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A three-dimensional coupled thermo-hydro-mechanical numerical model with partially bridging multi-stage contact fractures in horizontal-well enhanced geothermal system

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Abstract

Enhanced Geothermal Systems (EGS), engineered deep rock heat exchangers, are often touted for their massive untapped renewable energy potential. However, numerous technical and financial challenges must be overcome before the technology is widely deployed. To be viable, EGS must engineer a heat sweep by circulating fluid through a large volume of rock while minimizing fast pathways that create thermal short circuits. Here, we propose a new horizontal EGS well design with partially bridging multi-stage hydraulic fractures (Fig. 1b) to improve heat extraction from hot dry rock (HDR). In order to increase fluid circulation through the stimulated reservoir volume (SRV) between fractures, the hydraulic fractures are created in an alternating pattern between injection and production wells, with each stopping short of connecting the second well. To test this design, we developed a thermal-hydro-mechanical (THM) coupling model and investigated heat extraction performance and reservoir stress evolution during operation. Fractures were modelled as opening contact surfaces with system stresses evolving according to thermal, poroelastic, and fracture opening effects. Based on the model, the temperature performance of proposed EGS design model is compared with the commonly used fully bridging EGS design model (Fig. 1a). An investigation of

thermal performance showed that the proposed design obtains higher production temperatures and delays thermal breakthrough by several years compared to a fully-bridging fracture design. It also results in a greater degree of secondary stimulation of the SRV as cold fluids are forced further into the rock matrix. These results indicate that the partially-bridging fracture design is a promising candidate for practical EGS implementation.

Keywords: Horizontal EGS well design model; Thermal-hydro-mechanical coupling model; Opening fracture; Heat extraction performance; Induced reservoir failure volume

1. Introduction

Enhanced geothermal systems (EGS) are developed to accelerate the production of heat energy from hot dry rock (HDR) in ultra-low permeability formations.¹⁻³ More than a dozen research and industrial projects have attempted EGS development including the pioneering Fenton Hill (US), Soultz-sous-Forêts (France), Desert Peak (US), and Cooper Basin (Australia) projects.^{1,4} These projects typically involved the application of stimulation technologies like hydraulic fracturing, shear, thermal or chemical stimulation to improve permeability and fluid-rock contact area for heat transfer.

Many EGS projects have been performed with a single fracturing stage in nearly vertical wells with open-hole completion.⁵⁻¹¹ This is mostly because of the technical challenges and high costs of horizontal drilling in hard and high temperature granites that EGS typically targets. Other projects have pursued shear stimulation at a pressure lower than fracture propagation, which has been hypothesized to improve hydraulic transmissivity by a shear induced self-propping effect in natural fractures. However, practical applications have revealed enormous technical problems with conventional EGS design.¹²⁻¹⁶ Some researchers have expressed doubt about the self-propping capability of slipping fractures under in-situ stresses.^{12,13,17} Jung¹⁴ critically reviewed the results and observations of several major EGS projects and suggested that the primary mechanism controlling the stimulation process is not the shearing of the joint network but the formation of single large wing-cracks. There have been a few exceptions which has adopted the multiple fractures stimulation. AltaRock's Newberry EGS project, Groß Schönebeck project, Qiabuqia project, Petrathern's Paralana project and Salavatli project have applied multi-stage stimulation from fully perforated

casing with horizontal (or deviated) and multilateral drilling technology in sandstone and volcanic
 rocks.^{16,18–24}

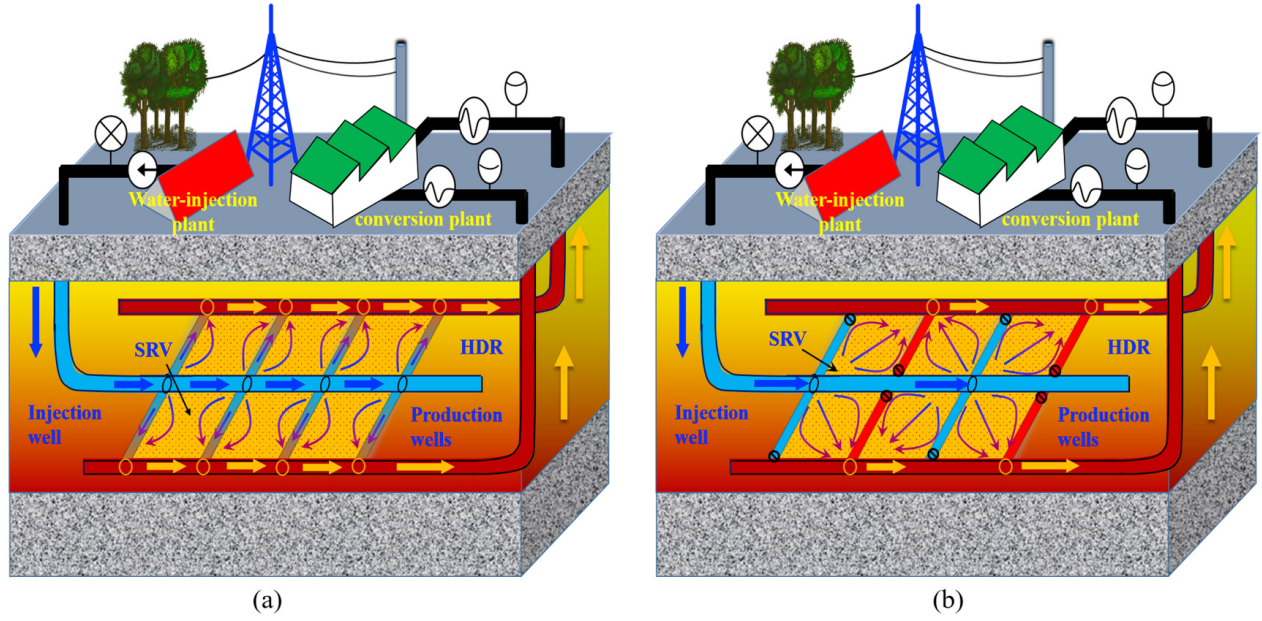


Fig. 1. Schematic diagram for the commonly used conceptual model and proposed conceptual model of the enhanced geothermal system (EGS). (a) Commonly used design: full bridging hydraulic fractures. (b) Proposed design: Partially bridging hydraulic fractures.

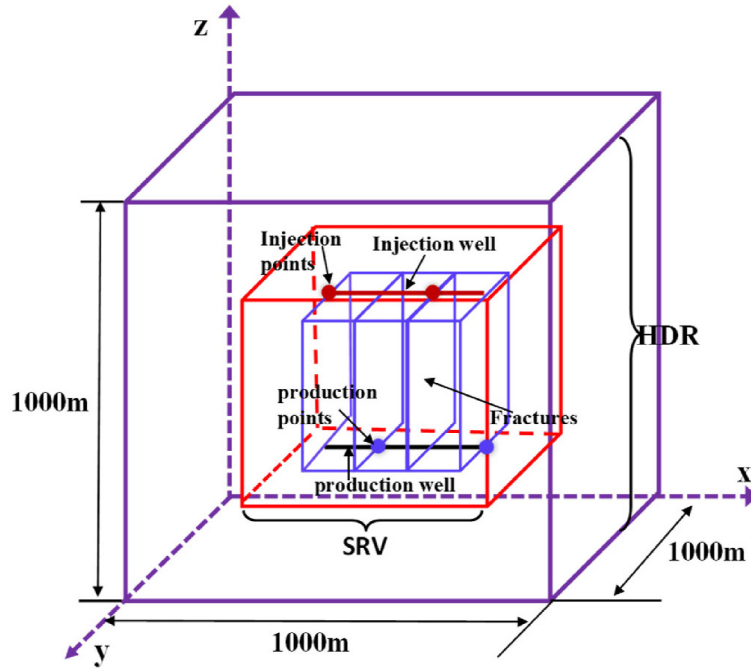


Fig. 2. Schematic of the computational geometry model.

Table 1

Geometrical parameters of the model.

Parameters	Values
Model dimensions (m^3)	$1000 \times 1000 \times 1000$
SRV dimensions (m^3)	one fracture case: $240 \times 500 \times 500$ two fractures case: $240 \times 500 \times 500$ four fractures case: $600 \times 500 \times 500$
Fracture numbers	one fracture case: 1 two fractures case: 2 four fractures case: 4
Well diameter (m)	0.1
Fracture width (m)	500
Fracture height (m)	400
Fracture spacing (m)	120
Well spacing (m)	400

Table 2

Reservoir and fracture properties.

Parameters	HDR	SRV	Fracture
Density (kg/m^3)	2600	2600	–
Heat conductivity ($\text{W}/(\text{m}\cdot\text{K})$)	2.8	2.8	–
Heat capacity ($\text{J}/(\text{kg}\cdot\text{K})$)	1000	1000	–
Porosity (%)	10	30	100
Permeability (m^2)	5×10^{-15}	5×10^{-14}	1×10^{-12} (k_0)
Thermal expansion coefficient ($1/\text{K}$)	5×10^{-6}	5×10^{-6}	–
Young's modulus (Pa)	6×10^{10}	6×10^{10}	–
Poisson's ratio	0.25	0.25	–
Biot-Willis coefficient	0.7	0.7	–

Table 3

Characteristics of different simulations.

