

Article

Influence of Injection-Induced Secondary Fault Slip on the Stability of an Adjacent Critically Stressed Fault

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Abstract

Fluid injection in deep reservoirs can induce fault reactivation and seismicity, posing challenges for geothermal and subsurface energy development. This study investigates the mechanical interaction between two adjacent non-intersecting faults under fluid injection using a pseudo-three-dimensional thermo-hydro-mechanical (THM)-coupled numerical model. The results show that injection first triggers slip on F2, which then redistributes stress onto F1. The response of F1 is strongly heterogeneous: some segments are stabilized due to a decrease in Coulomb failure stress, whereas other segments are destabilized due to an increase in Coulomb failure stress. Stress-path analysis indicates that the immediate response of F1 to F2 slip is mainly governed by changes in effective normal stress and shear stress, rather than abrupt pore pressure changes on F1. These findings demonstrate that fault slip can act as a mechanical stress source that either promotes or inhibits adjacent fault reactivation. Therefore, slip-induced stress transfer should be explicitly considered when assessing fault stability in reservoirs containing multiple closely spaced faults.

Keywords: fault reactivation; EGS; THM coupling; adjacent fault stability; stress transfer

1. Introduction

Fluid injection in deep geological formations is widely involved in enhanced geothermal systems, wastewater disposal, CO₂ geological storage, and hydrocarbon recovery. Although these engineering activities are important for energy production and subsurface resource utilization, they may disturb the original hydro-mechanical equilibrium of reservoirs and trigger the reactivation of pre-existing faults. Injection-induced seismicity has received increasing attention because several projects have induced felt or damaging earthquakes. Well-known examples include the Denver earthquakes associated with wastewater disposal, induced seismicity at the Geysers geothermal field, the Basel enhanced geothermal system, and the Mw 5.5 Pohang earthquake in South Korea [1–4]. These cases indicate that safe development of deep reservoirs requires a better understanding of how fluid injection modifies fault stress states and triggers fault slip.

The mechanisms of injection-induced fault reactivation have been widely investigated through laboratory experiments, field observations, analytical models, and numerical simulations [5–9]. A commonly recognized mechanism is pore pressure diffusion. Increasing pore pressure reduces the effective normal stress acting on fault planes, thereby decreasing the frictional resistance to sliding [3,10]. This mechanism is particularly important



Received: 5 June 2026

Revised: 25 June 2026

Accepted: 1 July 2026

Published: 4 July 2026

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when the injection well is hydraulically connected to a critically stressed fault. In addition to direct pore pressure diffusion, poroelastic stress changes may also promote fault slip. Reservoir deformation induced by fluid pressurization can redistribute stresses beyond the pressure diffusion front, potentially affecting faults that are not directly connected to the injection zone [11,12]. Thermal effects represent another important mechanism in geothermal reservoirs, where cold-fluid injection may induce thermal contraction of the rock mass, reduce effective normal stress, and promote delayed fault reactivation [13–16]. These mechanisms demonstrate that fault slip during fluid injection is governed not only by the magnitude of pressure perturbations but also by the coupled evolution of stress, temperature, permeability, and fault mechanical properties.

However, many subsurface reservoirs contain multiple pre-existing faults rather than a single isolated fault. In such systems, reactivation of one fault may modify the stress state of nearby faults through mechanical interactions. Once slip occurs on a fault, the slipped segment can act as a new source of stress perturbation. This slip-induced stress redistribution may increase Coulomb failure stress on some segments of an adjacent fault while decreasing it on others [17,18]. Therefore, the influence of fault slip on adjacent fault stability may be either destabilizing or stabilizing, depending on fault geometry, relative position, slip direction, and the local stress state. This process differs from direct hydraulic triggering because it does not necessarily require pore pressure diffusion to reach the adjacent fault. Instead, it represents a mechanical pathway for cascading fault reactivation.

Stress transfer has long been recognized as an important process in earthquake interactions, aftershock triggering, and fault system evolution [18]. In the context of injection-induced seismicity, recent studies have shown that aseismic or seismic slip can redistribute Coulomb failure stress and influence the timing and location of subsequent seismic events. For example, fluid-induced aseismic slip may propagate faster than pore-fluid migration, suggesting that mechanical stress transfer can outpace hydraulic diffusion [19]. Recent numerical and observational studies further suggest that stress transfer associated with injection-induced aseismic slip can be a viable mechanism for distant earthquake triggering [20]. In areas affected by wastewater injection, Coulomb failure stress transfer has been shown to influence fault reactivation and the spatial distribution of induced seismicity [21]. Nevertheless, compared with pore pressure diffusion and thermal effects, the role of slip-induced stress transfer between adjacent non-intersecting faults remains poorly constrained. In particular, it remains unclear how the first fault slip modifies the stability of different segments of a nearby fault and whether such stress changes promote or inhibit subsequent fault reactivation.

In contrast to previous studies that primarily focus on pore pressure diffusion, poroelastic effects, or long-term aseismic slip processes, the present study emphasizes a less explored mechanism: injection-induced slip on a secondary fault acting as an active mechanical source that redistributes stress to an adjacent fault system. In this framework, the slipped secondary fault is not only a passive responder to fluid injection but also acts as a transient stress source that modifies the stress state of nearby faults. This process results in a spatially heterogeneous response along the adjacent fault, where different segments may experience either stabilization or destabilization depending on local stress orientation and fault geometry.

Therefore, the novelty of this work lies in establishing a source–receiver fault interaction framework under injection conditions, where fault slip itself is treated as the primary driver of stress transfer between adjacent faults, rather than being considered solely as a secondary consequence of pore pressure diffusion or regional seismic interactions.

Based on this motivation, we establish a pseudo-three-dimensional coupled thermo-hydro-mechanical (THM) model containing two adjacent non-intersecting faults. The model

geometry and in situ stress conditions are constructed based on the Pohang Enhanced Geothermal System. Fluid is injected into the secondary fault, and the resulting slip behavior and its influence on the stability of the adjacent fault are analyzed. The main objective of this study is not to reproduce the complete seismic sequence of the Pohang earthquake, but to investigate how injection-induced slip on a secondary fault redistributes stress and modifies the stability of a nearby fault, with particular emphasis on the spatial heterogeneity of induced stress changes along the receiver fault.

2. Modeling Approach

2.1. Numerical Framework

The numerical model was developed to capture the coupled evolution of fluid pressure, temperature, stress, and fault slip during fluid injection. A sequential coupling strategy was adopted, in which flow and heat transfer calculations provide pore pressure and temperature fields, while the mechanical calculation updates stress redistribution, deformation, and fault slip. The updated mechanical state is then used to update fault permeability for the subsequent flow calculation. This type of coupled formulation has been widely used to investigate hydro-mechanical and thermo-hydro-mechanical processes in geothermal reservoirs [22].

