Simulated CO_2 storage efficiency in sandstone and carbonate reservoirs: CO_2-SCREEN tool upgrade

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INTRODUCTION

The Regional Initiative to Accelerate Carbon Capture, Utilization, and Storage (CCUS) Deployment is supporting the Office of Fossil Energy and Carbon Management's (FECM) mission to help the United States meet its need for secure, affordable, and environmentally sound fossil energy supplies. The U.S. Department of Energy's National Energy Technology Laboratory (DOE-NETL) has been developing methods and tools (the online Carbon Dioxide Storage prospeCtive Resource Estimation Excel aNalysis (CO_2-SCREEN) tool) to estimate carbon dioxide (CO_2) storage potential in subsurface reservoirs.

In this study $scCO_2$ was injected over the course of 30 years into brine-saturated heterogeneous reservoir models for clastics, limestone, and dolomite lithologies and Deltaic Fluvial, Aeolian, Shallow Marine, and Reef depositional environments.

The CO_2 storage efficiency terms are served as inputs in that tool to calculate storage potential in a targeted reservoir. Volumetric displacement (E_V) and microscopic displacement (E_d) were simulated using TOUGH3. The first term deals with efficiency of CO_2 propagation into an accessible reservoir volume, while the second term evaluates effectiveness of native fluid displacement with CO_2. The CO_2 storage efficiency factors were evaluated dynamically at select time points using P_{10}-P_{90} percentiles.

SALINE METHODOLOGY EQUATIONS

$$G_{CO_2} = \boxed{A_t h_g \phi_t \rho}\, E_{saline}$$

Idealistic CO_2 mass stored in total pore volume

where A_t, h_g, ϕ_t, ρ are the areal size of the formation, the thickness of the formation, total porosity, and CO_2 density (estimated at average pressure and temperature of the storage formation), respectively.

$$\boxed{E_{saline}} = E_A E_h E_\phi E_V E_d$$

The storage efficiency (E_{saline}) term reduces the estimation of stored CO_2 mass at a specific site to accommodate the complexities of the geologic factors and fundamental processes associated with injection, and storage.

where E_A, E_h, and E_ϕ are the fraction of the geologic area, thickness, and porosity accessible for CO_2 storage, respectively;
E_V is the volumetric displacement efficiency, represents the fraction of reservoir volume accessed by CO_2 plume;
E_d is the microscopic displacement efficiency, is the fraction of water displaced by CO_2.

Simulation-based E_V and E_d efficiency terms

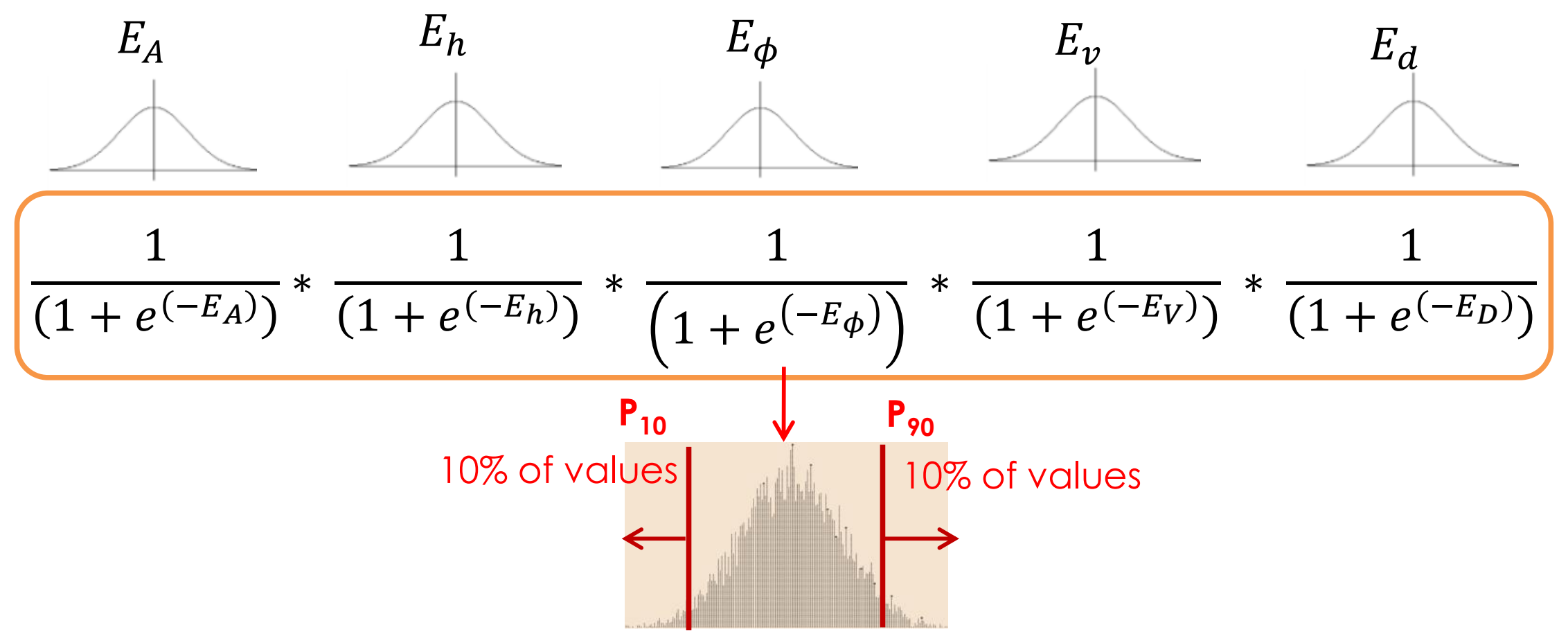
$$E_V = \frac{V_i}{Ah\phi(1 - S_{w_{irr}})} = \frac{Q_i t}{Ah\phi\rho(1 - S_{w_{irr}})}$$

V_i, Q_i, t, $S_{w_{irr}}$ are volume of injected $scCO_2$; mass flowrate, injection time, and irreducible water saturation.

