# Geological Storage: The Grand View

Sally M. Benson

Earth Sciences Division
Lawrence Berkeley National Laboratory
Berkeley, California 94720
smbenson@lbl.gov

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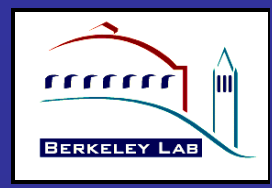


# The Grand View

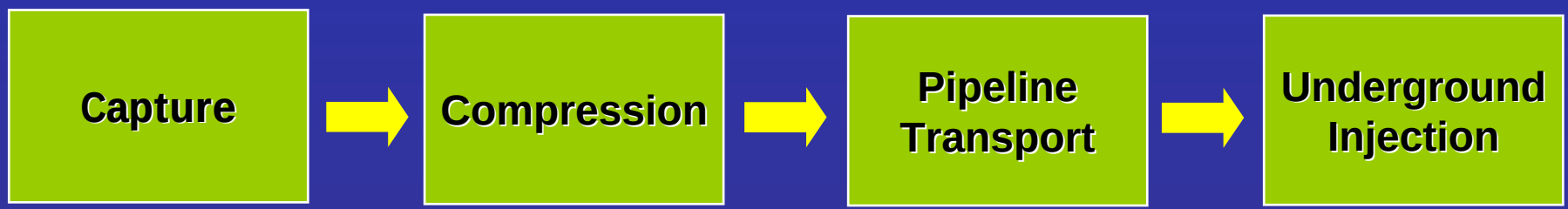
*Carbon dioxide capture and geologic storage (CCS) transforms fossil fuels into a low-carbon energy source.*

*Much of the technology for CCS exists today.*

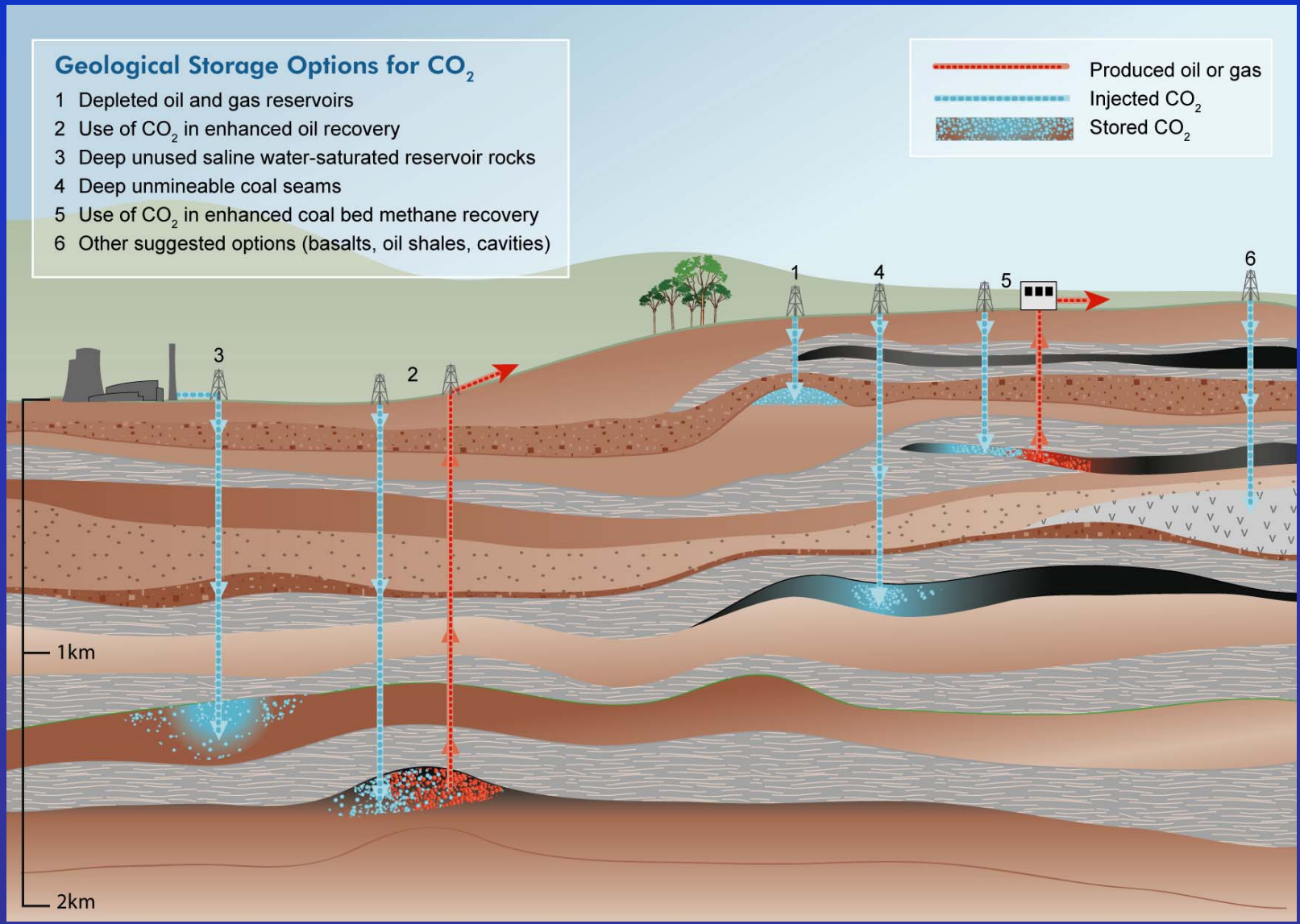
*There's more to learn before CCS is implemented on a grand scale.*

# $CO_2$ Capture and Storage Technology

- CCS is a four-step process
  - Pure stream of $CO_2$ captured from flue gas or other process stream
  - Compressed to ~100 bars
  - Transported to injection site
  - Injected deep underground geological formations



# Options for geological storage



# Topics

- Is geologic storage secure?
- How much capacity is there?
- Is it safe?
- How do you know its working?
- How much storage do we need to make a difference?
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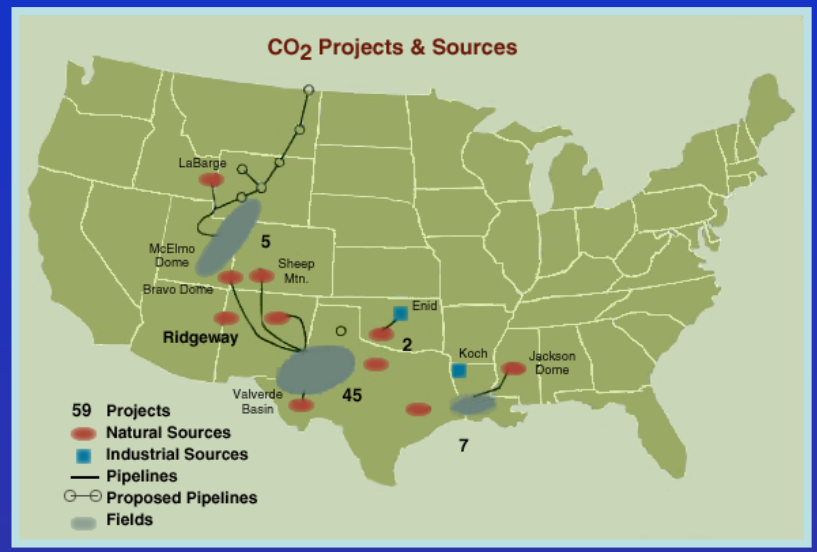
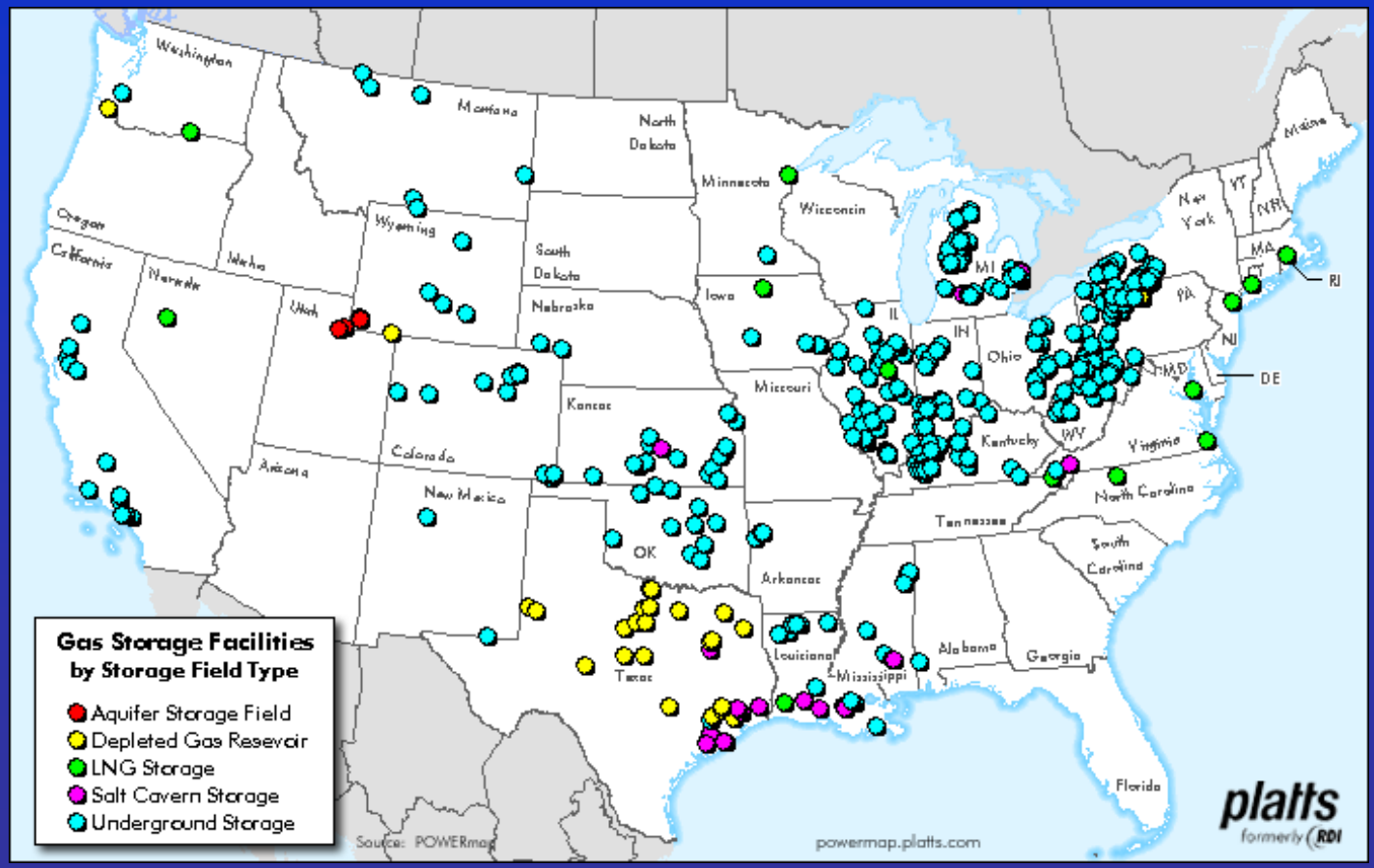
# Multiple Lines of Evidence Indicate Storage Can Be Secure and Effective

