Brittle-Ductile Behavior and Caprock Integrity

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Abstract

CO\(_2\) storage reservoirs are subject to mechanical stresses induced by CO\(_2\) injection and tectonic forces. Long-term integrity will require that storage reservoirs are capable of absorbing these stresses without creating or activating permeable leakage pathways. In the context of monitoring a CO\(_2\) storage site, induced seismicity occurring within the caprock indicates potential damage to the seal. However, the relationship between fracture activation and permeability (particularly temporal evolution of permeability) is poorly understood. Therefore the consequences of induced seismicity on reservoir integrity are not well bounded.

The brittle or ductile character of caprock should play an important role in assessing consequences of the activation of fracture systems. The transition from brittle to ductile behavior can be associated with a transition from dilatant to non-dilatant deformation (e.g., Ingram and Urai 1999) and therefore a transition from more to less permeable fracture systems. Controls on this transition include temperature, pressure, mineralogy and water content. In addition, creep (perhaps associated with ductile behavior) may result in a reduction of permeability with time as fractures close. At present, there are few experimental or field data that allow quantification of changes in permeability during the transition from brittle to ductile deformation.

In this study, we present experimental data in which we characterize fracture-permeability behavior of shale as a function of confining pressure as a means of exploring the brittle-ductile transition. The experiments were conducted using a triaxial coreflood system operated in a direct-shear configuration that creates through-going fractures for permeability measurements. Confining pressure was varied between 3.5 and 22 MPa. Fracture characteristics were examined using x-ray computed tomography in both \textit{ex situ} and \textit{in situ} modes. During \textit{in situ} operation, the triaxial coreholder and sample were imaged at pressure and temperature allowing direct visualization of \textit{in situ} fracture distribution and apertures.

At low confining pressure (3.5 MPa), permeability of fractured Utica shale was strongly dependent on fracture interactions with bedding planes and varied from 10s to 100s of mD (calculated with respect to the total sample area). Fracture systems crossing bedding planes resulted in tortuous paths with lower permeability. Fracture systems propagating parallel to bedding had substantially elevated permeability with some \textit{ex situ} apertures greater than 500 \textmu m. This behavior contrasted with fractures developed at high confining pressure (22 MPa). \textit{In situ} x-ray tomography showed that localized deformation occurred on sub-resolvable fractures (less than 25 \textmu m aperture) much smaller than apertures formed at low confining pressure. Permeability of the fractures formed at high confining pressure was less than 0.1 mD and about 3 orders of magnitude lower than the low confining pressure case.
Our experimental observations show the profound impacts of confining pressure on fracture permeability and illustrate the potential role of ductile behavior in mitigating fluid loss following fracture activation (Frash et al., submitted). Similar observations of low permeability in addition to self-sealing behavior have been made in studies of mechanical deformation in shale-based nuclear waste repositories (e.g., Bernier et al. 2007; Menaceur et al. 2015). Thus ductile caprock having suitable mineralogy (e.g., clay-rich shale) occurring at sufficient depth may be capable of absorbing significant deformation without generating transmissive fracture pathways. These results suggest that characterization of the fracture-permeability character of caprock at reservoir conditions should be an important component of site characterization and the criteria for a suitable storage site. With sufficient experimental and field observations, it may be possible to bound the potential magnitudes of CO₂ leakage resulting from injection-induced seismic events.


