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Geothermo-mechanical alterations due to heat energy extraction in enhanced geothermal systems: Overview and prospective directions

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Abstract

Geothermal energy from deep underground (or geological) formations, with or without its combination with carbon capture and storage (CCS), can be a key technology to mitigate anthropogenic greenhouse gas emissions and meet the 2050 net-zero carbon emission target. Geothermal resources in low-permeability and medium- and high-temperature reservoirs in sedimentary sequence require hydraulic stimulation for enhanced geothermal systems (EGS). However, fluid migration for geothermal energy in EGS or with potential CO_2 storage in a CO_2-EGS are both dependent on the in situ flow pathway network created by induced fluid injection. These thermo-mechanical interactions can be complex and induce varying alterations in the mechanical response when the working fluid is water (in EGS) or supercritical CO_2 (in CO_2-EGS), which could impact the geothermal energy recovery from geological formations. Therefore, there is a need for a deeper understanding of the heat extraction process in EGS and CO_2-EGS. This study presents a systematic review of the effects of changes in mechanical properties and behavior of deep underground rocks on the induced flow pathway and heat recovery in EGS reservoirs with or without CO_2 storage in CO_2-EGS. Further, we proposed waterless-stimulated EGS as an alternative approach to improve heat energy extraction in EGS. Lastly, based on the results of our literature review and proposed ideas, we recommend promising areas of investigation that may provide more insights into understanding geothermo-mechanics to further stimulate new research studies and accelerate the development of geothermal energy as a viable clean energy technology.

KEYWORDS

CO_2-EGS, enhanced geothermal systems, geomechanics, geothermal energy, underground thermal energy

Highlights

- Studies on the impact of geomechanical properties on heat extraction in enhanced geothermal systems (EGS) are reviewed.
- The most critical influence is summarized and highlighted using two working fluids: water and CO_2.
- Efficient geothermal energy extraction in EGS/CO_2-EGS is affected by a complex hydraulically induced fracture network.
- Thermo-mechanical interactions are complex and induce varying alterations of mechanical response in EGS.
- Waterless-stimulated EGS is proposed as an alternative approach to improve heat energy extraction in EGS.

1 | BACKGROUND

Climate change is taking place, and its effects are widely observed in the form of heat waves, drought, changes in rainfall, floods, melting of the glaciers, hurricanes and tornadoes, wildfires, endangered ecosystems, and other catastrophes (IPCC, 2021). A substantial reduction in global greenhouse gas (carbon dioxide, methane, nitrous oxide, etc.) emissions to curtail the global temperature increase below 1.5°C is required to comply with the Paris 2015 Agreement (IPCC, 2005; Kolawole et al., 2022). The continued emission of anthropogenic carbon dioxide (CO_2) and other greenhouse gases will cause further global warming and a long-lasting impact on global climate systems. Therefore, a substantial and sustained reduction in greenhouse gas emissions is vital to mitigate the effects of climate change (IPCC, 2005, 2021). It is also imperative to adopt and develop new sustainable energy and low-carbon solutions to mitigate the impact of climate change.

Among several sustainable energy alternatives, geothermal energy has been widely recognized due to its low carbon footprint (Asai et al., 2022; Homand-Etienne et al., 1989; Kolawole & Ispas, 2019; Kolawole, 2021; Kolawole, Ispas, Kolawole, et al., 2021; Ngoma et al., 2023; Olasolo et al., 2016; Zhang et al., 2021). However, some high-temperature geothermal resources have low permeability, making the extraction of thermal energy difficult. Therefore, hydraulic fracturing is used to stimulate low-permeable georesources, induce fractures, and extract fluid from these reservoirs (Kolawole, Ispas, Kolawole, et al., 2021; Kolawole, Ispas, Kumar, et al., 2021; Kolawole et al., 2019; Moska et al., 2021). In enhanced geothermal systems (EGS), hydraulic fracturing is adopted as a stimulation technique to induce fractures for improved heat extraction (Abe & Horne, 2023; Gong et al., 2020; Kolawole, Ispas, Kolawole, et al., 2021; Liu et al., 2020; McClure & Horne, 2014; Olasolo et al., 2016; Piris et al., 2018).

Cold fluid injected through a well in an EGS becomes heated as it flows through the fractures before the heat is extracted using a second interconnected (production) well. The continuous interaction between the cold-injected fluids and the hot rock can alter the mechanical properties of geothermal reservoirs (especially in EGS) and affect thermal energy recovery efficiency. Therefore, it is essential to study the mechanical properties of geothermal resources under certain conditions to better understand the potential implication of heat energy extraction over time.

Carbon capture and storage (CCS) and geothermal energy production are promising technologies for reducing greenhouse gas emissions while providing renewable and decarbonized energy. CCS in deep aquifers and depleted hydrocarbon reservoirs is considered a viable technology for reducing carbon dioxide (CO_2) emissions to combat global warming (AlRassas et al., 2022; Kolawole, Ispas, Kumar, et al., 2021; Kolawole et al., 2022; Ozotta et al., 2022; Ozotta, Liu, Ostadhassan, et al., 2021; Ozotta, Ostadhassan, Liu, et al., 2021).

CCS in geologic formations, also known as geologic carbon sequestration, involves CO_2 injection and pressurization of these rocks, which usually causes (macroscale) changes in the in situ stresses that can perturb the preexisting fractures. Studies have also shown that CO_2 injection in depleted hydrocarbon reservoirs has the potential to alter host rock properties, such as porosity, permeability, pore structure, mineral composition, and mechanical behavior (Kolawole et al., 2022; Ozotta et al., 2022). Therefore, in the current global climate change mitigation efforts, it is important to consider the potential of CO_2 injection in geologic formations to generate heat energy while simultaneously storing CO_2 in the pore spaces of the host reservoirs. This is referred to as a CO_2-EGS.

In recent years, studies have been carried out (using experimental and numerical methods) to explore the mechanical responses of geothermal-hosting rocks during heat extraction in EGS. However, these studies have provided varying and sometimes contrasting reports on the mechanical behavior of hot rocks as an EGS resource. Therefore, it is important for the rock mechanics community to better understand the changes in the mechanical properties of geothermal reservoirs because of the fracture pathway created during the development of these resources.

This study presents a systematic overview of the potential effect of the interaction between injected fluids (water and/or CO_2) and host hot rocks on the mechanical behavior and properties of EGS and EGS-CO_2. Additionally, we highlight the potential implications of continuous heat extraction from hot rocks in EGS and CO_2 storage in CO_2-EGS. We will also propose an approach for improving efficient fracturing in EGS and provide recommendations for future studies that may address some of the outstanding problems related to the long-term effects of heat extraction on the mechanical behavior of EGS.

