Optimization of CO_2 Sequestered as a Residual Phase in Brine-Saturated Formations

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Geologic sequestration of CO_2 in brine-saturated formations has been proposed as a possible method to reduce emissions of this greenhouse gas to the atmosphere. To optimize this method the largest possible volume of CO_2 should be sequestered over geologic time. This optimization goal can best be achieved by sequestering CO_2 as a residual phase under the most advantageous geological conditions. Geological conditions that impact the volume of CO_2 stored as a residual phase include petrophysics, burial effects, temperature and pressure gradients, and CO_2 pressure-volume-temperature character. Analyzing and integrating all of these properties results in an optimal CO_2 sequestration depth for a given geologic subprovince.

The integrated sequestration optimization model was constructed from petrophysical, geological, and CO_2 characteristics. Sequestering CO_2 as a residual nonwetting phase is the key to maintaining its residency in rock over geologic time. Thus residual saturation and porosity were pivotal modeling characteristics. Sediment burial depth affects porosity, temperature, and pressure; consequently, they were integrated together in the model. Finally, CO_2 density as a function of temperature and pressure was accounted for, resulting in a model that combines all the salient properties that affect the amount of CO_2 that can reside in buried rock.

A sequestration optimization curve for the Frio Formation, Upper Texas Gulf Coast, indicates that the largest volume of CO_2 could be trapped as a residual phase at about 11,000 feet. The sequestration optimization curve of depth versus CO_2 density is a concave-down parabolic shape having a broad maximum, indicating the optimal sequestration depth. Additionally, this depth decreases the risk of surface leakage and increases the differential between hydrostatic and lithostatic pressure, both characteristics having sequestration benefits.

END

OPTIMIZATION OF CO_2 SEQUESTERED AS A RESIDUAL PHASE IN BRINE-SATURATED FORMATIONS

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ABSTRACT

Geologic sequestration of CO_2 in brine-saturated formations has been proposed as a possible method to reduce emissions of this greenhouse gas to the atmosphere. To optimize this method the largest possible volume of CO_2 should be sequestered over geologic time. This optimization goal can best be achieved by sequestering CO_2 as a residual phase under the most advantageous geological conditions. Geological conditions that impact the volume of CO_2 stored as a residual phase include petrophysics, burial effects, temperature and pressure gradients, and CO_2 pressure-volume-temperature character. Analyzing and integrating all of these elements result in an optimal CO_2 sequestration depth for a given geologic subprovince.

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NEW SEQUESTRATION PARADIGM

- Sequester CO_2 as a residual phase saturation by capillary forces

PREVIOUSLY SUGGESTED APPROACHES TO GEOLOGIC SEQUESTRATION

- Structural trapping
- Mineral trapping
- Solution trapping
- Trapping associated with enhanced oil
- Trapping associated with coalbed methane

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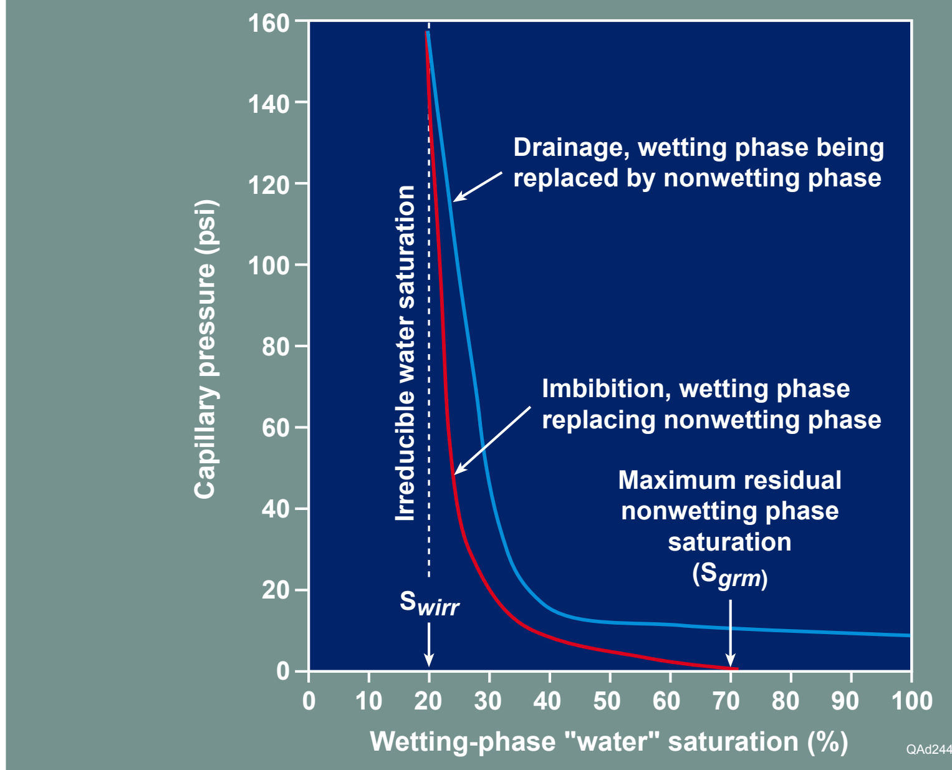
FLOW & SATURATION DEFINITIONS