The TOUGHREACT–FLAC3D coupled modeling framework has been widely applied and validated in previous studies of coupled thermo-hydro-mechanical (THM) processes in fractured rock systems, including geothermal reservoirs and injection-induced fault reactivation. Taron and Elsworth [22] demonstrated that the sequential coupling approach can capture first-order feedbacks between fluid flow, heat transfer, stress evolution, and mechanical deformation in fractured media. Similarly, Gan and Elsworth [13] applied this framework to investigate fault reactivation and seismic slip in enhanced geothermal systems.

In the present study, the same general coupling strategy is adopted. The objective is not to reproduce exact field-scale seismic sequences, but to capture the mechanical response of a fault system to stress perturbations induced by slip on a secondary fault. Therefore, the model provides a mechanistic representation of stress redistribution processes rather than a fully predictive seismic hazard forecasting model.

The governing equations for fluid flow and heat transport are based on mass and energy conservation formulations implemented in TOUGHREACT, while mechanical behavior is solved using equilibrium equations and constitutive relations in FLAC3D. The coupled thermo-hydro-mechanical (THM) behavior is represented using a sequential coupling strategy between the two codes.

A sequential iterative coupling scheme is adopted, in which TOUGHREACT first solves the fluid pressure and temperature fields, and the resulting pore pressure and temperature are transferred to FLAC3D to update effective stress and mechanical deformation. Changes in porosity and permeability induced by mechanical deformation are then fed back into TOUGHREACT, ensuring two-way coupling between hydraulic and mechanical processes.

Adaptive time-stepping is employed in TOUGHREACT to ensure numerical stability during rapid pressure changes, while mechanical equilibrium in FLAC3D is achieved at each coupling step based on force and displacement convergence criteria. In this study, convergence is considered to be achieved when both the force imbalance and displacement increment fall below predefined thresholds.

2.2. Model Configuration

A pseudo-three-dimensional reservoir model is constructed with two adjacent, non-intersecting faults. The fault arrangement is idealized based on geological and seismological interpretations of the Pohang Enhanced Geothermal System, where a major fault and a smaller secondary fault have been identified near the injection wells [23–25]. The model has a limited thickness in the fault-strike direction to reduce computational cost while preserving the main deformation and stress redistribution characteristics in the dip section.

Fault 1 (F1) represents the larger fault, which is assumed to be closer to a critically stressed state. Fault 2 (F2) represents the smaller fault that is directly affected by fluid injection. F2 is located close to F1 but does not intersect it (Figure 1). This geometry allows the effect of fault interaction to be examined without assuming direct hydraulic communication between the injection-affected fault and the adjacent fault. The computational mesh is refined in the vicinity of the faults and injection zone to better resolve stress gradients and slip localization. Coarser grids are used in regions far from the faults to improve computational efficiency while maintaining accuracy in the region of interest (Figure 1).

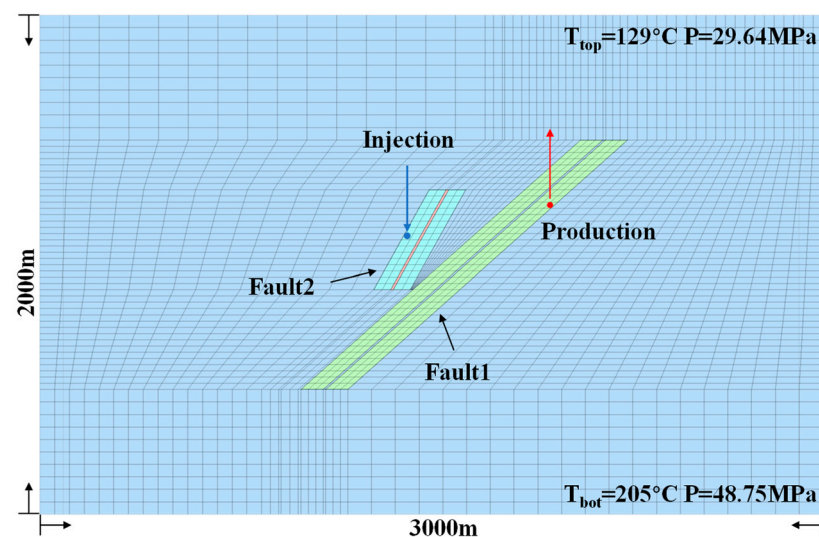


Figure 1. Schematic of the reservoir domain with the locations of injection and Faults.

Both faults are represented by a low-permeability fault core and relatively high-permeability damage zones. The fault core tends to restrict cross-fault flow, whereas the damage zones provide preferential pathways for pressure propagation along the faults. Fluid is injected into the damage zone of F2 to promote fault reactivation. The mechanical response of F1 is then monitored to assess whether slip on F2 stabilizes or destabilizes different segments of the adjacent fault.

The model is initialized under a reverse faulting stress regime. The magnitudes of the maximum horizontal stress, minimum horizontal stress, and vertical stress increase with depth and are assigned according to the reported in situ stress characteristics of the Pohang geothermal site [25]. The stress state follows a typical reverse faulting condition, with σ_{Hmax} (243 MPa) $>$ σ_v (120 MPa) $>$ σ_{Hmin} (106 MPa), consistent with previous geomechanical characterizations of the region. Initial pore pressure follows a hydrostatic gradient, resulting in a bottom boundary pore pressure of 48.75 MPa. The initial temperature field follows a regional geothermal gradient of 38 °C/km, corresponding to a bottom temperature of 205 °C. No-flow and no-heat-transfer conditions are assigned to the external boundaries. The lower boundary is fixed in the vertical direction, while lateral displacement in the y-direction is constrained to represent far-field in situ stress conditions. The remaining displacement degrees of freedom are left unconstrained to allow mechanical deformation.

The key parameters used in the simulation are listed in Table 1. A bilinear strain-softening ubiquitous-joint model is used to represent the elasto-plastic behavior of the faults. A linear strain-softening relationship is adopted, in which the friction angle decreases with increasing plastic shear strain. The joint friction angle of F1 is set to 32° , while that of F2 is set to 20° . Cold water is injected into the middle of the F2 damage zone at a depth of 3887.5 m at a constant rate of 5 kg/s. The production well is located in the F1 damage zone at a depth of 3762.5 m.

Table 1. Key parameters used in the simulation approach.