2 | INFLUENCE OF FLUID MIGRATION AND HEAT ENERGY EXTRACTION ON MECHANICAL PROPERTIES IN EGS

2.1 | Using only water or water and air as a working fluid for geothermal energy

Studies have explored the physical mechanisms involved when water is used as a working fluid for the extraction of heat from EGS (as illustrated in Figure 1). Rong et al. (2018) conducted an experimental investigation of thermal cyclic effects (0, 1, 2, 4, 6, 8, and 16 thermal cycles) on dolomitic marble and granite. To this end, the porosity and P-wave velocity (V_p) of the marble and granite samples were recorded. To simulate thermal cyclic effects, the samples were heated to 600°C (to imitate high temperatures in deep geothermal reservoirs) and maintained at that temperature for 4 h (Rong et al., 2018). The samples were then cooled naturally to room temperature (25°C).

The test results show that Young's modulus (Figure 2a), wave velocity (Figure 2b), and uniaxial compressive strength (*UCS*) (Figure 3) of the samples decrease as the number of thermal cycling treatment increases (Rong et al., 2018). This might have occurred due to the thermal cycling treatment inducing microcracks in the rock samples, and with an increasing number of cycles, the microcracks grow into larger fractures (Rong et al., 2018). The early stages of the experiment show a huge decrease in Young's modulus and P-wave velocity, which gradually decreases with an increase in the number of thermal cycles. This could be attributed to the possibility that the cracks may have propagated sufficiently after a few cycles. The effect of heat extraction on the Young's modulus of hot rocks is further supported by a study conducted by Shu et al. (2020).

The effect of fluid flow in fractured hot granite rocks was investigated using two experimental setups (Shu et al., 2020). The first experimental program was conducted at a constant temperature with increasing confining pressures, while the second experimental program was conducted at a constant confining pressure with increasing temperature. The temperature and pressure values were selected to model in situ conditions in deep bedrocks. The results (Shu et al., 2020) suggest that at high constant confining pressure and with an increase in temperature from 25 to 200°C, permeability can decrease by 30%, 28%, and 37% at confining pressures of 10, 15, and 20 MPa, respectively, due to the substantial pressure exerted on the low stiff fractures. Relatively, at low constant confining pressure values, the hydraulic properties and permeability can increase due to the negligible effect of the pressure (Figure 4). Similarly, at high constant temperature values, greater pressure results in a rapid decrease in permeability. This is because the dramatic drop in temperature results in a loss of the elastic modulus of the granite sample, which yields more tightly closed fractures (Shu et al., 2020). Therefore, it can be inferred from these studies (Rong

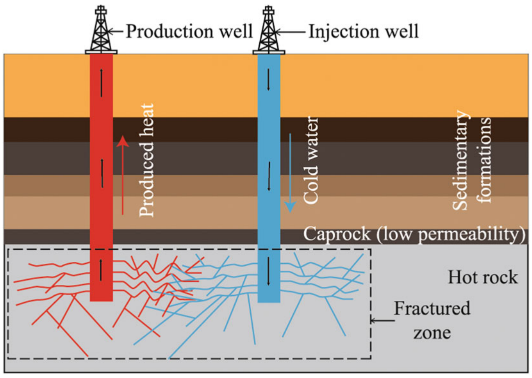

FIGURE 1 Conceptual schematic of an enhanced geothermal system with water as the working fluid.

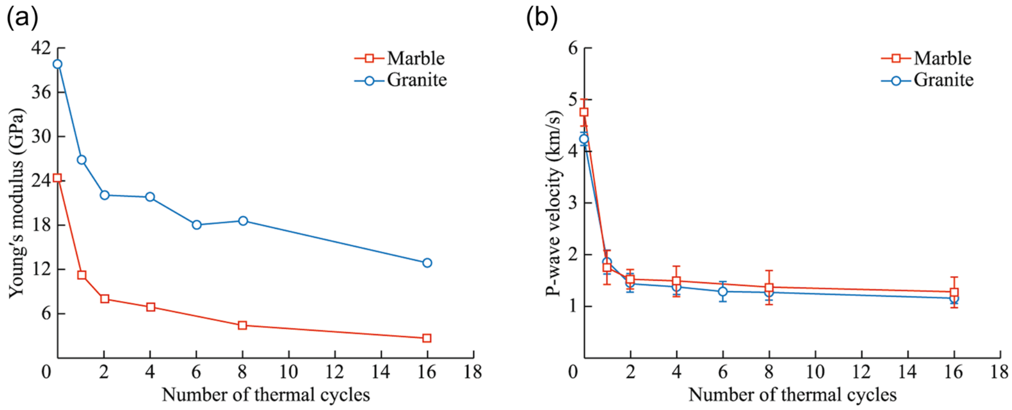

FIGURE 2 Variation of mechanical properties with the number of thermal cycles for marble and granite: (a) Young's modulus and (b) wave velocity. Modified from Rong et al. (2018).

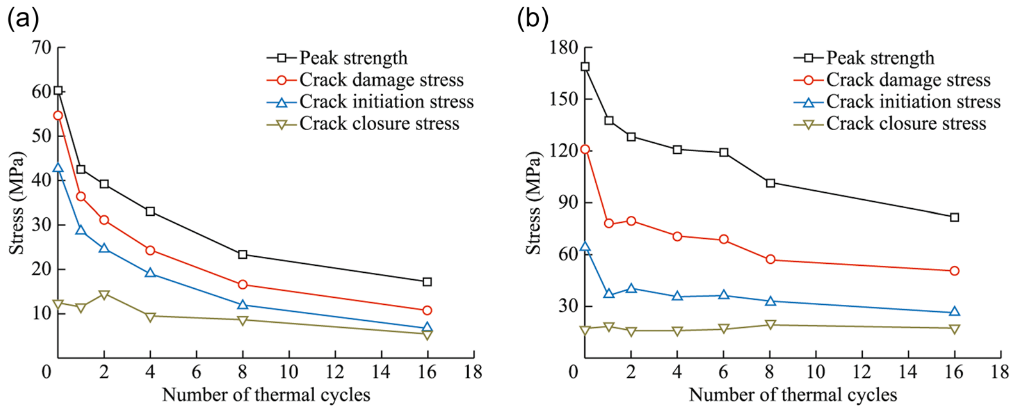

FIGURE 3 Variation of the characteristic stress threshold with the number of thermal cycles for (a) marble rock and (b) granite rock. Modified from Rong et al. (2018).