$$E_d = 1 - S_{w_{ave}} = S_{CO_{2ave}}$$

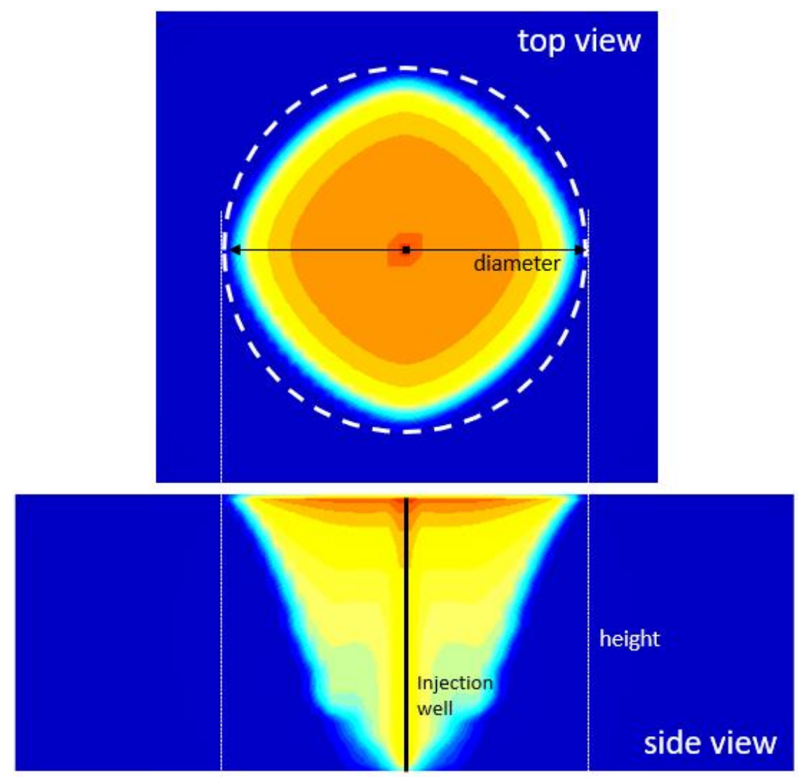
$S_{w_{ave}}$ and $S_{CO_{2ave}}$ are the average water and $scCO_2$ saturations within a CO_2 plume.

Log-odds Stochastic approach



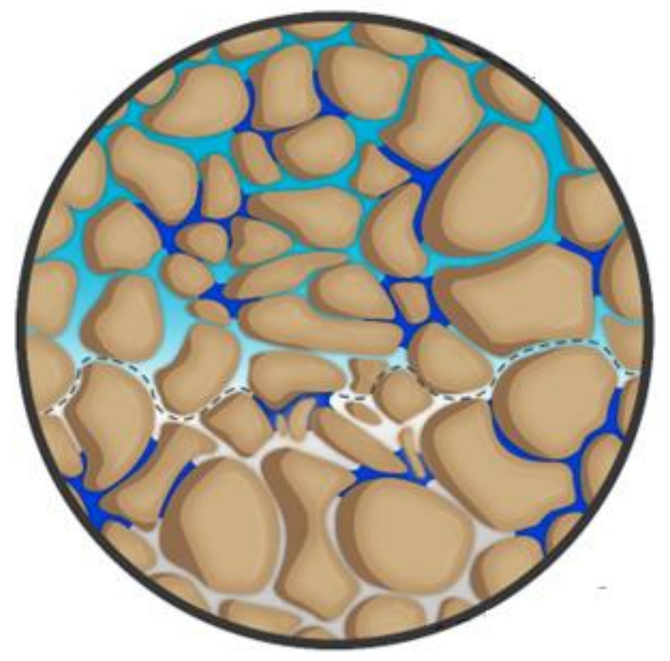
$$\frac{1}{(1+e^{(-E_A)})} * \frac{1}{(1+e^{(-E_h)})} * \frac{1}{\left(1+e^{(-E_\phi)}\right)} * \frac{1}{(1+e^{(-E_V)})} * \frac{1}{(1+e^{(-E_D)})}$$

E_V efficiency: reservoir scale



Minimum-area-circle approach to determine the accessible volume around the CO_2 injection well. The area of the dashed circle (***A***), enclosing the propagating CO_2 plume area (top view) is multiplied by the height (***h***) of the plume (side view) to determine the accessible volume.

E_d efficiency: pore scale



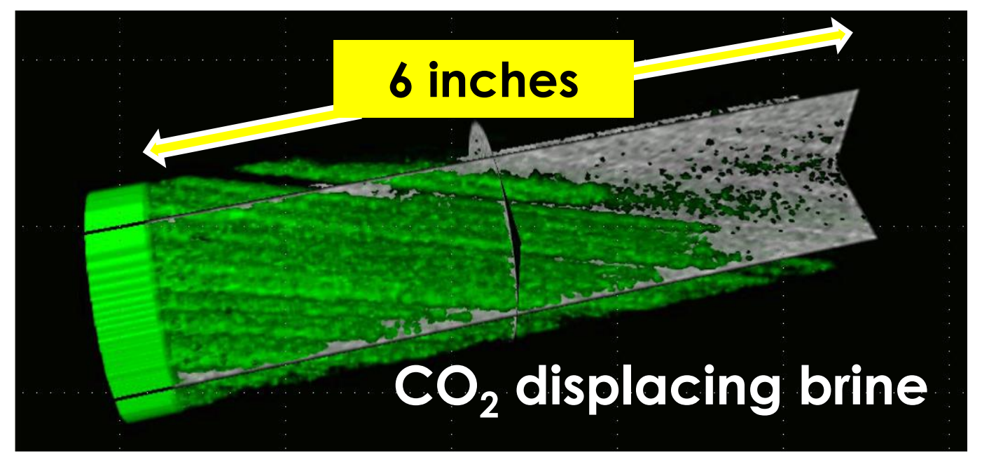
Cyan color: non-wetting invasion phase ($scCO_2$);
White color: mobile wetting phase (brine);
Blue color: trapped (irreducible and capillary bound) water.

