NATURAL CO_2 RESERVOIRS ON THE COLORADO PLATEAU AND SOUTHERN ROCKY MOUNTAINS, USA, A NUMERICAL MODEL

S.P. White[1], R.G. Allis[2], J. Moore[3] T.Chidsey[2], C.Morgan[2], W. Gwynn[2], M.Adams[3]

[1]Industrial Research Ltd, PO Box 31-310, Lower Hutt, New Zealand
[2]Utah Geological Survey, PO Box 146100, Salt Lake City, UT 84114, USA
[3]University of Utah, Salt Lake City, UT 84108, USA

ABSTRACT

We have developed a numerical model of the Farnham Dome Utah, USA CO_2 reservoir as a natural analogue of an artificial CO_2 reservoir. The two-dimensional model has 24 geologic layers characterized by three permeabilities: high (10^2 mD), medium (1 mD), and low (10^{-1} - 10^{-2} mD). Initial modeling investigated the effects of seal permeability and capillary pressure function on CO_2 sequestration. This assumed two-phase CO_2-water interaction but no reactions with the host rock. Subsequent modeling of the chemical interactions between reservoir brine, CO_2 gas and a simplified mineral assemblage using the simulator CHEMTOUGH2 produces results that are generally consistent with the water chemistry observed in basins of Eastern Utah.

INTRODUCTION

Gas reservoirs within the Colorado Plateau and Southern Rocky Mountains region are natural laboratories for studying the factors that promote long-term storage of CO_2 [1]. They also provide sites for storing additional CO_2 if it can be separated from the flue gases of coal-fired power plants in this part of the U.S.A. These natural reservoirs are developed primarily in sandstones and dolomites; mudstones and anhydrite form seals. In many fields, stacked reservoirs are present, indicating that the gas has migrated up through the section. There is also evidence of geologically young travertine deposits at the surface and CO_2-charged groundwater and springs in the vicinity of known CO_2 occurrences. These near-surface geological and hydrological features also provide examples of the environmental effects of leakage of CO_2 from reservoirs, and justify further study.

The goal of this work is to provide confidence in the predictions of numerical simulations by modeling a natural system of CO_2 reservoirs and comparing the modeling results with a number of observations. A numerical model based on the Farnham Dome CO_2 reservoir structure located in east-central Utah has been developed.

This reservoir is typical of those found on the Colorado Plateau with stacked CO_2 reservoirs contained within a Laramide, dome-like structure [2]. Several wells have been drilled at Farnham Dome, and a CO_2 reservoir was exploited for dry-ice production several decades before being abandoned in 1979.

MODEL DESCRIPTION

Farnham Dome is modeled using cylindrical symmetry, where the cylinder has a radius of 10 kilometers, and extends from the surface to a depth of almost 4 kilometers. A cross section through this cylinder is shown in Figure 1. This two-dimensional model has 24 geologic layers characterized by three permeabilities: high (10^2 mD), medium (1 mD), and low (10^{-1} - 10^{-2} mD).

