Identification of Gravitational Trapping Processes of CO_2 Sequestration in Offshore Marine Sediments

LA-UR-16-24009

Zhenxue Dai[1], Ye Zhang[2], Philip Stauffer[1], Mingkan Zhang[2]

[1]Earth & Environmental Sciences, Los Alamos National Laboratory, Los Alamos, NM, USA
[2]Department of Geology & Geophysics, University of Wyoming, Laramie, WY, USA

Abstract

A global Latin Hypercube sensitivity analysis is carried out to identify **gravitational trapping in marine sediments** exhibiting heterogeneous permeability and variable thicknesses. Based on geostatistical models populated with sediment data from 4 sites in the U.S. Gulf of Mexico, the sensitivity analysis varies: *sediment thickness, mean permeability and porosity, permeability anisotropy, log permeability variance, log permeability integral scales, water depth, CO_2 injection rate, seafloor temperature, and geothermal gradient*. Key parameters, their correlations, and their rankings in influencing CO_2 sub-seafloor injectivity and leakage are identified. Results indicate that *permeability heterogeneity and anisotropy, sea water depth, and sediment thickness can significantly impact CO_2 flow and trapping in marine sediments*. Strong permeability/porosity heterogeneity can enhance gravitational trapping, which acts to deter CO_2 upward migration and leakage through seafloor. When log permeability variance is high, gravitational trapping can be achieved at a water depth of 1.2 km, significantly extending previously identified self-sealing conditions requiring water depth > 2.7 km. Results suggest a far greater areal extent for relatively safe offshore CO_2 storage than previously proposed, with a likely reduction in overall costs associated with shallower emplacement targets.

