Monitoring technology to enable characterization of CCUS reservoirs

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Summary

Surveillance monitoring technology enables effective injection projects by accurately capturing the physical properties of the subsurface that impact injection. Without proper monitoring and planning, fluid injection into the subsurface can lead to adverse effects, including fault reactivation or microseismic events, out of zone injection, or even fracturing into the overburden. Subsurface data enables model calibration and inclusion of complexity that can accurately explain and constrain these multifaceted systems, helping to design reliable storage systems for CO_2 injection. A range of surveillance technologies are needed to adequately monitor the subsurface for proper characterization of the effectiveness of long-term storage in CCUS reservoirs and deliver innovations for increasing efficiency. As learnings are captured and innovations grow, utilization of the surveillance technologies will evolve and possibly be more selective.

Core measurements of depletion and injection cycles are needed to build models that accurately represent hysteresis or plastic deformation. Enhanced physical property models improve the understanding of the potential to inject into a reservoir without any adverse subsurface effects. Data from Interferometric Synthetic Aperture Radar (InSAR) and Pressure Monitor Transponders (PMTs) are useful to constrain model deformation and to identify deformation due to out of zone injection and fault reactivation. Microseismic is critical for monitoring injection in fractured and faulted fields. 4D seismic can be used to monitor CO_2 plume migration, but it is also useful for identifying strain responses associated with overburden fracturing and fault reactivation. Electromagnetic data can also be used to understand out of zone injection. Wellbore monitoring, including DAS / DTS / DSS / DPS, helps to understand cement integrity and long-term storage viability. CO_2 leak detection technology at the wellbore and the field scale ensures reliability of the system. The gamut of surveillance technologies enables perspectives from the well scale to the regional scale and helps to uncover the subsurface complexities that inhibit efficiency and storage capacity.

Introduction

A major challenge involved in CO_2 injection involves understanding the “injectivity” of a subsurface reservoir, or the ability to inject into a reservoir without adverse subsurface incidents occurring. A common misconception is that if a reservoir has been depleted, injection of CO_2 will result in filling the same pore space that hydrocarbons once filled. However, once a reservoir compacts, it may never return to the same uncompacted state even under large rates of injection. Thermodynamic changes in the reservoir can also lead to flow assurance issues, further reducing CO_2 injectivity.

Injection in depleted reservoirs or saline aquifers may lead to rock failure within or outside the reservoir. Understanding the stress changes from depletion or previous deformation can help to mitigate such hazards. Fractures within the reservoir create permeability highways for injected fluid to migrate through relatively quickly, in lieu of phase changes. Natural or injection-induced fractures can be captured in models to improve the prediction of the flow of injected fluid. Injection pressures above the caprock’s failure envelope can lead to out of zone injection or broaching. Safe injection pressure limits can be estimated by models that are constrained by geomechanical data from both the reservoir and the containment layers. Injection-related dilation on one side of a fault can lead to fault slip or reactivation. Pressure management to avoid compaction and dilation on either side of a fault is a mitigation technique for fault reactivation. Pore pressure changes in fractured and faulted zones may lead to induced seismicity events that can damage subsea and surface infrastructure. Adequate characterization of the faults and fractures can help to inform injection strategies to alleviate induced seismic events. The subsurface incidents that can occur from injection may not only cause unintended consequences with significant costs to mitigate, but they may inhibit the ability to inject high enough rates to maintain CCUS projects at economic thresholds. The data we acquire to monitor and characterize the subsurface is the key to driving innovation to deliver economic CCUS projects.

The utility of surveillance in CCUS

Geomechanical core data commonly demonstrates hysteretic behavior in rocks, where the samples behave differently upon loading (depletion) and unloading (injection). Usually, rocks are stiffer under unloading, and some also experience large amounts of plastic or permanent deformation. In general, during hysteresis, rocks that are unloaded do not recover all the strain they experienced during the loading phase (Jaeger et al., 2009). Modeling injection on a reservoir based on how it deformed during depletion can lead to gross overestimations of the “injectivity” of reservoirs.