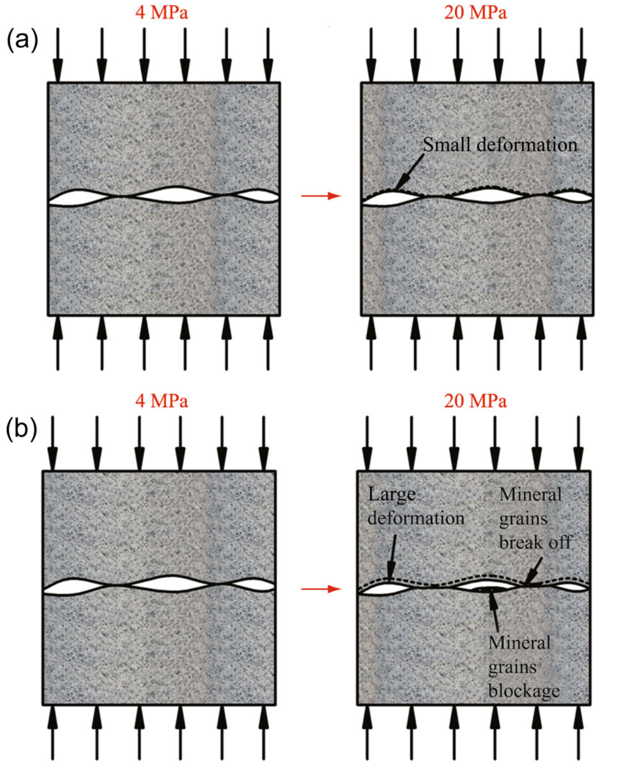

FIGURE 4 Schematic interpretation showing different rates of decrease in hydraulic properties: (a) at low temperature (i.e., 25°C) and (b) at high temperature (i.e., 200°C). The dashed line represents the fracture surface before the deformation. Modified from Shu et al. (2020).

et al., 2018; Shu et al., 2020) that there is a potential loss in the elastic modulus (stiffness) of EGS due to the cyclic thermal interaction with fluids during EGS. This may consequently affect the long-term stability of EGS for continuous heat extraction (Rong et al., 2018; Shu et al., 2020).

Temperature ranges vary depending on the depth of the EGS. Therefore, research studies have assessed the mechanical changes of hot rocks under different temperature conditions. The behavior of granite at specific temperatures (i.e., 200, 300, 400, 500, 600, 700, and 800°C) was studied using a uniaxial compression test (Yang et al., 2017). The results show that the strength and static elastic modulus of granite continuously increased as temperature increased up to 300°C. For temperatures above 300°C, Young's modulus and strength of the granite samples decreased (Yang et al., 2017). The increased strength and stiffness when rock samples are heated to 300°C may be due to the thermal expansion of mineral grains. When the temperature is above 300°C, this thermal expansion causes cracks in the rock, subsequently decreasing its strength and stiffness. A similar experiment was conducted on granite at specific heating temperatures between 200°C and 900°C (Zhang et al., 2018). The samples were maintained at their treatment temperature for 4 h and then cooled with water to room temperature (Zhang et al., 2018). The results suggest that below 500°C, thermal hardening in granite was dominant, thus resulting in an increase in the elastic modulus and compressive strength of the sample. In contrast, above 500°C, thermal cracking was induced, and the granite samples showed a significant decrease in their elastic modulus and compressive strength (Zhang et al., 2018). The findings from these studies indicate that there is less weakening of the mechanical properties of hot rocks at increasing temperatures in EGS (Yang et al., 2017; Zhang et al., 2018). Yang et al. (2017) suggest that there is a critical temperature threshold (300°C) below which the mechanical behavior of granite changes with an increase in temperature, while Zhang et al. (2018) reported the same trend but at a greater critical temperature threshold (500°C). These inconsistent critical temperature threshold values (Yang et al., 2017; Zhang et al., 2018) may be due to the difference in cooling methods used in each experimental study and the inherent heterogeneity features in the rock samples used. Despite this discrepancy, we concur that the changes in mechanical properties of hot rocks, especially granites, may vary depending on the established critical temperature threshold value in EGS. Therefore, we can infer that variations in the mechanical behavior of granites might occur under varying temperature conditions in EGS.

Geothermal resources have mechanical heterogeneity due to pre-existing alterations (Kolawole, Ispas, Kolawole, et al., 2021; Kolawole & Oppong, 2023; Ngoma & Kolawole, 2024; Siratovich et al., 2016). Kolawole, Ispas, Kolawole et al. (2021) analyzed a 0.91-m-long core sample of a hydrothermally altered rock (hot dolomitic sedimentary-hosted geothermal rock) from a potential geothermal area in the Permian Basin, United States. The results indicate variations of mechanical properties across the analyzed sample, with alternating low to high *UCS*, Poisson's ratio (v), and scratch-derived fracture (K_s) values at distinct mechanical zones along the core (Kolawole, Ispas, Kolawole, et al., 2021). The mechanically softer 0.17-m-thick Zone A and 0.18-m-thick Zone C have mean values of $UCS = 110$ MPa, $v = 0.25$, $K_s = 1.89$ MPa/m, and the mechanically harder 0.41-m-thick Zone B and 0.15-m-thick Zone D have mean values of $UCS = 166$ MPa, $v = 0.22$, and $K_s = 2.87$ MPa/m. The results could be attributed to the varying mineralogical compositions because of hydrothermal fluid migration and vein development at each mechanical zone in the core sample (Kolawole, Ispas, Kolawole, et al., 2021). We can, therefore, infer that the properties, morphological attributes, and mineral compositions in the production life of an EGS can induce the development of mechanical alterations because of continuous long-term heat extraction. We also suggest that mechanical changes in an EGS are complex and should consider existing mechanical heterogeneity in the heat extraction from an EGS.

Thermo-hydro-mechanical (THM) models have also been adopted to couple the effects of temperature, fluid flow, and rock deformation, with a focus on enhancing heat extraction efficiency (Cao et al., 2016; Norbeck et al., 2016; Wang et al., 2022). In a study, Cao et al. (2016) utilized a THM model that considered local thermal nonequilibrium to formulate convective heat exchange between the rock matrix and the working fluid in the reservoir. They also used their thermo-poroelastic model to estimate the stress in the rock matrix, in addition to evaluating the porosity and permeability changes as a function of time (Cao et al., 2016). The results indicate that the efficiency of heat energy extraction is highly dependent on the hydraulic stimulation area, injection rate, and thermal conductivity. By injecting the working fluid at high pressure and low temperature, a higher magnitude of the negative effective stress can be attained, which induces an enhancement of the fluid flow rate and the heat extraction rate as a result of the effect of enlargement of the hot rocks' permeability (Cao et al., 2016). Nevertheless, when the fluid is injected at a low temperature and high pressure, the working fluid viscosity significantly increases. The results (Cao et al., 2016) also suggest that a relatively larger hydraulic stimulation area and high fluid injection rate may yield a higher volumetric heat transfer coefficient. In contrast, a lower volumetric heat transfer coefficient can decrease the heat exchange between the hot rock and the working fluid, and may lead to lower effective stress magnitude, which can yield a resultant effect on the porosity and permeability in EGS.