Parameters	Fault Core	Fault Damage	Host Rock
Joint friction angle ($^\circ$)	32(F1) 20(F2)	32(F1) 20(F2)	- -
Matrix friction angle ($^\circ$)	45	45	45
Joint cohesion (MPa)	0	0	-
Matrix cohesion (MPa)	-	-	5
Joint tensile strength (MPa)	0.04	0.04	-
Tensile Strength (MPa)	9.2	9.2	20
Fracture permeability (m^2)	1×10^{-15}	3×10^{-13}	-
Matrix permeability (m^2)	2×10^{-16}	2×10^{-14}	2×10^{-16}
Fracture porosity	0.3	0.3	0.3
Matrix porosity	0.01	0.3	0.1
Dilation angle ($^\circ$)	5.3	5.3	5.3
Bulk modulus (GPa)	7.9	7.9	19.25
Shear modulus (GPa)	3.2	3.2	13.84
Poisson's ratio	0.21	0.21	0.21
Rock density (kg/m^3)	2630	2630	2630
Specific heat (kJ/kgK)	0.799	0.799	0.799
Thermal conductivity (W/mK)	3.02	3.02	3.02
Thermal expansion coefficient ($1/^\circ\text{C}$)	1.2×10^{-5}	1.2×10^{-5}	1.2×10^{-5}

2.3. Coulomb Stress Formulation and Sign Convention

The fault stability in this study is evaluated using the Coulomb failure stress (CFS) change and Coulomb stress ratio (CSR), which are widely adopted indicators for assessing fault reactivation potential in geomechanical systems.

The Coulomb failure stress change is defined as:

$$\Delta CFS = \Delta\tau + \mu(\Delta\sigma_n - \Delta p) \quad (1)$$

where $\Delta\tau$ is the shear stress change on the fault plane, $\Delta\sigma_n$ is the normal stress change, Δp is the pore pressure change, and μ is the friction coefficient. In this study, a compression-positive sign convention is adopted, meaning that positive $\Delta\sigma_n$ corresponds to an increase in compressive normal stress acting on the fault.

Under this convention, an increase in Coulomb failure stress ($\Delta CFS > 0$) indicates that the fault is brought closer to failure, i.e., a reduction in fault stability, whereas a decrease in ΔCFS indicates a stabilizing effect.

The Coulomb stress ratio (CSR) is defined as:

$$CSR = \frac{\tau}{\mu(\sigma_n - p)} \quad (2)$$

where τ is the shear stress acting on the fault plane, σ_n is the normal stress, and p is the pore pressure. CSR represents the ratio between the driving shear stress and the frictional resistance of the fault.

An increase in CSR indicates that the fault is progressively approaching failure conditions, whereas a decrease in CSR corresponds to enhanced fault stability.

3. Results

3.1. Injection-Induced Slip Sequence of the Two Faults

Fluid injection into F2 first alters the hydraulic and mechanical state of the injected fault and subsequently affects the adjacent fault F1. Figure 2 shows the evolution of pore pressure, permeability, and temperature at the injection and production locations, together with the spatial distributions of pore pressure and temperature at representative times. Pore pressure increased continuously around the injection point before the slip event, whereas temperature decreases were mainly restricted to the region surrounding the injected fault. The pressure perturbation propagated preferentially along the high-permeability damage zone of F2 and subsequently reached the vicinity of F1. Two abrupt pressure drops were observed at the injection location. The first occurred at 649,450 s and coincided with the initial slip of F2. At this moment, shear dilation on F2 increased local permeability, leading to a sudden pressure release at the injection point. The second pressure drop occurred at 6,641,500 s, corresponding to the slip of F1. These pressure drops indicate that fault slip not only responds to pore pressure and stress changes but also feeds back on the hydraulic system through permeability enhancement. In the present study, the first slip of F2 is of particular interest because it acts as a mechanical perturbation source for the adjacent fault F1. Although temperature decreases gradually around the injection zone, no abrupt thermal change occurs at the time of fault slip, indicating that thermal effects do not control the instantaneous triggering of fault reactivation.

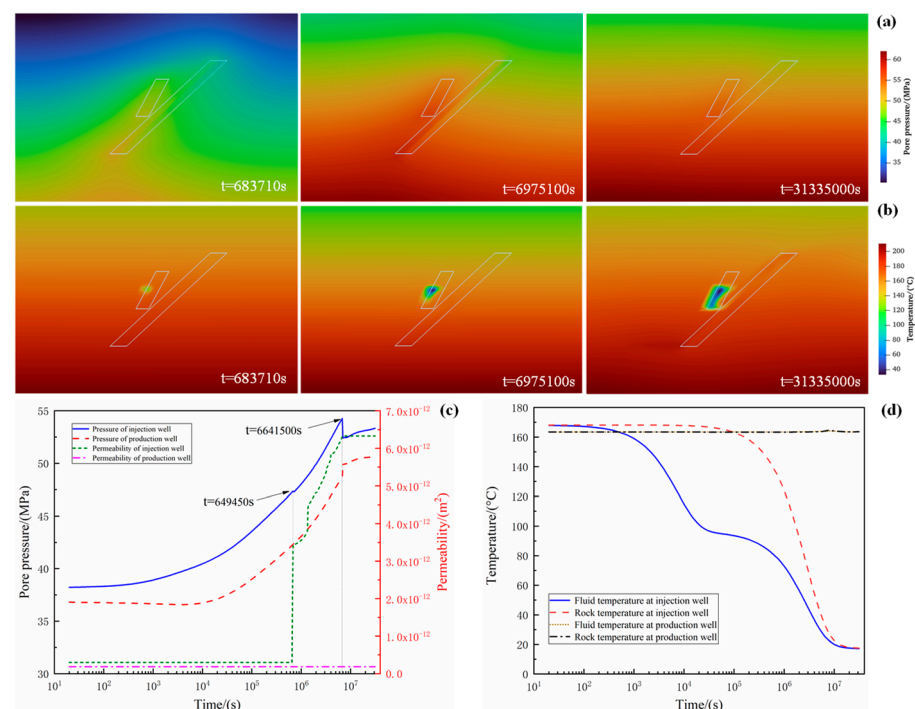


Figure 2. Hydraulic and thermal evolution during injection into F2. (a) Pore pressure and (b) temperature distribution in a geothermal reservoir with two faults at different times; (c) pore pressure, permeability, and (d) temperature evolution with time at injection and production wells.

The evolution of the Coulomb stress ratio on F2 further confirms that the injected fault was the first to approach failure. The evolution of the Coulomb stress ratio at different locations on F2 is shown in Figure 3, with the positions of A1–A6 indicated in Figure 4.

With cold water injection, the Coulomb stress ratio at A1–A6 shows an overall increasing trend, although the rate of increase varies among different locations. The rate of increase is higher closer to the injection well. Fluid injection increases pore pressure, which reduces effective normal stress and consequently increases the Coulomb stress ratio. The rapid pore pressure increase near the injection well leads to the highest rate of Coulomb stress ratio increase in this region. The Coulomb stress ratio at the injection point increases faster than at other locations on F2. This indicates that the combined effect of pore pressure increase and stress changes near the injection point is sufficient to reduce the stability of F2. When the Coulomb stress ratio at the injection location drops sharply at 649,450 s, fault slip is initiated. The Coulomb stress ratio at other locations on F2 also decreases to varying degrees after this event, indicating that fault slip induces a localized stress release along the injected fault.

