

Variational Phase-Field Modeling of Hydraulic Fracture Interaction With Natural Fractures and Application to Enhanced Geothermal Systems

Lepillier, Baptiste; Yoshioka, Keita; Parisio, Francesco; Bakker, Richard; Bruhn, David

DOI

[10.1029/2020JB019856](https://doi.org/10.1029/2020JB019856)

Publication date

2020

Document Version

Final published version

Published in

Journal of Geophysical Research: Solid Earth

Citation (APA)

Lepillier, B., Yoshioka, K., Parisio, F., Bakker, R., & Bruhn, D. (2020). Variational Phase-Field Modeling of Hydraulic Fracture Interaction With Natural Fractures and Application to Enhanced Geothermal Systems. *Journal of Geophysical Research: Solid Earth*, 125(7), Article e2020JB019856. <https://doi.org/10.1029/2020JB019856>

Important note

To cite this publication, please use the final published version (if applicable). Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.

Variational Phase-Field Modeling of Hydraulic Fracture Interaction With Natural Fractures and Application to Enhanced Geothermal Systems

Baptiste Lepillier¹ , Keita Yoshioka² , Francesco Parisio³ , Richard Bakker¹ , and David Bruhn^{1,4} 

¹Department of Geoscience and Engineering, Delft University of Technology, Delft, The Netherlands, ²Department of Environmental Informatics, Helmholtz Centre for Environmental Research-UFZ, Leipzig, Germany, ³Chair of Soil Mechanics and Foundation Engineering, Institute of Geotechnics, Technische Universität Bergakademie Freiberg, Freiberg, Germany, ⁴GFZ German Research Centre for Geosciences, Potsdam, Germany

Key Points:

- A novel approach for reservoir stimulation is applied to an Enhanced Geothermal System
- A robust numerical modeling of hydraulic fracture propagation and interaction with natural preexisting fractures is modeled using the variational phase field
- The numerical model is applied to the field case of Acoculco geothermal reservoir

Correspondence to:

B. Lepillier,
b.p.lepillier@tudelft.nl

Citation:

Lepillier, B., Yoshioka, K., Parisio, F., Bakker, R., & Bruhn, D. (2020). Variational Phase-field modeling of hydraulic fracture interaction with natural fractures and application to enhanced geothermal systems. *Journal of Geophysical Research: Solid Earth*, 125, e2020JB019856. <https://doi.org/10.1029/2020JB019856>

Received 27 MAR 2020

Accepted 12 JUN 2020

Accepted article online 15 JUN 2020

Abstract In every tight formation reservoir, natural fractures play an important role for mass and energy transport and stress distribution. Enhanced Geothermal Systems (EGS) make no exception, and stimulation aims at increasing the reservoir permeability to enhance fluid circulation and heat transport. EGS development relies upon the complex task of predicting accurate hydraulic fracture propagation pathway by taking into account reservoir heterogeneities and natural or preexisting fractures. In this contribution, we employ the variational phase-field method, which handles hydraulic fracture initiation, propagation, and interaction with natural fractures and is tested under varying conditions of rock mechanical properties and natural fractures distributions. We run bidimensional finite element simulations employing the open-source software OpenGeoSys and apply the model to simulate realistic stimulation scenarios, each one built from field data and considering complex natural fracture geometries in the order of a thousand of fractures. Key mechanical properties are derived from laboratory measurements on samples obtained in the field. Simulations results confirm the fundamental role played by natural fractures in stimulation's predictions, which is essential for developing successful EGS projects.

1. Introduction

Interest in predicting hydraulic fracture propagation is picking up since the Enhanced Geothermal System (EGS) concept could become a competitive solution as a sustainable and essentially carbon-free energy resource. In EGS, the reservoir is stimulated by injecting pressurized fluids in reservoir rock formations with the aim of enhancing permeability. Early application of permeability enhancement were performed in oil and gas reservoirs (Economides & Nolte, 1989), while nowadays the principles of hydraulic fracture mechanics are applied to a broad range of problems, such as nuclear waste disposal (Zoback et al., 2003), carbon-capture storage (Fu et al., 2017), glacier dynamics (Tsai & Rice, 2010), earthquake nucleation (Garagash & Germanovich, 2012), and geothermal systems (Fox et al., 2013; Legarth & Saadat, 2005; McClure & Horne, 2014). Hydraulic fracture propagation is intrinsically a multiscale problem (Garagash et al., 2011), with a wide range of scales of time and length controlling the fluid-driven crack propagation (Detournay, 2016). Under simplified assumptions of problem geometry and physical behavior, analytical solutions (Adachi & Detournay, 2002; Detournay, 2016; Garagash & Detournay, 2000; Savitski & Detournay, 2002) give good predictions of multiscale asymptotic behavior, which has been confirmed by laboratory experiments in highly controlled environments (Bunger & Detournay, 2008). Numerical methods are more computationally costly but can also overcome the simplifications typical of analytical solutions (Lecampion et al., 2018), such as planar cracks and homogeneous material properties (Bunger et al., 2013). Most numerical methods are based on Linear Elastic Fracture Mechanics (LEFMs) (Adachi et al., 2007), and the problem of hydraulic fracture propagation has been addressed either by (i) assuming planar and single mode crack propagation or (ii) accounting for nonplanar propagating cracks that interact with preexisting natural fractures (Weng, 2014).

The first approach assumes the crack as a planar object splitting the material in two parts with a displacement discontinuity that evolves over time: The dimensions of the hydraulic fracture (such as its length,

©2020. The Authors.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

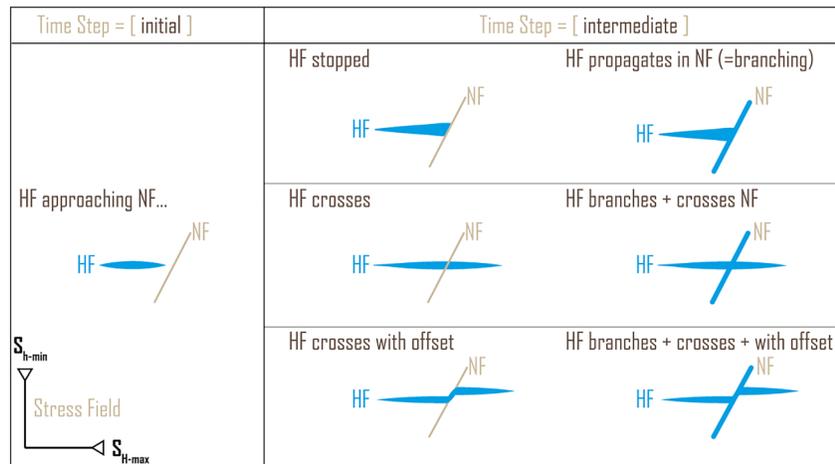


Figure 1. Possible interaction process of hydraulic fracture and natural fractures: (i) Hydraulic fracture encounters a natural fracture can arrest, cross, or be deviated by the natural fracture and (ii) hydraulic fracture encounters a natural fracture and propagates along its direction, which can generate branching.

height, and aperture) change as the fluid is injected. Models of three-dimensional (3-D) bi-wing planar fractures rely upon the known fracture models from Perkins, Kern, and Nordgren (PKN) (Perkins & Kern, 1961), Geertsma and de Klerk (GDK) (Geertsma & De Klerk, 1969), and more generalized three-dimensional models (Nordgren, 1972). The crack propagation criterion is based on the energy release rate (Griffith, 1921) and propagation occurs if the stress intensity factor reaches the critical value (Adachi et al., 2007). Viscous dissipation of fluid is an additional source of energy dissipation in hydraulic fracturing where the LEFM solution is coupled with Poiseuille's flow in the fracture and Carter's equation for leak-off from the fracture to the formation (Detournay & Cheng, 1993). The crack propagates along trajectories in a parametric space whose asymptotic regimes are characterized by a prevailing mechanism among leak-off, toughness, storage, and viscosity (Detournay, 2016). Rock's stiffness, strength, and permeability, fluid's viscosity, and injection rate control the trajectories of the parametric space. Although single Mode-I planar crack models give good estimates of the fracture dimensions whenever the basic assumptions hold valid, they fall short whenever heterogeneities cannot be neglected—a typical occurrence in geothermal reservoirs.

Models of fracture interaction (Jeffrey et al., 1994, 2009; McClure et al., 2015; Renshaw & Pollard, 1995; Warpinski & Teufel, 1987; Weng, 2014) have to account for hydraulic fracture arrest, cross, or branch at the intersection with a natural fracture (Figure 1). Although Yew and Weng (2015) report the Unconventional Fracture Model (UFM) by Weng et al. (2011) as one of the first models of hydraulic fracture propagation that accounts for fluid flow and complex network of natural fractures, several problems regarding the computational mechanics of hydraulic fracture remain unsolved. Two main approaches have so far emerged: (i) the first one employs the Displacement Discontinuity Method (DDM), such as the Unconventional Fracture Model (UFM) or Crack Tip Open Displacement (CTOD), and (ii) the second one uses Finite Elements or Finite Volumes Methods (FEM or FVM), where natural fractures are either smeared using an implicit approach (nonlocal damage or phase field) or embedded into Cohesive Zone Models. The DDM is computationally inexpensive, as it requires discretization of the boundaries only, but cannot handle reservoir heterogeneities. The FEM with explicit embedded discontinuities faces two main drawbacks: (i) it requires fine crack-tip discretization to preserve accuracy, hampering its applicability to real case scenarios where the hydraulic fracture is expected to propagate for several hundreds of meters, and (ii) it suffers from element-distortion issues that generate inaccuracies in crack opening calculations and induce numerical instabilities. The eXtended Finite Element Method (Belytschko & Black, 1999; Belytschko et al., 2001; Gupta & Duarte, 2016; Moës et al., 1999; Wang, 2019; Yazid et al., 2009) overcomes the classical finite elements limitations of resolving field discontinuities by use of enriched shape function, although it is computationally expensive, can hardly handle *hydraulic fracture-natural fractures* interaction and can on occasions be numerically unstable.

The phase-field method of fracture is a valid and promising alternative. Given its success in modeling propagation of brittle fracture, its development has been extended to ductile (Alessi et al., 2017; Ambati et al., 2015; Kuhn et al., 2016; Miehe, Mauthe, & Teichtmeister, 2015), fatigue (Alessi et al., 2018; Carrara et al., 2019; Seiler et al., 2018), and dynamic fractures (Borden et al., 2012; Bourdin et al., 2011; Fischer & Marigo, 2019; Hofacker & Miehe, 2012; Li et al., 2016; Schlüter et al., 2014). The variational phase field (V-pf) is a generalized Griffith criterion (Francfort & Marigo, 1998) numerically implemented using a phase-field variable, which smears the sharp interface fracture with a smooth transition function (Bourdin et al., 2000). The phase-field variable describes the transition from intact to fully damaged state of the material over a specific length scale. Seminal works of the application of the V-pf approach to hydraulic fracture include Bourdin et al. (2012) and Chukwudozie et al. (2013) while following studies addressed problems related to poroelasticity (Mikelić et al., 2015; Miehe, Hofacker, et al., 2015; Santillán et al., 2017; Wilson & Landis, 2016; Wheeler et al., 2014), fracture width computation (Lee et al., 2017; Xia et al., 2017), coupling with the theory or porous media (Ehlers & Luo, 2017; Heider & Markert, 2017), pressure-dependent failure mechanisms (Choo & Sun, 2018), mass conservation (Chukwudozie et al., 2019), and in situ stresses (Shiozawa et al., 2019). The smeared representation can handle complex fracture topology where natural fractures can be represented within nonconforming discretizations, without a priori assumptions on their geometry or restriction on hydraulic fracture growth trajectories (Yoshioka & Bourdin, 2016).

In this study, we solve the toughness-dominated hydraulic fracturing problem where the pressure drop within the fracture is negligible with a V-pf approach formulated with the constitutive model known as no tension or masonry model (Del Piero, 1989; Freddi & Royer-Carfagni, 2011). The main goal is to study the hydraulic fracture interaction with reservoir heterogeneities in the form of preexisting natural fractures with efficient computational V-pf models. We apply the V-pf method to a real case study of a potential EGS system, that is, the Aocolulco geothermal field located in Puebla, Mexico. Two exploration wells were drilled within the geothermal field and, through log data analysis, a high-temperature ($T \sim 300^\circ\text{C}$) and low permeable ($k = 1 \times 10^{-18} \text{ m}^2$) reservoir was identified at ~ 2 km depth. Natural fractures are modeled as complex Discrete Fracture Networks (DFNs) calculated from outcrop field measurements and mechanical rock properties are derived from laboratory testing on samples collected in the field.

This article is structured as follows: In section 2, we introduce the governing equations of the V-pf model, their implementation in the open-source software OpenGeoSys (Kolditz et al., 2012), the experimental program, and the stochastic method to build DFNs. In section 3 we introduce applications of simple computational scenarios and geothermal reservoir stimulation. Section 4 presents the results of the simulations and contains a wider discussion of our results as well as broader implications of our main findings. Finally, we draw general conclusions of the study in section 6.

