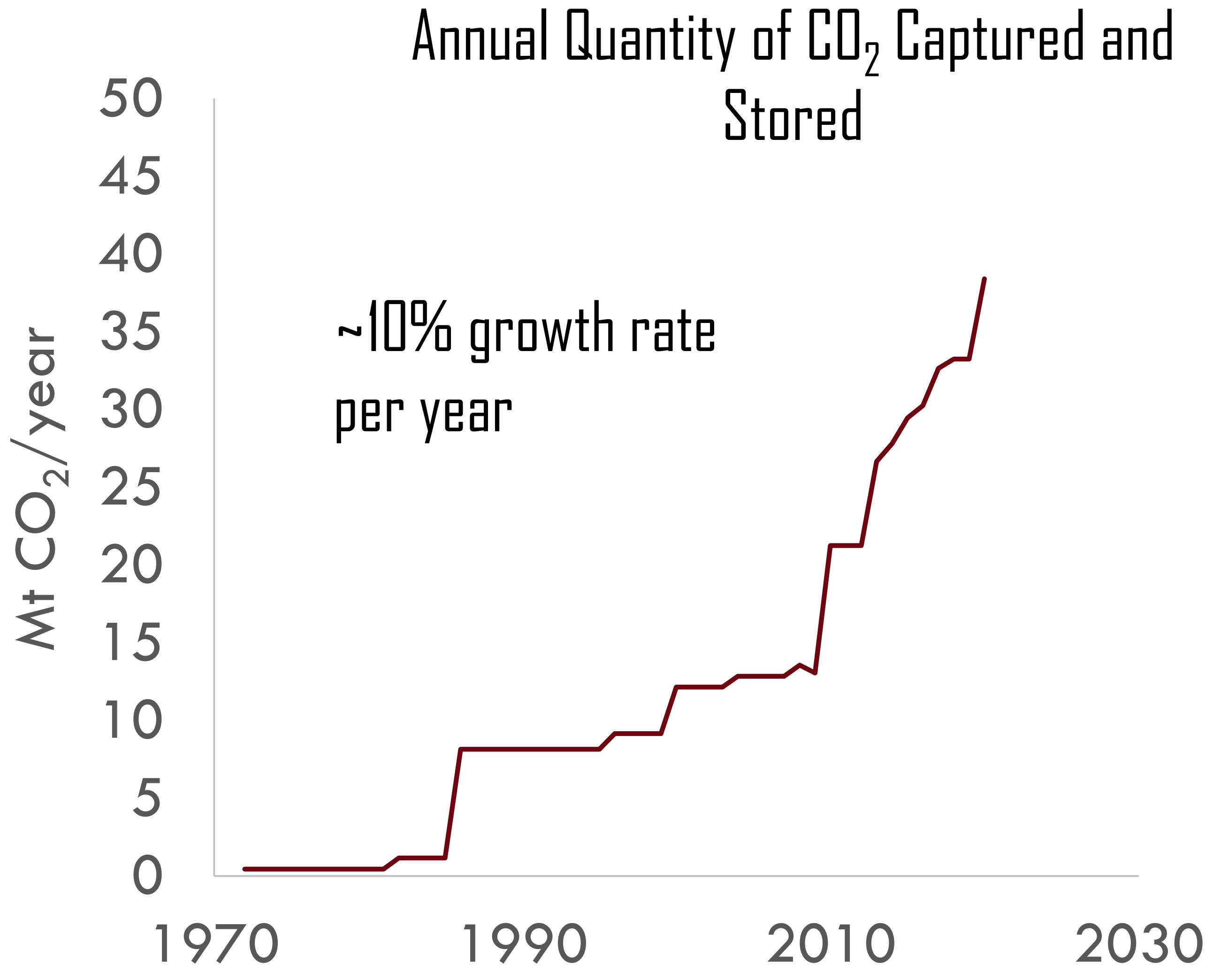
CREATING VALUE FROM MONITORING CO_2 STORAGE PROJECTS

Professor Sally M. Benson
Co-Director, Precourt Institute for Energy
Stanford University

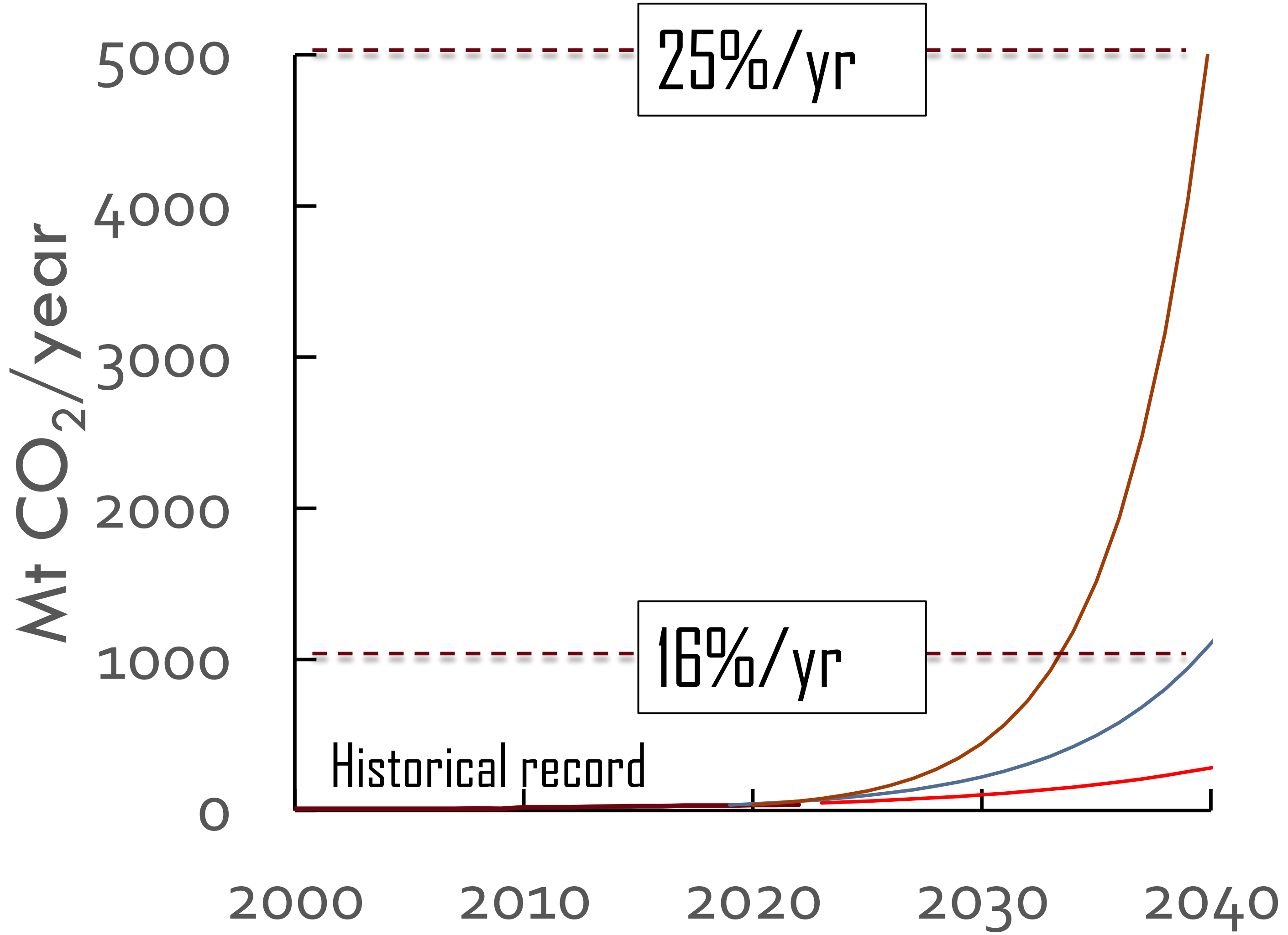
Where do we stand with CCUS today?

- 20 commercial projects, on track for 24 by early 2020s
- ~35 Mt CO_2/year
- CO_2-EOR at 65 Mt CO_2/year, but mostly from natural sources
- Capture, compression, transport and storage done at scale today



The Decades Ahead for CCUS

- ~1-5 Gt/year by 2040 is needed
- Rapid increases in deployment growth rates required
- Double to triple historic growth rates sustained for 2 decades



A Turning Point for CCUS

1970's - present	2020's and beyond
Limited policy drivers CO_2-EOR Sleipner Saline Aquifer Storage project, Snohvit, In Salah, Illinois, Gorgon Many small scale pilots (<< 1 Mt) Growth rate of ~10%/year Learning by doing	Compelling need for CCUS Stronger policy drivers Growth rates of 20% or more per year are needed 1 – 5 Gt/year by 2040 Many commercial scale projects 1+ Mt/year

Conditions to support rapid scale-up

Strong policy support

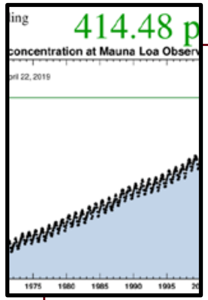
- Confidence of political leaders

Safety

- No accidents, damage, or environmental harm

Cost

- Competitiveness with other GHG reduction measures



Regulatory compliance

- Meet legal obligations

Public support

- Engagement and transparency

Technical Feasibility

- Secure storage

Monitoring plays a critical supporting role for rapid scale-up of CCUS

Technical feasibility	Safety	Compliance with regulations
• Ensure CO_2 stays trapped in the storage complex • Track the location of the CO_2 plume • Limit pressure buildup to safe levels to avoid geomechanical impacts • Identify and confirm storage efficiency and processes • Model calibration and performance confirmation	• Assess the integrity of shut-in, plugged or abandoned wells • Establish baseline conditions from which the impacts of CO_2 storage can be assessed • Detect and quantify surface leakage • Detect and avoid unsafe levels of micro-seismicity associated with CO_2 injection • Design and evaluate remediation efforts	• Ensure effective injection controls • Ensure groundwater protection • Evaluate interactions or impacts with other geological resources: for example nearby water, coal, oil & gas, mineral reserves or other geological waste disposal operations • Accounting where monetary transactions are involved such as with carbon trading and emission tax or emission reduction incentives

