Closing the Loop: 4D Seismic Constraints on CO_2 Flow Simulations from the Aquistore CO_2 Storage Site

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Summary

The Aquistore CO_2 Storage site is located within the Williston Basin in southeast Saskatchewan. The storage reservoir is a 200 m thick Cambro-Ordovician hyper-saline clastic formation lying unconformably on the Precambrian basement at ~3400 m depth. Initial characterization of the site was based on interpretation of a 30 km^2 3D seismic volume (White et al., 2016) and subsequent quantitative assessment (White, 2018). 3D porosity was calculated using acoustic impedance from model-based seismic inversion and a log-based porosity-impedance relation. The reservoir has a mean thickness of 219 m of which 51% is pay. Strata dip at ~2% SSE and include a prominent SSE-NNW structural fabric dominated by a ridge that corresponds to an interpreted Precambrian basement fault and overlying flexure. Porosity maps for Winnipeg-Black Island and Deadwood reservoir zones show a weak degree of directionality that is sub-parallel to the strong NNW-SSE structural trends.

CO_2 injection began at the site in April of 2015 and has continued to present at rates of ~60 ktonnes per year with a total of 361 ktonnes injected as of March 2021. Key components of reservoir monitoring at the Aquistore site include passive monitoring for induced seismicity, 4D seismic using a permanent 2D array of surface geophones and well-based distributed acoustic sensing (DAS). 4D surface seismic and VSPs have been acquired at times when cumulative injected CO_2 was 0, 36, 102, and 141, respectively (Roach and White, 2018). The most recent 4D survey was acquired in 2020 with 272 ktonnes of CO_2 injected. Passive seismic monitoring began prior to the start of injection.

Time-lapse amplitude differences observed in the 4D seismic volumes are interpreted as zones of CO_2 saturation. The CO_2 generally appears to be migrating in the regional up-dip direction (NNW) following the observed structural and porosity/permeability fabric in the reservoir. Results from the 4D seismic analysis are compared against in situ measurements of flow rates at the injector and time-lapse CO_2 saturation logs from an observation well. The 4D seismic data image a primary CO_2 plume within a ~10 m thick high-permeability interval within the upper Deadwood Formation of the reservoir. This plume has continued to expand in sequential 4D images. Most recently, a secondary plume has been imaged within the Black Island member of the Winnipeg Formation in the upper part of the reservoir.

Pre-injection CO_2 flow simulations (e.g., Jiang et al., 2017) predicted radial flow outward from the injection well in contrast to the observed prominent directionality of CO_2 spread interpreted from the 4D seismic. Furthermore, the interpreted structural flexure appears to be impeding the flow of CO_2 westward from the injection well. Revisions to the geological flow model for the reservoir have been made to improve the history match to the 4D seismic data (Rangriz Shokri et al. 2019). In particular, two key features have been included in the model: 1) anisotropy in the horizontal permeabilities based on the impedance inversion results, and 2) a lateral flow barrier corresponding to the interpreted stratal flexure/ basement fault that is sub-parallel to the dominant structural trends.

Using stochastic modeling tools, a set of realizations was generated to address the uncertainties associated with assigning the petrophysical variables (e.g. facies, porosity, permeability), as well as with locating the flexure (as a permeability baffle). Because CO_2 is injected at a substantially lower temperature (~70˚C) than the formation temperature (~120˚C), the non-isothermal option of CMG-GEM simulator was used to match the CO_2 injection history of the Aquistore injection well in the targeted saline formations, and its breakthrough at the observation well (~151 m away from the injector). Resultant flow simulations show lateral CO_2 spread that is more consistent with the 4D seismic images (Figure 1).

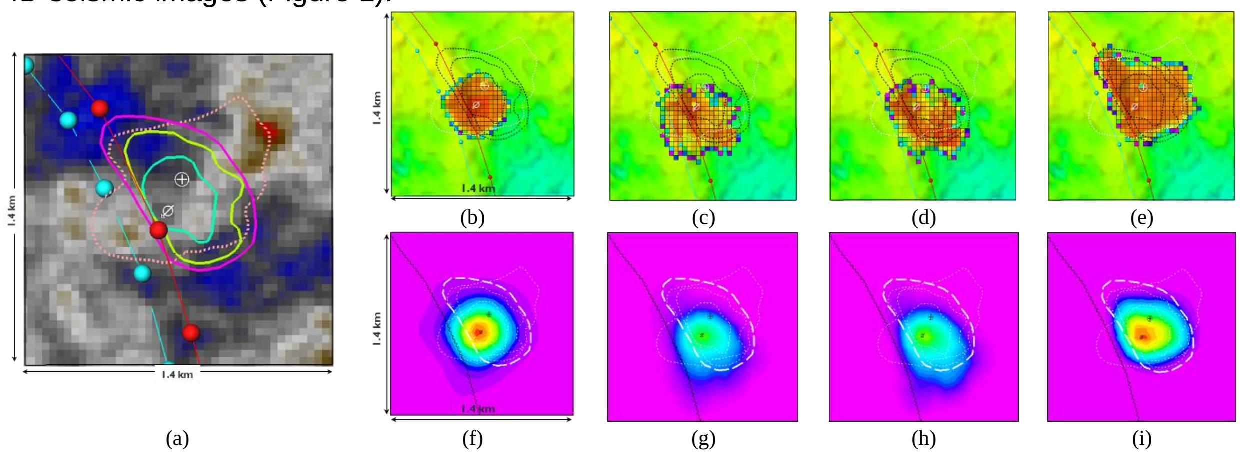

Figure 1: (a) outlines of the CO_2 plume interpreted from different seismic monitor surveys. (b)-(e): top-view of CO_2 saturation from the flow simulator in the top layer of the Deadwood D formation with respect to the outlines of the CO_2 plume for the following approaches to model building (b) layer cake geology, (c) stochastic properties, (d) stochastic properties with structural flexure, (e) petrophysical properties constrained by acoustic impedance and with structural flexure. (f)-(i) show their equivalent saturation-thickness average maps for all layers.

References

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