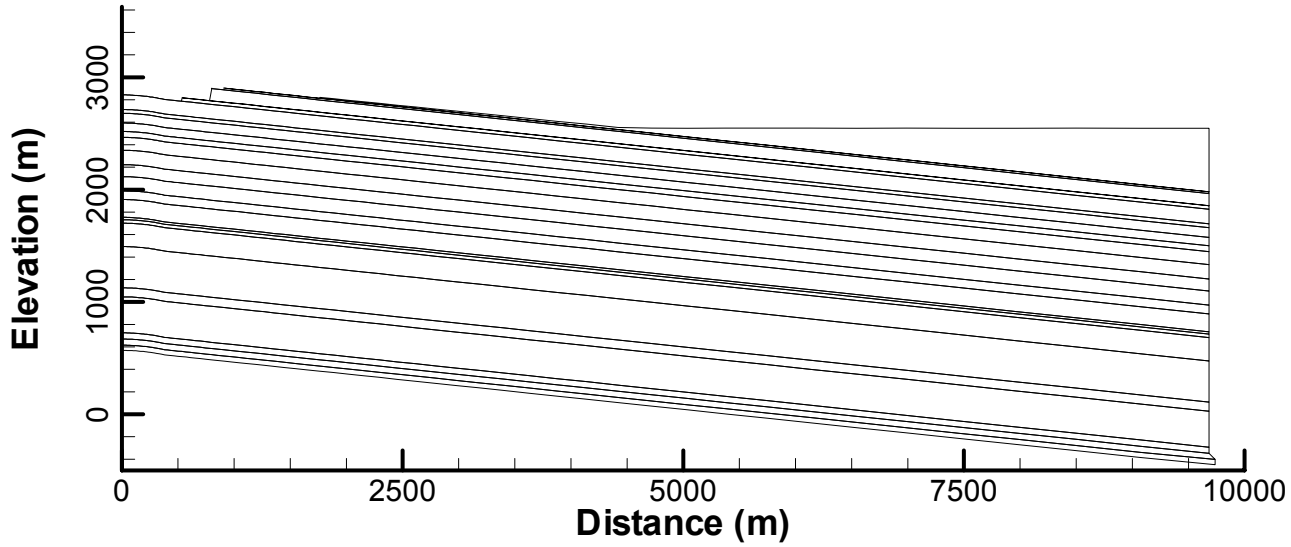

Figure 1:Geology used in Farnham Dome model, the geological units and their properties are given in Table 1.

Table 1: Reservoir parameters and mineralogy. The first unit in the table corresponds to the uppermost layer in Figure 1 (based in part on [3]).

		Bulk Mineralogy							
Unit	Permeability	Quartz	Feldspars (Ca, Na, K)	Rock & Chert	Calcite	Mixed Clay	Limestone Dolomite	Mica	Anhydrite
Mancos Sh	Low	20%	1%	Tr	1%	75%	1%	Tr	–
Ferron Ss	High	60%	1%	2%	2%	30%	Tr	Tr	–
Tununk Sh	Low	30%	1%	Tr	1%	60%	Tr	Tr	–
Dakota Ss	Medium	60%	2%	2%	2%	20%	Tr	Tr	–
Cedar Mt	Low	40%	2%	2%	2%	40%	1%	Tr	–
Buckhorn Cong	Medium	70%	2%	5%	1%	4%	Tr	1%	–
Brushy Basin	Low	40%	1%	2%	1%	40%	1%	Tr	–
Salt Wash	Medium	60%	1%	4%	2%	25%	Tr	Tr	–
Summerville	Low	60%	2%	5%	2%	20%	1%	–	1%
Curtis	Low	50%	2%	4%	2%	35%	4%	–	–
Entrada Ss	Low	80%	1%	1%	1%	10%	Tr	–	–
Carmel	Low	20%	1%	1%	1%	20%	50%	Tr	–
Navajo Ss	High	85%	2%	1%	1%	5%	1%	–	–
Kayenta-Wingate	Low	80%	1%	1%	1%	18%	–	–	–
Chinle	Low	40%	1%	1%	2%	40%	2%	Tr	-
Moenkopi upper	Low	40%	2%	4%	2%	40%	5%	Tr	–
Sinbad Ls	High	1%	–	–	10%	–	80%	–	–
Moenkopi Black Dragon	Medium	40%	1%	1%	2%	40%	2%	Tr	–
Kaibab Ls-Black Box Dolo	Medium	20%	–	4%	2%	5%	61%	–	–
White Rim Ss	High	85%	2%	1%	2%	5%	–	–	–
Paleozoic Carbonates	Medium	45%	1%	1%	2%	4%	45%	–	–

At the surface we assume that 10% of the annual 23 cm of precipitation falling on the surface enters the groundwater system. Precipitation is assumed to be water containing no dissolved solids or gases, having a pH of 7 and a constant temperature of 20°C. At the surface of the model is the atmosphere. This is a gas at 20°C and 1 bar. It is convenient to treat this gas as being composed of CO_2. This allows the formation of an unsaturated zone between the water table and the atmosphere without adding the complexity of modeling an extra component (air). On the vertical boundary of the model we assume either, hydrostatic pressures and temperatures consistent with a temperature gradient of 30°C/km or no flow.

