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A Geostatistical Study in Support of CO₂ Storage in Deep Saline Aquifers of the Shenhua CCS Project, Ordos Basin, China

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Abstract

The Shenhua Carbon Capture and Storage (CCS) project at the Shenbei Slope injection site in North Yulin is the first 100,000 ton-per-year scale CCS pilot project in China with an injection operation lasting nearly 3 years. In this study, we investigate various geostatistical methods and their impact on the respective geologic models on which simulation is performed to understand the phenomena observed during 3 years of Shenhua CCS operations. Although there was a brief period of wellhead pressure increase at the injection well, it unexpectedly dropped for most of the time. Another interesting observation showed that the majority of CO2 gas injection was received by the topmost sandstone Liujiagou formation instead of the basement limestone Majiagou formation, which was predicted to have much more injectivity and storage capacity. Based on the current geostatistical methods and available data, 3 steps of reservoir modeling and flow simulation are carried out and they go from having homogeneous property models to incorporating standard 2-point geostatistical methods to using object-based models. The layer-cake models generate a rather uniform plume shape and increased pressure response. Meanwhile, two-point statistical models add more complexity to the size and shape of CO₂ plume, however are not capable of reproducing the pressure decline behavior. These results demonstrate homogeneous and 2-point geostatistical models are inadequate in interpreting subsurface heterogeneity, both due to their method and data limitations. Further work is being done with object-based models to produce a system of meandering rivers based on the geological concept of Shenhua injection site. This will help offset the data limitation and bring our model closer to geologic reality.

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1. Introduction

Because of the numerous local point sources and the identification of multiple sites potentially suitable for CO_2 storage, Ordos Basin, the second largest sedimentary basin in China, is selected as a site for large-scale CO_2 geological storage demonstration projects in China. The Shenhua Carbon Capture and Storage (CCS) project at the Shenbei Slope injection site in North Yulin (Figure 1) is the first 100,000 ton-per-year scale CCS pilot project in China with an injection operation lasting nearly 3 years. Jiao et al. [1] concluded that the bottom limestone Majiagou formation had the most capacity for CO_2 storage and was the most promising injection target among the other geological formations. Interestingly at the end of 3 years of injection, the topmost Triassic siliciclastic sandstone Liujiagou formation has stored over 80% of the injected CO_2 and exhibited the best injectivity (Diao et al. [2]). In addition, pressure drop at the injection wellhead was observed throughout CCS operations (Wu [3]; Xie et al. [4]), sparking interest in the CCS community in China (Xie et al. [5]).

To evaluate CCS performance, multiple studies have been carried out including pre-injection screening and risk analysis (Li et al. [6]) and post-injection reservoir simulations to capture detailed plume dynamics, pressure response, and storage profiles (Liu et al. [7]; Xie et al. [5]; Xie et al. [4]; Liu et al. [8]; Xie et al. [9]; Liu et al. [10]). While improved understanding of reservoir heterogeneity at the Shenhua site has been gained, these studies were challenged by limited data availability and uncertainty, especially reservoir characterization data (Zhang et al. [11]). In this study, we explore various geostatistical methods and their impact on building geologic models on which simulation will be performed to interpret the pressure response and CO_2 plume dynamics of the Shenhua CCS project.
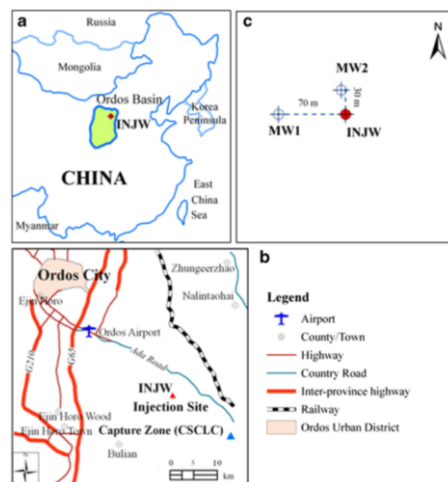

Figure 1: Shenhua CCS Project Location (adapted from Xie et al. [4])

