Kentucky Geological Survey
CO_2 Storage Research Program

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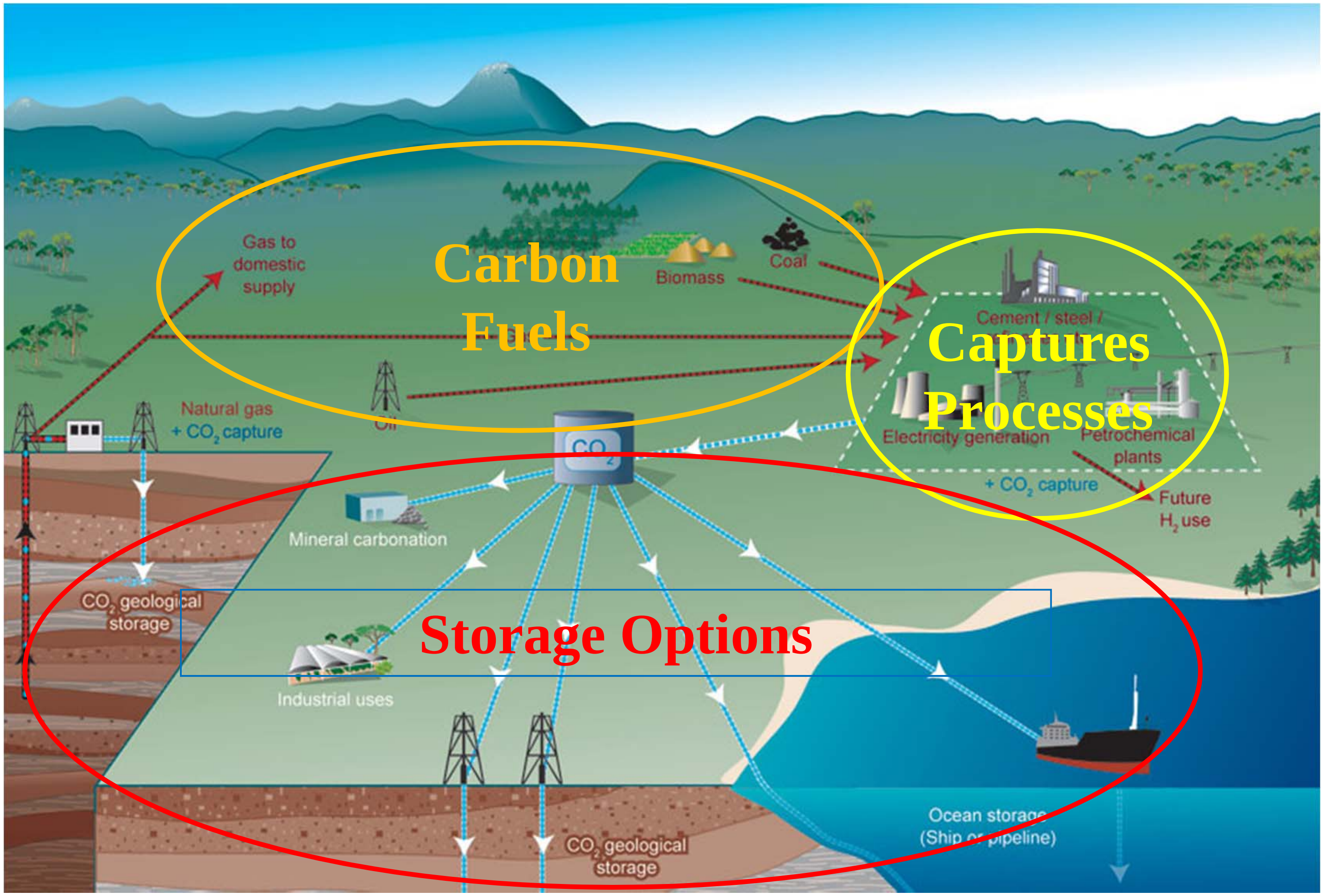
Discharge of CO_2 to the atmosphere is under regulatory review, and subsurface storage may be required for existing facilities and the financing and construction of new facilities.