2. Variational Phase-Field Model

2.1. Variational Approach to Fracture

LEFM is based on Griffith's observation that the energy dissipation by a propagating crack equals the mechanical energy decay (Griffith, 1921). Thus, the criterion for fracture propagation is given as

$$G_c = G, \quad (1)$$

where G_c is the critical surface energy release rate and G is the mechanical energy restitution rate. The energy restitution rate is defined as the derivative of the elastic energy \mathcal{P} with respect to a crack increment length a , which is often derived using the concept of stress intensity factor (Irwin, 1957). Griffith criterion reads then as

$$\frac{\partial \mathcal{P}}{\partial a} = G_c, \quad (2)$$

which was revisited by Francfort and Marigo (1998) noticing that it can be described in terms of critical values of the following total energy along a prescribed path as

$$\mathcal{P} + G_c a. \quad (3)$$

Griffith's criterion was generalized in the variational framework by considering a total energy with any crack set Γ as opposed to a prescribed path a as

$$\underbrace{\mathcal{F}}_{\text{Total energy}} = \underbrace{\mathcal{P}}_{\text{Mechanical energy}} + \underbrace{\int_{\Gamma} G_c \, dS}_{\text{Surface energy}}, \quad (4)$$

such that the fracture propagation criterion is obtained by solving for the set of mechanical energy \mathcal{P} and the crack geometry Γ that minimizes Equation 4. For a prescribed crack path (e.g., a), the approach converges to Griffith's criterion which can be viewed as a local energy minimum problem.

2.2. Governing Equations

The linear elastic constitutive equation of a brittle-elastic porous medium occupying a domain Ω can be expressed as (Biot, 1941)

$$\sigma = \mathbf{C}:\varepsilon(\vec{u}) + \alpha p_p \mathbf{I}, \quad (5)$$

where \mathbf{C} is the fourth-order linear elastic tangent operator, α is the Biot's coefficient, p_p is the pore pressure, \mathbf{I} is the identity matrix, and ε is the linearized strain tensor defined as the symmetric part of the displacement gradient $\nabla \vec{u}$

$$\varepsilon(\vec{u}) := \frac{\nabla \vec{u} + \nabla \vec{u}^t}{2}. \quad (6)$$

Also, consider crack set Γ filled with a fluid at pressure p_f and let $\partial\Omega_N$ be a portion of its boundary and $\partial\Omega_D := \partial\Omega \setminus \partial\Omega_N$ the remaining part, static equilibrium, and continuity of stress at the interfaces mandates that

$$\begin{cases} \nabla \cdot \sigma(\mathbf{u}) = \mathbf{0} & \text{in } \Omega \setminus \Gamma, \\ \sigma \cdot \mathbf{n} = \boldsymbol{\tau} & \text{on } \partial\Omega_N, \\ \mathbf{u} = \mathbf{u}_0 & \text{on } \partial\Omega_D, \\ \sigma^\pm \cdot \mathbf{n}_{\Gamma^\pm} = p_f \mathbf{n}_{\Gamma^\pm} & \text{on } \Gamma^\pm. \end{cases} \quad (7)$$

where \vec{f} denotes an external body force and $\boldsymbol{\tau}$ is a traction force. Multiplying (7) by a test function $\delta \mathbf{u} \in H^1(\Omega \setminus \Gamma)$ that vanishes on $\partial\Omega_D$ and using Green's theorem, we obtain

$$\int_{\Omega \setminus \Gamma} \mathbf{C} \left(\varepsilon(\vec{u}) - \frac{\alpha}{N\kappa} p_p \mathbf{I} \right) \cdot \varepsilon(\delta \vec{u}) \, dV = \int_{\partial\Omega_N} \boldsymbol{\tau} \cdot \delta \vec{u} \, dS + \int_{\Gamma} p_f [\delta \vec{u} \cdot \vec{n}_{\Gamma}] \, dS + \int_{\Omega \setminus \Gamma} \vec{f} \cdot \delta \vec{u} \, dV, \quad (8)$$

where $N=2$ and $N=3$ for 2-D and 3-D, respectively, and κ denotes the material's bulk modulus. We recall that given p_p , p_f , and Γ , Equation 9 is the unique solution of the minimization among all kinematically admissible displacement of

$$\mathcal{P} = \int_{\Omega \setminus \Gamma} W(\varepsilon(\vec{u}), p_p) \, dV - \int_{\partial\Omega_N} \boldsymbol{\tau} \cdot \vec{u} \, dS - \int_{\Gamma} p_f [\vec{u} \cdot \vec{n}_{\Gamma}] \, dS - \int_{\Omega \setminus \Gamma} \vec{f} \cdot \vec{u} \, dV, \quad (9)$$

where

$$W(\varepsilon(\vec{u}), p) := \frac{1}{2} \mathbf{C} \left(\varepsilon(\vec{u}) - \frac{\alpha}{N\kappa} p \mathbf{I} \right) \cdot \left(\varepsilon(\vec{u}) - \frac{\alpha}{N\kappa} p \mathbf{I} \right), \quad (10)$$

is the poroelastic strain energy density (Yoshioka & Bourdin, 2016).

2.3. Phase-Field Approximation

The numerical implementation of the minimization of Equation 4 involves discontinuous deformation across unknown discontinuity surfaces (the cracks), Γ , which pose significant challenges in terms of

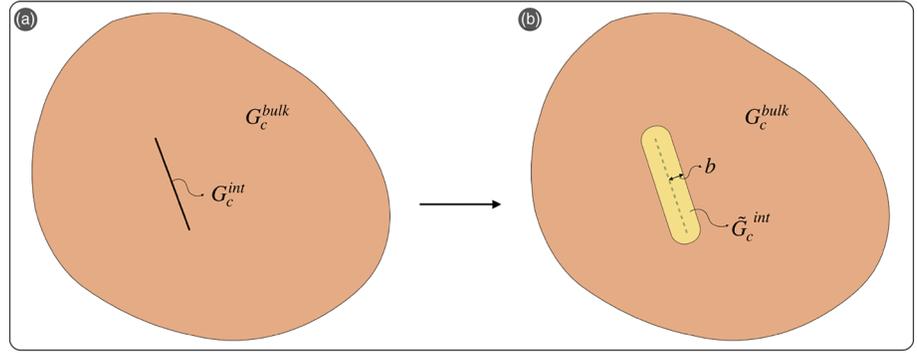


Figure 2. (a and b) Diffused representation of a discontinuous interface.

numerical implementation. Instead, Equation 4 is regularized using the phase-field approach (Bourdin et al., 2000, 2008).

Introducing a scalar phase-field variable, $v: \Omega \rightarrow [0,1]$, which represents a state of the material from intact material ($v = 1.0$) to fully broken ($v = 0.0$) with a continuous function and a regularization parameter with the dimension of a length, $\ell_s > 0$, which controls the transition length of the phase-field variable, Equation 4 can be approximated as (Bourdin et al., 2012)

$$\mathcal{F}_{\ell_s} = \int_{\Omega} v^2 W dV - \int_{\partial_{\Omega}^m} \tau \cdot \vec{u} dS - \int_{\Omega} \vec{f} \cdot \vec{u} dV + \int_{\Omega} P_f \vec{u} \cdot \nabla v dV + \frac{1}{4c_n} \int_{\Omega} G_c \left(\frac{(1-v)^n}{\ell_s} + \ell_s |\nabla v|^2 \right) dV, \quad (11)$$

where c_n is a normalization parameter defined as $c_n := \int_0^1 (1-s)^{n/2} ds$. Case $n = 1$ is often referred as AT_1 ($c_n = 3/2$) and Case $n = 2$ as AT_2 ($c_n = 1/2$) (Tanné et al., 2018). It can then be shown (Ambrosio & Tortorelli, 1990, 1992; Braides, 1998) that as ℓ_s approaches 0, the minimizers of Equation 11 converge to that of Equation 4 in the sense that the phase-field function v takes value 1 far from the crack Γ and transitions to 0 in a region of thickness of order ℓ_s along each crack faces of Γ .

We can observe that in Equation 11, the evolution of the phase-field (v) is driven by the strain energy (W) regardless of the deformation direction, which leads to equal strength in tension and compression—a wrong approximation for granular material such as rock. To overcome the limitation, the strain energy can be decomposed into the positive (extension) and negative (shortening) parts

$$W = W^+ + W^-. \quad (12)$$

Among the several approaches for the strain decomposition (Amor et al., 2009; Freddi & Royer-Carfagni, 2011; Miehe et al., 2010), we employ the so-called masonry model (Freddi & Royer-Carfagni, 2011), in which the material will not withstand tensile stresses.

Open natural fractures can be represented by assigning either the phase-field variable $v = 0.0$ (Ni et al., 2020; Yoshioka & Bourdin, 2016) or the fracture toughness $G_c^{int} = 0.0$ ($v = 0.0$ is achieved, where G_c^{int} is assigned with 0.0 at the first iteration). In this study we represent discontinuous interfaces by a diffused variable of the phase-field type (\tilde{G}_c^{int}) whose fracture toughness or cohesive strength (G_c) is different from the surrounding (Figure 2). Altering G_c gives us a greater flexibility as it can represent from open ($G_c^{int} = 0.0$), partially cemented/weakly bonded ($G_c^{int} < G_c^{bulk}$), to cemented with a stiffer material ($G_c^{int} > G_c^{bulk}$) while v represents a diffused state of fracture not the strength. To compensate the fracture toughness in the smeared interface $x < b$, we solve the surface energy functional in Equation 11 for the effective fracture toughness, \tilde{G}_c^{int} (Hansen-Dörr et al., 2019). The surface energy equality can be imposed as

$$\tilde{G}_c^{\text{int}} \int_{\Omega} S \, dV = G_c^{\text{int}} \int_{\xi=0}^{\xi=b} S \, dV + G_c^{\text{bulk}} \int_{\xi=b}^{\infty} S \, dV, \quad (13)$$

where

$$S = \frac{1}{4c_n} \left(\frac{(1-v)^n}{\ell_s} + \ell_s |\nabla v|^2 \right), \quad (14)$$

and ξ is the distance from the crack ($v = 0$). We built the FEM model containing natural fractures by assigning the equivalent fracture toughness computed in Equation 13 to the region within distance b from the fractures.

2.4. Numerical Implementation

We neglect leak-off to the rock mass because the permeability of the rock mass is sufficiently low. The pore pressure p_p can be considered invariant and set as $p_p = 0$, and $p'_f = p_f - p_p$ in the governing equations. We adopt the notation $p'_f = p$. Considering hydraulic fracturing in the toughness dominated regime (Detournay, 2016), the pressure loss within the crack is negligible and p is spatially constant. Equation 11 is solved by the alternate minimization with respect to the displacement \mathbf{u} and the phase-field v with a constraint of prescribed time-evolving fluid volume which must be equal to the crack volume, that is, $V_{\text{inj}} = V_{\text{crack}} = \int_{\Omega} \mathbf{u} \cdot \nabla v \, d\Omega$ (Yoshioka et al., 2019). The minimization problem can be stated as

$$(\mathbf{u}, v, p)^* = \begin{cases} \arg \min_{\mathcal{F}_{\ell_f}}(\mathbf{u}, d, p) \\ \mathbf{u} \in H^1 \\ v \in H^1, v^t \subset v^{t+\Delta t} \end{cases}, \quad (15)$$

with the constrain

$$V_{\text{inj}} = \int_{\Omega} \mathbf{u} \cdot \nabla v \, d\Omega. \quad (16)$$

The first variation of the energy functional with respect to \mathbf{u} is

$$\begin{aligned} \delta \mathcal{F}_{\ell_f}(\mathbf{u}, v, p; \delta \mathbf{u}) &= \frac{1}{2} \int_{\Omega} \varepsilon(\delta \mathbf{u}) : (v^2 \mathbf{C}^+ + \mathbf{C}^-) : \varepsilon(\mathbf{u}) \, d\Omega \\ &\quad - \int_{\partial_N \Omega} \boldsymbol{\tau} \cdot \delta \mathbf{u} \, d\Gamma - \int_{\Omega} \mathbf{f} \cdot \delta \mathbf{u} \, d\Omega + \int_{\Omega} p \delta \mathbf{u} \cdot \nabla v \, d\Omega, \end{aligned} \quad (17)$$

where \mathbf{C}^{\pm} is the tangent stiffness tensor

$$\mathbf{C}^{\pm} = \frac{\partial}{\partial \varepsilon} \left(\frac{\partial W^{\pm}}{\partial \varepsilon} \right). \quad (18)$$

The first variation of the energy functional with respect to v for AT₁ is

$$\delta \mathcal{F}_{\ell_s}(\mathbf{u}, v, p; \delta v) = \int_{\Omega} v \delta v \, \mathbf{C}^+ \varepsilon(\mathbf{u}) \cdot \varepsilon(\mathbf{u}) \, dV + \frac{3}{8} \int_{\Omega} G_c \left(-\frac{\delta v}{\ell_s} + 2\ell_s \nabla v \cdot \nabla \delta v \right) \, dV - \int_{\Omega} p \, \mathbf{u} \cdot \nabla \delta v \, dV, \quad (19)$$

and for AT₂ is

$$\delta \mathcal{F}_{\ell_s}(\mathbf{u}, v, p; \delta v) = \int_{\Omega} v \delta v \, \mathbf{C}^+ \varepsilon(\mathbf{u}) \cdot \varepsilon(\mathbf{u}) \, dV + \int_{\Omega} G_c \left(\frac{v-1}{\ell_s} \delta v + \ell_s \nabla v \cdot \nabla \delta v \right) \, dV - \int_{\Omega} p \, \mathbf{u} \cdot \nabla \delta v \, dV. \quad (20)$$

Equation 7 is linear to p and if we let the displacement solution with $p = 1.0$ be equal to \mathbf{u}_1 , the displacement solution $p = p$ is obtained as $\mathbf{u} = p\mathbf{u}_1$ and the crack volume is

$$\int_{\Omega} \mathbf{u} \cdot \nabla v \, d\Omega = p \int_{\Omega} \mathbf{u}_1 \cdot \nabla v \, d\Omega. \quad (21)$$

Table 1
Case Scenarios of the Sensitivity Analysis With Different Stress Fields Applied

Case	S_{Hmax}	S_{hmin}
A	21	20
B	30	20
C	40	20
D	60	20

Note. Stress values are expressed in MPa.