Gravitationally Stable Storage

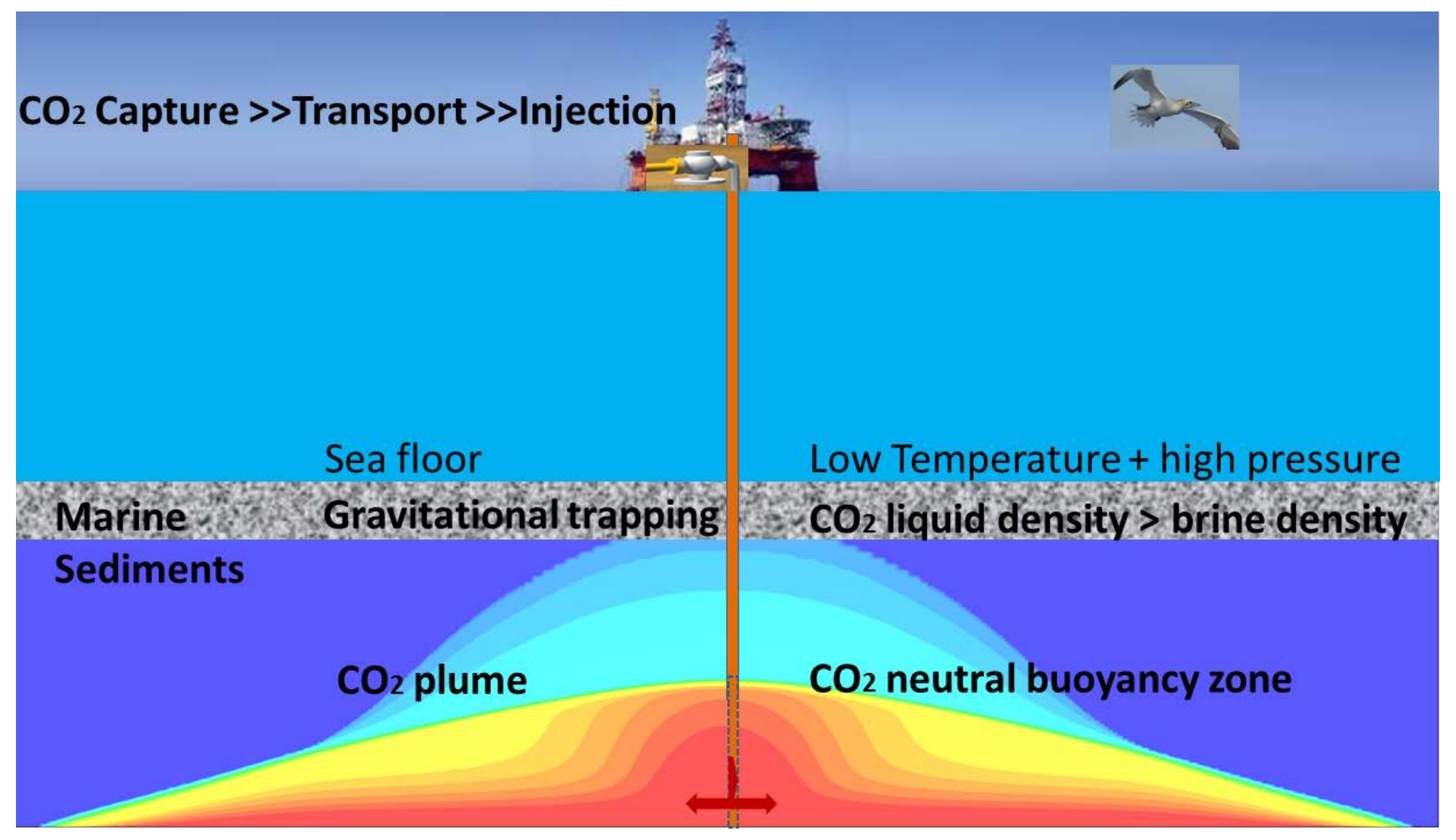

Figure 1. Schematic of gravitational trapping in marine sediments. Under suitable TP conditions, CO2 density can exceed pore water density, thus the injected CO_2 will move downward until it becomes gravitationally stable.

Gravitational trapping: By injecting CO_2 into sediments beneath the seafloor under suitable temperature and pressure conditions, CO_2 density can exceed pore water density and will sink until it is gravitationally neutral (**Figure 1**). The Gulf of Mexico (GOM) is identified as a potential gravitational trapping site with subsurface data, existing pipeline network, and boreholes. Using fluid flow and sediment data collected from 4 GOM sites (Alminos Canyon, Bullwinkle, Ursa Basin, and Eugene Island; **Figure 2**), this study investigates conditions and key parameters that contribute to gravitational trapping. At these sites, sediments of sufficient thickness, porosity, and permeability exist (**Figure 3**), providing potential reservoirs for sub-seafloor storage.

