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Simulation of EGS Fracturing Dynamics Using Phase-field Finite Element

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ABSTRACT

Harnessing geothermal energy offers a clean and renewable resource, but field-scale modeling of Engineered Geothermal Systems (EGS) presents challenges due to the complex coupling of fluid flow, heat transfer, and geomechanics. These processes span scales from micro-level fracture interactions to macro-level reservoir behavior. Traditional numerical approaches, such as finite difference (FD), Discrete Fracture Network (DFN) modeling, and hybrid Finite Element Method (FEM) coupled with finite volume or FD simulators, often face limitations in addressing the intricate physics of EGS. Key challenges include capturing the multi-scale physical processes, representing discontinuities at fracture-matrix interfaces, and efficiently integrating multiple interacting phenomena. Additionally, modeling the dynamic propagation of fractures driven by evolving pressure and temperature remains a difficult task. This paper introduces an advanced phase-field modeling approach to overcome these limitations, which can naturally represent fracture initiation and growth without requiring pre-defined fracture geometries. The enriched Galerkin method is employed to discretize flow and energy equations, providing enhanced accuracy in capturing discontinuities around fractures. A fixed-stress split strategy is used to decouple the fluid flow and energy equations from rock mechanics and the phase-field equations, resulting in improved computational efficiency. The implementation within the open-source MOOSE framework enables simulations across scales. The proposed methodology is validated against analytical benchmarks and a 3D triaxial laboratory experiment that replicates pressure-induced fracture propagation. Furthermore, the approach is applied to field-scale EGS simulations in the Forge geothermal project, with validation through microseismic and pressure data, demonstrating the model's accuracy in representing real-world geothermal system behavior. This framework offers a pathway for more precise and efficient modeling of complex geothermal systems.

1. INTRODUCTION

Traditional numerical methods like corner-point Finite Difference (FD) and cell-centered FD or Finite Volume (FV) offer advantages in computational efficiency and ease of implementation, particularly on regular grids. However, their accuracy diminishes in complex geometries with sharp interfaces, such as fractures in EGS reservoirs (Russell et al., 1983; Sheng et al., 2015; Wheeler et al., 2006). These methods struggle to represent the intricate network of fractures and their influence on fluid flow. Advanced approaches like Discontinuous Galerkin (DG) and Extended Finite Element Method (XFEM) excel at handling discontinuities, e.g., fracture/matrix systems. DG employs higher-order polynomials within each element, enhancing accuracy near fractures (Riviere et al., 2003; Wheeler et al., 2003). XFEM enriches the mesh with additional degrees of freedom around fractures, improving the ability to capture their influence on flow behavior (Belytschko et al., 1999; Hansbo et al., 2004). However, both DG and XFEM can be computationally more expensive compared to traditional FD/FV methods. Discrete Fracture Network (DFN) methods explicitly represent the fracture network, offering a detailed description of preferential flow paths within fractures (McClure et al., 2013; Riahi et al., 2013). This provides insights into fluid flow behavior within the fractures themselves. However, accurately characterizing the complex fracture network geometry remains a significant challenge.

DFN methods often require extensive geological data, which may not always be readily available. Additionally, upscaling DFN behavior to represent larger-scale reservoir behavior remains a challenge. Capturing complex fracture interactions and their impact on fluid flow at the reservoir scale is difficult, potentially limiting the applicability of DFN models for field-scale simulations. Furthermore, representing numerous fractures can significantly increase computational costs, hindering the application of DFN models in large-scale EGS systems (Sheng et al., 2015). Finally, FEM's strengths for complex geometries (including fractures) are highlighted when coupled with the robust multiphase flow and heat transfer capabilities of FV/FD reservoir simulators (Gan et al., 2019; Taron et al., 2009; Wong et al., 2018). Coupled FEM/FV offers a flexible framework for handling discontinuities through mesh refinement or enrichment techniques. However, this flexibility comes at the cost of increased computational expense compared to simpler methods like FD or DFN.

This paper presents a field-scale numerical framework for modeling Enhanced Geothermal Systems (EGS), with a focus on Utah FORGE. Building on the work of Almetwally, Wheeler, Mikelić, Wick, Lee, and Girault, it integrates key advancements in phase-field modeling, Enriched Galerkin (EG) discretization, and h-adaptivity (Ahmed G Almetwally et al., 2024; Girault et al., 2020; Lee et al., 2021; MF et al., 2014; Wheeler et al., 2020). The diffuse diffraction formulation for thermoporoelasticity enables smooth petrophysical transitions without artificial source terms. EG discretization efficiently captures pressure and temperature discontinuities while conserving mass and energy. Phase-field modeling eliminates remeshing, ensuring seamless fracture evolution. A fixed-stress split enhances computational efficiency by decoupling mechanics from flow and energy equations. Localized mesh refinement reduces computational cost while resolving fine-scale fractures. Together, these innovations enable efficient, high-fidelity EGS simulations at the field scale.