Section	Design	Fracture number	Injection operation	Simulated physics
3.1	Fully bridging	1	Constant rate (20 kg/s)	Thermo-poroelastic opening fractures
3.2	Fully bridging vs. partially bridging	2	Constant rate (50 kg/s)	Thermo-poroelastic opening fractures
3.3	Fully bridging vs. partially bridging	4	Constant rate (100 kg/s)	Thermo-poroelastic opening fractures
3.4	Partially bridging	4	Constant pressure (45 MPa) vs. constant rate (33 kg/s)	Thermo-poroelastic opening fractures
3.5	Partially bridging	4	Constant pressure (45 MPa)	Thermo-poroelastic opening fractures vs. thermo-poroelastic non-opening fractures vs. thermoelastic opening fractures vs. poroelastic opening fractures

1.1. Fracture designs

Refs.^{17,20,25} have discussed the availability and advantages of applying horizontal drilling and multi-stage fracturing in geothermal reservoirs. Their results showed that multiple stages significantly improve economic performance and allow a higher flow rate to be circulated through the system. The commonly used concept model of a multi-fractured horizontal well EGS doublet is shown in Fig. 1a. The main fractures are assumed to be created by high-pressure injection into a section of the well that has been isolated and perforated, with fracture growth terminating when it intersects the other well. We term these fractures “fully bridging” as they directly connect the two wells. During this process, the volume between the two main fractures may also be stimulated, usually by

the accumulation of poroelastic stresses, and its permeability may have increased. In this design, a portion of the injected water will enter the stimulated reservoir volume (SRV), absorb heat from the rock matrix, and then exit into the production well.²⁶ However, this flow scheme is usually associated with early thermal breakthrough; the size of the heat extraction zone will be limited by the penetration length of injected water into the SRV.

This paper proposes a new EGS well design that uses partially bridging hydraulic fractures to increase flow through the SRV, as illustrated in Fig. 1 (b). Half of the hydraulic fractures are generated from the production well but, through close control of fracture growth, are stopped short of the injection well. This could be achieved through high resolution, real-time microseismic monitoring of the propagating fractures. The other half are grown from the injection well and stop short of the production well. The position of production and injection fractures alternates down the length of the wells. The goal is for the fractures to provide connectivity to the SRV while preventing injected water directly flowing to the production well. Instead, the water in the injection fractures must enter and flow through the SRV, exiting in fractures connected to the production well.

The partially-bridging fracture scheme is likely not without its own challenges. Fracture growth is not entirely controllable, particularly in formations where pre-existing fractures alter the stress field or provide preferred propagation pathways.²⁷ This could be problematic in the event that fully-bridging fractures are inadvertently created and some type of plugging solution was required. Nevertheless, compared with the well design of the fully bridging scheme (Fig. 1a), the proposed design ought to delay thermal breakthrough and result in more heat extraction over the production lifetime. The order of fractures for the partially bridging EGS model could be achieved by the optimized zipper fracking (OZF) hydraulic technology, as proposed by Algarhy et al.²⁸ Algarhy et al.²⁹ explored the feasibility of OZF by numerical modelling and suggested that this technology could obtain an optimum stress shadow and maximize the stimulation of the SRV by ordering of fractures.

1.2. Numerical models

Many numerical models have been developed to simulate the various development stages of EGS focusing on coupled THM processes such as heat transfer, fluid seepage and rock deformation.^{4,6,30–33} Studies have shown that fracture aperture variation due to the normal and/or shear stresses acting

94 on the fracture surfaces strongly affects fluid flow and heat transfer in the fracture.³² However,
 95 few studies have taken into account the evolution of fracture permeability due thermo-poroelastic
 96 effects under a full contact formulation. Some researchers^{31,34,35} have proposed methods in which the
 97 permeability of a non-opening thin layer varies in response to a stress-dependent fracture stiffness,³¹
 98 or an effective normal stress imposed across the fracture plane.^{35,36} The assumption of a fracture as a
 99 non-opening surface significantly improved the convergence speed and reduced computational time.³⁷
 100 However, neglecting the opening nature of fractures might produce erroneous stress or aperture
 101 effects. McClure et al.^{38,39} studied contact theory in-depth with application to modelling fracture
 102 opening in EGS projects to demonstrate realistic behaviors of fractures.

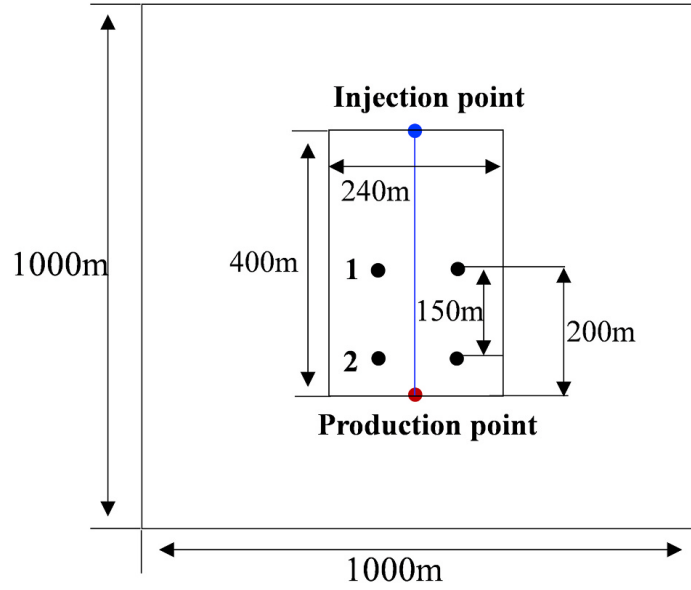


Fig. 3. Cut plane along $y = 500$ m of geometry.

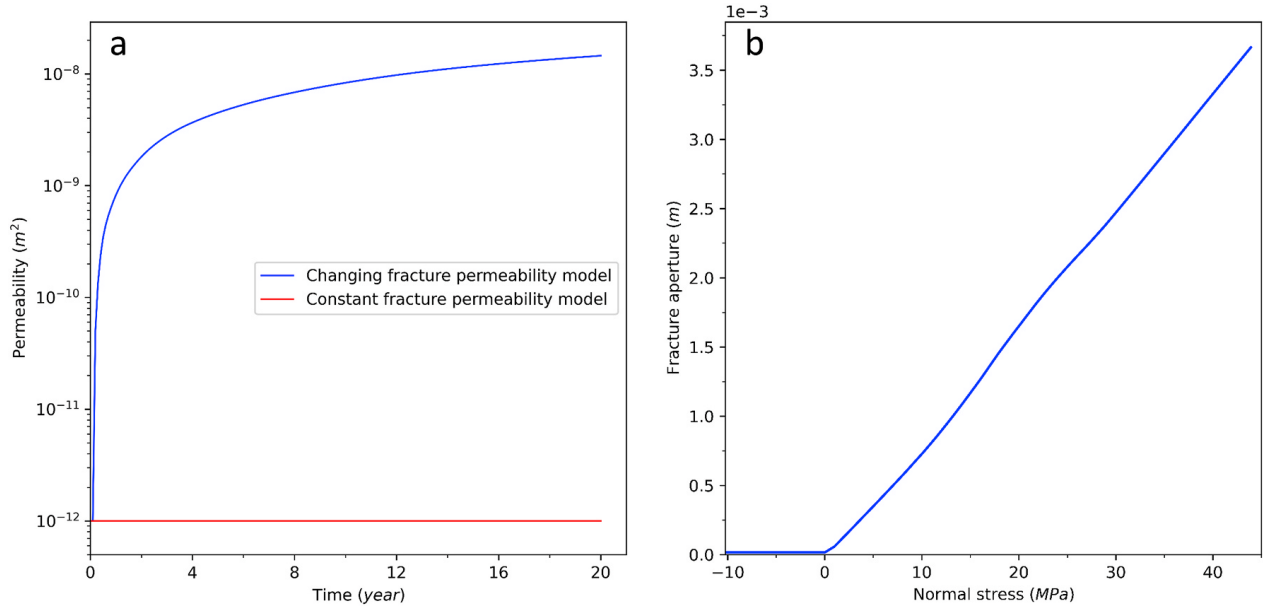


Fig. 4. The geometry of one fracture case and the fracture permeability comparison between two models. (a) Fracture permeability comparison; (b) relationship between fracture aperture and normal stress of changing fracture permeability model.

Fractures and fracture networks are fundamental components of EGS that determine its technical and economic feasibility. Although substantial efforts have been made on the numerical modelling of THM coupling process in EGS, there are still few studies addressing fracture aperture evolution in 3D under THM conditions and with multi-stage contacting fractures. Ghassemi et al.⁴⁰ analytically studied fracture aperture variation under thermo-poroelastic perturbation for a geothermal reservoir under the assumption of extremely low injection pressure, however opening due to pressure loading on the fracture surfaces was not considered. Ghassemi and Zhou⁴¹ used the displacement discontinuity method to integrate coupled fracture flow and heat transfer with thermoporoelastic deformation of rock. However, a sequential numerical coupling method was used and these can suffer from instability and inaccuracy for complex problems.³⁷ Nejati et al.⁴² and Salimzadeh et al.^{33,37,43} studied fractures as 2D surface discontinuities within 3D rock matrix. Mechanical deformation, as well as contact stresses on the opening fracture surfaces under compression are solved in a mechanical contact model based on the Augmented Lagrangian (AL) method.⁴² A key result of that study was to show a low likelihood of fracture propagation under a pure opening mode during production. However, the factors affecting induced reservoir failure evolution in SRV domain remain unclear. Besides, the uncertainties inherent in induced reservoir failure modelling using non-opening fractures are

still unknown. It remains challenging to demonstrate the role of thermoporoelastic effects on stress evolution in matrix rock adjacent to opening fractures, more so with our proposition of a new partially bridging fracture geometry.