Fluid on the boundaries is in equilibrium with the rocks that are assumed to make up the unaltered reservoir. No fluid or heat flow is possible across the base of the model. The normal terrestrial heat flow is simulated by a heat source in the bottom layer of the model.

The modeled region is divided into 24 layers each with thickness between 15 and almost 400 meters with the thickness being determined by the thickness of the stratagraphic layer containing the element (Figure 1). Each layer is divided into 100 'ring' elements, with the model containing a total of 2400 elements. These elements are smallest near the center of the model and larger towards the boundaries. The rock types specified in Table 1 are assigned to each of these layers.

Capillary Pressure Functions

Capillary pressure functions for all the seal units (shales in the Chinle and Morrison formations) were not available for this work and we have used published values for 'typical' shales ([5]; [6]).

The curves based on the data presented by Surdam [6] show $\log(P_{cap})$ to be almost linear with saturation and these curves have a significantly higher vapor entry pressure than the results of Varva [5]. Natural state simulations were run with both sets of curves but we were unable to obtain the observed stacked reservoirs using the Surdam [6] curves without very large over pressures occurring deeper in the reservoir. If the Surdam curves are adopted then gas can only be transported towards shallower areas of the reservoir through leaks in the trapping structures. While this may be a realistic model for gas transport in the reservoir, to implement it requires greater geological detail than we have available at present. We used the curves from Varva [5] for the simulations presented here. Measurements by this project on Mancos shale samples show curve shape more closely resembling the results of Varva [5] than Surdam [6].

RESULTS

Calculation of the natural state of the Farnham Dome reservoir is a two-part exercise. Firstly the pressure and temperature in all model elements is set to an arbitrary value, the boundary flows specified and the system is allowed to evolve in time until the reservoir is at a steady state. This represents a groundwater system without CO_2 and provides a starting point for the calculation of the evolution of the CO_2 reservoirs. Next a source of CO_2 is added at the base of the model representing the natural flux of CO_2 into the system. The conditions in the reservoir are allowed to evolve for 10^7 years and the modeled system compared with the observed state of the reservoir. There is little change in the reservoir after 10^6 years.

Initial modeling began by investigating the effects of seal permeability on the formation of CO_2 reservoirs. It was found that seal units must have permeability of the order of 0.01 mD for reservoirs to hold CO_2 for a time period of at least 1000 years.

Regions of anomalously high CO_2 flux are suspected in the Farnham Dome region [1] and perhaps fluxes similar to those measured by Bergfeld *et al.* [4] can be expected in localized regions. Bergfeld *et al*. [4] quote 1.8 g/m^2/day as a 'typical' value for the background flux in a basin fill environment. They measured values up to 200 g/m^2/day near cracks in steaming ground and at sites along the Stillwater fault in Nevada. After some experimentation, it was found a flux at depth of 0.2 g/m^2/day produced a flux of just over 50 g/m^2/day over the center of Farnham Dome dropping to zero at 800 meters (Figure 2). This flux varies significantly from these steady state values during the evolution of the reservoir and is quite sensitive to the permeability of the sealing (low permeability) units included in the model