2. MODEL FORMULATION

The generic mathematical formulation of an EGS system includes a model of dynamic fracture model, propagating in a thermo-poroelastic porous media (Li et al., 2021; Noii et al., 2019). A phase-field finite-element model captures the coupled effects of fluid flow, heat transfer, and mechanical deformation on fracture initiation/propagation (Kolesov et al., 2017; Mikelic et al., 2014). Building upon the thermodynamically consistent phase-field formulation (Amor et al., 2009; Francfort et al., 1998; Griffith et al., 1921; C Miehe et al., 2010; Christian Miehe et al., 2010), the pressure (p), temperature (T), displacement (u), and phase-field (φ) variables are incorporated into the phase field-Mechanics framework for fracture modeling. We investigated and benchmarked the model, in reference (A G Almetwally et al., 2023) (Ahmed G Almetwally et al., 2023), through comparison with analytical problems and modeling of EGS experiments.

2.1 Phase Field Fracture Propagation Model

The energy functional, ($E_\varepsilon(\mathbf{u}, p, T, \varphi)$), encapsulates the mechanical energy linked to displacement ($\mathbf{u}$), pressure (p), temperature (T), and the phase-field (φ), as defined in Equation 1 (A G Almetwally et al., 2023). It incorporates contributions from elastic strain, surface and fracture energy, internal forces (stress tensor), pressure-displacement coupling (Biot's coefficient), volumetric plastic dissipation, and the work exerted by fluid pressure and thermal loading. The regularization parameter (ε) defines the fracture zone width, while the fracture energy (G_c) quantifies the energy needed to create a crack surface. The phase-field variable influences elastic degradation and volumetric changes, governed by the degradation function ($g_D(\varphi)$). Internal forces and deformation are captured through the stress tensor ($\sigma(\mathbf{u})$) and strain tensor ($e(\mathbf{u})$) Biot's (α) characterizes pressure-displacement coupling, while temperature-displacement relationships are derived from (Noii et al., 2019). Fracture width is linked to the phase field following the approach of (Wheeler et al., 2020).

$$\underbrace{E_\varepsilon(\mathbf{u}, p, T, \varphi)}_{Energy\ Functional} = \underbrace{\int_\Lambda \frac{1}{2} g_D(\varphi)\sigma(\mathbf{u}) : e(\mathbf{u}) dx}_{Strain\ Energy} - \underbrace{\int_{\partial A} \tau \cdot \mathbf{u} dS}_{External\ Load} + \underbrace{- \int_\Lambda (\alpha - 1)\varphi^2 p \nabla \cdot \mathbf{u} dx + \int_\Lambda (\varphi^2 \nabla p)\mathbf{u} dx}_{Hydraulic\ Work} + \underbrace{- \int_\Lambda (\alpha_T + \mathrm{C})\varphi^2 T \nabla \cdot \mathbf{u} dx + \int_\Lambda (\varphi^2\, \mathrm{C}\, \nabla T)\mathbf{u} dx}_{Thermal\ Work} + \underbrace{G_c \int_\Lambda \left(\frac{1}{2\varepsilon}(1 - \varphi^2) + \frac{\varepsilon}{2}|\nabla \varphi^2|\right) dx}_{Fracturing\ Energy} \tag{1}$$

2.2 Enriched Galerkin Fluid Flow and Energy Balance Model

The cracked reservoir body, denoted as Λ, is divided into three computational domains for fluid flow analysis: the reservoir $\Omega_R(t)$, fracture ($\Omega_F(t)$), and transition ($\Omega_t(t)$) regions, distinguished by the phase-field variable φ, where $\varphi \leq 0$, $\varphi \geq 1$, and 0< φ <1, respectively (Wheeler et al., 2020). To standardize material properties, auxiliary variables χ_r and χ_f are introduced, defining material constants such as density ρ, permeability κ, viscosity η, Biot coefficient α_p, thermal expansion coefficient α_T, Biot modulus reciprocal c_p, heat capacity c_T, hydrothermal coupling coefficient β, hydraulic conductivity k_p, and thermal conductivity k_T as $(\cdot) = (\cdot)_r \chi_r + (\cdot)_f \chi_f$.

Fluid flow conservation is governed by:

$$c_p \frac{\partial p}{\partial t} - \beta \frac{\partial T}{\partial t} + \alpha_p\, \chi_r \frac{\partial \operatorname{div} u}{\partial t} - \operatorname{div}(k_p \operatorname{grad} p) = q_p \tag{2}$$

Energy conservation is described by:

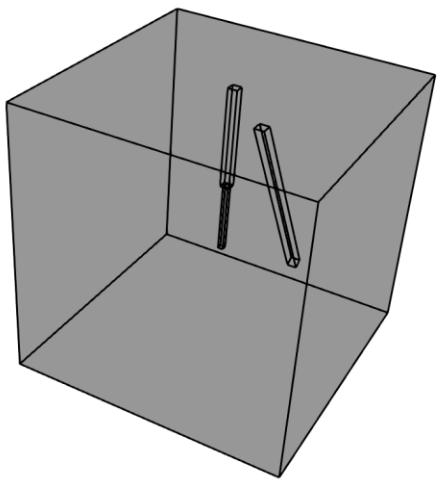
$$c_T \frac{\partial T}{\partial t} - \beta T_0 \frac{\partial p}{\partial t} + \alpha_T T_0\, \chi_r \frac{\partial \operatorname{div} u}{\partial t} - \operatorname{div}(k_T \operatorname{grad} T + \alpha_c\, T\, k_p \operatorname{grad} p) = q_T \tag{3}$$

where α_c represents fluid heat convective capacity, T_0 is the initial temperature, f denotes body forces, and q_p and q_T correspond to fluid and heat sources. The system couples energy, fluid flow, and solid mechanics through equations of state, source terms, the effective stress tensor, and variations in porosity, permeability, and thermal strains. The thermoporoelasticity equations, integrated with the phase field for fracture evolution, are solved using the Enriched Galerkin scheme for energy and mass conservation, while the Continuous Galerkin scheme addresses the momentum balance. The system is iteratively coupled with fluid flow using a fixed-stress split scheme for computational efficiency (Ahmed G Almetwally et al., 2023; Lee et al., 2016, 2017, 2018).

