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An integrated site characterization-to-optimization study for commercial-scale carbon dioxide storage

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ABSTRACT

Injection of supercritical carbon dioxide ($scCO_2$) into deep saline aquifers is considered a promising option to mitigate global climate change. At a storage site, the main objectives of carbon dioxide sequestration are to maximize the volume of $scCO_2$ injected and minimize the leakage risk, while effectively managing formation fluid pressure buildup and the brine displaced by $scCO_2$. An integrated characterization-to-optimization study is carried out for potential commercial-scale deep saline aquifer carbon dioxide storage proposed in western Wyoming. A three-dimensional heterogeneous reservoir model is built for which petrophysical and fluid flow parameters are populated using field characterization data and state-of-the-art laboratory measurements. The measured $scCO_2$ relative permeability end point is low compared to previous measurements on similar sandstones, which poses a challenge for CO_2 flow, formation pressure control, and storage efficiency. By carefully selecting a set of optimal well locations, perforation intervals, and bottomhole pressure constraints that lead to maximum CO_2-in-place and minimal CO_2 breakthrough at the producers, an injection rate ranging from 10.8 to 15.1 Mt/year is achieved for a duration of 50 years. After $scCO_2$ injection ceases, up to 62% of the total injected $scCO_2$ can be immobilized as residual $scCO_2$ in 1000 years. Because of the low $scCO_2$ relative permeability end point, post-$scCO_2$-injection chase brine operation is not found to be an effective means of enhancing residual trapping. Instead, by modulating reservoir fluid pressure, boundary conditions of the reservoir exert a more significant impact on flow. Given the same well configuration and bottomhole pressure constraints, an open reservoir with lateral background flow allows 40% additional $scCO_2$ injection compared to a compartmentalized system without background flow. However, background flow leads to a lower trapping efficiency – after 1000 years post-$scCO_2$-injection, only 54% of the total injected $scCO_2$ is immobilized as residual $scCO_2$. This research suggests that a careful engineering design can contribute to significant CO_2 storage at commercial scales while enhancing storage security. Site-specific multi-phase flow data should be measured for such a design, since for the study site, chase-brine operation is not effective when $scCO_2$ relative permeability is low.

1. Introduction

Injection of supercritical carbon dioxide ($scCO_2$) into deep saline aquifers is considered a promising option to mitigate global climate change (IPCC, 2005). In a deep saline aquifer, driven by pressure gradient due to injection, $scCO_2$ will move through aquifer pore space, displacing brine. As $scCO_2$ continues to migrate, brine will begin to replace it, leaving some $scCO_2$ trapped by capillary forces (residual trapping). $scCO_2$ will also dissolve into the brine (dissolution trapping). Mineral trapping occurs from the reactions of dissolved CO_2 with solid grains. Geologic storage of carbon dioxide has been proposed for the state of Wyoming. From 2000 to 2011, energy-related CO_2 emissions in Wyoming increased from 62.9 to 63.8 million tons (Mt) (Stauffer et al., 2009; U.S. Energy Information Administration, 2014) and is further projected to increase with new energy demand, e.g., the proposed Southern California Edison (CEPL) project (Deng et al., 2012; WIA, 2013). Power plants such as these are the chief targets for conversion, to allow for the capture of CO_2 and subsequent sequestration underground.

To store CO_2 at the commercial scale, deep saline aquifers with large storage capacity are required. According to a review of existing storage operations in such environments, strategies that

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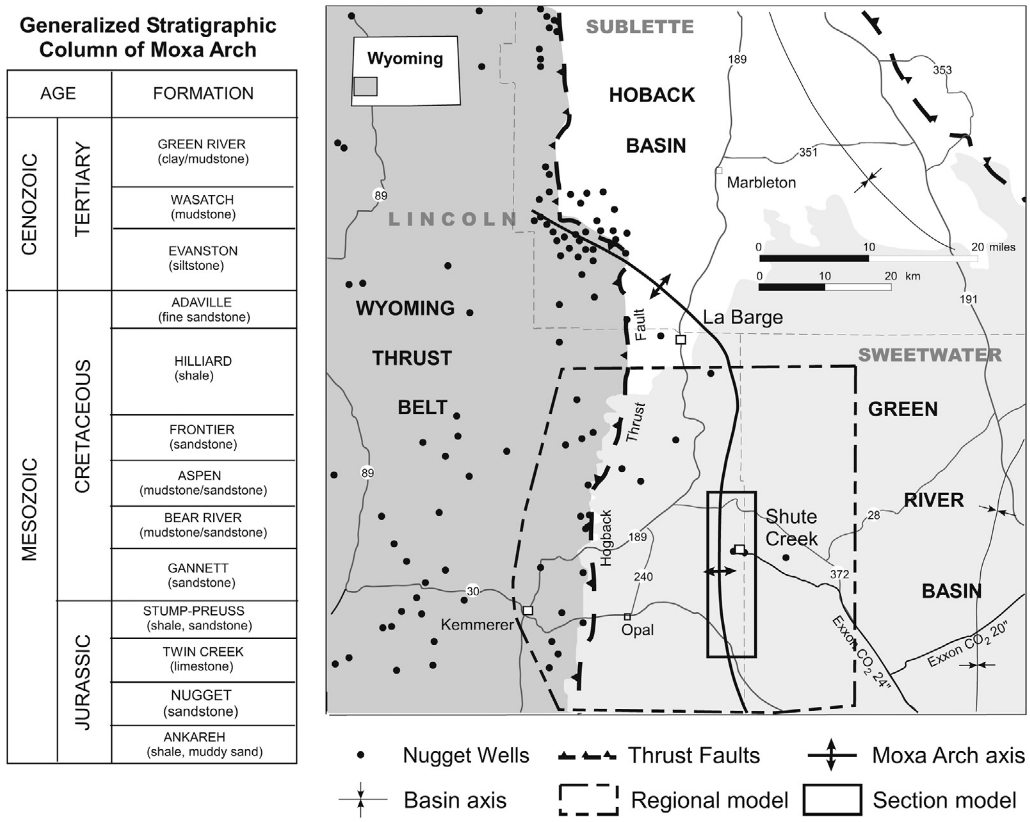