At a given time step, a volume V_{inj} is injected and Equation 16 yields the mass balance in the porous medium such that the corresponding p is

$$p = \frac{V_{inj}}{V_p}, \quad (22)$$

where

$$V_p = \int_{\Omega} \mathbf{u}_1 \cdot \nabla v \, d\Omega, \quad (23)$$

and the whole solution procedure is described in Algorithm 1.

Parallel simulations were run on the high-performance computing system JUWELS, maintained at the Jülich Supercomputing Centre. The total number of degree of freedom for the Aocoluco case scenarios is 513,108 with 170,996 linear quadrilateral elements with a few triangular elements in the mesh resolution transition zone. Domain decomposition was done using METIS (Karypis & Kumar, 1998), and both linear and nonlinear solvers from PETSc Balay et al. (2019) were used. More specifically, the Newton-Raphson solver for the deformation problem and a Newton based variational inequality solver for the phase field, since the phase-field solution is bounded in $[0,1]$ domain and constrained by the irreversibility. The simulations were distributed into 384 cores over eight nodes (Dual Intel Xeon Platinum 8168) with 2×24 cores. While the computation time differs depending on the nonlinearity of each problem, all the simulations shown in the subsequent section were completed within ~ 20 hr.

Algorithm 1 Incorporation of the volume constraint in the phase-field model.

```

1: repeat
2:   Update the injected volume,  $V_{inj}(t_n + \Delta t)$ 
3:   repeat
4:     Solve for  $\mathbf{u}_1^i$ , given  $v^{i-1}$  and  $p = 1.0$ 
5:     Solve for  $v^i$ , given  $\mathbf{u}^i$  and  $p = p^{i-1}$ 
6:     Calculate  $V_p^i$  from  $\int_{\Omega} \mathbf{u}^i \cdot \nabla v^i \, d\Omega$ 
7:     Update pressure,  $p^i = V_{inj}/V_p^i$ 
8:   until  $\|v^i - v^{i-1}\| < 10^{-4}$ 
9: until  $V < V_{final}$ 

```

3. Applications

3.1. Sensitivity Analyses

We perform a sensitivity analysis to highlight the complex interactions between fluid-driven propagating fractures and existing ones. We analyze simplified models assuming a perfectly homogeneous brittle linear elastic material containing one or two preexisting natural fractures. We evaluate the impact on fracture initiation and propagation given by stiffness (elastic parameters) and strength (fracture toughness) of the bulk rock, existing fractures, state of stress, and orientation angle of the natural fractures. The base case parameters of the sensitivity analysis are in the range of the studied rocks of the Aocoluco reservoir, that is, $G_c = 100$ Pa m, $E = 25$ GPa, and $\nu = 0.2$.

As implemented in the V-pf, the interaction with the preexisting natural fractures is partly controlled by the critical energy release rate of the natural fracture \tilde{G}_c^{int} . We compare results for $G_c = 1$ with different values of \tilde{G}_c^{int} spanning 4 orders of magnitude, that is, $\tilde{G}_c^{int} = 0.01, 0.05, 0.1, 10$. We analyze the impact of the far-field deviatoric stress by increasing the S_{Hmax} from 21 to 60 MPa with a fixed $S_{hmin} = 20$ MPa. All case scenarios are presented in Table 1. We finally analyze the influence of a natural fracture oriented 45° from the direction of hydraulic fracture propagation to study the effect of the incidence angle between the direction of propagation and the orientation of a natural fracture.

3.2. The Aocoluco Geothermal Reservoir

In this manuscript, we analyze the potential permeability enhancement in a fractured reservoir by modeling the fracture growth from a well-bore injection. We apply the developed numerical methodology described in

Table 2
Rock Mechanical Properties From Rock Physics Laboratory Measurements

Lithology	E GPa	ν -	K_{Ic} MPa m ^{1/2}	G_c Pa m
Limestone Late Cretaceous	37.8	0.31	2.76	201
Limestone Early Cretaceous	37.9	0.23	2.49	164
Limestone	37.9	0.27	2.63	182
Marble from Pueblo Nuevo	46.8	0.25	1.90	77.3
Marble from Tatatila	51.6	0.29	1.85	66.2
Marble	49.2	0.27	1.87	71.4
Exo-skarn from Eldorado	56.9	0.11	2.70	127
Endo-skarn from Boquillas	41.1	0.13	1.92	89.3
Skarn	49.0	0.13	2.31	108

Note. This table summarizes the main results of the laboratory measurements for the concerned lithologies: limestones, marbles, and skarns. For each of them the table gives the Young's modulus (E), the Poisson's ratio (ν), the fracture toughness (K_{Ic}), and Griffith's critical energy release rate (G_c). A single final value for specific lithology was selected as the average between different locations outcrops.

tory. Young's modulus and Poisson's ratio were determined by Unconfined Compression Strength (UCS) tests (UCS—20 experiments). Brazilian disc (BD—80 experiments) and Chevron Bend tests (CB—12 experiments) were employed to determine the fracture toughness K_{Ic} of the rock formations, which was later employed to derive the critical energy release rate (G_c). Fracture toughness was determined from the two sets of experiments: (i) from BD tests, it was done following the method proposed by Guo et al. (1993), and (ii) for CB tests, following the method suggested by Franklin et al. (1988). All material parameters employed in the model are summarized in Table 2.

The general DFN is derived from scanline measurements from multiple outcrops analogues of the Acoculco geothermal system (Lepillier et al., 2020) that are later extrapolated using the multiple point statistic method (Bruna et al., 2019). The method yields three separate DFNs, that is, one per lithology. Each one of the three DFNs is a bidimensional georeferenced section of 600×600 m² (Figure 3). Some further processing is necessary to build the FEM models. In the first step, we extracted from each DFN a smaller subdomain of 100×100 m² (Figure 3). Each extraction has a specific fracture distribution: to analyze the impact of stimulating one or another specific section of the domain. In the second step we extracted an additional three subdomain from each of the DFNs. The three sub-DFNs, one for each DFN, are then rotated in the third step to align the maximum horizontal stress S_{Hmax} with the x axis and further downscaled in the fourth step to fit the a -dimensional V-pf formulation.

The in situ stress state is believed to be of the normal faulting type and the orientation of the stress tensor is taken from the World Stress Map (Heidbach et al., 2016; Lepillier et al., 2019). Based on this assumption, having $S_v > S_{Hmax} > S_{Hmin}$, we defined certain values for S_{Hmax} and S_{Hmin} . In normal faulting regime, the hydraulic fracture propagates along the vertical plane oriented perpendicular to S_{Hmin} . Because of this, we assume two-dimensional plane-strain conditions were we assign only S_{Hmax} and S_{Hmin} .

4. Results

4.1. Sensitivity Analysis

Figure 4 shows the influence of strength (G_c) and stiffness (E and ν) on the internal fracture overpressure and length evolution during hydraulic fracture propagation at constant fluid injection rate. The critical energy release rate G_c is the dominant parameter controlling the hydraulic fracture response (Figure 4a): G_c represents the resistance to fracture propagation and hence is proportional to the maximum overpressure reached and inversely proportional to the rate of crack length growth during injection. The stiffness parameters play a smaller role on the problem evolution, and, while the influence of Poisson's ratio seems to be negligible over the selected range (Figure 4c), an increase in Young's modulus entails an increase in fracture

section 2 on the Acoculco case scenario, considering the local geological features and the rock properties gathered from field campaigns and laboratory measurements. Here we report a brief synthesis of the experimental program, field campaign, DFN construction algorithm, and results, while further details can be found in the original works (Lepillier et al., 2019, 2020).

The Acoculco geothermal field, located in Mexico, hosts two vertical exploration wells (named EAC1 and EAC2) drilled at ~500 m apart horizontally, both reaching a total depth of ~2 km (Canet et al., 2015; López-Hernández et al., 2009; Weydt et al., 2018). On the one hand, Acoculco is considered a tight reservoir because the rock formations are little permeable (10⁻¹⁸ m²) and the fractures are scarcely connected (Lepillier et al., 2020); on the other hand, it is a suitable candidate for EGS development because of its high geothermal energy potential given that the geothermal gradient is above average (~150°C km⁻¹). The stratigraphy encountered during drilling is simplified into three lithological units: limestones, marbles, and skarns. Stiffness (E and ν), strength, and critical energy release rate (G_c) of the three lithologies were measured in the rock physics laboratory.

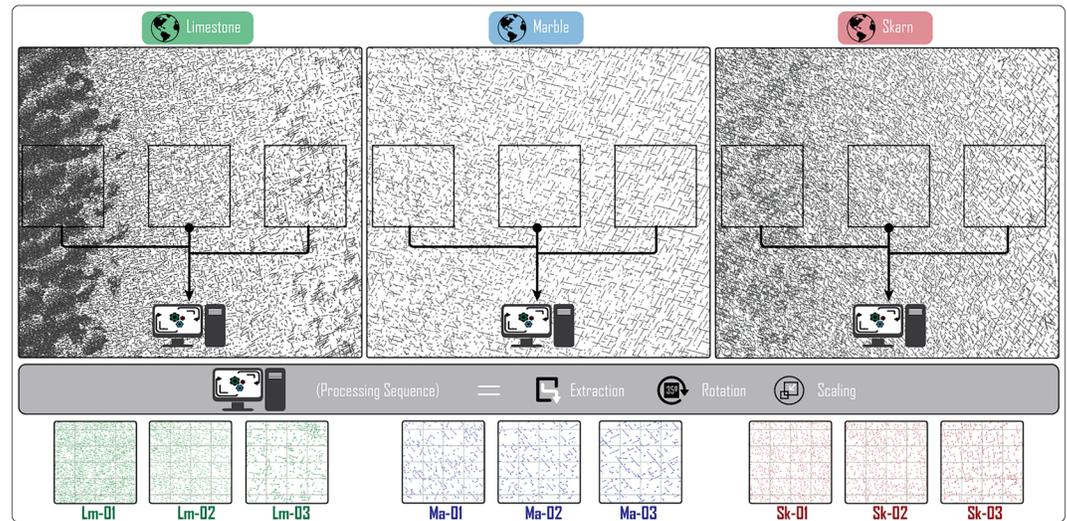


Figure 3. This figure presents the preprocessing sequence: from original reservoir scale DFN, to extracted, rotated, and scaled models to fit the numerical analyses requirements. From left to right, the DFN for the Limestone formation, the DFN for the marble formation and the DFN for the skarn formation. Symbols Lm/Ma/Sk-01, Lm/Ma/Sk-02, and Lm/Ma/Sk-03 are referred to the sub-DFN extracted from initial DFN.

propagation resistance (Figure 4b). Maximum overpressure is proportional to Young’s modulus and inversely proportional to the injected volume at propagation onset.

The delay in crack propagation onset is a consequence of lower stiffness: the more the rock is compliant, the larger the volume of fluid needs to be injected before the crack internal pressure reaches the propagation condition and the energy release rate equals its critical value. Globally, it can be interpreted as a higher system compressibility, where more compliant systems require higher volume of injected fluids.

Figure 5 shows results of the sensitivity analysis of the interaction between a fluid-driven fracture (the phase field) and two natural fractures at equivalent time steps.