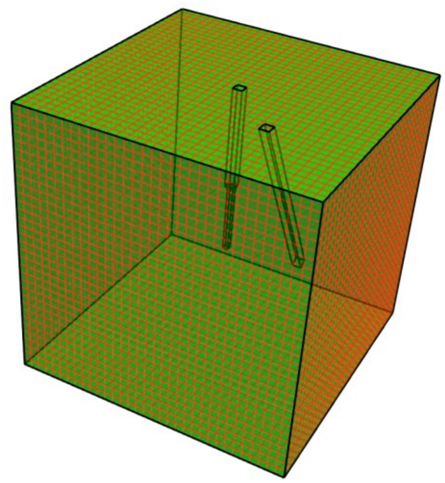
3. EXPERIMENTAL VALIDATION FOR EGS SIMULATION (TRIAXIAL EXPERIMENT)

Here, validation through a simulation of a laboratory-scale simulation of fracture propagation in Colorado Rose Red Granite, replicating the true-triaxial experiment conducted by Frash et al. (Frash et al., 2014). This experiment serves as a comprehensive benchmark, encompassing critical processes of hydraulic fracturing, fracture intersection with a borehole, and the EGS multiphysics coupling between thermal, hydraulic, and mechanical physics. The granite specimen, with dimensions of 300 x 300 x 300 mm, was prepared to ensure surface tolerance within ±0.5 mm, and instrumentation, including strain gauges and thermocouples, was installed. It was carefully placed into the true-triaxial apparatus, using passive concrete platens for confining pressures. The specimen was subjected to confining stresses of 12.5 MPa, 8.3 MPa, and 4.1 MPa along the vertical, maximum horizontal, and minimum horizontal axes, respectively. A 10 mm diameter injection borehole and a 6 mm production borehole were drilled, and hydraulic fracturing was initiated by injecting water at a controlled rate of 0.05 mL/min (Figure 1: Experimental validation of the phase field EGS modeling framework.-a). The key mechanical and thermal properties of the Colorado Rose Red Granite used in the simulation are summarized in Table 1. Importantly, the granite's low permeability (1.16 µD) is anticipated to minimize fluid leak-off during the fracture creation process. The modeling mesh (Figure 1: Experimental validation of the phase field EGS modeling framework.-b) was constructed to replicate the geometry of the injection and production boreholes, as well as to honor the stress and injection surfaces of the triaxial apparatus. This mesh provides an accurate representation of the experimental setup, enabling a direct comparison between simulated and observed behaviors.

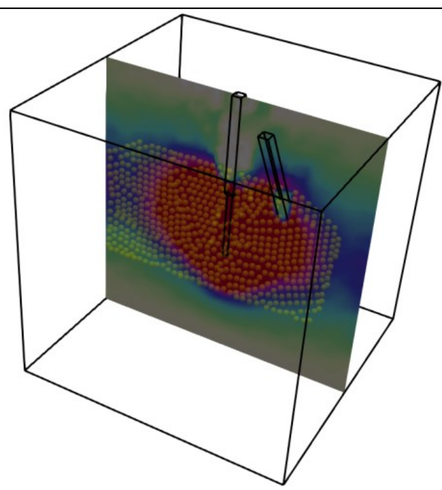
The initial hydraulic fracturing was performed by injecting water at a controlled rate until the breakdown pressure was reached, as illustrated in Figure 2: **Matching the breakdown pressure recorded from the experiment**.. The recorded pressure data matches the simulated pressure, indicating a breakdown pressure of 18 MPa and a fracture initiation pressure of 12.5 MPa. Following this, a re-stimulation test was conducted to enhance hydraulic connectivity by injecting a small volume of water at high pressure over a short impulse duration. Figure 1: Experimental validation of the phase field EGS modeling framework.-c and -d show the phase field distributions during the hydraulic fracturing and re-stimulation tests, with high values indicating fully fractured regions. The simulated 3D fracture growth patterns closely match the experimentally observed fracture profiles for both the initial and re-stimulated fracture profiles, as mapped by the recorded microseismicity during the experiment. This demonstrates the model's capability to replicate the complex fracture dynamics observed in the experimental setup.