2. Reservoir Geology and Characterization

This study is mainly concerned with 6 deep aquifers (starting from 1576m) at the Shenhua site from top to bottom: Triassic Liujiagou formation, Permian Shiqianfeng formation, Permian Shihezi formation, Carbonic Shanxi formation, Carbonic Taiyuan formation, and Ordovician Majiagou formation (Figure 2). The basement Majiagou formation is filled with marine limestones alternating with mudstones. The other 5 overlaying formations are characterized with low-permeability sandstones interbedding mudstones and

sandy muds, as typical of the Ordos basin (Xie et al. [4]). To simplify, in this study we lump both mudstones and sandy muds into one baffle (non-permeable) facies.
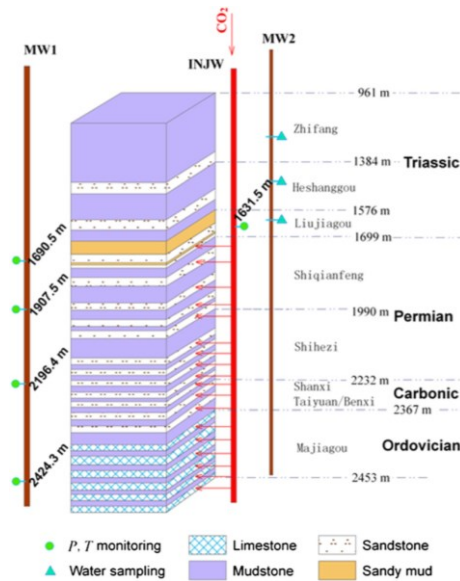

Figure 2: Stratigraphic column of the Shenhua injection site (adapted from Xie et al. [4])

Site characterization data include (1) well logs for all three wells, including AC, RD, RS, GR, CNL, density, SP, etc. (2) well logging reports for all wells including lithology description, (3) formation structure, porosity, permeability interpreted from the seismic data, (4) a stratigraphic column corresponding to the perforation interval in INJW, from the Liujiagou formation to the Majiagou formation (depth range is 1570-2453m). (5) Porosity and permeability data, as inferred from cores and well logs, from Liujiagou to Majiagou formations, (6) pore pressure and temperature measurements at all wells prior to the injection test. (7) INJW wellhead pressure from April 2011 to January 2014, along with the cumulative volume of the injected CO_2. (8) 3-phase time-lapse VSP seismic data (1 taken before the injection and 2 after) which are used to delineate the approximate extent of the CO_2 plume (Figure 3), (9) observed pressure at different formations along injection and monitoring wells, and (10) observed water chemistry at monitoring wells.
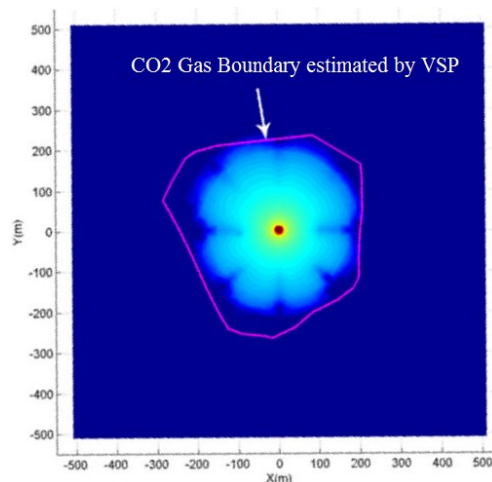

Figure 3: VSP data estimating the extent of CO_2 Plume after 3 years of injection (after Li et al. [12])

Examination of cores and well logs suggests that the Liujiagou formation has a lithology dominated by sandstone and interlayers of mudstone deposited in fluvial, deltaic, and shallow-lacustrine depositional environment. During CO_2 injection, wellhead pressure dropped from ~7 MPa to less than 5 MPa much later without buildup (Figure 4), suggesting connectivity from the injection interval to neighboring formations with lower pressure.
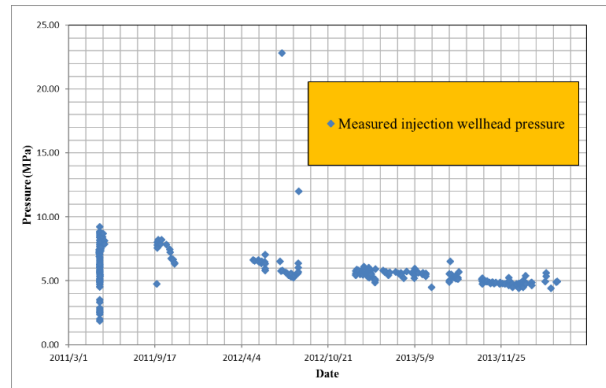

Figure 4: Measured wellhead pressure drop throughout the injection (after Bai et al. [13])

3. Geostatistical Methods

Considering the amount of data publicly available at the time of this study and current geostatistical methods, we have arrived at a 3-step approach to tackle the challenge of data availability and uncertainty. Each single step adds more complexity to the model from being simplistic to representing the facies trend.

