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CO₂ PUSH–PULL INTO THE DUAL FAULTS OF THE DIXIE VALLEY GEOTHERMAL SYSTEM: SENSITIVITY AND DATA–WORTH ANALYSES FOR REDUCING PREDICTION UNCERTAINTY OF CO₂ DISTRIBUTION

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ABSTRACT

Feasibility of exploration and exploitation of geothermal energy from Enhanced Geothermal Systems (EGS) involves consideration of flow in naturally occurring fractures and faults. However, seismic imaging of fractures and faults in geothermal systems is difficult because the same fluid (hot brine) fills the fractures and faults as fills the matrix rock. To address this lack of geophysical contrast for imaging, we investigated the technical feasibility of a supercritical CO₂ (scCO₂) push-pull process to enhance characterization of transmissive features such as fault zones. We developed a conceptual reservoir model of the Dixie Valley Geothermal Area of Nevada that consists of two intersecting fault systems. The 2D conceptual model grid includes the main and conjugate faults by using irregular grid blocks. We performed numerical simulations of scCO₂ push-pull to investigate the CO₂ distribution in the faults. Sensitivity analysis was used to determine the most controlling unknown parameters and the most sensitive output responses in the fault zones. Using the selected sets of unknown parameters and output responses, we performed data-worth analyses to reveal the most valuable output response to be measured for the best prediction of CO₂ distribution in the fault zones and to estimate the prediction uncertainty. Our results provide information on the optimal design of scCO₂ 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).

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 systems (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 CO₂ (scCO₂) into the faults and fractures at EGS sites with active-source seismic monitoring and well-logging improved seismic detection of the transmissive fault zone because of the high compressibility of CO₂ (Borgia et al., 2017; Oldenburg et al., 2016; Zhang et al., 2015). After imaging the fracture and fault zone following injection, fluid production (pull) from the fault zone allows partial recovery of the injected scCO₂.

In this study, we investigate the technical feasibility of a scCO₂ push-pull process in the conjugate faults system at Dixie Valley Geothermal System (DVGS) in central Nevada, USA (Figure 1) (Lee et al., 2018). 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).

CONCEPTUAL MODEL

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 CO₂ and therefore retains the fundamental fault-flow-related aspects of the system.

Figure 2 shows the grid we developed for the 2D domain using WinGridder (Pan, 2008). The model contains a total of 10,728 grid blocks. This irregular grid system has elements connected along the fault zones parallel to flow directions, rather than the staggered connections that result from regular rectangular grid system. 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. Our model includes 32.5 m-thick and 22.5 m-thick fault zones in the main and conjugate faults, respectively. Hydrogeologic properties of the system for the numerical simulations are provided in Table 1. Potentially influential and unknown parameters for the flow of injected CO₂ in the fault zones are indicated with an asterisk (*).

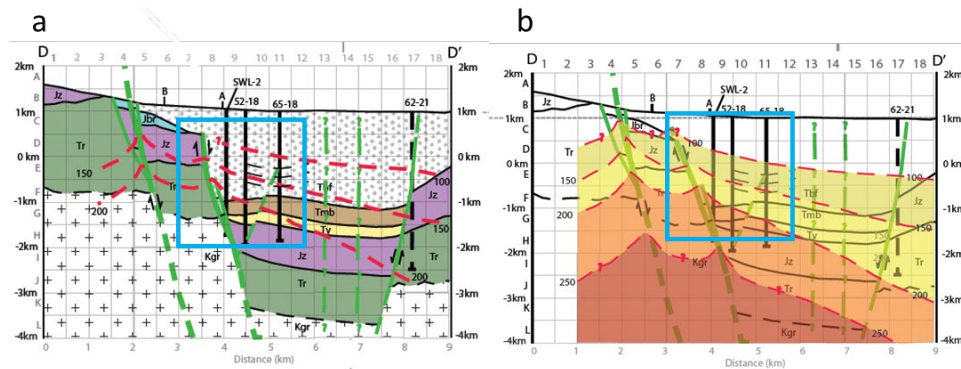


Figure 1. The Dixie Valley Geothermal System (DVGS) (Iovenitti et al., 2016): (a) geologic cross section involving dual faults, (b) isotherms along the cross section. The blue outline box superimposed on the cross-sections of Iovenitti et al. (2016) shows our model domain boundary.