In this study, a 3D THM numerical model is presented that explores the effects of cold water injection into multi-stage contact fractures. To demonstrate the advantages of the proposed geometry, heat extraction performance and thermal breakthrough extent are compared against alternative fracturing designs. In addition, a series of factors controlling reservoir stimulation are analyzed, including the effects of dynamic fracture opening and permeability, different EGS design models, different injection operation regimes. The separate roles of thermoelastic effect and poroelastic effects are also investigated.

2. Description of the THM fracture model

2.1. Model assumptions

Modelling heat extraction from a horizontal-well EGS must account for the dominant physical phenomena including fluid seepage, heat transfer and solid mechanics in fractured porous media. The following assumptions are made, consistent with prior studies^{35,44–46}: (1) The EGS is a HDR reservoir that includes four hydraulic fractures linking one horizontal injection well and one horizontal production well, with the fractures enclosing the SRV; (2) the SRV and HDR domains are simplified as equivalent continuous porous medium with homogeneous and isotropic properties; (3) the permeability of the SRV domain is much higher than that of the HDR; (4) local thermal equilibrium is assumed between the solid rock and fluid; and (5) under operating conditions, water does not vaporise and can be considered a liquid.⁴⁷ Hence, the reservoir is saturated with a single-phase fluid and flow within the porous media and fractures obeys Darcy’s law. The physical properties of water are described as a function of temperature.⁴⁸

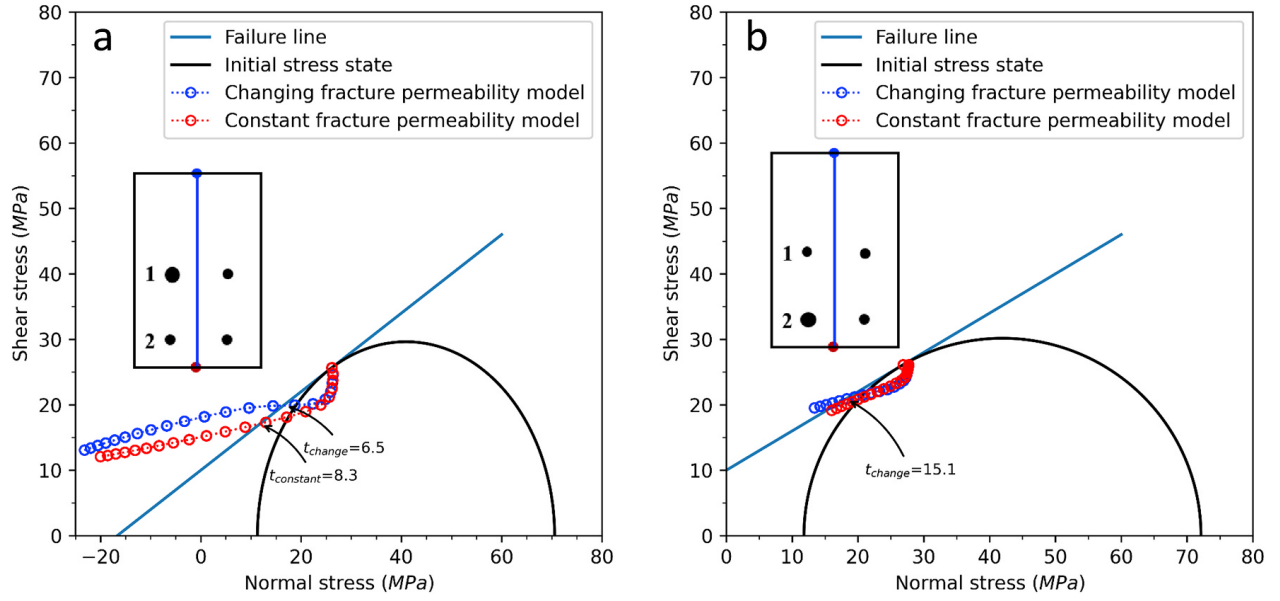


Fig. 5. Points stress path evolution comparison between changing fracture permeability model and constant fracture permeability model. (a) Point1 (reservoir center point); (b) point 2 shown in Fig. 6

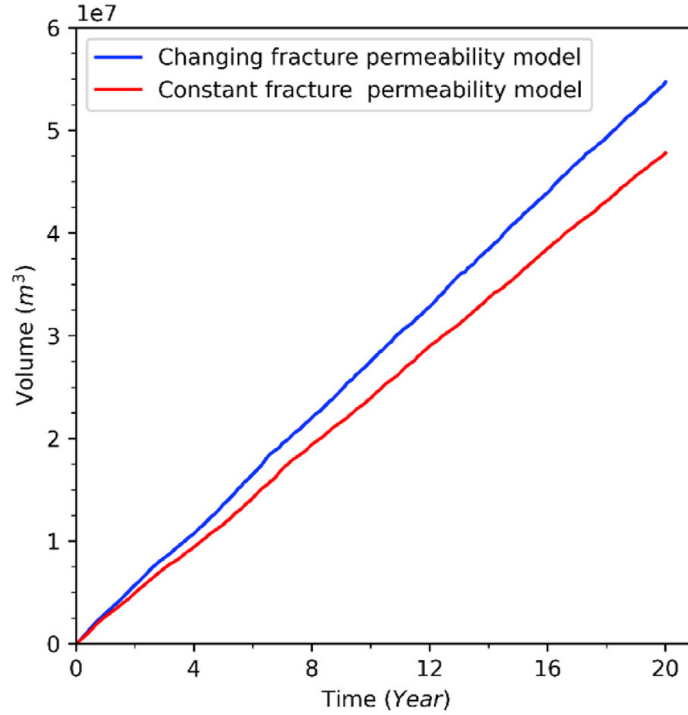


Fig. 6. Reservoir failure volume comparison between changing fracture permeability model and constant fracture permeability model.

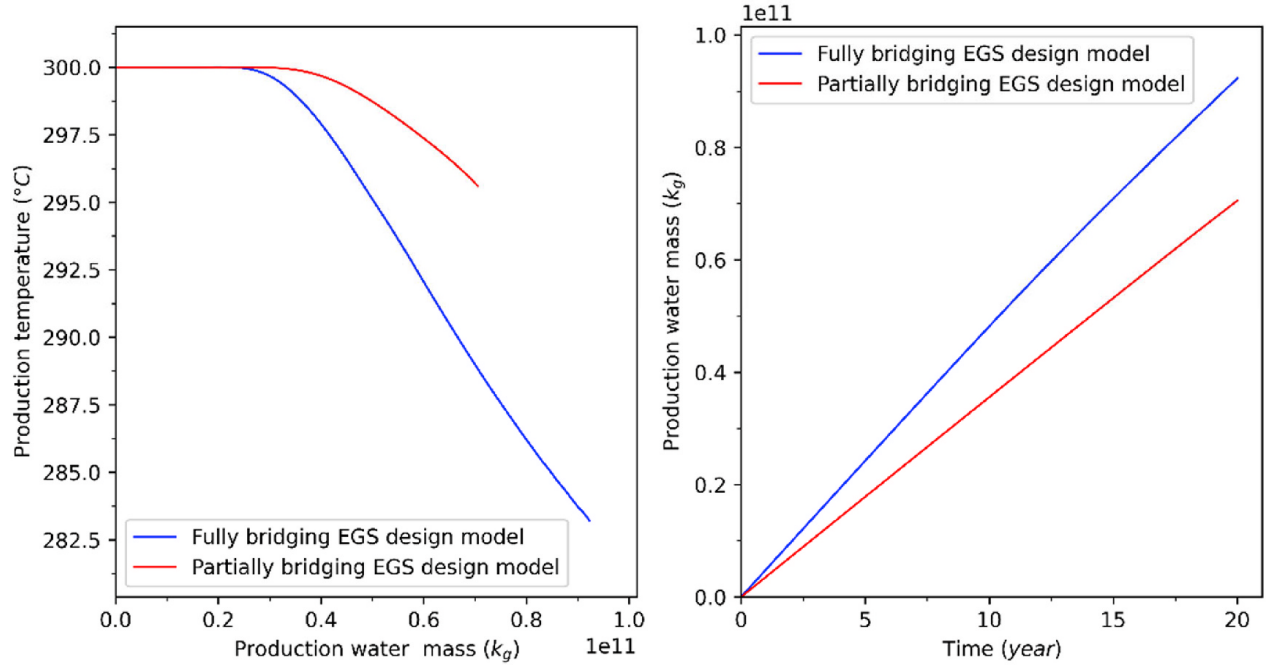


Fig. 7. The relationship of extracted water temperature and produced water mass as well as production time comparison between fully and partially bridging two contact fractures EGS design model.