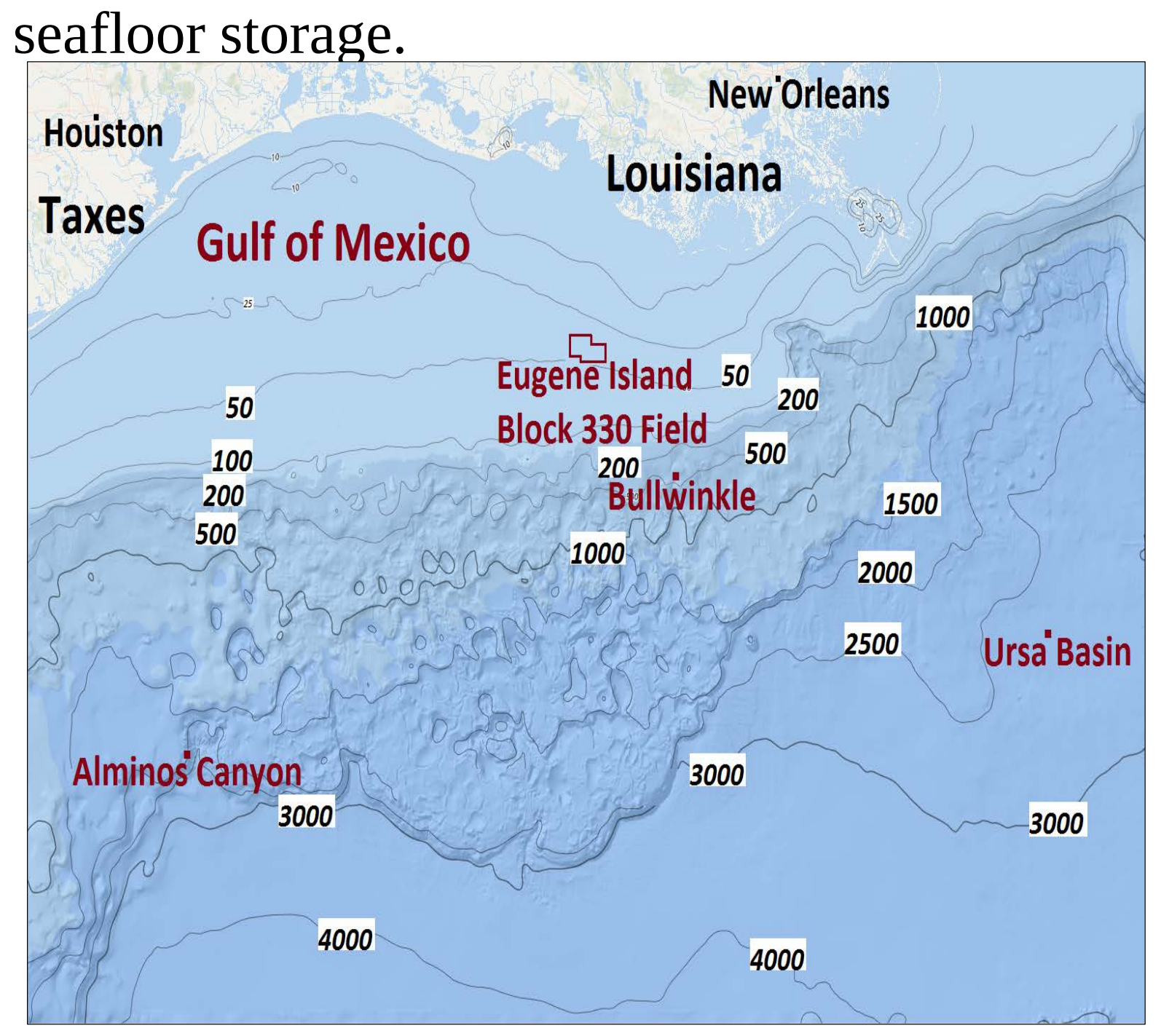

Figure 2. Select sites from the GOM where sediment data are used to populate models.