When the natural fracture strength is considerably weaker, the fracture turns at and propagates along the vertical natural fractures ($\tilde{G}_c^{int} = 0.01$ and $\tilde{G}_c^{int} = 0.05$). These cases exhibit asymmetrical growth when the tips hit the natural fractures by extending only one of the tips rather than the both. Energetically, propagation of one of the tips is as easy as that of the other while propagating the both simultaneously is more expensive. In other words, the energy required to propagate the right tip equals the energy required for the left tip propagation. As a consequence of the energy minimization in such a situation, propagation of one of the tips (not the both) will be eventually chosen as “minimum” energy state since numerically one of the energies is always smaller than the other by some truncation. However, once either one is chosen, this

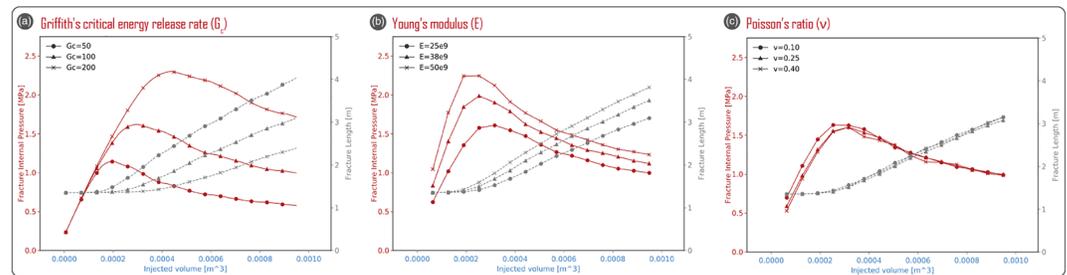


Figure 4. Sensitivity analysis of mechanical material properties. The plots report the evolution of fracture internal overpressure (reds) and fracture length (grays) against the injected volume: in (a) for different values of the critical energy release rate of the bulk solid $G_c = 50, 100, 200 \text{ Pa m}^{-1}$; in (b) for different elastic parameters of Young’s modulus with $E = 25, 38, 50 \text{ GPa}$; and (c) different Poisson’s ratio $\nu = 0.10, 0.25, 0.40$.

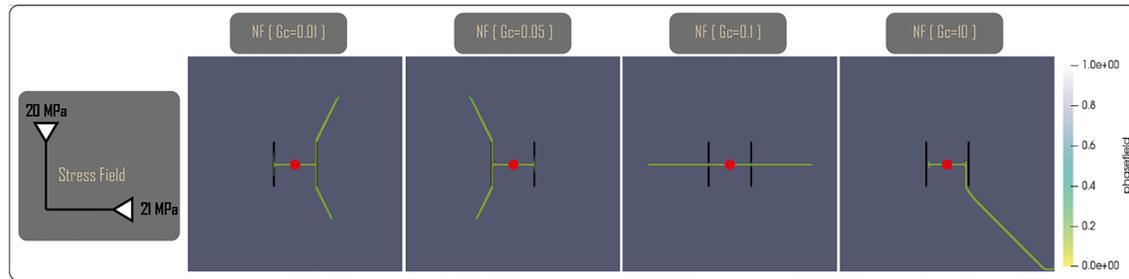


Figure 5. Sensitivity analysis of the influence of two vertical natural fractures. The results show the phase-field distribution contour map in the domain at the same time step for a constant stress field and different critical energy release rate of the natural fracture \tilde{G}_c^{int} . The stress field is oriented such that S_{Hmax} is aligned along the horizontal direction. The red dots represents the well-bore and initial fracture position (and initial phase-field implementation).

side will be always the easier direction (will require less energy) in the subsequent propagation. For $\tilde{G}_c^{int} = 0.1$, the natural fractures do not have low enough strength and are crossed by the hydraulic fracture without branching (Figure 5). For $\tilde{G}_c^{int} > G_c$, the natural fracture act as a barrier to the hydraulic fracture. After the crack hits the natural fracture, it propagates in a path avoiding the natural fracture. In this case, the natural fracture acts as a barrier, shielding the hydraulic fracture propagation. Note that branching in general is energetically more expensive (less favored) as it is avoided in the $\tilde{G}_c^{int} = 10$ case but does happen when the surface energy of the natural fractures are so low that crack propagation along them becomes more attractive.

At increasing values of differential stress (Figure 6), and for fixed $\tilde{G}_c^{int} = 0.01$, the branching observed at low deviatoric stress disappears for $S_{Hmax} \geq 30$ MPa. The critical stress intensity factor at the tip of the natural fracture is proportional to the horizontal stress and propagating a fracture parallel to S_{Hmax} through the bulk rock requires less energy than propagating it through the vertical natural fracture. Therefore, with higher deviatoric stress, considering a natural fracture oriented 90° will not change the propagation direction as the stress dictates the propagation direction.

A 45° oriented fracture has an orientation, which is closer to the critical one for the given state of stress; hence, it influences the propagation and interaction regime differently than vertical natural fracture (Figure 7). With only one natural fracture present, the problem is intrinsically asymmetric. At $\tilde{G}_c^{int} = 0.01$, the hydraulic fracture first interacts with the natural fracture and later propagates in the direction of S_{Hmax} (Figure 7a) and at $\tilde{G}_c^{int} = 0.1$, the hydraulic fracture propagation is still attracted by the inclined natural fracture but not as much as the case with $\tilde{G}_c^{int} = 0.1$. For high values of the natural fractures' critical energy release rate, that is, for $\tilde{G}_c^{int} = 10$, even though the natural fracture is more favorably oriented, it becomes once again a barrier to fracture propagation (Figure 7a). For $\tilde{G}_c^{int} = 0.01$ with varying horizontal stresses S_{Hmax} , the hydraulic fracture propagation along the natural fracture is progressively hindered with increasing S_{Hmax} (Figure 7b). At $S_{Hmax} = 40$ MPa, the hydraulic fracture shows a small offset at the natural fracture's crossing point while the hydraulic fracture becomes agnostic to the natural fracture with $S_{Hmax} = 60$ MPa.

4.2. Stimulation of the Acoolco Geothermal Reservoir

The natural fractures of the Acoolco reservoir are assumed to be cemented and hydraulically closed prior to stimulation. Following our sensitivity studies, we assume the fracture toughness of the natural fracture is 10% of the surrounding ($G_c^{int} = 0.1G_c^{bulk}$). The simulated domain is discretized using a fixed mesh where the element size is 25 cm.

Figures 8–10 show the results of the stimulation scenarios in the Acoolco geothermal reservoir for the different lithologies and for different DFNs. On the left of all figures is plotted the fracture pressure and length with injected volume, while on the right is shown the contour map of the phase-field along with the distribution of natural fractures. For all the cases, the propagation pressure decreases with injected volume as the crack length increases. The pressures started declining rapidly from the onset of the injection/stimulation. This is because the simulations were initiated with a borehole without setting a priori (initial) fracture

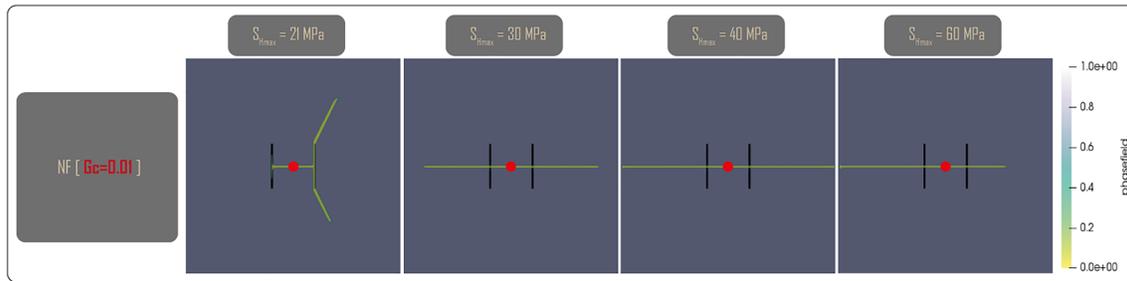


Figure 6. Sensitivity analysis of the influence of two vertical natural fractures. The results show the phase-field distribution contour map in the domain at the same time step for a constant critical energy release rate of the natural fracture \tilde{G}_c^{int} and different stress field values $\tilde{G}_c^{int} = 0.01$. The stress field is oriented such that S_{Hmax} is aligned along the horizontal direction. The red dots represents the well-bore and initial fracture position (and initial phase-field implementation).

lengths, as often done in practice, which led to the high breakdown pressures. Such high pressure responses may not be observed in fields because (1) the borehole intersects with preexisting fractures or defects or (2) the borehole is completed with perforations or well production packers. However, if fracture is initiated in a intact rock, this level of high pressure should be expected. The fracture length increment with time shows a burst-like behavior: Whenever the hydraulic fracture interacts with a natural fracture, the pressure drops as a consequence of the increase in available fluid storage capacity given by the crack sudden propagation over a finite distance within the natural fracture.

Considering all lithologies, the final fracture length ranges between ~ 75 and ~ 95 m and a the lowest propagation pressure is observed for the marble stimulation cases (Figure 9), while the highest propagation pressure is observed for the stimulation into the limestone formation (Figure 8)—a result in agreement with the sensitivity analysis.

Figure 11 shows a polar representation of the hydraulic fracture deviation from the x direction during propagation. The limestone simulations show the larger range of fracture lengths spanning from ~ 75 to ~ 95 m while the marble's one have the smallest range, spanning from ~ 78 to ~ 79 m. The angular deviation ranges

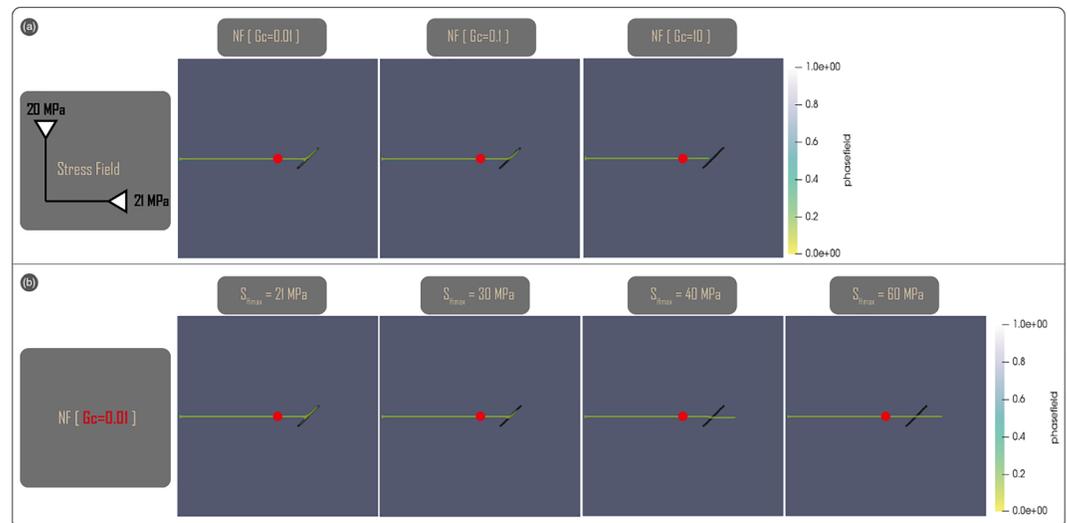


Figure 7. Sensitivity analysis of the influence of one natural fracture inclined at 45° from the horizontal axis. The results show: (a) the phase-field distribution contour map in the domain at the same time step for a constant stress field and different critical energy release rate of the natural fracture \tilde{G}_c^{int} ; and in (b) for different values of the stress field and a constant critical energy release rate of the natural fracture $\tilde{G}_c^{int} = 0.01$ (b). The stress field is oriented such that S_{Hmax} is aligned along the horizontal direction. The red dots represents the well-bore and initial fracture position (and initial phase-field implementation).