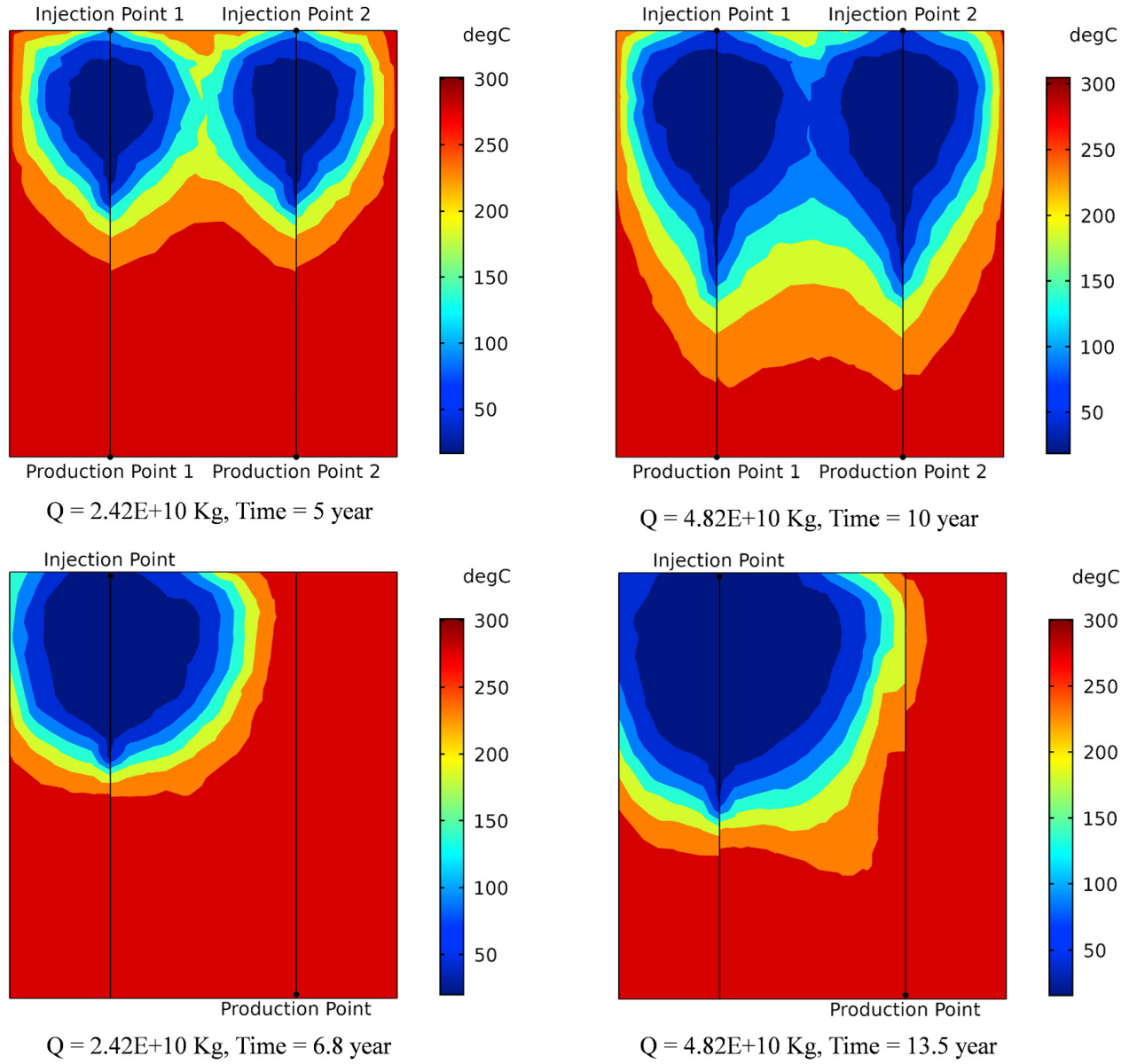


Fig. 8. Comparison of temperature contours in the SRV at equivalent production masses. (first row) fully bridging EGS design model, (second row) partially bridging EGS design model.

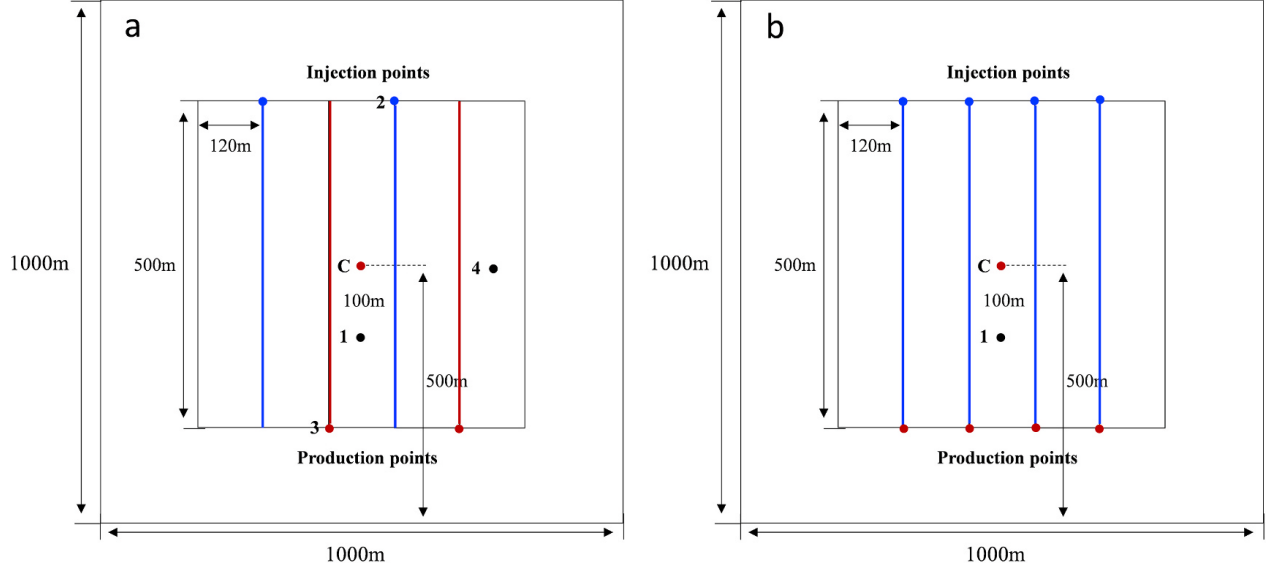


Fig. 9. Model slice at $y = 500$ m with four opening fractures in (a) partially bridging configuration, and (b) fully bridging configuration. Blue and red circles indicate injection and production locations. Points marked 1 through 4 are referred to in Figs. 10, 12 and 14. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

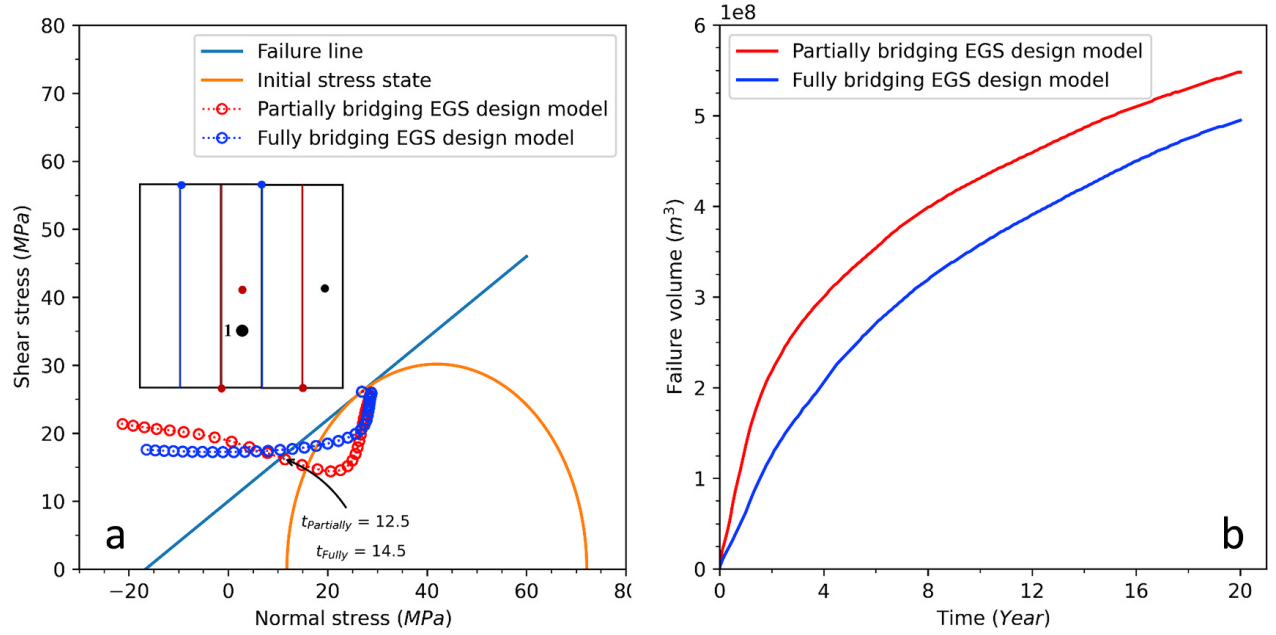


Fig. 10. Points stress evolution and reservoir failure volume comparison between fully bridging EGS design model and partially bridging EGS design model with four opening fractures under constant injection rate condition. (a) Point 1 shown in Fig. 9; (b) Failure volume comparison.