The first step is to build a layer-cake model with homogeneous porosity and permeability in each layer. This approach is to compare results with those presented by Xie et al. [4]. Table 1 shows the Step 1 model input parameters, which include porosity, permeability, capillary entry pressure, m parameter in van Genuchten's equation (Pruess et al. [14]), irreducible water saturation, residual CO_2 saturation, maximum water saturation, and maximum CO_2 saturation. While Xie et al. [4] made TOUGH2 their reservoir simulator, in this study we use Eclipse Compositional (E300) as our simulation software.

	φ [−]	K_h [mD]	K_v [mD]	P_o [Kpa]	m [−]	S_{lr} [−]	S_{gr} [−]	S_{ls} [−]	S_{gs} [−]
Liujiagou	0.106	9.40	0.800	14.7	0.45	0.30	0.05	1.00	0.99
Shiqianfeng	0.101	0.64	0.640	35.8	0.95	0.05	0.01	0.89	0.99
Shihezi	0.122	0.70	0.700	12.8	0.95	0.05	0.01	1.00	0.99
Shanzi	11.30	0.21	0.021	24.4	0.45	0.05	0.05	1.00	0.99
Taiyuan	0.0006	0.00116	1.16E-05	62.1	0.40	0.22	0.25	0.99	0.99
Majiagou	0.035	0.05	0.005	35.8	0.95	0.05	0.05	0.89	0.99

Table 1: Homogeneous reservoir model input parameters (adapted from Xie et al. [4])

Second, the standard two-point statistical (SIS and SGS) methods are used to incorporate more reservoir heterogeneity to the geologic model. The challenge in using these methods is it is difficult to create complex reservoir shapes and bodies typically found in a fluvial system. Another setback to consider is even the data may not be representative of the entire reservoir of interest and therefore do not carry the overall trend that needs to be in the model. Step 2 generates models that capture the statistics of the log data of two wells but do not necessarily represent geologic reality.

Third, step 3 will attempt to capture a conceptual model of meandering rivers by building object-based facies models as it is a relatively simple and easy method. These facies realizations will result in a range of property models used in flow simulation to screen out those that are not well-constrained to the log and seismic data, not matching wellhead pressure drop, and/or overestimating the CO_2 plume shape at the end of injection. The difficulty of building such object-based models lies in constraining them to observed data, especially soft data such as seismic data. In this study, we employ a screening process to clean out models that are not satisfactory in terms of all available constraints.

Since E300 does not automatically determine the relationship between flow and pressure along the wellbore, an explicit finite difference method developed by Bai et al. [15] is implemented to derive wellhead pressure response from E300 bottom-hole pressure results.

4. Results and Discussion

a. Step 1: Horizontally Homogeneous Models

Xie et al. [4] presented a horizontally homogeneous model in TOUGH2 to help understand CO_2 sequestration at the Shenhua site. This model was built using input parameters (Table 1) correlated from core measurements and assumptions when there is a lack of experimental data. Model areal extent is a 5km by 5km square to ensure infinite boundary effects while vertical length is divided into 66 grid layers throughout the entire 6 aquifers. A more detailed radial grid is built around INJW to better model gas movement throughout the injection period.