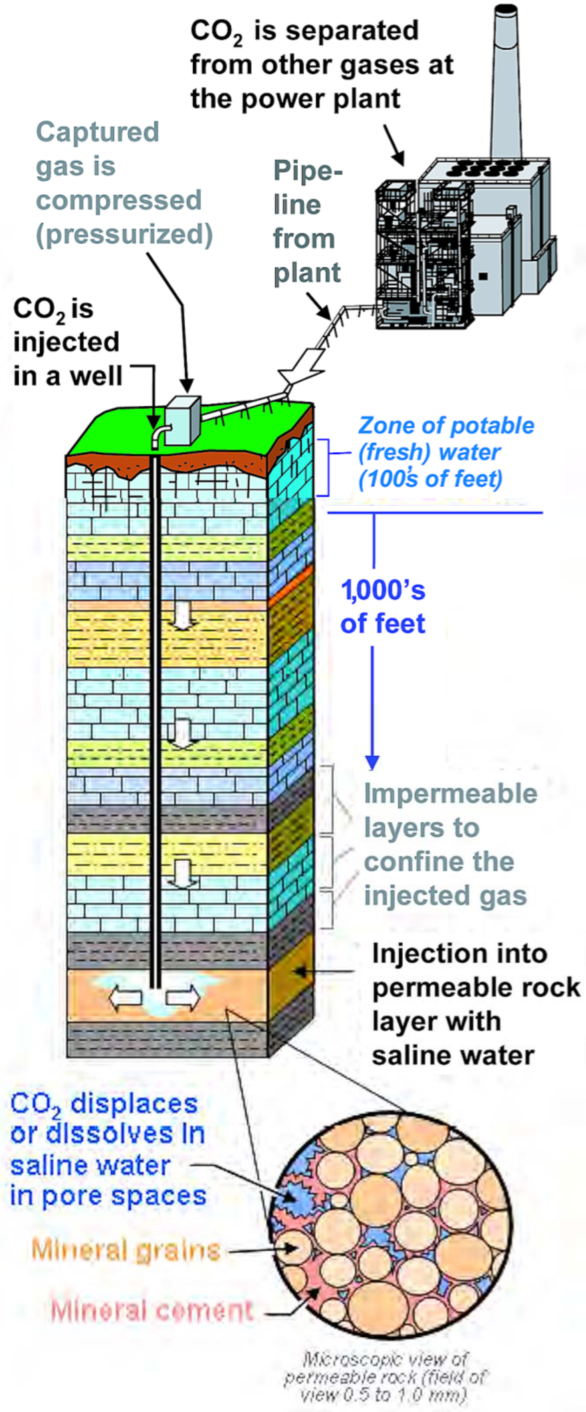
CO_2 Sources, Capture, and Storage



Modified from www.ipcc.ch

House Bill 1, August 2007

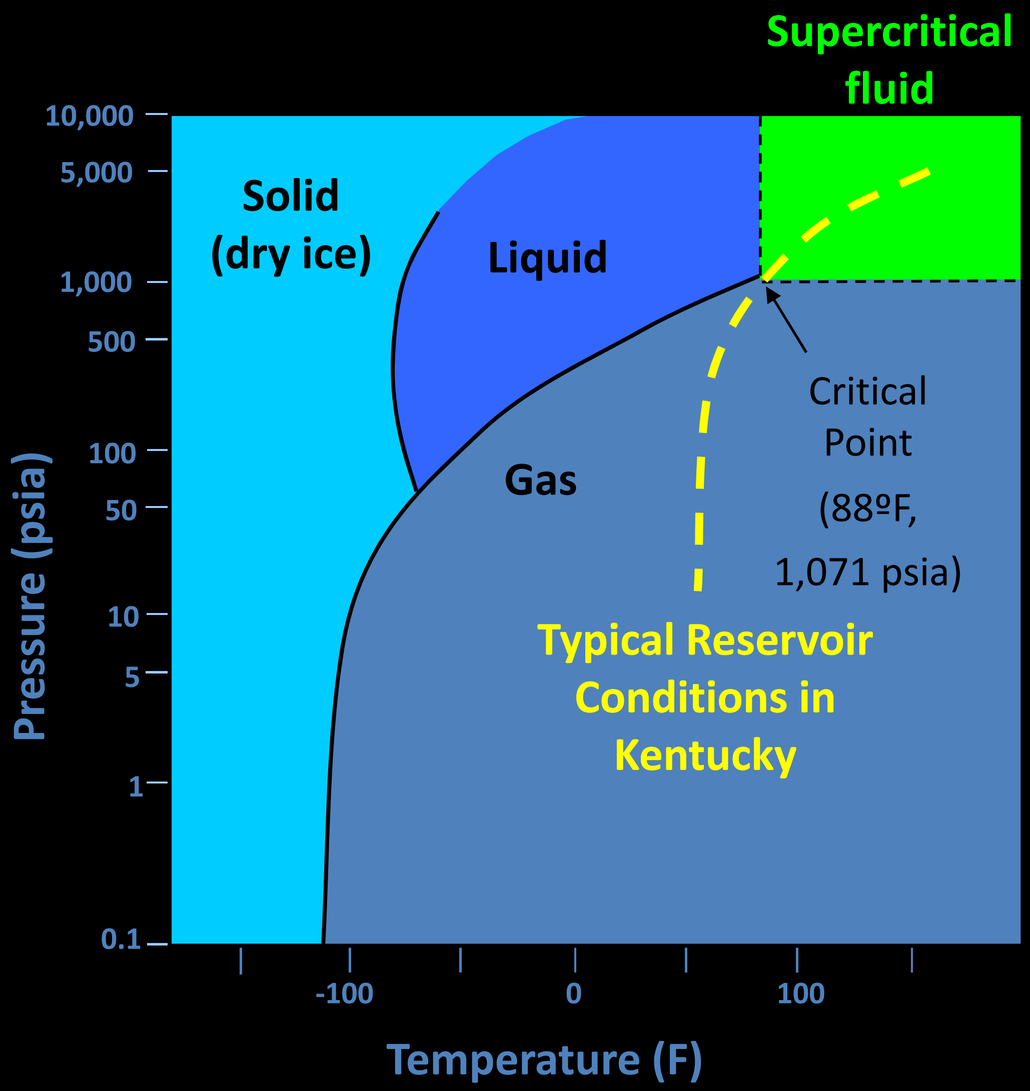
- Kentucky House Bill 1, passed in a special legislature session and signed into law in August 2007, appropriated $5 million funding for KGS to research the storage and use of CO_2 throughout the Commonwealth.
- House Bill 1 mandates the drilling deep saline reservoir CO_2 storage demonstration wells in the East and West Kentucky Coal Fields, a CO_2 enhanced oil recovery (EOR) demonstration, and a CO_2 enhanced gas recovery (EGR) demonstration in the Devonian black shale.
- Additional funding was provided to the Center for Advanced Energy Research (CAER) at UK for research and development of carbon capture technology.



CO_2 Storage Principles

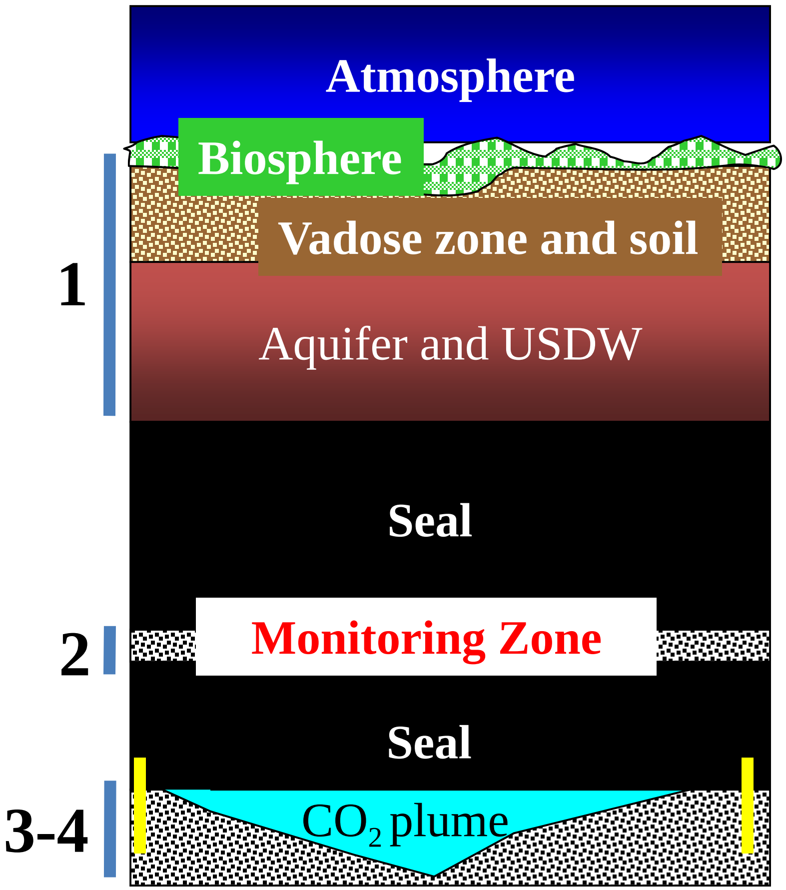
- CO_2 is produced by burning carbon-based fuels (coal, oil, natural gas)
- CO_2 is captured at its source, compressed, and injected into deep saline reservoirs in a supercritical state
  - Free CO_2 in reservoir rock pores, displacing storage reservoir brine
  - Dissolved in storage reservoir brine
  - Reacts with minerals in the storage reservoir rock
- Overlying impermeable strata contain the CO_2 in the storage reservoir
- Surrounding shallow aquifers and surface area is monitored for leaks

Minimum CO_2 storage depth in Kentucky



Large-scale CO_2 storage will require supercritical conditions: reservoir pressure >1071 psi and temperature >88° F. Supercritical CO_2 is a dense fluid with the viscosity properties of a gas. The volume reduction is 250 times (0.4%) that of gaseous CO_2. However, it is less than water, and thus buoyant.