2.2. Governing equations

The mass conservation equation for fluid flow in porous media can be expressed:

$$\frac{\partial}{\partial t}(\rho_w \phi) + \nabla \cdot (\rho_w \mathbf{u}_w) = -Q_m - \rho_w \alpha_B \frac{\partial \varepsilon}{\partial t} \quad (1)$$

Where ϕ is porosity, $\mathbf{u}_w$ (m/s) is Darcy velocity, ε is volumetric strain in the reservoir domain, Q_m is mass transfer between rock matrix and fractures, ρ_w (kg/m³) is density, and α_B is the Biot-Willis coefficient, which is defined in terms of the bulk modulus⁴⁹:

$$\alpha_B = 1 - \frac{K_d}{K_s} \quad (2)$$

Here, K_s (Pa) is the bulk modulus of a homogeneous block of the solid material, while K_d (Pa) is the drained bulk modulus of porous matrix of the same material. According to Darcy's law, the flow velocity is expressed in terms of the pressure gradient:

$$\mathbf{u}_w = -\frac{k_m}{\mu_w}(\nabla p + \rho_w \mathbf{g} \nabla z) \quad (3)$$

where k_m (m²) is permeability, μ_w (Pa·s) is viscosity, and p (Pa) is fluid pressure. The second term on the RHS of (3), $\rho_w \mathbf{g} \nabla z$, represents the effects of gravity, where $\mathbf{g}$ (m/s²) is the gravity vector. Using the storage model in,⁵⁰ we have

$$\frac{\partial}{\partial t}(\rho_w \phi) = \rho_w S \frac{\partial p}{\partial t} \quad (4)$$

Where S (Pa⁻¹) is the storage coefficient of reservoir, which can be expressed

$$S = \phi C_w + (\alpha_B - \phi) \frac{1 - \alpha_B}{K_d} \quad (5)$$

Where C_w (Pa⁻¹) is the compressibility of water. Thus, the equation of mass conservation is reformulated:

$$\rho_w S \frac{\partial p}{\partial t} - \nabla \cdot \left[\frac{k_m}{\mu_w} (\nabla p + \rho_w \mathbf{g} \nabla z) \right] = -\rho_w \alpha_B \frac{\partial \varepsilon}{\partial t} - Q_m \quad (6)$$

156 Similarly, an equation for flow in the fracture is obtained as:

$$d_f \rho_w S_f \frac{\partial p_f}{\partial t} - \nabla \cdot d_f \rho_w \left[\frac{k_f}{\mu_w} (\nabla p + \rho_w \mathbf{g} \nabla z) \right] = -d_f \rho_w \alpha_B \frac{\partial \varepsilon_f}{\partial t} + d_f Q_m \quad (7)$$

157 Where S_f (Pa^{-1}), k_f (m^2), d_f (m), and ε_f are the specific storage, permeability, aperture and
 158 volumetric strain of the fracture, respectively. To obtain a more realistic description of fracture fluid
 159 flow with variation of the fracture aperture, the cubic law is employed⁵¹:

$$k_f = \frac{a_f^2}{12\chi} \quad (8)$$

160 Where k_f (m^2), χ , and a_f (m) are the permeability, roughness and aperture of fracture. In this
 161 study, local thermal equilibrium is assumed between the pore water and the HDR reservoir. The
 162 energy conservation equation in the matrix is formulated as⁵²:

$$(\rho c_p)_m \frac{\partial T}{\partial t} + \nabla \cdot (\rho_w c_{p,w} \mathbf{u}_m T) - \nabla \cdot (\lambda_m \nabla T) = -Q_{f,E} \quad (9)$$

163 Where T (K) is temperature, $C_{p,w}$ ($\text{J}/(\text{kg}\cdot\text{K})$) is heat capacity, λ_w $\text{W}/(\text{m}\cdot\text{K})$ is thermal conductivity,
 164 and $Q_{f,E}$ is the heat exchange between matrix and fractures, $(\rho c_p)_m$ and λ_m ($\text{W}/(\text{m}\cdot\text{K})$) are the
 165 effective volumetric heat capacity and the effective thermal conductivity, calculated as:

$$(\rho c_p)_m = (1 - \phi) \rho_s c_{p,s} + \phi \rho_w c_{p,w} \quad (10)$$

166

$$\lambda_m = (1 - \phi) \lambda_s + \phi \lambda_w \quad (11)$$

167 Where ρ_s (kg/m^3), $c_{p,s}$ ($\text{J}/(\text{kg}\cdot\text{K})$) and λ_s ($\text{W}/(\text{m}\cdot\text{K})$) are the density, heat capacity and thermal
 168 conductivity of the solid rock, respectively. Similarly, the energy conservation equation in fractures
 169 is written:

$$d_f (\rho c_p)_f \frac{\partial T}{\partial t} + \nabla \cdot (d_f \rho_w c_{p,w} V_f T) - \nabla_\tau \cdot (d_f \lambda_f \nabla T) = d_f Q_{f,E} \quad (12)$$

170 Where $(\rho c_p)_f$ and λ_f are the effective volumetric capacity and the effective thermal conductivity of
 171 fractures. For this study, we have assumed that the reservoir behaves elastically, which is reason-
 172 able for the fluid pressures considered and for most thermal-induced deformation.^{32,48} The linear

173 equilibrium equation under quasi-static conditions is expressed

$$\text{div}\boldsymbol{\sigma} + \mathbf{F} = 0 \quad (13)$$

174 Where $\mathbf{F}$ (N/m³) is the body force per unit volume, and $\boldsymbol{\sigma}$ (Pa) is the total stress tensor. The
175 effective stress tensor $\boldsymbol{\sigma}'$ (Pa) for the rock matrix with pore fluid pressure is defined as⁵³

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} + \alpha_B p \mathbf{I} \quad (14)$$

176 Where $\mathbf{I}$ is the second-order identity tensor. Linear thermal strains induced by temperature changes
177 are formulated

$$\boldsymbol{\varepsilon}_T = -\boldsymbol{\alpha}_T (T - T_{ini}) \quad (15)$$

178 Where T_{ini} (K) is the initial rock temperature and $\boldsymbol{\alpha}_T$ (K⁻¹) is the linear thermal expansion coeffi-
179 cient. For isotropic rock, $\boldsymbol{\alpha}_T$ is related to the volumetric thermal expansion coefficient β_s (K⁻¹).³⁷

$$\boldsymbol{\alpha}_T = \frac{\beta_s}{3} \mathbf{I} \quad (16)$$

180 The stress-strain relationship for thermo-elasticity is written⁵⁴:

$$\boldsymbol{\sigma}' = \mathbf{D}\boldsymbol{\varepsilon} - \beta_s K_d (T - T_{ini}) \mathbf{I} \quad (17)$$

181 Where $\mathbf{D}$ is the elasticity matrix, and K_d (Pa) is the bulk modulus, expressed as:

$$K_d = \frac{E}{3(1 - 2\nu)} \quad (18)$$

182 Where E (Pa) is the elastic modulus, ν is Poisson's ratio. Meanwhile, $\boldsymbol{\varepsilon}$ is the linear strain tensor

$$\boldsymbol{\varepsilon} = \frac{1}{2} (\nabla \mathbf{u} + \nabla \mathbf{u}^T) \quad (19)$$

183 in which $\mathbf{u}$ denotes the displacement vector.

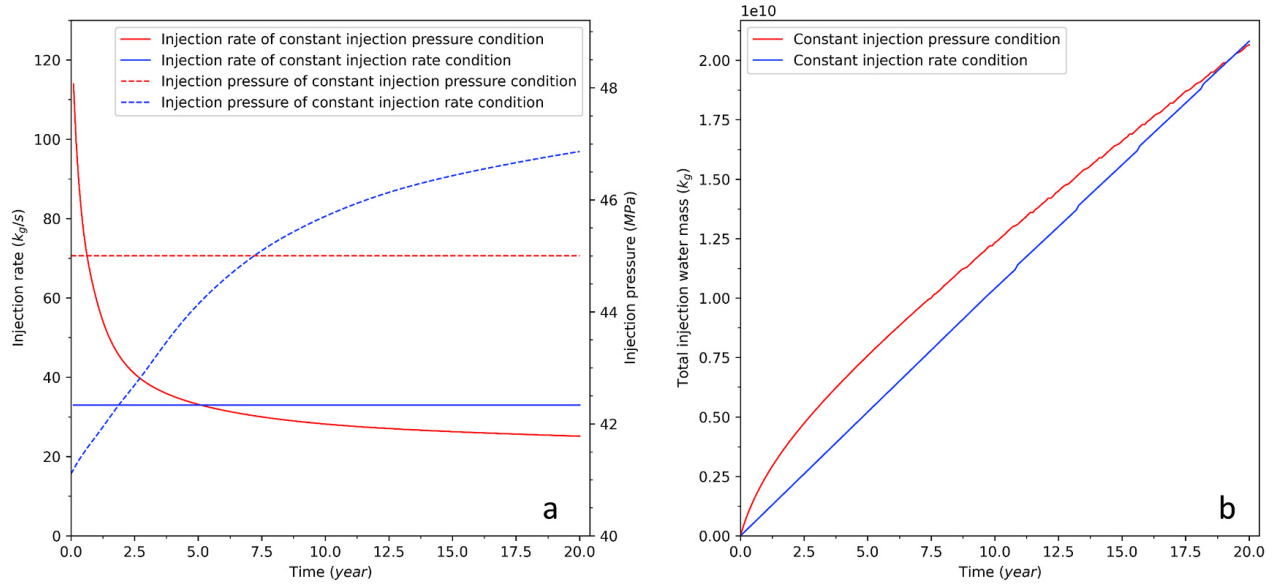


Fig. 11. Comparison of injection rate, injection pressure, and total injection water mass comparison between constant injection rate condition and constant injection pressure condition model at the injection well for the partially bridging fractures EGS design (a) injection rate and injection pressure comparison (b) total injection water mass comparison.