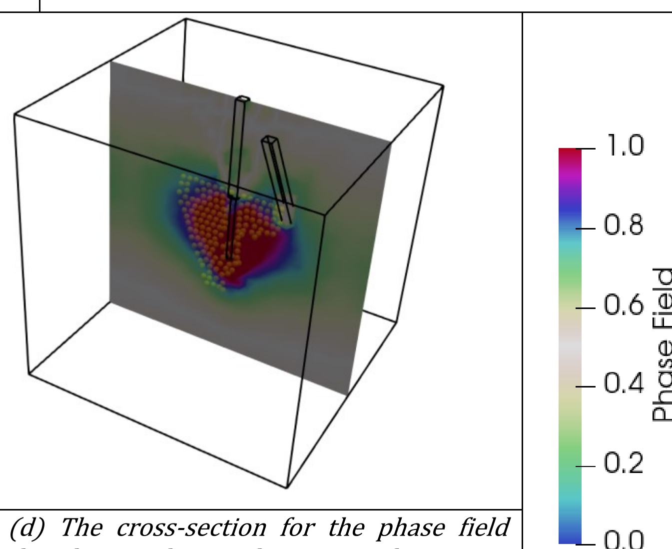
(a) mesh configuration representing the geometry of the injection and production boreholes



(b) refined mesh used to model fracture propagation for the triaxial experiment



(c) Cross-section of simulation results showing the phase field distribution during hydraulic fracturing (stage 1) along with digitized fracture surface (yellow spheres) based on recorded microseismicity



(d) The cross-section for the phase field distribution during the re-stimulation test (stage 2)

Figure 1: Experimental validation of the phase field EGS modeling framework.

Table 1: Reservoir Rock Properties of the Granite Specimen Used in the Triaxial Experiment

Property	Value	Property	Value
Permeability	1.15E-18 m²	**Young's Modulus**	5.69E+10 Pa
Porosity	0.0077	**Drained Poisson's Ratio**	0.32
Rock Grain Density	2630 kg/m³	**Biot Coefficient**	0.3
Specific Heat Capacity	2063 J/kg K	**UCS**	1.52E6 Pa
Grain Thermal Conductivity	3.15 W/m K	**Fracture Toughness**	0.72E6 Pa $m^{0.5}$

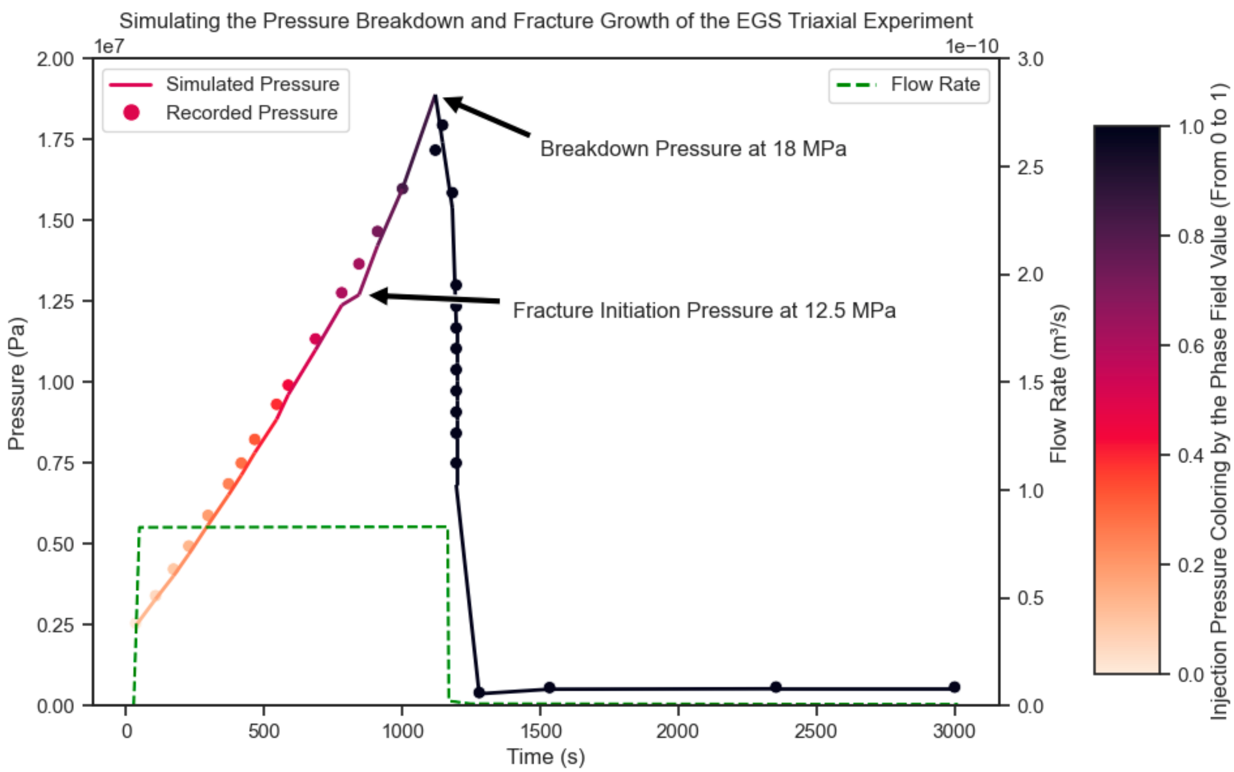


Figure 2: **Matching the breakdown pressure recorded from the experiment**.