A series of experimental investigations have been performed to mimic EGS using different cooling methods at different temperatures. For instance, Zhu et al. (2021) examined the mechanical changes of granite using two different cooling methods. The rock samples were heated to predetermined temperatures (i.e., 200–600°C) and then maintained at the final temperature for 2 h before cooling. Afterward, the specimens were cooled using either rapid water cooling or slow air-cooling methods. The results show that the mechanical properties of the samples reduced with increasing temperature. At temperatures lower than 600°C, the samples showed ductile characteristics. At 600°C, the water-cooled samples yielded an 85% decrease in average V_p, a 73% decrease in average *UCS*, and a 66% decrease in the average elastic modulus (Zhu et al., 2021). Similarly, the air-cooled samples showed a 74%, 56%, and 49% decrease in the average P-wave velocity, *UCS*, and elastic modulus, respectively (Zhu et al., 2021). Using similar treatment methods, Li et al. (2020) examined granite rocks at increasing temperatures (between 100 and 600°C) with two different cooling modes—the natural cooling method and rapid cooling with water. The samples were heated to the desired temperature and maintained at this temperature for a few hours to obtain their corresponding results. The results (Li et al., 2020) show that the elastic moduli and *UCS* of the samples decrease with an increase in temperature, which is consistent with the trend observed in Yang et al. (2017), Zhang et al. (2018), and Zhu et al. (2021). The magnitude of these mechanical strength losses was greater with water cooling than with the natural cooling method (Li et al., 2020). A similar pattern was observed in a study conducted by Liu et al. (2021) on heated granite samples, where the permeability increased more when the samples were cooled in cold water than when they were cooled in air. It was also observed that when the temperature was less than 300°C, there were no changes in the crystal structure of the granite samples, which gradually expanded and eventually developed into larger fractures when the temperature exceeded 300°C (Li et al., 2020). However, the original microfractures gradually expanded and eventually developed into larger fractures when the temperature exceeded 300°C (Li et al., 2020).

Previous studies have emphasized the relevance of the cooling methods used for high-temperature experimental tests and analysis of granite. This is important because it could provide valuable insights into the process of heat extraction from EGS. When cold water is utilized as the cooling method or working fluid, the rock experiences a more significant decrease in mechanical strength in these experiments than when air-cooled samples are used. This may occur due to the rapid cooling effect of cold water on the low-permeability geothermal rocks when compared to using either air or air and water for cooling, thus inhibiting the formation of more structured bonds between minerals. This may eventually result in decreased mechanical strength of the rock, which requires further investigation. These observed comparisons unlock the potential of using nonaqueous fluids (other than water) as working fluids in EGS.

2.2 | Using CO_2 as a working fluid for geothermal energy and storage

Studies have explored the potential of using CO_2 as a working fluid (An et al., 2021; He & Li, 2020; Li et al., 2019; Liao et al., 2020; Shen et al., 2020; Shu et al., 2020; Song et al., 2020; Tong et al., 2022; Zhong et al., 2022) in EGS because of its potential to not only improve fracture stimulation for heat energy extraction but also promote CO_2 storage (Tong et al., 2022). CO_2 sequestration (CCS) can be coupled with geothermal energy extraction in a naturally permeable and porous geologic formation (Figure 5). Zhong et al. (2022) developed a wellbore reservoir model to analyze and compare a CO_2 versus a water EGS system in fractured geothermal reservoirs. Another study by Randolph and Saar (2011) developed numerical simulations to assess geothermal heat energy extraction using CO_2-plume geothermal. The results (Randolph & Saar, 2011; Zhong et al., 2022) indicate that due to the thermodynamic and fluid mechanical properties of CO_2, there is a more efficient transfer of geothermal energy compared to water. Additionally, the numerical predictive tools developed in these studies can be adopted for mitigating greenhouse gas emissions on a field scale while generating renewable energy (Randolph & Saar, 2011; Zhong et al., 2022).

Shu et al. (2020) investigated the mechanical properties of granite samples from China by water and CO_2 injections at different confining pressures (2–20 MPa), different pore fluids (10 MPa water or CO_2), and different temperatures (25–150°C). The study used triaxial compression experiments and scanning electron microscopy to determine their mechanical and microstructural properties. The results indicate that combined water and CO_2 injections can decrease the Young's modulus of hot rocks (Shu et al., 2020). At a confining pressure of 15 MPa, the *UCS* increases with an increase in temperature. The type of pore fluid injected can impact the elastic moduli of hot rocks, and the mechanical weakening of the rocks due to CO_2 injection is more obvious (Shu et al., 2020).

In an experimental investigation on granite rocks, the samples were exposed to three different treatments, namely, pure thermal stimulation, pure CO_2-bearing solution stimulation, and combined stimulation of thermal and supercritical CO_2-bearing solution (Tong et al., 2022). The results show that the most significant

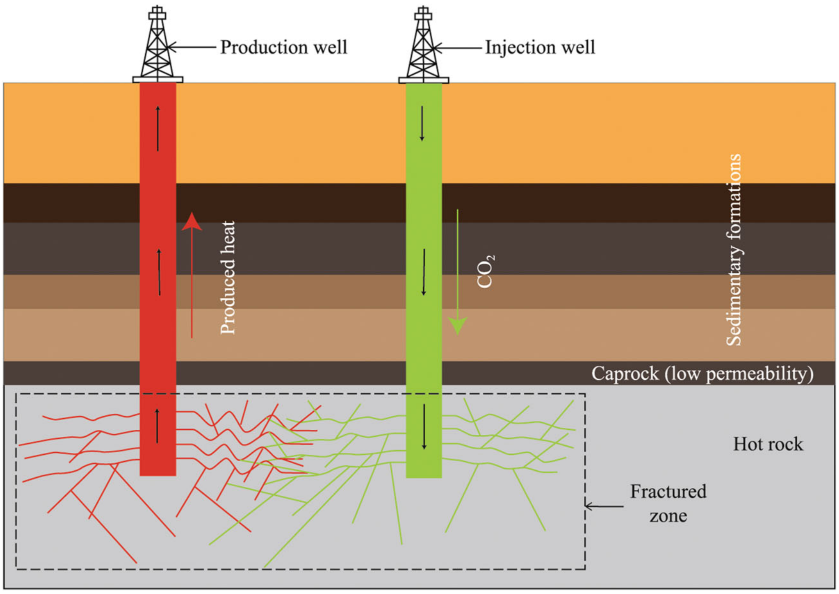

FIGURE 5 Conceptual schematic of a CO_2-enhanced geothermal system with CO_2 as the working fluid.

