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Simulations of CO_2 injection into fractures and faults for improving their geophysical characterization at EGS sites

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A B S T R A C T

We propose the use of CO_2 in push-pull well tests to improve geophysical identification and characterization of fractures and faults at enhanced geothermal system (EGS) sites. Using TOUGH2/ECO2N, we carried out numerical experiments of push-pull injection-production cycling of CO_2 into idealized vertical fractures and faults to produce pressure-saturation-temperature conditions that can be analyzed for their geophysical response. Our results show that there is a strong difference between injection and production mainly because of CO_2 buoyancy. While the CO_2-plume grows laterally and upward during injection, not all CO_2 is recovered during the subsequent production phase. Even under the best conditions for recovery, at least 10% of the volume of the pores still remains filled with CO_2. To improve EGS characterization, comparisons can be made of active seismic methods carried out before and after (time lapse mode) CO_2 injection into the fracture or fault. We find that across the CO_2 saturation range, C_{11} (the normal stiffness in the horizontal direction perpendicular to the fracture plane) varies between maximum and minimum values by about 15%. It reaches a maximum at around 6% gas saturation, decreasing exponentially to a minimum at higher saturations. Our results suggest that CO_2 injection can be effectively used to infiltrate fault and fracture zones reaching about optimal saturation values in order to enhance seismic imaging at EGS sites.

1. Introduction

For sustainable geothermal energy production, fracture permeability is essential to provide both rock-fluid surfaces for adequate heat transfer and sufficient fluid production rates. In most geothermal fields, a small number of extensive fractures and faults dominate fluid production. At enhanced geothermal system (EGS) sites, stimulation is used to create a more pervasive network of fractures to access more efficiently the heat stored in the volume of hot rock (Genter et al., 2010).

In order to design and evaluate reservoir development and stimulation strategies, effective fracture and fault network characterization of both natural and stimulated reservoirs is essential. To achieve this characterization, we propose to do active-source geophysical monitoring and well logging, and use CO_2 in push-pull well testing to enhance the contrast in geophysical properties between fractures and matrix and thereby improve fracture characterization (Borgia et al., 2015; Oldenburg et al., 2016).

The flow and transport properties of supercritical CO_2 relevant to its use in brightening faults and fractures for active seismic (or well-logging) imaging are:

1) CO_2 is much more compressible than water at EGS conditions, creating significant variations in stiffness tensor and correspondingly in seismic velocity;
2) CO_2 is non-wetting and will therefore tend to stay in the fault/fracture and resist flowing into fine-grained matrix; and
3) CO_2 is less viscous than ambient brine at geothermal conditions, facilitating fracture/fault permeation.

Although supercritical CO_2 has gas-like viscosity, which enhances its mobility, it is quite dense relative to other gases like nitrogen, which is an advantage for decreasing the negative consequences of strong buoyant rise in vertical faults and fractures.

In this paper, we report on simulated push-pull injection-production cycling of CO_2 into single fractures and faults to produce pressure-

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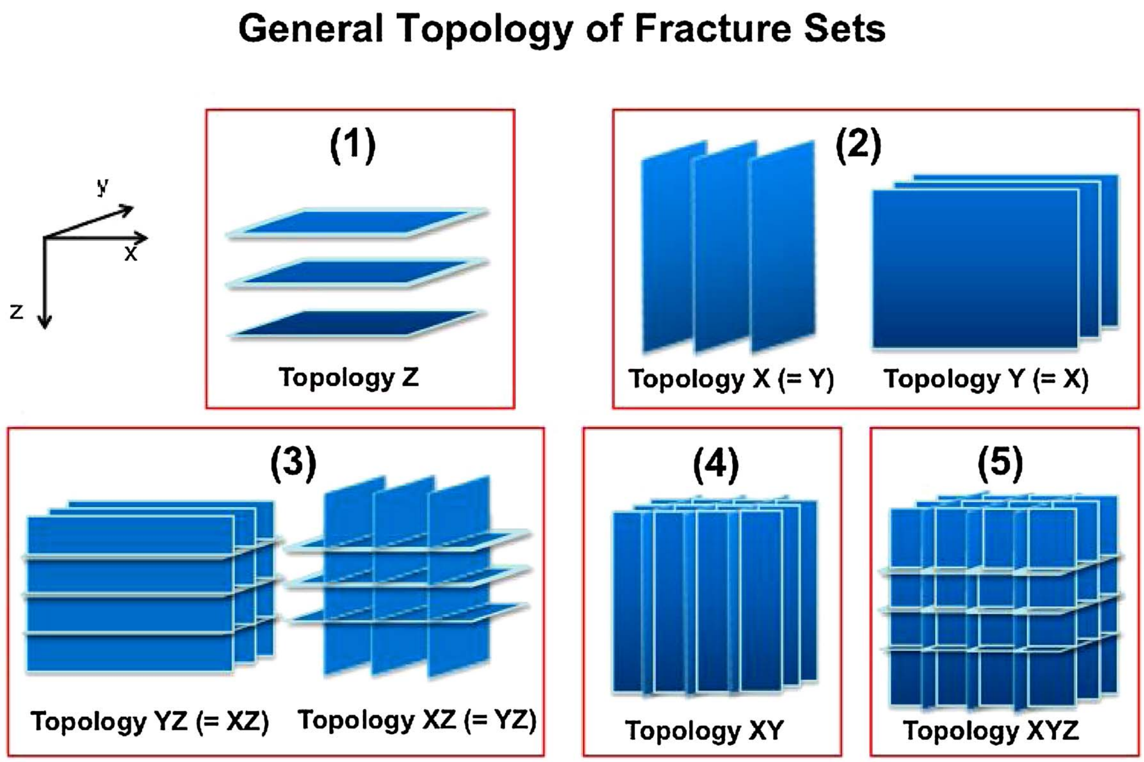

Fig. 1. The five independent fracture topologies. See text for explanation.

Table 1
Characteristic fracture geometry and ranges used in our modeling studies. See Fig. 2 for symbol definitions.

		min	max
A = fracture aperture		10^{-5}	10^{-4} (m)
d = damage zone thickness		10^{-1}	10^{1} (m)
S = fracture spacing		1	10^{2} (m)
D = fracture density	=1/S	1	10^{-2} (fracture/m)
H = fracture zone thickness		1	10^{3} (m)
L = fracture length		1	10^{3} (m)
W = fracture width		1	10^{3} (m)

saturation-temperature conditions that can be analyzed for their geophysical and wellbore logging response.

2. Conceptual model

Faults and fractures may be conceptualized using five independent topologies (Fig. 1), which serve to define basic model geometries. While these end-member topologies may only grossly represent the details and complexity of fractures and faults in an actual geothermal field, and their relations to true tectonic stresses, they are useful abstractions to understand fundamental behaviors that will be observed in natural systems.

Unconnected horizontal faults and fractures belong to Topology 1 where horizontal faults and fractures are perpendicular to the z-axis (which is here assumed vertical). Topology 2 occurs when vertical faults and fractures are perpendicular either to the x or y spatial