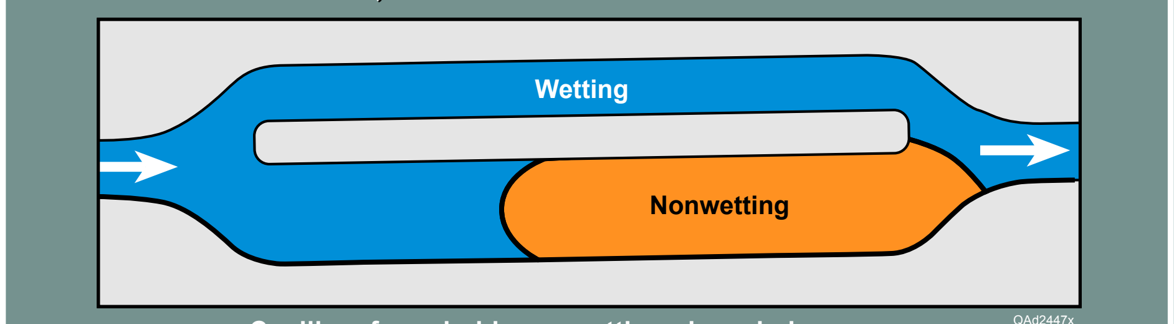
The hysteresis between drainage and imbibition causes a residual nonwetting phase saturation to occur in rocks.