A key reservoir parameters, initial conditions, and injection scenarios

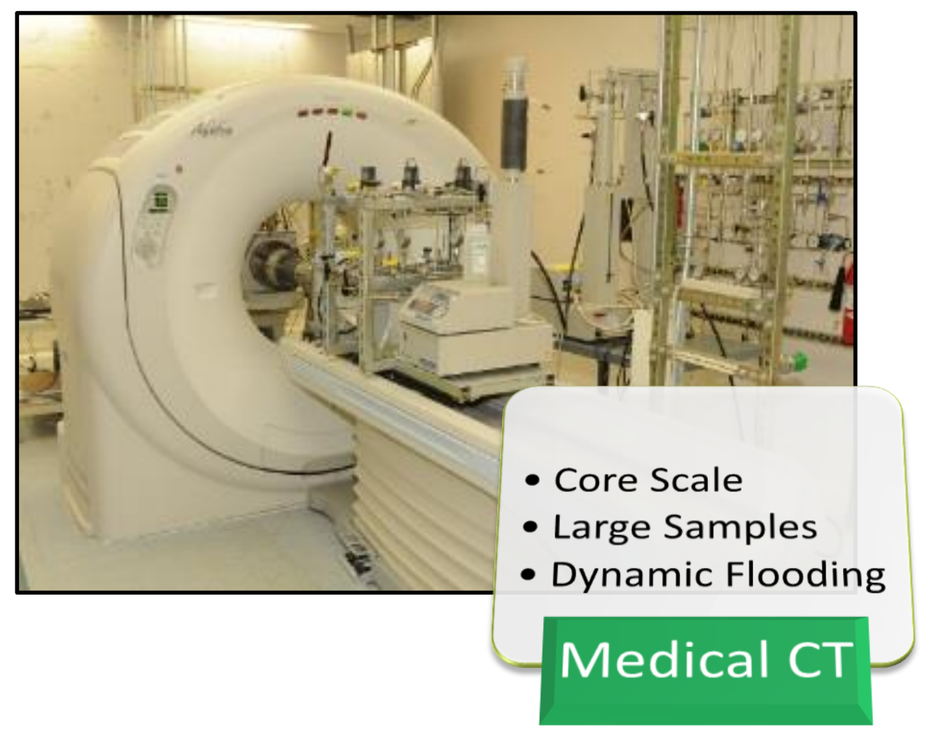
Mesh size and model dimensions	
Length	5,000 m
Thickness	55 and 75 m
Mesh size	35 × 42 and 35 × 62
Number of elements	1,470 and 2,170
Rock properties	
Porosity	Heterogeneous
Permeability	Heterogeneous
Number of geostatistical realizations	9
Relative permeability	CO_2BRA database
Capillary pressure	Lithology-sensitive*
Initial conditions	
Initial pressure	GASIS database
Pressure gradient	10.14 kPa/m
Initial temperature	GASIS database
Temperature gradient	0.02°C/m
Brine concentration	8 wt.%
Pore compressibility	4.5^{-10} Pa^{-1}
Injection scenarios	
Injection rate	400 and 800 tons/day
Injection period	30 years
Perforation	Reservoir thickness

Formation and CO_2BRA sample names corresponding to similar lithology and depositional environments, and CO_2BRA sample porosity, permeability (md), and parameters of relative permeability curves

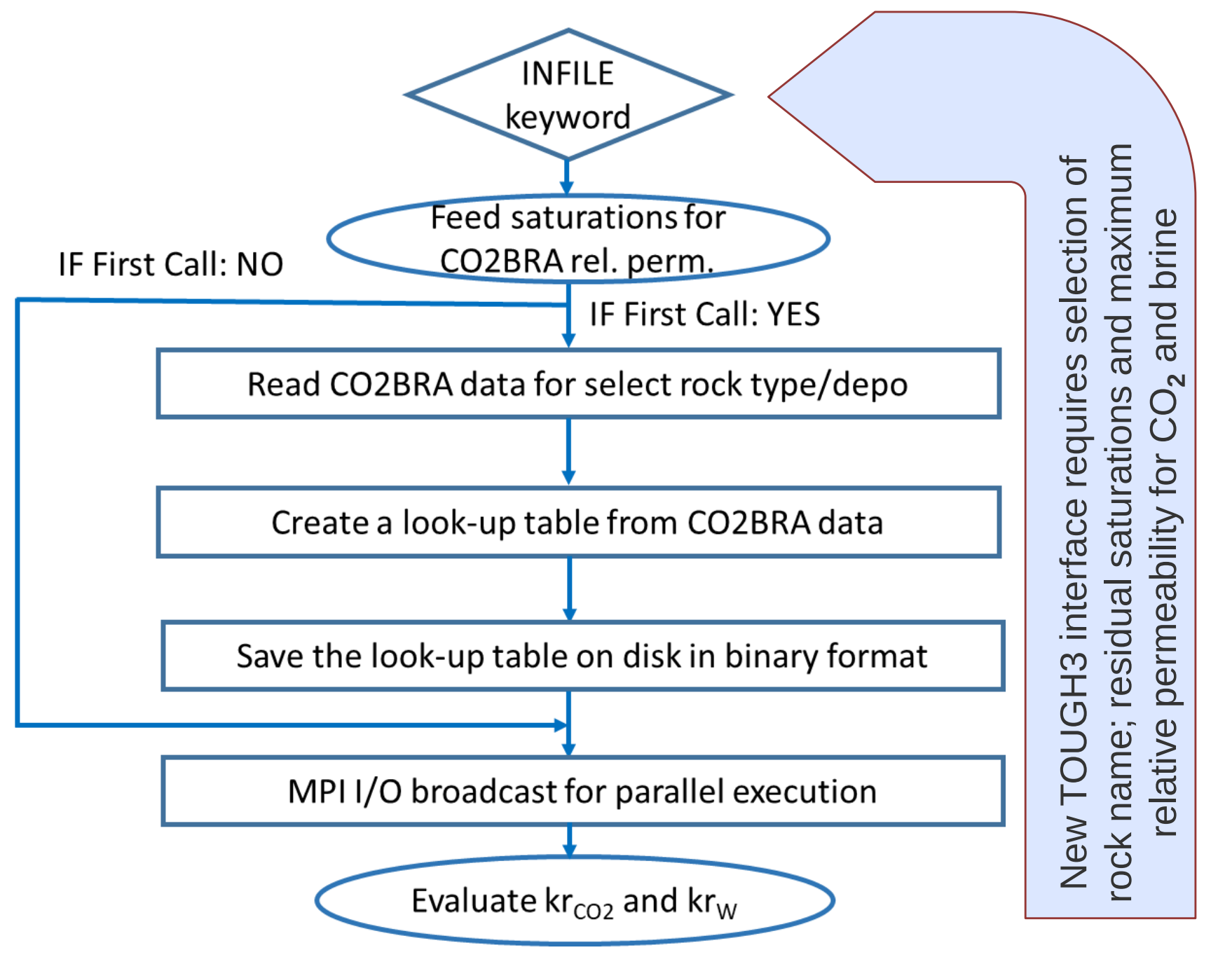
N	Formation name	Lithology	Depositional environment	CO_2BRA sample name	Sample porosity	Sample perm. (mD)	S_{wir}	k_{rw}^{max}	S_{CO2ir}	k_{rCO2}^{max}
1	Lower Mt. Simon	Sandstone	Marginal marine	Bandera Brown A	0.164	124	0.566	1.00	0.00	0.320
2	Cranfield	Sandstone	Deltaic complex fluvial	Castlegate	0.252	865	0.705	1.00	0.00	0.185
3	Broom Creek	Sandstone	Aeolian	Navajo	0.156	41	0.497	1.00	0.00	0.271
4	Middle Duperow	Carbonate, limestone	Shallow marine	Edwards Yellow	0.192	25	0.460	1.00	0.01	0.102
5	Bass Island	Carbonate, dolomite	Shallow marine/reef	Silurian	0.129	327	0.453	1.00	0.10	0.032