Assuring Security: Monitoring Options



1. **Surface and shallow groundwater**
   - Very late leak detection
   - May be large annual variations in groundwater chemistry
2. **Above-injection zone monitoring**
   - First indicator
   - Monitors small signals
   - Annually more stable water chemistry, thus more sensitive
3. **In injection zone - plume**
   - Oil-field type technologies
   - Will not find small leaks
4. **In injection zone - outside plume**
   - Assure lateral migration of CO_2 and brine is acceptable

CO_2 Leakage Mechanisms

- Reservoir Seal Leakage
  - Requires stored gas in the reservoir to overcome capillary entry pressure of the reservoir sealing interval
  - Seal will not leak unless this occurs
- Seal integrity
  - Faults
  - Fractures
- Human intervention
  - Old oil and gas wells greatest problem
  - Failures in CO_2 injection wells
  - Wells drilled after injection begins
- CO_2 diffusion to the surface through rock strata is infinitesimally slow

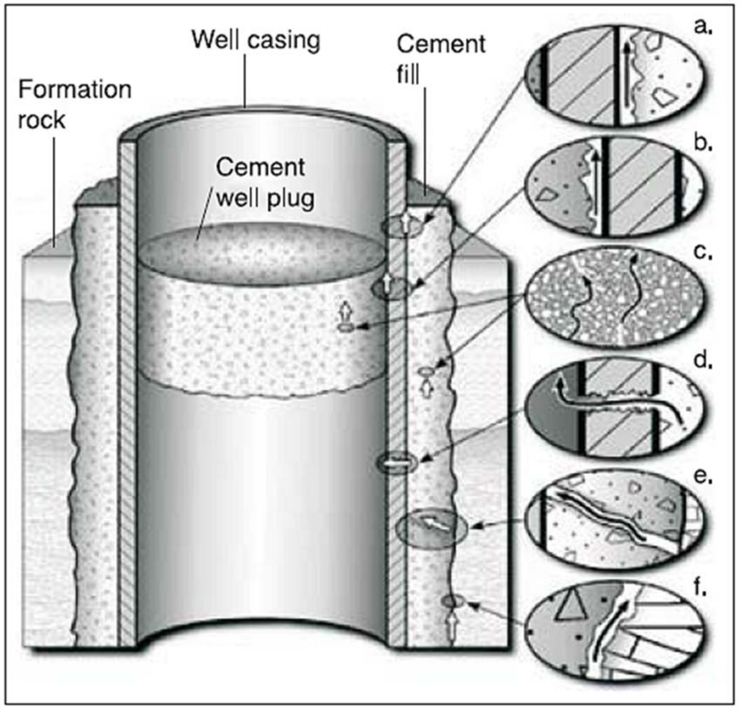


Figure 5.26 Possible leakage pathways in an abandoned well: (a) and (b) between casing and cement wall and plug, respectively; (c) through cement plugs; (d) through casing; (e) through cement wall; and (f) between the cement wall and rock (after Gasda *et al.*, 2004).

Monitoring CO_2 Plume Migration in the Sleipner Field, North Sea

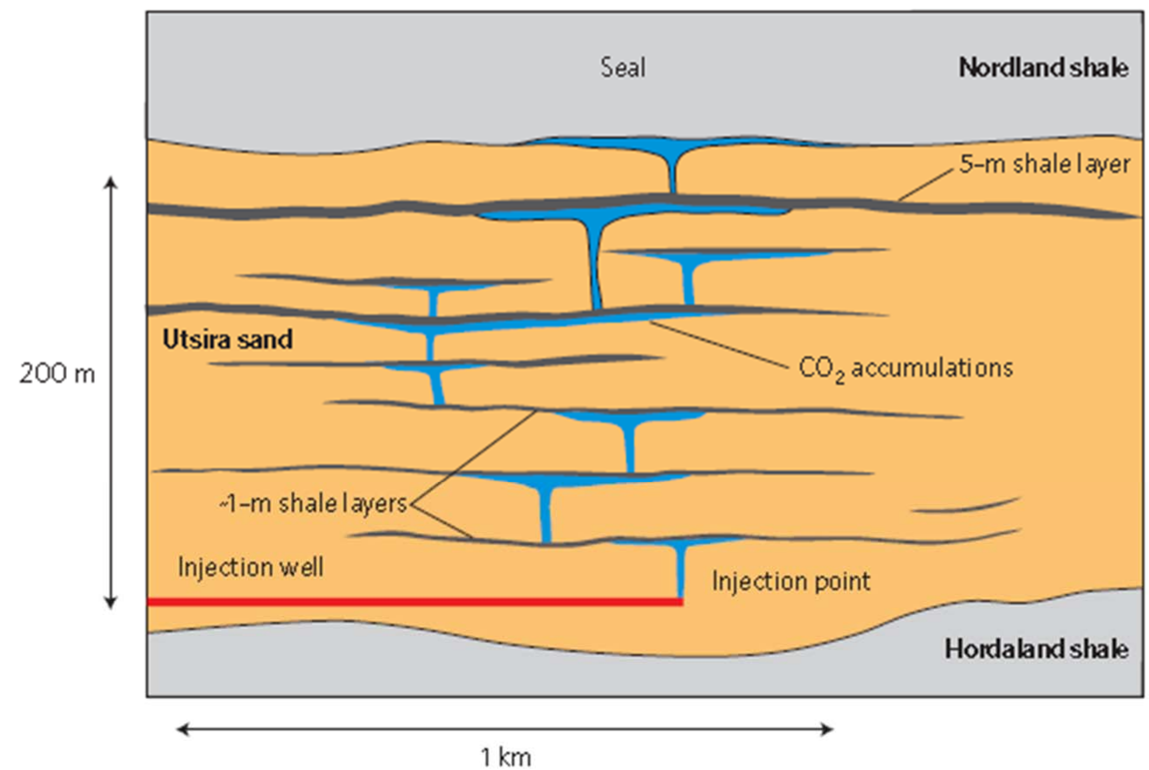


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Figure 2 | Diagram of carbon dioxide storage at the Sleipner Field based on seismic images. Rising CO_2 plumes impinge and spread out beneath thin mudstones within the reservoir before ponding beneath the top seal. This geometry causes a large increase in the CO_2-brine contact area, which will increase solubility trapping. Diagram redrawn from ref. 22, © 2007 Elsevier.