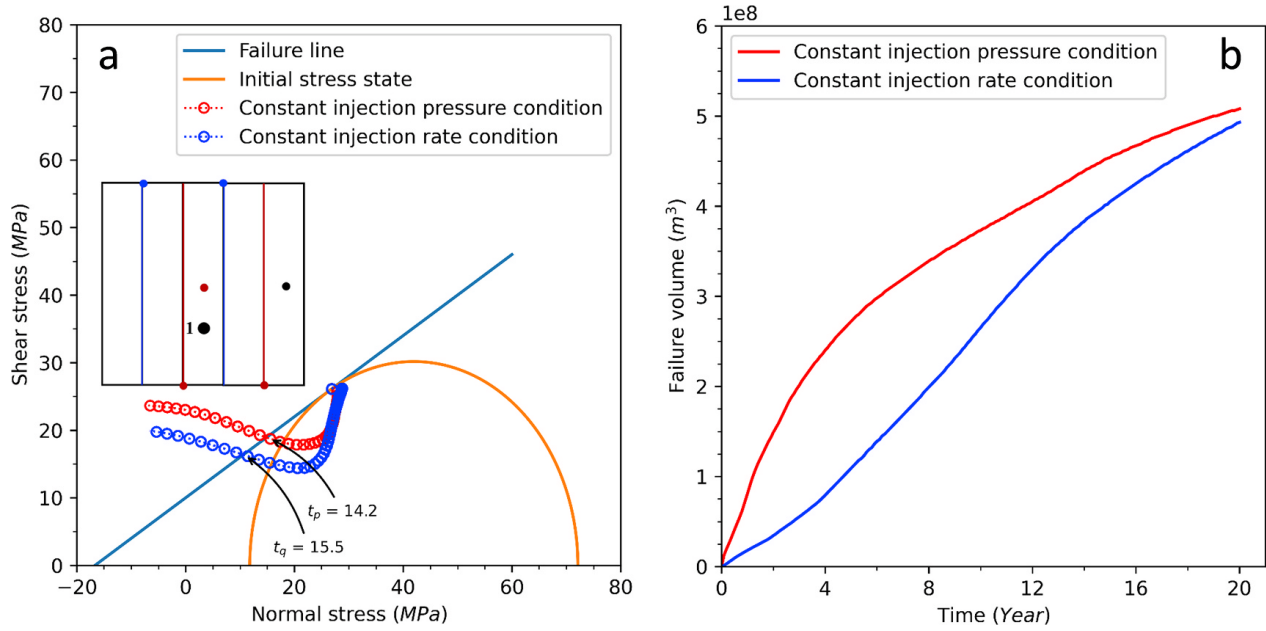


Fig. 12. Points stress evolution and failure volume comparison between constant injection pressure and constant injection rate condition for four partially bridging opening fractures EGS design model (a) Point 1 shown in Fig. 10a; (b) failure volume comparison.

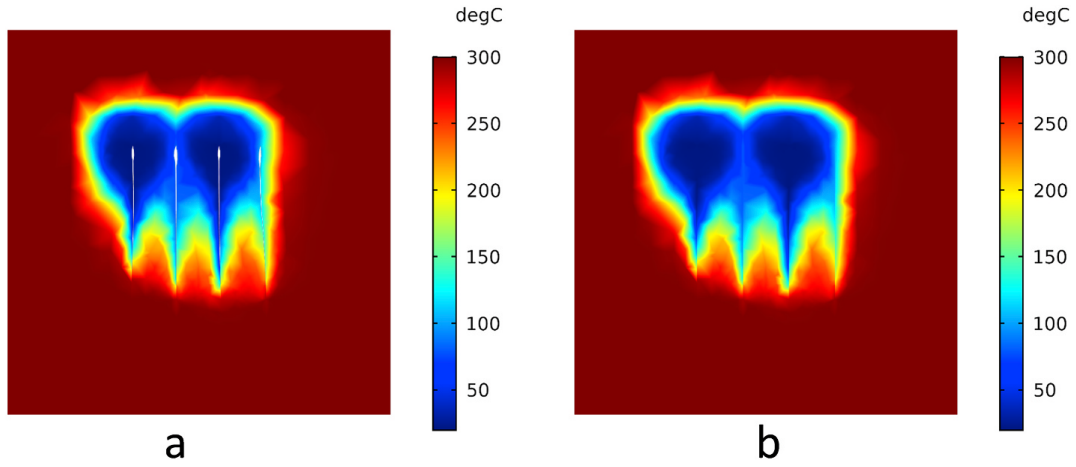


Fig. 13. Temperature distribution comparison of cut plane at $y = 500$ m between opening fracture and non-opening fracture model for four partially bridging fractures EGS design models under constant injection pressure condition. (a) Opening fracture model; (b) non-opening fracture model.

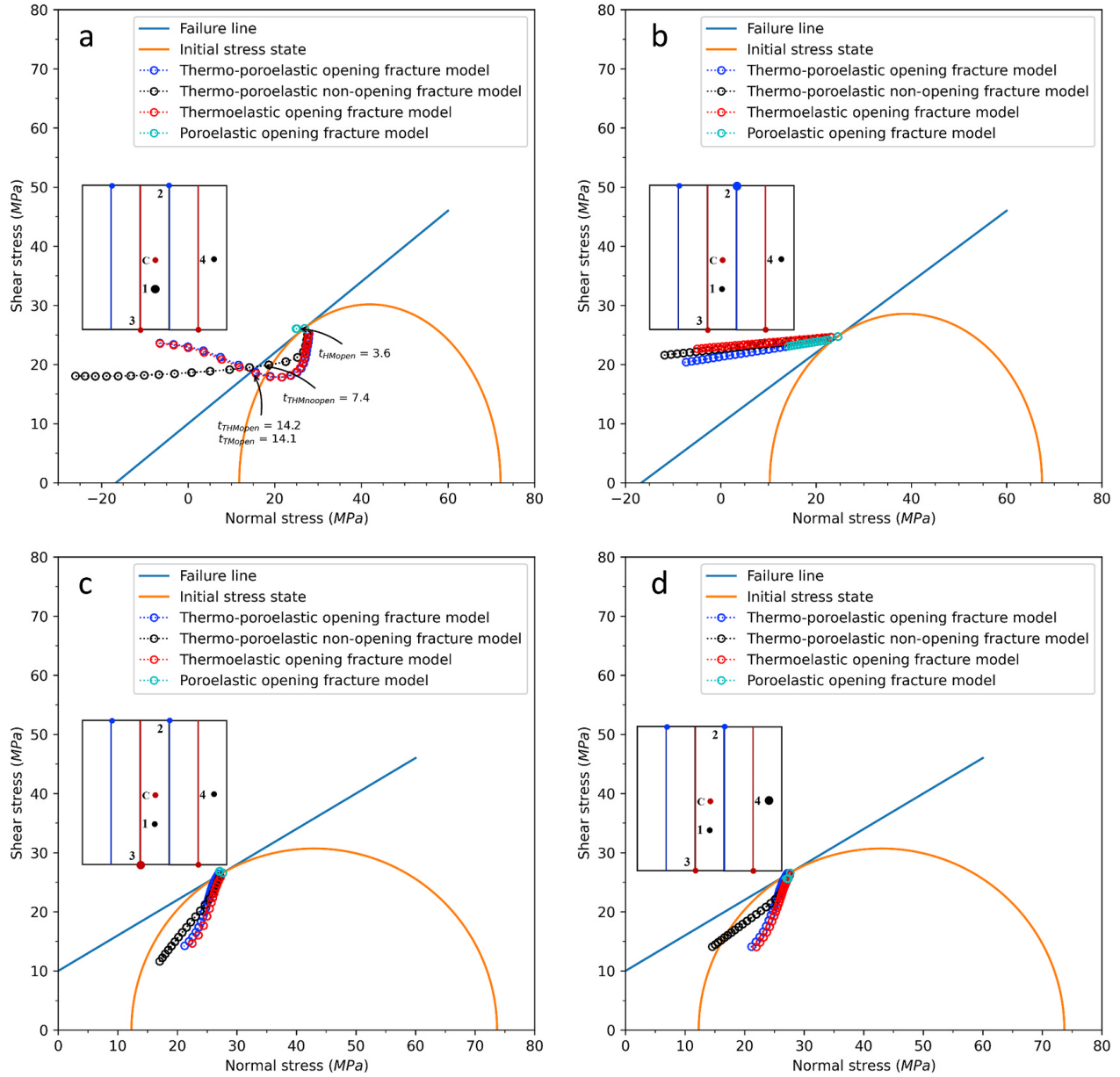


Fig. 14. Points stress evolution comparison between thermo-poroelastic opening fracture model, thermo-poroelastic non-opening fracture model, thermoelastic opening fracture model, and poroelastic opening fracture model for four partially bridging fractures EGS design models under constant injection pressure condition (a) Point 1 shown in Fig. 9; (b) Point 2 (the injection well point); (3) Point 3 (the production well point); (4) Point 4 (located outside of fractures).

