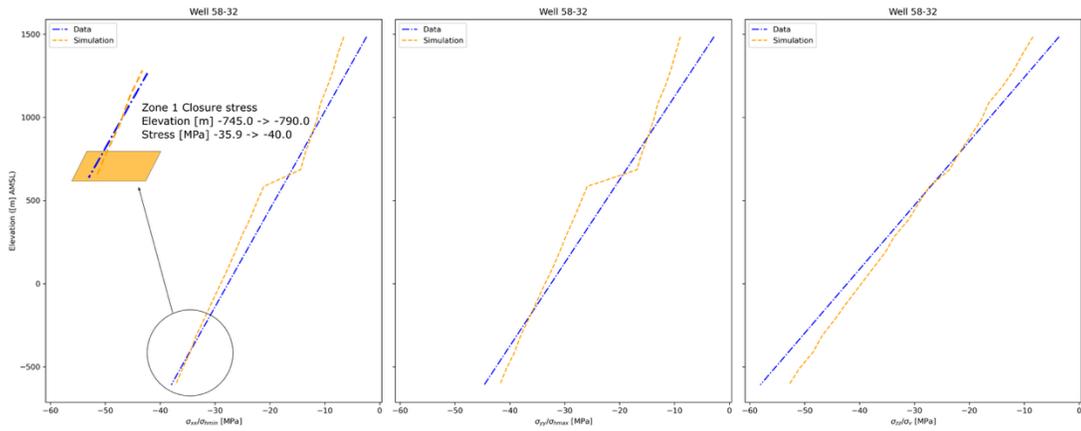


Figure 7: Model calibration to the principal stress data from Well 58-32

4 CONCLUSION

A coupled multi-field geothermal reservoir model with complex boundary conditions has been developed for FORGE Phase 3 native state modeling. The model has been successfully simulated and calibrated using field well-logging data and is expected to serve as a reference for building more accurate models with improved boundary condition definitions.

ACKNOWLEDGEMENT

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”. This research made use of the resources of the High-Performance Computing Center at Idaho National Laboratory, which is supported by the Office of Nuclear Energy of the U.S. Department of Energy and the

Nuclear Science User Facilities under Contract No. DE-AC07-05ID14517. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the DOE or the U.S. Government.

REFERENCES

- Liu, R., Podgorney, R., Finnila, A., Xing, P., McLennan, J., & Moore, J.: Development of a Coupled Multi-Field Utah FORGE Native State Model: Phase 3 Update. In 2022 Geothermal Rising Conference: Using the Earth to Save the Earth, GRC 2022 (pp. 589-596). Geothermal Resources Council, (2022).
- Xia, Y., Plummer, M., Mattson, E., Podgorney, R., Ghassemi, A.: Design, Modeling, and evaluation of a double heat extraction model in enhanced geothermal systems, *Renewable Energy*, 105, (2017), 232-247.
- Xia, Y.; Podgorney, R.: Falcon: Finite Element Geothermal Reservoir Simulation Code. Available online: <https://mooseframework.inl.gov/falcon/> (accessed on 1 August 2021).
- Gaston, D.; Guo, L.; Hansen, G.; Huang, H.; Johnson, R.; Knoll, D.; Newman, C.; Park, H.K., Podgorney, R.; Tonks, M.; et al.: Parallel Algorithms and Software for Nuclear, Energy, and Environmental Applications Part I: Multiphysics Algorithms. *Commun. Comput. Phys.* 2012, 12, 807–833.
- Kirby, S.: Utah FORGE: Groundwater Levels - Updated 2021. [Data set]. Geothermal Data Repository. Energy and Geoscience Institute at the University of Utah, (2021). <https://doi.org/10.15121/1825660>.
- Podgorney, R., and Allis, R.: Utah FORGE: Roosevelt Hot Springs Analytical Well-Based Temperature Model Data. [Data set]. Geothermal Data Repository. Idaho National Laboratory, (2018). <https://doi.org/10.15121/1495404>.
- Tounsi, H., Damjanac, B., & Radakovic-Guzina, Z.: A coupled hydro-mechanical analysis of the impact of DFN on reservoir stimulation at FORGE. Proceedings of the 50th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, (2025). (SGP-TR-229).
- Liu, R., Podgorney, R., Finnila, A., Xing, P., McLennan, J., & Moore, J.: Development of a Coupled Multi-Field Utah FORGE Native State Model: Phase 3 Update. In 2022 Geothermal Rising Conference: Using the Earth to Save the Earth, GRC 2022 (pp. 589-596). Geothermal Resources Council, (2022).
- Alcaraz, S., Lane, R., Spragg, K., Milicich, S., Sepulveda, F., & Bignall, G.: 3d geological modelling using new Leapfrog Geothermal software. In Proceedings, Thirty-sixth workshop on geothermal reservoir engineering Stanford University, Stanford, California, (2011).
- Podgorney, R., Finnila, A., Simmons, S., & McLennan, J.: A reference thermal-hydrologic-mechanical native state model of the Utah FORGE enhanced geothermal site. *Energies*, (2021), 14(16), 4758.
- McLennan, J., Nadimi, S., Trang, T. and Forbes, B.: Permeability Measurements, FORGE Utah Technical Report, Report to Department of Energy, Geothermal Technologies Office, April 2018, (2018).
- Moore, J., McLennan, J., Handwerger, D., Finnila, A., and Forbes, B.: Mechanical Property Measurements, FORGE Utah Technical Report, Report to Department of Energy, Geothermal Technologies Office, April 2018, (2018).
- Prince, Z. M., Munday, L., Yushu, D., Nezyur, M., & Guddati, M.: MOOSE Optimization Module: Physics-constrained optimization. *SoftwareX*, 26, 101754, (2024).
- Moore, J., McLennan, J., Pankow, K., Simmons, S., Podgorney, R., Wannamaker, P., ... & Xing, P.: The Utah Frontier Observatory for Research in Geothermal Energy (FORGE): a laboratory for characterizing, creating and sustaining enhanced geothermal systems. In Proceedings of the 45th workshop on geothermal reservoir engineering. Stanford University, (2020, February).