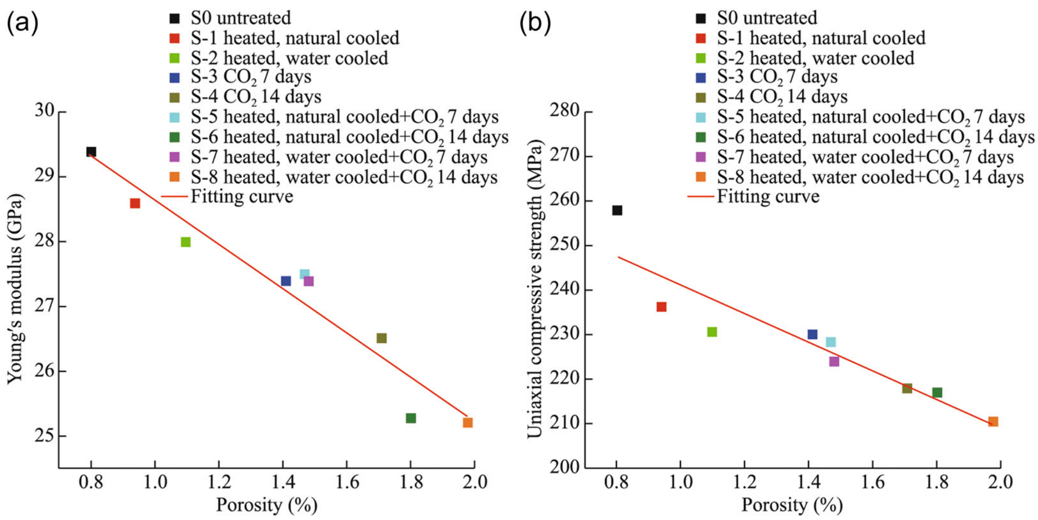

FIGURE 6 Relationship between mechanical and hydraulic properties of hot granite samples after using water and CO_2 as working fluids: (a) Young's modulus versus porosity and (b) uniaxial compressive strength (*UCS*) versus porosity. Modified from Tong et al. (2022).

effect on the samples was due to water cooling on the heated granite combined with the CO_2-bearing fluid stimulation. With this treatment, the permeability of granite was 17 times higher than that of the samples in the untreated state. The porosity increased by 144%, whereas the elastic modulus and compressive strength decreased by 14% and 18%, respectively (Figure 6). Compared to the single thermal stimulation and CO_2-bearing fluid hydro-chemical stimulation, the results show that the superposition effect of thermal and CO_2-induced hydro-chemical stimulation can increase the number of microfractures in granite rocks more effectively (Tong et al., 2022). Therefore, the permeability increased, whereas the elastic modulus and compressive strength decreased. These results are in agreement with an investigation by An et al. (2021), where a dynamic alteration damage apparatus was developed to study long-term CO_2–water–granite interactions.

Representative test results indicated that the mechanical properties of granite rocks deteriorated considerably in supercritical carbon dioxide ($ScCO_2$)–water mixtures as the reaction proceeded, while the dispersion in the mechanical properties increased (An et al., 2021). The results show that the *UCS* and Young's modulus of the samples decreased by 5% and 19%, respectively (An et al., 2021). We deduce from the results that when CO_2 is coupled with water as a working fluid for stimulation in EGS, the *UCS* and Young's modulus of the EGS are expected to decrease over time. This may be accompanied by an increase in permeability because of the reduced mechanical strength of the hot rock, which consequently affects the heat extraction efficiency. However, there are uncertainties concerning the extent of degradation of the mechanical properties observed and if this might result in further long-term instability in geothermal reservoirs.

Using a coupled thermo-hydro-mechanical-chemical (THMC) model (Gan et al., 2021), the feasibility and potential benefits of using $ScCO_2$ as a working fluid in deep geothermal systems were investigated by accounting for the thermodynamic, hydraulic, mechanical, and chemical behavior of $ScCO_2$-EGS. The results show that $ScCO_2$ injection can increase the reservoir pressure, which enhances the productivity and heat transfer in EGS and leads to a higher power output. The work also indicated that mineral dissolution and/or precipitation can significantly affect the tendency of $ScCO_2$-EGS to yield greater connected fracture networks, but this requires further studies (Gan et al., 2021). The effect of CO_2 injection on cloud-fracture network development in granites under moderate and superhot geothermal conditions was studied by Pramudyo et al. (2021). They used X-ray computed tomography (CT) imaging and digital image analysis techniques to analyze the induced fracture network development. The results showed that CO_2 injection resulted in the development of complex fracture networks that were significantly different from the control samples, especially under superhot conditions. The fracture networks developed in a multistage process, with the initial stage dominated by microfracturing and the later stage dominated by macrofracturing (Pramudyo et al., 2021). The study concluded that CO_2 injection under superhot conditions resulted in a more connected fracture network than under conventional conditions. This suggests that CO_2 injection can enhance geothermal energy production by creating more permeable fracture networks (Pramudyo et al., 2021).

To improve the understanding of the effect of heterogeneity features in EGS, a three-dimensional finite element method-based geothermal reservoir model (Singh et al., 2023) was developed to understand the impact of reservoir heterogeneity on modified reservoir mechanical properties and resultant dual geothermal energy extraction and CO_2 sequestration. The findings in Singh et al. (2023), also reported in Kolawole, Ispas, Kolawole et al. (2021) and Kolawole and Oppong (2023), suggest that mechanical heterogeneity in tight reservoirs may significantly dictate injected fluid behavior and heat distribution, and influence the mechanical stability of EGS and operational efficiency of coupled geothermal heat extraction and CO_2 storage operations.

Wu and Li (2020) discussed the potential of combining CCS and geothermal energy production in a CO_2-EGS. They reported on a study of CO_2 injection used as a working fluid into deep low-permeability geothermal reservoirs, leading to induced fractures to enhance heat energy extraction while at the same time storing CO_2 in a geological formation. The results of their studies indicate that CO_2-EGS has the potential to be a cost-effective and sustainable method for both geothermal energy production and CCS because it increases permeability and heat transfer in the reservoir, and yields higher energy recovery. However, the study also identified technical uncertainties and public acceptance issues as the main challenges that must be addressed to commercialize CO_2-EGS as a technique for curtailing greenhouse gas emissions and mitigating climate change.