4. VALIDATION AGAINST FIELD-SCALE EGS SIMULATION (FORGE PROJECT)

FORGE project is a pioneering initiative by the U.S. Department of Energy, aimed at advancing EGS technologies. The FORGE site is strategically located near Milford, Utah, within the southeastern margin of the Great Basin (Allis et al., 2019; Moore, 2019). The primary objective of FORGE is to serve as a dedicated field laboratory for the development, testing, and optimization of EGS technologies. This involves the artificial creation and management of subsurface fractures to enhance geothermal heat extraction from hot, dry rock formations, specifically crystalline granitoid rocks overlain by sedimentary and volcanic deposits (Nielson et al., 1986). Comprehensive subsurface data, including temperature, pressure, and stress profiles, have been gathered through deep exploratory wells (Gwynn et al., 2019). The static finite-element model for the FORGE site was developed using the FALCON code within the MOOSE framework, which integrates detailed three-dimensional parameter distributions and boundary conditions to simulate the thermal, hydraulic, and mechanical behavior of the geothermal reservoir (Podgorney et al., 2021). Table 2 details the 3D petrophysical properties of FORGE granitoid rock.

In April of 2022, the FORGE project team carried out a 3-stage fracture stimulation program. Stage 1 involves the initial formation breakdown pressure and identifying potential fracture initiation sites through jagged pressure patterns and microseismic event analysis, indicative of fracture activity (Forbes et al., 2019). Stage 2 simulates the use of slickwater at a maximum rate of 35 bpm (5.56 m³/min), monitoring the formation breakdown pressure, and conducting a hard shutdown to evaluate fracture behavior. This stage also includes flowback analysis at 4 bpm (0.64 m³/min), with observations of wellhead pressure dropping to 0 psi (McLennan, 2022). Stage 3 utilizes a crosslinked CMHPG fluid at similar pump rates to Stage 2, introducing microproppant to enhance fracture geometry and sustain fracture conductivity. The microseismicity recorded during the hydraulic fracturing stages at the FORGE site provided critical insights into the behavior of the fracture network. Analysis conducted in reference (Riahi et al., 2019; Xing et al., 2021) established fracture network, characterized by fracture density, size distribution, and orientation based on microseismic data. The recorded microseismic events indicated the activation and propagation of fractures, highlighting a broad range of fracture lengths with many small fractures and fewer large ones. The observed fracture density and connectivity were crucial in determining the effective permeability and fluid flow pathways within the reservoir. The fracture orientation, identified through stereo net analysis, revealed multiple fracture sets with distinct mean angles, impacting the overall connectivity and mechanical behavior of the reservoir.

Table 2: Reservoir Rock Properties at the FORGE Project

Property	Value	Property	Value
Permeability	1.00E-18 m²	**Young's Modulus**	6.50E+10 Pa
Porosity	1.00E-03	**Drained Poisson's Ratio**	0.3
Rock Grain Density	275 kg/m³	**Biot Coefficient**	0.3
Specific Heat Capacity	790 J/kg K	**Thermal Expansion Coefficient**	6.00E-06
Grain Thermal Conductivity	3.05 W/m K	**Fracture Toughness**	0.72E6 Pa $m^{0.5}$

When simulating porous media problems, mesh refinement is crucial, especially with complex geometries and localized phenomena like fractures (Schrefler et al., 2006). By strategically increasing mesh resolution in areas of rapid solution changes or where high accuracy is needed, the accuracy of the solution can be improved (Heister et al., 2015). Several techniques can achieve this, including h-refinement (dividing elements), p-refinement (increasing polynomial order), r-refinement (relocating nodes), and hp-refinement (combining h- and p-refinement) (Kita et al., 2001). Error estimators, like residual-based, recovery-based, and goal-oriented estimators, are important tools for guiding mesh refinement by quantifying errors and enabling targeted refinement (Fang, 2021). In coupled flow and geomechanics simulations, where fluid flow and solid deformation interact, and fractures pose additional challenges, adaptive mesh refinement techniques guided by error estimators are key for efficiently resolving the solution (Girault et al., 2020). The adapted approach, in this paper, h-refines the mesh around the fracture network, achieving high resolution near fractures and using coarser meshes in the far-field reservoir to balance accuracy and computational cost. By combining dynamic h-refinement with EG formulation for flow and energy, we effectively capture sharp gradients and discontinuities near fractures while managing the problem size. Figure 3 illustrates the refined mesh used in modeling the FORGE Enhanced Geothermal System (EGS) research laboratory (to be discussed in detail in the following section) project, localized around the fracture network and the injection-production wells. This mesh is based on error estimators developed by Girault et al (Girault et al., 2020).

