A feasibility study of geological CO₂ sequestration in the Ordos Basin, China

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Abstract

The Shaanxi Province/Wyoming CCS Partnership (supported by DOE NETL) aims to store commercial quantities of CO₂ safely and permanently in the Ordovician Majiagou Formation in the northern Ordos Basin, Shaanxi Province, China. This objective is imperative because at present, six coal-to-liquid facilities in Shaanxi Province are capturing and venting significant quantities of CO₂. The Wyoming State Geological Survey and the Shaanxi Provincial Institute of Energy Resource and Chemical Engineering conducted a feasibility study to determine the potential for geological CO₂ sequestration in the northern Ordos Basin near Yulin. The Shaanbei Slope of the Ordos Basin is a huge monoclinic structure with a high-priority sequestration reservoir (Majiagou Formation) that lies beneath a 2,000+ meter-thick sequence of Mesozoic rocks containing a multitude of low-permeability lithologies. The targeted Ordovician Majiagou Formation in the location of interest is more than 700 meters thick. The carbonate reservoir is located at depths where pressures and temperatures are well above the supercritical point of CO₂. The targeted reservoir contains high-salinity brines (20,000–50,000 ppm) that have little or no economic value. The targeted reservoir is continuous as inferred from well logs, and cores show that porosity ranges from 1 to 15% with average measured porosity of 8%, and that permeability ranges from 1–35 md. This paper focuses on calculations that will help evaluate the capacity estimates through the use of high-resolution multiphase numerical simulation models, as well as a more simple volumetric approach. The preliminary simulation results show that the Ordovician Majiagou Formation in the Ordos Basin has excellent potential for geological CO₂ sequestration and could store the CO₂ currently emitted by coal-to-liquid facilities in Shaanxi Province for hundreds of years (i.e., 9 Mt/year CO₂; 450 Mt over a 50-year period at one injection site).

Keywords: Ordos Basin; CO₂ storage capacity; Performance assessment

Introduction

Successful implementation of geological CO₂ sequestration to manage carbon and mitigate climate change requires subsurface storage space for huge volumes of supercritical CO₂. The chosen storage formations must be capable of retaining the stored CO₂ for hundreds to thousands of years. A superior geological storage site must possess three essential characteristics: adequate pore space, well connected permeability, and a high-quality trapping mechanism. The Wyoming State Geological Survey (WSGS) and the Shaanxi Provincial Institute of Energy Resource and Chemical Engineering (SPIERCE) propose that the Ordovician Majiagou Formation (in the Ordos Basin, northern Shaanxi Province, China) has the potential to be a superior geological storage reservoir. Therefore, we have conducted a feasibility study to determine the potential for storing commercial quantities of CO₂ safely and
permanently in the Ordovician Majiagou Formation. This search is imperative because at present, commercial coal-to-liquid facilities in Shaanxi Province are capturing and venting significant quantities of CO₂ (~20 MT/yr). Storage capacity of the Majiagou Formation is assessed both on a regional scale (based on a volumetric approach), and on a site-specific scale (based on detailed numerical injection simulations). This paper presents preliminary results of the geological CO₂ sequestration capacity assessment for the Ordos Basin, China.

**Geological Setting**

The Ordos Basin is the second largest sedimentary basin in China with an area of 370,000 km², and covers portions of Shaanxi, Shanxi, and Gansu provinces, and Ningxia Hui and Inner Mongolia autonomous regions. The basin lies in the western part of the North China Block and is bordered by Luliang Mountain to the east, Qinling Mountain to the south, Liupan Mountain and Helan Mountain to the west, and Lang and Yin mountains to the north (Figure 1). Separated by an east–west line through Yulin and Dinhian cities, the basin is covered by the Maowusu Desert in the north and the Loess Plateau in the south. The Ordos Basin is a typical cratonic basin that developed into a large stable basin during the Paleozoic, with tectonic movements dominated by regional uplift and subsidence. With the exception of uplifts and depressions that developed at the margins, the basin is characterized by a huge monoclinal structure (320,000 km²) with a 1 – 2 degree dip to the west, called the Shaanbei Slope (Figures 2). The Shaanbei Slope is dominated by a relatively stable tectonic environment with rare regional faults, and is therefore a favorable structural unit for geological CO₂ sequestration in China.