1. Natural analogues
   - Oil and gas reservoirs
   - $CO_2$ formations
2. Industrial analogues
   - $CO_2$ EOR
   - Natural gas storage
   - Liquid waste disposal
3. Fundamental physical and chemical processes
4. Numerical simulation of long term performance
5. Monitoring existing projects



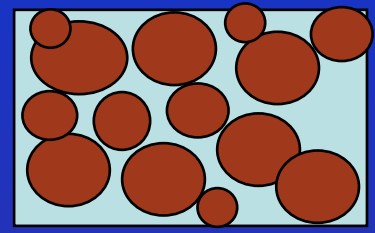
# Industrial Analogues



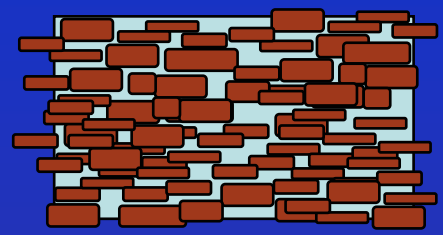

*Location of Natural Gas Storage Projects in the U.S.*

# Storage Security: Trapping Mechanisms

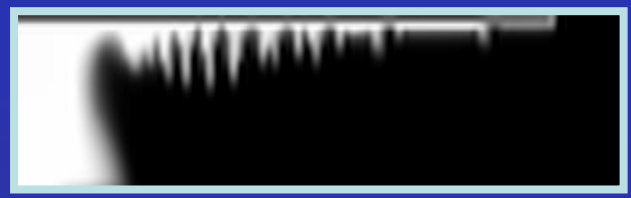
- Structural and stratigraphic trapping
  - Permeability barrier
  - Capillary barrier
- Solubility trapping



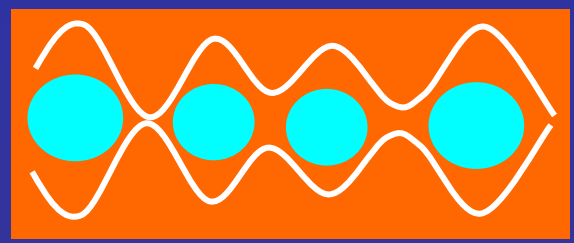
**Sandstone**



**Shale**



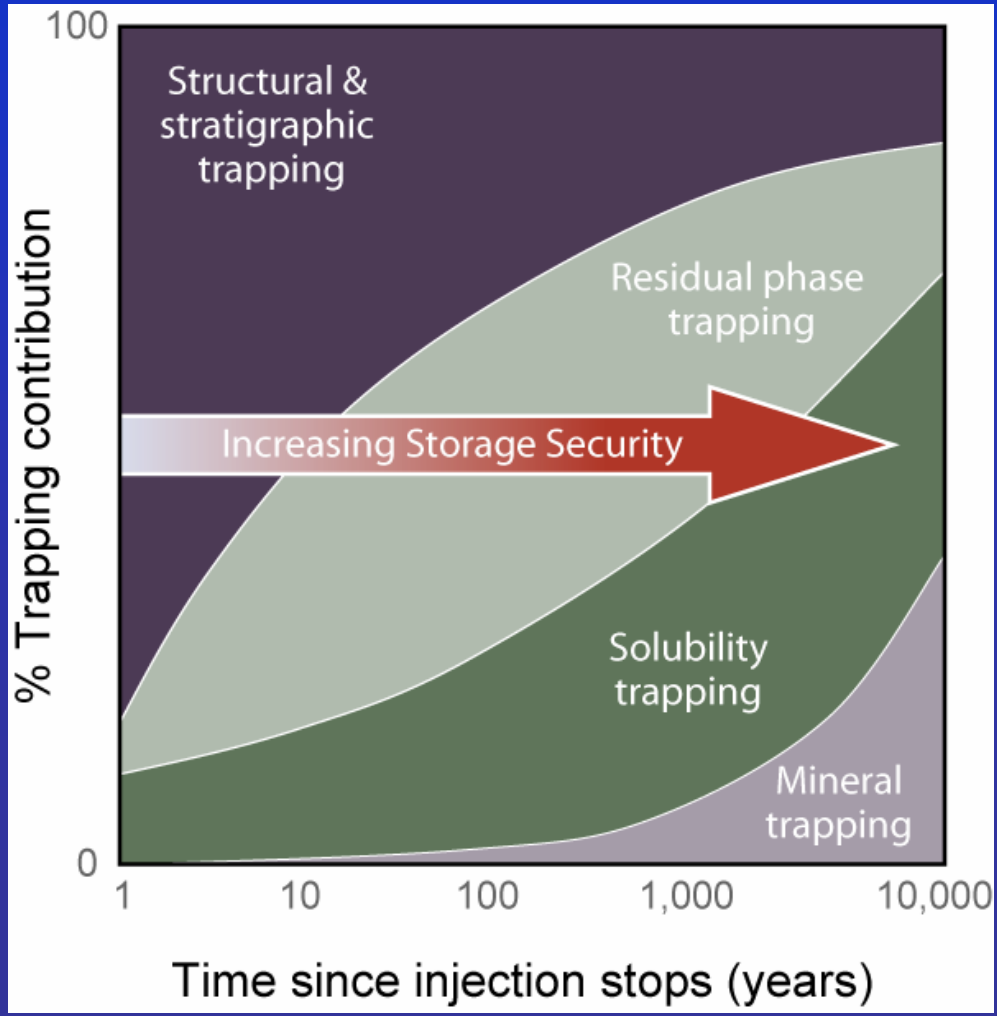
- Residual saturation trapping



- Mineral trapping

# Temporal Evolution of Trapping Mechanisms

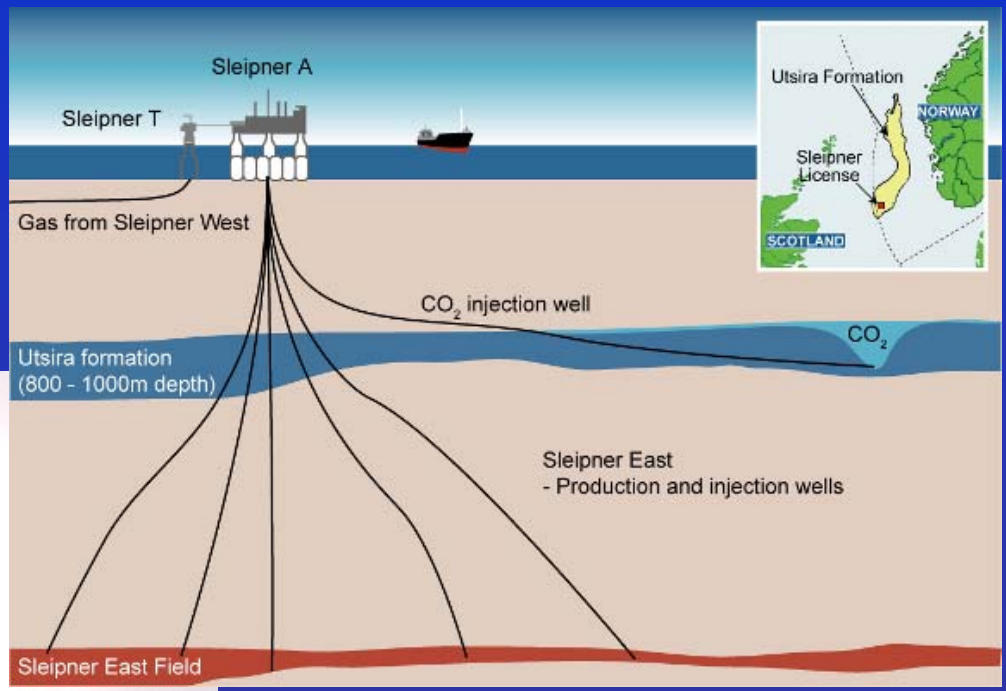
*Storage security should increase with time at an effective storage site.*




*Theoretical and experimental studies are needed to confirm this hypothesis.*

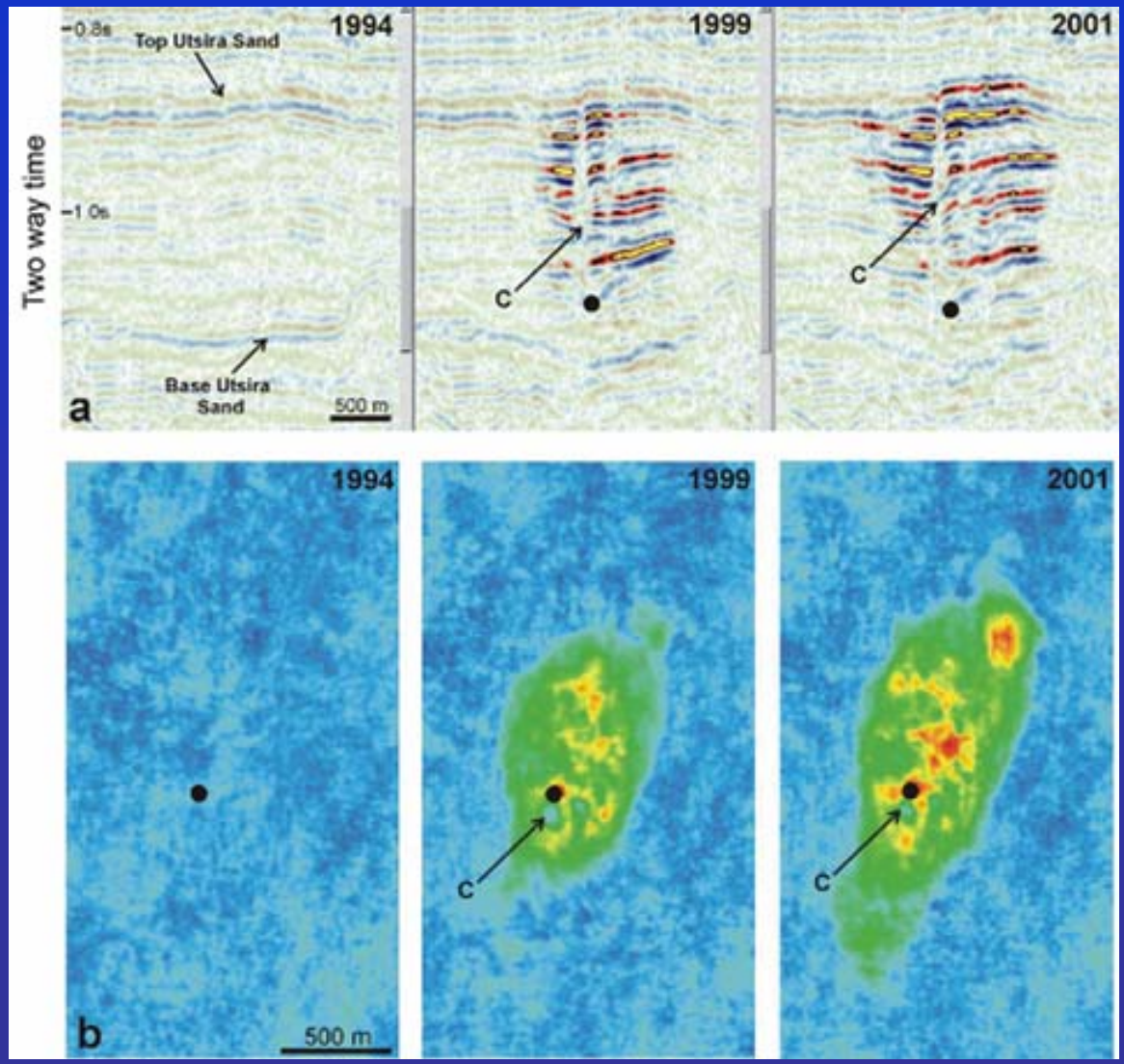
# Sleipner Project, North Sea

- 1996 to present
- 1 Mt $CO_2$ injection/yr
- Seismic monitoring



Picture compliments of *Statoil*

# Monitoring $CO_2$ Migration with 3-D Seismic Imaging




From Chadwick, 2004

# Weyburn $CO_2$-EOR and Storage Project

- 2000 to present
- 2.7 Mt/year $CO_2$ injection
- $CO_2$ from the Dakota Gasification Plant in the U.S.

