Introduction

The Southwest Partnership on Carbon Sequestration (SWP), one of seven large scale CO₂ sequestration projects sponsored by the U.S. Department of Energy beginning in 2003. The project has culminated in a large-scale demonstration project at an active commercial-scale carbon capture, utilization and storage (CCUS) project site. CO₂ stored during the injection period was sourced from a fertilizer and an ethanol plant, and would have otherwise entered the atmosphere. This project has demonstrated all aspects of a commercial CCUS field operation, including reservoir engineering, monitoring, simulation, and risk. The project has successfully optimized the Enhanced Oil Recovery (EOR) to CO₂ storage balance, used direct monitoring for leakage, and 4D seismic to observe both the distribution and phase of CO₂ in the storage formation. In addition, the project has contributed to best practices manuals for associated carbon storage.

The SWP Phase demonstration project is located within a mature waterflood in the Farnsworth Unit, Texas, and began conversion to a CO₂ flood in October of 2010. The SWP began studying the site in October of 2013. Between October, 2013 and July 31, 2018, injection in 15 wells sequestered more than 800,000 metric tonnes of CO₂. An additional 440,516 tonnes of CO₂ storage were associated with CO₂ EOR efforts prior to October, 2013. The site operator converted a row of inverted 5-spot patterns to CO₂ every year between 2011 and 2015, making the site an excellent testing facility for CO₂ monitoring technologies. Each new row of injectors provided a new opportunity to record baseline data, mid-flood data, and data from fully flooded patterns. The project acquired comprehensive data sets for site characterization, monitoring CO₂ plume growth, and storage security. The project drilled, logged, and collected core from three characterization wells which has allowed for creation of increasingly detailed geocellular models. Studies of rock mechanics in both the reservoir and seal units, and comprehensive laboratory studies of relative permeability examined 8 distinct sub-facies of the Morrow sandstone reservoir were incorporated into flow models for use in history matching, predicting CO₂ concentrations and distributions in the reservoir, production/storage optimization, and risk assessment of long-term storage security.

This paper discusses the evolution of static geocellular models for the project over a period of six years, and highlights techniques which could be applied to other sites considered for similar development.

Methods

During each year of the injection period, an updated fine-scale geologic model was produced and distributed for simulation analyses necessary for effective risk assessment and for increased resolution of monitoring, verification and accounting tasks. The SWP continually refined the FWU geological model during the course of the project. The data incorporated includes logs, reprocessed 3D seismic, fault, fracture features, updated hydraulic flow units, and information gleaned from the microseismic analysis. In the most recent iteration, geological, geophysical, and geomechanical data were integrated to generate a new static geomodel based on reprocessed 3D surface seismic data. Described in detail in this paper are the stratigraphic framework and hydrodynamic property distribution algorithms. Seismic time interpretations benefited from an updated velocity model to form the stratigraphic framework for the new model (Figure 1). The new model grid has the following attributes: Rotation to conform with principal stress direction (18/108 deg); Extends from Wellington to 10,000’ depth (Mississippian); Includes 3 previously mapped faults; 14 horizons, 13 zones; Had 189x179x106. ~ 3.6 million cells; Cells size 100’ x 100’ x variable from 3’ (Morrow B) to 1,100’ (Wellington); and benefitted from more detailed stratigraphy in reservoir and seal intervals.
Porosity and permeability have been interpolated in from the Thirteen Finger to base of the Morrow formation. The property interpolation workflow applied to each formation depended on the data available and the formation characteristics. Integration methods included artificial neural network facies identification from well logs and core, spatial variogram analysis, discrete and continuous distributions, and co-simulation with elastic inversion properties. Due to the limited well log data in all formations except the Morrow B, spatial variograms from seismic impedance were used as proxies for well log data variograms in property interpolation. Such use of variogram proxies, and the use of secondary variables in co-simulation, were justified by observed correlations in available well log data.

The method applied within the Morrow B was distinct from other formations due to availability of legacy well logs and research into HFUs conducted by SWP. A “Winland R35” transform was derived from analysis of core porosity and permeability for 51 wells. Eight different sub populations were identified in poro-perm space and used to create R35 cut-offs defining HUF. Poro-perm relationships were derived for each HFU sub population from core data. The R35 transformation was used to compute R35 logs for the 51 wells with data used in core analysis. For poro-perm interpolation, porosity logs were upscaled into the grid and interpolated through Gaussian co-simulation with seismic acoustic impedance supported by the correlation shown in Figure 2 (a). This resulted in the porosity distribution shown in Figure 3 (a). Next, R35 logs were upscaled into the grid and

Figure 1. X and Y direction slices through the model showing main zones (right), layering (left), and faults.

Figure 2. (a) Acoustic impedance vs porosity in Morrow B formation used to support co-simulation of porosity with seismic impedance. (b) R35 vs porosity in Morrow B used to support co-simulation of R35 with interpolated porosity.
interpolated through Gaussian co-simulation with interpolated porosity supported by the correlation shown in Figure 2 (b). This resulted in the R35 distribution shown in Figure 3 (b). HFU cut-offs were applied to the 3D Log35 property to create the 3D HFU (discrete) property model shown in Figure 3 (c). The poro-permeability relationships were applied for each HFU to create the permeability distribution shown in Figure 3 (d).

The property interpolation method applied to Thirteen Fingers formation was distinct because of clear internal litho-stratification evidenced by bi-modal property distributions. First, unsupervised classification was used to identify the distinct litho-units known to exist and evidenced by distinct poro-perm characteristics (Figure 4 (a) and (b)). This process resulted in discrete flow unit logs for wells 13-10A and 13-14. These 2 flow units display the same correlation with porosity (Figure 5 (a)) allowing a single porosity co-simulation with seismic impedance (Figure 6 (a)). Next, the discrete hydraulic units were interpolated (Figure 6 (b) using seismic impedance as a horizontal trend, and a vertical trend (Figure 5 (b)) extracted from the upscaled discrete flow unit logs. Finally, permeability was assigned for each flow unit using the appropriate poro-perm relationship extracted from the data shown in Figure 4 (b) to produce the permeability distribution shown in Figure 6 (c). All other formations were generally treated by co-simulation of porosity logs with seismic AI, followed by application of an appropriate poro-perm relationship extracted from available data.

Conclusions

The evolution of five versions of a geologic model at Farnsworth unit have highlighted the ability to integrate new interpretations, newly generated data, and feedback from monitoring and simulation efforts into increasingly comprehensive models over extended periods of time, while allowing for useful models at each stage of development. Technical advances in model building and design of comprehensive workflows should aid future projects with the goal of commercial carbon storage at EOR sites.

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Figure 4. (a) Unsupervised classification of hydraulic units in the Thirteen Finger formation, (b) Poro-perm data for Thirteen Finger hydraulic units.

Figure 5. (a) Acoustic impedance vs porosity for Thirteen Finger flow units, (b) Vertical trend in discrete flow unit log used in interpolation of flow units.

Figure 6. (a) Interpolated Thirteen Finger porosity, (b) Interpolated Thirteen Finger flow units, (c) Thirteen Finger permeability.