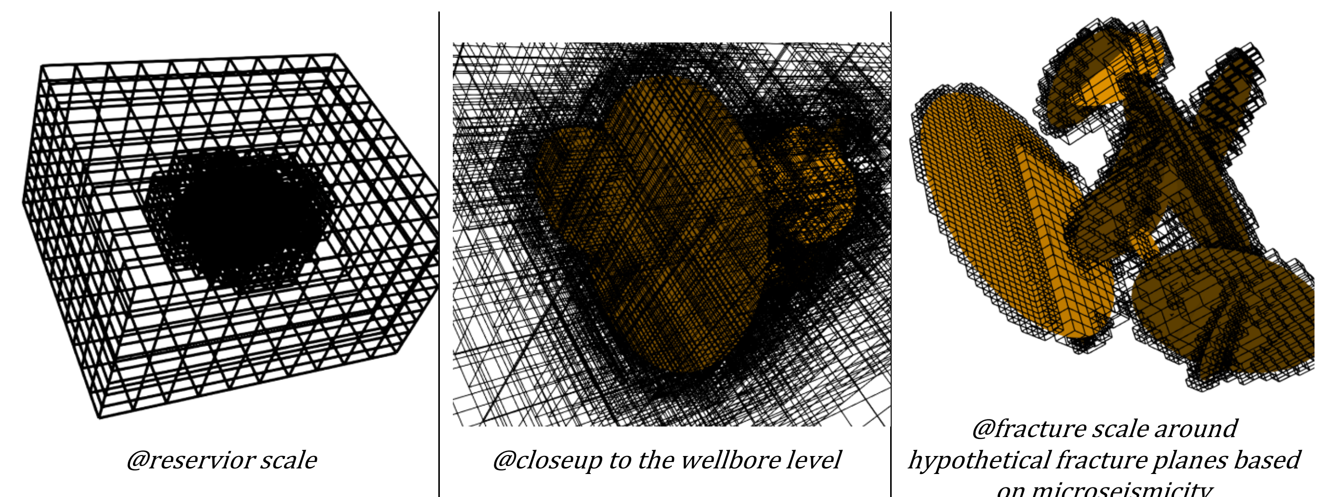


Figure 3: Example of localized mesh refinement for Forge project simulation.

We focus our simulations on the growth and behavior of hydraulic fractures across three distinct stages, aimed at understanding and optimizing future stimulation efforts and aim to capture the dynamic evolution of the fracture network, from re-opening existing fractures to extending them further using the developed MOOSE-based EG-phase-field framework, thereby optimizing fluid flow and pressure management for enhanced geothermal energy extraction. Validation against microseismicity data and recorded pressure confirm the accuracy of our model. By integrating the diffusive diffraction thermoporoelastic formulation with EG discretization, the model adeptly simulates the coupled processes of fluid flow, heat transfer, and rock deformation while maintaining computational efficiency. The use of a small mesh with only 25,000 elements highlights the computational efficiency of our approach, enabling a detailed simulation of the fully coupled model without compromising accuracy.

The results, as shown in the figures, demonstrate the robustness of our simulation framework. Figure 4 presents a precise match of pressure data across the three fracturing stages, displaying the evolution of the phase field variable at the injection nodes over time. Figure 5 illustrates the pressure propagation through the system, from the gentle reactivation of existing pathways (Stage #1) to aggressive, pressure-driven fracture growth (Stage #2), and finally, stabilization with proppant to enhance flow (Stage #3). Figure 6 provides a compelling visualization of phase field propagation that closely aligns with recorded microseismicity, underscoring the model's capability to accurately capture fracture initiation, propagation, and interaction. The use of the phase-field method allows for seamless fracture representation without the need for computationally intensive re-meshing. Additionally, the fixed-stress split decoupling technique, coupled with specialized solvers, significantly accelerates simulation times compared to traditional monolithic approaches. Furthermore, the strategic use of localized mesh refinement around evolving fracture zones, guided by the phase-field model, drastically reduces the computational burden associated with large-scale simulations.