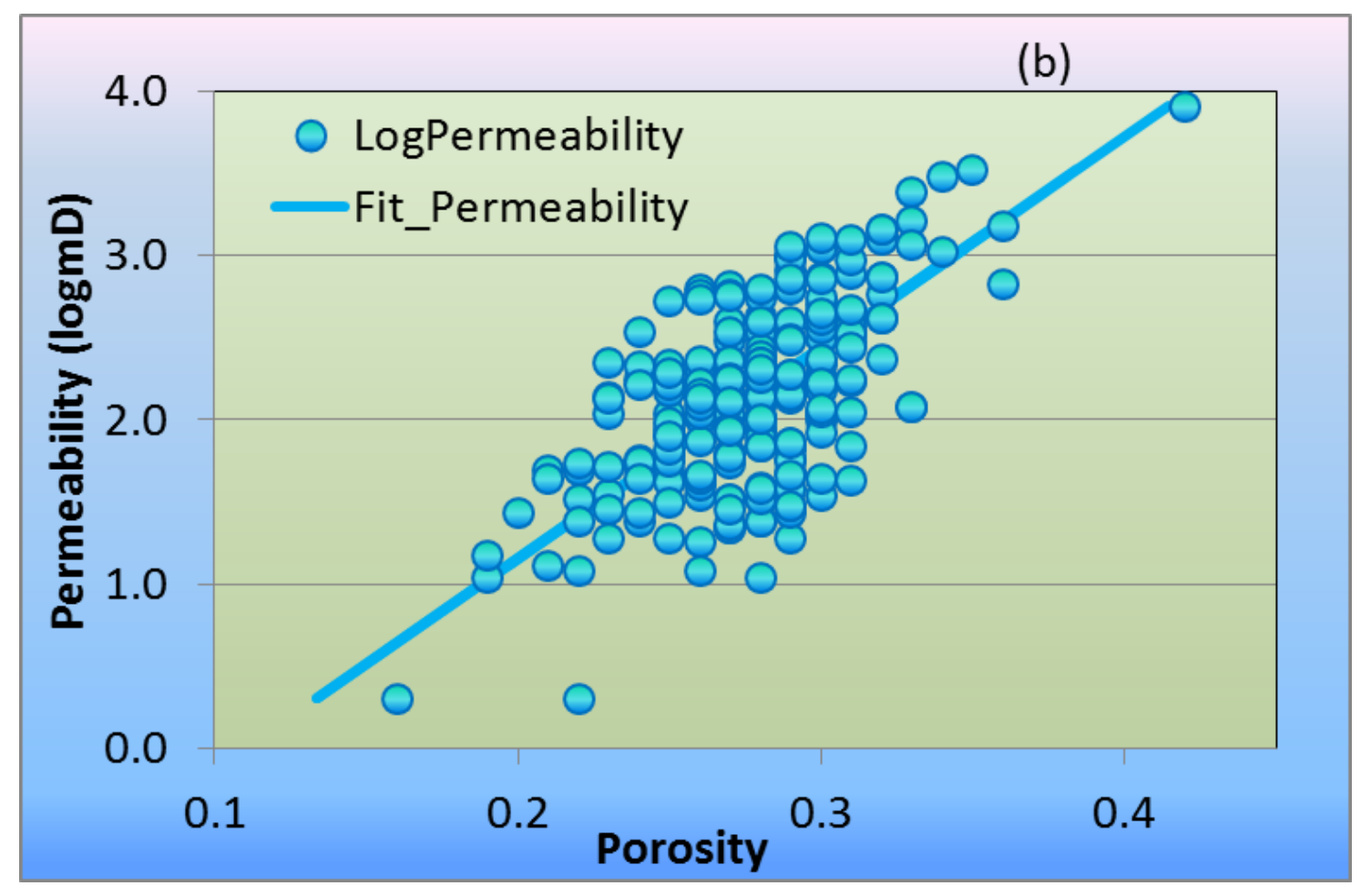

Figure 3. Permeability (k) and porosity (ϕ) of sediments from the 4 GOM sites. A linear regression relation is fitted (ϕ = a + b $\log_{10}k$), for which a = 0.102 and b = 0.078.

Global Sensitivity Analysis

This study conducts a global sensitivity analysis simulating CO_2 injection into marine sediments[2]. Sediment heterogeneity and anisotropy were incorporated at the reservoir scale, while solubility, heterogeneity, and gravitational trapping processes were modeled. Given variable reservoir conditions (i.e., thickness, T, P) and uncertainty in the fluid flow parameters, a statistical framework for identifying & ranking key parameters that influence CO_2 gravitational trapping was developed. Parameters varied include: *sediment thickness, mean permeability and porosity, permeability anisotropy, log permeability variance, log permeability integral scales, water depth, CO_2 injection rate, seafloor temperature, and geothermal gradient* (Table 1). Uncertainty in CO_2 storage and leakage was quantified.

Global Sensitivity Analysis: A computationally efficient technique based on multivariate adaptive regression spline (MARS) with normalized indices was applied to investigating the sensitivities of an output variable (e.g., CO_2 leakage) to variation of an input parameter[3,4]. MARS is based on computing the variance of conditional expectation (VCE) of an output variable (Y):

		Min.	Max.	Base case	Distribution
Sediment Property	Sediment thickness (km)	0.005	0.9	500	Uniform
	Mean permeability (D)	0.001	8	1.0	Log uniform
	Permeability anisotropy factor	0.01	0.5	0.1	Uniform
	Permeability variance	0.0	5.0	0/1.0	Uniform
	Horizontal integral scale (km)	0.5	5.0	1.0	Uniform
	Mean porosity	0.1	0.42	0.2	Correlated to perm
Physical Parameter	Water depth (km)	0.1	4.4	2.5	Uniform
	CO_2 injection rate (kg/s)	0.002	2.0	0.3	Correlated to depth
	Seafloor temperature (ºC)	1	20	2	Correlated to depth
	Geothermal gradient (ºC/km)	5	50	20	Correlated to depth

Table 1: Parameter distribution for MC simulations of CO_2 storage in GOM sediments.

$$VCE(X_k)=\frac{100}{s}\sum_{j=1}^{s}(\overline{Y}_j-\overline{Y})^2-\frac{1}{sr^2}\sum_{j=1}^{s}\sum_{i=1}^{r}(Y_{ij}-\overline{Y}_j)^2$$

where VCE quantifies the variability in the conditional expected values of Y when an uncertain input parameter (X_k) varies in its parameter space. For X_k, s is the number of distinct values sampled from its distribution, and r is the number of replications. $N = sr$ is sample size. Using Eqn. (1), sensitivities of Y to a number of input parameters can be quantified and ranked, representing the relative importance of each input parameter to the prediction of Y. Using the MARS response surface functions, the suite of VCE is then evaluated to generate a prediction envelop of Y given the uncertain input parameters.

Base Case Simulations (Homogeneous vs. Heterogeneous Reservoirs)

Two base cases were simulated using representative parameters from GOM (reservoir thickness = 500 m, length = 5 km). For **base case A**, sediments are assumed homogeneous with a horizontal permeability of 1D; for **base case B**, heterogeneous horizontal permeability distribution is generated with SGS (mean k = 1D, $\log_{10}k$ variance =1.0, horizontal $\log_{10}k$ integral scale =1.0 km). Porosity in this model is computed from the horizontal k (Figure 3). The remaining parameters of the two base cases are identical. A uniform CO_2 injection rate (0.3 kg/s) is assigned at the bottom-center of the model for 10 years. After injection ceases, CO_2 migration is modeled until 200 years. Results of the two base case simulations are shown in **Figures 4 & 5**. Gravitationally stable storage is accomplished in both cases, although **B** has a more complex plume geometry. The importance of the parameters is then ranked using Monte Carlo simulations of CO_2 injection based on several sets of geostatistical reservoir models populated with GOM reservoir parameters (**Figures 6 & 7**).