World CO_2 Injection Projects

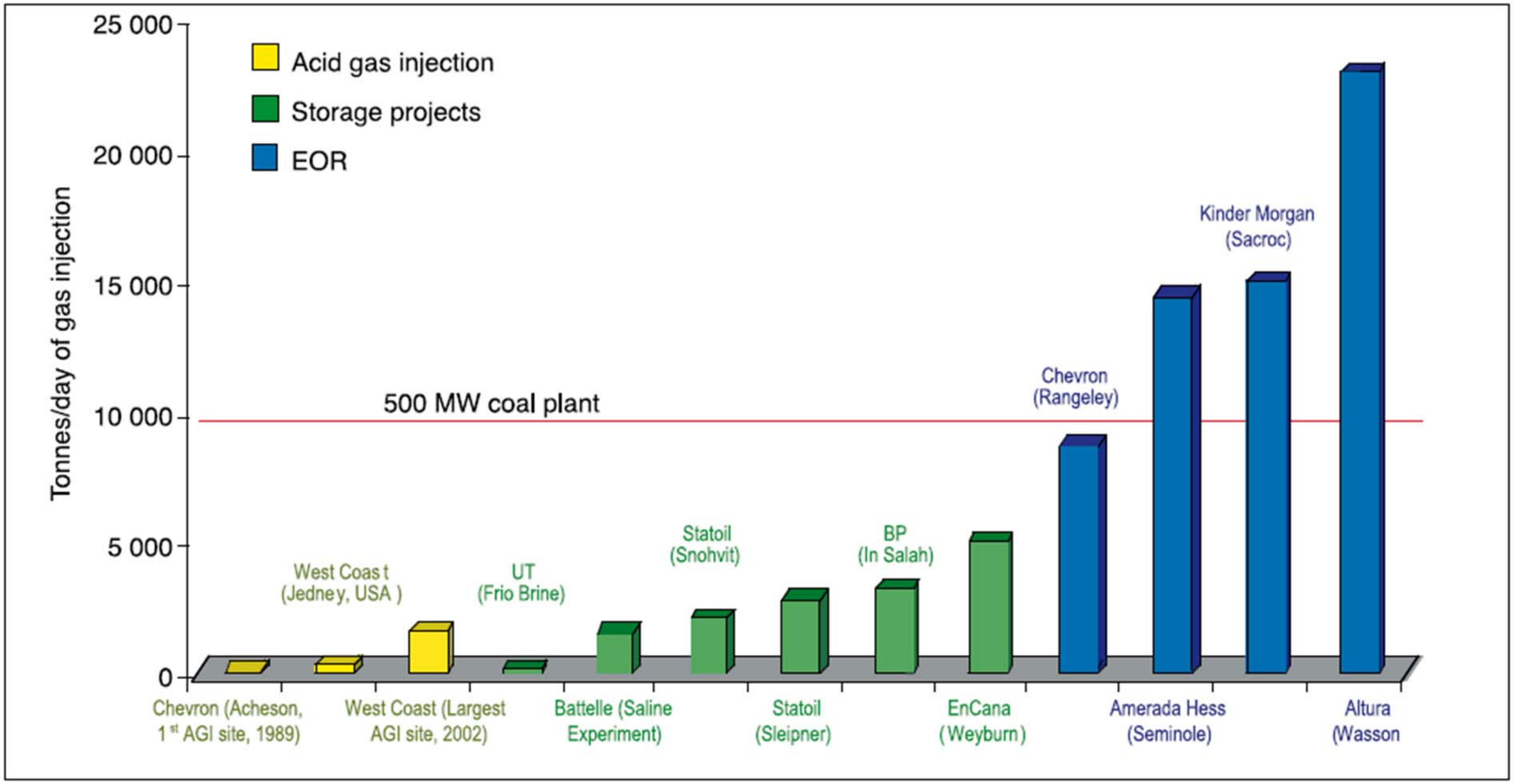
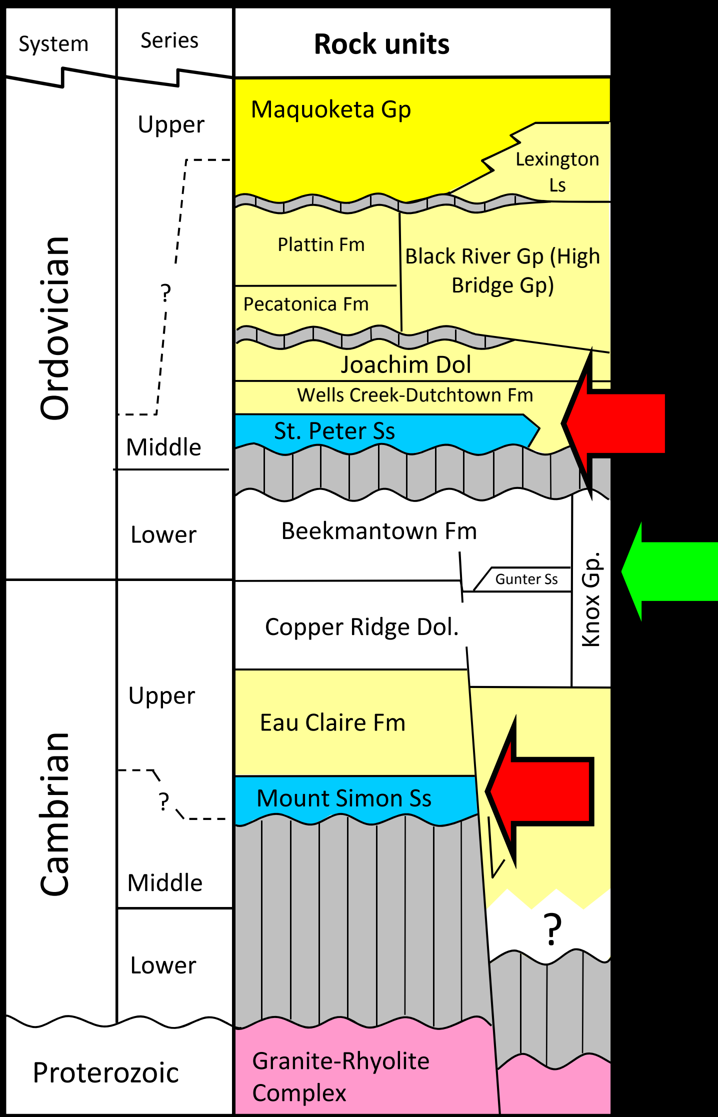


Figure 5.22 Comparison of the magnitude of CO_2 injection activities illustrating that the storage operations from a typical 500-MW coal plant will be the same order of magnitude as existing CO_2 injection operations (after Heinrich *et al*., 2003).

Project Goals

- Demonstrate CO_2 storage and EOR/EGR
- Demonstrate the integrity of reservoir sealing strata for long-term CO_2 storage
- Develop best practices for the evaluation of CO_2 storage in Kentucky deep saline reservoirs
- Publish the project results for use by government, industry, and the public
- Accomplish this project with consideration of the interests and concerns of industry and the citizens of the Commonwealth

Western Kentucky Stratigraphy



Regional saline reservoirs:

- Mount Simon Sandstone
- St. Peter Sandstone
- Knox Group

Potential CO_2 sinks/ reservoirs

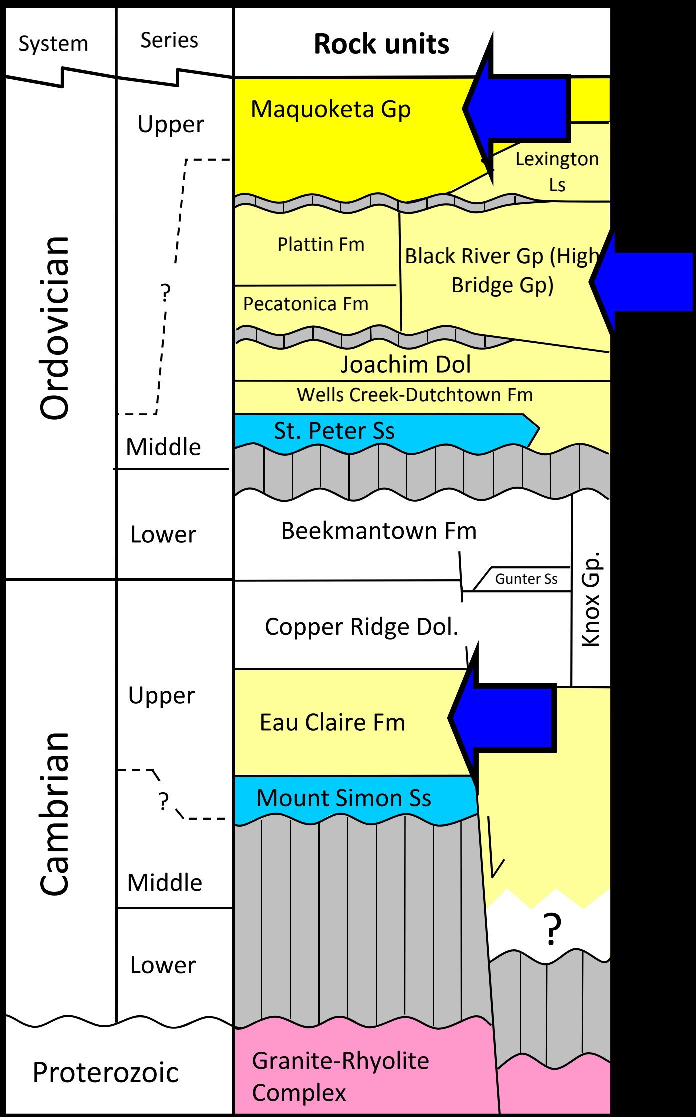
Sealing interval

Missing section

Sink or seal (*depends on location)*

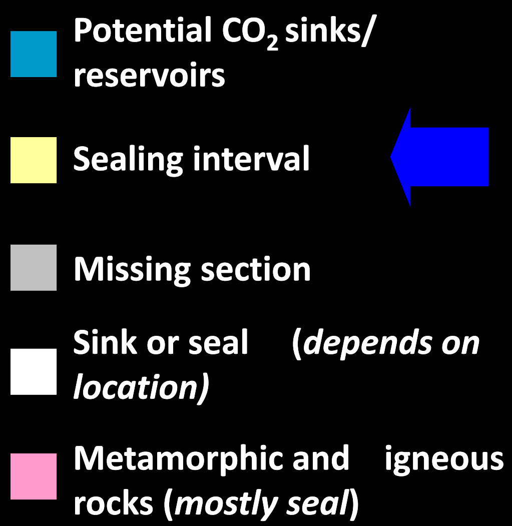
Metamorphic and igneous rocks (*mostly seal*)

Western Kentucky Stratigraphy

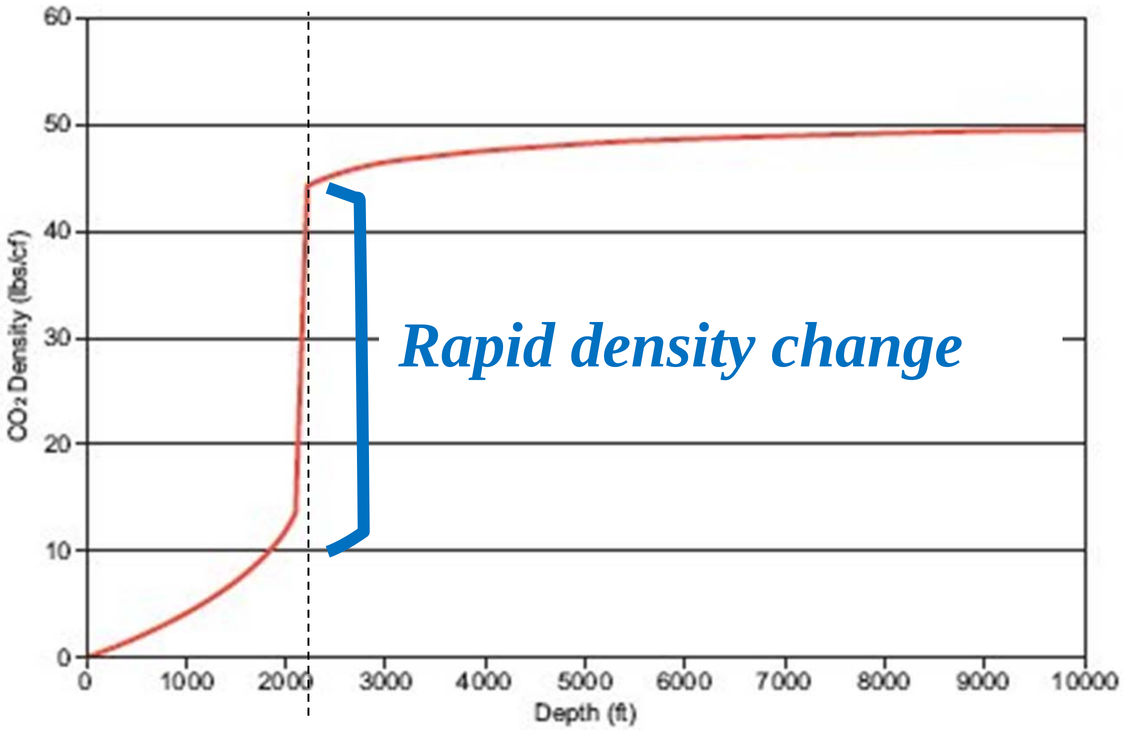


Just as important in an injection project are the sealing units:

- Eau Claire Formation
- Maquoketa Shale
- Ordovician carbonates
- Devonian Shales