THEORETICAL AND EXPERIMENTAL INVESTIGATION

PORE-SCALE NONWETTING PHASE TRAPPING MODELS

Pore Doublet Model

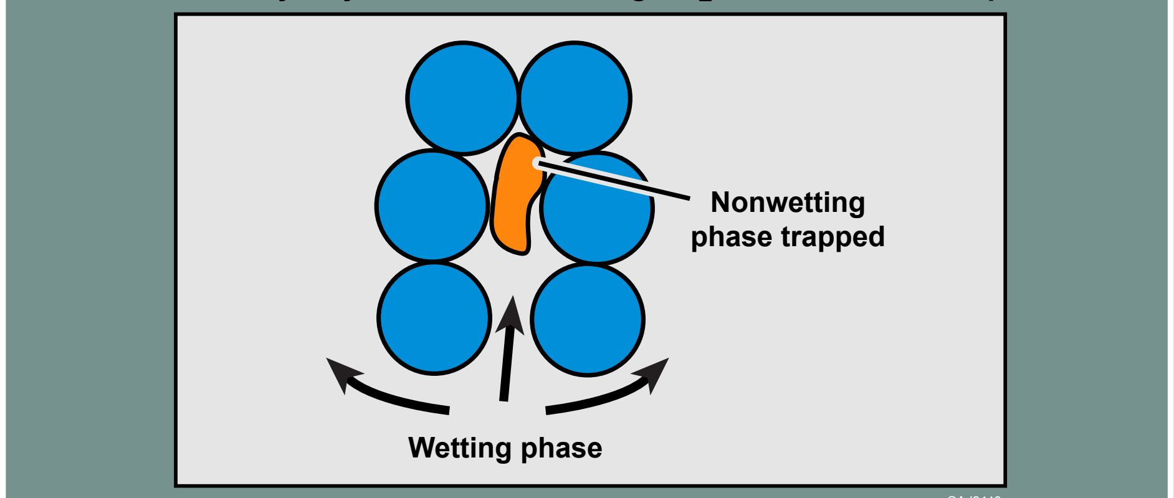
- Moore and Slobod, 1956



Capillary force holds nonwetting phase in larger pore

Dead-end Model

- Buoyancy forces of nonwetting CO_2 can form a microtrap

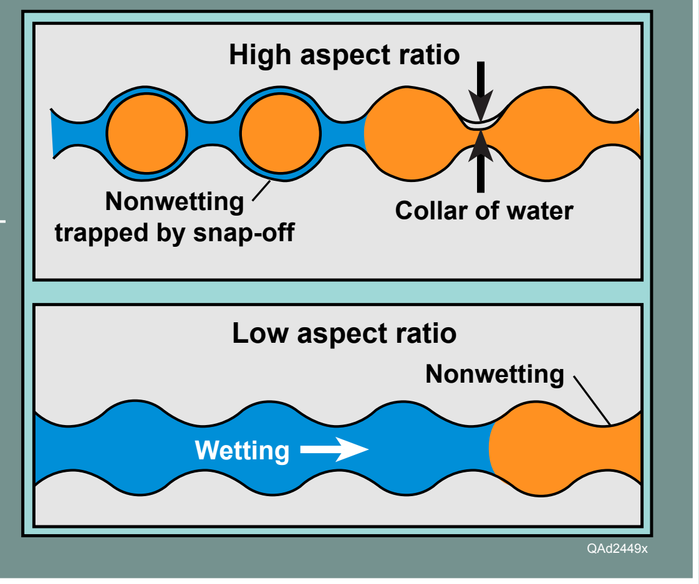


Pore Snap-off Model

- Oh and Slattery, 1976

$$\text{Aspect ratio} = \frac{\text{Pore radius}}{\text{Pore-throat radius}}$$

Capillary force causes nonwetting phase to snap off into pore



EXPERIMENTAL INVESTIGATIONS

- Wardlaw, 1982
  - Applied glass tubes micromodel
  - Demonstrated snap-off
  - Concluded that snap-off caused residual saturation and was strongly affected by pore/pore-throat aspect ratio
- Chatzis et al., 1983
  - In consolidated cores 80% of trapped nonwetting phase was caused by snap-off

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EMPIRICAL INVESTIGATIONS
Measurement and Correlation with Other Properties

- Properties having poor or no correlation on S_{gr}
  - Imbibition mechanism, rate, and nonwetting fluid type (Geffen et al., 1952; Cromwell et al., 1952; Jerauld,1996, Kyte et al., 1956)
  - Temperature and pressure (Geffen et al., 1952; McKay, 1956; Delclaud, 1991)
  - Permeability (Keelan, 1976)
- Properties having a correlation on S_{gr}
  - Rock and pore type, grain size, and sorting
  - Wetting strength
  - Porosity

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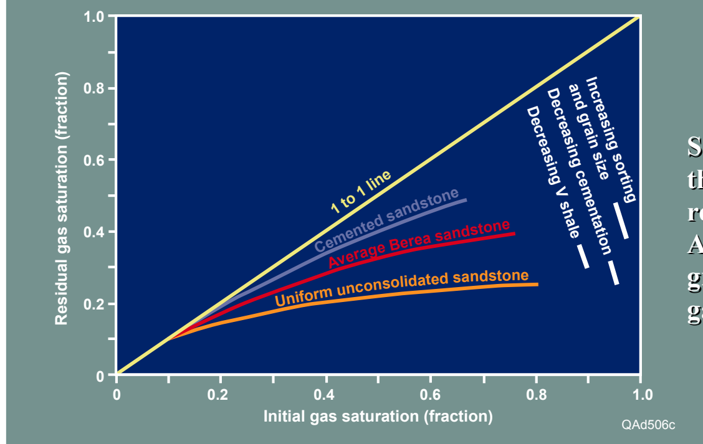
GEOLOGIC EFFECTS ON RESIDUAL GAS SATURATION

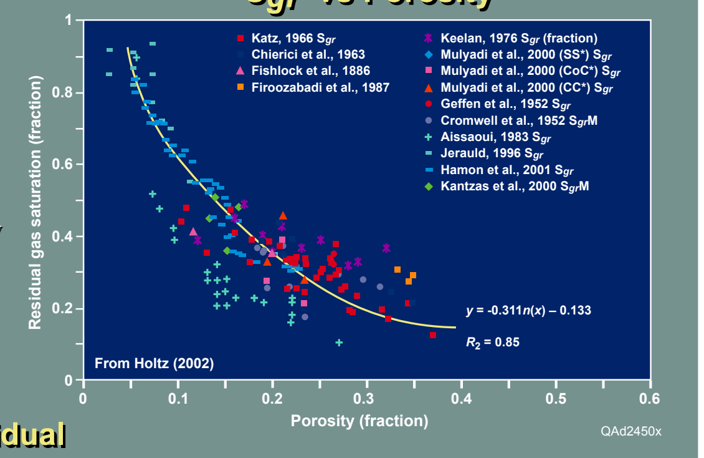


Several geologic characteristics affect the relationship between initial and residual gas saturation in sandstones. As sandstones become more uniform in grain size and less cemented, residual gas saturation decreases.