![Figure 1. Geographic map of the Ordos Basin, China. From Jiao et al., 2010.](image1)

![Figure 2. Geological map and cross section of the Ordos Basin show the huge monoclinal structure of the Shaanbei slope and the targeted CO₂ storage formation Ordovician carbonate. Modified from Li et al., 1992.](image2)

The Ordos Basin includes 2,559 to 7,847 m of Paleozoic and Mesozoic sedimentary strata (Figure 3). The Upper Ordovician, Silurian, Devonian, and Carboniferous strata do not occur within the basin. These absences are marked by a major regional unconformity that lies between the Middle Ordovician and Pennsylvanian strata. During a 150-ma-long hiatus from the Middle Ordovician to the Mississippian, intense karstification of the Ordovician dolomites resulted in a wide distribution of karst strata along the regional unconformity, in which the
reservoir rocks of the Jingbian gas field developed. From the Cambrian to the Early Ordovician, the Ordos Basin region was a shallow marine carbonate platform, and in the region 300 – 600 m of thick carbonate rocks were deposited in the main part of the Ordos Basin [9]. During the later Early Ordovician to Middle Ordovician, the North China Block (including the Ordos Basin) experienced a large-scale marine transgression that deposited the Majiagou Formation, which consists of dolomite, limestone, and evaporites with a thickness of 100 – 900 m in the interior of the basin [11]. From the Pennsylvanian through the Jurassic, a thick terrestrial stratigraphic section accumulated consisting of lacustrine, fluvial, wetland, and deltaic strata, including shales, mudstones, coal, and sandstones with a thickness of 2,300 – 5,700 m. During the Early Cretaceous, 100 – 1,200 m of eolian sediments were deposited in the Ordos Basin.

The potential sequestration reservoirs in the Majiagou Formation lie beneath a 2,000+ meter-thick sequence of Mesozoic rocks containing a multitude of low-permeability sealing lithologies. The targeted Ordovician Majiagou Formation in the location of interest is more than 700 meters thick. The carbonate reservoir is located at depths where pressures and temperatures are well above the supercritical point of CO2 (31 °C and 7.4MPa). The targeted reservoir contains high-salinity brines (20,000–50,000 ppm) with little or no economic value at present. The targeted reservoir is continuous as inferred from well logs and cores show that porosity ranges from 1 to 15% with average measured porosity of 8% and that permeability ranges from 1–35 md.

Geological structural model

A regional 3-D geological model was constructed for the Ordos Basin utilizing well logs, isopach maps, and geological data assembled from published articles [4, 9, 10, and 11]. The model covers a 420 km by 750 km area of the major Shaanbei Slope Block, and was built using the commercial software EarthVision®, a 3-D geospatial modelling package. No faults are included in this geological structural model. The gridding sizes for the x, y, and z axes are 69 x 99 x 71, or 5000 m x 5000 m x 100 m, respectively, and the 2-D and 3-D minimum tension griddings were used to construct this model. Figure 4a shows the incline view to the southeast of the geological structural model for the Ordos Basin. Zone 2 represents the Majiagou Formation, and Zone 9 represents the Triassic sequence dominated by fluvial and lacustrine low-permeability shales and mudstones. Figure 4b shows the Majiagou Formation dipping 1 to 2 degrees to the west, with gentle structures favourable for geological CO2 storage. This 3-D geological structural model was used to calculate the CO2 storage capacity of the Majiagou Formation using a volumetric approach.

A smaller 3-D geological model 50 km x 50 km centered at Yulin was extracted from the regional geological structural model. This smaller scale model was used to generate a 3-D computational mesh for the Majiagou CO2 injection simulations.
Figure 4. Incline view to southeast of the geological structural model for the Ordos Basin with the location of the potential injection site near the Yulin City (a); the 3-D view of Majiagou Formation dipping 1 to 2 degrees to the west, with gentle structures favourable for geological CO₂ storage (b). From Jiao et al., 2010.