Figure 5a shows the CO_2 plume shape (map view) at the end of injection in 2014 in comparison with a CO_2 gas boundary defined by VSP seismic data. This boundary is adapted from Li et al. [12]. The CO_2 plume modeled by E300 displaces brine rather uniformly in all horizontal directions. This homogenous effect is seen from top to bottom of the stratigraphic column. Similarly, simulation results from TOUGH2 indicate a uniform areal extent of gas saturation around INJW in Figure 5b. This shared behavior of both models is the result of predefined reservoir homogeneity.
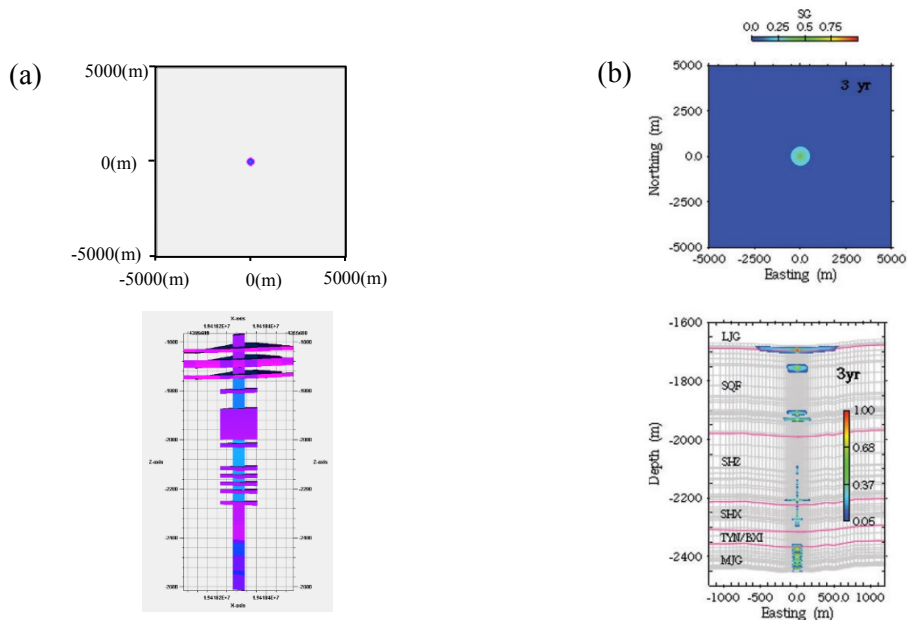

Figure 5: CO_2 plume shape at the end of injection (a) E300 and (b) TOUGH2

On the pressure behavior, Xie et al. [4] were able to match a relatively short initial period of 20 days when CO_2 was still causing pressure to rise. As injection continued, the TOUGH2 model predicted further increase in pressure which was contradictory to the observed wellhead pressure decline. This behavior occurs to our E300 simulation as a result of homogeneous reservoir properties (Figure 6). Since fluid loss took place during drilling through Liujiagou, it could be suspected that there is at least a local high-permeability area that the injected supercritical gas would escape to (Xie et al., [4]).
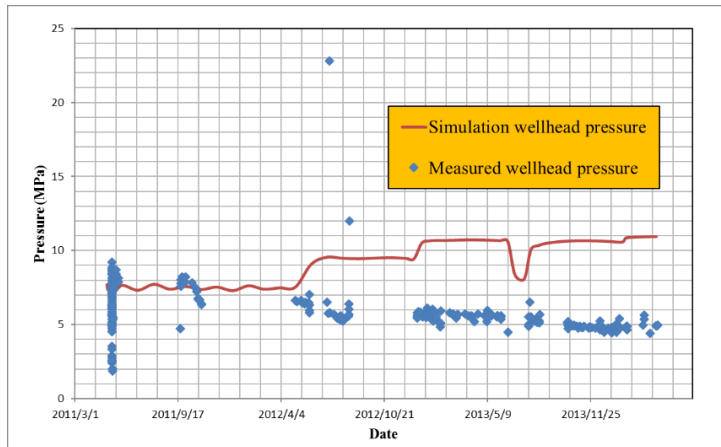

Figure 6: E300 simulation wellhead pressure versus measured wellhead pressure

b. Step 2: Two-point Statistical Facies Models

In step 2, a facies model is constructed using SIS to guide the porosity and permeability models. The improvement of this approach is that SIS takes into account the statistics of well log input data. Figure 7a shows the histogram of facies in the model, upscaled cells, and log interpretation. Facies log interpretation was performed in 3 wells based on the stratigraphic column from Figure 2. Facies population in the model represents the percentage of baffle, sandstone, and limestone (0, 1, and 2 respectively) rather well. This leads to a facies model which has mostly sandstone and baffle for the upper formations while the basement Majiagou is largely filled with limestone and baffle in Figure 7b.
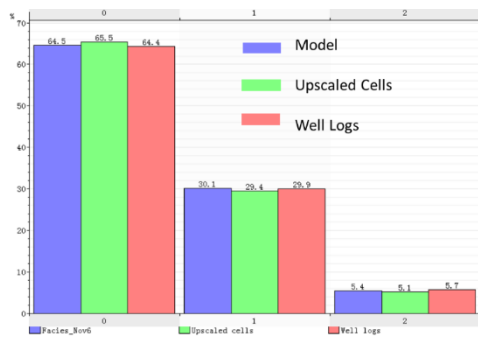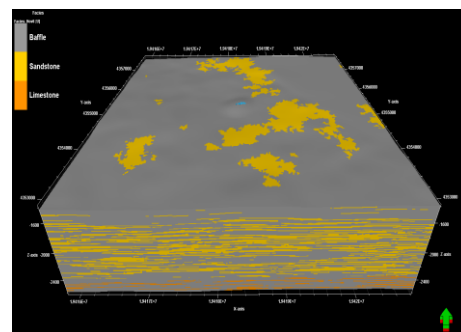
(a)   (b)