Minimum CO_2 storage depth in Kentucky

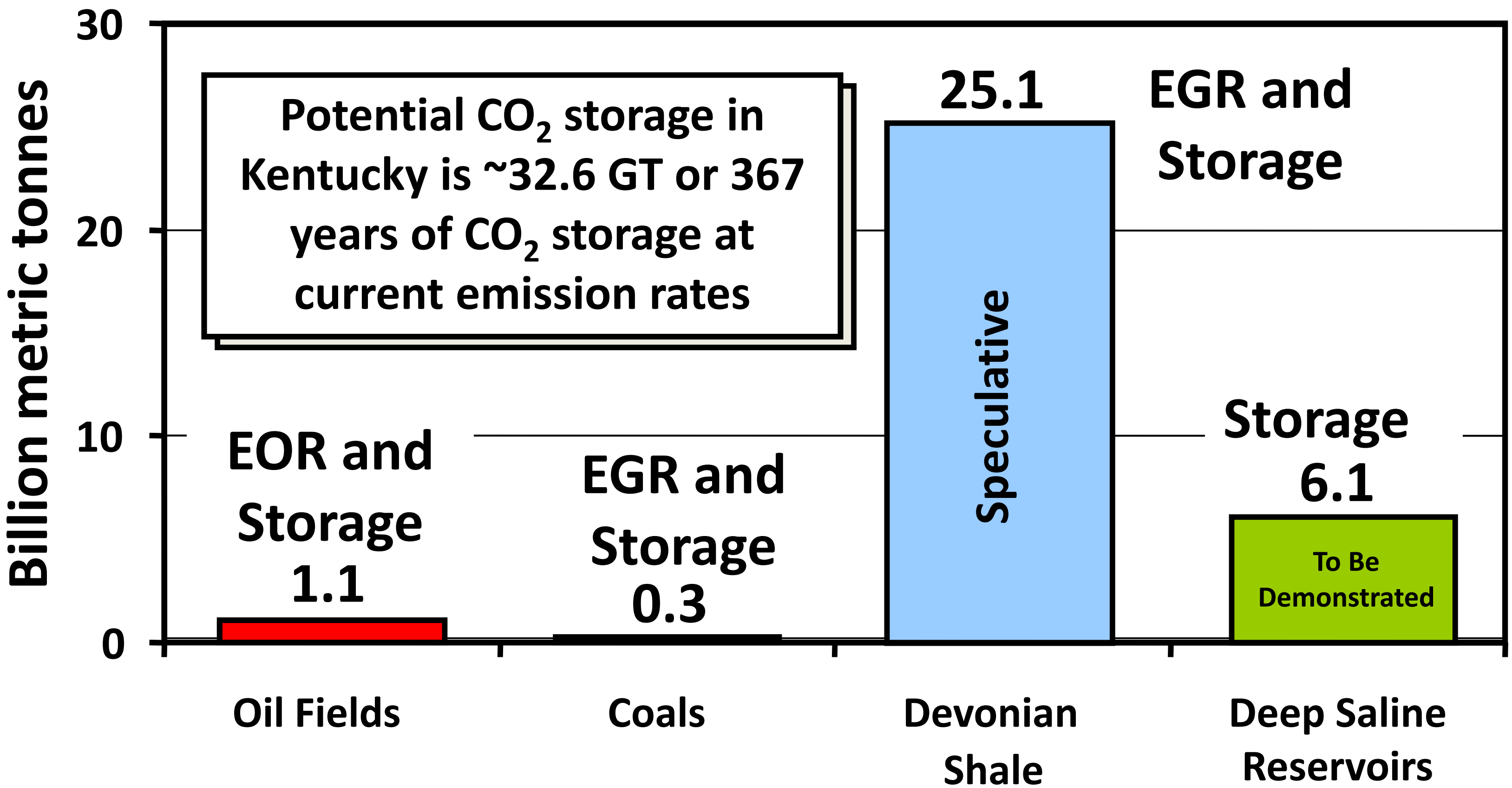


Key to being able to success in storing CO_2 is keeping it in a supercritical state.

Figure 23.—Diagram showing CO_2 density with depth for a typical pressure gradient, surface temperature, and geothermal gradient in the MRCSP area. CO_2 density data is from Lemmon and others (2003).

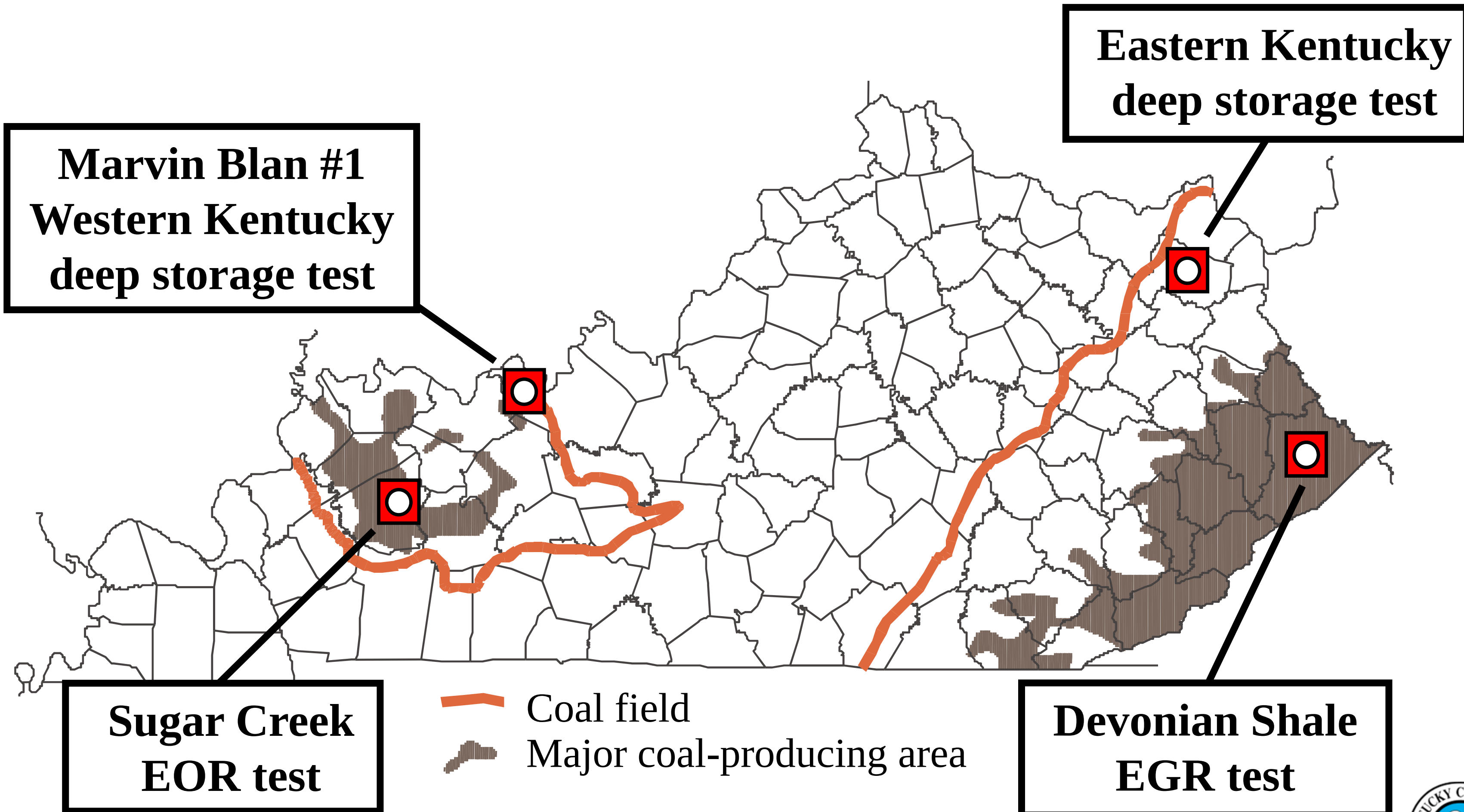
Research by the MRCSP and MGSC indicate that the critical point for CO_2 in the Midwest and Kentucky should occur at a depth of ~2350 ft.

DOE Phase I CO_2 Storage Estimates for Kentucky



While CO_2 EOR potential is significant, Devonian shales or deep saline reservoir storage will be needed to handle expected CO_2 volumes, currently 98.3 MT/yr.

The challenge for Kentucky is to demonstrate CO_2 EOR/EGR and storage in diverse reservoirs with a limited number of tests.



Marvin Blan #1, Hancock County

- Drilling commenced on April 24, 2009
- Seven cores cut to test reservoir and seal properties
  - Reservoir seals
    - New Albany Shale (30 ft)
    - Maquoketa Shale (31 ft)
    - Black River Limestone (61 ft)
  - CO_2 storage reservoirs
    - Knox Group (three cores, 243 ft total)
    - Precambrian Middle Run Sandstone (30 ft)
- Reached TD at 8126 ft on June 14 after 63 days of drilling