**Generation of the 3-D computational Mesh**

Following the logic and methodology outlined in Miller et al. 2007 [5], a computational hydrostratigraphic mesh was created from the 50 km by 50 km geological structural model described above. In this computational mesh, the simulation cells or nodes were aligned to follow the curvature of the unit interfaces and do not stair-step in the manner of a traditional finite element grid. This allows more accurate calculation of CO₂ moving along the caprock in the up-dip direction. The numerical mesh presented in this paper is centered at Yulin, and consists of a block that is 50 km x 50 km in map view within the 420 km x 750 km regional geological structural model of the Shaanbei Slope Block, with the elevation extending from 200 m above sea level to -3200 m below sea level. Grid spacing is 250 m in the x and y directions at the injection area and increases logarithmically away from the injection area. The grid spacing in the vertical direction is 50 m at the injection interval and 100 m both above and below the injection interval. The total mesh is consisted of 320,000 nodes with 1.92 million volume elements.

**Carbon dioxide injection simulation setups**

Simulations of CO₂ injection were run on the Los Alamos National Laboratory Finite Element Heat and Mass Transfer (FEHM) multiphase porous flow simulator. FEHM has been used successfully for many multiphase applications, including isotopic fractionation in the vadose zone, methane hydrate dissolution and transport, geothermal energy analysis, and simulations of CO₂ injection into saline aquifers [1, 6, 7, and 8].

Initial conditions for the model domain included a geothermal gradient of 26 °C/km with a domain bottom temperature of 120 °C and a domain top temperature of 47 °C, and a hydrostatic pressure ranging from 13 MPa at the top of the modeling domain, 200 m above sea level to 44 MPa at the bottom of the modeling domain, -3200 m below sea level. Further simplifying assumptions for the 3-D injection calculations are that thermal conductivity of the rocks is constant at 0.5 W/m-K, rock density is constant at 2,650 kg/m³, and heat capacity is constant at 1,000 J/kg-K. Relative permeability for all rocks was assigned with a residual saturation of 10% for both brine and CO₂ using a linear relationship. Capillary pressure effects were ignored; brine TDS is constant at 20,000 ppm for all formations, and water viscosity is calculated independently of brine content or dissolved CO₂. The initial dissolved CO₂ concentration was set to zero. During CO₂ injection simulation, the simulator accounts for CO₂ dissolution in water. For all simulations, the down-dip sides (west and south sides of the domain) are closed, whereas the up-dip sides (north and east sides) are open to the reservoir fluid.

In order to evaluate the impacts of injection rate, porosity and permeability on storage capacity, reservoir pressure evolution, and CO₂ plume migration trends, a series of CO₂ injection simulations were conducted using various injection rates, porosities, and permeabilities for the targeted Majiagou Formation.
Simulations and results for the Majiagou Formation

An important consideration in the CO₂ injection simulation results from FEHM for the various scenarios is the pressure buildup during injection. A limiting value of 75% of overburden pressure was selected for all simulations in order to ensure that the Majiagou Formation and overlain sealing formations are not fractured during injection.

The various FEHM injection simulation scenarios were utilized for the Majiagou Formation, including injection rates of 0.5 Mt/year, 1.0 Mt/year, and 2.0 Mt/year, and porosities of 5% and 10%, and permeabilities of 1 and 5 md, and all within a formation thickness of 500 m (actual thickness of the Majiagou Formation at the site is more than 700 m). Using nine injection wells, the above injection rates resulted in storage capacities of 4.5 Mt, 9 Mt, and 18 Mt per year, respectively. All simulations were run for 100 years with CO₂ injection ending after the first 50 years.

Three Majiagou simulations (9 injection wells) were run with injection rates of 0.5 Mt/year, 1 Mt/year, and 2 Mt/year, at a constant porosity of 10 percent, and a permeability of 5 md (Figures 5a). As injection rates for the 9 injection wells increase from 4.5 Mt per year to 18 Mt per year, the reservoir pressure gradually increases from initial reservoir pressure 40 MPa to 55 MPa, but remain below 75% of the fracture pressure (60 MPa) of the Majiagou Formation in the study area. With increasing CO₂ injection, the amount of fluid displaced during CO₂ injection also increase.