CO_2BRA relative permeability for CO_2-brine drainage



Coupling CO_2BRA and TOUGH3 using a lookup table

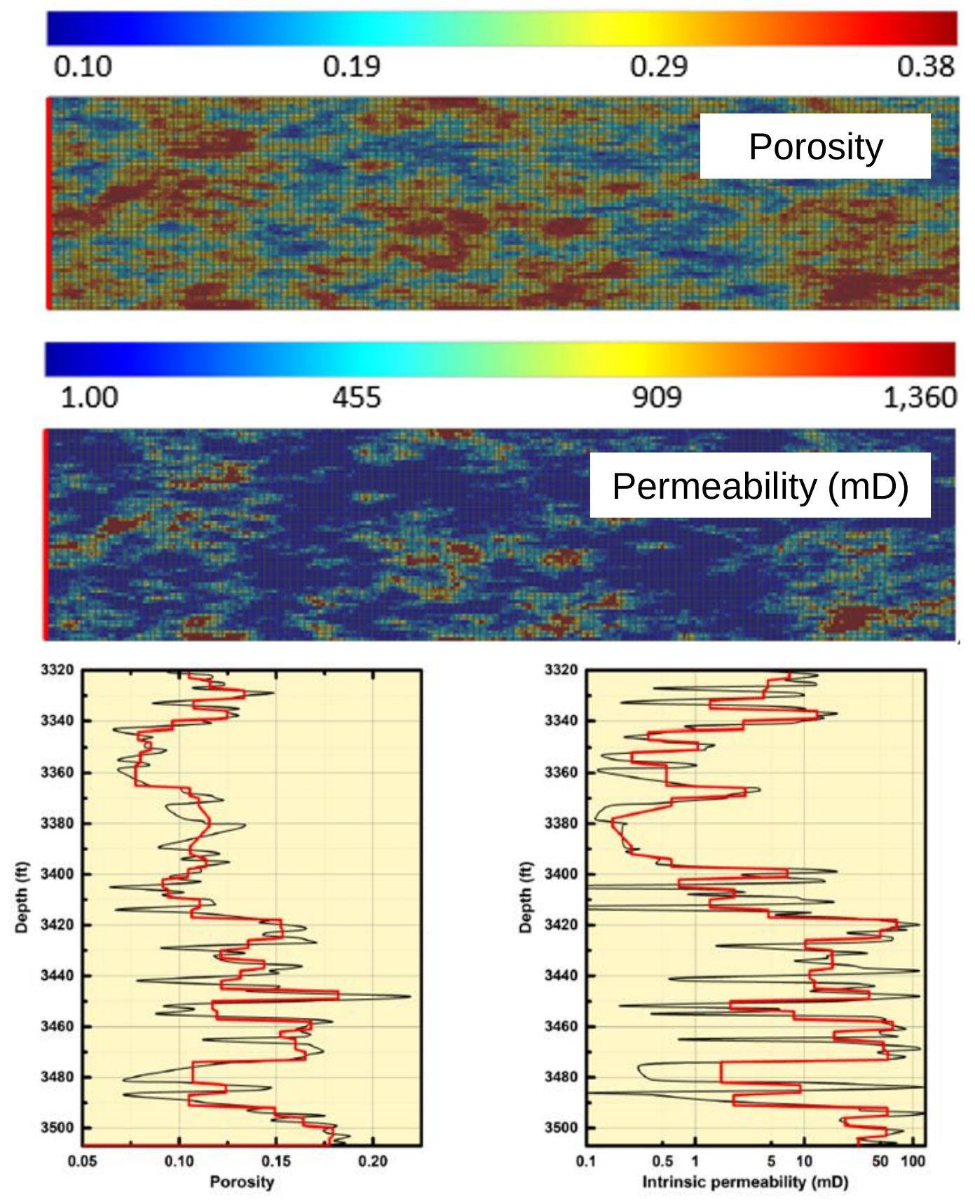


INFILE keyword
Feed saturations for CO2BRA rel. perm.
IF First Call: NO
IF First Call: YES
Read CO2BRA data for select rock type/depo
Create a look-up table from CO2BRA data
Save the look-up table on disk in binary format
MPI I/O broadcast for parallel execution
Evaluate kr_{CO2} and kr_W