Figure 7: Facies histogram (a) and facies model (b)

Figure 8 displays histograms of porosity and permeability of upscaled values in the model, upscaled values in the wells, and the original well log values. An approach using thresholds is implemented to assign porosity and permeability value range to each facies code. For porosity, baffle facies is from 0 to 0.02, sandstone is from 0.02 to 0.2, and limestone is from 0.01 to 0.1 (Figure 8a). For permeability, baffle is from 0 to 0.1mD, sandstone is from 0.1 to 40mD, and limestone is from 0.01 to 0.1mD (Figure 8b). The model

values capture the overall statistics of well logs rather well. However, given that log data are only available in a small number of wells, there is a possibility that the data may not bear overall facies trend and thus may not guide the modeling process toward geologic reality.
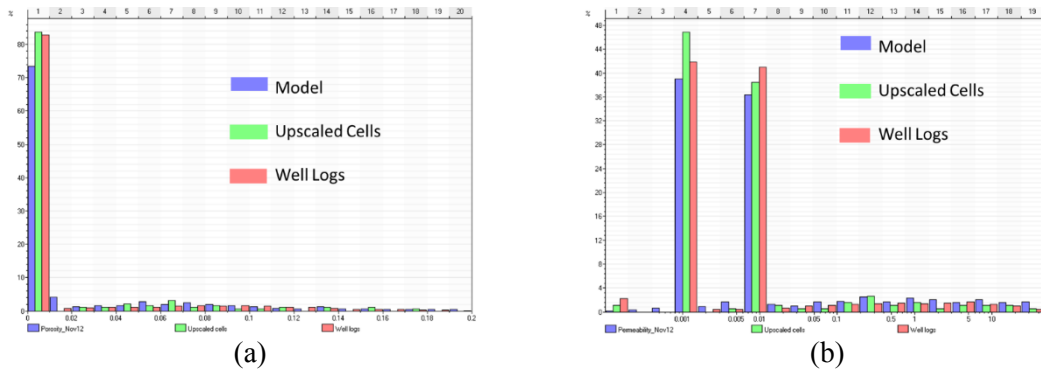

Figure 8: (a) Porosity and (b) Permeability Histograms

The improvement of having 2-point statistics guide the modeling process is demonstrated in Figure 9. CO_2 movement displays some complexity in its directions instead of filling a relatively simplistic uniform area around the well location. Plume shape has increased in size to match the gas boundary better than step 1. Nonetheless, this method is challenged by the scarcity and uncertainty of measured data that guide a variogram-based modeling approach. Another shortcoming of SIS and SGS is their inability to create realistic geological features, but rather "homogenously heterogeneous" models due to the assumption of stationarity. To tackle these drawbacks, the next step of using object-based models is proposed.
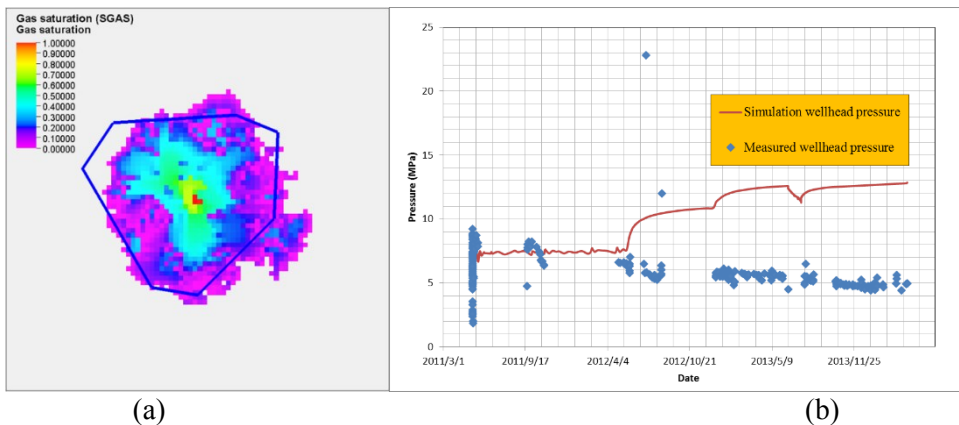