![Figure 5. FEHM simulation results for the various porosities, permeabilities, and CO₂ injection rates. From Jiao et al., 2010.](image)

Figures 5b show the results of three simulations with injection rates varying from 0.5 Mt/year, 1 Mt/year, and 2 Mt/year, at a constant porosity of 5 percent, and a permeability of 1 md. As shown by the simulation results with 10% porosity and 5 md permeability, both the reservoir pressure and volume of displaced fluid increases gradually with increasing injection rates, but the magnitude of increase is much larger. With 1 md permeability and at an injection rate of 18 Mt/year, the reservoir pressure reaches 75% of the fracture pressure of the Majiagou Formation after 10 years of injection, and keeps increasing to near the lithostatic pressure. In all cases, the reservoir pressure drops sharply when CO₂ injection stops (Figures 5).

Based on all available measured data, an average porosity of 10% and a relative permeability of 5 md for the Majiagou Formation were considered the most likely values for preliminary simulation. The input parameters for
the most reasonable simulation were a 1 Mt/yr per well injection rate, 10% porosity, and 5 md permeability. Using this set of parameters, results from the 50-year injection simulation show that a total of 450 Mt of CO₂ can be injected into the targeted reservoir while a total of 166 Mt of original pore fluids will be displaced by the CO₂. Furthermore, the targeted reservoir pressures remain well below the 75% of fracture pressure limit (Figure 5b). Simulation results suggest that saturation of the CO₂ plumes ranges from 0.1 to 0.9. The modelling results from this simulation showed that the CO₂ plume produced from 1 Mt/year injection rate was relatively small after a total of 450 million tonnes of CO₂ were injected (Figures 6a and 6b). The CO₂ plume remained within the 16 km by 15 km injection area after 50 years of CO₂ injecting and stayed within an area of 17.7 km by 16 km after 100 years or 50 year post injection (Figures 6c and 6d).

Storage capacity based on the volumetric approach

The USGS Open-File Report 2009-1035 [2] provides a formula for assessing the CO₂ storage capacity called the Total Known Volume (TKV). TKV is based on the total volume of pore space within the targeted reservoir. The formula for the TKV calculation is as follows:

\[ S_{TKV} = T_a \cdot t_i \cdot N_{ip} \cdot \Theta \cdot C_e \cdot C_i \cdot \rho_{CO₂} \]

Where \( S_{TKV} \) is the storage resource of the assessed reservoir, in million tonnes; \( T_a \) is the trap area in \( km^2 \); \( t_i \) is the interval thickness of the storage formation in m; \( N_{ip} \) is a fraction of \( t_i \); \( \Theta \) is porosity, fraction; the product \( (t_i \cdot N_{ip}) \) is commonly called net pay; \( C_e \) is the storage efficiency factor (fraction of the pore space that can be occupied by CO₂); \( C_i \) is a conversion factor, (using the units given here, it is 1); and \( \rho_{CO₂} \) is the density of CO₂ in metric tons per cubic meter (metric tons/m³).

In order to use the above equation to calculate the CO₂ storage capacity of the Majiagou Formation, the trap area \( (T_a) \) must first be defined. In other words, we must determine the upper depth limit and the lower depth limit of the targeted reservoir. The pressure and temperature required for CO₂ to be a supercritical fluid (31 °C and 7.4MPa) are typically met at depths greater than 800 m (2,600 ft) under a normal hydrostatic pressure gradient. To reduce the chance that CO₂ may migrate into pressure regime and temperature conditions where it could convert from the supercritical state to liquid and vapor, a minimum storage depth of 1,000 m (3,280 ft) was chosen in the study. The minimum storage depth sets the upper depth limit of a potential CO₂ reservoir. The lower depth limit for CO₂ storage is more arbitrary than the upper depth limit. If the CO₂ pressure at the wellhead is 15 MPa (2,175 psi), and CO₂ density is 0.65 g/cm³, the CO₂ pressure will be 41 MPa (6,000 psi) at the bottom of a 4,000-meter-deep (13,120 ft) well. Therefore, CO₂ injected at this depth will displace normally pressured formation water without additional compression. In the present study, 4 km (13,120 ft) is chosen for the maximum storage depth. Assuming that 25% of the formation thickness is available, then, the 14,500 km³ of total volume of rock and pore spaces available for
the CO₂ storage \( (T_\alpha T_\beta N_{\alpha \beta}) \) is determined from the EarthVision geological structural model for the Majiagou Formation of the Ordos Basin, China.