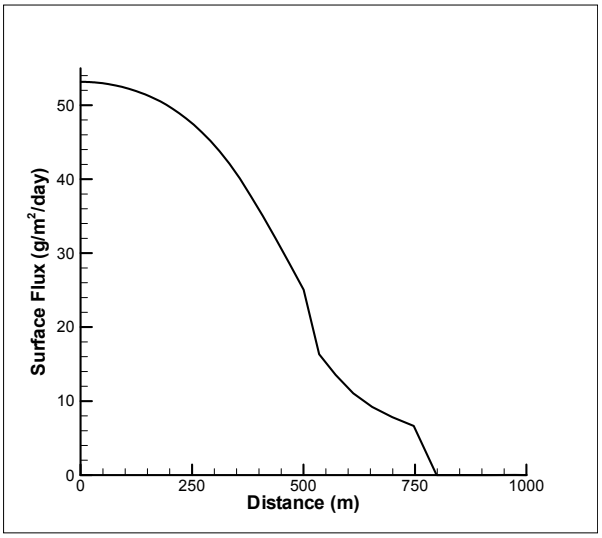

Figure 2: Calculated CO_2 flux over Farnham Dome with a CO_2 flux at depth of 0.2 g/m^2/day. This flux was calculated at 10^6 years by which time the model has reached a steady state.

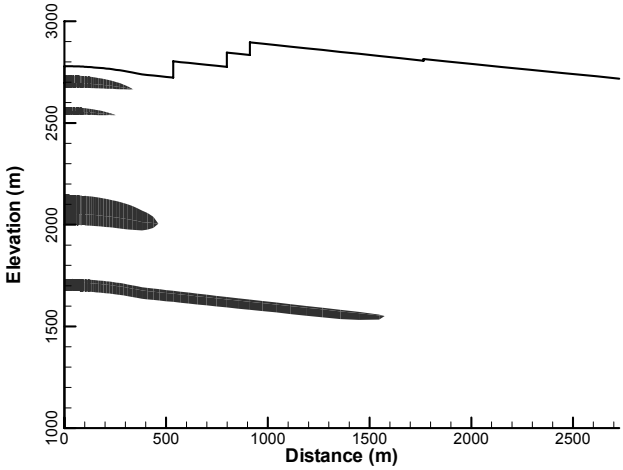

Figure 3: Natural reservoirs formed from a CO_2 flux at the base of the model. This figure represents the reservoir after 10^6 years. The gas reservoirs are shown in black and represent areas where the gas saturation exceeds 50%

The flux reaches a steady state in less than 10^6 years after the gas phase injection at the base of the model begins. Beyond about 800m, there was no CO_2 flux to the surface from the source at depth.

During the simulation, CO_2 reservoirs developed in the Sinbad Limestone, a member of the Moenkopi formation, and the Navajo Sandstone, similar to those discovered by exploration drilling at Farnham dome. The model also predicted another two smaller reservoirs in permeable strata at shallower levels as can be seen in Figure 3. Although these have not been observed, they could easily have been overlooked during the shallow part of the drilling at Farnham Dome. Alternatively, these shallower permeable reservoirs could be connected to the surface by high permeability faults, and gas is unable to accumulate.

RESERVOIR CHEMISTRY

This phase of reactive modeling between CO_2 and Colorado Plateau sediments uses a simplified version of the reservoir mineralogy given in Table 1. The mixed clays are restricted to kaolinite and sodium smectite, the micas to illite and the iron minerals to hematite and magnetite. The simulator CHEMTOUGH [9] is used to track chemical changes as this simplified reservoir mineralogy is allowed to react with the CO_2 rich fluids in the reservoir for 1000 years.