Fig. 1. Study area (Moxa arch) in western Wyoming. A generalized stratigraphic column is shown on the left. A regional model is indicated by the dashed outline within which a section model, centered at the Shute Creek gas plant, is extracted for the simulation study. Regionally, wells that penetrate to the depth of the Nugget Sandstone and deeper are shown.

Table 1
Dimensions and petrophysical properties of the Nugget Sandstone "core" used in this study. $K_{abs,brine}$ is the absolute permeability of the sandstone to brine.

Sample	Length (cm)	Diameter (cm)	Avg. porosity (%) (X-ray)	$K_{abs,brine}$ (mD)	Pore volume (cm^3)
Nugget Sandstone	14.8	3.81	14.28	312	24.09

Table 2
Physical properties of the fluid phases used in this study at 55 °C and 11.0 MPa (Span and Wagner, 1995; Bachu and Bennion, 2009; Batzle and Wang, 1992). IFT is interfacial tension.

Fluids	Density ρ (kg/m^3)	Viscosity μ (mPa s (cP))	$scCO_2$/Brine IFT (mN/m)
$scCO_2$	0.393	0.044	38.15
Brine	1.123	0.91	–

consider multiple injection wells and the optimization of aquifer pore volume sweep efficiency are key to the development of successful commercial-scale storage (Michael et al., 2010). Moreover, previous simulation studies suggest that subsurface boundary conditions – whether the deep saline aquifer has active or stagnant hydrodynamic flow – can significantly impact storage by contributing to active imbibition and dissolution (Li et al., 2011; Liu et al., 2011). Finally, safety and effectiveness of geostorage require that not only the volume of $scCO_2$ injected be maximized, but also that leakage risk be minimized.

The option of using a deep saline aquifer for commercial-scale carbon dioxide storage has pros and cons. Saline aquifers often have large storage volumes and are easily accessible to CO_2 point sources. However, it can be difficult to locate perfectly sealing caprocks at the extent of the plume footprint created by commercial-scale storage. At such scales, a variety of potential leakage pathways can exist inside and above the storage formation, including faults/fractures, lateral facies changes in the caprocks, and possibly leaky abandoned wellbores (Fitts and Peters, 2013; Song and Zhang, 2013; Shukla et al., 2010; Rosenbauer et al., 2005). To reduce migration and the subsequent encounters of leakage pathways, $scCO_2$ needs to be immobilized in the storage formation at or near the injection site. In addition, during injection, fluid pressure buildup can create additional leakage pathways if formation and caprocks experience geomechanical failures (Garridoa et al., 2013; Vilarrasa et al., 2014; Olabode and Radonjic, 2013; Smith et al., 2011; Mbia et al., 2014; Martinez et al., 2013). Finally, deep aquifer brine can be displaced into overlying formations via distinct pathways or diffusion, posing contamination hazards for shallow drinking water aquifers. Heavy metals and toxic compounds, for example, can be mobilized and transported to the near-surface environment by the displaced brine (Kharaka et al., 2009). All these factors must be taken into consideration when designing and executing a commercial-scale geostorage project in a deep saline aquifer.

To address the above issues, various strategies have been proposed that aim to achieve commercial-scale storage with enhanced storage security (a large fraction of the $scCO_2$ is immobilized at or near the injection site), while limiting migration and leakage (Flett et al., 2008; Qi et al., 2009; Surdam et al., 2009). These strategies may include: (1) using brine producers during $scCO_2$ injection to control formation fluid pressure buildup (Li et al., 2011), (2)