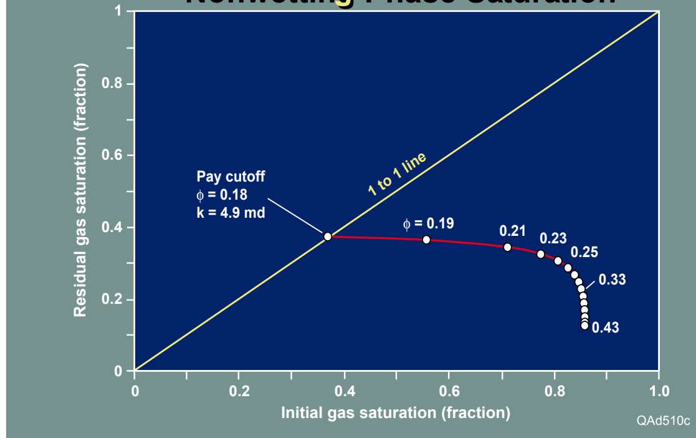
Modified from Lake (1996)

POROSITY EFFECTS ON RESIDUAL GAS SATURATION
S_{gr} vs Porosity

A large group of published sources indicate that in sandstones there is a nonlinear relationship between porosity and residual gas saturation.



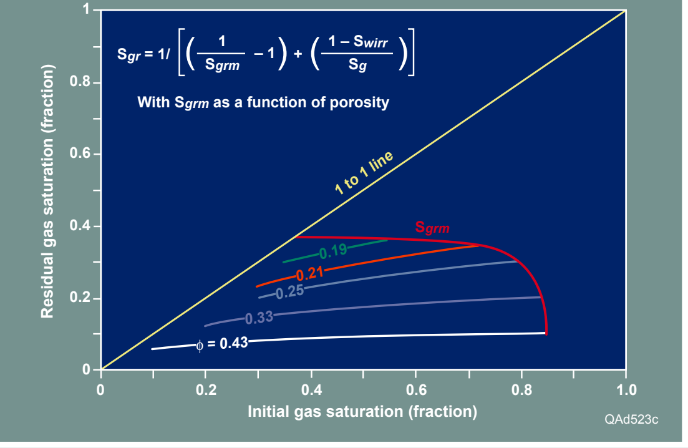
Initial vs. Residual Nonwetting Phase Saturation



The outer envelope on an I-R curve can be defined by applying the empirical porosity- residual gas saturation relationship and varying porosity.

Gas Initial-Residual Curves

From the empirically derived residual nonwetting phase saturation equation as a function of porosity, an initial-residual relationship is obtained for varying porosity.

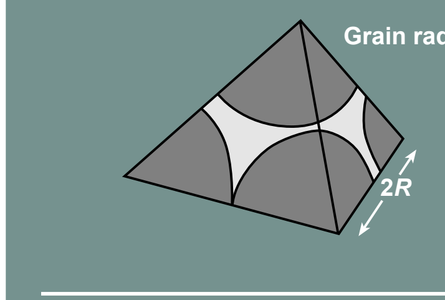


PORE GEOMETRY MODELING OF ASPECT RATIO

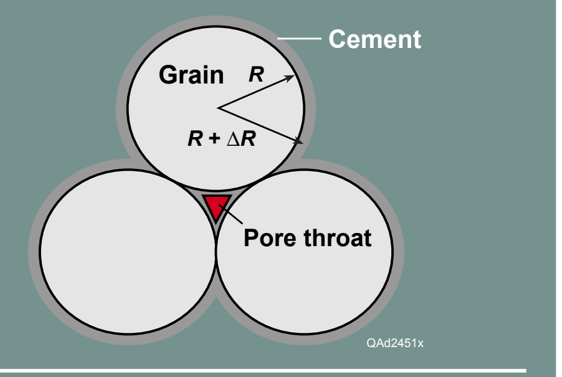
POROSITY REDUCTION MODEL
Delaunay cell as unit bulk volume

Delaunay cell

- Tetrahedra in 3D
- Joins nearest neighbor grains at center



Bryant cementation model



PORE/PORE-THROAT ASPECT RATIO MODEL

- Apparent pore radius (R_{pa})
  – Approximate pore volume as a sphere

$$R_{pa} = 10^{\frac{\log\left(\frac{3V_p}{4\pi}\right)}{3}}$$

- Apparent pore-throat radius (R_{pta})
  – Approximate radius as a circle from pore-throat area

$$R_{pta} = \sqrt{\frac{A_t}{\pi}}$$

- Incrementally increase cementation in Delaunay cell
  – Decreases porosity (pore throat and pore size)

$$\phi = 2.6269\left[1 + \frac{\Delta R}{R}\right]^2 - 7.2655\left[1 + \frac{\Delta R}{R}\right] + 5.0014$$