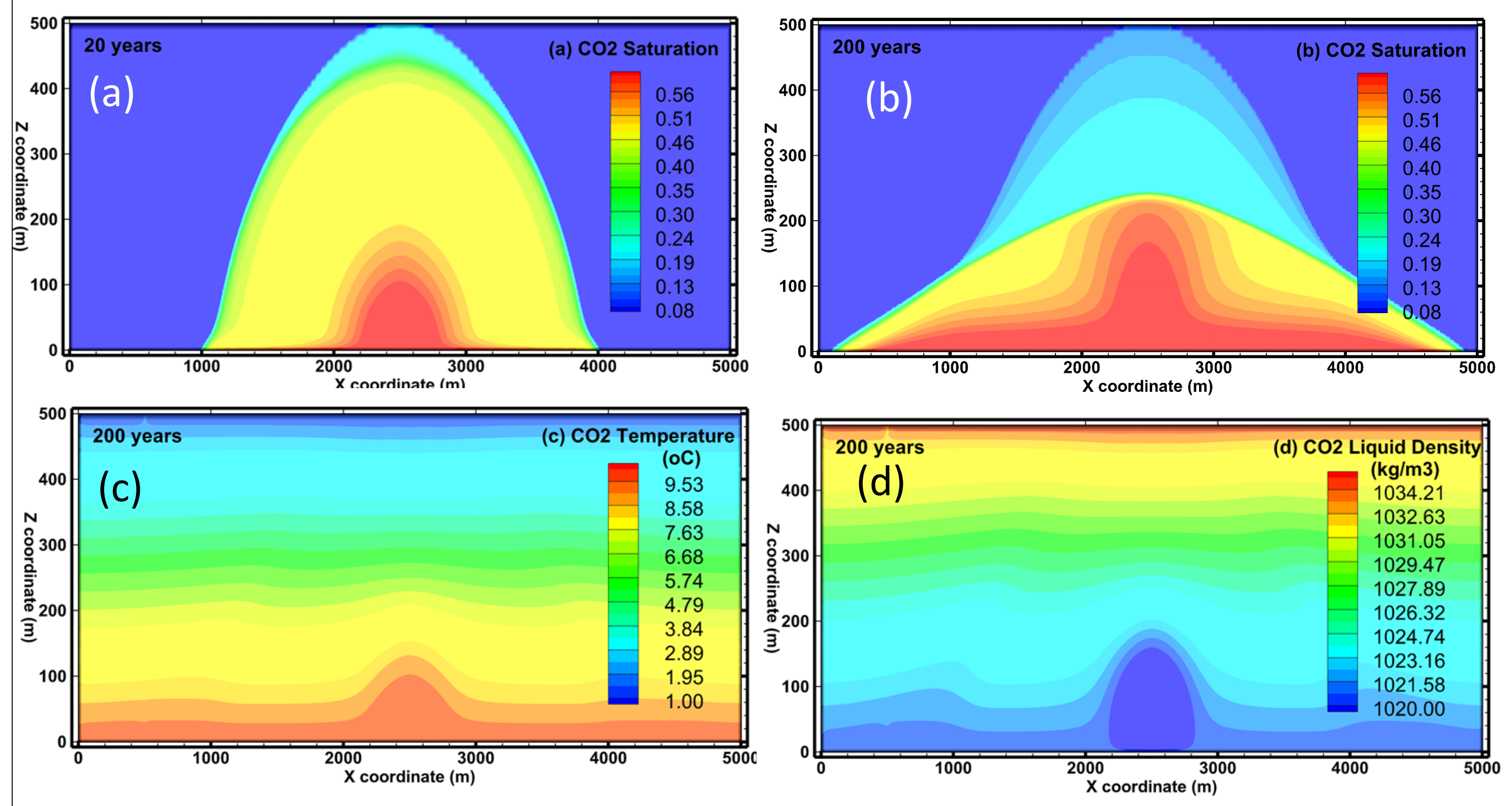

Figure 4. Simulated liquid CO_2 saturation at 20 years (a) and 200 years (b), reservoir temperature distribution (c), and CO_2 liquid density (d) for base case A.