New TOUGH3 interface requires selection of rock name; residual saturations and maximum relative permeability for CO_2 and brine

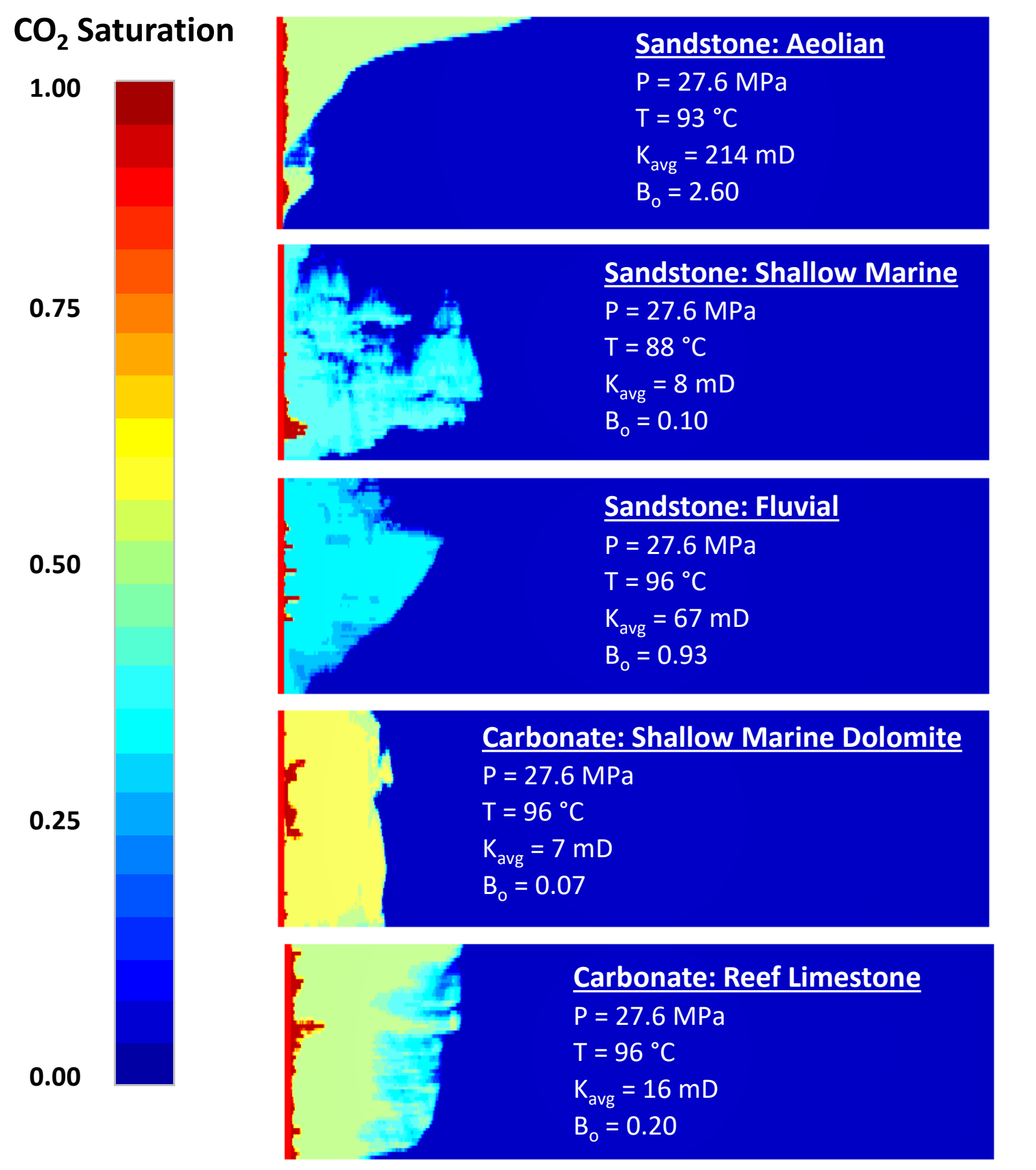
CO_2BRA experimental relative permeability data is directly used in reservoir simulations for a corresponding model of select lithology and depositional environment

Reservoir models



Geostatistical porosity and permeability distributions (top) and well logs for a sandstone/marine formation (bottom)