Photo's and map courtesy of PTRC and Encana

# In Salah Gas Project

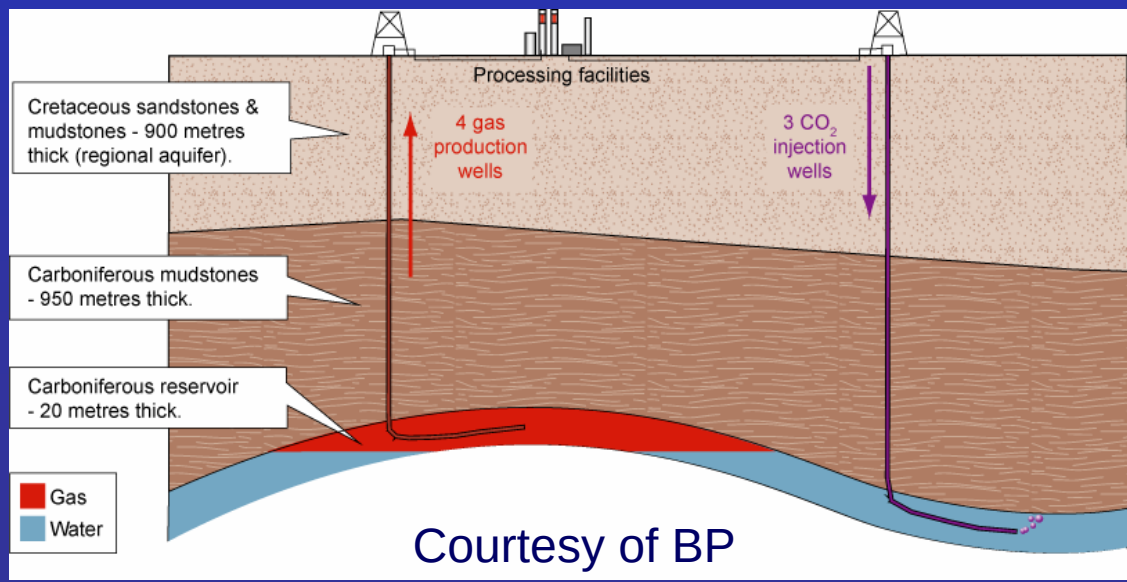
Gas Processing and $CO_2$ Separation Facility

In Salah Gas Project
- Krechba, Algeria

Gas Purification
- Amine Extraction

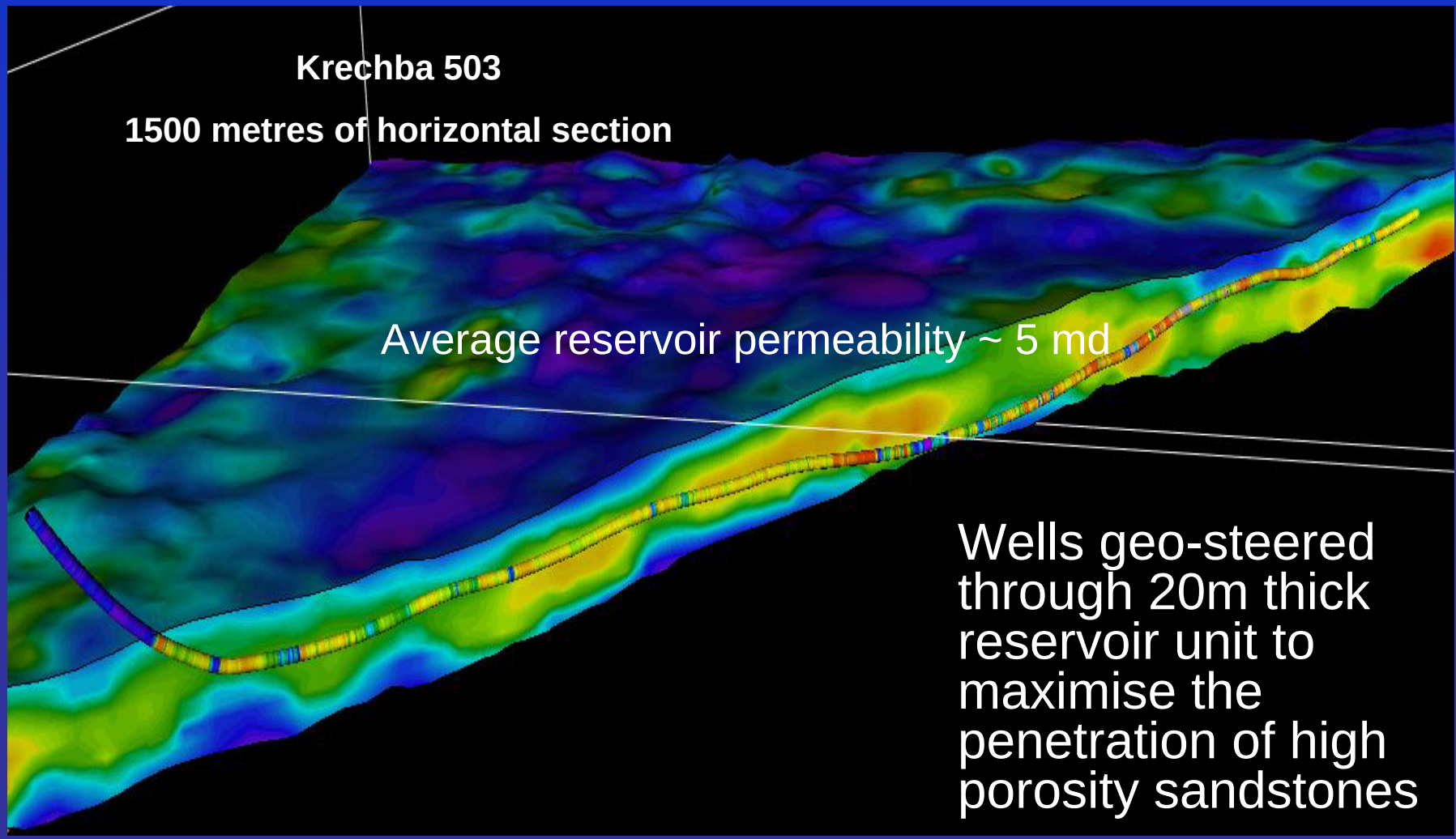
1 Mt/year $CO_2$ Injection

Operations Commence
- June, 2004




Courtesy of BP

# Optimizing Sweep Efficiency and Injectivity with Long Reach Horizontal Wells




Courtesy of BP

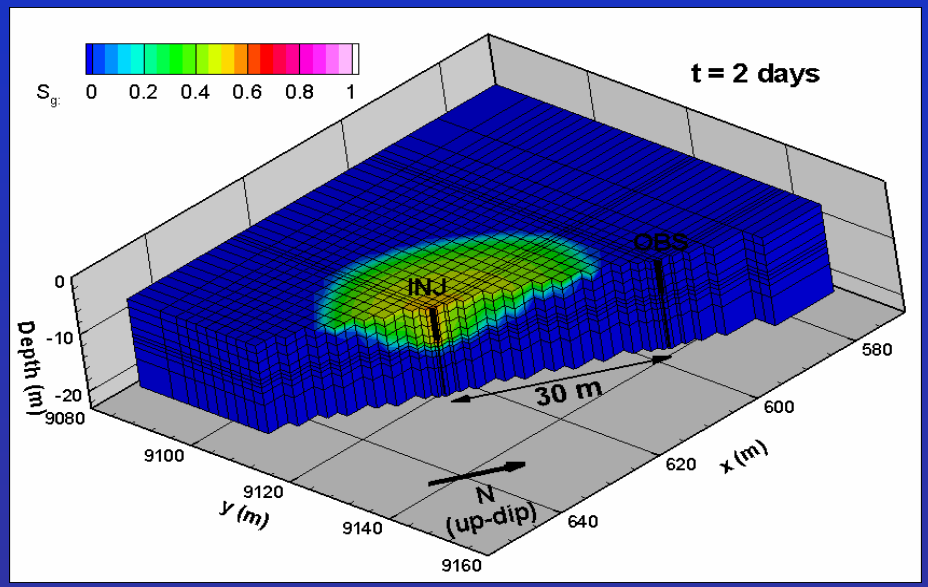
# The Frio Brine Pilot, Texas

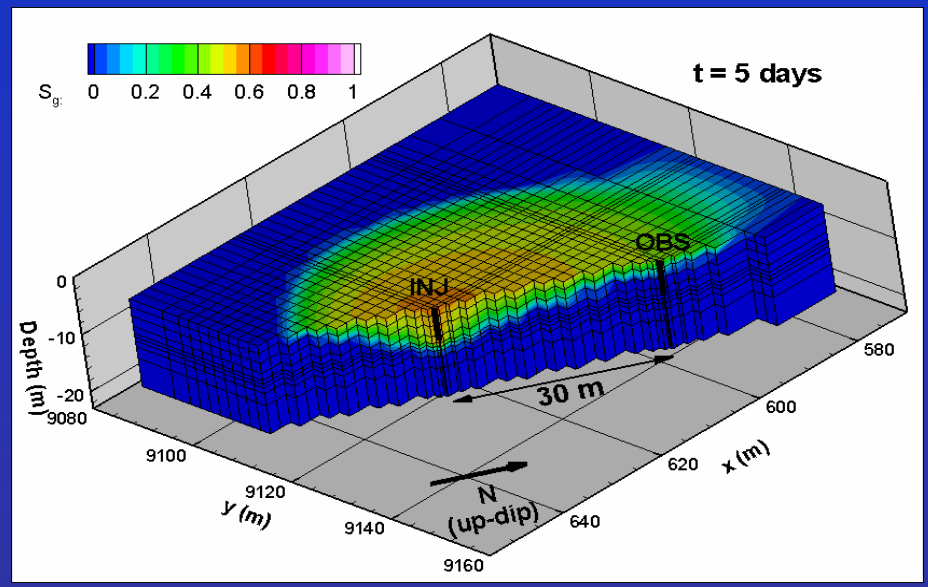
- Led by Susan Hovorka, UT Austin
- Injection: 1600 tonnes $CO_2$ over 10 days
- Well Depth: 1540 m
- Observation well 30 m from injection well
- Monitoring
  - Formation pressure
  - Tracers
  - Geochemical sampling
  - VSP
  - Cross-well seismic and EM
  - RST logging