Creating value from monitoring

Benefits of monitoring >> costs

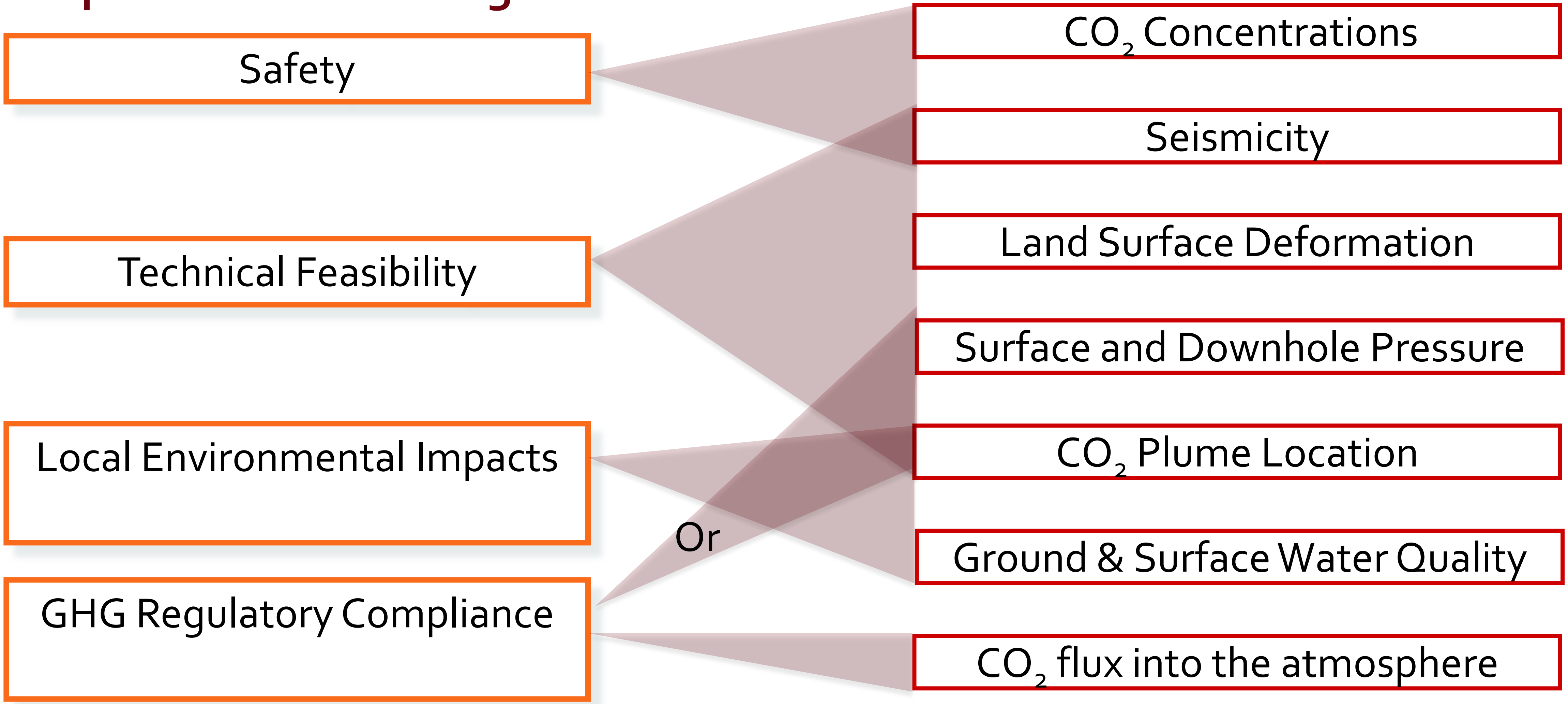
- How much monitoring, for what purposes, using which technologies and at what cost?
- Under which circumstances is it worth doing more than the minimum amount of monitoring required by regulatory requirements?
- Which types of monitoring provide the greatest value for the cost?
- If regulatory requirements provide the flexibility to choose between a variety of options, how do you choose one approach over the other?
- What is of greater value, high spatial resolution or high temporal resolution?

Costs for monitoring vary over wide range depending on program.

What Needs to be Measured?

Purposes for Monitoring

Parameters



What Needs to be Measured?

CO_2 concentra-tions	Seismicity	Land surface deform-ation	Surface and downhole pressure	CO_2 plume location	Ground and surface water quality	CO_2 flux into the air
Infrared spectrometer	Geophones	Satellite imagery	Pressure gauges	Seismic imaging	Fluid sampling and analysis	Eddy covariance
				Other geophysical imaging techniques (EM, ERT, gravity)		
Gas sampling and analysis	Fiber networks	Strain sensors	Distributed fiber	Saturation logs	Well logs	Surface-based CO_2 sensors and data analysis

Monitoring Requirements and Metrics

- Where, when, how, and how precisely?
- It depends…
  - Regulations
  - Risks
  - Site constraints
  - Technology availability
  - Cost
- Minimum requirements
  - Wellhead and formation pressures
  - Location of the CO_2 plume
  - Evidence that CO_2 is not leaking
  - Induced seismicity
  - Worker safety related measurements

Cost effective and reliable methods for meeting the minimum requirements are needed!

Monitoring Costs Are Important

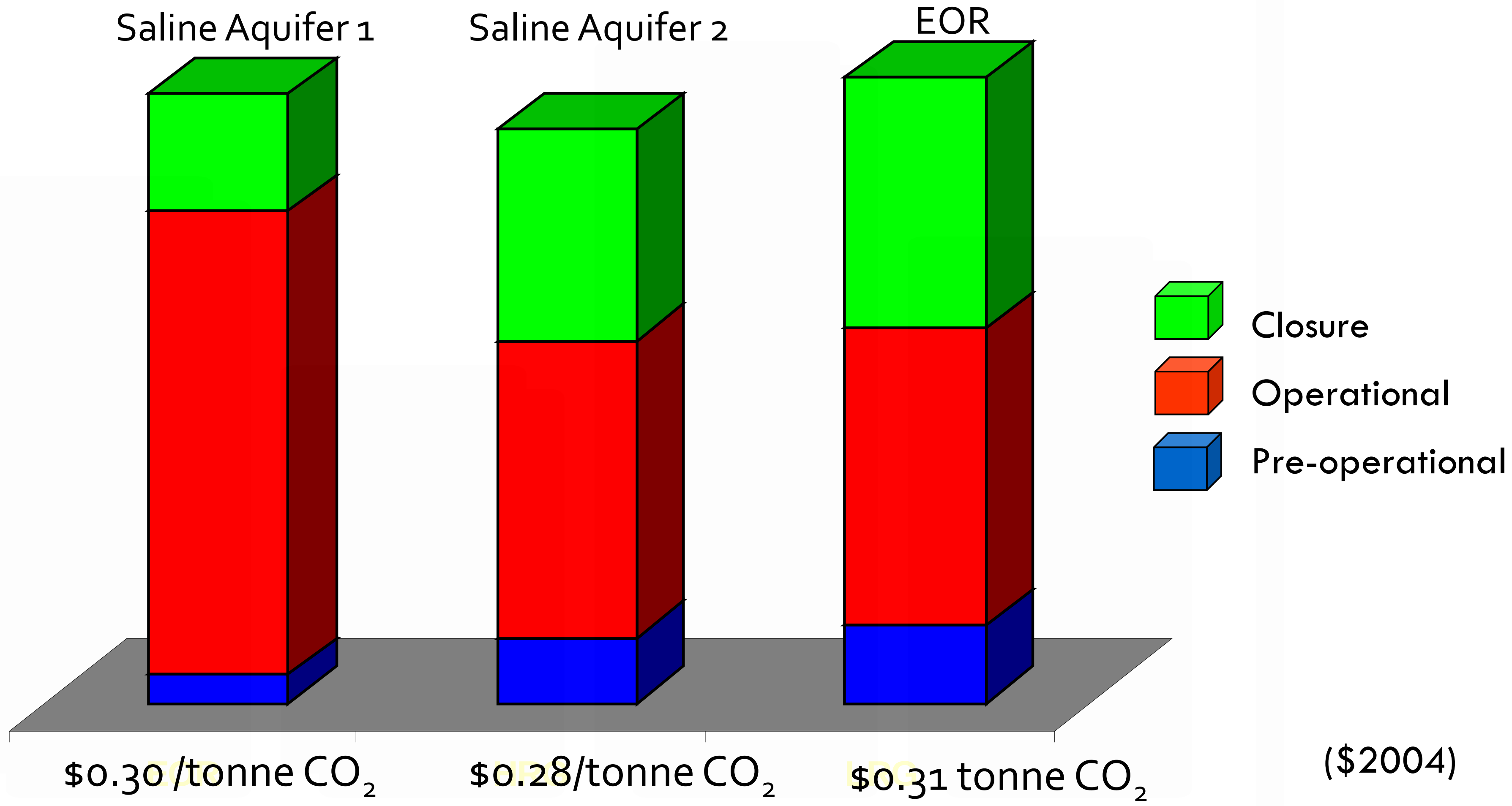
Benefits of monitoring >> costs

- Industry is concerned over high monitoring costs
- Long term stewardship – Post Closure Site Care -- is in impediment to final investment decision
- Oilfield monitoring practices are much less stringent – raising questions about why so much additional monitoring is needed for CCUS projects
- Conversion from EOR to storage projects results in significant additional compliance costs

What are the costs for monitoring?