Reservoir modeling



Sandstone: Aeolian
P = 27.6 MPa
T = 93 °C
K_{avg} = 214 mD
B_o = 2.60

Sandstone: Shallow Marine
P = 27.6 MPa
T = 88 °C
K_{avg} = 8 mD
B_o = 0.10

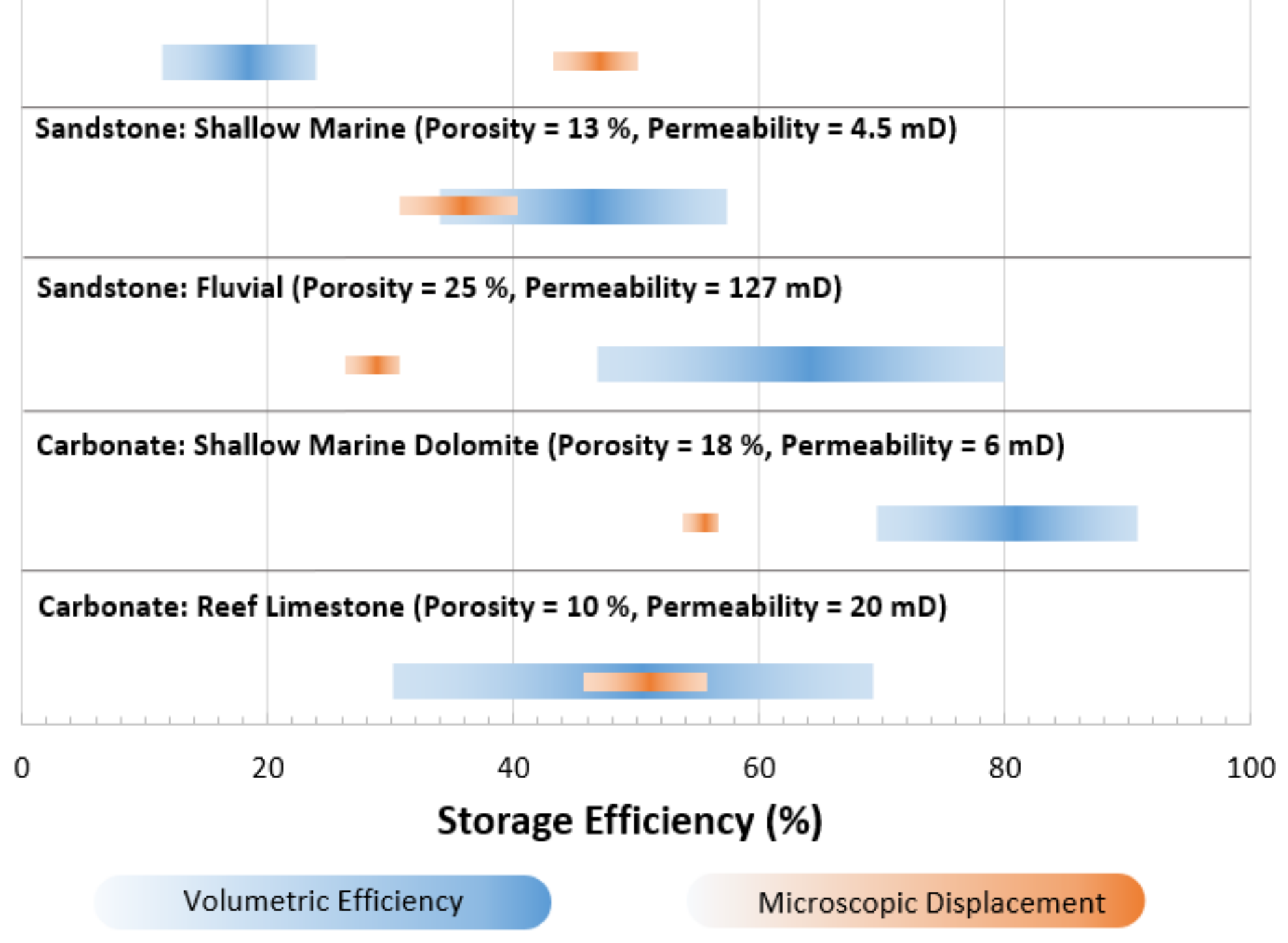
Sandstone: Fluvial
P = 27.6 MPa
T = 96 °C
K_{avg} = 67 mD
B_o = 0.93

Carbonate: Shallow Marine Dolomite
P = 27.6 MPa
T = 96 °C
K_{avg} = 7 mD
B_o = 0.07

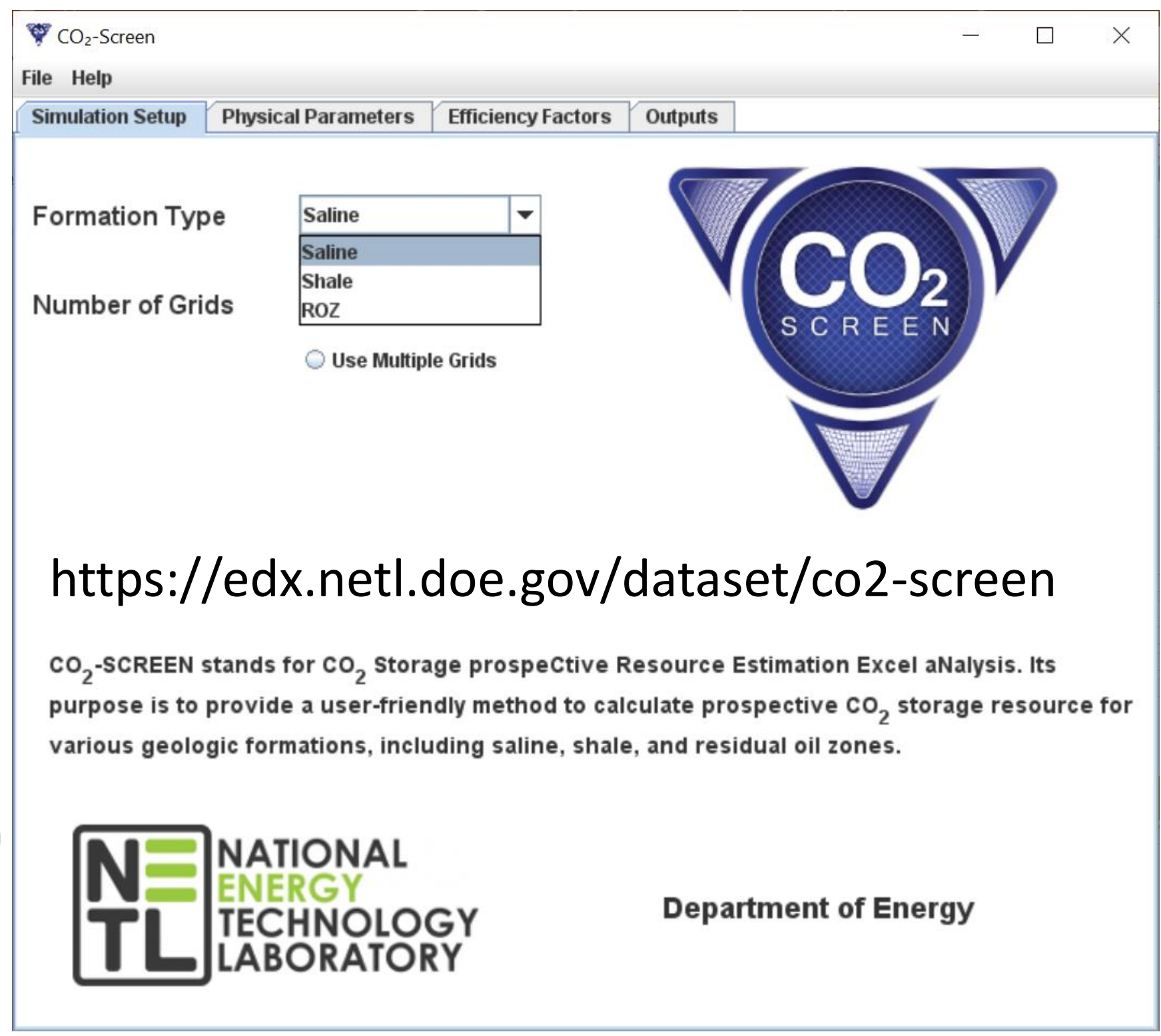
Carbonate: Reef Limestone
P = 27.6 MPa
T = 96 °C
K_{avg} = 16 mD
B_o = 0.20