Maquoketa Shale Reservoir Sealing Formation

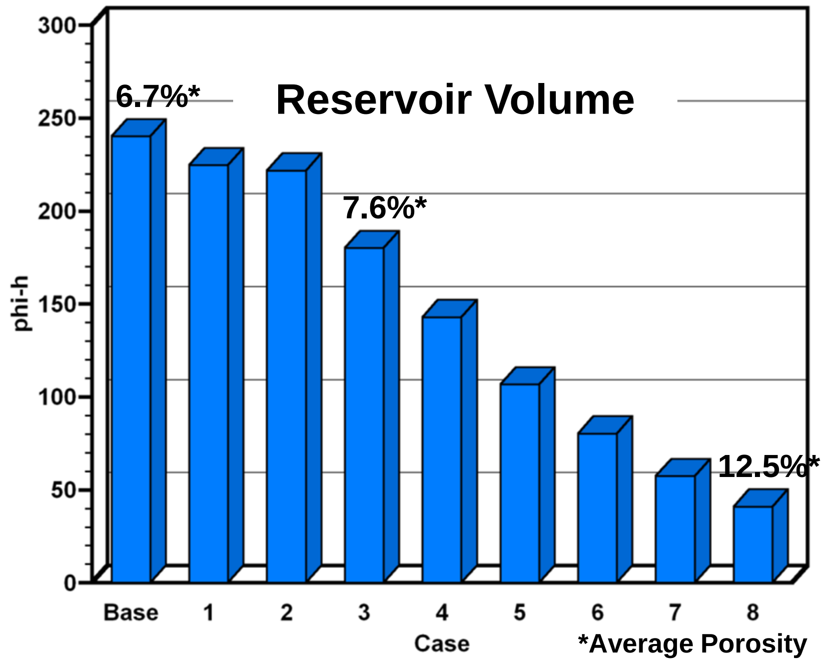
- Maquoketa Shale was cored 2800-2831 ft to test reservoir seal properties
- Analyses of seal properties
  - Core analysis: impermeable
    - Porosity 0.4%
    - Permeability 1.63×10^{-5} md
  - Compressive strength 17,264 psi
  - XRD mineralogy
    - 39% clays, 15% carbonates, 36% silicates, balance other minerals

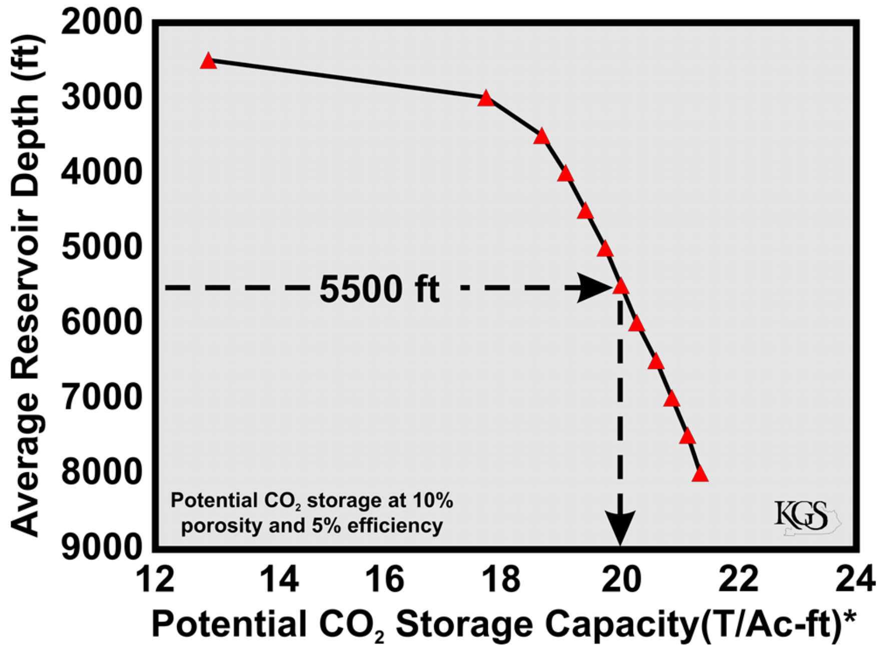
Knox Dolomite Cores

- Knox Dolomite was cored in three intervals (total 243 ft) to test reservoir properties
  - “St Peter”-Beekmantown (123 ft)
  - Beekmantown-Gunter (101 ft)
  - Copper Ridge (19 ft)
- Found porosity system to be a complex of preserved fabric, primary dolomite porosity, vugs, and fractures
  - Average porosity 6.7%
  - Fracture system trends NNW and dips to the SW
- Knox sealing intervals variable
  - Porosity 0.4 to 10.4%
  - Permeability <0.0001 to 15 md

Marvin Blan #1 Potential Reservoir Volume in the Knox

- Base
  - All data
  - Volume 240 Ac-ft
  - Storage 3200 T/Ac
  - Requires 208 Ac/MT
- Case 3
  - Porosity >5%
  - Volume 180 Ac-ft
  - Storage 2743 T/Ac
  - Requires 365 Ac/MT
- Case 8
  - Porosity >10%
  - Volume 41 Ac-ft
  - Storage 1022 T/Ac
  - Requires 978 Ac/MT