Monitoring Costs (A Look Back to 2004)

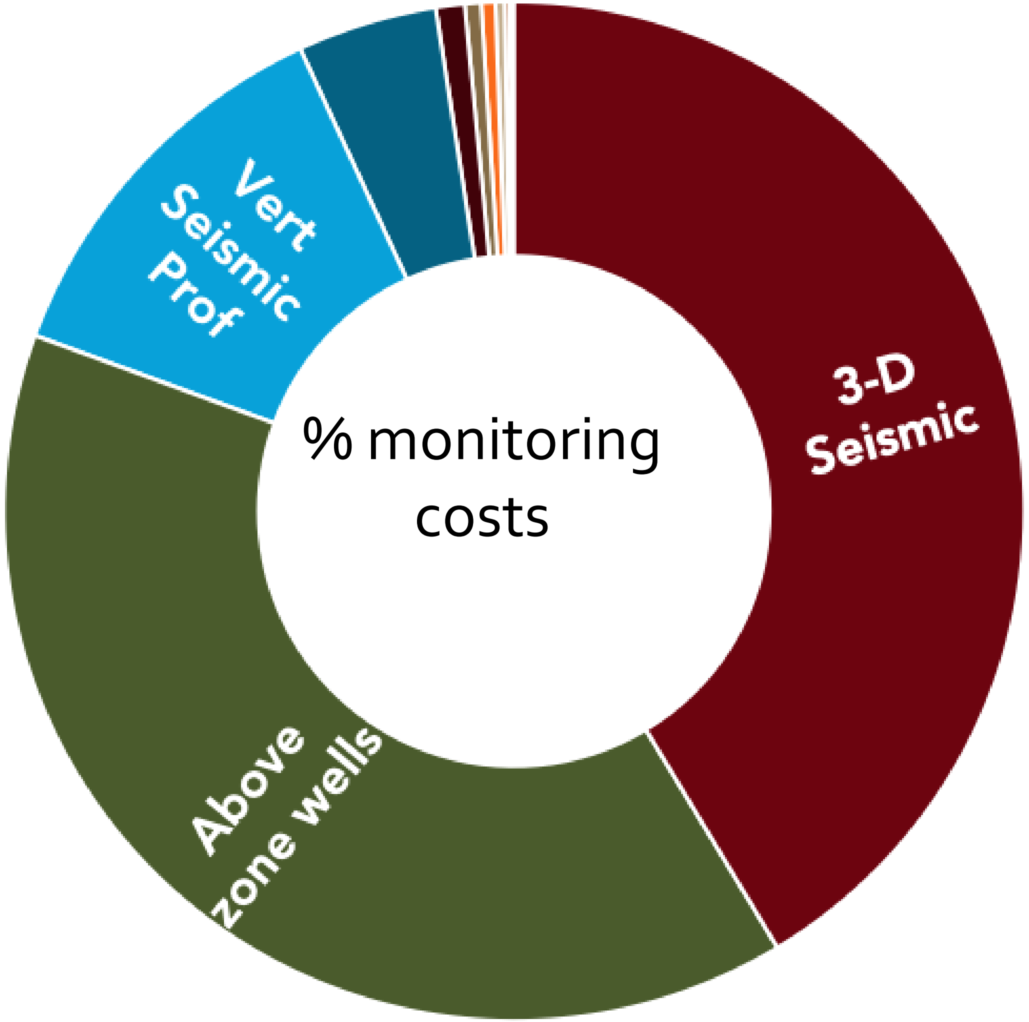
- Basic and enhanced monitoring program
- 258 Mt injected
- Monitoring during all phases of the project through site closure



Benson et al., 2004. Overview of Monitoring Techniques and Protocols for CO_2 Storage Projects, IEAGHG Report.

Example Costs for Monitoring

- Woodbine formation example (NETL storage cost estimator)
  - 96 Mt CO_2 over 30 years
  - 1.6 km deep
  - 3 injection wells
  - Total cost of storage $9.3/tonne of CO_2
- Extensive monitoring program
  - 3-D seismic, VSP, eddy covariance
    - 200 km² seismic monitoring area
  - In reservoir and above-zone monitoring wells (40 total)
  - Cost of monitoring: $7/tonne



($2008)

National Energy Technology Laboratory, FE/NETL CO2 Saline Storage Cost Model. U.S. Department of Energy. September 2017.

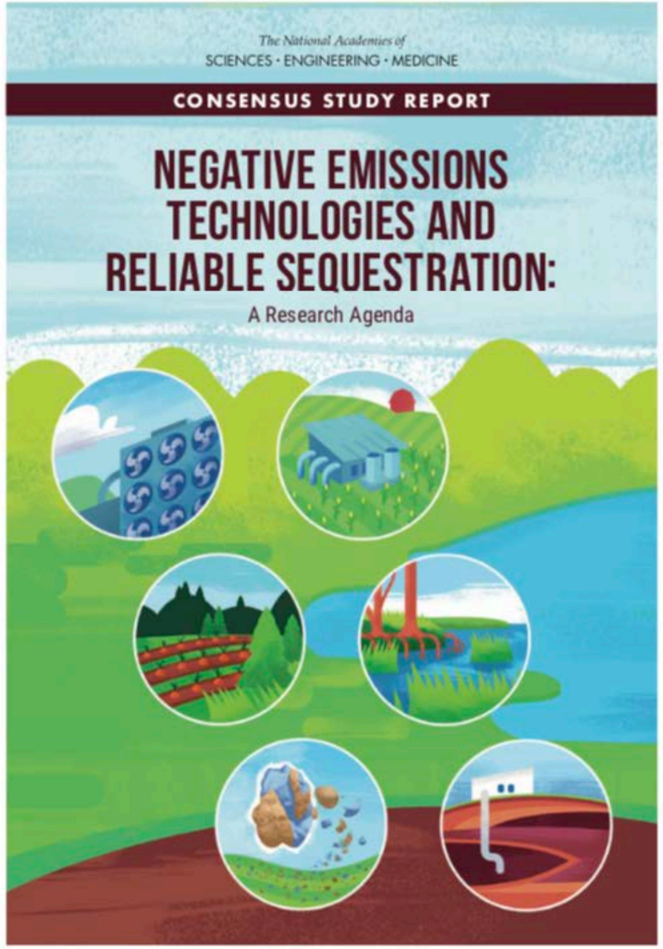
Lower Cost Monitoring Approaches and Packages are Needed

- 3-D seismic, the workhorse of CO_2 monitoring is very expensive – comprising the largest single cost for monitoring (and sometimes of the whole storage project)
- Due to high costs for seismic monitoring, measurements are only made periodically (~5 years is typical for planning purposes)
- Seismic imaging is not suitable for all environments
  - Reservoir or seal properties
  - Proximity to other resources
  - Difficulties in surface access

Research to develop cost effective monitoring programs is needed.

Monitoring Program Gaps (NAS, 2018)

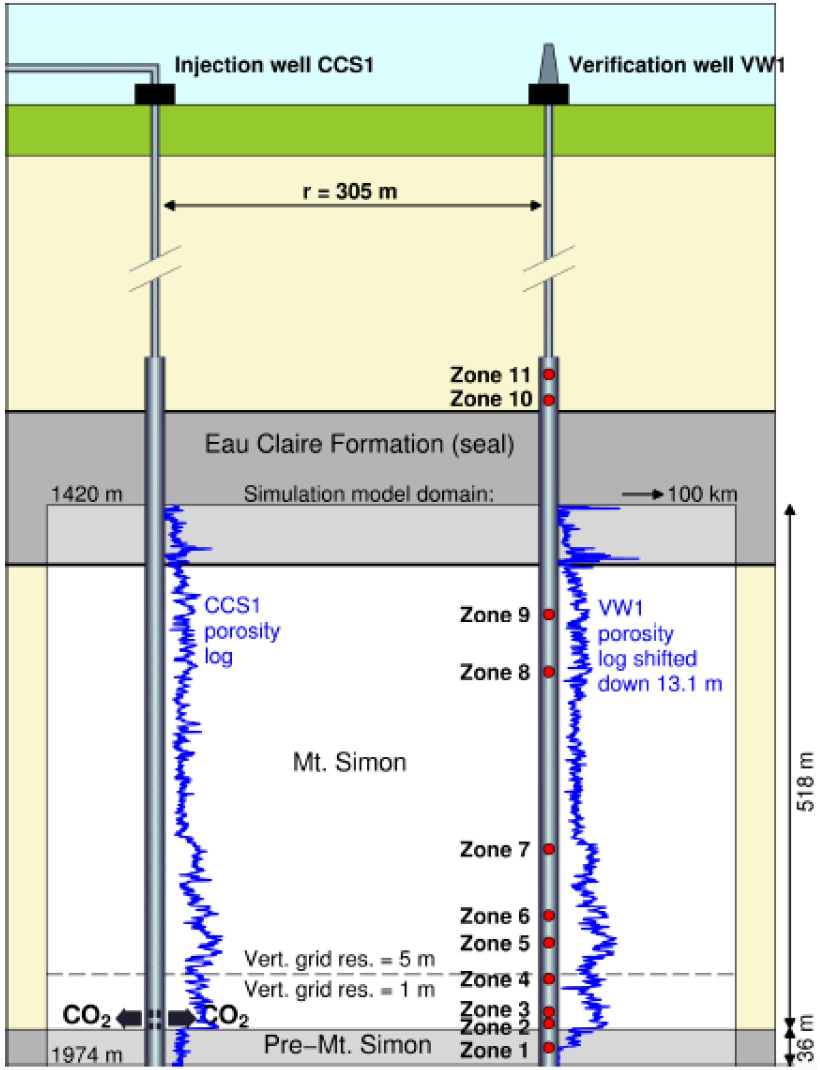
- Mathematical approaches for data assimilation and co-inversion.
- Strategies and technologies are needed for adaptive monitoring program that is site-specific and respond to changing needs and conditions
- Providing real-time data for tracking performance.