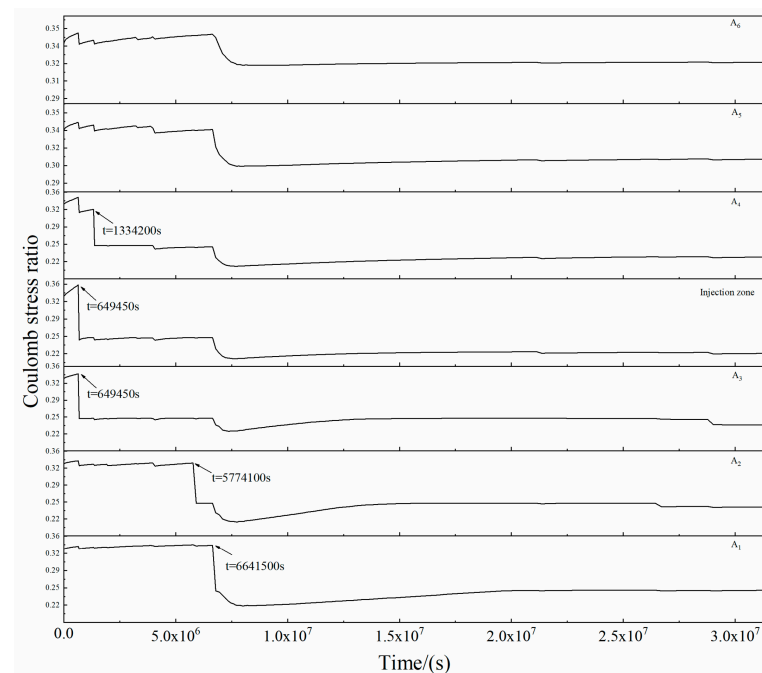


Figure 3. Evolution of Coulomb stress ratio along the injected F2.

Although slip on F1 was also observed at a later stage, the following analysis focuses on the stress perturbation transferred from the initial slip of F2 to F1. This approach allows the mechanical effect of F2 slip to be distinguished from the longer-term effects of continuous pressure diffusion and thermal evolution.

3.2. Immediate Response of F1 to F2 Slip

Slip on F2 produces an immediate but spatially heterogeneous response on F1. Figure 5 shows the temporal evolution of the Coulomb stress ratio at different monitoring points along F1. At the moment of F2 slip, the Coulomb stress ratio at several locations on F1 changes abruptly, whereas other locations show only weak responses. This indicates that F2 slip does not uniformly destabilize or stabilize the adjacent fault, but instead depends strongly on the relative position between the slipped portion of F2 and points on F1. As illustrated in Figure 5, at 649,450 s, the Coulomb stress ratio at points B1, B6, and B7 shows no significant change, whereas it increases abruptly at B2–B5 (see curves highlighted in the red circle in Figure 5). The variation in the Coulomb stress ratio at each point on F1 at 649,450 s (Figure 5) is extracted and plotted in Figure 4. At B1, B2, and B3, the Coulomb stress ratio decreases by 0.00088, 0.00138, and 0.0077, respectively, indicating a stabilizing response. In contrast, at B4, B5, B6, and B7, the Coulomb stress ratio increases by 0.0082,

0.0053, 0.0018, and 0.0013, respectively, indicating a destabilizing response. Therefore, the same slip event on F2 induces both stabilizing and destabilizing effects on F1.

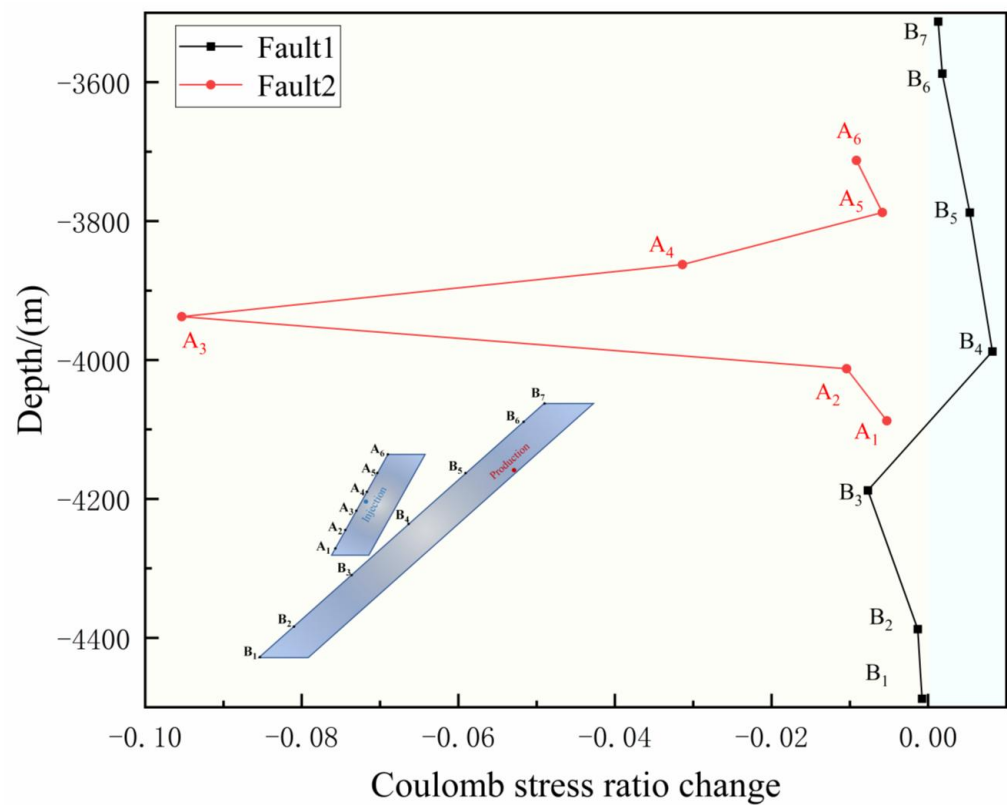


Figure 4. Spatial variation in Coulomb stress ratio on F1 induced by the first slip of F2 (the line marks the zero contour of the Coulomb stress ratio change, and the yellow background indicates negative values).