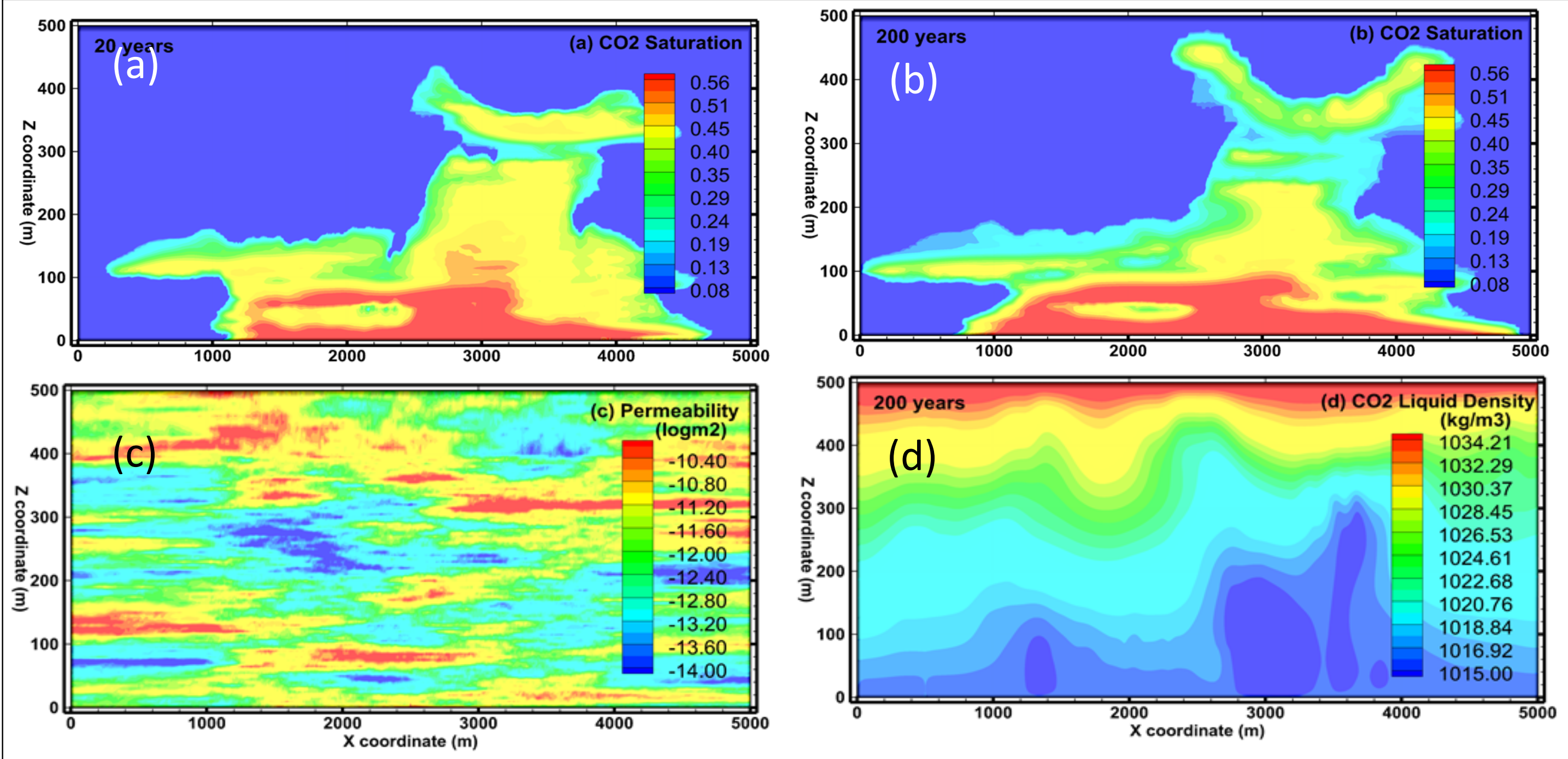

Figure 5. Simulated liquid CO_2 saturation at 20 years (a) and 200 years (b), reservoir horizontal k (c), and CO_2 liquid density (d) for base case B.