- Calculate aspect ratio as a function of porosity

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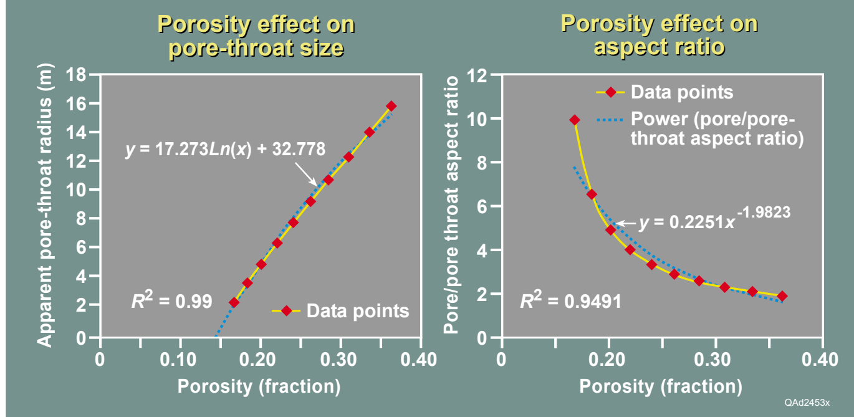
POROSITY INFLUENCE ON ASPECT RATIO


Porosity effect on pore-throat size
Porosity effect on aspect ratio

Modeling indicates that as porosity decreases with increasing cement the aspect ratio increases as a power function.

RESIDUAL GAS SATURATION AS A FUNCTION OF ASPECT RATIO

Empirical porosity correlation

$S_{gr} = -0.3136\,Ln\,(\text{porosity}) - 0.1334$

Porosity reduction model correlation

$\text{Aspect ratio} = 0.2251\,(\text{porosity})^{-1.9823}$

$$S_{gr} = 0.1582\,Ln\,(\text{aspect ratio}) + 0.1025$$

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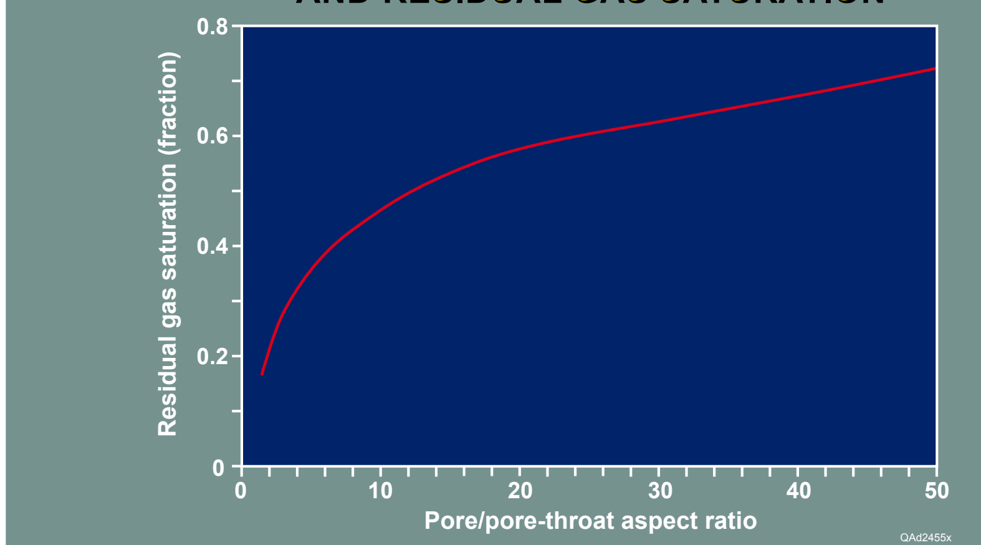
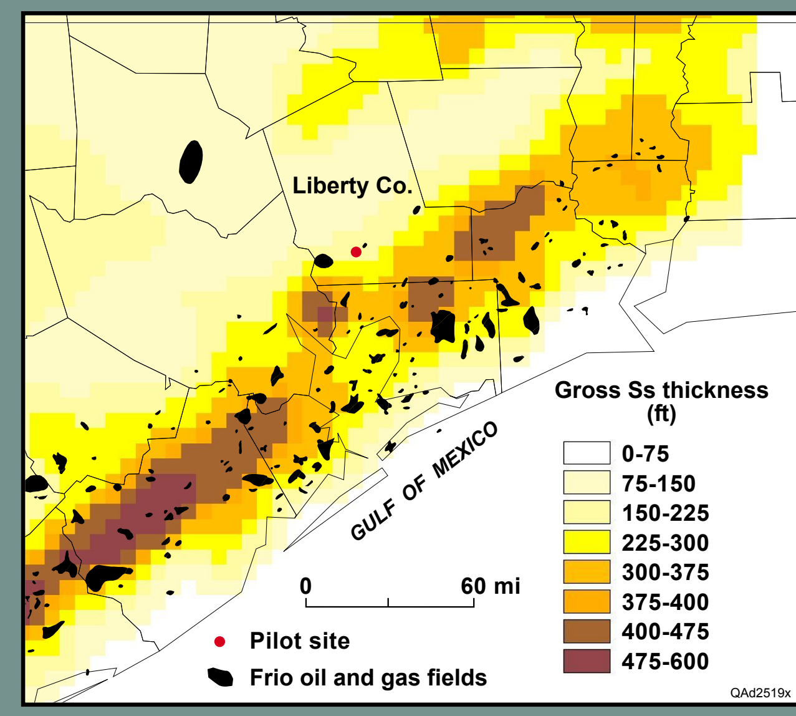
RELATIONSHIP BETWEEN ASPECT RATIO AND RESIDUAL GAS SATURATION