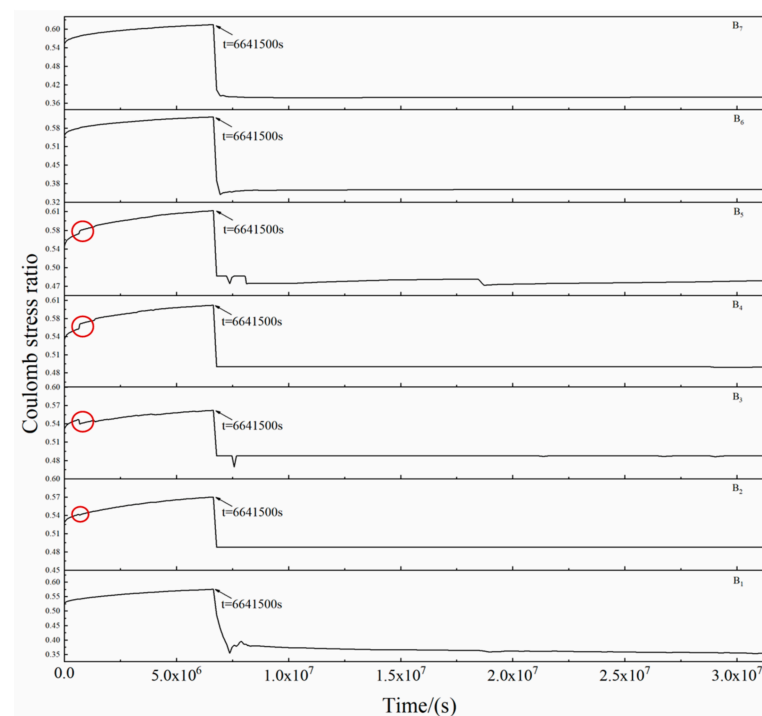


Figure 5. Immediate Coulomb stress ratio response of F1 to F2 slip.

This spatially heterogeneous response represents the central result of this study. It suggests that the adjacent fault should not be treated as a single receiver with a uniform stability change. Instead, the transferred stress perturbation may push some segments closer to failure while simultaneously stabilizing other segments. Such a pattern is important for evaluating cascading fault reactivation in reservoirs containing multiple closely spaced faults.

3.3. Stress Redistribution Induced by F2 Slip

To understand the spatial response of F1, the stress field evolution before and after fault slip is examined. Figure 6 presents the stress distributions at representative stages surrounding the slip events, including pre- and post-slip conditions for both F2 and F1. At $t = 649,450$ s (prior to F2 slip), the horizontal and vertical stresses generally increase with depth, while slightly elevated stresses are observed along F1 and F2 compared with surrounding rock at the same depth. This reflects the combined effects of poroelastic compression induced by fluid injection and thermal contraction associated with cold-water injection. At the early stage of injection, the cooling effect remains limited, and thus its contribution to stress variation is relatively small. The interaction between poroelastic and thermal effects leads to a slight increase in both horizontal and vertical stresses near the fault zones. In addition, stress heterogeneity induces shear stress development, with negative values surrounding the fault zones and positive values in the northwest and southeast regions of the model. After slip of F2 ($t = 683,710$ s), the stress field undergoes significant redistribution in both the fault zone and surrounding rock. In the vicinity of the injection well, horizontal stress decreases while vertical stress increases. Shear stress becomes more localized, showing negative values near the injection zone and positive values on both sides of F2, with increased magnitude compared to the pre-slip state. This change is primarily attributed to shear dilation on F2, which enhances permeability and strengthens the cooling effect. The intensified cooling promotes additional thermal contraction of the surrounding rock, leading to further reduction in horizontal stress. With continued injection after F2 slip, the spatial extent of reduced horizontal stress, increased vertical stress, and elevated shear stress gradually expands, indicating progressive stress redistribution in the reservoir. After slip of F1, the overall stress state of the system is further modified, with decreases in horizontal and shear stresses and an increase in vertical stress in the vicinity of F2, reflecting strong fault–fault mechanical interaction.

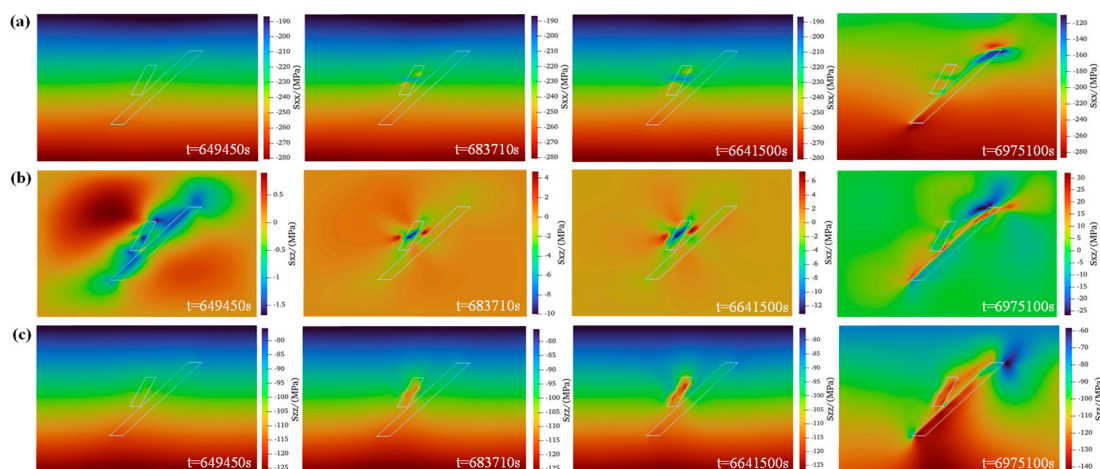


Figure 6. Stress redistribution before and after the first slip of F2 and the subsequent slip of F1. (a) horizontal stress (S_{xx}), (b) shear stress (S_{xz}), and (c) vertical stress (S_{zz}).

Before the first slip of F2, the stress disturbance was mainly concentrated near the injected fault. After F2 slips, the surrounding stress field changes abruptly, indicating that the slipped fault segment acts as a mechanical source of stress redistribution. The stress perturbation generated by F2 slip propagates toward the adjacent fault and modifies the stress state of F1. The response of F1 is not simply controlled by the distance to the injection point but is governed by the combined effects of fault geometry, slip direction, and stress orientation. Some segments of F1 experience increased normal compression or reduced shear loading, whereas other segments experience reduced normal compression or increased shear loading. This results in a spatially heterogeneous distribution of the Coulomb stress ratio along F1. The subsequent slip of F1 also influences the stress state of F2, as indicated by later stress ratio changes on F2. This mutual interaction suggests that once one fault is reactivated, the stress state of nearby faults can be modified even without direct hydraulic communication. Therefore, fault interaction provides a mechanical pathway for the development of cascading fault instability.

3.4. Stress-Path Evidence from Effective Normal Stress, Shear Stress, and CFS Evolution

The stress changes and pore pressure evolution resulting from cold water injection alter the effective normal stress and shear stress acting on F1 and F2, thereby influencing fault stability. Figure 7 shows the evolution of changes in effective normal stress, shear stress, and Coulomb failure stress at the injection location on F2 and at point B6 on F1. Before slip on F2, the effective normal stress at the injection location decreases gradually due to increasing pore pressure. This results in a destabilizing stress path on F2. Shear stress changes only slightly before slip, indicating that failure of F2 is mainly controlled by the reduction in effective normal stress.