CO_2 plume propagation in heterogenous reservoir models after 30 years of injection

E_V and E_d efficiencies after 30 years of CO_2 injection in reservoir models of various lithology and depositional environments



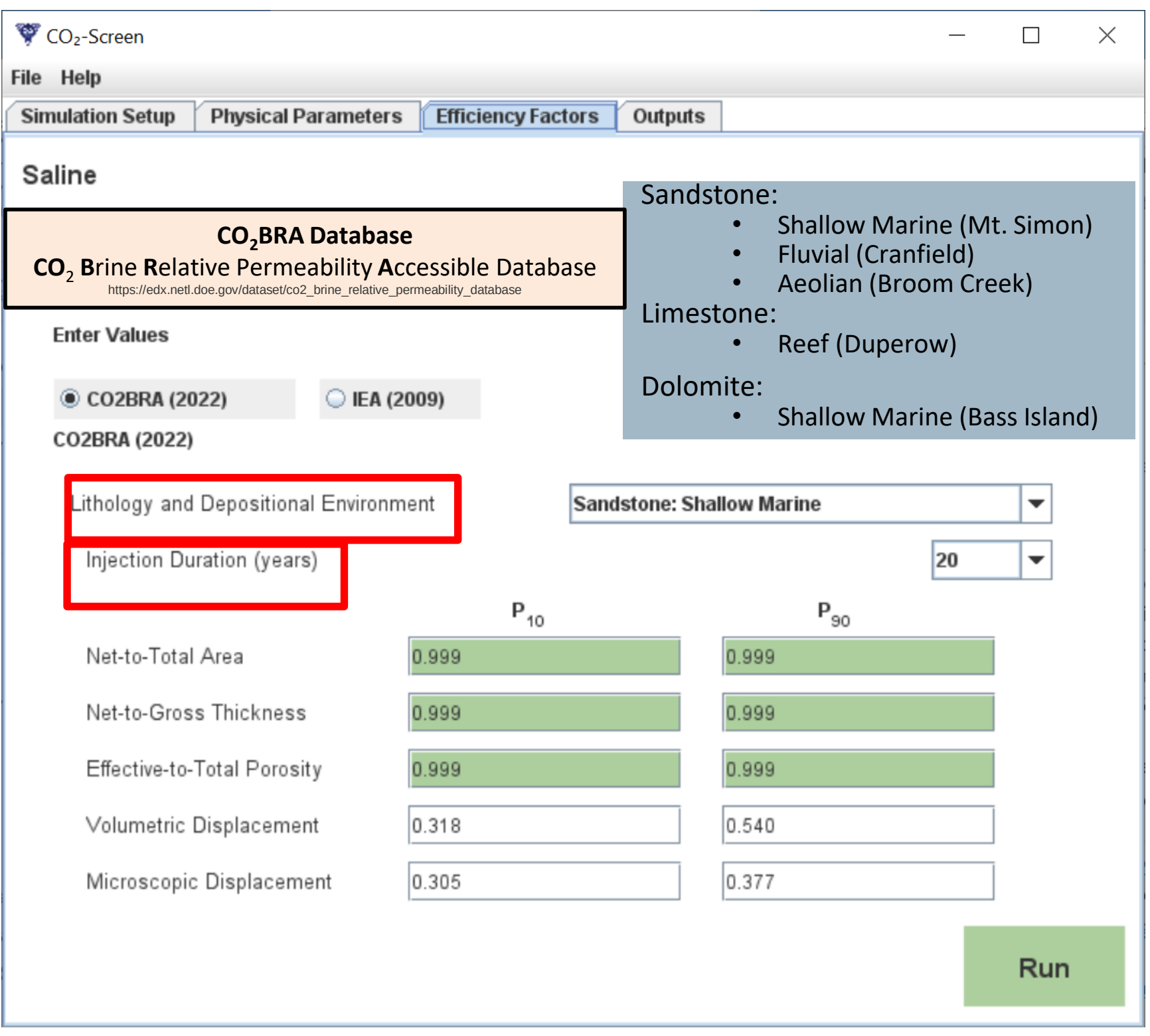
Calculating Prospective Storage – CO_2-SCREEN Tool



Formation Type: Saline
Saline
Shale
ROZ
Number of Grids
○ Use Multiple Grids

https://edx.netl.doe.gov/dataset/co2-screen

CO_2-SCREEN stands for CO_2 Storage prospeCtive Resource Estimation Excel aNalysis. Its purpose is to provide a user-friendly method to calculate prospective CO_2 storage resource for various geologic formations, including saline, shale, and residual oil zones.