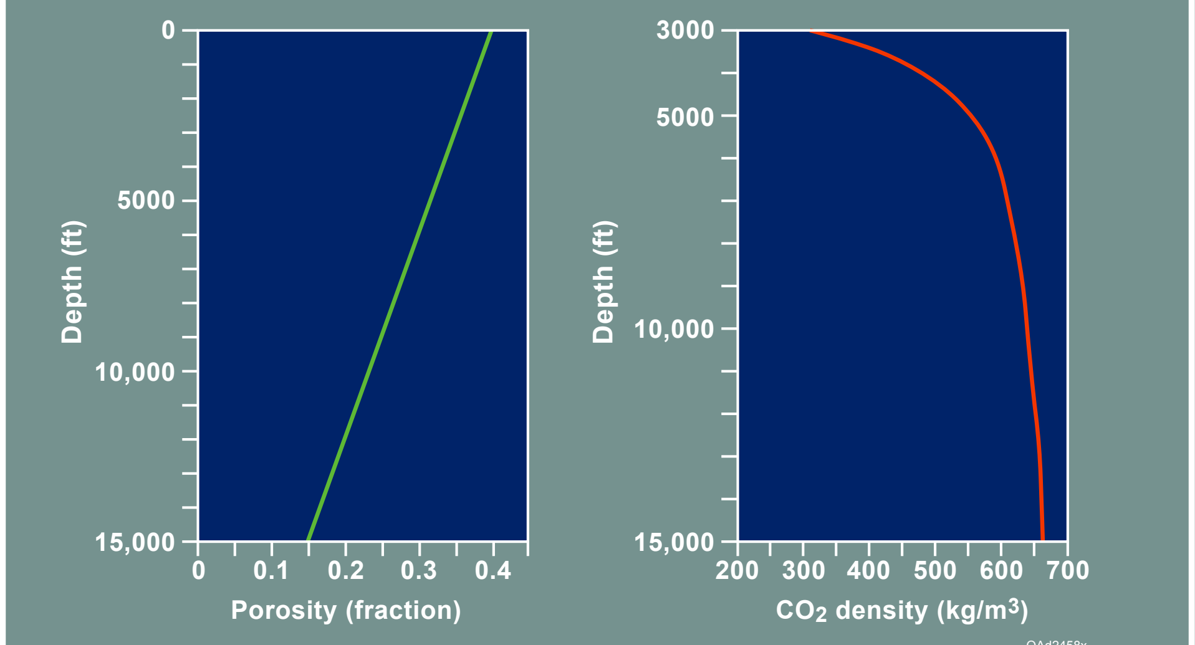
By combining the relationships of core-measured porosity – residual gas saturation with the porosity – aspect ratio model relationship, there can be derived an equation of residual gas saturation as a function of aspect ratio.

DEVELOPMENT OF A CO_2 SEQUESTRATION OPTIMIZATION CURVE
Example from the Upper Gulf Coast, Texas