Natural fractures have a strong hysteretic behavior, as observed in the lab. Once fractures close due to depletion, it takes a longer rate of injection to re-open the fractures and they usually do not return to their initial aperture (Bandis, et

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al., 1983). Injection in depleted, fractured zones may require significant rates to increase the porosity, which may in turn lead to induced seismicity. Such induced seismicity events are helpful to identify where in the subsurface injection-related events occur but differentiating the events that are due to fractures shearing vs. fault reactivation is challenging. Fault reactivation can be monitored on land using InSAR and GPS, and in deepwater fields using PMT data, where the transponders are positioned on either side of a fault. Sudden relative movement in the data can be tied to localized fault movement at the seafloor.

Another assumption for long-term storage is that the stress state in the reservoir and overlying seal remains constant after injection has occurred. Creep occurs when a rock deforms while stresses, pore pressure and temperature are held constant (Jaeger et al., 2009). The presence of creep is an indication that the rock deformation depends on the rate or speed of loading or unloading, and it requires a visco-elastic material model to describe the behavior. Core tests or "creep holds" can be performed to measure the visco-elastic parameters of rocks under different loading conditions. In cases where rocks exhibit creep, slowly loading (or depleting) the rock will lead to more compaction than a similar rock undergoing a fast depletion rate. Visco-elasticity can reduce the strain and porosity recovery in a depletion-injection cycle with low rates of loading or unloading.

Visco-elastic effects are often difficult to unravel because surveillance data is relatively limited, providing "snapshots" in time for the state of the field. InSAR data provides frequent measurements of surface displacements for sub-aerial fields, which can be utilized to invert for the underlying subsurface production effects and infer the root causes of deformation. Deepwater reservoirs are often monitored utilizing 4D, or Time Lapse, seismic data to understand production effects. Fields like Sleipner demonstrate the utility of monitoring the CO_2 injected plume using multiple 4D seismic amplitude difference volumes, which predominantly highlight changes in pressure and saturation (Chadwick et al., 2010). Fractures out of zone may be observed using 4D seismic time shift volumes, which illuminate strain changes that have occurred in the overburden. Resistive CO_2 plume migration can be monitored with electromagnetic data, and out of zone injection can be understood utilizing inversion methods.

Fiber-optic wellbore monitoring, including DAS, DTS, DSS, and DPS, may provide key information about the success of the novel cements for CCUS and their long-term viability. Pipeline and wellbore leak detection technology are needed to ensure system integrity.

Driving innovation

Surveillance data provides insights into the failures of our current thinking for subsurface characterization that supports CCUS. Microseismic arrays identify sub-seismic faults and fractures that were not previously characterized. InSAR highlights surface deformation that cannot be explained by current models. 4D seismic highlights plume migration and unexpected overburden anomalies, and core measurements provide calibration to quantify the observed changes in the subsurface. Fiber optic data provide observations that enable safe well completions and wellbore integrity monitoring.

Many mechanical models for injection rely on a linear elastic model that may overestimate the amount of porosity recovery due to injection in a depleted reservoir. Such models also tend to underestimate the stiffness of the reservoir during unloading, potentially magnifying the upward deformation of the reservoir and overburden. Thermodynamic phase changes during CO_2 injection require a coupled simulation that accounts for the phase changes, temperature changes, and mechanical changes created from injection. In some cases, coupled reservoir and geomechanical models will require the use of non-linear models (hysteretic, elasto-platic, visco-elastic, or all these effects) to make a more consistent prediction of strain and porosity changes. Such models require calibration data from core measurements that can adequately represent the injection or depletion-injection effects. As the industry continues building more complex models to understand and explain CO_2 injection and storage, the data we acquire to build these models is also needed to drive the innovations for more efficient subsurface characterization, reservoir management, and technology utilization. Surveillance deformation data can constrain the subsurface models and help to drive new insights into innovative methods for developing CCUS.

Acknowledgements

The authors would like to thank Chevron and its affiliates for permission to publish this work, as well as the many colleagues that provided thoughtful feedback and dialogue.

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