The reaction rate is described by a simplification of the rate law based on transition theory developed by Lasaga [7] and Steefel and Lasaga[8]:

$$R_m = A_m k_m \left(1 - \frac{Q_m}{K_m}\right) \quad \text{where} \quad k_m = k_{25} \exp\left(\frac{-E_a}{R}\left(\frac{1}{T} - \frac{1}{298.15}\right)\right)$$

R_m is the dissolution/precipitation rate, A_m is the specific reactive surface area, k_m is the rate constant (M m^{-2} s^{-1}), K_m is the equilibrium constant for the mineral-water reaction, Q_m is the ion activity product, E_a is the activation energy (M), k_{25} (M m^{-2} s^{-1}) is the rate constant at 25 ˚C, R is gas constant, T is absolute temperature. The kinetic parameters are given in Table 2. The precipitation kinetic constant is assumed to be one order of magnitude greater than its corresponding dissolution rate constant. A total surface area of 10^4 m^2/m^3 medium was used. The surface area of each primary mineral is calculated by multiplying its volume fraction at any time with the total surface area. When a mineral is not present but becomes supersaturated the reactive surface is set to 25 m^2/m^3 at all time.

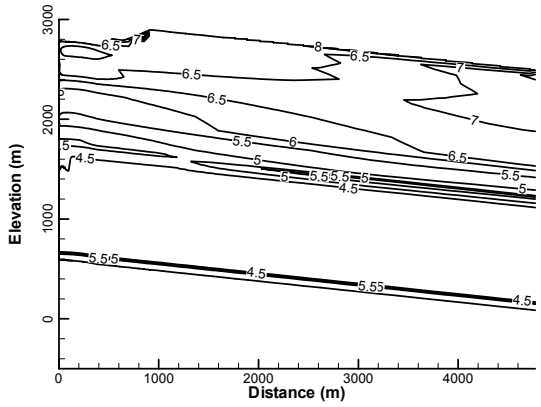

Figure 4:Reservoir pH

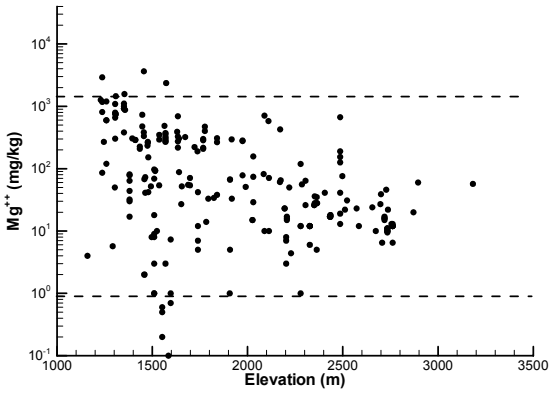

Figure 5: Mg^{++} concentration (ppm). The dashed lines show the range of model values over the area shown in Figure 3.

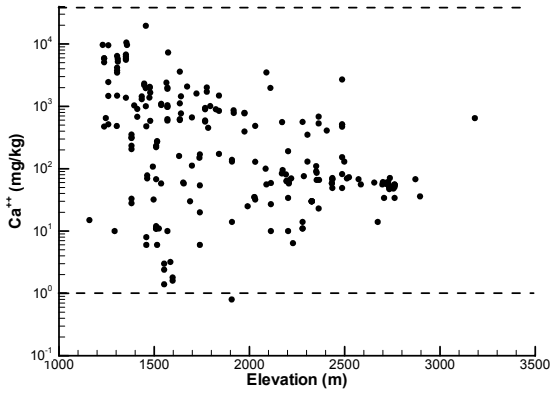

Figure 6: Ca^{++} concentration (ppm). The dashed lines show the range of model values over the area shown in Figure 3.

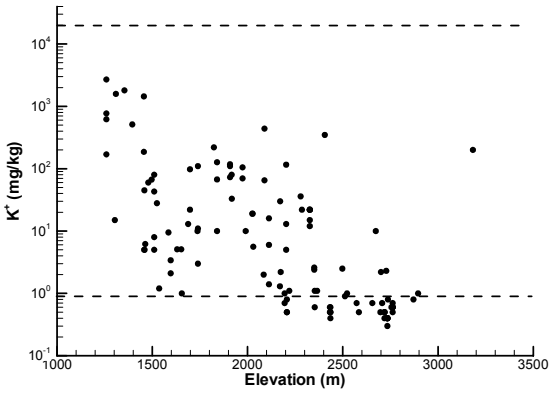

Figure 7: K^{+} concentration (ppm). The dashed lines show the range of model values over the area shown in Figure 3.