LOCATION OF UPPER GULF COAST FRIO SANDSTONE DISTRIBUTION AND FRIO RESERVOIRS

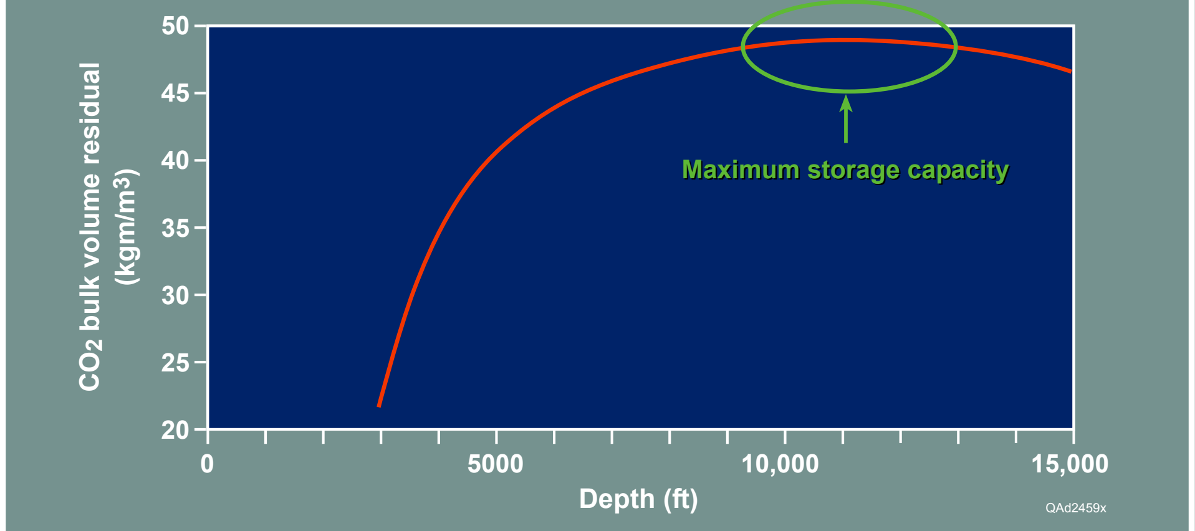


PROPERTY CHANGES WITH DEPTH POROSITY AND CO_2 DENSITY



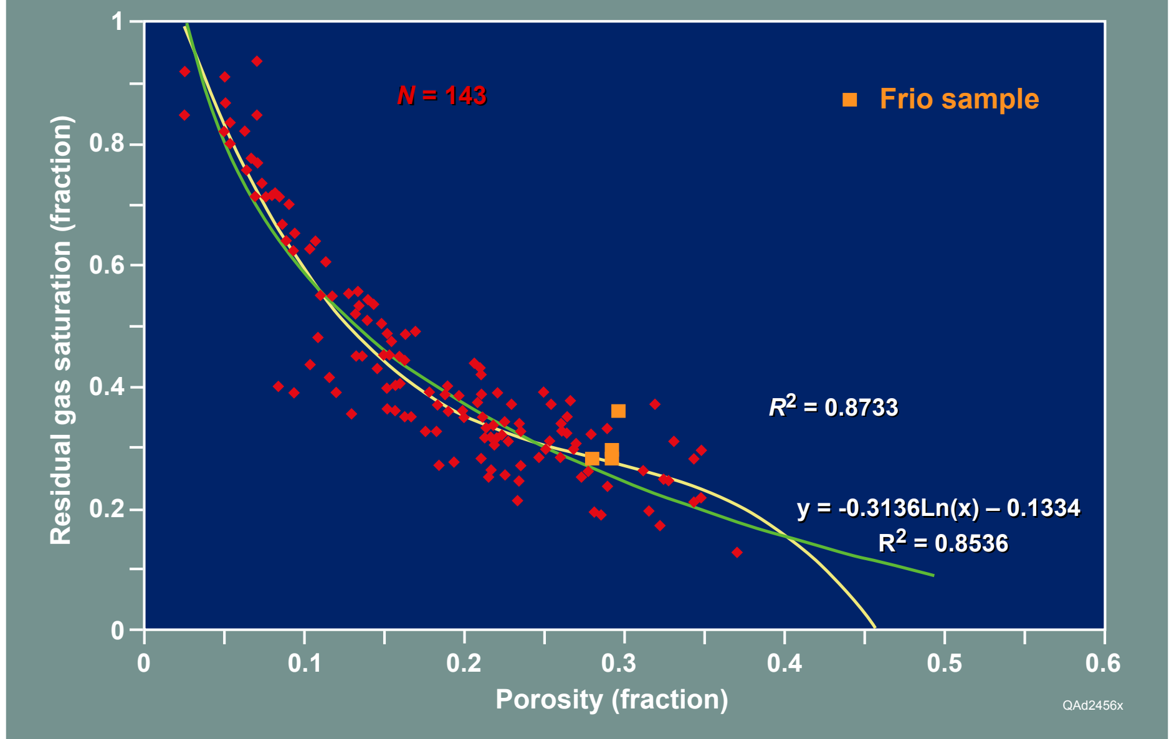
In the upper Gulf coast Texas Frio porosity decreases with depth. Temperature and pressure increase with depth, which results in CO_2 density increasing with depth. Therefore, depth increases oppose each other in optimizing CO_2 sequestration because the volume to store CO_2 decreases with depth at the same time the amount of CO_2 that can be stored per unit volume increases.