3 | INFLUENCE OF OTHER PARAMETERS ON MECHANICAL ALTERATIONS AND HEAT ENERGY EXTRACTION IN EDS

In recent years, experimental and numerical analyses have been utilized to explore hydraulic rock properties, such as the permeability and porosity changes of reservoir rocks during geothermal heat extraction. Feng et al. (2022) established a transport model based on data from an EGS injection well in the Matouying uplift of Hebei Province, China. The model used the radial grid method, and the boundary conditions were established with the lower boundary set as impermeable to maintain a constant temperature and pressure (Feng et al., 2022), whereas the injection well was assigned the Dirichlet boundary condition, allowing for variation in the flow rate over time (Figure 7). The model was used to extrapolate and predict permeability changes due to water–rock reactions in geothermal reservoirs. The study further analyzed the effects of injection flow rate, injection temperature, and chemical composition of water in EGS (Feng et al., 2022). The results reveal that the porosity at the injection point decreased by 60% and the permeability decreased by 94% because of the dissolution of minerals (Figure 8). The decreased permeability and porosity were observed as far as 7.5 m away from the injection well in the EGS reservoir.

An increase in the fluid injection rate, injection temperature, potassium, and magnesium content in the injected water were considered as major contributing minerals to the decrease in the permeability and porosity of the EGS (Feng et al., 2022). This result validates the observations in Kolawole, Ispas, Kolawole et al. (2021) and highlights the relevance of mineral alterations and injection conditions in heat energy extraction from EGS. Therefore, we infer that the injection fluid mineral content can induce dissolution or precipitation of new

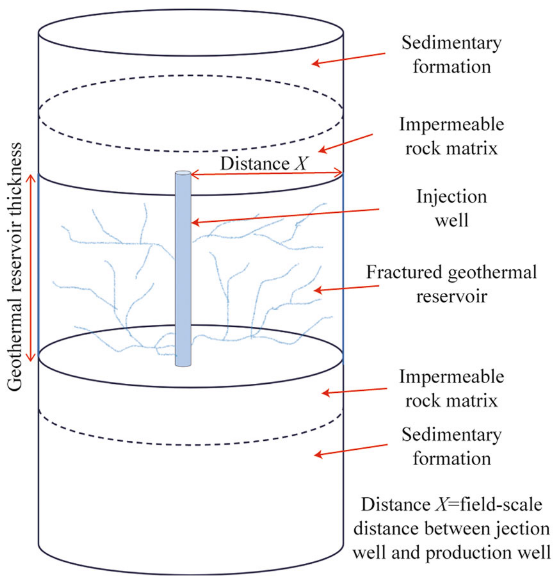

FIGURE 7 Conceptual model design of varied time simulation in enhanced geothermal systems.

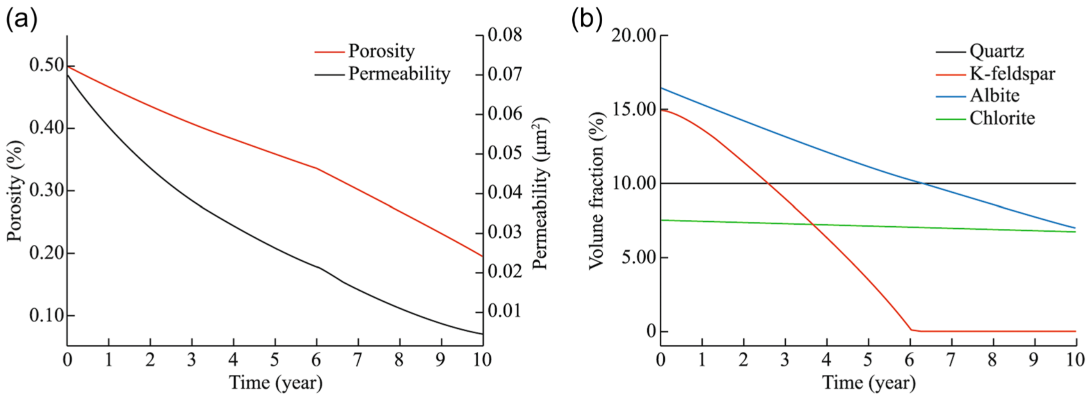

FIGURE 8 Simulated time variation of injection with (a) porosity and permeability alteration and (b) primary mineral dissolution. Modified from Feng et al. (2022).

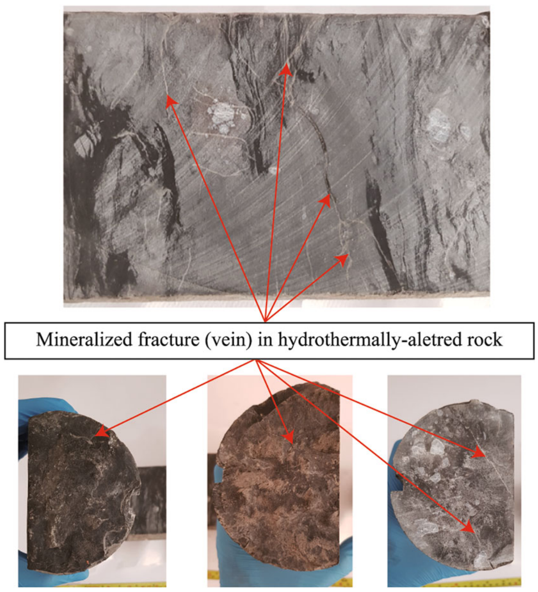

FIGURE 9 Physical observations of mineralized fractures (veins) and flow pathways due to continuous mineral dissolution and precipitation in hydrothermally altered core samples from a potential geothermal reservoir.

minerals, which could impact the flow pathway in stimulated geothermal reservoirs, as shown in Figure 9.

The changes in the permeability of a hot rock were analyzed by Zhao et al. (2017), with the permeability tests being conducted at high temperature and pressure values. The results indicated that the permeability of granite rocks increased when heated at a critical temperature. Using the micro-CT method, it was discovered that thermal cracking occurred at grain boundaries and developed with increasing temperature. Therefore, these results suggest that in hot dry rocks, the permeability can be enhanced by heating to critical temperature values. However, this study does not consider the influence of a working fluid on the permeability. Therefore, further investigations into the influence of different fluids at critical temperatures would be required before this result can be generalized to EGS. In fractured granite rocks subjected to heating and cooling cycles (ranging between 25 and 500°C) and varying periods (2–72 h), the permeability initially decreased because of the closure of the microcracks during heating, and subsequently increased during cooling, as a result of the opening of new microcracks (Shu et al., 2019). The study identified mineral dehydration and alterations in surface roughness and microstructure as the main controlling factors in permeability evolution (Shu et al., 2019). This further supports our hypothesis that permeability could be impacted during heat energy extraction at higher post-injection temperatures due to hydraulically induced fractures during heat extraction in granitic EGS and CO_2 storage in subsurface reservoirs.