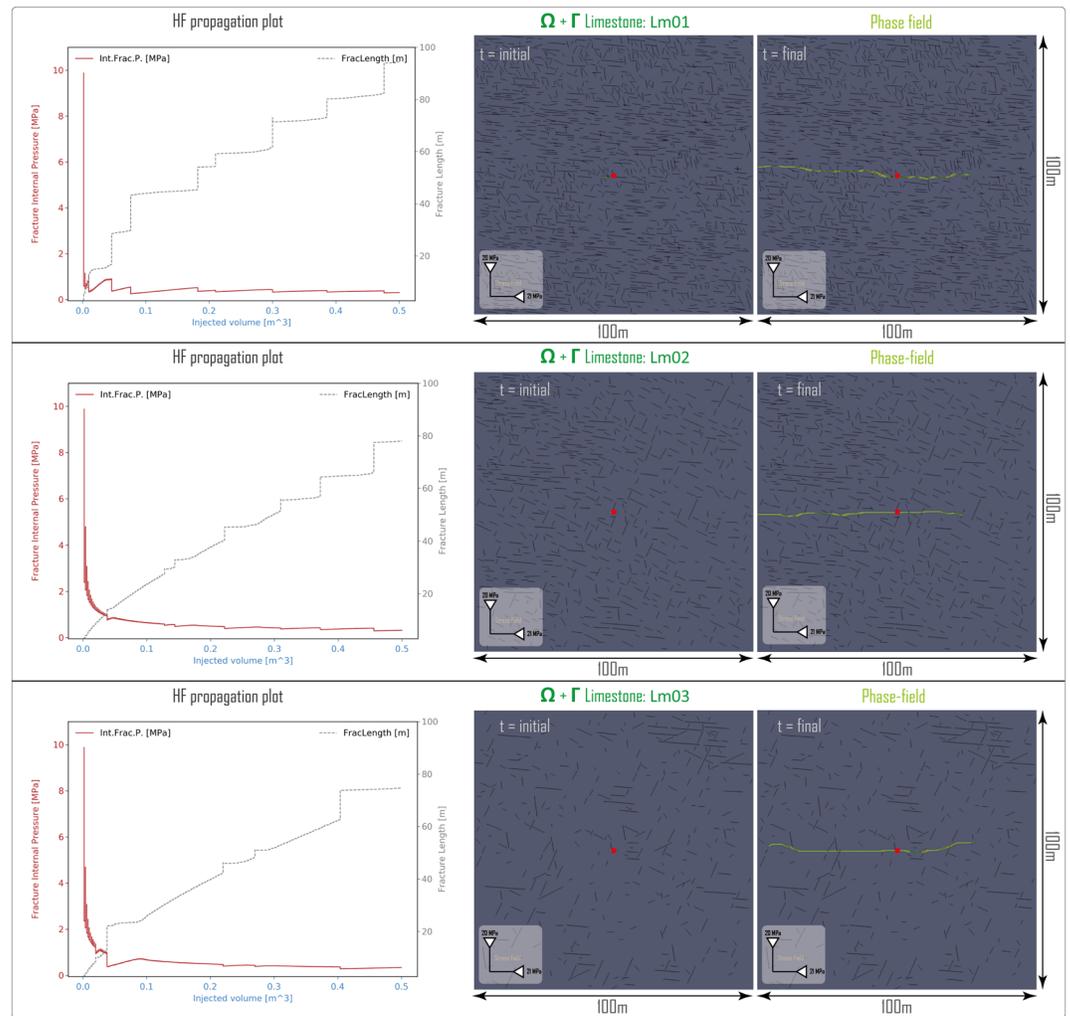


Figure 8. Hydraulic fracture models using V-pf with the sub-DFN of the limestone reservoir. The matrix material domain Ω is represented in gray, the natural fracture Γ are discretized in black. Lm01 is composed with 1,483 natural fractures, Lm02 is composed with 709 natural fractures, and Lm03 is composed with 327 natural fractures. The stress field is oriented such that S_{Hmax} is aligned along the horizontal direction. The red dots represent the well-bore and initial fracture position (and initial phase-field implementation).

in an interval of 20° above and below the reference axis given by S_{Hmax} direction. Maximum deviations are observed in marble and skarn simulations, reaching 30° in both simulations, while the deviation angle for the Limestone simulations is contained in a 20° interval.

The asymmetrical propagation of hydraulic fracture from the borehole is a consequence of the intersection angle between natural fracture and the approaching hydraulic fracture. Assuming θ as the angle between a natural fracture and the S_{Hmax} axis, we observed that (i) low- θ natural fracture act as pathways for the hydraulic fracture, which propagates faster along natural fractures; (ii) high- θ natural fracture ($\sim 90^\circ$) are bypassed by the hydraulic fracture and no interaction takes place. Intermediate values of θ offer a pathway for hydraulic fracture to propagate along a certain distance, until the pressure buildup is sufficiently high to allow further propagation within in the matrix.

5. Discussion

The V-pf method presented here is an implicit smeared approach, which represents the fracture with a smoothly transitioning function that spans from intact to fully damaged state of the material. Natural fractures are represented in a non-conforming mesh with the reduced fracture toughness by enforcing energetic

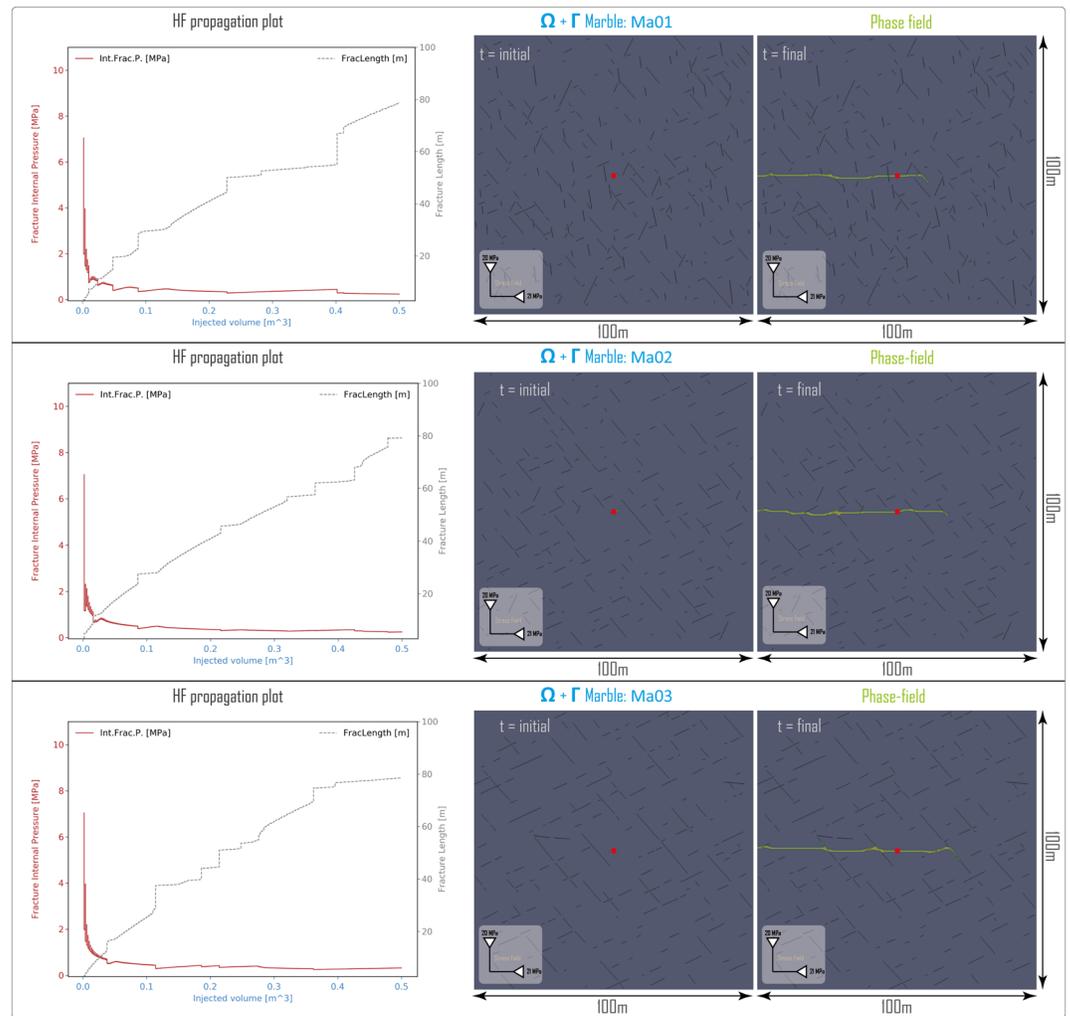


Figure 9. Hydraulic fracture models using V-pf with the sub-DFN of the marble reservoir. The matrix material domain Ω is represented in gray; the natural fractures Γ are discretized in black. Ma01 is composed with 295 natural fractures, Ma02 is composed with 215 natural fractures, and Ma03 is composed with 198 natural fractures. The stress field is oriented such that S_{Hmax} is aligned along the horizontal direction. The red dots represent the well-bore and initial fracture position (and initial phase-field implementation).

equivalence, which is one of the advantages of the method since it allows exploring multiple DFNs scenarios with a single discretization. As presented in this study, the ability of the V-pf is to handle complex fracture topologies with unified criteria—energy minimization—that seeks for an admissible displacement and a set of fracture geometry that minimizes the total energy without a need for ad hoc criteria for branching or turning. The model exhibits asymmetric crack growth under some circumstances: the phenomenon is intrinsic to the variational approach, where the energy minimization leads to the occurrence of asymmetric solutions whenever the total energy of the system is smaller than its symmetric counterpart (Tanne, 2017). This instability has been theoretically pointed out by Gao and Rice (1987), and it is observed in experiments for a penny-shaped crack propagation in toughness dominated regime (Bunger et al., 2008, 2013).

The interaction behavior between hydraulic fracture and natural fractures depends (i) on the combination of the critically energy release rate ratio between natural fractures and bulk rock (\tilde{G}_c^{int}/G_c), (ii) on the natural fractures orientation relative to the stress field, and (iii) on the magnitude of principal stress components. Natural fractures can either favor or hamper the propagation of a hydrofracture according to specific combinations of the input parameters. Natural fractures attract hydraulic fractures for relatively low values of

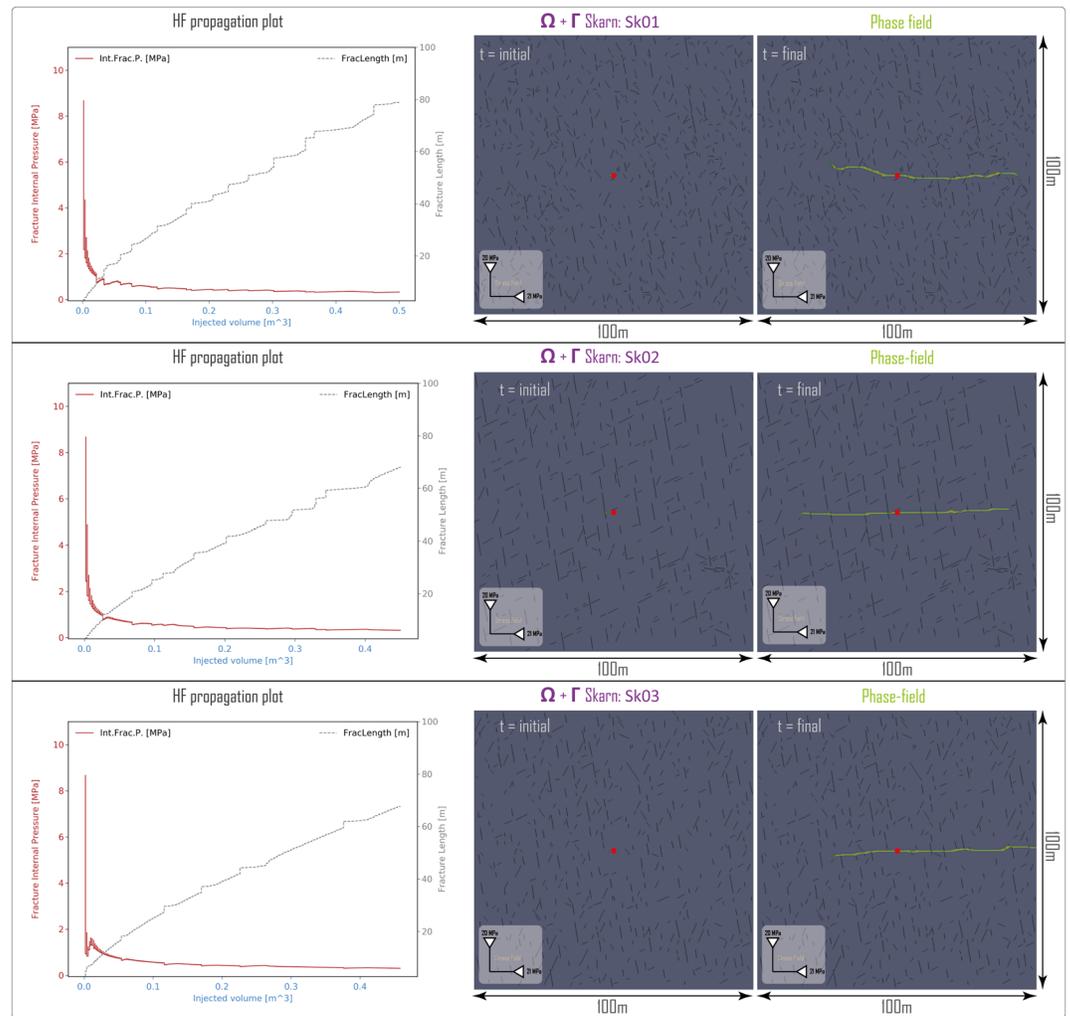


Figure 10. Hydraulic fracture models using V-pf with the sub-DFN of the skarn reservoir. The matrix material domain Ω is represented in gray; the natural fractures Γ are discretized in black. Sk01 is composed with 706 natural fractures, Sk02 is composed with 495 natural fractures, and Sk03 is composed with 375 natural fractures. The stress field is oriented such that S_{Hmax} is aligned along the horizontal direction. The red dots represent the well-bore and initial fracture position (and initial phase-field implementation).

critical energy release rate ratio, when they have orientations close to the critical ones and for relatively isotropic stress states. Natural fractures can be an obstacle to hydraulic fracture growth whenever the fracture resistance becomes higher than the one of the intact rock. Although counterintuitive, the presence of higher strength discontinuities is a relatively frequent occurrence in deep geothermal systems: The environmental conditions could enhance geochemical reactions of dissolution and precipitation (Singurindy & Berkowitz, 2005; Watanabe et al., 2020), such as silica precipitation (Lu et al., 2018; Scott & Driesner, 2018), and the existence of active volcanism could favor the presence of magmatic intrusions even at shallow depth (Elders et al., 2014), which, if old and cold enough, could represent higher strength and stiffness bodies.