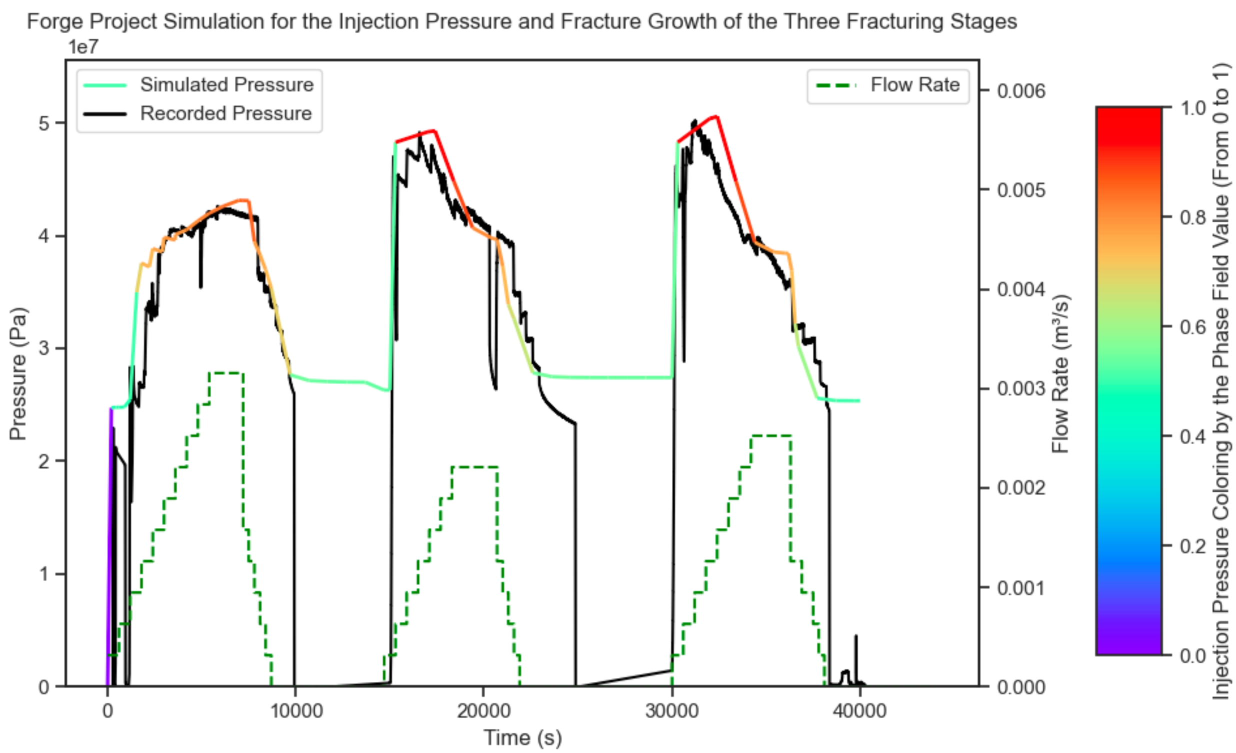


Figure 4: Pressure match for the three stages, colored by the value of the phase field variable at the injection node.

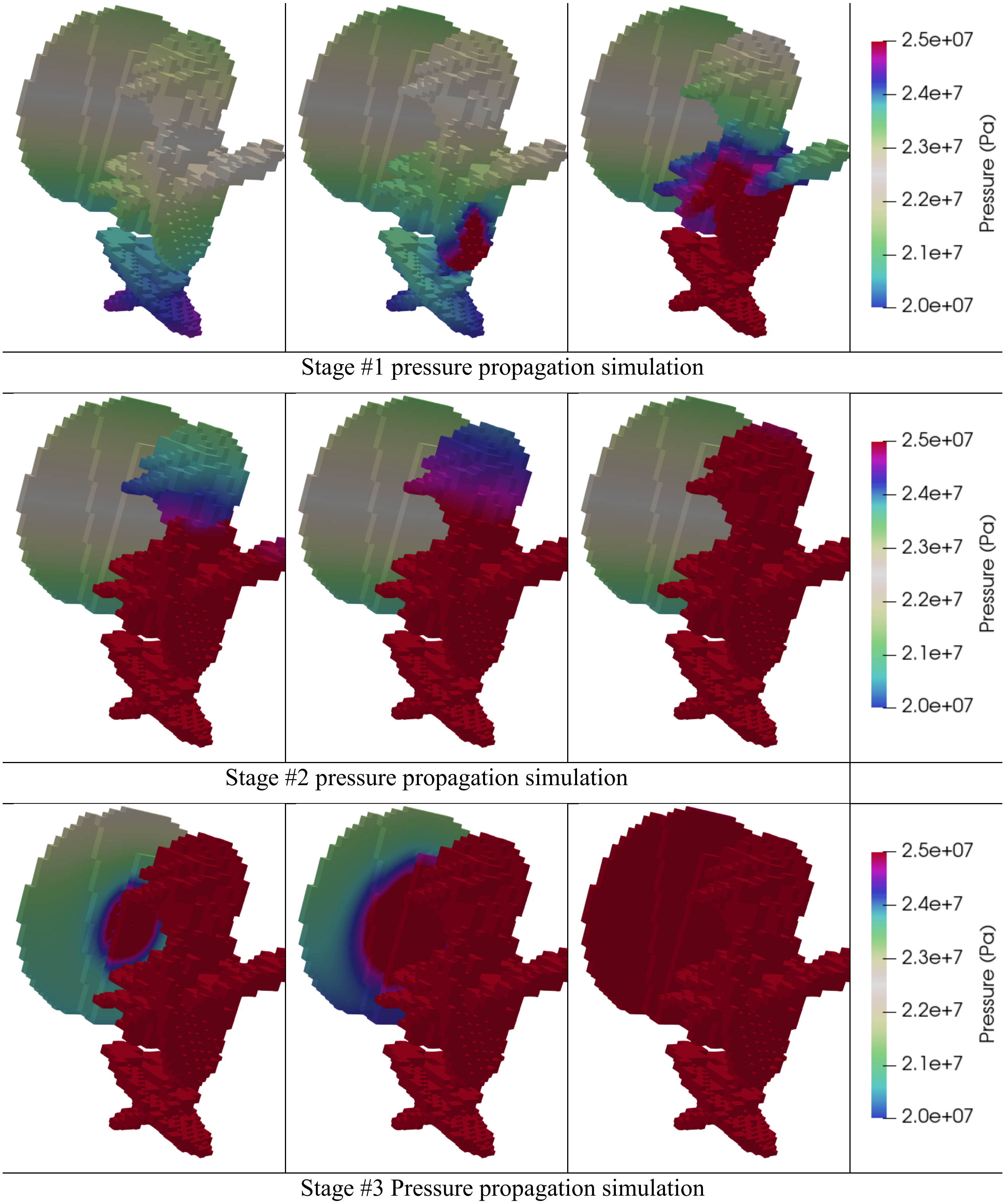


Figure 5: Simulation of pressure propagation during the three stages of hydraulic fracturing, showing the transition from gentle reactivation of existing pathways (Stage #1) to aggressive pressure-driven growth (Stage #2), and stabilization with proppant (Stage #3).

