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Simulations of carbon dioxide push-pull into a conjugate fault system modeled after Dixie Valley—Sensitivity analysis of significant parameters and uncertainty prediction by data-worth analysis

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A B S T R A C T

Characterizing the faults and fractures that provide flow pathways for efficient geothermal energy production is critical for design of sustainable geothermal energy production. Both natural faults and stimulated fractures in enhanced geothermal systems (EGS) are difficult to image and map by seismic methods because hot brine filling the fractures and faults does not create a strong seismic property contrast relative to surrounding rock. We investigate here the technical feasibility of using supercritical CO_2 ($scCO_2$) injection into faults in a single-well push-pull scenario to characterize the hydraulic properties of the fault zone by emplacing $scCO_2$ that can serve as a contrast fluid for seismic monitoring. We develop a conceptual and numerical reservoir model of two intersecting faults based on the Dixie Valley geothermal system in Nevada, USA. The 2D conceptual model consists of a system with a main fault and an intersecting conjugate fault. The corresponding numerical model is discretized using irregular grid blocks with fine discretization around the slip plane, gouge, and damage zones. We perform forward modeling along with sensitivity and data-worth analyses of $scCO_2$ push-pull to investigate the CO_2 distribution in the fault gouge during 30 days of push (injection) and 30 days of pull (production). Formal sensitivity analysis is conducted to determine the most controlling unknown parameters in the fault zones. Using the selected set of unknown parameters and output responses, we perform data-worth analysis to reveal the most valuable output response to be measured for the best prediction of CO_2 distribution in the fault zones and its uncertainty. From the results of data-worth analysis, we determine the optimal properties to target in monitoring, their locations, and the minimum observation time. Our results provide information on the optimal design of $scCO_2$ push-pull testing in a conjugate fault system modeled after Dixie Valley that can be used to enhance monitoring by active seismic and well-logging methods to better characterize the transmissive fault(s).

1. Introduction

Networks of naturally occurring and engineered fractures and faults must be explored and characterized in order to optimize exploitation of geothermal energy from enhanced geothermal sites (EGS). However, faults and fractures occurring in many EGS sites are difficult to image with traditional seismic and well-logging tools because they are filled with hot brine and not easily distinguishable from the surrounding formation. Previous research showed that the injection (push) of supercritical CO_2 ($scCO_2$) into (i) a fracture zone at a geologic carbon sequestration site with active source seismic monitoring (e.g., Zhang et al., 2015) and (ii) into a fault zone at a prototypical EGS site with active-source seismic monitoring and well-logging allowed seismic detection of the transmissive zones (Borgia et al., 2017; Oldenburg et al., 2016). After imaging the fracture and fault zone following injection, fluid production (pull) from the fault zone allows partial recovery of the injected $scCO_2$.

There are several advantages to using $scCO_2$: (1) much higher compressibility of $scCO_2$ relative to water facilitates seismic detection by changing the stiffness tensor components; (2) the non-wetting characteristic of $scCO_2$ tends to exclude the $scCO_2$ from the matrix leaving it preferentially within the fractures and faults; (3) the smaller viscosity of $scCO_2$ relative to brine helps it to easily permeate into the fractures and faults; and (4) the higher density of $scCO_2$ relative to

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other gases mitigates the buoyancy effect and enables the better recovery of injected CO_2 during the pull phase (Borgia et al., 2017).

In this study, we investigate the technical feasibility of a $scCO_2$ push-pull test in the conjugate faults system of the geothermal resource at Dixie Valley in central Nevada, USA. The geothermal system in the Dixie Valley is of basin-and-range type, and the temperature of the field is estimated to approach a 260 °C at a depth of 3 km, based on measured well data (Blackwell et al., 2007; Iovenitti et al., 2016). The geothermal system in the Dixie Valley is believed to be a promising EGS site owing to high temperature range at relatively shallow depth, existence of faults and brittle fractured zones for permeability, and favorable stress regime at the depth of 1–3 km for EGS development (Iovenitti et al., 2016).

In the forward modeling of $scCO_2$ push-pull in this study, we simulate the injection and production of $scCO_2$ into the junction of two conjugate faults in the Dixie Valley Geothermal System (DVGS). We investigate the efficacy of injecting and producing CO_2 so that it spreads in the fault zones where it can be useful for improving imaging and characterization by seismic methods.

We conduct a sensitivity analysis to evaluate the factors affecting CO_2 inflow into the faults and outflow from the faults. The sensitivity coefficient of each influential parameter on the system response is quantified. We conduct a data-worth analysis to predict the uncertainty of CO_2 distribution after the push and pull phases by measuring the system responses. In this procedure, the data worth of each measurement is computed to indicate the relative importance for the prediction of future system behavior.

From this study, we determine (1) technical feasibility of CO_2 push-pull in the DVGS fault zones, (2) important flowing parameters in fault zones that affect the efficiency of CO_2 push-pull in the Dixie Valley geothermal system, (3) system responses that should be measured to predict CO_2 distribution after push-pull, and (4) prediction uncertainty of CO_2 distribution in the conjugate faults.