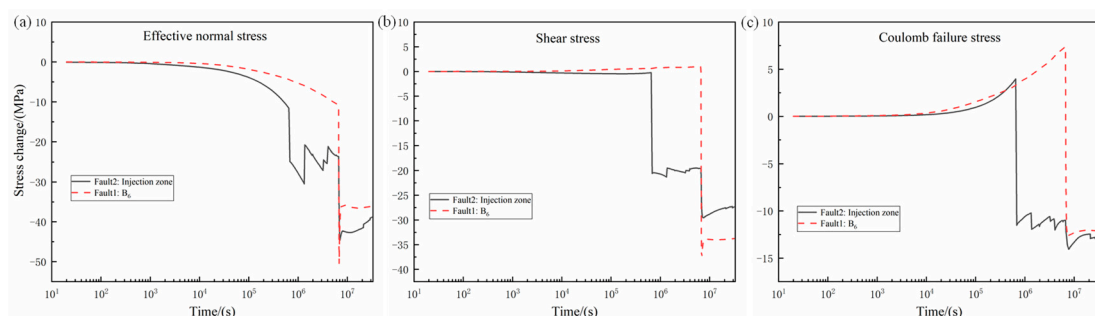


Figure 7. Evolution of the (a) effective normal stress change, (b) shear stress change, and (c) Coulomb failure stress change at the injection location of F2 and B₆ of F1.

At the moment of F2 slip, both effective normal stress and shear stress at the injection location change abruptly, resulting in a sudden decrease in Coulomb failure stress. This reflects stress release on the slipped fault segment. At B₆ on F1, the response to F2 slip is much weaker than that at the injection location, but it still reflects the transferred stress perturbation. The later slip of F1 produces a stronger stress perturbation that feeds back to F2, suggesting that the two faults interact mechanically through stress redistribution.

The comparison between F2 and F1 stress paths shows that the injected fault and the adjacent fault experienced different mechanical roles. F2 was the source fault that first released stress through slip, whereas F1 was the receiver fault whose stability was modified by the transferred stress perturbation. This source–receiver interpretation provides a mechanistic framework for understanding fault interaction during fluid injection.

3.5. Mechanism of Stabilizing and Destabilizing Responses on F1

The opposite responses at different locations on F1 can be further explained by examining the detailed stress components at representative points. Figure 8 shows the evolution

of S_{xx} , S_{zz} , S_{xz} , pore pressure, effective normal stress, and shear stress at B3 and B4 on F1. These two points represent different responses to F2 slip: B3 shows a decrease in the Coulomb stress ratio, whereas B4 shows an increase.

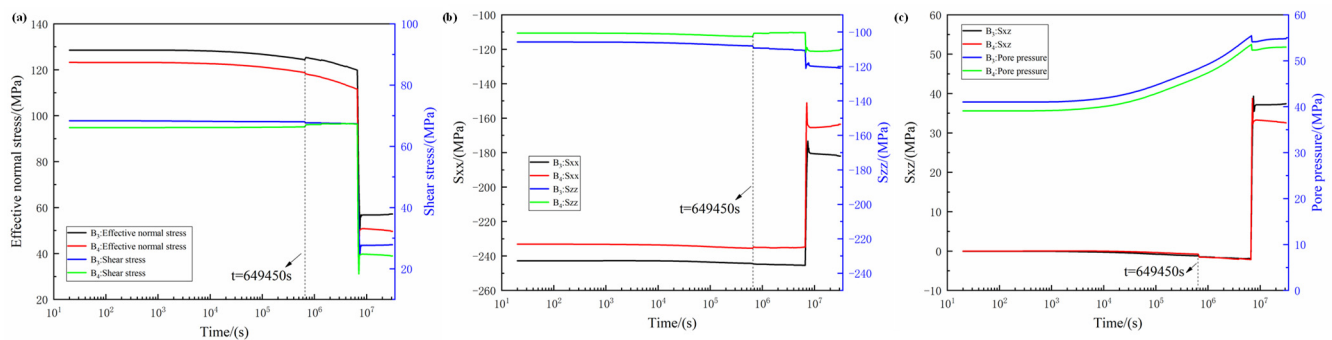


Figure 8. Evolution of the (a) effective normal stress and shear stress, (b) horizontal stress and vertical stress, and (c) S_{xz} and pore pressure at the B₃ and B₄ locations on F1.

At 649,450 s, the horizontal stress (S_{xx}) at B3 increases by 0.301 MPa, the vertical stress (S_{zz}) increases by 1.22 MPa, and the shear stress (S_{xz}) increases by 0.279 MPa. At B4, the horizontal stress decreases by 0.638 MPa, the vertical stress decreases by 1.797 MPa, and the shear stress increases by 0.763 MPa. At B3, slip on F2 leads to an increase in effective normal stress and a decrease in shear stress on the F1 plane. These changes drive the fault segment away from failure, resulting in a decrease in the Coulomb stress ratio. In contrast, at B4, slip on F2 leads to a decrease in effective normal stress and an increase in shear stress. These two changes jointly promote fault instability, resulting in an increase in the Coulomb stress ratio. Pore pressure at F1 does not show an abrupt change at the moment of F2 slip, indicating that the instantaneous response of F1 is mainly controlled by mechanical stress redistribution rather than direct hydraulic diffusion.

This contrast between B3 and B4 demonstrates that the sign of slip-induced stability change is controlled by relative changes in normal and shear stress. A segment is stabilized when the slip-induced stress perturbation increases effective normal stress or reduces shear stress. Conversely, a segment is destabilized when the stress perturbation reduces effective normal stress or increases shear stress. Therefore, the spatial heterogeneity of F1 response arises from different local stress paths induced by the same slip event on F2.

Figure 9 shows the spatial distribution of effective normal stress, shear stress, and Coulomb failure stress on F2 (Figure 9a) and F1 (Figure 9b) at different stages. Under the initial stress state, both effective normal stress and shear stress increase with depth, whereas the Coulomb failure stress decreases with depth, indicating that the upper portions of the faults are more prone to failure. With the injection of cold water, at 649,450 s (prior to F2 slip), the effective normal stress on F2 decreases overall, with a more pronounced reduction near the injection well. Shear stress increases slightly near the injection zone and decreases in other regions. Consequently, Coulomb failure stress increases, particularly near the injection well, indicating a progressive reduction in fault stability. The slip of F2 induces significant stress redistribution along both faults. After F2 slip, effective normal stress decreases above the injection well, whereas an increase is observed below it. Shear stress decreases overall, with the largest reduction occurring in the injection region. In areas where effective normal stress increases, the reduction in shear stress is less pronounced, indicating a coupled stress adjustment following fault slip. On F1, effective normal stress decreases along the entire fault plane, maintaining a similar spatial pattern until reactivation occurs at 6,641,500 s. Prior to F1 slip, shear stress exhibits a clear spatial contrast: above −4100 m, it increases gradually, whereas below −4100 m it decreases gradually. The reduction in effective normal stress leads to an overall increase in Coulomb failure stress, thereby

progressively reducing the stability of F1 over time. After the slip of F1, both effective normal stress and shear stress along F1 decrease significantly, indicating a system-wide stress release. Overall, these results highlight the spatially heterogeneous nature of slip-induced fault interaction, which cannot be explained by pore pressure diffusion alone, but results from coupled mechanical stress redistribution within the fault system.