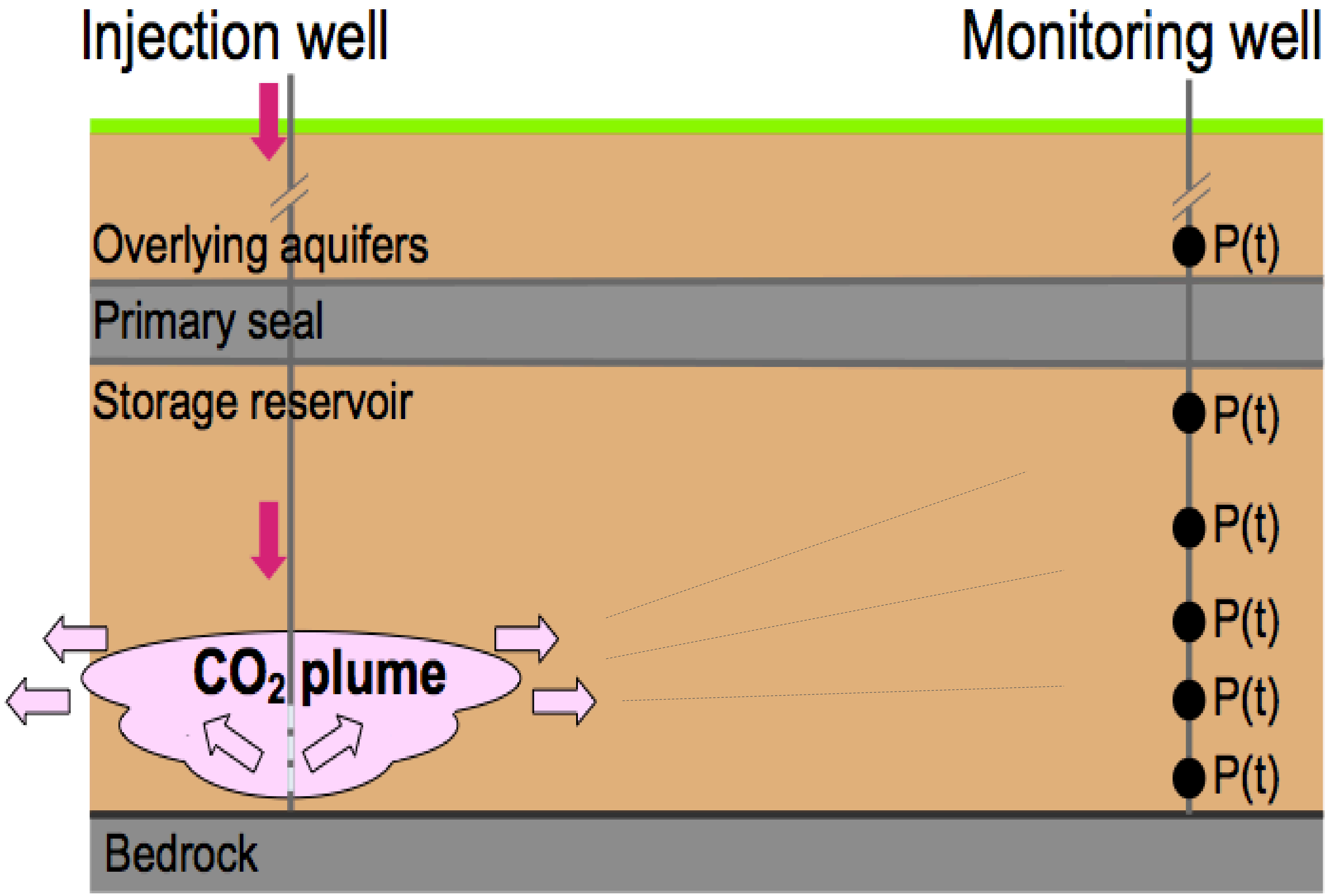
National Academy of Sciences, 2018.

Downhole Pressure Based Monitoring Approaches

- In reservoir pressure monitoring for plume migration
- Above-zone pressure monitoring for leakage detection
- Applications in the Illinois Basin Decatur Site



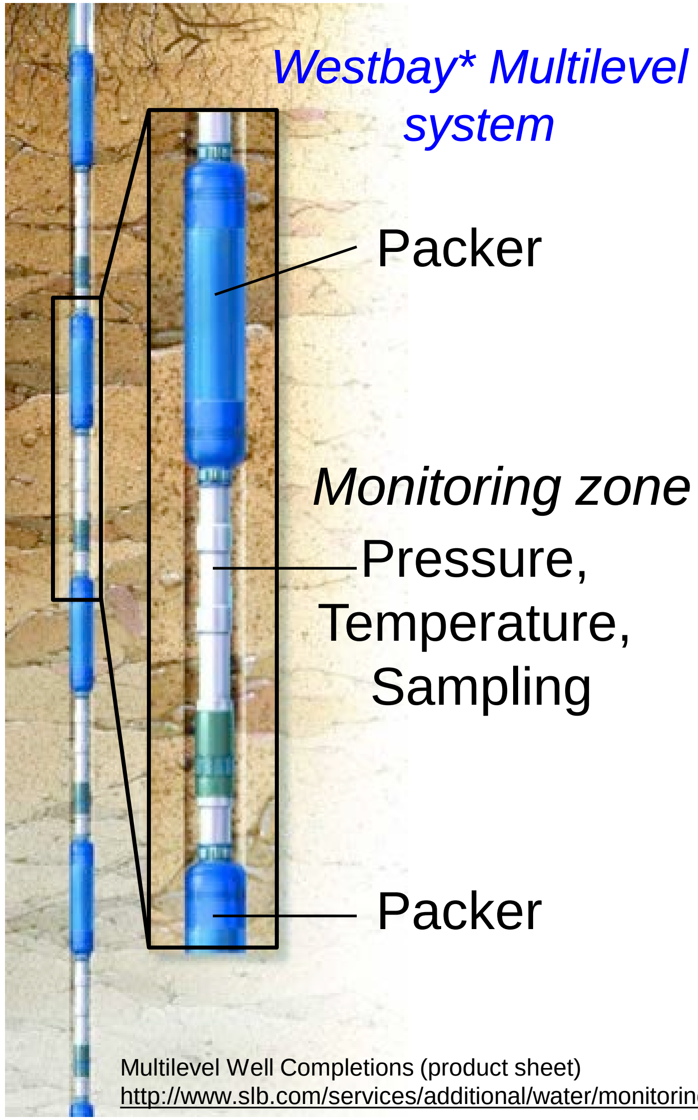
In Reservoir Pressure Monitoring



Above Zone Monitoring

In Zone Monitoring

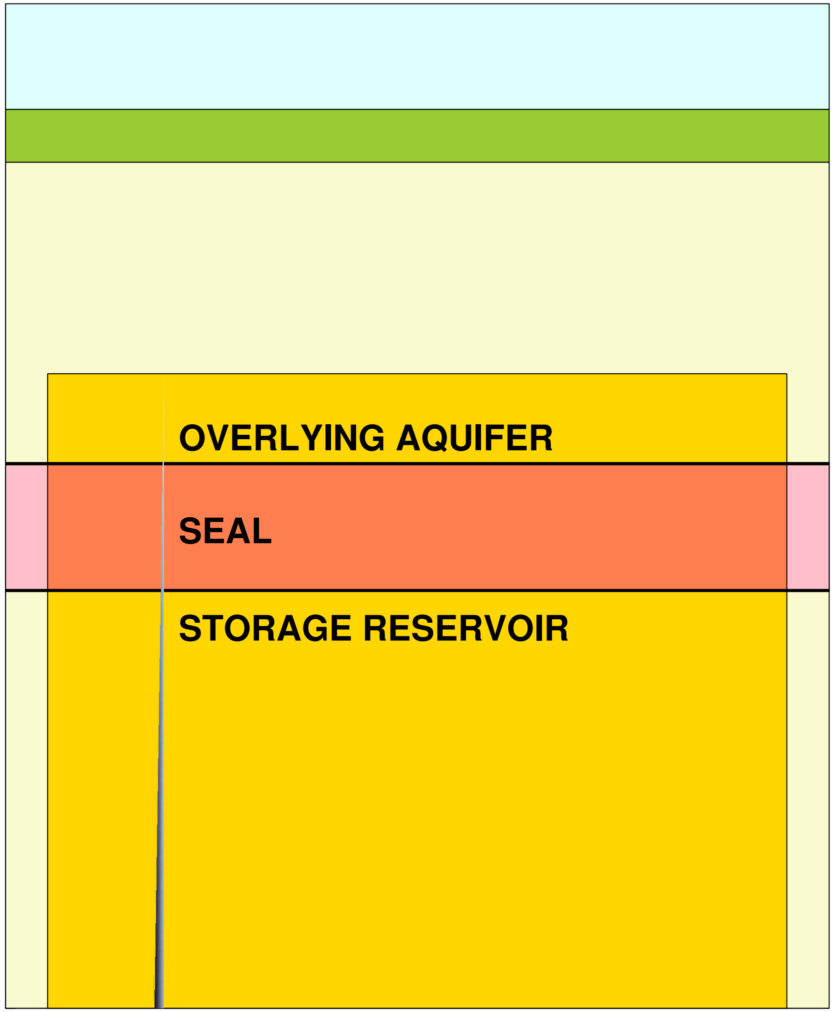
In Zone Pressure Monitoring



Hydrogeology	CCS
Studies emphasize value of: • Vertical pressure gradients • High-resolution monitoring E.g. Mercer and Spalding (1991); Parker et al. (2006); Fisher and Twining (2011)	Studies emphasize the value of: • Plume tracking • Reservoir structure

Multilevel Well Completions (product sheet)
http://www.slb.com/services/additional/water/monitoring/multilevel_well_system/well_completion.aspx

Diagnostic Study: Can In Zone Measurements Track Plume Migration?