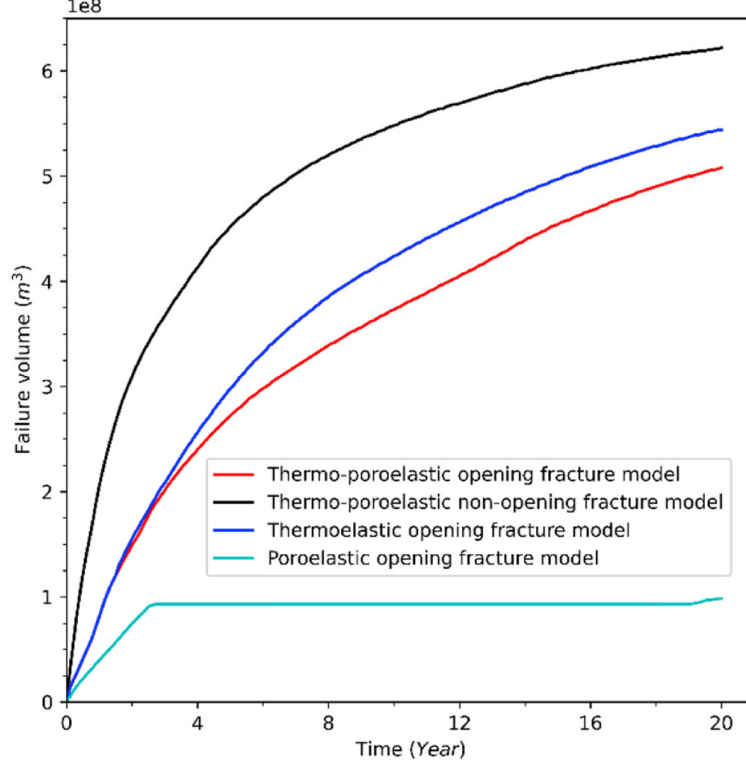


Fig. 15. Failure volume comparison between thermo-poroelastic opening fracture model, thermo-poroelastic non-opening fracture model, thermoelastic opening fracture model, and poroelastic opening fracture model for four partially bridging fractures EGS design models under constant injection pressure condition.

For the fracture contact model, thermal-induced strain and hydraulic loading are applied to the fracture walls. We neglect any propagation of the fracture in a pure opening mode under normal operation (i.e., outside of hydraulic stimulation). It is not clear whether sufficient cooling could be achieved at the dead-end fracture tip (minimal flow occurs without a closed circuit) for further propagation to occur. In the event there was propagation, this wouldn't substantially modify the flow field unless a connection to the second well was achieved, in which case some sort of plugging remediation would be needed. Based on the work of Salimzadeh et al.,^{33,37,43} the tractions applied on the fixed fracture boundary Γ_c are expressed as

$$\mathbf{F}_c = \boldsymbol{\sigma}_c - p_f \mathbf{n}_c \quad (20)$$

Where $\boldsymbol{\sigma}_c$ (Pa) is the contact traction on the fracture walls, p_f (Pa) is the fluid pressure applied on the fractures, and $\mathbf{n}_c$ is the outward directed unit normal. Substituting Eqs. (14)–(20) and inte-

grating Eq. (13), the differential equation describing the deformation field considering the fracture mechanical contact model under fluid pressure and thermal contraction for the HDR is given by

$$\int_{\Omega} [div(\mathbf{D}\boldsymbol{\varepsilon} - \alpha_{BP}\mathbf{I} - \beta_s K_d(T - T_{ini})\mathbf{I}) + F] d\Omega + \int_{\Gamma_c} (\boldsymbol{\sigma}_c - p_f \mathbf{n}_c) d\Gamma_c = 0 \quad (21)$$

2.3. Model geometry

We consider an idealised multi-stage fractured horizontal-well EGS geometry, commonly used in other numerical EGS studies.^{9,44,55,56} Fig. 2 illustrates the schematic of the computational model for a doublet EGS horizontal well. The model includes a HDR layer that encloses the SRV and four hydraulic fractures, one horizontal injection well with two injection points and one production well with two production points. Water is only injected from the injection points and produced from the production points. The parameters of this model are adopted from (Shi et al., 2019; Song et al., 2018b). The computational domain is located at a depth of 4500–5500 m and has dimensions 1000 m $\times$ 1000 m $\times$ 1000 m. The SRV is 600 m $\times$ 500 m $\times$ 500 m and is located at the center of the computational domain. The injection well is 50 m below the top of SRV and the production well is 50 m above the bottom of the SRV. Each fracture comprises two surfaces that are initially merged together. Key geometry and reservoir physical properties are given in Tables 1 and 2 with most values derived from previous numerical studies of EGS.^{4,17,35,36}

2.4. Initial and boundary conditions

At a depth of 5 km, we assumed an initial temperature of 300 °C and pressure of 40 MPa. Gradients in temperature and pressure are ignored in this study. Dirichlet boundary conditions are applied at the boundaries of the model, setting these to the initial temperature and pressure. The initial stress state is assumed to reflect a critically stressed crust close to the Mohr-Coulomb frictional failure limit in a normal faulting environment. The initial vertical stress is set to 101.92 MPa assuming an average density of 2600 kg/m³ in the overburden of 4000 m depth. The initial minimum horizontal stress, which is oriented normal to the fractures, is computed in terms of the effective vertical stress, σ'_v , and the frictional properties of fractured rock.⁵⁷

$$\sigma'_h = 2C \left[(1 + f_s^2)^{1/2} + f_s \right] + \left[(1 + f_s^2)^{1/2} + f_s \right]^2 \sigma'_v \quad (22)$$

Where f_s is the coefficient of rock friction, and C is the cohesion. For typical values $f_s = 0.6$ and $C = 10 \text{ MPa}$, then for example, at the depth of 4500 m, σ'_h is 70.56 MPa, and this implies a horizontal stress induced by the fluid pressure and thermal stress decrease of 11.3 MPa would be required to exceed the least principal stress and open a fracture.

All boundaries of the computational model are constrained in normal directions. Besides, the injection temperature of the water is set as 293.15 K. 45 MPa is employed at the injection well for the constant injection pressure condition.

2.5. COMSOL implementation

Our model has been implemented in the general purpose finite element simulator COMSOL Multiphysics. Three modules are utilised: Solid mechanics, Darcy flow and Heat transfer in porous media. These modules solve the equations described in Section 2.2 using a standard finite element discretisation in space domain and finite difference discretisation in time domain. The solid mechanics module implements both the linear elastic material model for the matrix and the contact fracture model, in which the two fracture walls are set as one contact pair. The Darcy flow module includes the poroelastic storage model and fracture flow model. Finally, the heat transfer in porous media module solves the energy conservation equation. The initial and boundary conditions in Section 2.4 are implemented and all of the three modules are coupled together via the poroelastic and thermal expansion terms.

To obtain tightly coupled solutions in this study, we use the segregated scheme implemented in COMSOL due to its ease of implementation and reliable convergence. Temperature and pressure are placed in one segregated step and solved together while the displacement and fracture contact model is placed in the following segregated step. The implicit generalized- α method is used for time integration, which ensures unconditional stability when using the solid mechanics module.^{48,58} To obtain the solution at time t_i , an initial guess for the two staggered steps is obtained from the solution in the former time step. Then, the two segregated steps are solved sequentially and the relative error ε_r is estimated. If ε_r is less than our prescribed tolerance ε_t (1×10^{-5} in this paper), the calculation moves from time step i to $i+1$. Otherwise, a new iteration step will be started until $\varepsilon_r < \varepsilon_t$. In order to accelerate convergence, the Newton iterations and Anderson acceleration method are used.

3. Results and discussion

In this section, we compare the operational performance of a simulated EGS project under different fracture configurations and using different physics. The main aim is to identify first-order design decisions that improve heat recovery. A secondary aim is to resolve different aspects of the THM fracture physics and rank their impact on our numerical solutions. We chose to monitor both these aspects by measuring two performance metrics for the simulated EGS.

The most important performance criterion for an EGS is production fluid temperature. The aim is to maintain this as high as possible (to maximize the efficiency of energy generation) for as long as possible (to maximize investment recovery), two factors that reflect the efficiency of the heat sweep. Thermal short-circuiting via fast flow pathways in the reservoir will result in a premature drop of the production temperature. This can be artificially delayed by simply flowing the system at a much lower rate, which reduces the rate at which the cooling front propagates through the reservoir but at the same time undermines performance. Therefore, a fairer measure of thermal performance is to inspect plots of production temperature vs. total produced volume or mass. Fracture designs or operational protocols that maintain higher temperature for the same produced mass can claim superior performance.

A second performance metric is long-term improvement of permeability within the reservoir during normal operations. Although substantial permeability is presumed to be created during a period of dedicated stimulation prior to production, long-term injection of cold water can perturb stresses in the reservoir and induce additional fracture failure. We quantified this additional stimulation as the volume of rock in which stress exceeds the Mohr-Coulomb failure criterion. We assumed that all rock was initially at the Mohr-Coulomb limit, i.e., a critically stressed reservoir, and that there was no stress depletion (Kaiser effect) from prior stimulations. These assumptions may not be valid at every EGS site, however, they simplify the analysis and enable a straightforward comparison between simulations.

In the sections that follow, we investigate the effects of fracture geometry and number, opening behaviour, various THM physics, and different injection operations, which is summarized in Table 3.