Geochemical Sampling

$CO_2$ Transportation Trucks

# Modeled $CO_2$ Distribution

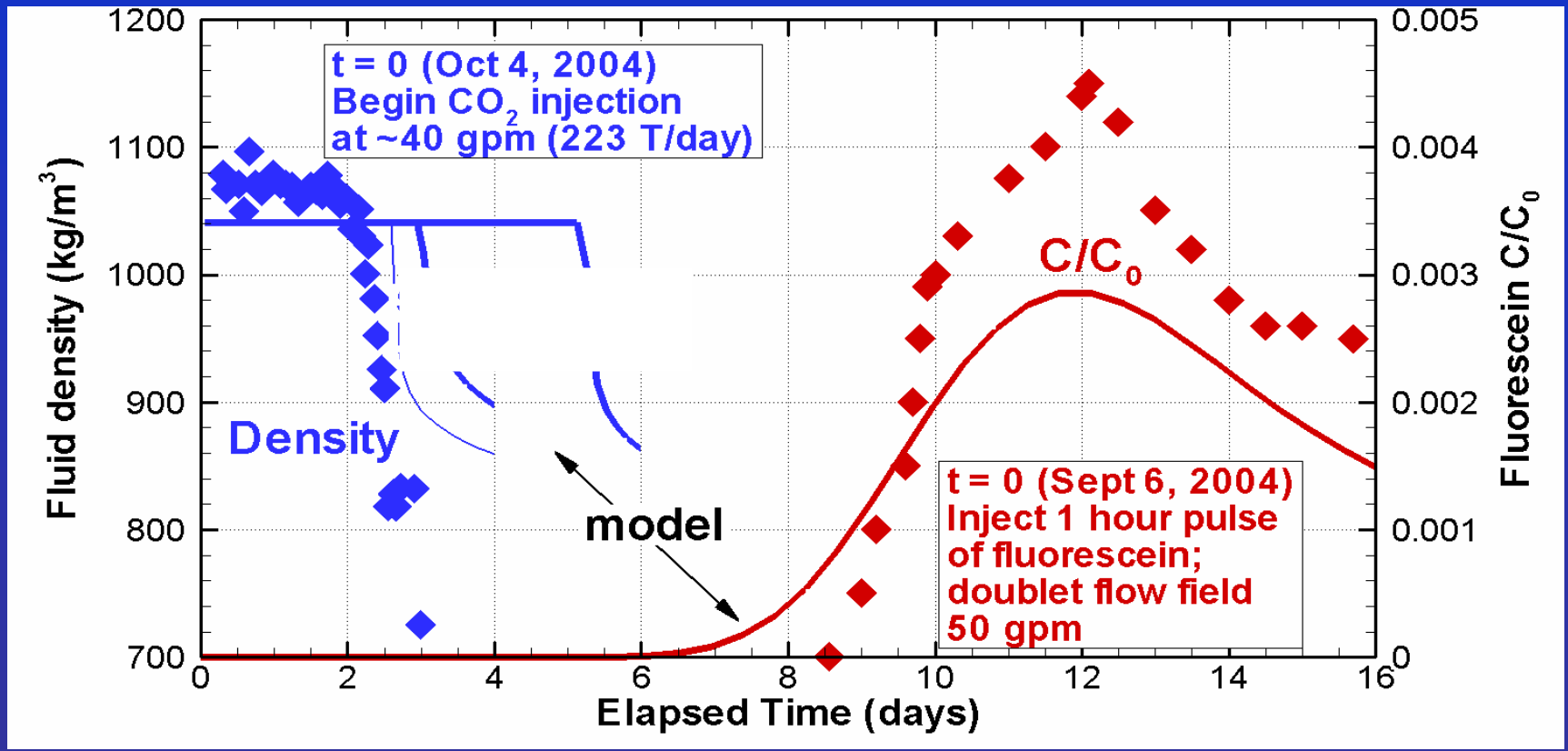



Simulations from C. Doughty, LBNL

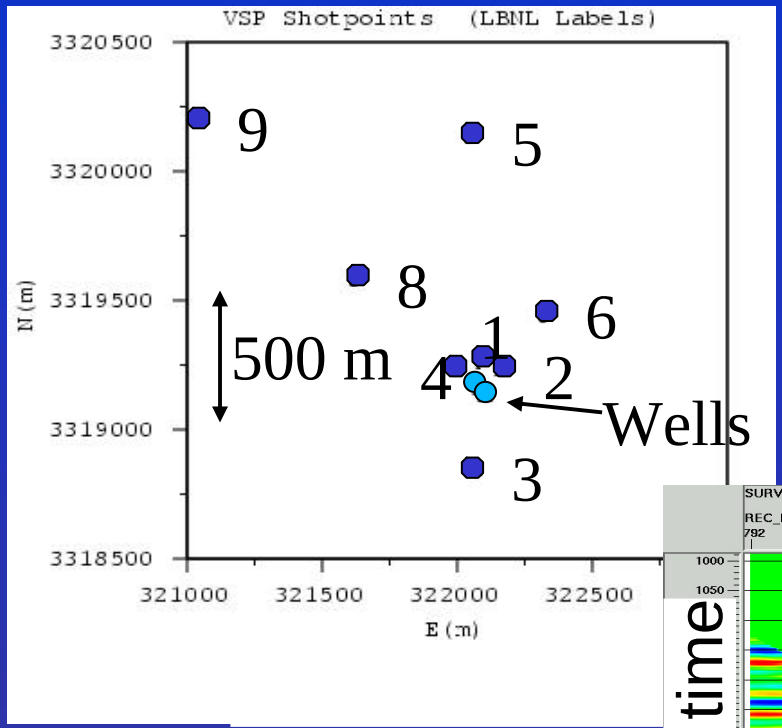
Predicted Breakthrough: 2 to 5 days

# Observed Data and Model Predictions



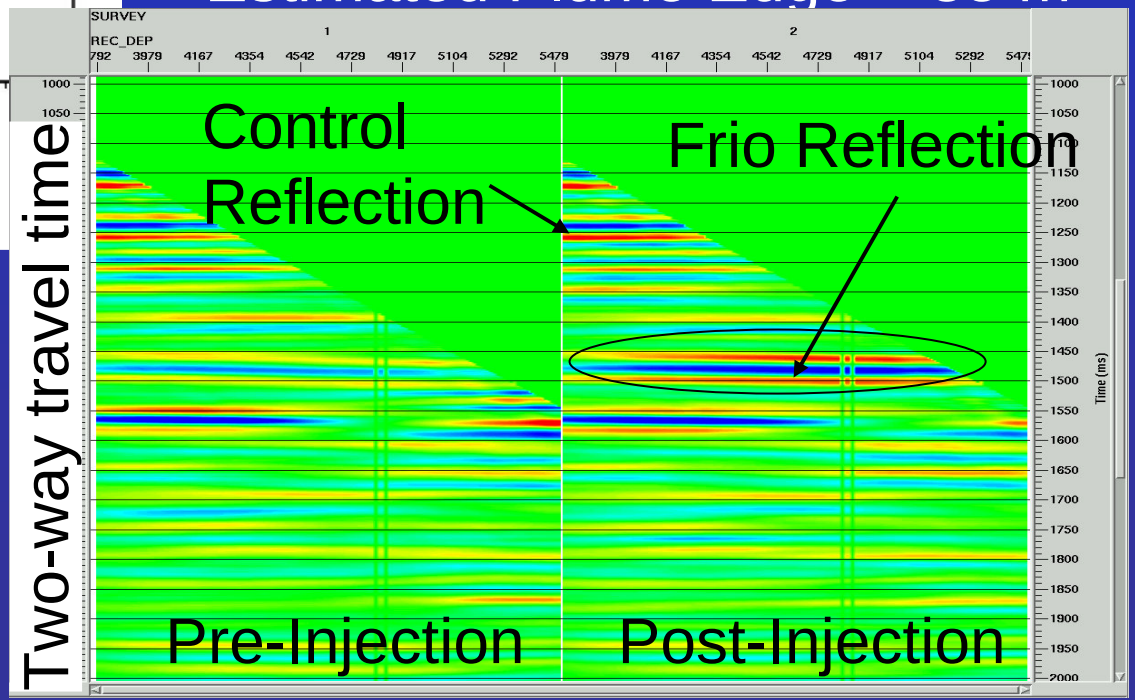

Field data provided by Barry Freifeld and Rob Trautz, LBNL

# Frio Brine Pilot: Vertical Seismic Profiling



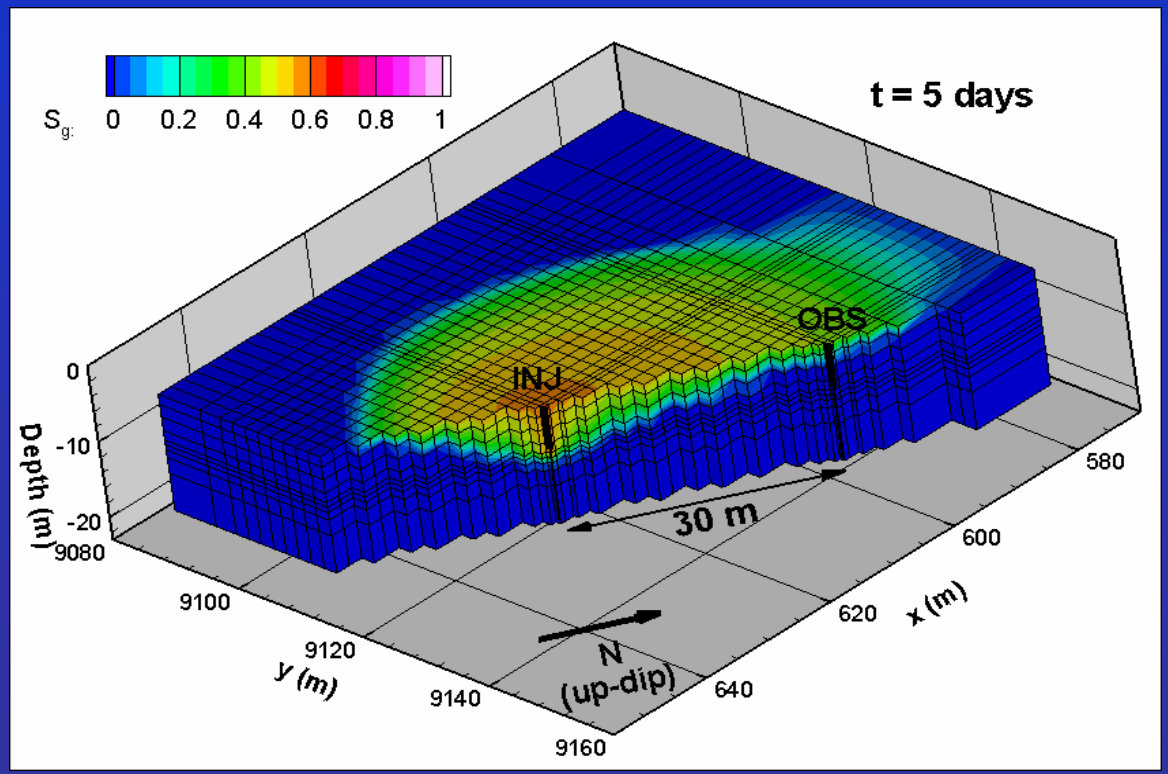

Data and interpretation from Tom Daley, LBNL

Estimated Plume Edge = 85 m



# The Frio Brine Pilot, Texas

- 5%-10% average saturation over thickness of swept zone
- Relative permeability for drainage with $s_{rCO2} \sim 5\%$