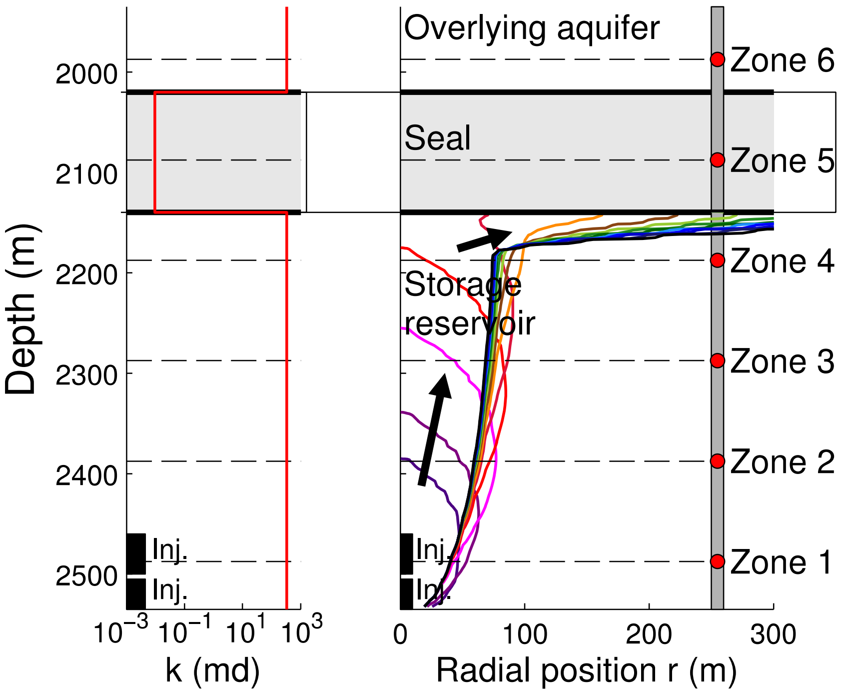


Strandli, C. W., & Benson, S. M. (2013). Identifying diagnostics for reservoir structure and CO2 plume migration from multilevel pressure measurements. *Water Resources Research*, *49*(6), 3462-3475.

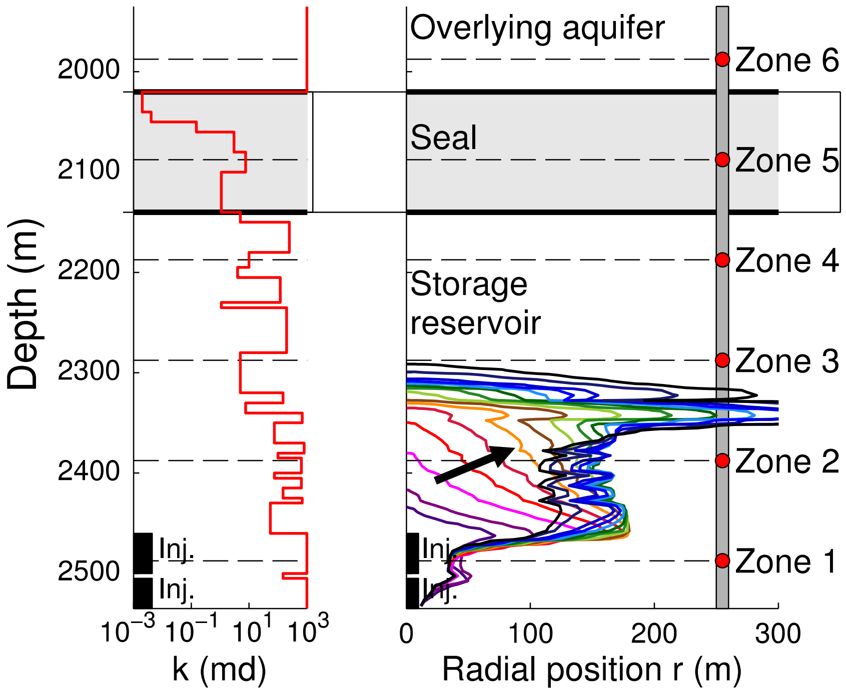
Different Reservoir Structures

	Homogeneous	Heterogeneous
Isotropic	X	X
Anisotropic	X	X

Homogeneous, isotropic scenario



Heterogeneous, isotropic scenario



Different Reservoir Structures

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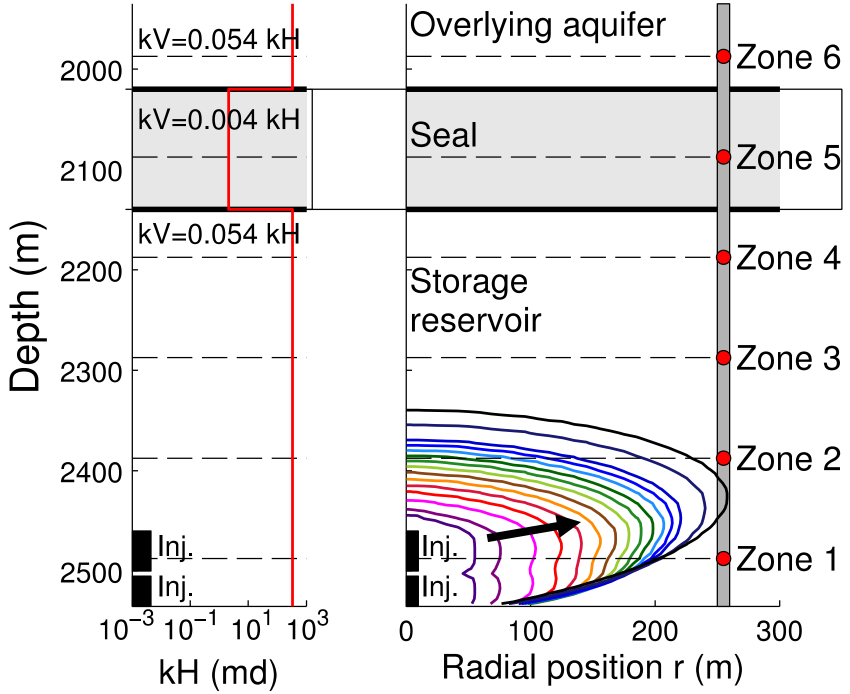
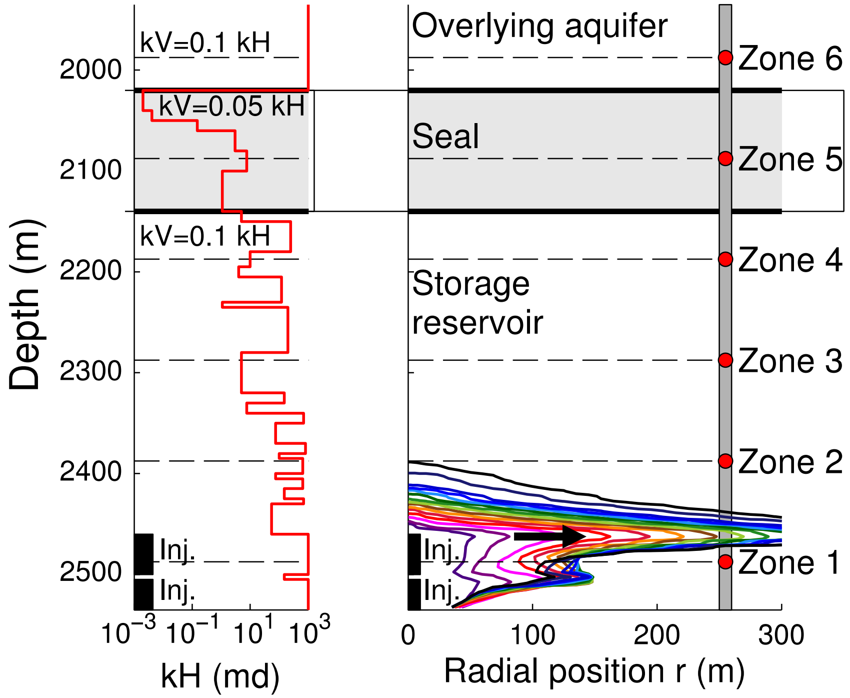
Isotropic	X	X
Anisotropic	X	X