2. Dixie Valley geothermal system

The DVGS is one of the most thoroughly characterized geothermal systems in the U.S. The data include geological cross-sections, gravity-magnetic surveys, lithologic and resistivity models, seismic models of P-wave velocity and S-wave velocity, and thermal numerical models (Blackwell et al., 2009; Iovenitti et al., 2016; Iovenitti et al., 2013; Smith et al., 2011).

The DVGS occupies an area of approximately 170 km^2 within the larger project area of 2500 km^2 (Iovenitti et al., 2016). In the geothermal system, there are a number of N-to NE-trending fault systems identified from thermal anomalies (Fig. 1(a)), which are formed by well-connected normal and associated conjugate faults of 1–3 km-depth.

The geologic cross section DD' is shown in Fig. 1(b). Here, brittle and permeable zones within the Tbf (basin-filling sediments), Tmb (Miocene basalt), Jz (Jurassic mafic volcanics), and Tr (Triassic meta-sediments) provide the flow pathways of fluid and heat.

Hot brine rises along the main faults giving rise to the isotherms shown in Fig. 1(C) (Smith et al., 2011). Regarding the system temperature, depth, and the distributions of high-permeability zones, we define our model domain area of 2750 m × 2750 m as shown in Fig. 2.

3. Development of the conceptual and numerical models

We developed a 2D cross-sectional conceptual model of the DVGS involving the main and conjugate faults. The conceptual model includes the geometry of reservoir rocks and faults, as well as simplified representation of system heterogeneity, initial conditions, and transport properties. Although the conceptual model is very simplified, it includes the essential components that affect flow of injected CO_2 and therefore retains the fundamental fault-flow-related aspects of the system. We chose to use a 2D model over a 3D model for computational efficiency. This choice is justified by the observation that a CO_2 plume in a steeply dipping fault zone expands more easily upward than horizontally due to buoyancy as observed in a3D simulation study (Borgia et al., 2017).

Fig. 3(a) shows the grid we developed for the 2D domain using WinGridder (Pan, 2008) corresponding to the cross section DD' (Fig. 1(a)). The model contains a total of 10,728 grid blocks. This irregular grids system has elements connected along the fault zones parallel to flow directions, rather than staggered connections that result from regular rectangular grids system. The expanded view at the junction of the faults is shown in Fig. 3(b). The width and height of the elements in the fault zones are 2.5 m and 10 m, respectively.

To characterize the fault zones, we use the conceptual model of a generic fault developed by Gudmundsson et al. (2002), which contains a few meter-thick fault gouge, a slip plane within the fault gouge, and a damage zone outside the fault gouge (Fig. 4(a)). Our model includes 32.5 m-thick and 22.5 m-thick fault zones in the main and conjugate faults, respectively (Fig. 4(b)). The main fault zone has a thicker fault gouge than the conjugate fault zone has. Fault zones are conceptualized as being composed of brittle rocks and contain cracks, which provide flow pathways for fluid and heat.

Fig. 5 shows the initial pressure and temperature distributions. The system is initially filled with brine; and a hydrostatic pressure gradient of 9.79 kPa/m is applied. The initial temperature distribution shows the effect of rising flow of fluid and heat through the main fault, which was obtained by running a natural-state simulation, which started with the temperature distribution of Fig. 1(c), for sufficiently long time of 10^6 days to get steady-state condition. Constant pressure and temperature are set at the top boundary; and the other three sides are set at no flow condition of heat and fluid, in light of the short time of our push-pull test.

Hydrogeologic properties of the system for the numerical simulations are provided in Table 1. Potentially influential and unknown parameters for the flow of injected CO_2 in the fault zones are indicated with *—the absolute permeability, and the input parameters for the relative permeability and capillary pressure functions in the fault slip plane, fault gouge, and damage zone. Sensitivity and data-worth analyses will be performed for these parameters after the forward modeling section.

4. Forward simulations

We simulated the processes of $scCO_2$ push-pull into the faults of DVGS by using TOUGH2-ECO2N (Pan et al., 2015), a fluid property module for mixtures of CO_2, water, and NaCl. Push and pull of $scCO_2$ continued for t = 0–30 days and t = 30–60 days, respectively. In the numerical simulations, a small mass fraction of NaCl in aqueous phase ($= 1 \times 10^{-7}$) was used.

In the push phase, CO_2 was injected by using a 0.3 MPa constant overpressure above the local hydrostatic pressure in the injection grid blocks in the fault slip plane and fault gouge of the main fault at Z-coordinates between −3018 m and −3024 m, which is just below the junction of the main and conjugate faults. The injection grid blocks contain 100% CO_2. Temperature of injected CO_2 was same as the local ambient temperature of 265 °C. In the pull phase, fluid was produced by 0.3 MPa underpressure at the same locations as the injection.

Results of numerical simulations are provided in Figs. 6–12. Fig. 6 shows the distribution profiles of pressure, temperature, and gas saturation in the reservoir, after push (a–c) and pull processes (d–f). After the 30 days of push, the system pressure slightly increased along the faults (Fig. 6(a)). Similarly, system pressure slightly decreased along the faults after the subsequent 30-day pull process (Fig. 6(d)). System temperature insignificantly changed in the faults after the push and pull, as the CO_2 was injected at the ambient temperature (Fig. 6(b) and (e)). (From the preliminary simulation using lower temperature-CO_2,