Model results from C. Doughty, LBNL

# Topics

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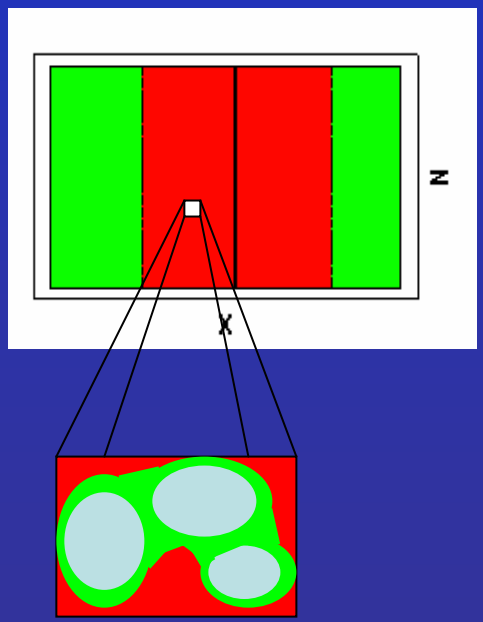
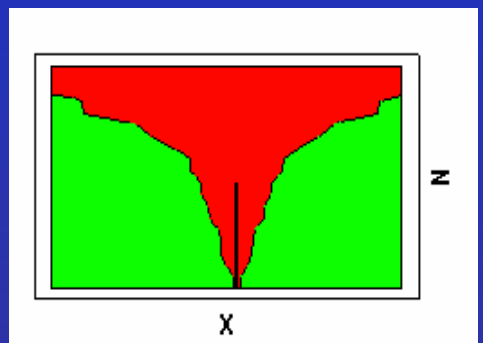
# Volumetric Storage Capacity

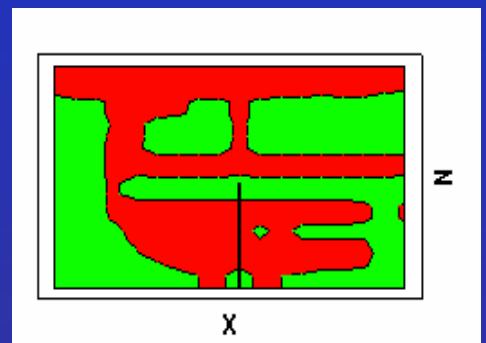
**Multiphase Flow Effects**



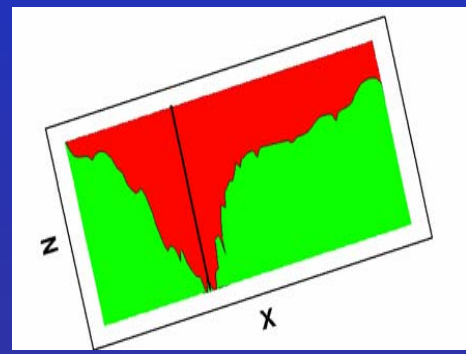

**Gravity Effects**




**Heterogeneity Effects**




**Structural Effects**

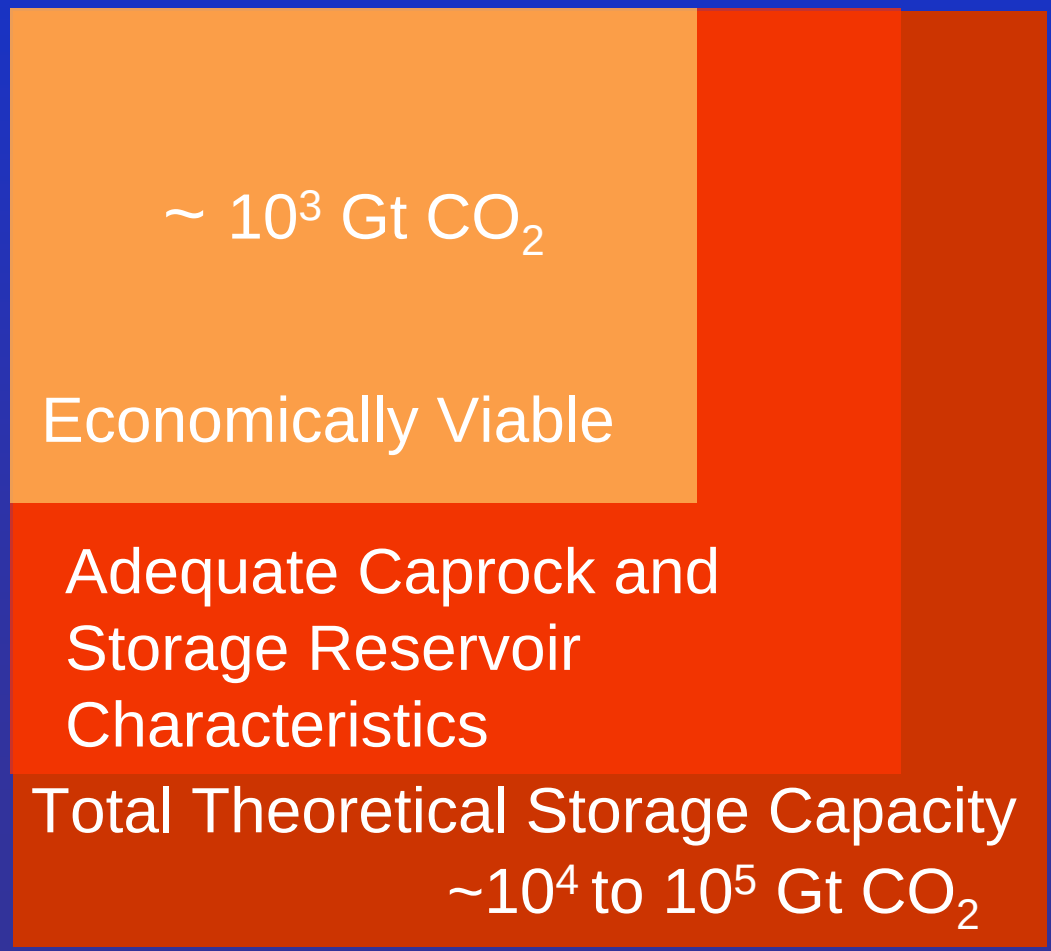



From Doughty et al., 2002

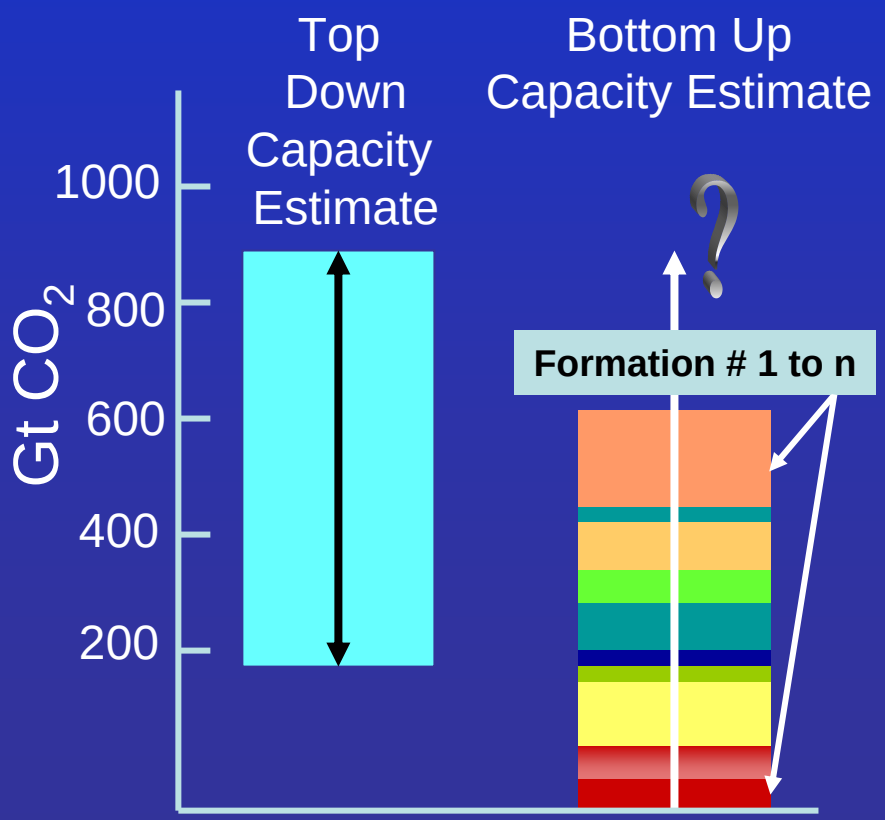
# More Work is Needed to Establish "Proven Storage Capacity" in Saline Formations