Saline

CO_2BRA Database
CO_2 Brine Relative Permeability Accessible Database
https://edx.netl.doe.gov/dataset/co2_brine_relative_permeability_database

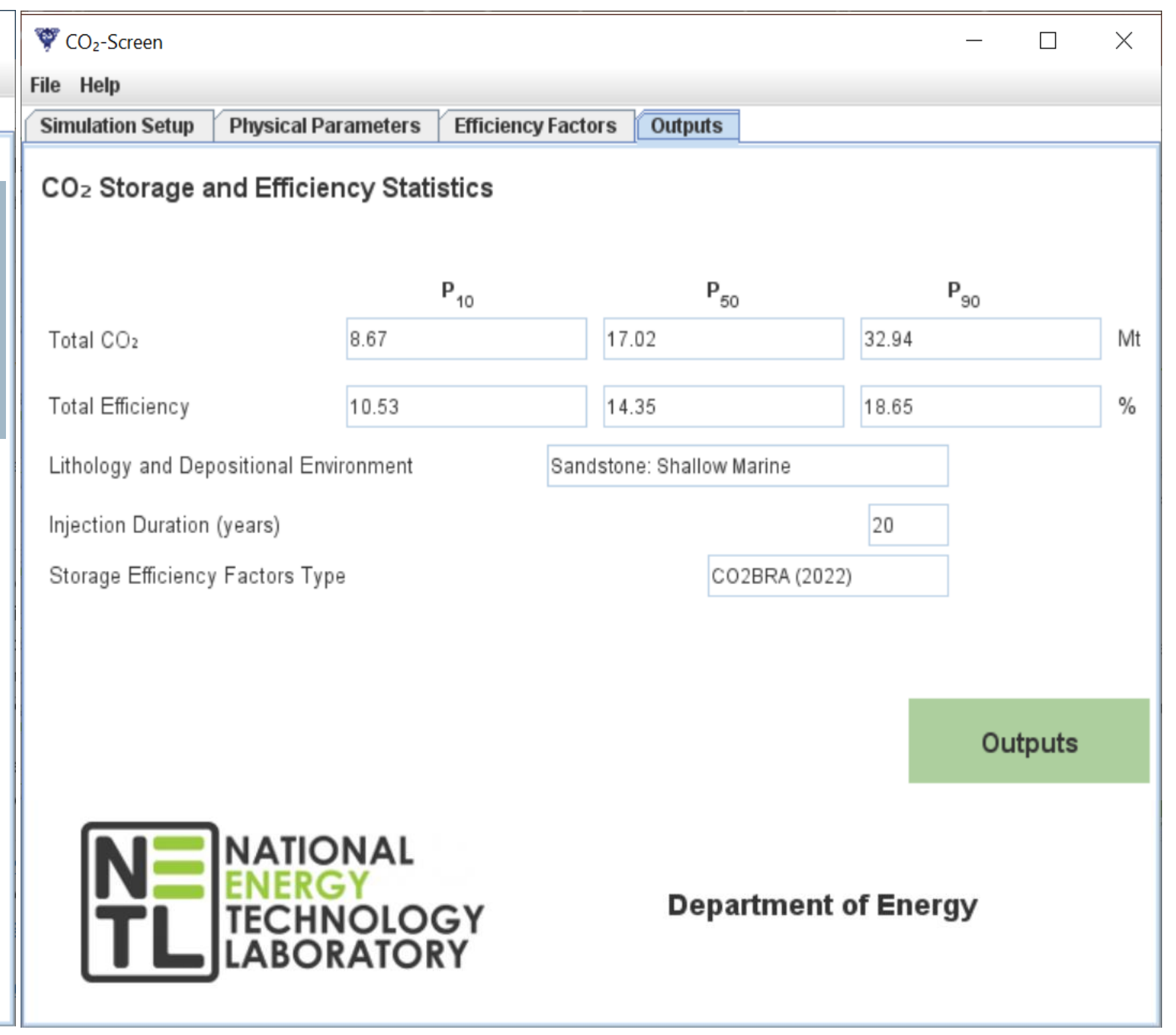
Sandstone:
- Shallow Marine (Mt. Simon)
- Fluvial (Cranfield)
- Aeolian (Broom Creek)

Limestone:
- Reef (Duperow)

Dolomite:
- Shallow Marine (Bass Island)

Enter Values
● CO2BRA (2022) ○ IEA (2009)
CO2BRA (2022)
Lithology and Depositional Environment: Sandstone: Shallow Marine
Injection Duration (years): 20

	P_{10}	P_{90}
Net-to-Total Area	0.999	0.999
Net-to-Gross Thickness	0.999	0.999
Effective-to-Total Porosity	0.999	0.999
Volumetric Displacement	0.318	0.540
Microscopic Displacement	0.305	0.377



CO₂ Storage and Efficiency Statistics

	P_{10}	P_{50}	P_{90}	
Total CO₂	8.67	17.02	32.94	Mt
Total Efficiency	10.53	14.35	18.65	%

Lithology and Depositional Environment: Sandstone: Shallow Marine
Injection Duration (years): 20
Storage Efficiency Factors Type: CO2BRA (2022)

SUMMARY

1. The heterogenous reservoir models mimicking various lithology and depositional environments were created using well logs and core sample measurements of corresponding formations.
2. The geostatistical approach was used to generate up to 9 realizations of porosity and coupled permeability fields for reservoir models.
3. CO_2BRA relative permeability database was utilized for reservoir simulation using select lithology and depositional environment.
4. There is a strong effect of the reservoir parameters and injection rate on the volumetric efficiency, while microscopic efficiency is less influenced as it is evident by narrow ranges of P_{10}-P_{90} values for E_d compared to corresponding ranges for E_V.
5. The heterogenous reservoir models using high porosity and permeability had the lowest volumetric efficiency. That was attributed to dominance of buoyancy forces leading to poor utilization of reservoir volume by the plume. For other heterogenous reservoirs the higher contribution of capillary forces results in better E_V values (expressed through P_{10} and P_{90} values).
6. Tight reservoirs with low permeability and porosity demonstrate higher E_V and E_d, implying more efficient volume and pore network utilization. In other words, higher efficiency factors do not mean more CO_2 can be placed in a formation, rather that the available volume and pore space will be more fully filled. A low porosity reservoir with a high efficiency factor might hold less CO_2 than a high porosity reservoir with a low efficiency factor.
7. New time-dependent volumetric and microscopic efficiency factors are incorporated into CO_2-SCREEN tool that now provides a capability to tailor storage efficiency to select lithology and depositional environment.

ACKNOWLEDGEMENTS
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