3.1. Thermal opening of a fracture

Here, we modelled a single fracture connecting the injection and production wells using the geometry shown in Fig. 3. As the rock matrix cooled and normal stress decreased, the fracture opened mechanically. Fracture permeability enhancement is modelled by the cubic law, whose aperture is the opening distribution along fracture. A second simulation without fracture opening and hence constant permeability was performed for comparison (Fig. 4a). Fracture aperture evolution with normal stress across the fracture is shown in Fig. 4b. It demonstrates that fracture aperture will remain at its initial value while the normal stress is less than zero. As the normal stress becomes tensile, the fracture walls separate, opening linearly with increasing tensile stress to about 3.5 mm at the end of simulation.

To analyse accompanying reservoir stimulation, stress paths are plotted on top of an initial Mohr circle for two selected points (Fig. 3). For a point halfway between injection and production wells, the model with an opening fracture experienced failure about 1.8 years earlier than constant permeability fracture (Fig. 5a). At a second point closer to the production well (Fig. 5b), failure only occurred for the model with the opening fracture. Rock failure is more extensive when using opening fractures (Fig. 6) because the elevated fracture permeability allows cold fluid to penetrate further into the reservoir, thereby perturbing stresses across a larger volume. Opening fractures also disturb the stress field, and this effect is demonstrated later in Section 3.5.

3.2. Thermal performance of fully and partially bridging fracture designs

To compare the temperature performance for the fully and partially bridging EGS design model, a set of numerical EGS models with opening fractures under the constant injection rate condition are simulated. Geometric and reservoir parameters are listed in Tables 1 and 2. For a fair comparison between these two designs, the production water temperature of the production well is compared under the same amount of produced water mass in this study for 20 years production time. As shown in Fig. 7, the produced water temperature of the partially bridging model is higher than that of the fully bridging model for the same amount of produced water mass. However, the produced water mass of partially bridging EGS model is smaller than the fully bridging EGS model because the partially EGS design forces the water to enter the SRV domain, which results in water flow

slowing compared with fully bridging EGS design. Nevertheless, the partially bridging model has a lower rate of temperature decline post breakthrough, and a higher long-term stabilised temperature.

Advancement of temperature fronts through the SRV and fractures were analyzed to account for the difference above (Fig. 8). For the fully bridging model, injected water percolated within the SRV adjacent to the fracture. As the permeability of the SRV is much smaller than the fracture, the advective heat exchange of injected water with surrounding rock is limited, and the majority of injected water flows in the fractures. In contrast, the temperature changes in the partially bridging model are limited to alternating fractures connected to the injection well. The thermal front does not reach the production fractures until it has passed through the SRV, hence increasing the efficiency of heat sweep. For the same injected volume, the thermal front has penetrated further into the SRV for the partially bridging fracture configuration.

3.3. Stimulation performance of fully and partially bridging fracture designs

In this section, we describe the effect of the two fracture designs on matrix stress evolution and stimulation. Four partially and fully bridging opening fractures EGS design models with constant injection rate are simulated. The geometry of two models along with stress measurement points are shown in Fig. 9.

Fig. 10a shows the evolving stress path at a point located halfway between two fractures. Failure conditions are met after 14.5 years of injection for the fully bridging configuration, and 12.5 years for the partially bridging fractures. This indicates that, by forcing fluids to penetrate further into the SRV, the partially bridging fracture configuration induces larger stress changes and more rapid failure. Integrating failure across the entire modelled volume, Fig. 10b shows that for both models, the stimulated zone grows rapidly at first, slowing at later time. The total failure volume is always larger for the partially bridging configuration, which suggests the stress paths exhibited in Fig. 10a are representative of much of the reservoir.

3.4. Effect of injection: constant pressure vs. constant rate

While injection rate targets might normally be specified to deliver a fixed production flow rate, practical considerations like pumping limits or rock stability might sometimes require injection to be capped at an upper pressure. The effect of injection at constant pressure and constant rate

were considered from the perspective of reservoir stress evolution. For these simulations, the model geometry in Fig. 9a for the partially bridging EGS well design was used. For a fair comparison, the same total injection volume was considered in both cases (Fig. 11b). At fixed pressure, the injection rate gradually decreases over time (Fig. 11a) as near well elevation of fluid pressure reduces injectivity. In contrast, to maintain the constant injection rate condition, an increasingly higher injection pressure is required, reaching a final injection pressure of 47 MPa.

Stress paths in the reservoir (Fig. 12a) have a similar shape, although the failure time for a constant injection pressure condition is earlier than that of constant injection rate condition. In addition, a larger reservoir volume was failed for the constant injection pressure model. This is because more water are injected at the early production time and there is a correspondingly larger stress disturbance in the reservoir. These results imply that careful thought should be given to prescribing a realistic injection scheme when using numerical models to predict EGS performance.

3.5. Contribution of individual THM physics to stimulation

The purpose of this section is to understand the individual contribution of modelling choices to the simulated distribution of failure. In particular, we have looked at the effect of explicitly modelling fracture opening, and the individual contributions of poroelasticity and thermoelasticity. To this end, the model with four partially bridging fractures was used (Fig. 9a), and injection was simulated under constant pressure conditions. As noted in Section 3.1, non-opening fractures have different permeability properties and therefore different temperature evolution through the reservoir. To enable a fair comparison against a model without opening fractures we mapped the fracture permeability evolution for a simulation with open fractures onto a simulation without. This allows us to distinguish the stress effects due to fracture opening from those due to permeability increase.

For the temperature contour comparison of Fig. 9a is shown in Fig. 13, which we could see that the opening fracture model could open due to the water pressure and the contraction induced by the temperature change (Fig. 13a). However, the fractures in the non-opening fracture model is modelled by a thin surface which cannot achieve the fracture opening. In addition, the temperature distribution for these two models is the same, which can also see from Fig. 13.

For the opening and non-opening fracture models, we compared evolving stress paths at four points (Fig. 14). Generally, non-opening fractures exhibit failure earlier and to greater degrees than

when fracture opening was modelled. This is because opening fractures release stress that would otherwise build-up were the fracture held non-opening. Total failure reservoir volume is also less the simulation with opening fractures (Fig. 15). For these simulations, electing not to model the effects of fracture opening would lead to an overestimate of stimulation by 10–20%. This inaccuracy depends both on the duration of injection as well as the ambient stress conditions. For example, a deeper EGS with higher ambient stresses would not necessarily reach conditions for fracture opening to occur (zero normal stress) and neglecting fracture opening becomes less inaccurate.

Poro and thermoelastic effects also make individual contributions to reservoir stress evolution (Figs. 14 and 15). Poroelastic stress changes have only a minor influence on the simulation outcome, which is evident in similar failure times and volumes in simulations from which they are omitted. However, it is interesting to note that, when present, they appear to play a role of stabilizing⁵⁹ and delaying the stress changes that induce failure. In contrast, the thermoelastic effect plays a leading role in controlling stress changes of the SRV, as evidenced by much smaller failure volumes when they are omitted (Fig. 15).

We have also considered stress evolution for a point on the injection and production wells (Fig. 14b and c). The injection well very rapidly encounters failure conditions whereas stresses at the production well are stabilised during operation of the EGS. This is because the significant thermoelastic stress change by cooling water is local to the injection well, whereas temperature in rock matrix surrounding the production well is much more stable. Stabilizing injection boreholes in large cooled rock masses may become challenging for long-term EGS implementation. Finally, stress changes were considered at a point outside of fractures (Fig. 14d). Due to small temperature changes, and a distant EGS operation, the stress changes here are minor and stabilizing.

4. Conclusion

In this study, we proposed a new horizontal EGS well design that uses partially bridging multi-stage hydraulic fractures. The goal is to force water to pass through a reservoir matrix rather than short-circuiting fractures, thereby improving heat sweep and delaying thermal breakthrough. A 3D THM model with contacting fractures was established for the new design and its heat extraction performance was evaluated alongside traditional designs. The following key findings were made:

(1) Total water production for the partially-bridging model is less than a fully bridging model because the principle flow path (SRV) has a lower permeability than the connecting fractures. Nevertheless, the partially-bridging design maintained higher production temperatures for longer at equivalent production volumes, owing to its larger heat exchange zone.

(2) Stress evolution trajectories suggest that the partially-bridging model would promote more extensive secondary shear failure during production owing to the comparatively larger volume of water that transits the reservoir matrix. Ideally this would translate to improvements in reservoir permeability, although we caution that thermal channeling⁶⁰ could undermine heat sweep efficiency if fast pathways started to dominate.

(3) Modelling assumptions that neglect the opening of fracture surfaces could result in an overestimate of induced reservoir failure. This occurs because non-opening fractures amplify thermoelastic stresses that are otherwise dissipated by opening mode displacement. The inaccuracy is likely to be particularly pronounced at shallow depths where normal stresses are low.

(4) Comparisons show that thermoelastic stresses play a larger role than poroelastic stresses.

Although our theoretical analysis of the proposed fracturing design is encouraging, much work remains to be done. The parameters we used were largely inspired from literature studies but these nevertheless provide only a handful of representative models in much larger space of possible realizations. A significant point for future studies would be to explore optimization of operational and reservoir parameters such as the inlet temperature, injection pressure, well spacing, fracture spacing, and fracture numbers, to improve performance in specific field applications. Embedding this optimization-style approach alongside a rigorous analysis of economic and environmental factors ought to provide a rational basis for establishing the feasibility of partially-bridging fracture designs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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