The lognormal porosity distribution with a mean of 0.085, a standard deviation of 0.02, and a skewness of 0.44 was determined from all available measured data. For a saline aquifer, the upper limit on the storage efficiency factor was related to the irreducible water saturation of the trap in the presence of CO₂. Values for irreducible water saturation in petroleum reservoirs are not well known, but they probably range from a minimum of about 0.2 in gas reservoirs to about 0.6 in oil reservoirs [3]. The results of the CO₂ injection simulation using FEHM presented in the previous section show that the majority of CO₂ saturation ranges from 0.1 to 0.6. The storage efficiency in this study was chosen between 0.1 and 0.6. Using the above parameters, a Monte Carlo simulation from Goldsim with 10,000 realizations was set up for the Majiagou Formation between depths of 1,000 m and 4,000 m in the Shaanbei Slope of the Ordos Basin, China. Figure 7 shows the probability density of the CO₂ storage capacity of the Majiagou Formation in the Ordos Basin: CO₂ storage capacity ranges from 60 Gt to 700 Gt, with a mean of 287 GT. Therefore, the Majiagou Formation has sufficient storage capacity to accommodate decades of CO₂ emissions generated by the coal industries in the Ordos Basin.

![Probability Density of the CO₂ Storage Capacity of the Majiagou Formation](image)

**Figure 7.** The probability density of the CO₂ storage capacity of the Majiagou Formation in the Ordos Basin. A cumulative probability of 25% yields a value of 200 Gt. This indicates that for this particular distribution, we have a 25% chance of storing 200 Gt of CO₂ or less. Put another way, this indicates that we have a 75% chance of storing at least 200 Gt CO₂ in the Majiagou Formation in the Ordos Basin, China. From Jiao et al., 2010.

**Conclusions**

The preliminary results of the feasibility study are exciting because they demonstrate the following: 1) the Majiagou Formation is a superior geological storage reservoir for CO₂ and has sufficient storage capacity to accommodate decades of CO₂ emissions generated by multiple coal-fired power plants and/or commercial coal to chemical plants. The simulation and modelling work (utilizing 9 injection wells) shows that at least 9 Mt/year of CO₂ could be injected into the Majiagou Formation near Yulin over a 50-year period. Therefore, all of the existing plants and all of the coal-to-chemical plants that will be built in the Ordos Basin can be brought to “clean coal” standards (50% reduction in CO₂ emission) by utilizing the Majiagou Formation as a carbon storage reservoir; 2) the injection and storage of the CO₂ into the Majiagou Formation can be done with reservoir pressure well below fracture gradient and with the injected CO₂ remaining within relatively small storage domains; 3) displaced fluid management will be accomplished more easily in the Majiagou Formation than in many other CCS projects (i.e., Wyoming Rock Springs Uplift geological CO₂ sequestration site) because this stratigraphic unit is regionally underpressured; and 4) stored CO₂ later can be utilized in enhanced oil recovery projects in adjacent oil and gas reservoirs.
More characterization of the prospective reservoirs, including degree of compartmentalization, lithologies, distributions of porosities and permeabilities, injectable thicknesses of the formations, and injectivity, must be investigated in more detail before any CO₂ storage project can begin. The greatest scientific uncertainty in numerically simulating CO₂ storage processes in the Ordos Basin is characterizing geological heterogeneity in three dimensions. In the next phase of this study, the uncertainty will be greatly reduced by the acquisition of a 3D seismic survey over the target area and the drilling of a stratigraphic test well, both designed to optimize the data sets required to minimize uncertainty.

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References