The Effect Of Facies Heterogeneity In The Late Jurassic Arabian Carbonate Strata On Fluid Flow And Time-lapse Seismic Monitoring During Carbon Capture And Storage (CCS): An Insight From Outcrop-based Models

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Abstract

Objectives/Scope: The laterally heterogeneous Late-Jurassic Arabian carbonate aquifers are excellent candidates for geological CO$_2$ storage. However, inadequate resolution of heterogeneities in the subsurface prevents assessing the effect of facies heterogeneity on CO$_2$ flow and potential seismic monitoring for these typical coarsening-upward strata. This study utilizes facies architecture from outcrops simulated under analog subsurface conditions coupled with a forward time-lapse seismic model to investigate the effect of reservoir heterogeneity on monitoring CO$_2$ injection and subsurface propagation.

Methods, Procedures, Process: We mapped the 3D facies heterogeneity of Late-Oxfordian to Eary Kimmeridgian outcrops using a digital outcrop model, cores, ground-penetrating radar, and near-surface seismic surveys. Using process-based modeling, we built a 16 km$^2$ geologically realistic facies model that mimics the observed heterogeneity. We compiled subsurface analogous reservoir porosity and permeability and utilized them to construct analog static models. We calculated facies-dependent seismic properties under different saturation using differential effective media and fluid substitution models and simulated 50 years of CO$_2$ sequestration using the constructed models. A zero-offset forward seismic model was calculated for every simulated year parallelly.

Results, Observations, Conclusions: Permeability contrast and connectivity between stromatoporoid/coral facies and grainstone units with the enveloping bioturbated wackestone-packstone facies impacts the evolution of the CO$_2$ plume in the analog reservoir. Different stratigraphic levels exhibit different sweep efficiency, with CO$_2$ plumes showing bypass, irregular sweep, and fingering controlled by facies architecture. The sweep is relatively homogenous in strata with coeval stromatoporoid/coral facies and skeletal bioclastic and oncoidal grainstones. In strata of stromatoporoid/coral facies associated with bioturbated foraminiferal wackestone background, the sweep advances anisotropically following the general shape and orientation of buildups. The sweep is again more homogenous in the lower reservoir units characterized by grainstone facies enveloped by bioturbated wackestone-packstone units. Due to limited vertical resolution, these stratigraphic-dependent flow patterns are sub-seismic. Bandlimited destructive interference due to vertical facies heterogeneity caused faint (~5%) amplitude difference between modeled baseline and monitor seismic surveys.
Additionally, the time-lapse anomalies only show the most-advanced CO\textsubscript{2} plume at a time, which mainly originated from the expansion due to permeability bridges caused by stromatoporoid/coral facies.

**Novel/Additive Information:** Facies heterogeneities and the resulting permeability contrast in the Late Jurassic Arabian carbonate strata affect the evolution of CO\textsubscript{2} plumes during sequestration. This facies-controlled flow preference results in a portion of the reservoir being favorably flooded by CO\textsubscript{2}. Time-lapse seismic anomalies, while detectable, are faint and do not fully capture the flow heterogeneity. Thus, to increase the resolution for monitoring, time-lapse borehole seismic surveys might be needed.