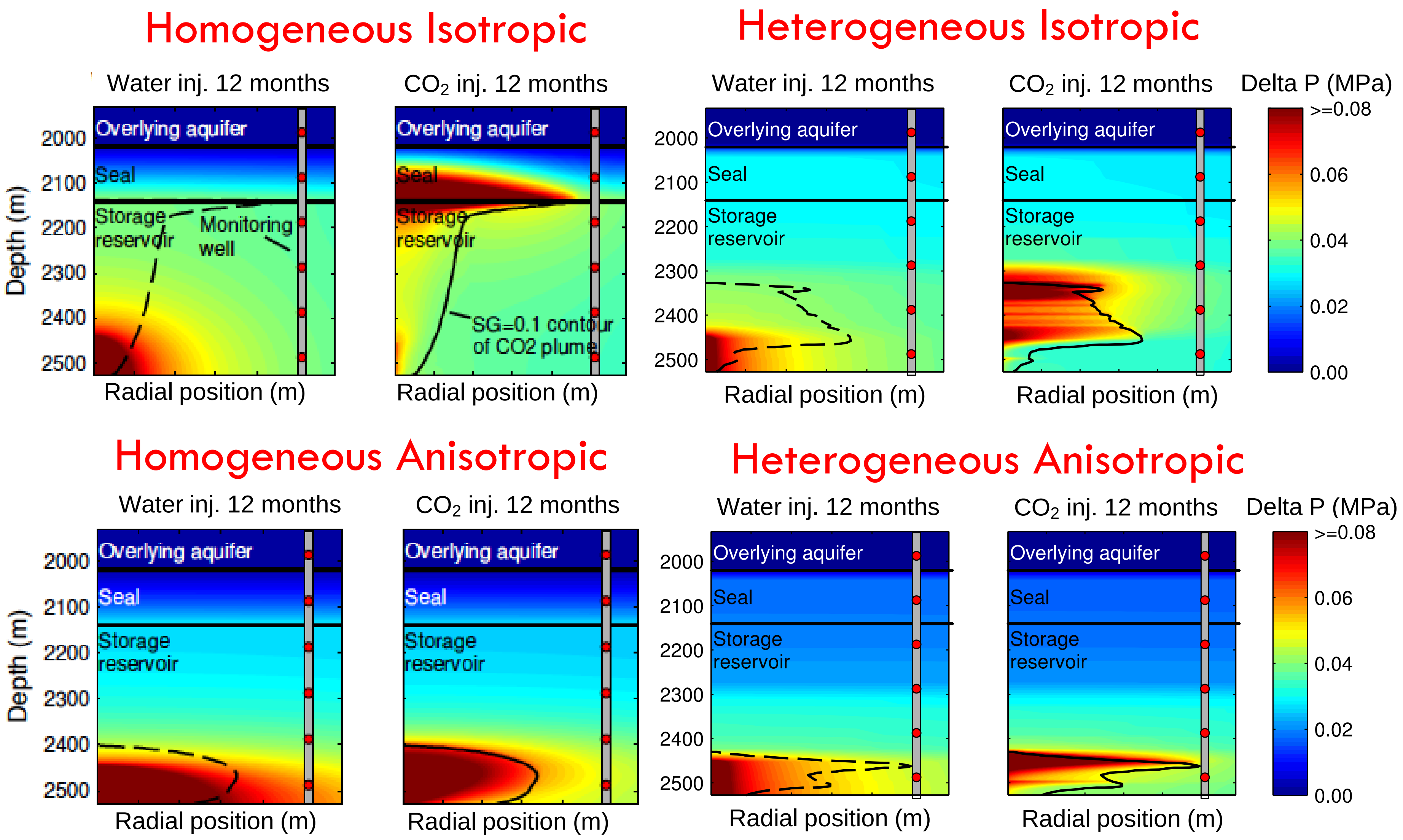
Homogeneous, anisotropic scenario



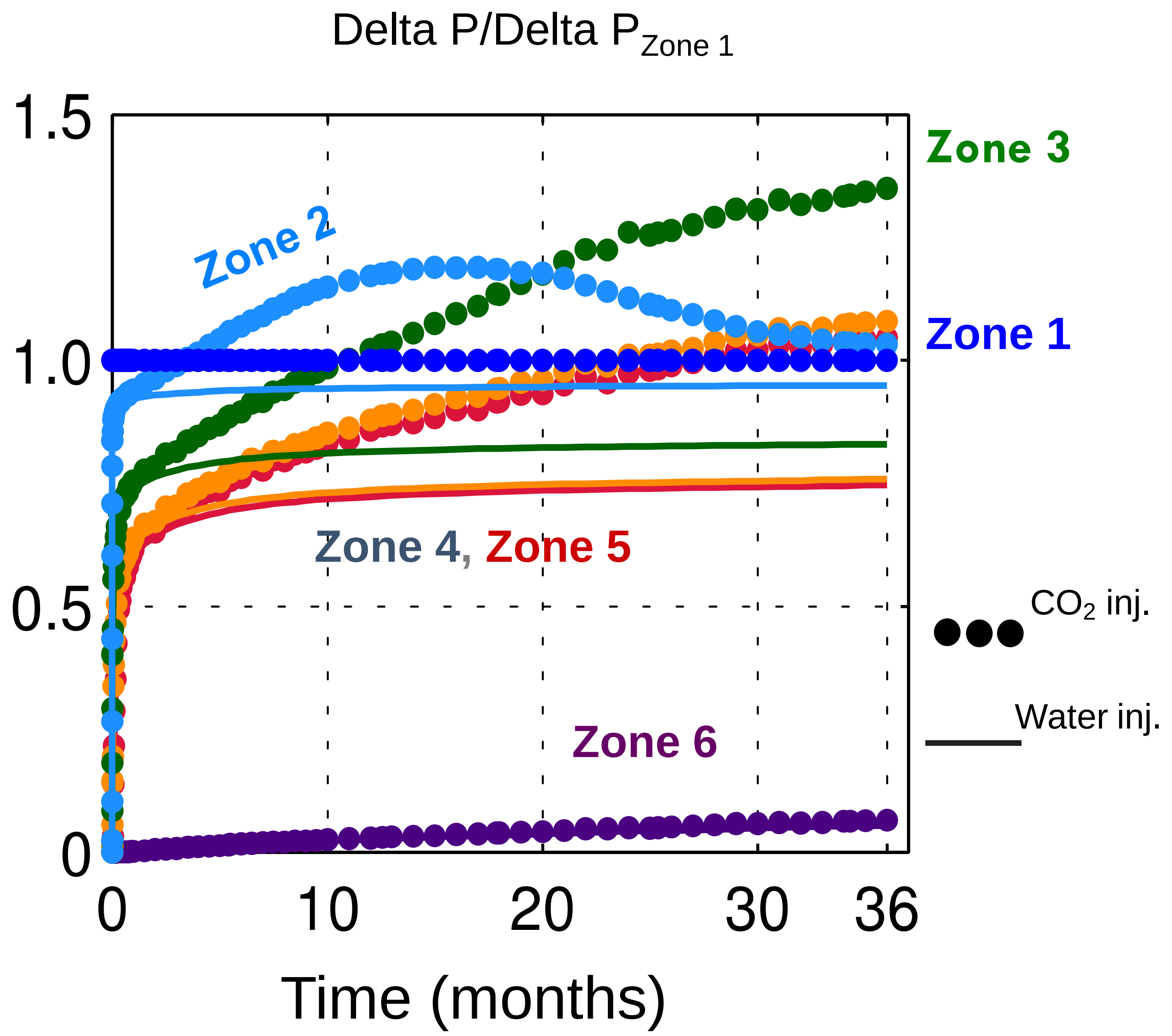
Heterogeneous, anisotropic scenario



Pressure Buildup Is Controlled By Reservoir Heterogeneity and Isotropy



Pressure Transient Behavior Diagnoses Height of the Plume

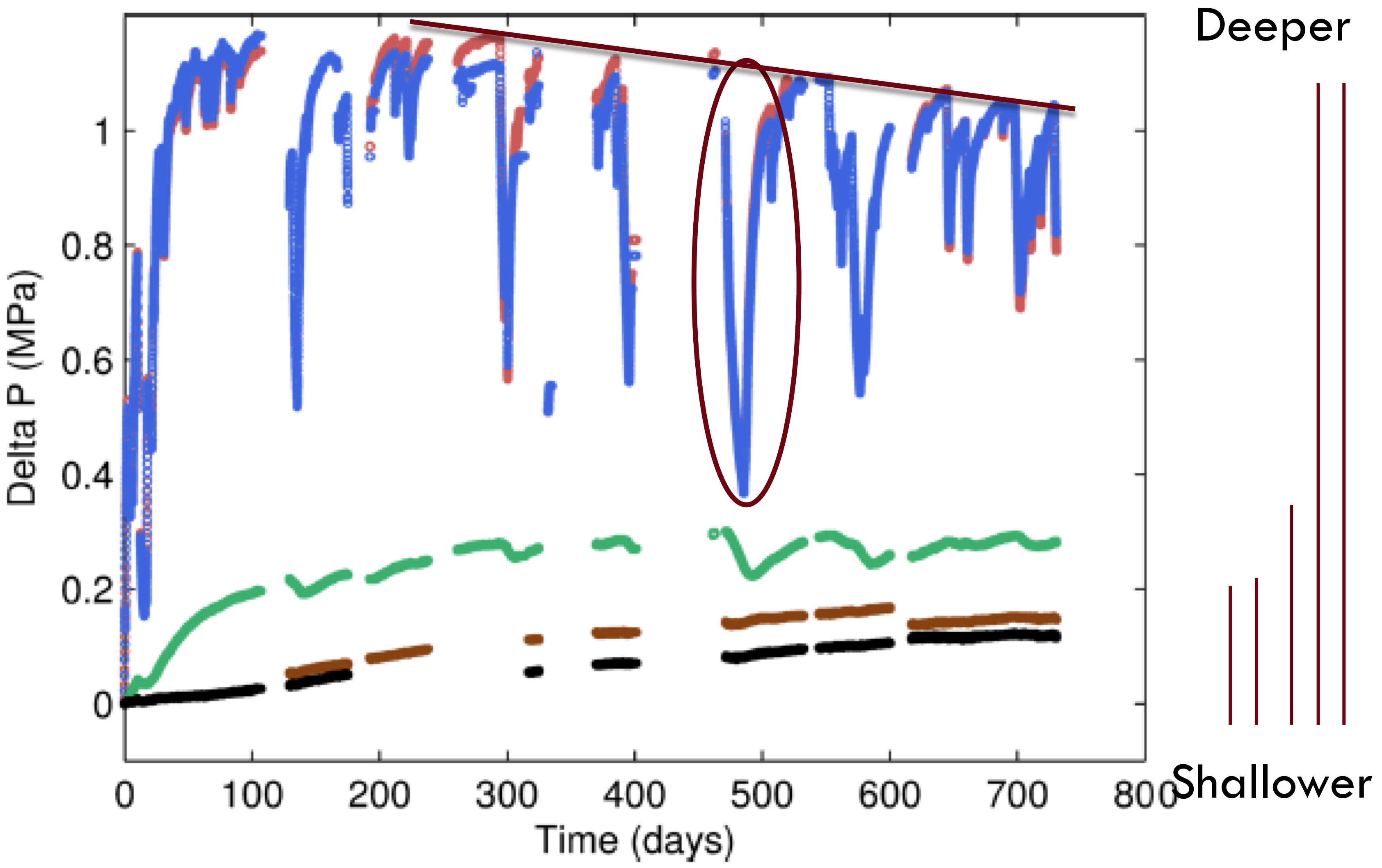


- Pressure buildups deviate from the behavior for water injection
- Pressure decreases indicate that the CO_2 plume has passed above the monitoring zone