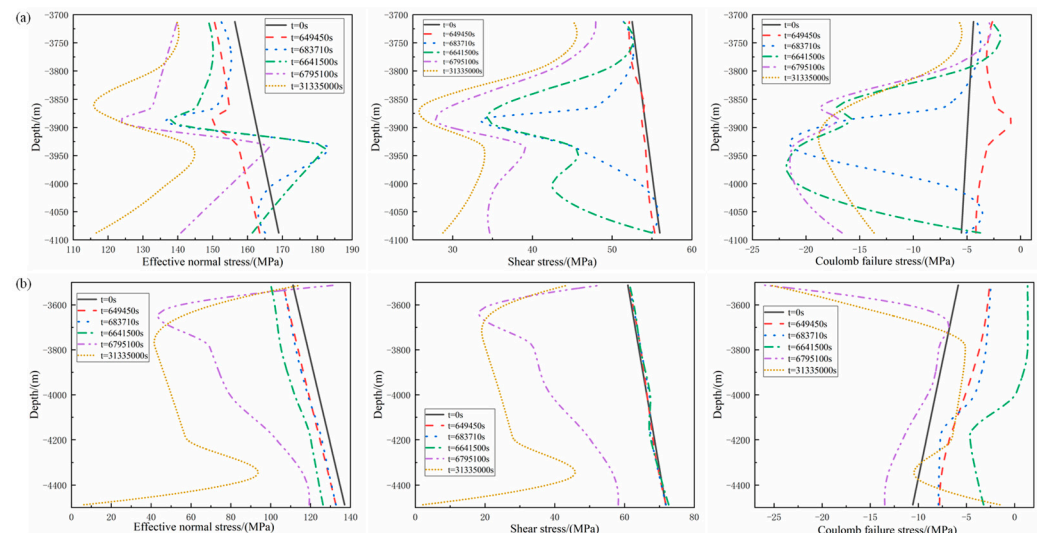


Figure 9. Evolution of effective normal stress, shear stress, and Coulomb failure stress over time along F2 (a) and F1 (b).

4. Discussion

A key distinction between the present study and previous works lies in the treatment of stress sources. Most existing studies focus on either pore pressure-driven fault activation or static Coulomb stress transfer induced by regional tectonic or seismic events. In contrast, this study considers slip on a secondary fault as an active stress source, which dynamically redistributes stress to an adjacent fault system. This leads to a spatially heterogeneous stress response that cannot be fully captured by conventional single-fault models or purely static stress transfer approaches. The comparison between this study and previous representative works is summarized in Table 2.

Table 2. Comparison between this study and previous representative studies.

Study	Stress Source	Fault System	Coupling Method	Main Focus
Stein [18]	Earthquake coseismic slip	Multi-fault systems	Elastic Coulomb stress transfer	Earthquake triggering by static stress changes
Harris [26]	Earthquake slip	Fault networks	Elastic dislocation modeling	Aftershock distribution and stress triggering
Segall & Lu [11]	Fluid injection	Single fault	Hydro-mechanical/poroelastic	Injection-induced seismicity
Guglielmi, Y. et al. [27]	Fluid-induced aseismic slip	Single fault	Rate-dependent friction	Stress transfer from slow slip
This study	Slip on secondary fault (dynamic stress source)	Dual faults (F2 and F1)	Sequential THM+slip-induced stress transfer	Heterogeneous stabilizing/destabilizing responses along receiver fault

To further interpret the physical implications of this distinction, it is necessary to examine how slip on the secondary fault modifies the stress field within the surrounding medium and how the resulting perturbations are transferred to the adjacent fault system. Unlike previous studies that primarily focus on either static stress transfer or pore pressure

diffusion, the present work emphasizes a dynamic stress source associated with fault slip. Therefore, the following section analyzes the mechanical origin of the spatially heterogeneous stress response observed along the receiver fault (F1), based on the distributions of effective normal stress, shear stress, and Coulomb failure stress.

4.1. Mechanical Origin of Spatially Heterogeneous Stress Transfer

The results show that injection-induced slip on F2 does not produce a uniform stability change on the adjacent fault F1. Instead, the transferred stress perturbation produces a segmented response, where some portions of F1 are stabilized while others are destabilized. The upper portion of F1 is more susceptible to destabilization because it is closer to the slipped segment of F2 and experiences a stress perturbation that reduces effective normal stress and increases shear loading. In contrast, lower portions of F1 experience increased normal compression or reduced shear loading, resulting in a stabilizing response. Thus, the impact of F2 on adjacent fault stability is governed not only by the distance between faults but also by the spatial relationship between the source slip patch and receiver fault segments.

The slip of the secondary fault (F2) acts as a localized stress source that redistributes the stress field within the surrounding medium. The adjacent fault (F1) behaves as a spatially extended receiver, where stress perturbations are resolved into fault-normal and fault-shear components depending on local orientation. Because different segments of F1 have different geometrical orientations relative to the stress perturbation field, the resolved stress changes are not uniform. This leads to a spatially heterogeneous response, where some segments experience strengthening due to increased effective normal stress or reduced shear stress, while others are weakened due to the opposite stress changes. This heterogeneous pattern reflects the tensor nature of stress transfer, rather than a uniform pressure-driven response.

4.2. Difference Between Pore Pressure Diffusion and Slip-Induced Stress Transfer

Pore pressure diffusion and slip-induced stress transfer represent two distinct fault-triggering mechanisms. Pore pressure diffusion reduces fault strength by lowering effective normal stress and requires hydraulic connectivity or sufficient pressure propagation to the fault. Slip-induced stress transfer, however, can modify the stress state of an adjacent fault immediately after slip occurs on a nearby fault. This mechanical effect can occur even when pore pressure on the adjacent fault does not change abruptly. In addition, the comparison between thermal evolution and stress evolution suggests that thermal effects mainly govern the long-term evolution of reservoir conditions, whereas fault slip initiation and stress transfer are dominated by hydraulic pressure buildup and mechanical stress redistribution.

The comparison between B3 and B4 further supports this interpretation. At the moment of F2 slip, pore pressure at F1 does not show a sudden change, whereas effective normal stress and shear stress change abruptly. This indicates that the immediate response of F1 is dominated by mechanical stress transfer rather than direct pore pressure diffusion. Continuous injection and subsequent pressure migration may still contribute to the eventual reactivation of F1. However, the first slip of F2 modifies the stress state of F1 in advance, making certain segments more favorable for subsequent failure.