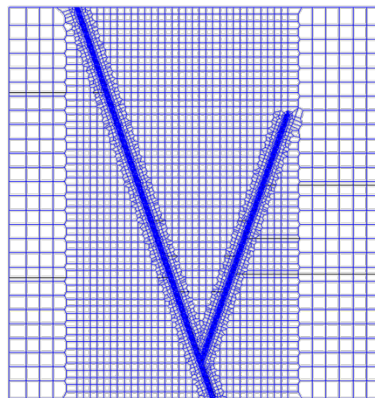


Figure 2. Grid geometry of the 2D conceptual model domain.

SENSITIVITY AND DATA-WORTH ANALYSIS

We used the PEST protocol of iTOUGH2 to perform sensitivity and data-worth analyses, along with the forward simulation of TOUGH2-ECO2N (Finsterle, 1999; Finsterle and Zhang, 2011). We conducted a formal sensitivity analysis of system responses in the fault zones to the unknown parameters shown in Table 1. From the formal sensitivity analysis, we determined the most influential unknown parameters and the most sensitive system responses. Next, we conducted data-worth analysis to determine the most valuable data to be measured for better prediction of CO₂ distribution in the fault zones, with respect to the influential unknown parameters.

Table 1. Properties of the DVGS (Borgia et al., 2017; Oldenburg et al., 2016).

Zone	Porosity [vol. frac.]	Permeability [m ²]	Parameters of capillary pressure	Parameters of relative permeability
Slip plane	0.30	$2 \times 10^{-12} *$ (1)	None	Corey, $S_{lr}^* = 0.3; S_{gr}^* = 0.05$
Fault gouge	0.10	$2 \times 10^{-12} *$ (1)	van Genuchten, $\lambda^* = 0.4438; S_{lr}^* = 0.30; S_{ls} = 1.0;$ $1/P_0^* = 2.100 \times 10^{-4} \text{ Pa}^{-1}; P_{max} = 10^8 \text{ Pa}$	Corey, $S_{lr}^* = 0.3; S_{gr}^* = 0.05$
Damage zone	0.05	$2 \times 10^{-15} *$ (1)	van Genuchten, $\lambda^* = 0.4438; S_{lr}^* = 0.30; S_{ls} = 1.0;$ $1/P_0^* = 6.641 \times 10^{-6} \text{ Pa}^{-1}; P_{max} = 10^8 \text{ Pa}$	Corey, $S_{lr}^* = 0.3; S_{gr}^* = 0.05$
High-permeability zone	0.10	5×10^{-16}	van Genuchten, $\lambda = 0.4438; S_{lr} = 0.30; S_{ls} = 1.0;$ $1/P_0 = 3.321 \times 10^{-6} \text{ Pa}^{-1}; P_{max} = 10^8 \text{ Pa}$	Corey, $S_{lr}^* = 0.3; S_{gr}^* = 0.05$
Low-permeability zone	0.05	10^{-16}	van Genuchten, $\lambda = 0.4438; S_{lr} = 0.30; S_{ls} = 1.0;$ $1/P_0 = 1.485 \times 10^{-6} \text{ Pa}^{-1}; P_{max} = 10^8 \text{ Pa}$	Corey, $S_{lr}^* = 0.3; S_{gr}^* = 0.05$
Impermeable zone	0.01	10^{-19}	van Genuchten, $\lambda = 0.4438; S_{lr} = 0.30; S_{ls} = 1.0;$ $1/P_0 = 4.696 \times 10^{-8} \text{ Pa}^{-1}; P_{max} = 10^8 \text{ Pa}$	Corey, $S_{lr}^* = 0.3; S_{gr}^* = 0.05$

We observed the following system responses using geothermal well logging tools: pressure and temperature at three different locations at $Z = -2925 \text{ m}$, -2520 m , and -2100 m in the main fault and conjugate fault. The system responses were measured from 2 days to 30 days with a measurement frequency of 1 day, both in push and pull. From the sensitivity analysis, we can narrow down the most influential unknown parameters in the push and pull phases. As results of formal sensitivity analysis after push and pull processes, Table 2 shows the sum of absolute scaled sensitivity coefficients of the five most sensitive parameters and responses. Subscripts *FS*, *FG*, and *DZ* indicate fault slip plane, fault gouge, and damage zone, respectively; and *M* and *C* indicate main fault and conjugate fault, respectively.