In our analyses, we have assumed a low permeability that is typical of poorly fractured crystalline rock, a hypothesis that entails no leak-off between the fracture and the porous rock. Such an assumption is equivalent to an undrained response where the change in effective stress within the porous rock is null during injection. Although the fracture toughness (critical energy release rate) is more predominant in controlling propagation conditions when compared to stiffness, Young's modulus of the rock also plays a role. In particular, a more compliant rock requires higher injected volumes but overall generates lower overpressure. On

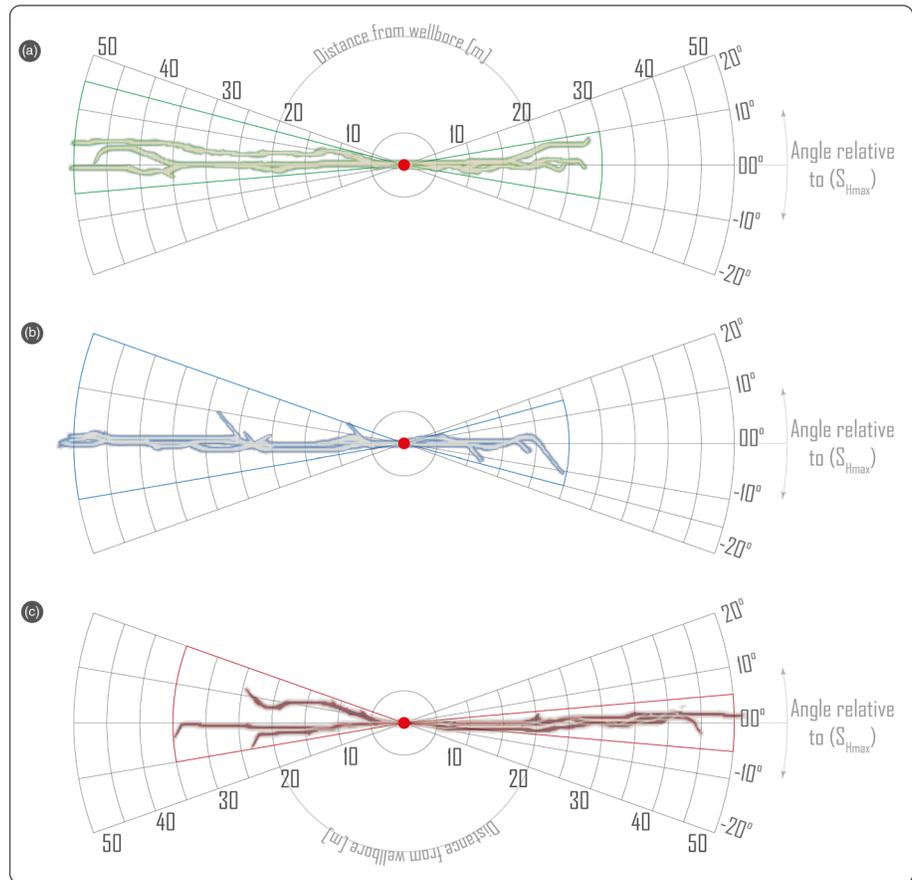


Figure 11. A comparison of hydraulic fracture simulation V-pf models for (a) the limestones (green color); (b) the marbles (blue color); (c) the skarns (red color); hydraulic fracture lengths are given by the concentric dividers, and hydraulic fracture angles compared to S_{Hmax} 's orientation is given by the radial dividers.

the contrary, stiff rocks generate higher overpressure for a lower injected volume. Because of the high fracture strength, high stiffness, and low permeability of basement crystalline rocks, during stimulation of a deep geothermal reservoir high overpressure can be achieved with relatively low values of injected volume (Ellsworth et al., 2019).

The V-pf simulations of the Aocolco reservoir highlighted a fluctuation in the pressure and crack length response in time, with intermittent crack advancement and burst-like behavior—a phenomenon observed during several hydraulic stimulations (Milanese et al., 2016). The V-pf implementation adopted is numerically stable and provides continuous pressure-volume response in absence of viscous flow dissipation. The intermittent advancements are a direct consequence of the interaction between existing fractures with lower crack resistance and the fluid-driven crack: Whenever the hydraulic fracture encounters a natural fracture, if the latter is favorably oriented, the hydraulic fracture encounters almost no resistance and propagates rapidly over a finite length. The pressure drop is associated with a stress release in the rock, which in combination with the crack length increment, can be associated with micro-earthquakes. Microseismicity has been widely observed during hydraulic fracturing (Davies et al., 2013; Lopez-Comino et al., 2017; Schultz et al., 2015) and our results suggest that, in crystalline reservoirs, the phenomenon is associated with hydraulic fractures propagating along preexisting natural fractures.

Results show that the marble formation in the Aocolco reservoir is the optimal one for a potential stimulation because the lowest values of propagation overpressure. The orientation of the natural fractures controls the propagation extent and direction independently of the lithology and the fracture topology dominates the hydraulic fracture response in all cases analyzed. In the present case study we have analyzed homogeneous

rock matrix properties, although a more realistic approach should be based on representing fluctuation of the material properties within the rock matrix. Three-dimensional analyses would be an additional improvement of the current scenarios. Nonetheless, the additional complexity of a three-dimensional reservoir model should be justified by a sufficient knowledge of the reservoir's structure and its property—a current shortcoming for the Acoculco reservoir. Although a normal fault regime is likely at Acoculco reservoir and hydraulic fractures are expected to propagate mainly vertically, there are indications that a strike-slip faulting system could also be active (Liotta et al., 2020), making the full three-dimensional propagation topology rather complex and difficult to estimate a priori.

There is current uncertainty about the in situ state of stress at the Acoculco geothermal reservoir and different values of the stress components could yield a different output in terms of hydraulic fracture propagation. Although the DFNs that are built from outcrop extrapolations are also a source of additional uncertainty, the small prominence of fractures in the DFNs seems to be in good agreement with the very low permeability that was observed during well logging: small and poorly connected fractures hamper fluid flow in the tight reservoir.

Stimulating a highly fractured zone of the Acoculco geothermal reservoir requires a lower stimulation pressure, therefore reducing the drilling costs. Additionally, according to the well temperature measurements, the marble and skarn formations are more likely to be targeted for stimulation because they are present at a higher depth, and therefore, they are at a higher temperature. The formation breakdown pressure is lower for the marble, which also has a lower density of natural fractures. Nonetheless, the natural fractures in the marble are longer and better connected when compared to the ones in the skarn, which are shorter but more frequent. A trade-off arises between the objective of stimulating the hotter formations of the reservoir on the one hand, and stimulating the formations that would yield a longer propagation of the hydraulic fracture on the other hand. The optimal solution would depend on the ultimate goals of the EGS development and a detailed cost-balance analysis is necessary to optimize the stimulation depth.

6. Conclusions

We have presented a method for modeling hydraulic fracture propagation and interaction with a network of natural fractures in a geothermal reservoir. The fracture simulations are based on a variational phase-field approach that proved high numerical stability. We have highlighted the main factors controlling the hydraulic fracture propagation and its interaction with natural fractures through sensitivity analyses on simplified models. We have applied the method to model a realistic EGS stimulation scenario of the geothermal reservoir of Acoculco, Mexico. The numerical model is built from field data and model parameters are derived from laboratory experiments.

Building a realistic DFN is an essential piece of the puzzle for numerical analyses of stimulation of complex reservoirs, which can lead to counterintuitive findings of the propagation mechanisms as opposed to simplified models of single-oriented crack families. Pressure fluctuations and burst-like crack propagation are intrinsically connected to the presence of the complex network of natural fractures.

The numerical model is implemented in the open-source software OpenGeoSys (www.opengeosys.org), which can be freely downloaded at <https://github.com/ufz/ogs> website. We provide a working methodology for the study of EGS systems and the feasibility analyses of hydraulic stimulation of geothermal reservoirs.

Data Availability Statement

The data sets generated during and/or analyzed during the current study are available in the repository (<https://doi.org/10.6084/m9.figshare.12033624.v2>).

References

- Adachi, J. I., & Detournay, E. (2002). Self-similar solution of a plane-strain fracture driven by a power-law fluid. *International Journal for Numerical and Analytical Methods in Geomechanics*, 26(6), 579–604.
- Adachi, J., Siebrits, E., Peirce, A., & Desroches, J. (2007). Computer simulation of hydraulic fractures. *International Journal of Rock Mechanics and Mining Sciences*, 44(5), 739–757. <https://doi.org/10.1016/j.ijrmms.2006.11.006>
- Alessi, R., Marigo, J. J., Maurini, C., & Vidoli, S. (2017). Coupling damage and plasticity for a phase-field regularisation of brittle, cohesive and ductile fracture: One-dimensional examples. *International Journal of Mechanical Sciences*, 149, 1–18. <https://doi.org/10.1016/j.ijmecsci.2017.05.047>

Acknowledgments

This work is part of the GEMex consortium, a European-Mexican collaboration, which aims at investigating nonconventional geothermal systems: (i) an Enhanced Geothermal System, as studied in the case of Acoculco site, (ii) and a supercritical system, as studied in the geothermal field of Los Humeros. We would like to thank all the GEMex team, and especially our Mexican partners who guided us in the field. GEMex has received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement 727550 and the Mexican Energy Sustainability Fund CONACYT-SENER, Project 2015-04-268074. More information is available online (<http://www.gemex-h2020.eu>). K. Y. gratefully acknowledges the funding provided by the German Federal Ministry of Education and Research (BMBF) for the GeoInt project, Grant 03G0866A, within the BMBF Geoscientific Research Program "Geo:N Geosciences for Sustainability." The contribution of F. P. and K. Y. was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Project PA 3451/1-1. Laboratory works would not have been possible without help and support from the laboratory staff. B. L., R. B., and D. B. give thanks to the Delft University of Technology GSE laboratory staff. The authors gratefully acknowledge the Earth System Modeling Project (ESM) for funding this work by providing computing time on the ESM partition of the supercomputer JUWELS at the Jlich Supercomputing Centre (JSC).