Figure 9: (a) CO_2 plume shape at the end of injection versus CO_2 boundary estimated by VSP data and (b) E300 simulation wellhead pressure versus measure wellhead pressure

c. Step 3: Object-based (Meandering Rivers) Facies Models

Last but not least, to build more fluvial patterns into our model, particularly meandering rivers, an object-based approach is implemented to generate channels that vary in their dimensions. These rivers have a direction going from Northeast to Southwest. Except for the basement Majiagou formation, the rest are non-marine aquifers that are characterized by meandering rivers. In this study, the levee sand and flooding plain in the fluvial system are simplified as baffle (non-permeable) facies. Figure 10 shows the map view

of Liujiagou sandstone formation with Northeast-Southwest meandering rivers. These rivers have an average 45-degree angle and are characterized by an average width of 300m and thickness of 15m.
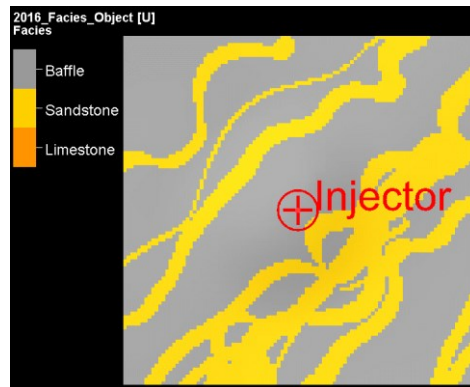

Figure 10: Step 3 object-based facies model

Based on this facies model, reservoir properties are populated using the SGS method discussed in step 2. Property models of the fluvial channels are shown in Figure 11. They are one pair among many other realizations that are created to address a range of variation in size and shape. Simulation will be performed on these models to determine whether a realization is satisfactory in terms of data constraints.
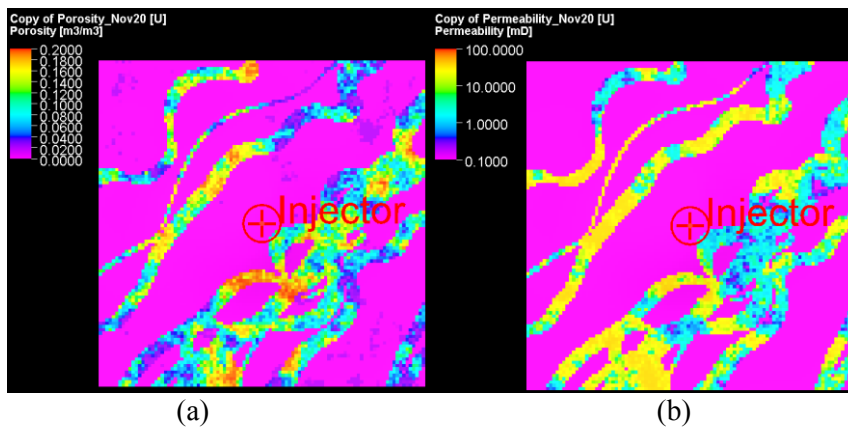

(a)   (b)

Figure 11: (a) porosity and (b) permeability models from the object-based models

5. Conclusions and Future Work

This research project reviewed and examined currently available geostatistical methods in the context of CO_2 geological storage at the Shenhua Carbon Storage site. Various techniques are present in the literature however only some are suitable given the amount of acquired data during CO_2 injection. Three approaches were employed: horizontally homogeneous, two-point statistical, and object-based models. Simulation results indicate that the layer-cake style model poorly represented reservoir heterogeneity and did not explain the pressure drop very well. On the other hand, while two-point statistical models introduce more complexity by conditioning porosity and permeability to a facies model, there is uncertainty in the data which may not carry the general trend of facies distribution across the study area. To address this issue, multiple object-based geostatistical models are built to represent a system of meandering rivers based on the geological concept of Shenhua injection site.

For further investigation, the goal is to generate more realizations of meandering rivers and perform sensitivity analysis given the amount of constraints currently available. The purpose of this approach is

twofold: to account for uncertainty in data acquisition and attempt to reproduce the bigger picture of subsurface heterogeneity. In addition, we plan to investigate the effect of boundary conditions in the next step to help understand fluid inflow and outflow of the system. Interactions at the boundary may play a significant role on pressure response at the injection well and possibly CO_2 long-term storage safety.

6. Acknowledgements

7. References

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