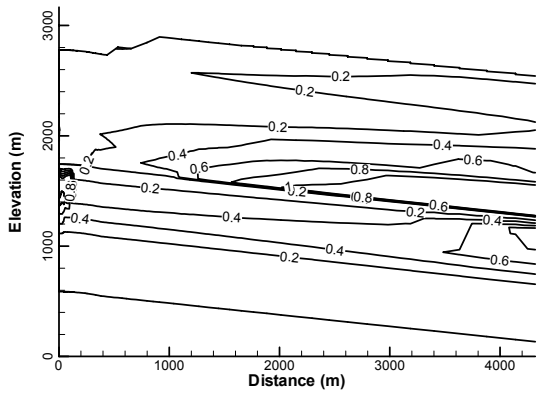

Figure 8: Contours of Ca^{++} concentration (M).

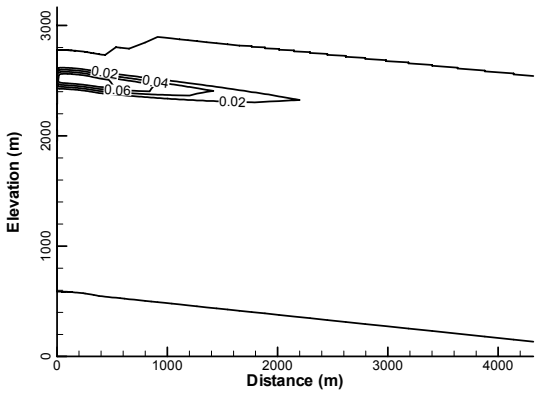

Figure 9: Contours of $SO4^{--}$ concentration (M).

Figure 4 shows the effect of the initial mineral assemblage on the calculated pH. The waters become more acid with depth with the pH being controlled by the partial pressure of CO_2.

Figures 5-7 compare the chemistry calculated by allowing the reservoir shown in Figure 3 to evolve for 1000 years assuming the reservoir fluid is initially a 0.3 M NaCl brine with data from oil well brines, shallow well water and springs located on the Utah portion of the Colorado Plateau. Figures 8 and 9 show the Ca^{++} and $SO4^{--}$ ion concentration and again we see the effect of reservoir rock types and the modification of this by the presence of CO_2. The high SO_4^{2-} concentration in Figure 9 corresponds to the Summerville formation containing 1% anhydrite.

CONCLUSIONS

We have developed a conceptual and numerical model of a Laramide-type structure based on Farnham Dome, Utah and determined appropriate parameters for the sealing structures required for the formation of natural CO_2 reservoirs. Numerical modeling using seal permeabilities of the order of 0.01 mD produces CO_2 reservoirs in the appropriate locations. Equally important is the choice of a realistic capillary pressure function for the seal units.

Modelling results using a rock assemblage that is a simplification of the structures at Farnham Dome but that contains the main mineralogical elements of the geology produces pH and anion concentrations that are generally consistent with values measured on the central Utah portion of the Colorado Plateau. Future work will use observed rock alteration and reservoir chemistry to provide constraints on the numerical modeling.

Table 2: Kinetic reaction parameters

Mineral	E_a (J)	k_{25} ($M/m^2/s$)	A_m (m^2/dm^3)
beide-Na	62760	1e-13	10
Anorthite	41870	1.6e-9	10
Calcite	41870	1.6e-9	10
Dolomite	41870	0.6e-9	10
k-feldspar	41870	1.6e-9	10
Kaolinite	62760	1.0e-13	1000
Quartz	87500	1.26e-14	10
Gypsum	41870	1.6e-9	10
Illite	58620	1.0e-14	1000
Hematite	62800	1.0e-11	10
magnetite	62800	1.0e-11	10
Albite-hi	38200	3.09e-12	10

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