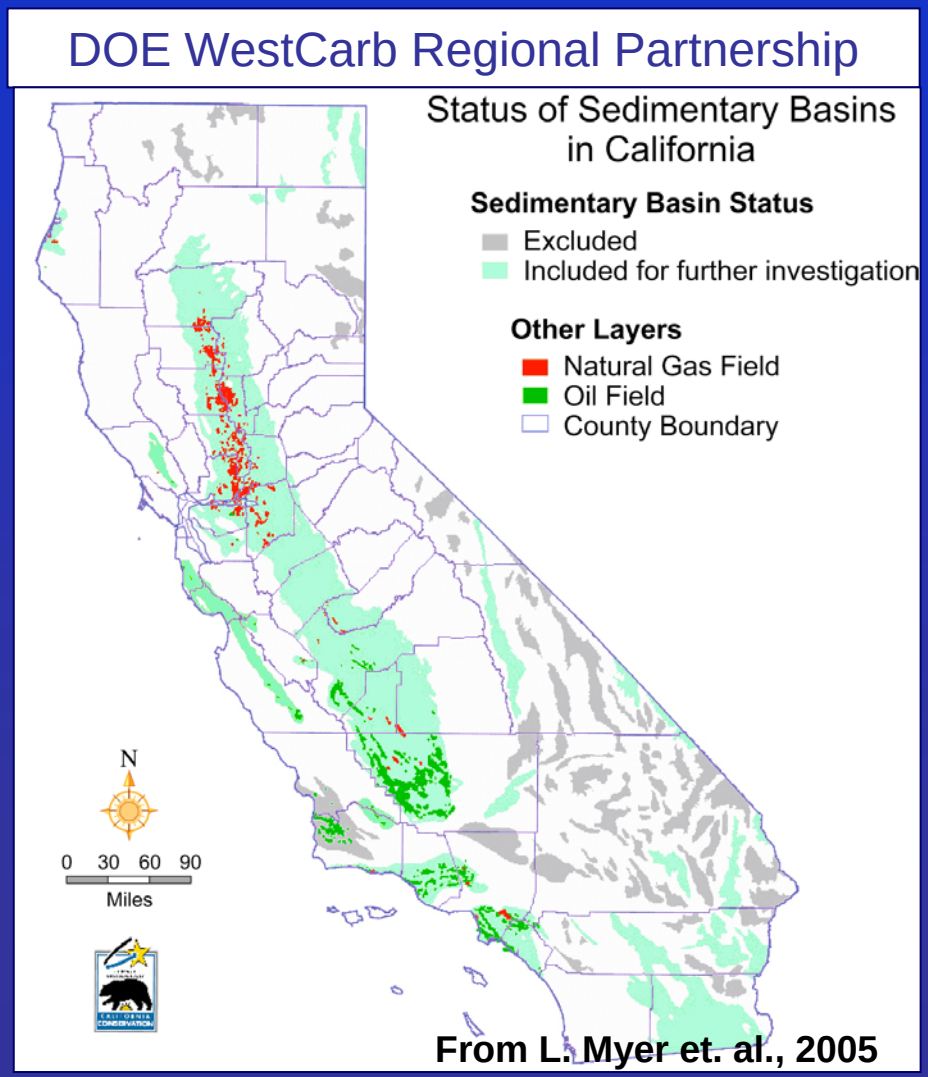
- Regional
- National
- Global

*100's of years of capacity is available at today's emission rates.*



# Reconciling Top-Down and Bottom-Up Storage Capacity Estimates



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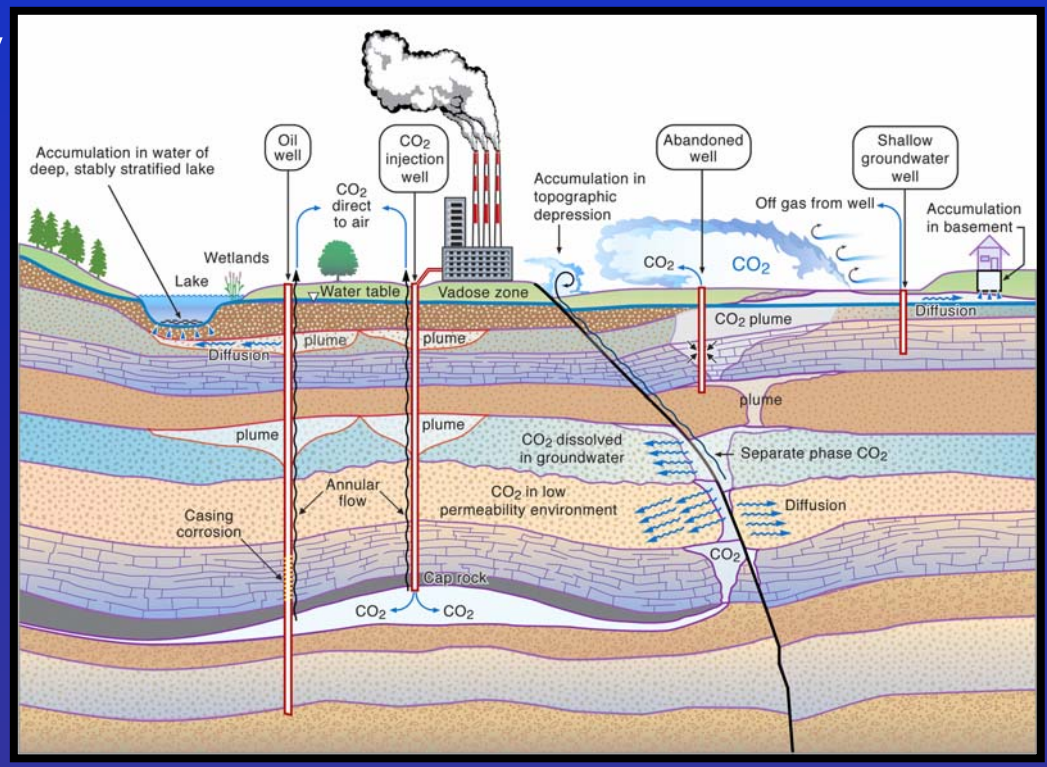
# Biggest Risks Have Been Identified

- Industrial analogues identify major risks
- Leakage through poor quality or aging injection well completions
- Leakage up abandoned wells
- Leakage due to inadequate caprock characterization
- Inconsistent or inadequate monitoring




*Maturation of the technology and improved regulations have mitigated most of these problems for the industrial analogues.*

# Risk Management

- To prevent such risks
  - Careful site selection
  - Pressure and injection rate control
  - Monitoring
  - Remediation of leaking wells
  - Abandoning ineffective storage sites
  - Effective regulatory oversight

EOR in US(2001): 30 $MtCO_2/y$

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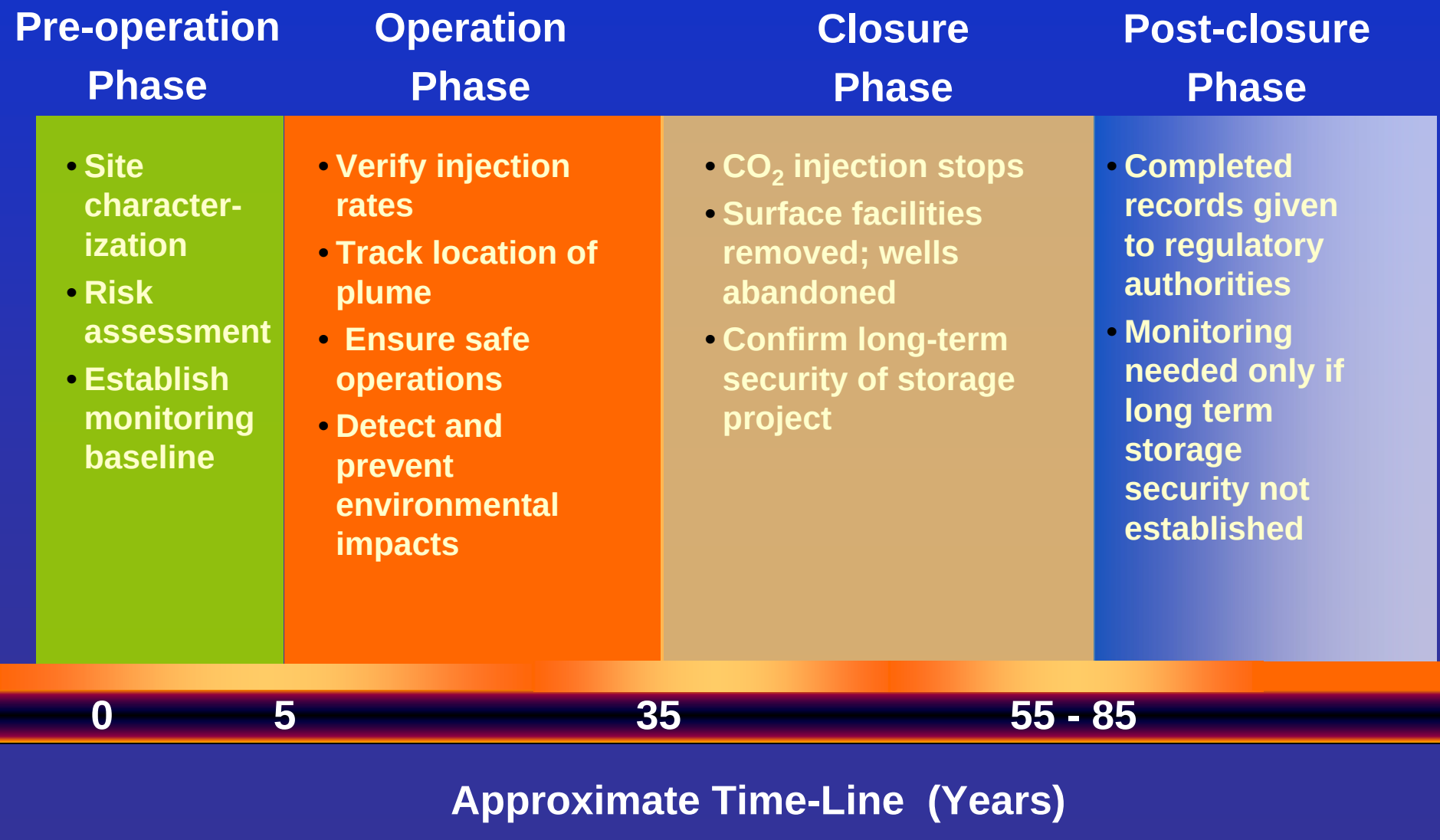
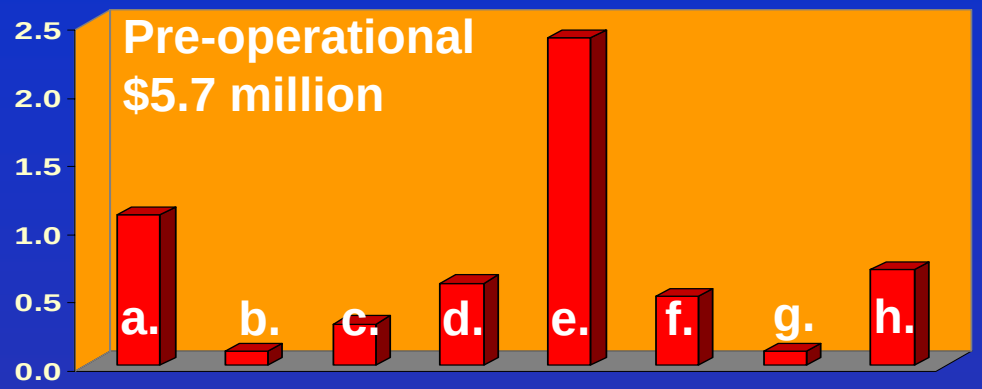
# Life Cycle of a Storage Project and Monitoring Requirements



# Components of the Basic and Enhanced Monitoring Packages

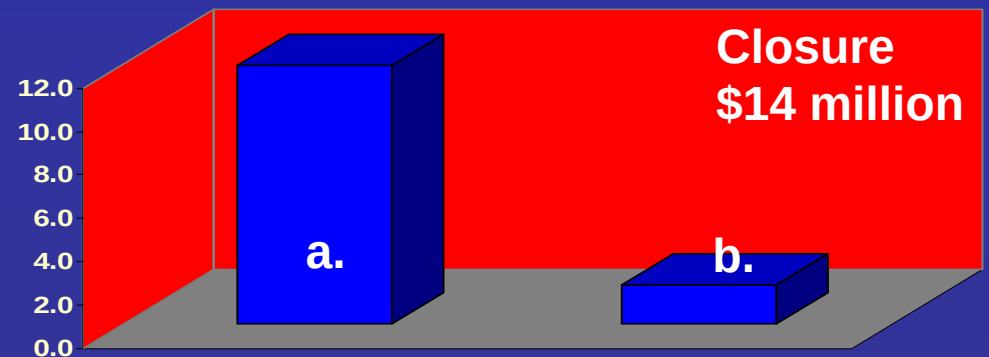
| | Basic Monitoring Package | Additional Measurements for Enhanced Monitoring Package |
|---|---|---|
| Pre-operational Monitoring | • Well logs<br>• Wellhead pressure<br>• Formation pressure<br>• Injection and production rate testing<br>• Seismic survey<br>• Atmospheric $CO_2$ monitoring | • Gravity survey<br>• Electromagnetic survey<br>• $CO_2$ flux monitoring<br>• Pressure and water quality above the storage formation |
| Operational Monitoring | • Wellhead pressure<br>• Injection and production rates<br>• Wellhead atmospheric $CO_2$ monitoring<br>• Microseismicity<br>• Seismic surveys | • Well logs<br>• Gravity survey<br>• Electromagnetic survey<br>• Continuous $CO_2$ flux monitoring at 10 stations<br>• Pressure and water quality above the storage formation |
| Closure Monitoring | • Seismic surveys | • Gravity surveys<br>• Electromagnetic surveys<br>• Continuous $CO_2$ flux monitoring at 10 stations<br>• Pressure and water quality above the storage formation<br>• Wellhead pressure monitoring for 5 yeas, after which time the wells will be abandoned |