Pressure Data from Monitoring Wells

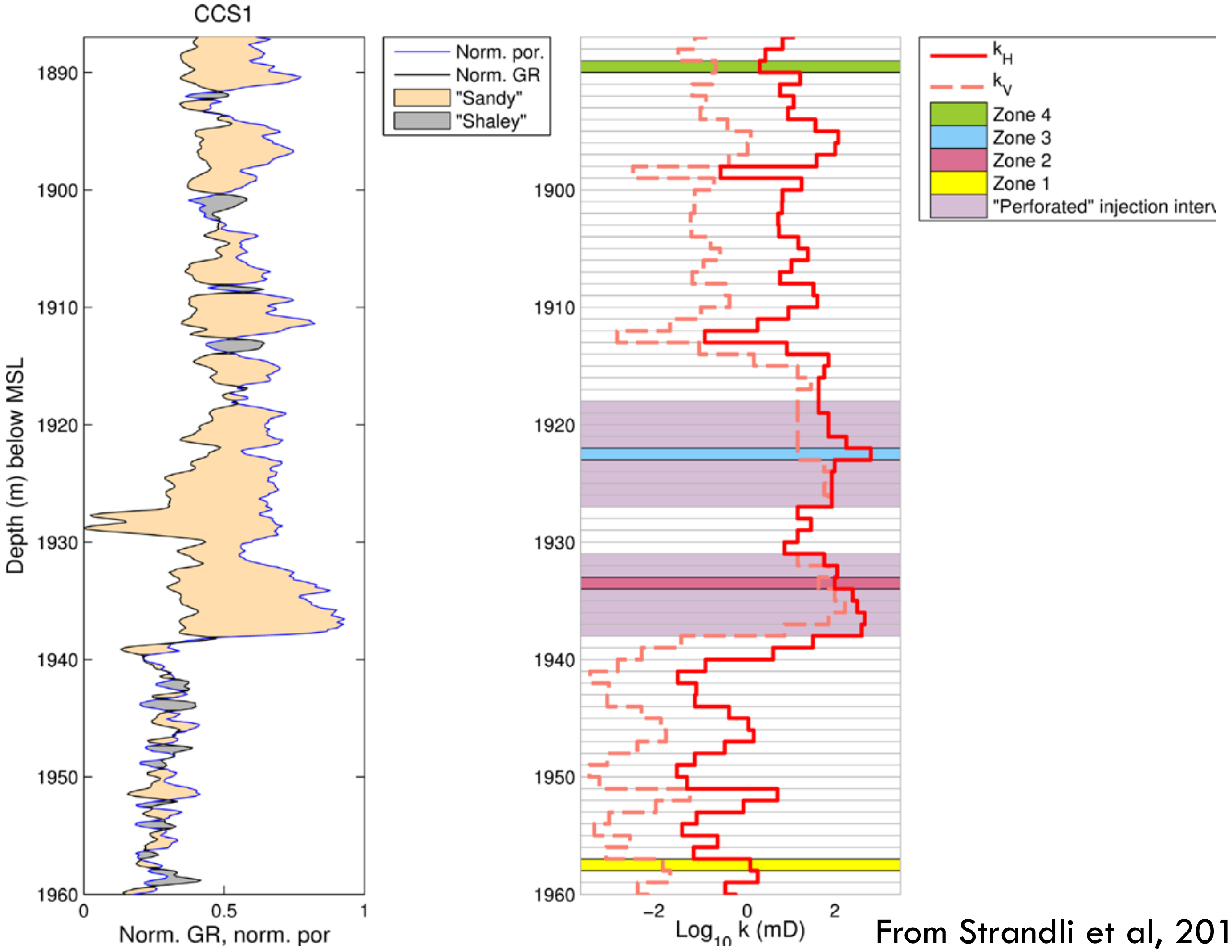
Three Diagnostics

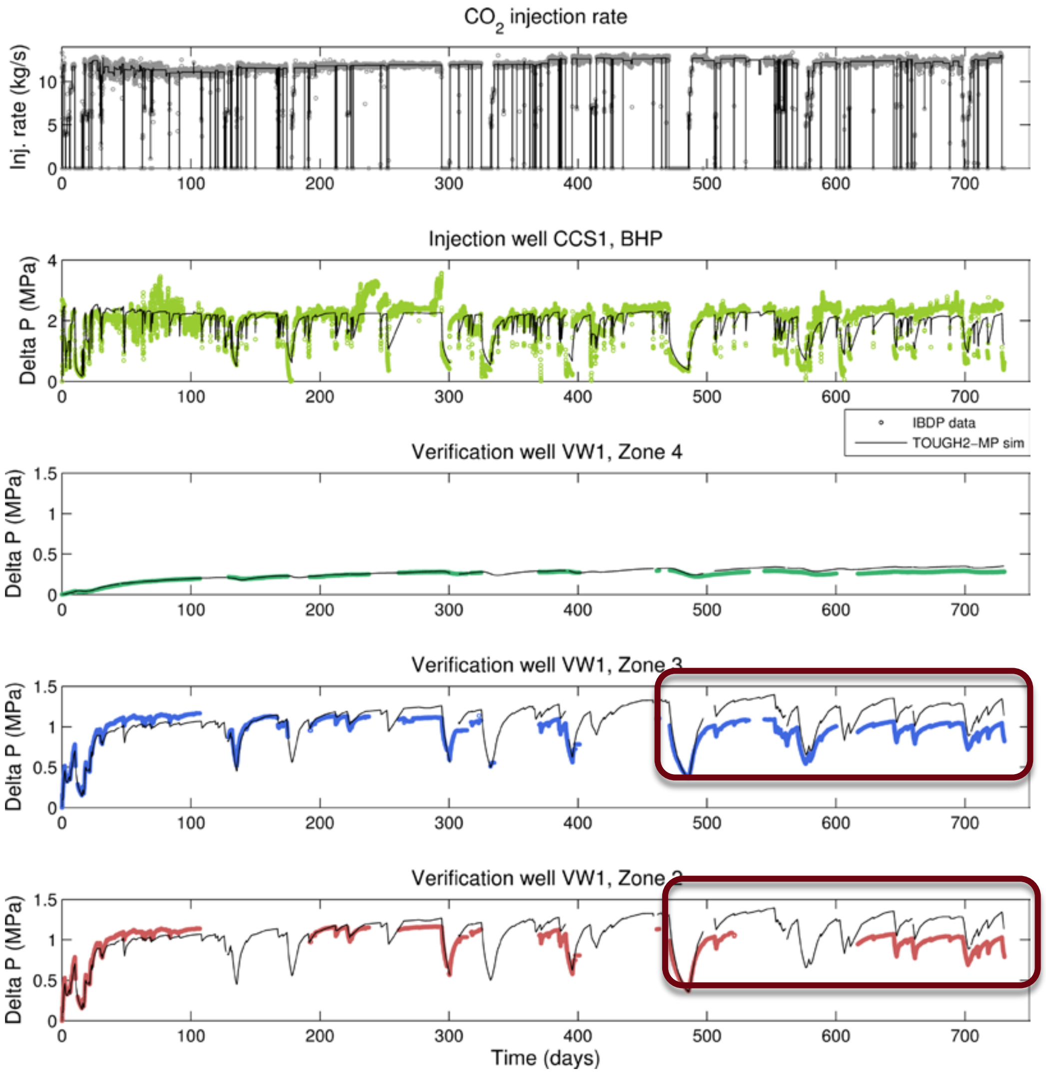
- Magnitude of pressure buildup
- Amplitude of response to injection fluctuations
- Decline in pressure buildup over time



Strandli and Benson, IJGGC, 2013.