Siratovich et al. (2016) studied the effects of stress conditions, permeability, and hydrothermal alteration on the mechanical behavior of rock samples collected from the Rotokawa andesite, a significant geothermal reservoir rock in the Taupo Volcanic Zone, New Zealand. The results reveal that the porosity and permeability of the rocks changed depending on the initial state of the samples. The samples with high porosity under high-pressure conditions showed reduced porosity at the end of the experiment. In contrast, samples with low porosity at low stresses yielded an increase in porosity (Figure 10). The mechanical deformation results (Figure 10a,b) from the stress–strain curves indicated moderately altered samples with a porosity of 14.8% and highly altered samples with a porosity of 14.0%. The post-deformation analysis revealed distinctive fracture patterns, with the moderately altered sample having an apparent through-going shear fracture, whereas the highly altered sample contained minor macroscopic fractures near the middle of the sample axis. The study concluded that changes in porosity depend on the initial rock porosity and pressure conditions in EGS (Siratovich et al., 2016). This research provides valuable insights into the structural integrity and deformation behaviors of geothermal reservoir rocks under high-pressure conditions. The implications of these results also align with the findings of Kolawole, Ispas, Kolawole et al. (2021). It can be inferred from Siratovich et al. (2016) and Kolawole, Ispas, Kolawole et al. (2021) that the pre-existing conditions and mechanical alteration of a geothermal resource can influence its physico-hydro-mechanical properties and impact the long-term stability of geothermal resources.

The overview of these studies shows that the experimentally observed changes in the properties of rocks are different under varying temperatures and cooling

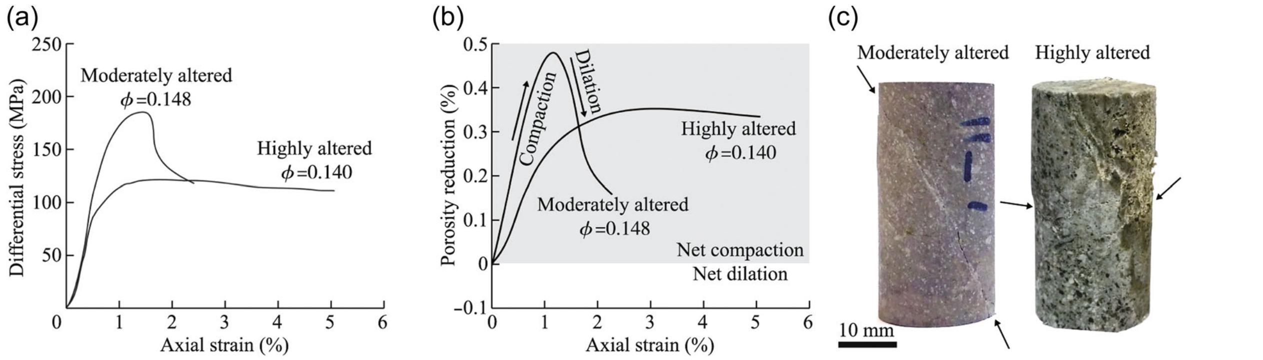

FIGURE 10 Mechanical deformation of Breccia rocks on moderately altered rock (with porosity of 14.8%) and highly altered (with porosity of 14.0%): (a) stress–strain curves of the rock deformation behavior, (b) porosity reduction as a function of axial strain, and (c) photographs of the samples post deformation. Modified from Siratovich et al. (2016).

conditions. This provides an insight into the potential changes in an EGS when fluid flows through induced fractures during heat extraction under varying reservoir (temperature and pressure) conditions. These studies also provide valuable insight into the prediction of the mechanical integrity of EGS with implications for heat energy extraction in EGS and CO_2 storage in CO_2-EGS.

Despite the numerous studies showing the potential and viability of EGS for sustainable energy and low-carbon solutions, it still faces particular challenges from the public, and some in the industry still identify EGS as a contentious energy technology because of its assumed influence in promoting induced seismicity or microseismicity in certain areas (Piris et al., 2018; Trutnevyte & Azevedo, 2018; White et al., 2017). These contrasting opinions have resulted in delays and the potential cancellation of at least two EGS projects globally. While microseismicity has had minimal or no negative operational consequences on nearby communities, there is still public apprehension regarding the extent and intensity of seismic activity linked to present and future EGS operations. Instances of seismic events measuring 2.0 or higher magnitudes, as observed in EGS projects like Soultz in France (Baria et al., 2005), have raised apprehensions among residents. These concerns revolve around potential damage caused by individual EGS events and their cumulative impact (Majer et al., 2007). Moreover, there is a fear that these smaller events could serve as precursors to more significant ones in the future. Concerns also exist regarding the allocation of adequate resources toward addressing the challenges associated with more significant induced events and establishing independent monitoring of seismic activity before implementing large-scale fluid injection and heat energy production in EGS and CO_2-EGS.

4 | PROPOSED WATERLESS STIMULATION OF EGS FOR EFFICIENT HEAT ENERGY EXTRACTION

The challenges to EGS using water or CO_2 as the working fluid are multifaceted and complex, which can have temporal effects on heat extraction and the mechanical behavior of EGS. A critical challenge is managing and controlling the induced seismicity that can result from the injection of fluids into geothermal reservoirs to induce fractures and extract the heat energy (Knoblauch & Trutnevyte, 2018; Majer et al., 2007; Zang et al., 2014). This continued process can alter the state of stress in a geologic formation, potentially triggering such induced seismicity events (Hamilton et al., 2021; Kolawole et al., 2019; Majer et al., 2007). Another significant challenge is the thermal stress induced by the injection of cold fluids into hot EGS rocks, which can lead to rock contraction and potentially damage the mechanical integrity of the EGS reservoir. Additionally, maintaining the permeability of the reservoir over time is crucial to efficient heat extraction from EGS, as the interaction of the injected fluids with the EGS reservoir can lead to mineral precipitation or dissolution, altering the reservoir mechanical properties. Further, the long-term mechanical stability of the EGS is also a concern, as continuous fluid injection and extraction can change the stress regime in the reservoir, potentially leading to subsidence or uplift at the surface (Hamilton et al., 2021; Knoblauch & Trutnevyte, 2018; Majer et al., 2007; Zang et al., 2014).

