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Heterogeneity, pore pressure, and injectate chemistry: Control measures for geologic carbon storage

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A B S T R A C T

Desirable outcomes for geologic carbon storage include maximizing storage efficiency, preserving injectivity, and avoiding unwanted consequences such as caprock or wellbore leakage or induced seismicity during and post injection. To achieve these outcomes, three control measures are evident including pore pressure, injectate chemistry, and knowledge and prudent use of geologic heterogeneity. Field, experimental, and modeling examples are presented that demonstrate controllable GCS via these three measures. Observed changes in reservoir response accompanying CO_2 injection at the Cranfield (Mississippi, USA) site, along with lab testing, show potential for use of injectate chemistry as a means to alter fracture permeability (with concomitant improvements for sweep and storage efficiency). Further control of reservoir sweep attends brine extraction from reservoirs, with benefit for pressure control, mitigation of reservoir and wellbore damage, and water use. State-of-the-art validated models predict the extent of damage and deformation associated with pore pressure hazards in reservoirs, timing and location of networks of fractures, and development of localized leakage pathways. Experimentally validated geomechanics models show where wellbore failure is likely to occur during injection, and efficiency of repair methods. Use of heterogeneity as a control measure includes where best to inject, and where to avoid attempts at storage. An example is use of waste zones or leaky seals to both reduce pore pressure hazards and enhance residual CO_2 trapping.

1. Introduction

Injection of carbon dioxide (CO_2) into the subsurface modifies local and regional subsurface stress and perturbs chemical environments. This displacement from quasi-equilibrium can have both beneficial and detrimental consequences to secure storage of CO_2, requiring these consequences be managed – or controlled – to maximize benefit and efficiency. Three challenges for geologic carbon storage (GCS) include sustaining injectivity over the lifetime of a field or project, maximizing storage efficiency, and avoiding unwanted consequences (such as unintended leakage or induced seismicity).

In this paper, we argue that injectate chemistry, pore pressure, and reservoir/caprock heterogeneity are controllable elements to meet these subsurface science and engineering challenges. Few subsurface variables are as easily manipulated or controlled as injectate fluid chemistry and this is best exemplified by practices in the shale gas industry. Abundant experimental evidence shows a clear but not well-understood link between chemical environment and rock compressive,

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tensile, shear, and frictional strength. GCS injection involves a major perturbation of subsurface chemical environments (Romanak et al., 2013), and the inherent couplings between this chemical perturbation and geomechanical response are largely unknown and mechanistically not understood.

Regarding pore pressure, suggested risk profiles for GCS (e.g. Benson, 2007; Li and Liu, 2016) peak during an injection phase and taper to zero post injection. This mimics rise and fall of pore fluid overpressure and size of pressure build-up, showing that pore pressure rise with CO_2 injection is considered a main source of risk for GCS. Risks include caprock leakage pathway development (Cartwright and Santamarina, 2015), migration up abandoned wellbores (Nordbotten et al., 2005), dilatant faults and fractures in caprock (Ingram and Urai, 1999; Nicot et al., 2013), and induced seismicity (Zoback and Gorelick, 2012; Rutqvist et al., 2014; Ellsworth et al., 2015).

Heterogeneity is a critical consideration for aspects of GCS and especially for the challenges of injectivity sustainment (Deng et al., 2012), maximization of storage efficiency (Mozley et al., 2016; Kuo and Benson, 2015; Delshad et al., 2013; Shamshiri and Jafarpour, 2012; Saadatpoor et al., 2009; Hovorka et al., 2004) and leakage pathway development (Cartwright and Santamarina, 2015). Geostatistical and stochastic methods are necessary to surmount the relative scarcity of data from the subsurface (Lee et al., 2007), and this is exacerbated for GCS as many saline formation targets, having no petroleum or water resources, are relatively unexplored and uncharacterized.

Framing our discussion in the contrasting geological environments of the US Gulf Coast and the midcontinent Illinois Basin, in this paper we investigate examples of science-based engineered solutions to challenges of controlling injectivity, storage efficiency and undesirable behavior. In the following, we intertwine these three themes in examples from field, laboratory, and modeling studies, over length scales ranging from 10's of km to a few microns, to demonstrate: role of injectate chemistry in permeability enhancement; pore pressure control through brine extraction; high fidelity coupled hydromechanical modeling used for prediction and decision making; mitigating wellbore damage and leakage; and using reservoir-seal heterogeneity to maximum benefit.