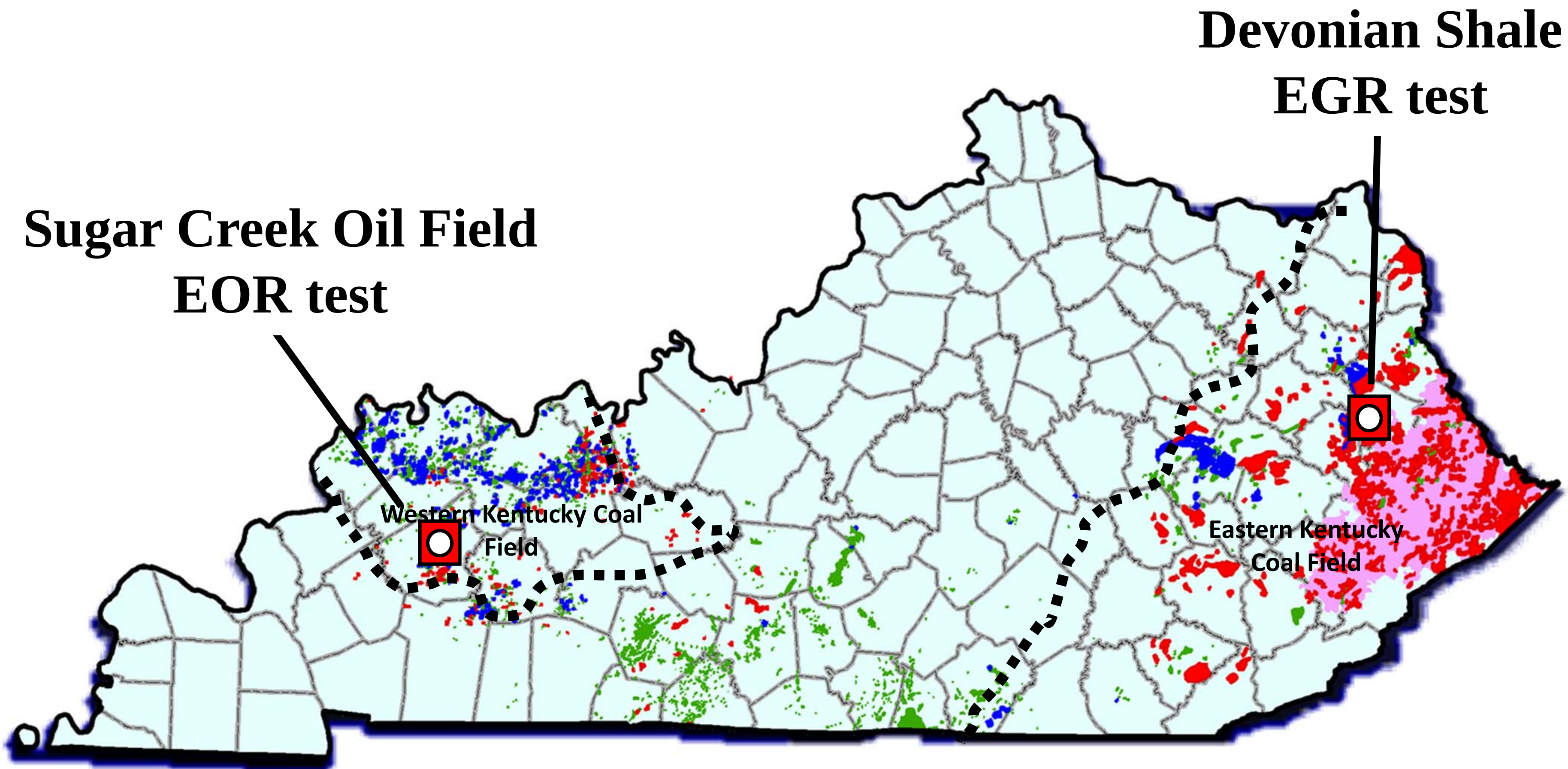




CO_2 EOR in Kentucky

- CO_2 has been used for EOR for over 30 years
- Limited use of CO_2 in Kentucky to date despite very good results
- Advantages
  - Proposed coal gasification plants could provide a CO_2 source closer to our producing areas
  - Waste CO_2 may have value and could improve production in Kentucky oil and gas fields
- Problems
  - CO_2 sources, cost, and pipeline infrastructure
  - Nature of our oil reservoirs
    - Small size and shallow depths
    - Low reservoir temperatures
    - Extensive reservoir fracturing

Kentucky Oil and Gas FieldsCO_2 EOR/EGR Pilot Tests



- OOIP: 2.4 MMMBO
- Gas resource: 125 Tcfg
- Cumulative Production 780 MMBO and 5.6 Tcfg

Coal Fields

CO_2 Enhanced Oil Recovery

- Pilot site is Sugar Creek oilfield near Madisonville. It is an immiscible CO_2 flood (${CO_2}$ gas in the reservoir).
- Eight oil producing wells and three monitoring wells surrounding the centrally located injection well.
- 8800 tons of CO_2 are budgeted for this pilot.
- CO_2 injection is planned for about 6-10 months into one injector, followed by water injection.
- KGS is providing funding and field and lab support to the MVA shallow groundwater program of this pilot.

CO_2 Cyclic Stimulation EOR in Big Andy Field

Photo by Brandon Nuttall, KGS

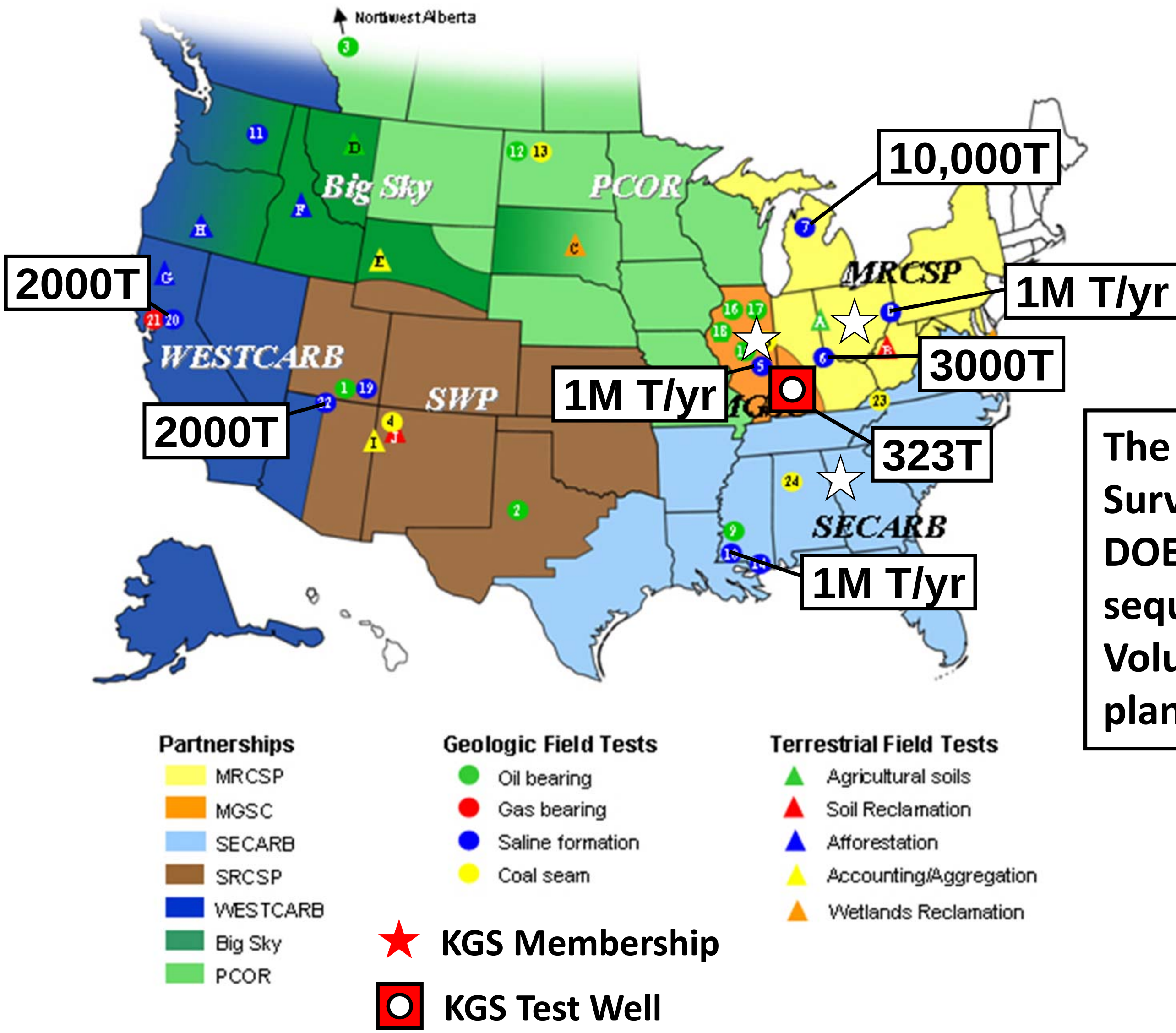
Devonian Shale EGR Test Success Measures

- Increased gas production
- Mass balance indicates CO_2 adsorption vs methane
- Minimal CO_2 content of produced gas after flowback and cleanup
- Marvin Blan #1 Results
  - est. 10% storage efficiency
  - est. 181 tons CO_2/Ac possible storage

Additional Work

- Testing planned for 2010, funded by DOE research award of $1.6 million
  - Additional brine, possibly additional CO_2 injection
  - 3D VSP to image injection plume
  - Knox reservoir evaluation
- Plug and abandon the Marvin Blan #1 in compliance with State and EPA regulations
- Remediate drillsite
- Groundwater and soil gas monitoring through 2012

Regional Sequestration Partnerships



The Kentucky Geological Survey is a member of three DOE-sponsored regional sequestration partnerships. Volumes of CO_2 injected or planned noted.

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