- Alessi, R., Vidoli, S., & De Lorenzis, L. (2018). A phenomenological approach to fatigue with a variational phase-field model: The one-dimensional case. *Engineering Fracture Mechanics*, *190*, 53–73. <https://doi.org/10.1016/j.engfracmech.2017.11.036>
- Ambati, M., Gerasimov, T., & De Lorenzis, L. (2015). Phase-field modeling of ductile fracture. *Computational Mechanics*, *55*(5), 1017–1040.
- Ambrosio, L., & Tortorelli, V. M. (1990). Approximation of functional depending on jumps by elliptic functional via Γ -convergence. *Communications on Pure and Applied Mathematics*, *43*(8), 999–1036.
- Ambrosio, L., & Tortorelli, V. M. (1992). On the approximation of free discontinuity problems. *Bollettino dell'Unione Matematica Italiana* (7), *6*(1), 105–123.
- Amor, H., Marigo, J., & Maurini, C. (2009). Regularized formulation of the variational brittle fracture with unilateral contact: Numerical experiments. *Journal of Mechanics and Physics of Solids*, *57*(8), 1209–1229. <https://doi.org/10.1016/j.cmi.2006.11.005>
- Balay, S., Abhyankar, S., Adams, M. F., Brown, J., Brune, P., Buschelman, K., et al. (2019). PETSc users manual. Argonne National Laboratory, ANL-95/11 - Revision 3.11.
- Belytschko, T., & Black, T. (1999). Elastic crack growth in finite elements with minimal remeshing. *International Journal for Numerical Methods in Engineering*, *45*(5), 601–620. [https://doi.org/10.1002/\(SICI\)1097-0207\(19990620\)45:5<601::AID-NME598>3.0.CO;2-S](https://doi.org/10.1002/(SICI)1097-0207(19990620)45:5<601::AID-NME598>3.0.CO;2-S)
- Belytschko, T., Moës, N., Usui, S., & Parimi, C. (2001). Arbitrary discontinuities in finite elements. *International Journal for Numerical Methods in Engineering*, *50*(4), 993–1013. [https://doi.org/10.1002/1097-0207\(20010210\)50:4<993::AID-NME164>3.0.CO;2-M](https://doi.org/10.1002/1097-0207(20010210)50:4<993::AID-NME164>3.0.CO;2-M)
- Biot, M. A. (1941). General theory of three-dimensional consolidation. *Journal of Applied Physics*, *12*(2), 155–164.
- Borden, M. J., Verhoosel, C. V., Scott, M. A., Hughes, T. J. R., & Landis, C. M. (2012). A phase-field description of dynamic brittle fracture. *Computer Methods in Applied Mechanics and Engineering*, *217*–220, 77–95. <https://doi.org/10.1016/j.cma.2012.01.008>
- Bourdin, B., Chukwudozie, C., & Yoshioka, K. (2012). A variational approach to the numerical simulation of hydraulic fracturing. *Proceedings - SPE Annual Technical Conference and Exhibition*, *2*, 1442–1452. <https://doi.org/10.2118/159154-ms>
- Bourdin, B., Francfort, G. A., & Marigo, J.-J. (2000). Numerical experiments in revisited brittle fracture. *Journal of the Mechanics and Physics of Solids*, *48*(4), 797–826.
- Bourdin, B., Francfort, G. A., & Marigo, J.-J. (2008). The variational approach to fracture. *Journal of Elasticity*, *91*(1–3), 5–148.
- Bourdin, B., Larsen, C. J., & Richardson, C. L. (2011). A time-discrete model for dynamic fracture based on crack regularization. *International Journal of Fracture*, *168*(2), 133–143. <https://doi.org/10.1007/s10704-010-9562-x>
- Braides, A. (1998). *Approximation of free-discontinuity problems, Lecture Notes in Mathematics*. London: Springer.
- Bruna, P. O., Straubhaar, J., Prabhakaran, R., Bertotti, G., Bisdorn, K., Mariethoz, G., & Meda, M. (2019). A new methodology to train fracture network simulation using multiple-point statistics. *Solid Earth*, *10*(2), 537–559. <https://doi.org/10.5194/se-10-537-2019>
- Bunger, A. P., & Detournay, E. (2008). Experimental validation of the tip asymptotics for a fluid-driven crack. *Journal of the Mechanics and Physics of Solids*, *56*(11), 3101–3115.
- Bunger, A. P., Gordeliy, E., & Detournay, E. (2013). Comparison between laboratory experiments and coupled simulations of saucer-shaped hydraulic fractures in homogeneous brittle-elastic solids. *Journal of the Mechanics and Physics of Solids*, *61*(7), 1636–1654.
- Bunger, A. P., Jeffrey, R. G., & Detournay, E. (2008). Evolution and morphology of saucer-shaped sills in analogue experiments, *Structure and emplacement of high-level magmatic systems* (pp. 109–120). London: Geological Society.
- Canet, C., Hernández-Cruz, B., Jiménez-Franco, A., Pi, T., Peláez, B., Villanueva-Estrada, R. E., et al. (2015). Combining ammonium mapping and short-wave infrared (SWIR) reflectance spectroscopy to constrain a model of hydrothermal alteration for the Acoculco geothermal zone, Eastern Mexico. *Geothermics*, *53*(July), 154–165. <https://doi.org/10.1016/j.geothermics.2014.05.012>
- Carrara, P., Ambati, M., Alessi, R., & Lorenzis, L. D. (2019). A framework to model the fatigue behavior of brittle materials based on a variational phase-field approach. *Computer Methods in Applied Mechanics and Engineering*, *361*, 112731. <https://doi.org/10.1016/j.cma.2019.112731>
- Choo, J., & Sun, W. C. (2018). Cracking and damage from crystallization in pores: Coupled chemo-hydro-mechanics and phase-field modeling. *Computer Methods in Applied Mechanics and Engineering*, *335*(March), 347–379. <https://doi.org/10.1016/j.cma.2018.01.044>
- Chukwudozie, C., Bourdin, B., & Yoshioka, K. (2019). A variational phase-field model for hydraulic fracturing in porous media. *Computer Methods in Applied Mechanics and Engineering*, *347*, 957–982. <https://doi.org/10.1016/j.cma.2018.12.037>
- Chukwudozie, C., Bourdin, B., Yoshioka, K., Buchmann, T., & Connolly, P. (2013). A new modeling approach to natural fracturing process. *47th US Rock Mechanics / Geomechanics Symposium 2013*, *4*, 2663–2672.
- Davies, R., Foulger, G., Bindley, A., & Styles, P. (2013). Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. *Marine and Petroleum Geology*, *45*, 171–185.
- Del Piero, G. (1989). Constitutive equation and compatibility of the external loads for linear elastic masonry-like materials. *Meccanica*, *24*(3), 150–162. <https://doi.org/10.1007/BF01559418>
- Detournay, E. (2016). Mechanics of hydraulic fractures. *Annual Review of Fluid Mechanics*, *48*(1), 311–339. <https://doi.org/10.1146/annurev-fluid-010814-014736>
- Detournay, E., & Cheng, A. H. D. (1993). Fundamentals of poroelasticity. *Comprehensive Rock Engineering*, *2*, 113–171. <https://doi.org/10.1017/cbo9781139051132.003>
- Economides, M. J., & Nolte, K. G. (1989). *Reservoir stimulation*. Prentice Hall: Wiley.
- Ehlers, W., & Luo, C. (2017). A phase-field approach embedded in the Theory of Porous Media for the description of dynamic hydraulic fracturing. *Computer Methods in Applied Mechanics and Engineering*, *315*, 348–368. <https://doi.org/10.1016/j.cma.2016.10.045>
- Elders, W. A., Fridhleifsson, G., & Albertsson, A. (2014). Drilling into magma and the implications of the Iceland Deep Drilling Project (IDDP) for high-temperature geothermal systems worldwide. *Geothermics*, *49*, 111–118.
- Ellsworth, W. L., Giardini, D., Townend, J., Ge, S., & Shimamoto, T. (2019). Triggering of the Pohang, Korea, earthquake (Mw 5.5) by enhanced geothermal system stimulation. *Seismological Research Letters*, *90*(5), 1844–1858.
- Fischer, A. G., & Marigo, J.-J. (2019). Gradient damage models applied to dynamic fragmentation of brittle materials. *International Journal of Fracture*, *220*, 143–165. <https://doi.org/10.1007/s10704-019-00356-y>
- Fox, D. B., Sutter, D., Beckers, K. F., Lukowski, M. Z., Koch, D. L., Anderson, B. J., & Tester, J. W. (2013). Sustainable heat farming: Modeling extraction and recovery in discretely fractured geothermal reservoirs. *Geothermics*, *46*, 42–54. <https://doi.org/10.1016/j.geothermics.2012.09.001>
- Francfort, G. A., & Marigo, J.-J. (1998). Revisiting brittle fracture as an energy minimization problem. *Journal of the Mechanics and Physics of Solids*, *46*(8), 1319–1342.
- Franklin, J. A., Zongqi, S., Atkinson, B. K., Meredith, P. G., Rummel, F., Muller, W., et al. (1988). ISRM suggested methods for determining the fracture toughness of rock. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, *25*(2), 71–96. [https://doi.org/10.1016/S0148-9062\(96\)00015-0](https://doi.org/10.1016/S0148-9062(96)00015-0)

- Freddi, F., & Royer-Carfagni, G. (2011). Variational fracture mechanics to model compressive splitting of masonry-like materials. *Annals of Solid and Structural Mechanics*, 2(2-4), 57–67. <https://doi.org/10.1007/s12356-011-0018-4>
- Fu, P., Settigast, R. R., Hao, Y., Morris, J. P., & Ryerson, F. J. (2017). The influence of hydraulic fracturing on carbon storage performance. *Journal of Geophysical Research: Solid Earth*, 122, 9931–9949. <https://doi.org/10.1002/2017JB014942>
- Gao, H., & Rice, J. R. (1987). Somewhat circular tensile cracks. *International Journal of Fracture*, 33, 155–174.
- Garagash, D., & Detournay, E. (2000). The tip region of a fluid-driven fracture in an elastic medium. *Journal of Applied Mechanics*, 67(1), 183–192.
- Garagash, D. I., Detournay, E., & Adachi, J. I. (2011). Multiscale tip asymptotics in hydraulic fracture with leak-off. *Journal of Fluid Mechanics*, 669, 260–297.
- Garagash, D. I., & Germanovich, L. N. (2012). Nucleation and arrest of dynamic slip on a pressurized fault. *Journal of Geophysical Research*, 117, B10310. <https://doi.org/10.1029/2012JB009209>
- Geertsma, J., & De Klerk, F. (1969). Rapid method of predicting width and extent of hydraulically induced fractures. *Journal of Petroleum Technology*, 21(12), 1571–1581. <https://doi.org/10.2118/2458-pa>
- Griffith, A. A. (1921). The phenomena of rupture and flow in solids. *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character*, 221(1921), 163–198.
- Guo, H., Aziz, N. I., & Schmidt, L. C. (1993). Rock fracture-toughness determination by the Brazilian test. *Engineering Geology*, 33(3), 177–188. [https://doi.org/10.1016/0013-7952\(93\)90056-I](https://doi.org/10.1016/0013-7952(93)90056-I)
- Gupta, P., & Duarte, C. A. (2016). Coupled formulation and algorithms for the simulation of non-planar three-dimensional hydraulic fractures using the generalized finite element method. *International Journal for Numerical and Analytical Methods in Geomechanics*, 40(10), 1402–1437. <https://doi.org/10.1002/nag.2485>
- Hansen-Dörr, A. C., de Borst, R., Hennig, P., & Kästner, M. (2019). Phase-field modelling of interface failure in brittle materials. *Computer Methods in Applied Mechanics and Engineering*, 346, 25–42. <https://doi.org/10.1016/j.cma.2018.11.020>
- Heidbach, O., Rajabi, M., Reiter, K., Ziegler, M., & Team WSM (2016). World stress map database release 2016. <https://doi.org/10.5880/WSM.2016.001>
- Heider, Y., & Markert, B. (2017). A phase-field modeling approach of hydraulic fracture in saturated porous media. *Mechanics Research Communications*, 80, 38–46. <https://doi.org/10.1016/j.mechrescom.2016.07.002>
- Hofacker, M., & Miehe, C. (2012). Continuum phase field modeling of dynamic fracture: Variational principles and staggered FE implementation. *International Journal of Fracture*, 178(1-2), 113–129. <https://doi.org/10.1007/s10704-012-9753-8>
- Irwin, G. R. (1957). Analysis of stresses and strains near the end of a crack traversing a plate. *Journal of Applied Mechanics*, 24, 361–364.
- Jeffrey, R. G., Bungler, A. P., Lecampion, B., Zhang, X., Chen, Z. R., Van As, A., et al. (2009). Measuring hydraulic fracture growth in naturally fractured rock. *Proceedings - SPE Annual Technical Conference and Exhibition*, 6(January), 3750–3768. <https://doi.org/10.2118/124919-ms>
- Jeffrey, R. G., Weber, C. R., Vlahovic, W., & Enever, J. R. (1994). Hydraulic fracturing experiments in the great northern coal seam. SPE - Asia Pacific Oil & Gas Conference, 361–371.
- Karypis, G., & Kumar, V. (1998). A fast and high quality multilevel scheme for partitioning irregular graphs. *SIAM Journal of Scientific Computing*, 20(1), 359–392. <https://doi.org/10.1137/S1064827595287997>
- Kolditz, O., Bauer, S., Bilke, L., Böttcher, N., Delfs, J. O., Fischer, T., et al. (2012). OpenGeoSys: An open-source initiative for numerical simulation of thermo-hydro-mechanical/chemical (THM/C) processes in porous media. *Environmental Earth Sciences*, 67(2), 589–599. <https://doi.org/10.1007/s12665-012-1546-x>
- Kuhn, C., Noll, T., & Müller, R. (2016). On phase field modeling of ductile fracture. *GAMM Mitteilungen*, 39(1), 35–54. <https://doi.org/10.1002/gamm.201610003>
- López-Hernández, A., García-Estrada, G., Aguirre-Díaz, G., González-Partida, E., Palma-Guzmán, H., & Quijano-León, J. L. (2009). Hydrothermal activity in the Tulancingo-Acocolco Caldera Complex, central Mexico: Exploratory studies. *Geothermics*, 38(3), 279–293. <https://doi.org/10.1016/j.geothermics.2009.05.001>
- Lecampion, B., Bungler, A., & Zhang, X. (2018). Numerical methods for hydraulic fracture propagation: A review of recent trends. *Journal of Natural Gas Science and Engineering*, 49, 66–83.
- Lee, S., Wheeler, M. F., & Wick, T. (2017). Iterative coupling of flow, geomechanics and adaptive phase-field fracture including level-set crack width approaches. *Journal of Computational and Applied Mathematics*, 314, 40–60. <https://doi.org/10.1016/j.cam.2016.10.022>
- Legarth, B. A., & Saadat, A. (2005). Energy consumption for geothermal wells. Proceedings world geothermal congress, antalya, turkey, 24–25.
- Lepillier, B., Bruna, P.-O., Bruhn, D., Bastesen, E., Daniilidis, A., Garcia, O., et al. (2020). From outcrop scanlines to discrete fracture networks, an integrative workflow. *Journal of Structural Geology*, 133(January), 103992. <https://doi.org/10.1016/j.jsg.2020.103992>
- Lepillier, B., Daniilidis, A., Gholizadeh, N., Bruna, P., Juliane, K., & Bruhn, D. (2019). A fracture flow permeability and stress dependency simulation applied to multi-reservoirs, multi-production scenarios analysis. *Geothermal Energy*, 7, 24. <https://doi.org/10.1186/s40517-019-0141-8>
- Li, T., Marigo, J.-J., Guilbaud, D., & Potapov, S. (2016). Gradient damage modeling of brittle fracture in an explicit dynamic context. *International Journal for Numerical Methods in Engineering*, 108(March), 1381–1405. <https://doi.org/10.1002/nme>
- Liotta, D., Bastesen, E., Bianco, C., Brogi, A., Caggianelli, A., Garduño-Monroy, V.-H., et al. (2020). Analogue geothermal systems in Mexico: Insights into the deep part of Los Humeros geothermal field from the Las Minas mining area (Eastern Mexico). Proceedings World Geothermal Congress 2020, 1–9.
- Lopez-Comino, J. A., Cesca, S., Kriegerowski, M., Heimann, S., Dahm, T., Mirek, J., & Lasocki, S. (2017). Monitoring performance using synthetic data for induced microseismicity by hydrofracking at the Wysin site (Poland). *Geophysical Journal International*, 210, 42–55.
- Lu, R., Nagel, T., Shao, H., Kolditz, O., & Shao, H. (2018). Modeling of dissolution-induced permeability evolution of a granite fracture under crustal conditions. *Journal of Geophysical Research: Solid Earth*, 123, 5609–5627. <https://doi.org/10.1029/2018JB015702>
- McClure, M., Babazadeh, M., Shiozawa, S., & Huang, J. (2015). Fully coupled hydromechanical simulation of hydraulic fracturing in three-dimensional discrete fracture networks. SPE Hydraulic Fracturing Technology Conference, Texas, USA, <https://doi.org/10.2118/173354-MS>
- McClure, M. W., & Horne, R. N. (2014). An investigation of stimulation mechanisms in Enhanced Geothermal Systems. *International Journal of Rock Mechanics and Mining Sciences*, 72(November), 242–260. <https://doi.org/10.1016/j.ijrmm.2014.07.011>
- Miehe, C., Hofacker, M., Schänzel, L. M., & Aldakheel, F. (2015). Phase field modeling of fracture in multi-physics problems. Part II. Coupled brittle-to-ductile failure criteria and crack propagation in thermo-elastic-plastic solids. *Computer Methods in Applied Mechanics and Engineering*, 294, 486–522. <https://doi.org/10.1016/j.cma.2014.11.017>