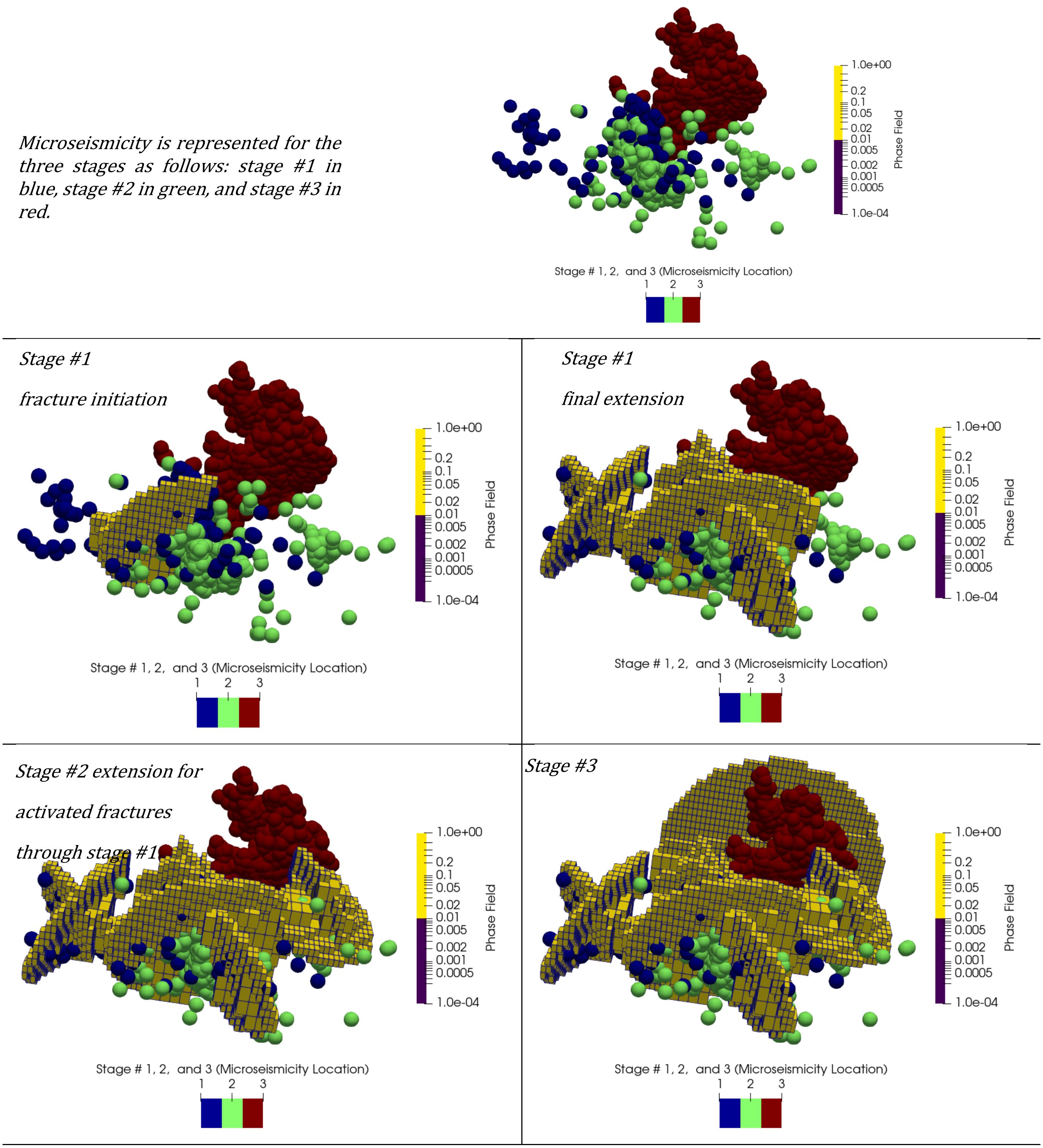


Figure 6: Fracture propagation (yellow grids) and recorded microseismic events: (1) initial fracture initiation (Stage 1, blue), (2) final extension of fractures (Stage 1, blue), (3) fractures activated in Stage 2 (green), (4) hydraulic fractures formed in Stage 3 (red), and (5) an overlay of all stages (Ahmed G Almetwally et al., 2024)**.**

CONCLUSION

This study introduces a robust field-scale framework for modeling Enhanced Geothermal Systems (EGS), integrating phase-field modeling, Enriched Galerkin (EG) discretization, fixed-stress split coupling, and localized mesh refinement to enhance accuracy and computational efficiency. Validated across analytical solutions, laboratory experiments, and FORGE field data, the framework captures the coupled thermal, hydraulic, and mechanical processes governing EGS behavior. It accurately simulates fracture evolution, pressure responses, and hydraulic fracturing dynamics, demonstrating strong agreement with microseismic and pressure data. By overcoming limitations of traditional methods, this framework advances geothermal reservoir modeling, optimizing EGS development and supporting sustainable geothermal energy production.

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