We performed the data-worth analysis to reduce the prediction uncertainty of CO₂ distributions in the fault zones, using the most influential unknown parameters affecting observation variables, which were obtained from the previous sensitivity analysis. The results of data-worth analysis are provided in Figure 3. In the push phase, $P_{M_2520 \text{ m}}$ showed the highest data worth for reducing prediction uncertainty, followed by $P_{C_2520 \text{ m}}$, $P_{C_2100 \text{ m}}$, and $P_{M_2100 \text{ m}}$. By summing up the data-worth values, we found that the measurement of these four observation data reduced the prediction uncertainty by 86.45%. In the pull phase, $P_{C_2100 \text{ m}}$ showed the highest data worth, followed by $P_{M_2100 \text{ m}}$, $P_{C_2520 \text{ m}}$, and $P_{M_2520 \text{ m}}$. The measurement of these four observation data reduced the prediction uncertainty by 99.97%.

Table 2. Sum of scaled sensitivity coefficients in descending order during the push and pull processes.

Parameters	Push	Parameters	Pull	Output responses	Push	Output responses	Pull
$1/P_{0_FG}$	4142.86	S_{gr_FG}	1320.00	$P_{M_2100 \text{ m}}$	4280.89	$P_{M_2100 \text{ m}}$	1988.90
λ_{FG}	2140.60	$1/P_{0_FG}$	942.86	$P_{C_2100 \text{ m}}$	3868.49	$P_{C_2100 \text{ m}}$	1821.98
S_{gr_FG}	1280.00	S_{gr_FS}	700.00	$P_{M_2520 \text{ m}}$	3102.24	$P_{C_2520 \text{ m}}$	894.35
S_{lr_FG}	1270.00	S_{gr_DZ}	370.25	$P_{C_2520 \text{ m}}$	1697.08	$P_{C_2925 \text{ m}}$	725.66
S_{gr_FS}	1220.00	K_{DZ}	462.82	$P_{M_2925 \text{ m}}$	927.11	$P_{M_2520 \text{ m}}$	698.18

CONCLUSIONS

In this study, we investigated the technical feasibility of scCO₂ push-pull testing in a conjugate fault system modeled after the EGS site in Dixie Valley, Nevada, USA. We performed forward numerical simulations of scCO₂ push-pull processes that could be carried out to emplace CO₂ as a contrast agent for seismic and well-logging characterization of the fault zones. Along with the forward simulations, we performed sensitivity analysis and data-worth analysis. From the formal sensitivity analysis, we determined the most

influential parameters in the fault zones on the measureable system responses such as pressure and temperature, and the most sensitive system responses among them. From the data-worth analysis, we determined the most valuable observation data to be measured for the best prediction of CO₂ distribution in the faults. These results can be used to guide field monitoring efforts to measure CO₂ saturation in order to calibrate and constrain active seismic monitoring used to characterize the extent and properties of fault zones relevant to EGS objectives.

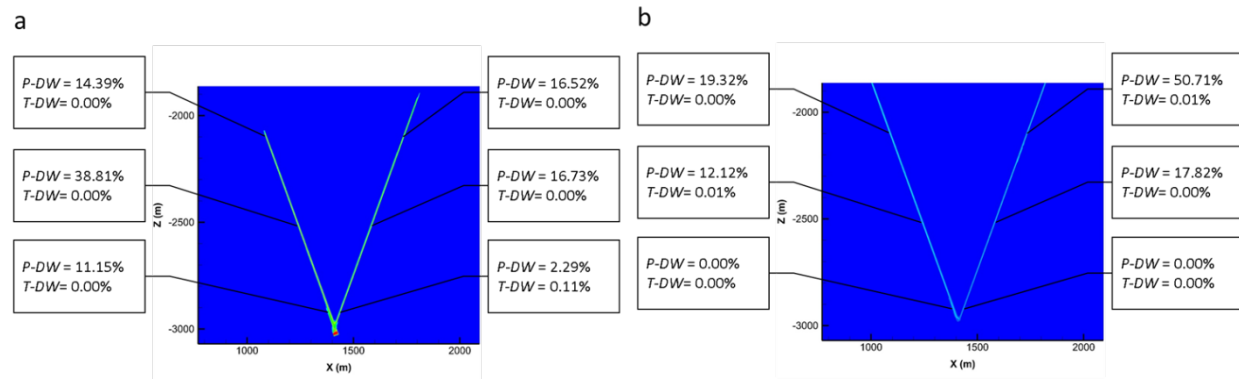


Figure 3. Data worth values at each observation point: (a) in push phase, (b) in pull phase.

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