- Miehe, C., Mauthe, S., & Teichtmeister, S. (2015). Minimization principles for the coupled problem of Darcy-Biot-type fluid transport in porous media linked to phase field modeling of fracture. *Journal of the Mechanics and Physics of Solids*, *82*, 186–217. <https://doi.org/10.1016/j.jmps.2015.04.006>
- Miehe, C., Welschinger, F., & Hofacker, M. (2010). Thermodynamically consistent phase-field models of fracture: Variational principles and multi-field FE implementations. *International Journal for Numerical Methods in Engineering*, *83*(10), 1273–1311. <https://doi.org/10.1002/nme.2861>
- Mikelić, A., Wheeler, M. F., & Wick, T. (2015). A phase-field method for propagating fluid-filled fractures coupled to a surrounding porous medium. *Multiscale Modeling & Simulation*, *48*(1), 162–186.
- Milanese, E., Rizzato, P., Pesavento, F., Secchi, S., & Schrefler, B. A. (2016). An explanation for the intermittent crack tip advancement and pressure fluctuations in hydraulic fracturing. *Hydraul Fract J*, *3*(2), 30–43. [https://doi.org/10.1002/\(SICI\)1097-0207\(19990910\)46:1h131::AID-NME726>3.0.CO;2-J](https://doi.org/10.1002/(SICI)1097-0207(19990910)46:1h131::AID-NME726>3.0.CO;2-J)
- Moës, N., Dolbow, J., & Belytschko, T. (1999). A finite element method for crack growth without remeshing. *International Journal for Numerical Methods in Engineering*, *46*(1), 131–150. <https://doi.org/10.1002/nme.2861>
- Ni, L., Zhang, X., Zou, L., & Huang, J. (2020). Phase-field modeling of hydraulic fracture network propagation in poroelastic rocks. *Computational Geosciences*.
- Nordgren, R. P. (1972). Propagation of a vertical hydraulic fracture. *Society of Petroleum Engineers Journal*, *12*(04), 306–314. <https://doi.org/10.2118/3009-pa>
- Perkins, T. K., & Kern, L. R. (1961). Widths of hydraulic fractures. *Journal of Petroleum Technology*, *13*(09), 937–949. <https://doi.org/10.2118/89-pa>
- Renshaw, C. E., & Pollard, D. D. (1995). An experimentally verified criterion for propagation across unbounded frictional interfaces in brittle, linear elastic materials. *International Journal of Rock Mechanics and Mining Sciences and*, *32*(3), 237–249. [https://doi.org/10.1016/0148-9062\(94\)00037-4](https://doi.org/10.1016/0148-9062(94)00037-4)
- Santillán, D., Juanes, R., & Cueto-Felgueroso, L. (2017). Phase field model of fluid-driven fracture in elastic media: Immersed-fracture formulation and validation with analytical solutions. *Journal of Geophysical Research: Solid Earth*, *122*, 2565–2589. <https://doi.org/10.1002/2016JB013572>
- Savitski, A. A., & Detournay, E. (2002). Propagation of a penny-shaped fluid-driven fracture in an impermeable rock: Asymptotic solutions. *International Journal of Solids and Structures*, *39*(26), 6311–6337.
- Schlüter, A., Willenbücher, A., Kuhn, C., & Müller, R. (2014). Phase field approximation of dynamic brittle fracture. *Computational Mechanics*, *54*(5), 1141–1161. <https://doi.org/10.1007/s00466-014-1045-x>
- Schultz, R., Stern, V., Novakovic, M., Atkinson, G., & Gu, Y. J. (2015). Hydraulic fracturing and the crooked lake sequences: Insights gleaned from regional seismic networks. *Geophysical Research Letters*, *42*, 2750–2758. <https://doi.org/10.1002/2015GL063455>
- Scott, S. W., & Driesner, T. (2018). Permeability changes resulting from quartz precipitation and dissolution around upper crustal intrusions. *Geofluids*, *2018*, 6,957,306.
- Seiler, M., Hantschke, P., Brosius, A., & Kästner, M. (2018). A numerically efficient phase-field model for fatigue fracture - 1D analysis. *Pamm*, *18*(1), e201800207. <https://doi.org/10.1002/pamm.201800207>
- Shiozawa, S., Lee, S., & Wheeler, M. F. (2019). The effect of stress boundary conditions on fluid-driven fracture propagation in porous media using a phase-field modeling approach. *International Journal for Numerical and Analytical Methods in Geomechanics*, *43*(February 2018), 1316–1340.
- Singurindy, O., & Berkowitz, B. (2005). The role of fractures on coupled dissolution and precipitation patterns in carbonate rocks. *Advances in Water Resources*, *28*(5), 507–521.
- Tanné, E., Li, T., Bourdin, B., Marigo, J.-J., & Maurini, C. (2018). Crack nucleation in variational phase-field models of brittle fracture. *Journal of the Mechanics and Physics of Solids*, *110*, 80–99. <https://doi.org/10.1016/j.jmps.2017.09.006>
- Tanne, E. (2017). Thèse de doctorat de l' université Paris-Saclay (Ph.D. Thesis), Diss. Université de Bordeaux.
- Tsai, V. C., & Rice, J. R. (2010). A model for turbulent hydraulic fracture and application to crack propagation at glacier beds. *Journal of Geophysical Research*, *115*, F03007. <https://doi.org/10.1029/2009JF001474>
- Wang, H. Y. (2019). Hydraulic fracture propagation in naturally fractured reservoirs: Complex fracture or fracture networks. *Journal of Natural Gas Science and Engineering*, *68*(June), 102911. <https://doi.org/10.1016/j.jngse.2019.102911>
- Warpinski, N. R., & Teufel, L. W. (1987). Influence of geologic discontinuities on hydraulic fracture propagation (includes associated papers 17011 and 17074). *Journal of Petroleum Technology*, *39*(02), 209–220. <https://doi.org/10.2118/13224-pa>
- Watanabe, N., Saito, K., Okamoto, A., Nakamura, K., Ishibashi, T., Saishu, H., et al. (2020). Stabilizing and enhancing permeability for sustainable and profitable energy extraction from superhot geothermal environments. *Applied Energy*, *260*, 114,306.
- Weng, X. (2014). Modeling of complex hydraulic fractures in naturally fractured formation. *Journal of Unconventional Oil and Gas Resources*, *9*, 114–135. <https://doi.org/10.1016/j.juogr.2014.07.001>
- Weng, X., Kresse, O., Cohen, C., Wu, R., & Gu, H. (2011). Modeling of hydraulic fracture network propagation in a naturally fractured formation. *Society of Petroleum Engineers - SPE Hydraulic Fracturing Technology Conference 2011*, i, 298–315. <https://doi.org/10.1016/j.juogr.2014.07.001>
- Weydt, L., Bär, K., Colombero, C., Comina, C., Deb, P., Lepillier, B., et al. (2018). Outcrop analogue study to determine reservoir properties of the Los Humeros and Acoculco geothermal fields, Mexico. *Geophysical Research Abstracts EGU General Assembly*, *20*(727550), 2018–7228. <https://doi.org/10.5194/adgeo-45-281-2018>
- Wheeler, M. F., Wick, T., & Wollner, W. (2014). An augmented-Lagrangian method for the phase-field approach for pressurized fractures. *Computer Methods in Applied Mechanics and Engineering*, *271*, 69–85. <https://doi.org/10.1016/j.cma.2013.12.005>
- Wilson, Z. A., & Landis, C. M. (2016). Phase-field modeling of hydraulic fracture. *Journal of the Mechanics and Physics of Solids*, *96*, 264–290. <https://doi.org/10.1016/j.jmps.2016.07.019>
- Xia, L., Yvonnet, J., & Ghabzloo, S. (2017). Phase field modeling of hydraulic fracturing with interfacial damage in highly heterogeneous fluid-saturated porous media. *Engineering Fracture Mechanics*, *186*(October), 158–180. <https://doi.org/10.1016/j.engfracmech.2017.10.005>
- Yazid, A., Abdelkader, N., & Abdelmadjid, H. (2009). A state-of-the-art review of the X-FEM for computational fracture mechanics. *Applied Mathematical Modelling*, *33*(12), 4269–4282. <https://doi.org/10.1016/j.apm.2009.02.010>
- Yew, C. H., & Weng, X. (2015). Fracture propagation in a naturally fractured formation. *Mechanics of Hydraulic Fracturing*, *1*, 133–175. <https://doi.org/10.1016/b978-0-12-420003-6.00007-0>
- Yoshioka, K., & Bourdin, B. (2016). A variational hydraulic fracturing model coupled to a reservoir simulator. *International Journal of Rock Mechanics and Mining Sciences*, *88*, 137–150. <https://doi.org/10.1016/j.jrmms.2016.07.020>

- Yoshioka, K., Parisio, F., Naumov, D., Lu, R., Kolditz, O., & Nagel, T. (2019). Comparative verification of discrete and smeared numerical approaches for the simulation of hydraulic fracturing. *GEM - International Journal on Geomathematics*, *10*(1), 1–35. <https://doi.org/10.1007/s13137-019-0126-6>
- Zoback, M. D., Barton, C. A., Brudy, M., Castillo, D. A., Finkbeiner, T., Grollmund, B. R., et al. (2003). Determination of stress orientation and magnitude in deep wells. *International Journal of Rock Mechanics and Mining Sciences*, *40*(7-8), 1049–1076. <https://doi.org/10.1016/j.jrmms.2003.07.001>