CO_2 SEQUESTRATION OPTIMIZATION CURVE



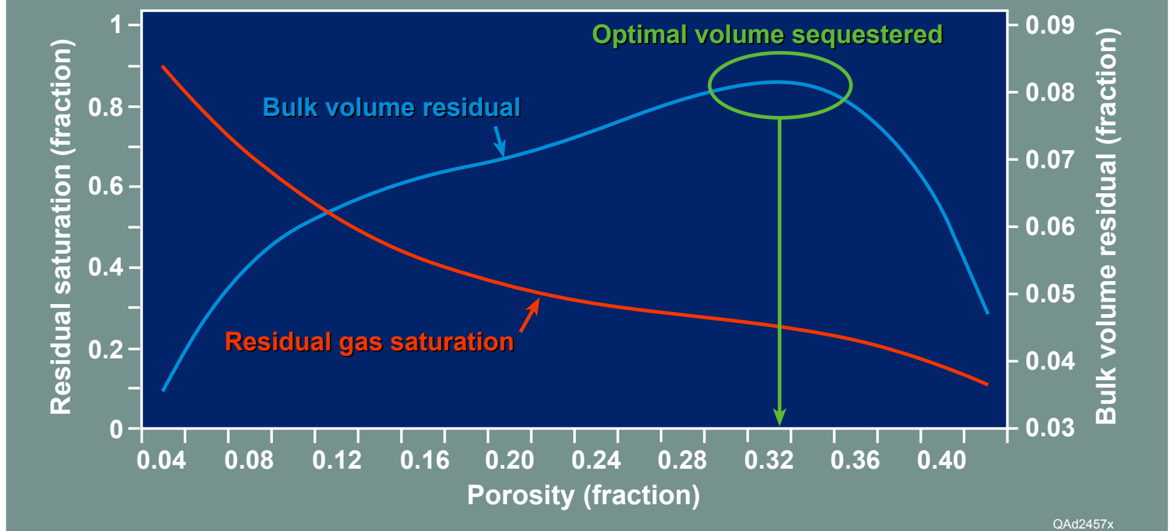
A sequestration optimization curve can be calculated by combining the effects of CO_2 density, temperature, pressure, burial depth, porosity, and residual gas saturation. The optimization curve is nonlinear and displays a maximum storage capacity between 9,000 and 13,000 ft deep.

COMPARISON OF FRIO SGR WITH PUBLISHED DATA



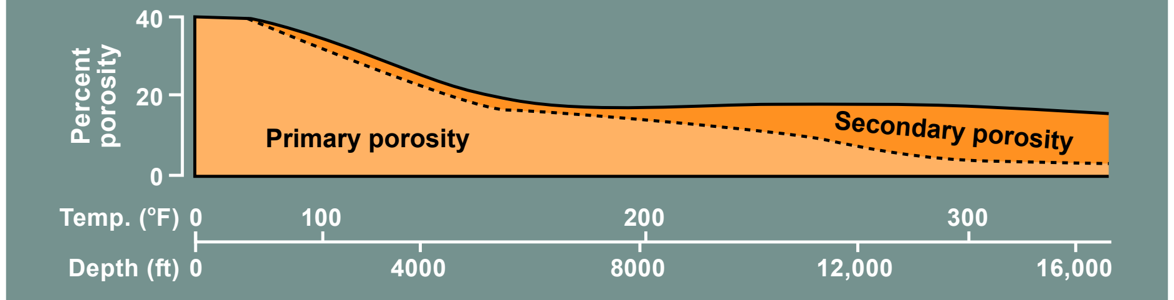
The Frio barrier bar samples from the upper Gulf coast have a residual gas saturation – porosity character very similar to that shown in other published sandstone data indicating that the general sandstone model is applicable.

RESIDUAL PHASE SEQUESTRATION OPTIMIZATION CURVE



The objective of CO_2 sequestration is to trap the largest volume possible over geologic time. A maximum volume of CO_2 trapping as a residual phase takes place at 0.32 porosity when both residual phase saturation and pore volume are accounted for.

DEPTH OPTIMIZATION AIDED BY SECONDARY POROSITY DEVELOPMENT



Modified from Loucks et al (1986)

An added feature that makes deep CO_2 storage in the Frio more favorable is the increase in secondary porosity with depth. Secondary porosity increases the aspect ratio, thereby increasing residual nonwetting phase saturation.

SUMMARY AND CONCLUSIONS

OPTIMIZATION OF CO_2 SEQUESTRATION IN THE UPPER GULF COAST, FRIO FORMATION

- A depth of 9,000 – 13,000 ft is the optimal sequestration depth from the perspective of optimizing volume of residual saturation
- At this increased depth the additional influence of secondary porosity aids in optimization by increasing the aspect ratio
- Deep depths reduce the risk of any mobile CO_2 migrating to the surface
- The pressure difference between hydrostatic pressure and rock fracture pressure increases with depth

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CONCLUSIONS

- Residual nonwetting phase saturation is a logarithmic function of porosity.
- The increase in aspect ratio with decreasing porosity in intergranular porosity is a likely control on residual phase saturation.
- The greatest bulk volume storage of a nonwetting phase in sandstones occurs at 0.32 porosity.
- CO_2 sequestration optimization is a function of temperature, pressure, CO_2 density, burial depth, porosity, and residual gas saturation.
- The optimal depth to sequester CO_2 in the Gulf Coast Frio Formation is between 9,000 and 13,000 ft.
- CO_2 optimization curves are necessary when determining regional sequestration potential.
- To sequester CO_2 over geologic time, one of the most promising and previously neglected mechanisms would be to trap it as a nonwetting residual phase.

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ACKNOWLEDGMENTS

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Bureau of Economic Geology
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