# Monitoring Cost for Saline Formation



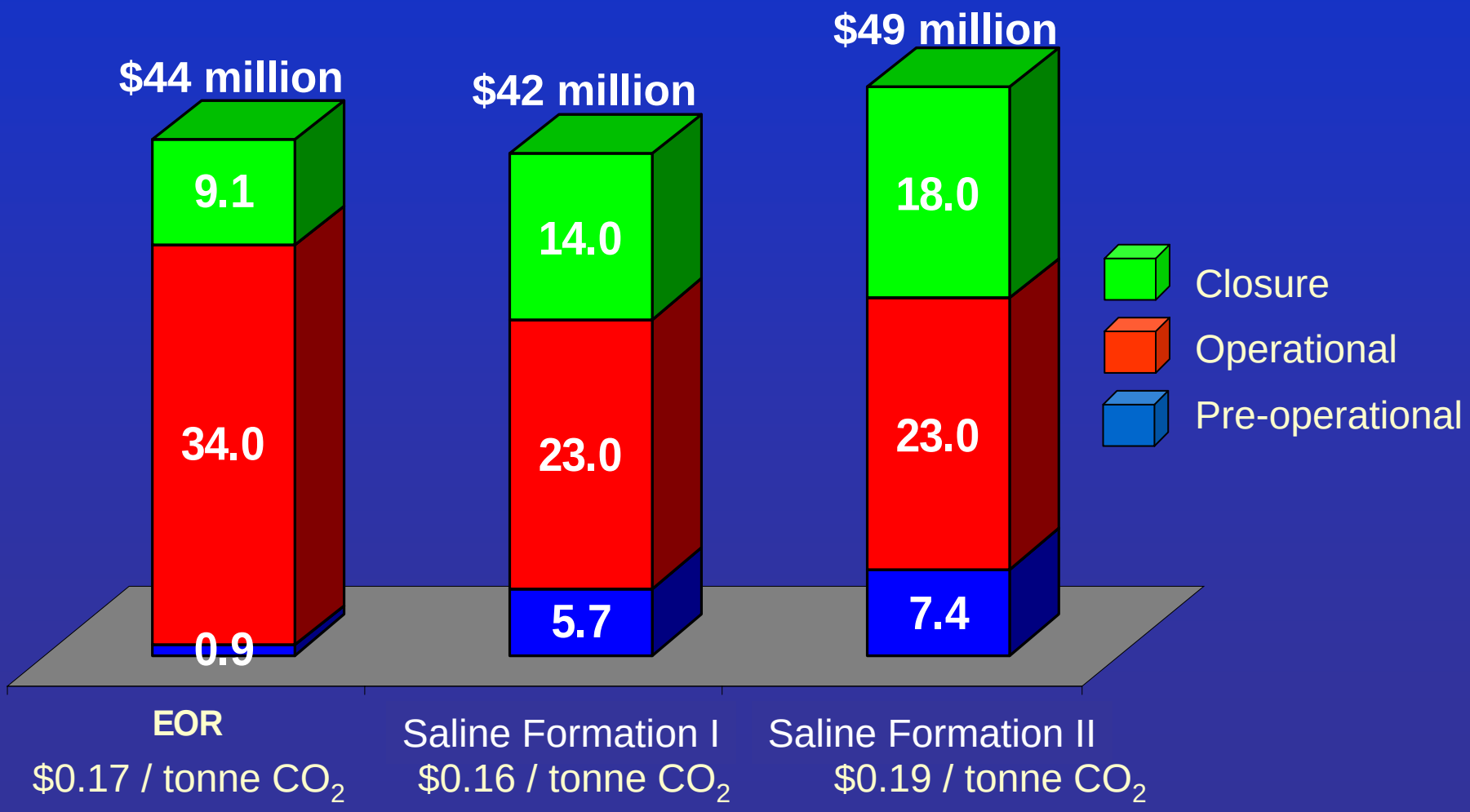

a. Well logs
b. Wellhead pressure
c. Formation pressure
d. Injection and production rate testing
e. Seismic survey
f. Microseismicity baseline
g. Baseline atmospheric $CO_2$ monitoring
h. Management (15%)

a. Seismic survey
b. Wellhead pressure
c. Injection and production rates
d. Wellhead atmospheric $CO_2$ concentration
e. Microseismicity
f. Management (15%)

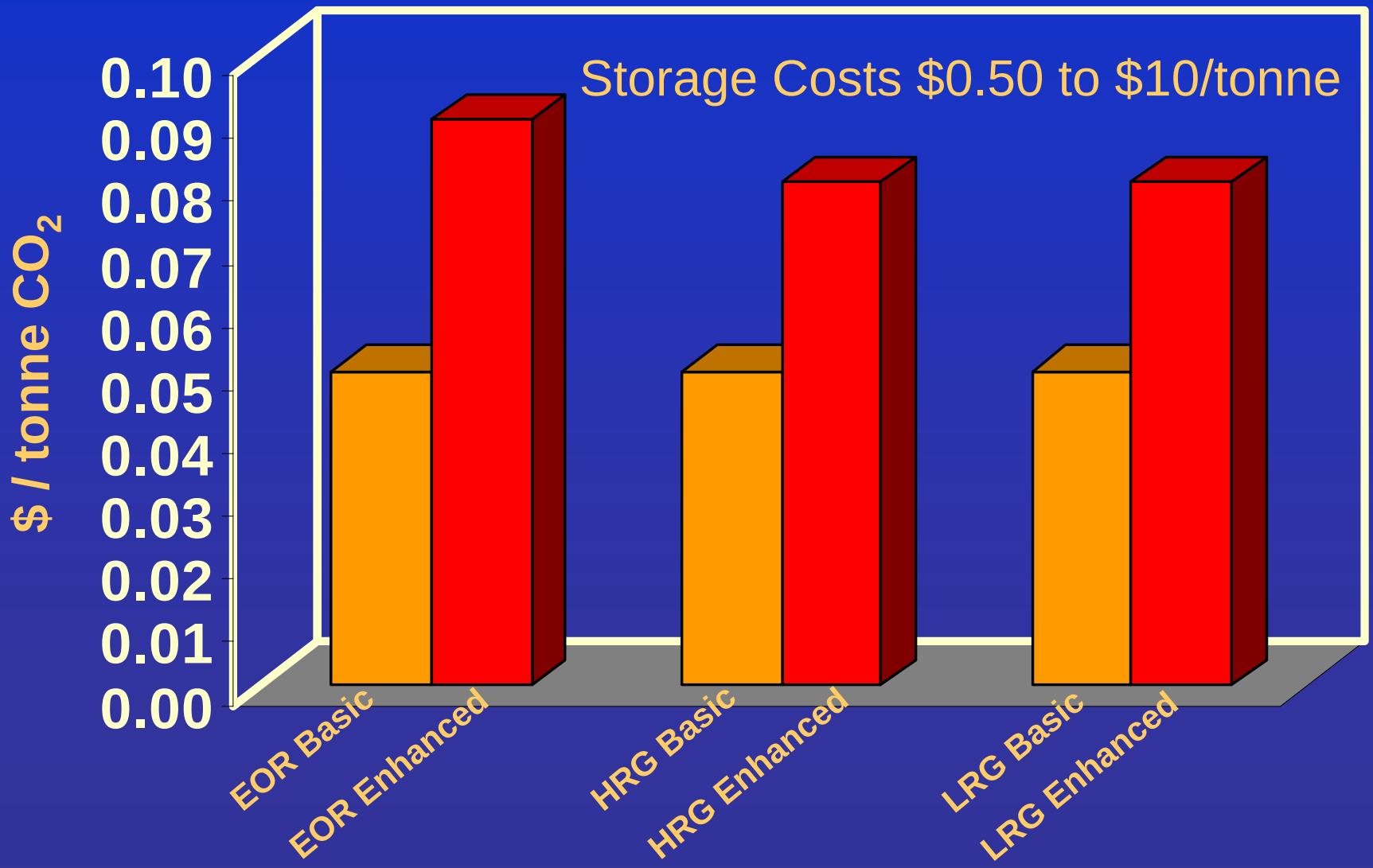



a. Seismic survey
b. Management (15%)

# Comparison of Monitoring Costs



# Discounted Monitoring Costs (@10%)



# Implications of Longer-term Monitoring

- 1000 year period
- Repeat seismic surveys every 10 years
- Basic monitoring package
  - Intergenerational discount rate of 1% after 30 years
  - $0.053/tonne increases to $0.059/tonne
- 10% increase in cost
- Non-financial issues
  - Responsibility for monitoring
  - Oversight and record keeping
  - Responsibility for remediation