Therefore, to address these challenges mentioned above to using water or CO_2 as the working fluid in EGS, in addition to the limited access to water (for fracturing and as a working fluid) in different parts of the world, recent studies have suggested alternative technologies for creating fractures instead of hydraulic fractures (Figure 11) (Liew et al., 2020; Rassenfoss, 2013). One such alternative is slot–drill fracturing, which involves mechanically cutting fractures in the subsurface using tensioned cables that abrade into rocks as they are pulled back and forth. This approach was initially introduced for cutting large rock outcrops (Farrar et al., 1991; Hurd, 1980) but has also been suggested to be efficient for subsurface tight rocks like unconventional hydrocarbon reservoirs (Amer & Olorode, 2022; Carter, 2009; Odunowo et al., 2013) and geothermal reservoirs (Rashid & Olorode, 2024). Figure 11a illustrates the state-of-the-art EGS technique, which is field-tested in the Utah FORGE project, United States (Utah Forge, n.d.). It involves drilling and hydraulically fracturing a horizontal

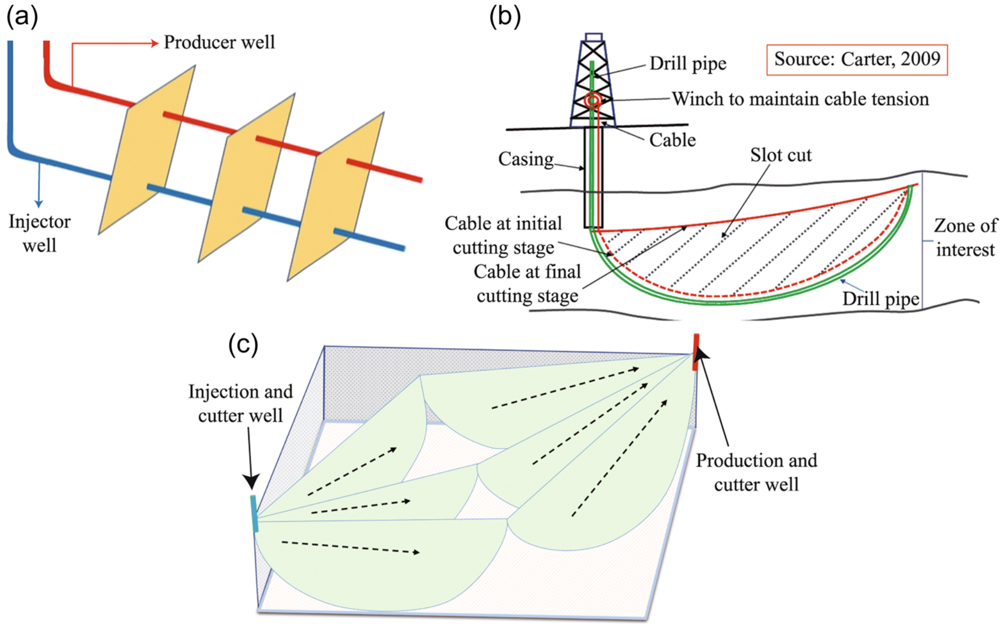

FIGURE 11 (a) Enhanced geothermal system (EGS) development using multistage fractured horizontal wells. The conceptual schematic of the proposed waterless-stimulated EGS approach consisting of (b) slot–drill fracturing and (c) a new EGS based on slot–drill fractures.

injection well (shown in blue) in multiple stages, while a second horizontal production well (shown in red) is then drilled to intersect the hydraulic fractures propagated from the injector wellbore. After that, cold water will be continuously injected into the hot EGS rock through the injector, while hot water or steam is withdrawn from the producer. This approach (Figure 11a) could yield low and unpredictable thermal recoveries in the field because of its limited control over the hydraulic fracture orientation, location, and size, as well as the low probability of the producer intersecting all the hydraulic fractures. Based on these limitations, Rashid and Olorode (2024) recently suggested and simulated the use of the configuration of slot–drill fractures as shown in Figure 11c and the results indicate a greater heat energy recovery efficiency from all parts of the geothermal reservoir.

Here, we propose adopting the slot–drill fracturing technique and retrofitting it as waterless stimulation of EGS for efficient heat energy extraction (Figure 11b,c). Figure 11b illustrates the slot–drill fracturing process, where the shaded region is cut by the oscillating movement of a tensioned abrasive cable (shown as the dotted red and solid red lines at the beginning and end of the slot–drill fracturing process). The advantage of this proposed waterless-stimulated EGS approach lies in the precise control over the placement and orientation of these mechanically cut fractures. Although the modified slot–drill fracturing technique proposed in Rashid and Olorode (2024) did not consider coupled geomechanics in their studies, the proposed waterless-stimulated EGS is less likely to induce seismicity and rock deformation because it is waterless, and continuously remains efficient below the fracture pressure of geothermal reservoirs. Finally, there is no need to dispose of wastewater in the subsurface, and the subsurface rocks are not subjected to high fracture fluid pressures.

5 | CONCLUSIONS AND RECOMMENDATIONS

In this study, we provided a comprehensive review of alterations in the mechanical and hydraulic properties of hot rocks due to elevated temperatures, varying pressures, distinct cooling modes, and other factors in EGS. Our conclusions are as follows:

1. Pre-existing mechanical alterations of rocks can influence current and future mechanical behaviors in EGS.
2. Young's modulus, *UCS*, Poisson's ratio, fracture toughness, porosity, and permeability of rocks will change due to hydrothermal fluid migration through analyzed samples, which can be dependent on different confining pressures, temperature, and cooling conditions.
3. In EGS (and other deep geothermal energy resources), the working fluid injected for heat extraction and its chemical compositions can induce mechanical alterations, with a simultaneous impact on its flow pathway and hydraulic properties.
4. The interaction of water and/or CO_2 fluids in hot underground rocks can result in the dissolution or precipitation of minerals, thus changing their properties, and influencing their long-term CO_2 storage potentials.

Using slot–drill fracturing technology, we proposed the concept of waterless stimulation of EGS for efficient heat energy extraction. We envisage that this technique could mitigate the challenges to the long-term efficiency of EGS caused by using water or CO_2 as the working fluid, but it still requires further investigation by coupling waterless-stimulated EGS with geomechanical studies for validation.

Based on these findings, we provide the following recommendations for further investigations and analyses of the alterations in underground hot rocks due to temperature and cooling changes caused by water and CO_2 flow in EGS:

1. Extended studies should be carried out on the comingled injection of water and CO_2 for heat extraction with potential CO_2 storage in EGS to better control the rock properties and the fracture development for improved geothermal energy production and efficiency.
2. Numerical analyses should be carried out to predict the long-term effects of heat extraction on the mechanical properties in EGS.
3. The potential for induced seismicity and CO_2 leakage needs to be carefully evaluated and carefully studied before implementing CO_2 as a working fluid in deep geothermal systems for subsequent heat energy extraction.
4. Further studies and analysis should be conducted on the equilibria of reduced mechanical strength, greater porosity/permeability, and increased induced fractures that can allow for efficient heat energy extraction, while ensuring the stability of the EGS.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

No data are available.

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