2. Control measures for GCS

It is our view that three major challenges to GCS are sustaining injectivity over the lifetime of an injection project, maximizing storage efficiency in a particular reservoir, and avoiding unwanted consequences such as leakage through caprock or along faults. Control measures are desired science-based solutions that directly address these engineering challenges, enabling more efficient, economical, safe and secure storage of carbon in the subsurface. For example, fractures and fracture permeability can be both a desired, beneficial aspect to reservoir storage, improving injectivity, sweep efficiency, and storage. But fractures and faults can be detrimental, serving as leakage pathways or perhaps leading to induced seismicity accompanying fluid injection. Control measures in this case serve to maximize the benefical aspects while minimizing the detrimental and/or hazardous. This could include extending fractures and improving permeability and sweep in a manner similar to reservoir stimulation in unconventional hydrocarbon reservoirs, while avoiding unwanted fracture permeability enhancement through caprocks or by fault movement. We propose that manipulation of injectate fluid chemistry, maintaining a level of control of pore fluid pressure, and extensive knowledge of subsurface heterogeneity, are means to best control fracture permeability and other desirable attributes of GCS. The following examples serve to demonstrate the usefulness of these control measures, but certainly are not exclusive with respect to other means to manage GCS.

2.1. Control of fracture permeability by injectate chemistry

Injectate chemistry is used by the shale gas industry to deliver proppant within new fracture permeability generated by hydrofracture. Within GCS, the potential regulatory constraint on limiting injection pressure to be below a formation breakdown pressure at given depth (Wu et al., 2015) may limit the ability to stimulate near-wellbore permeability by hydrofracture for improvements in sweep and storage efficiency. Mineral dissolution and precipitation are known to have an obvious effect on fracture permeability (Morrow et al., 1990; Yasuhara et al., 2006; Tokan-Laval et al., 2015) and rock strength (Hu and Hueckel, 2013; Rohmer et al., 2016) but require multiple pore volumes of fluid displacement for changes to occur. Chemically assisted subcritical fracture growth, or stress corrosion cracking, is thought to be the main controlling factor in the time and deformation-rate-dependent failure of rocks (e.g. Anderson and Grew, 1977; Atkinson, 1984; Swanson, 1984; Holder et al., 2001) and poses no such volumetric constraint. Can injectate chemistry be used for reservoir stimulation via subcritical fracture or other mechanisms?

The significance of chemically assisted fracture growth has been demonstrated for natural fracture networks in mudstones and other lithologies (Wiltschko and Morse, 2001; Eichhubl et al., 2001; Eichhubl and Aydin, 2003; Eichhubl, 2004; Jamtveit et al., 2009; Becker et al., 2010) and in experiment (Atkinson, 1980; Karfakis and Akram, 1993; Olson, 1993, 2004; Baud et al., 2000; Espinoza and Santamarina, 2012; Brantut et al., 2013) suggesting that sub-critical fracture growth provides a mechanism of fracture growth and failure in quasi-static subsurface environments (Becker et al., 2010) occurring on time scales from annual to decadal and millennial (Brantut et al., 2013, 2014; Atkinson, 1980, 1984). In aqueous-dominated fluids, mineral reactions have been shown to play a key role in subcritical fracture development at both bulk and microscopic scales. Application of water to Lyons sandstone results in force reductions of 25% of the ultimate strength (Baud et al., 2000). Dove (1995) demonstrates that molecular level dissolution reactions govern subcritical fracturing of quartz single crystals; in particular, availability of water to fracture tips promotes fracture growth by two chemical reactions: 1) reaction of a protonated surface with molecular water, and 2) reaction of hydroxyl ions at an ionized surface. Similarly, water weakening of chalk has been attributed to the sorption of water on calcite surfaces (Risnes et al., 2005; Røyne et al., 2011).

For GCS, the subsurface chemical environment is unavoidably perturbed by injection of supercritical CO_2 ($scCO_2$) fluids, reactive gases such as NO_x, SO_x, or O_2, and engineered materials. Mineral reactivity regimes span both aqueous-dominated $scCO_2$-equilibrated brines with a range of water activity, pH, and salinity, and supercritical fluid-dominated water-bearing $scCO_2$ with a range of H_2O activities associated with pore dry-out and $scCO_2$ plume migration (Kharaka and Cole, 2011; DePaolo and Cole, 2013). These chemical changes may influence mechanical integrity of reservoir and caprock lithologies. Major et al. (2014) show large changes in fracture toughness in a variety of lithologies from the Crystal Geyser (Green River, UT, USA) region from varying exposures to CO_2-bearing fluids associated with fault-related leakage. Dissolution of grain-coating iron oxide mineral cements was shown to lower sandstone fracture toughness, whereas precipitation of calcite pore cement from CO_2 seepage was shown to increase fracture toughness. Major et al. (2014) also show changes in subcritical crack index (which relates subcritical fracture propagation rate to stress intensity) to be also influenced by CO_2-related alteration. This suggests two end-member behaviors to chemo-mechanical coupling for fracture: a short-time, kinetic effect associated with near-instantaneous stress-corrosion or sub-critical fracture mechanisms, and a longer-time effect associated with dissolution or precipitation of pore-filling cements with or without accompanying oxidation-reduction reactions, which would depend on amount of pore volume flushing.

In supercritical fluid-dominated water-bearing $scCO_2$ systems,

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