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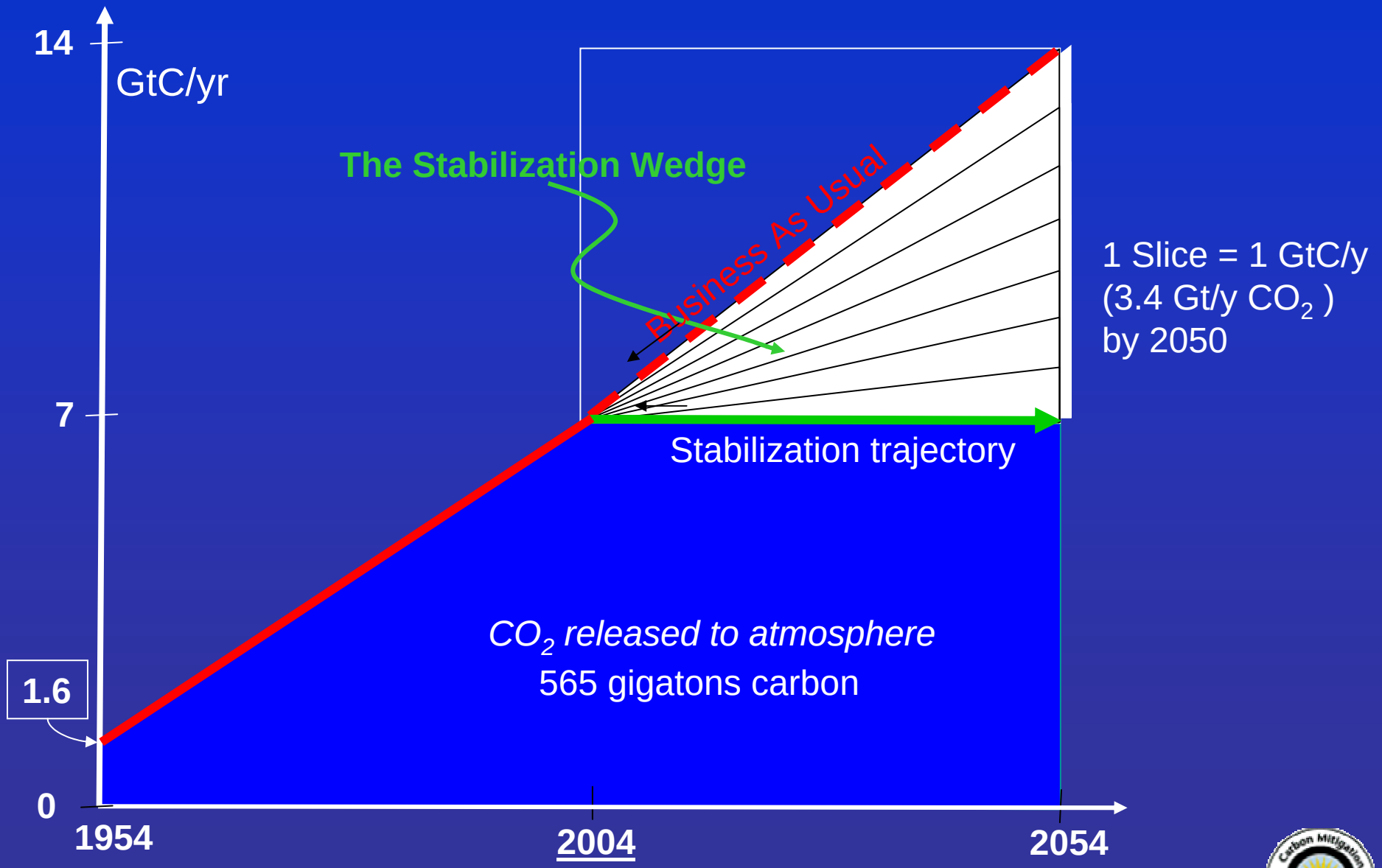
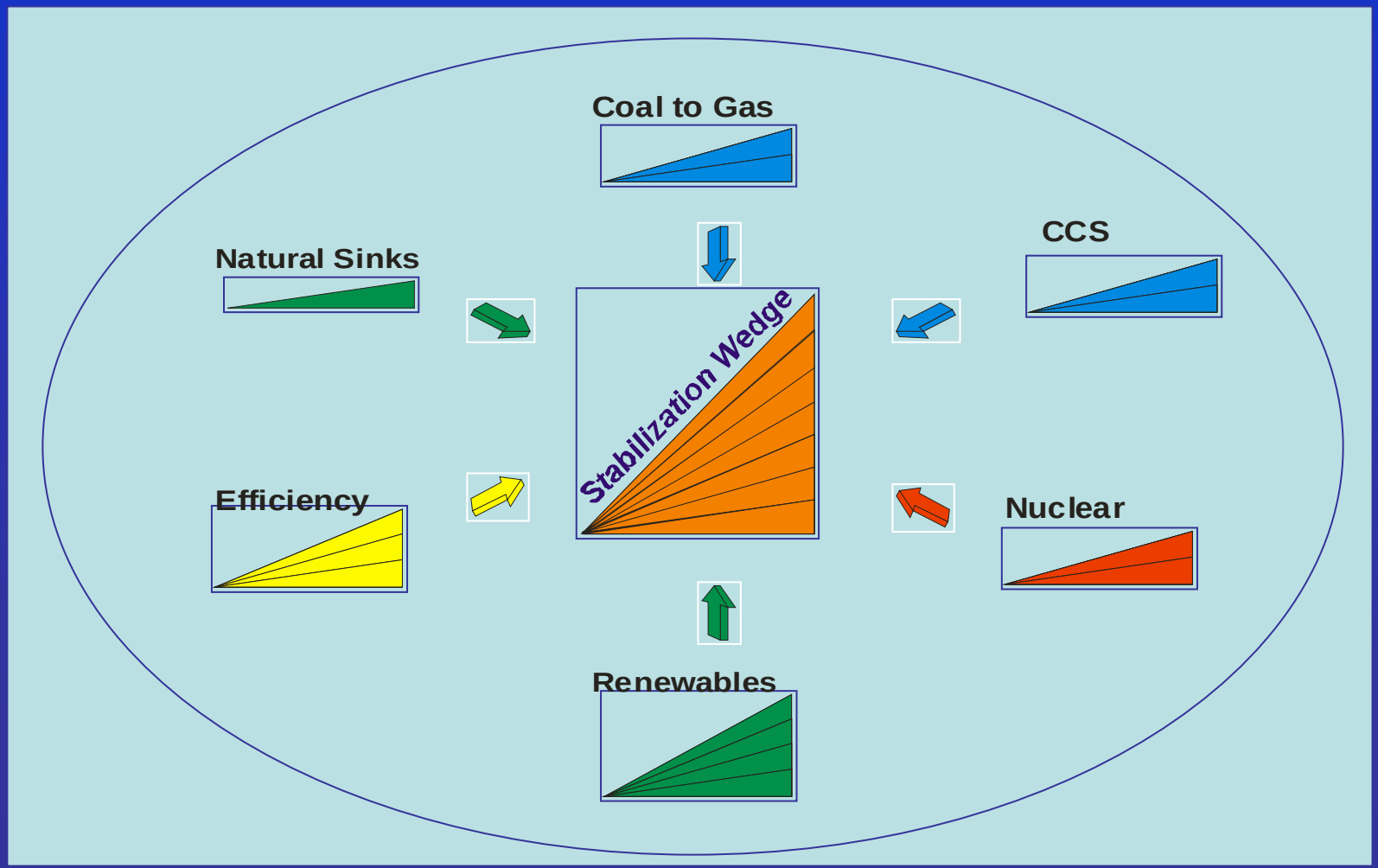
# Concept of the Wedge and Slices




From Pacala and Socolow, *Science*, 2004

# Filling the Wedge

The strategies available to provide the slices to fill the wedge are grouped below. All strategies are based on technologies already in use.

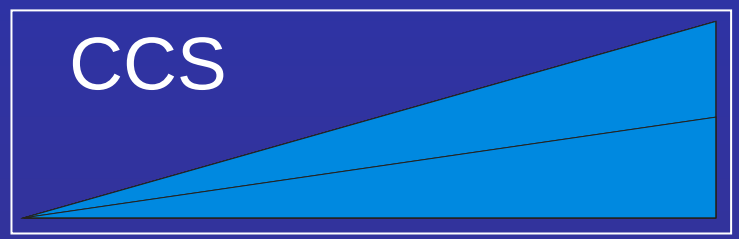


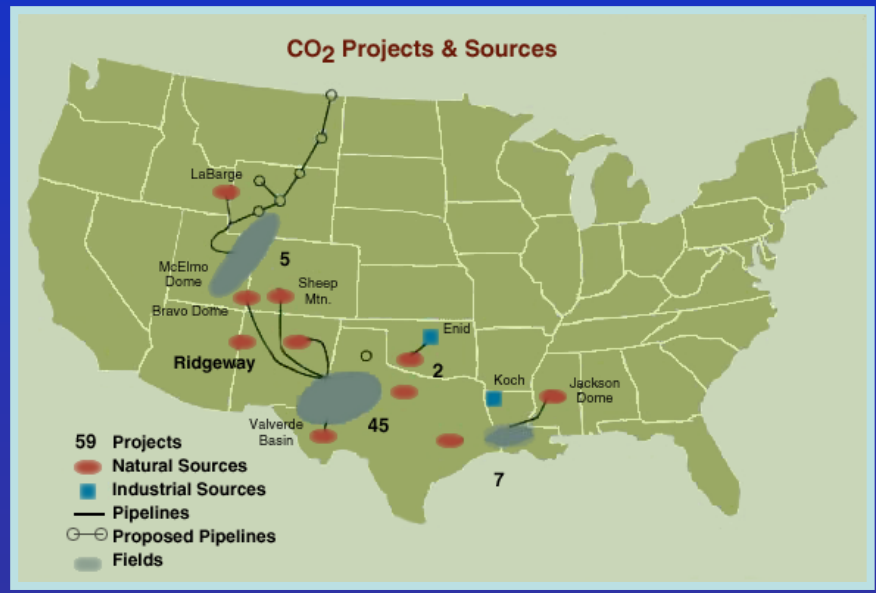

From Pacala and Socolow, *Science*, 2004

# $CO_2$ Capture and Storage

**Effort needed for 1 slice:**

World-wide, build or replace 8 1000 MW coal fired power plants with CCS every year and maintain them until 2054




*World-wide 100-fold increase in the amount of $CO_2$ injected for EOR each year in the U.S.*

Modified from Pacala and Socolow, *Science*, 2004

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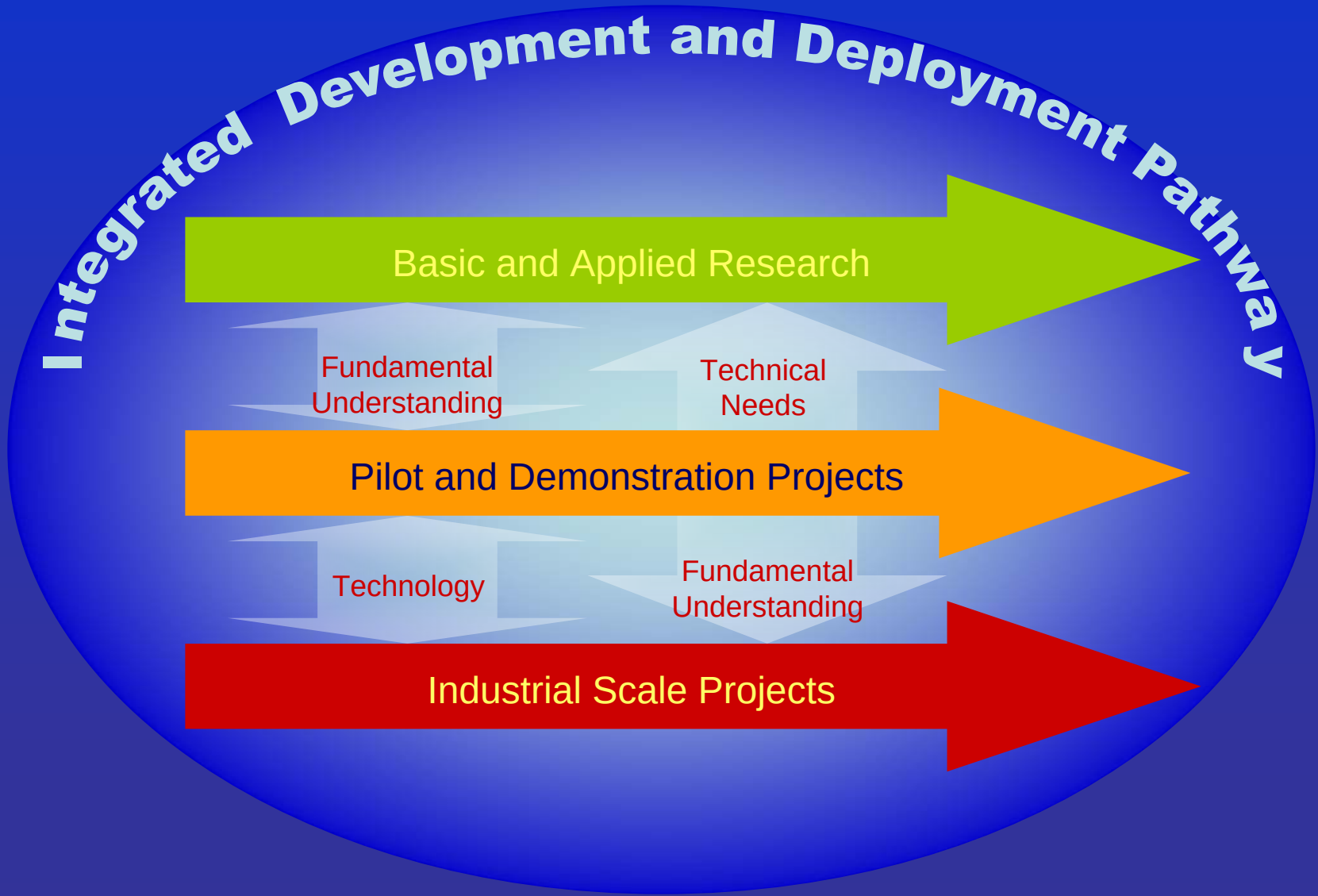
# Key Issues for Technology Development and Deployment

- Evaluating Abandoned Well Impacts On Storage Integrity
- Optimizing Sweep Efficiency and Injectivity
- Demonstrating Long-Term Storage Integrity
- Developing Criteria for Site Selection
- Reconciling Top-Down and Bottom-Up Capacity Estimates
- Establishing Cost-Effective Monitoring and Verification Protocols

# Cooperation and Knowledge Sharing will Greatly Accelerate Learning and Successful Deployment