Significance Ranking

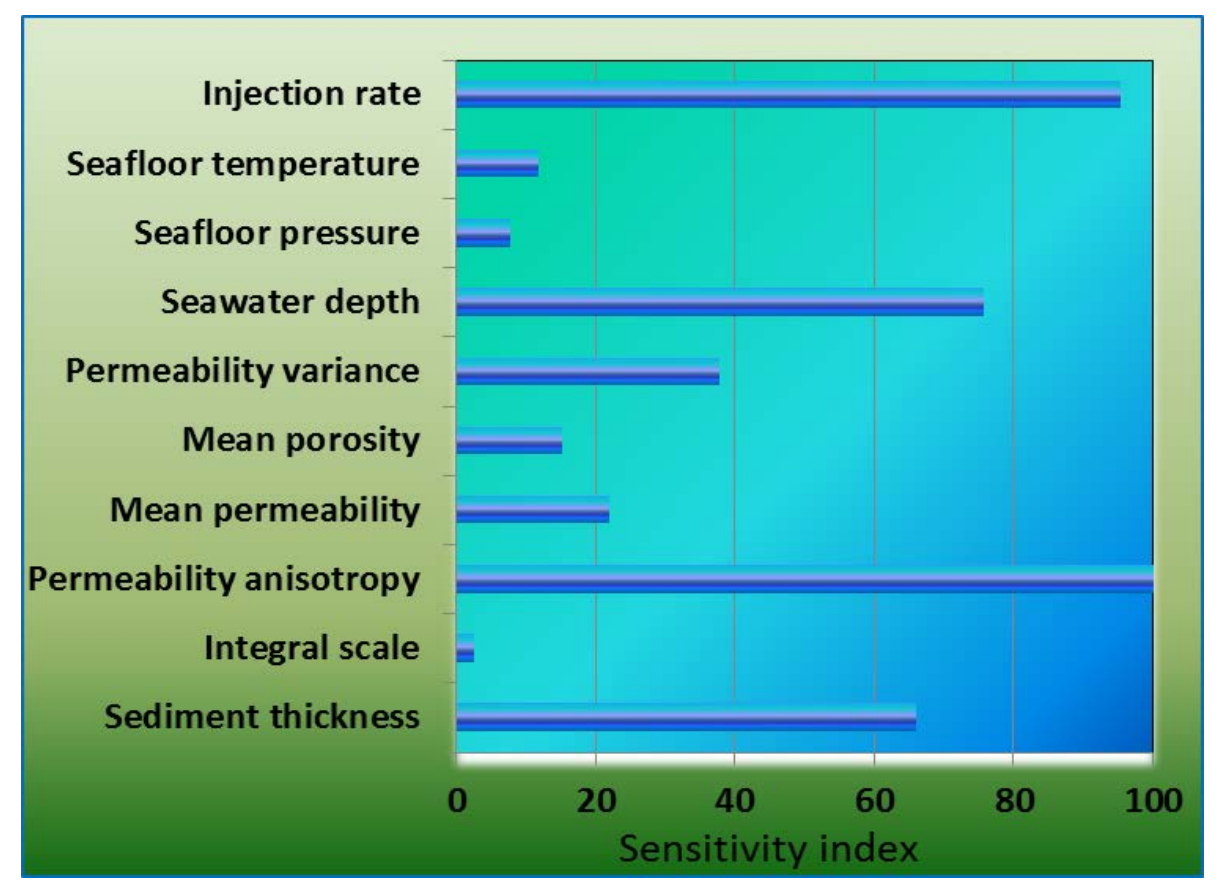

Figure 6. Computed sensitivity index of the output variable (percent CO_2 leakage from reservoir top) to each uncertain input parameter.