4.3. Implications for Injection-Induced Cascading Fault Reactivation

The results have important implications for fault stability assessment in reservoirs containing multiple closely spaced faults. Conventional assessments typically focus on whether pore pressure reaches a critically stressed fault. However, the present results indicate that slip on a nearby fault may modify the stability of an adjacent fault before

direct hydraulic effects become dominant. Therefore, faults that are not initially connected to the injection pathway may still be affected through mechanical stress transfer.

This mechanism is particularly important in faulted geothermal reservoirs, where injection may first activate a smaller or more permeable fault and subsequently influence a nearby fault. If the transferred stress perturbation increases Coulomb stress on the nearby fault, the likelihood of slip increases. Conversely, if the transferred stress perturbation reduces Coulomb stress, it may temporarily stabilize portions of the adjacent fault. Therefore, both stabilizing and destabilizing effects should be considered when evaluating injection strategies.

The Coulomb failure stress change (ΔCFS) provides a first-order indicator of fault stability evolution and is commonly used to evaluate the potential for earthquake nucleation. Positive ΔCFS values indicate that a fault segment is brought closer to failure, whereas negative values suggest a stabilizing effect.

In this study, the slip of the secondary fault (F2) produces a spatially heterogeneous ΔCFS distribution along the adjacent fault (F1). This indicates that injection-induced fault slip may not uniformly increase or decrease seismic hazard, but instead redistributes nucleation potential along the fault plane. As a result, some segments of F1 may become more prone to failure, while others are temporarily stabilized.

This heterogeneous response highlights that induced seismicity in faulted reservoirs should be interpreted in a spatially distributed framework, where rupture initiation is controlled not only by overall stress level but also by localized stress perturbations caused by nearby fault slip.

4.4. Limitations

Although the adopted TOUGHREACT–FLAC3D coupled framework is widely used and capable of capturing first-order thermo-hydro-mechanical responses in fractured reservoirs, several limitations should be acknowledged when interpreting the results.

First, the fault geometry in this study is simplified as two idealized non-intersecting planar faults. Natural fault systems are typically characterized by complex three-dimensional geometries, including segmentation, roughness, and branching structures, which may influence local stress concentration and stress transfer patterns. In addition, the present study considers only a single representative fault configuration. Variations in fault dip angle, fault spacing, relative orientation, frictional properties, and regional stress regime may affect the magnitude and spatial distribution of stress transfer. Therefore, the results should be interpreted as a mechanistic case study rather than a universal predictive model for all geological settings.

Second, the mechanical behavior of faults is represented using a classical Mohr–Coulomb constitutive law with constant frictional parameters. In reality, fault friction may evolve with slip rate, slip history, and fluid–rock interactions, which are not explicitly considered in the present model. This simplification may affect the detailed slip evolution and stress drop magnitude, although the overall stress redistribution pattern remains governed by the imposed fault geometry and stress field.

Third, a sequential coupling strategy is adopted between TOUGHREACT and FLAC3D. Although this approach has been widely validated in previous studies, it does not fully resolve strongly coupled nonlinear interactions within a single time step, and therefore may smooth certain short-term feedback effects during rapid slip events.

Finally, the model is intended to provide a mechanistic interpretation of slip-induced stress transfer rather than a deterministic prediction of seismic events. Therefore, the results should be interpreted in terms of relative stress redistribution patterns and fault interaction mechanisms, rather than absolute seismic hazard forecasting.

In addition to the above limitations, parameter uncertainty should also be considered. It should be acknowledged that the magnitude of stress transfer and fault slip evolution is sensitive to uncertainties in key input parameters, including fault friction coefficient, in situ stress magnitude, permeability structure, and hydraulic conditions. Variations in these parameters may influence the absolute values of Coulomb stress change and the timing of fault reactivation.

However, the primary objective of this study is to identify the first-order mechanical mechanism of stress redistribution induced by secondary fault slip. This mechanism is mainly controlled by fault geometry and relative stress orientation. Therefore, although the quantitative results may vary under different parameter realizations, the spatially heterogeneous pattern of stabilizing and destabilizing responses along the receiver fault is generally governed by stress redistribution physics and is expected to remain qualitatively consistent within a reasonable range of geological conditions.

5. Conclusions

This study investigates the mechanical impact of fault slip on the stability of an adjacent fault in a faulted geothermal reservoir under fluid injection. Using a pseudo-three-dimensional coupled numerical model, the temporal evolution of pore pressure, effective normal stress, shear stress, and Coulomb failure stress is analyzed along both the injected fault (F2) and the adjacent fault (F1).

The main conclusions are summarized as follows:

- (1) The injected fault (F2) reaches failure first due to local increases in pore pressure and stress perturbations. Slip on F2 acts as a mechanical source that redistributes stress along the adjacent fault (F1), demonstrating that F2 can initiate cascading fault responses.
- (2) Slip on F2 produces a spatially heterogeneous response along F1. Some segments experience an increase in Coulomb failure stress (destabilization), whereas others experience a decrease (stabilization). This highlights that adjacent faults cannot be treated as mechanically uniform receivers, as the response depends on fault geometry, relative position, and local stress orientation.
- (3) Comparison of pore pressure and stress evolution reveals that the immediate response of F1 to F2 slip is dominated by mechanical stress transfer rather than direct hydraulic communication. The Coulomb failure stress analysis further indicates that the heterogeneous response on F1 is primarily controlled by variations in effective normal stress and shear stress induced by slip on F2.
- (4) The study highlights the importance of considering adjacent fault slip when evaluating fault stability in injection projects. Even faults not directly connected to injection wells may be affected mechanically through slip-induced stress transfer, potentially advancing or delaying subsequent fault reactivation. This insight is particularly relevant for geothermal operations, CO₂ storage, and wastewater disposal in faulted reservoirs.

Overall, the results demonstrate that fault slip plays a critical role in the mechanical interaction between adjacent faults. Incorporating slip-induced stress transfer into fault stability assessments provides a more comprehensive understanding of cascading fault activation and may help improve risk evaluation and operational strategies in deep subsurface injection projects.

Author Contributions: Conceptualization, Y.M.; Methodology, W.S. and Y.M.; Software, Y.M.; Formal analysis, W.T.; Investigation, W.S., W.T. and H.Z.; Data curation, H.Z. and J.L.; Writing—original draft, W.S.; Writing—review & editing, W.T., H.Z., J.L., Q.Z. and Y.M.; Funding acquisition, W.S. and Y.M. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Science and Technology Research Program of Chongqing Municipal Education Commission (Grant No. KJQN202303221), Natural Science Foundation of Chongqing China (Grant No. CSTB2024NSCQ-MSX0433), Doctoral Fund Project of Chongqing Industry Polytechnic College (Grant No. 2023GZYBSZKE08), and the Science and Technology Research Program of Chongqing Municipal Education Commission (Grant No. KJQN202303249).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author upon reasonable request.

Conflicts of Interest: Author Jinfeng Li was employed by the company China Construction Eighth Engineering Division Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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