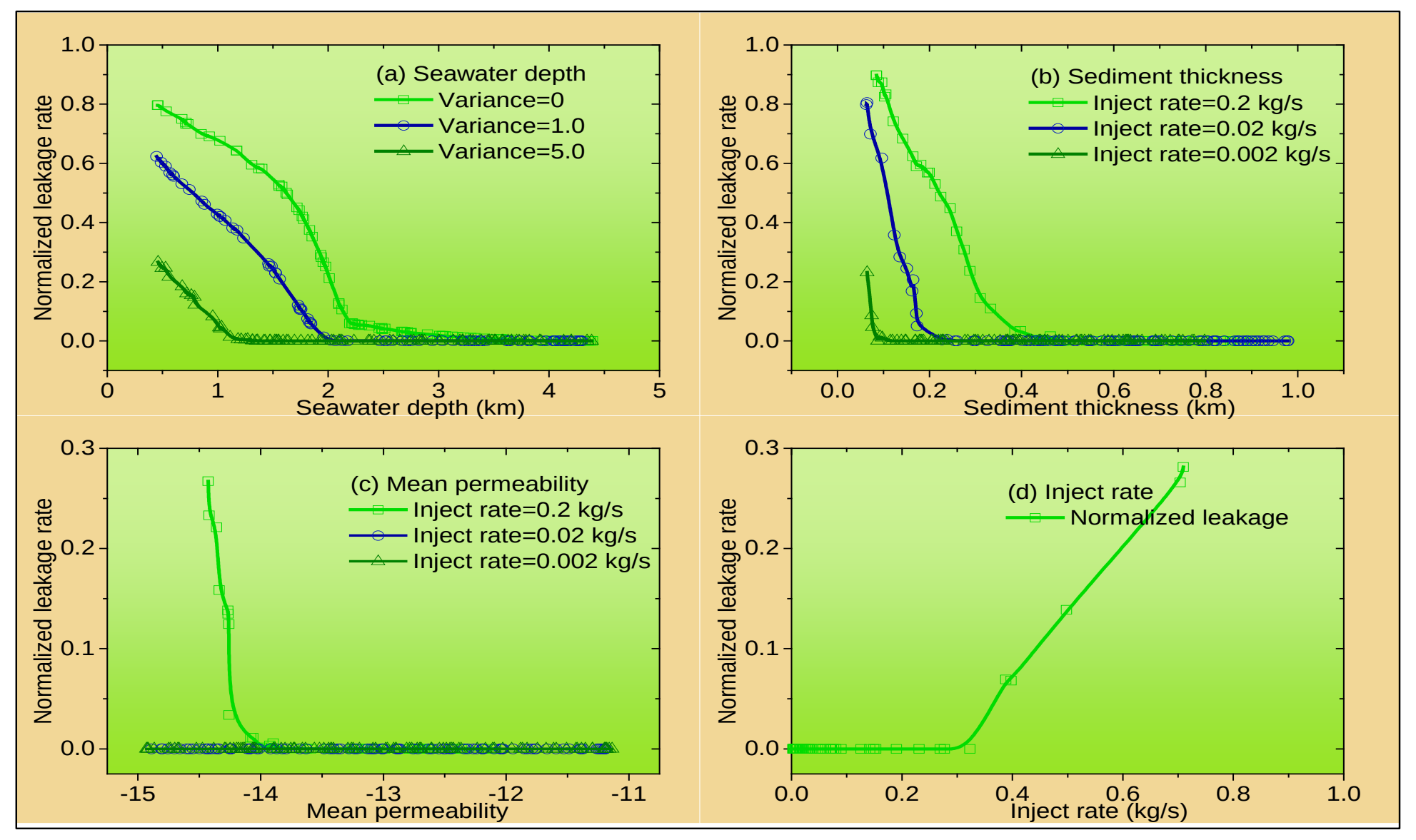

Figure 7. Impact of water depth (a), sediment thickness (b), mean permeability (c), and injection rate (d) on the predicted CO_2 leakage onto the seafloor.

Conclusions

This study conducts an uncertainty analysis of CO_2 gravitational trapping in GOM sediments. Uncertain reservoir input parameters are defined based on data from 4 GOM sites. Under conditions representative of such reservoirs, gravitationally stable storage can be accomplished.

- When reservoir is homogeneous ($\log_{10}k$ variance = 0), an approximate water depth ≥ 2.5km is identified as a threshold for gravitational trapping to occur; when permeability (and porosity) are heterogeneous ($\log_{10}k$ variance = 1.0), water depth ≥ 2.0 km is identified as a threshold; when log permeability variance increases to 5.0, water depth ≥ 1.2 km. This extends the previously identified self-sealing condition requiring water depth be greater than 2.7 km.
- Under increasing injection rate, thicker sediment is required to help deter CO_2 upward migration and leakage onto the seafloor. On the other hand, larger mean permeability and porosity can help sequester more CO_2 safely in the sediments under gravitational trapping.
- Safe storage could be accommodated in GOM sediments with *a large thickness, high mean permeability and porosity, and using a relatively low injection rate*.

References

1. House, K. Z., D. P. Schrag, C. F. Harvey, and K. S. Lackner, Permanent carbon dioxide storage in deep-sea sediments., Proc. Natl. Acad. Sci. U. S. A. 2006, 103, 12291–12295.Li et al. (2013), *Application of a health, safety, and environmental screening and ranking framework to the Shenhua CCS project*, IJGGC.
2. https://fehm.lanl.gov/
3. Tong, C.. PSUADE User's Manual (Version 1.2.0), LLNL-SM-407882, Lawrence Livermore National Laboratory, Livermore, CA 94551-0808, May, 2011.
4. Friedman, J. H., Multivariate adaptive regression splines. The Annals of Statistics 1991, 19: 1. doi:10.1214/aos/1176347963.

Acknowledgement

This project was funded by the Department of Energy, Office of Fossil Energy, under DE-FE-0009238. The 2nd author acknowledges the support by EES-16 of Los Alamos National Laboratory for her sabbatical in Spring 2015, which made some of the work reported here possible.