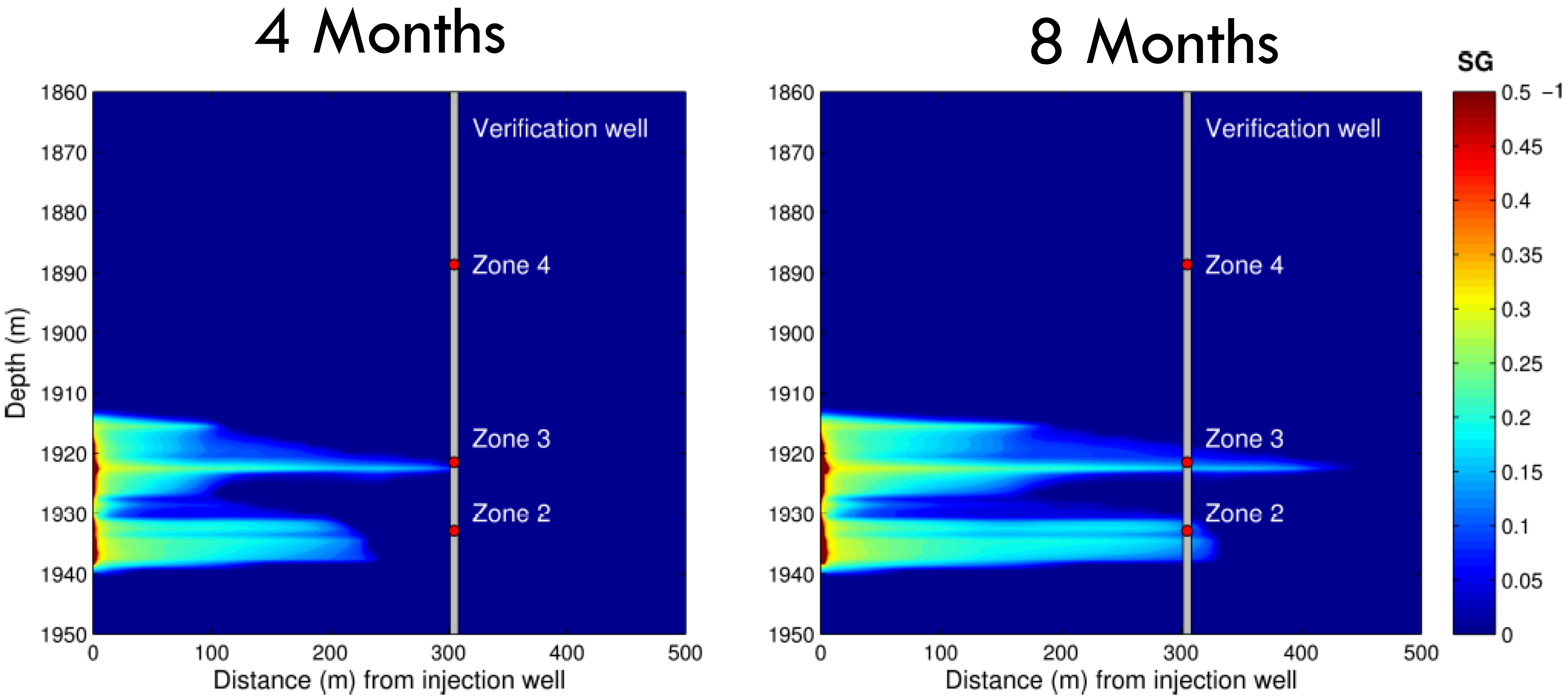
History Matching of Pressure Data



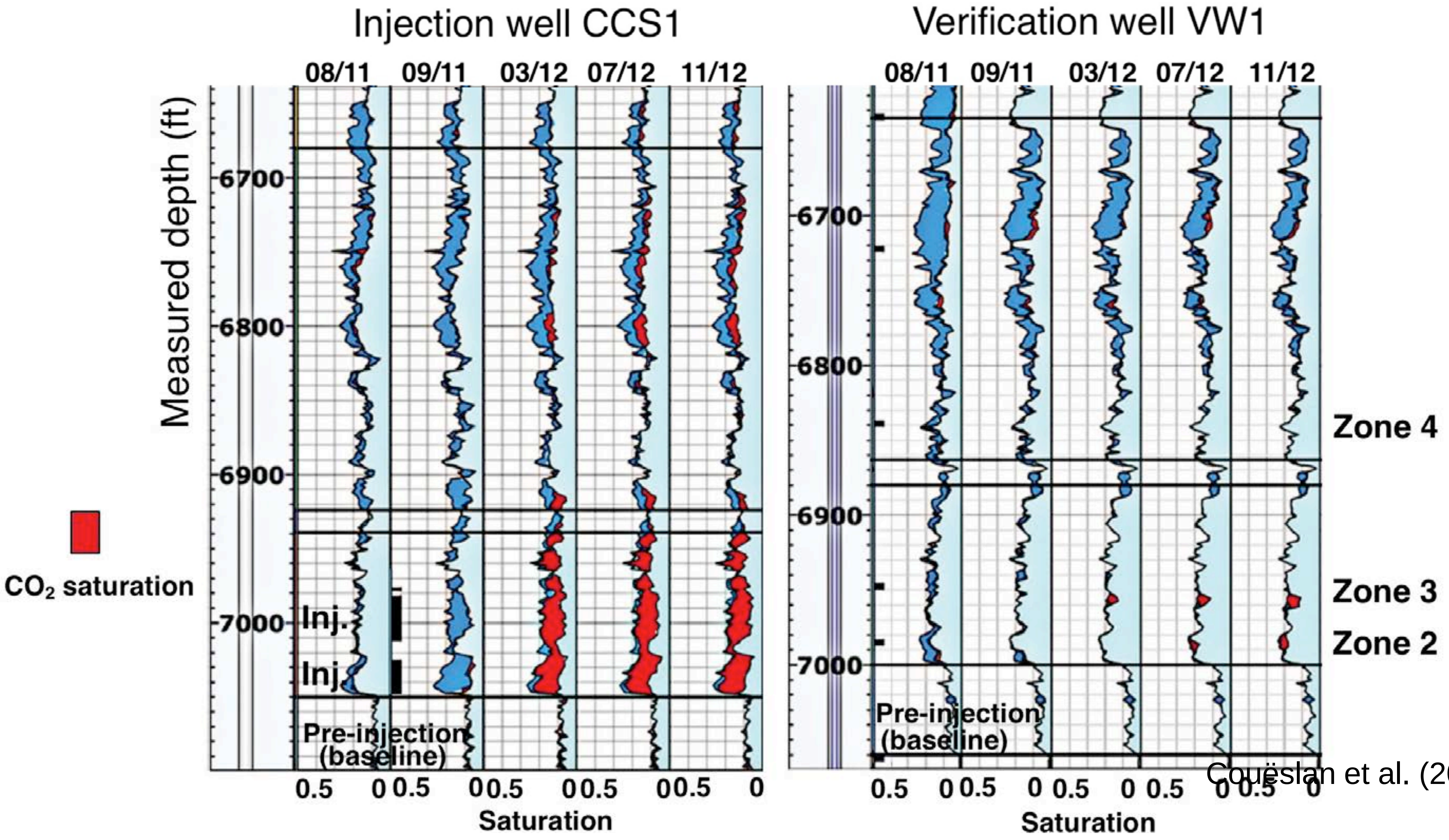


From Strandli et al, 2014

Plume Migration Predictions

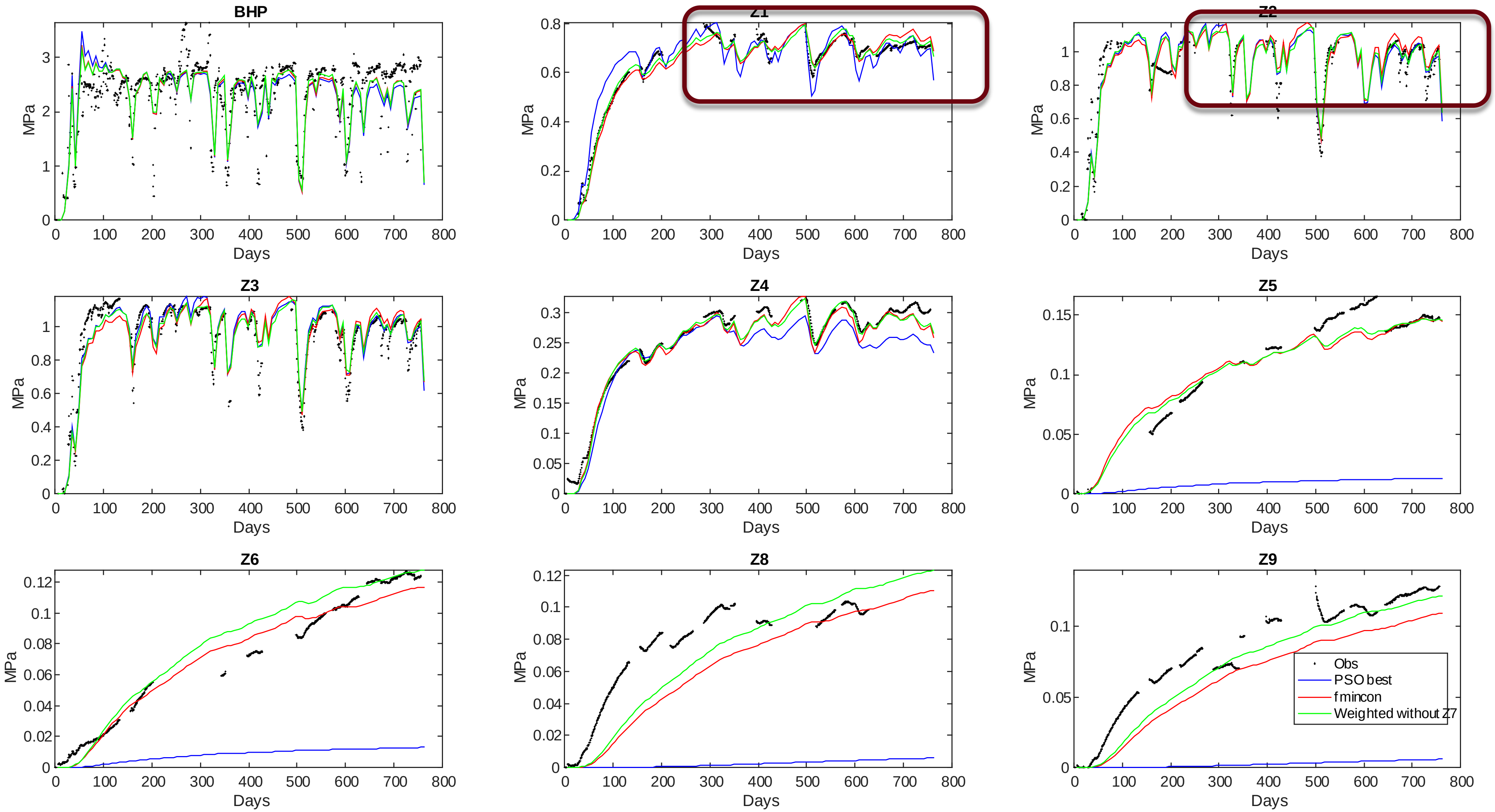


Measured CO_2 Saturation Agrees Well With Predictions



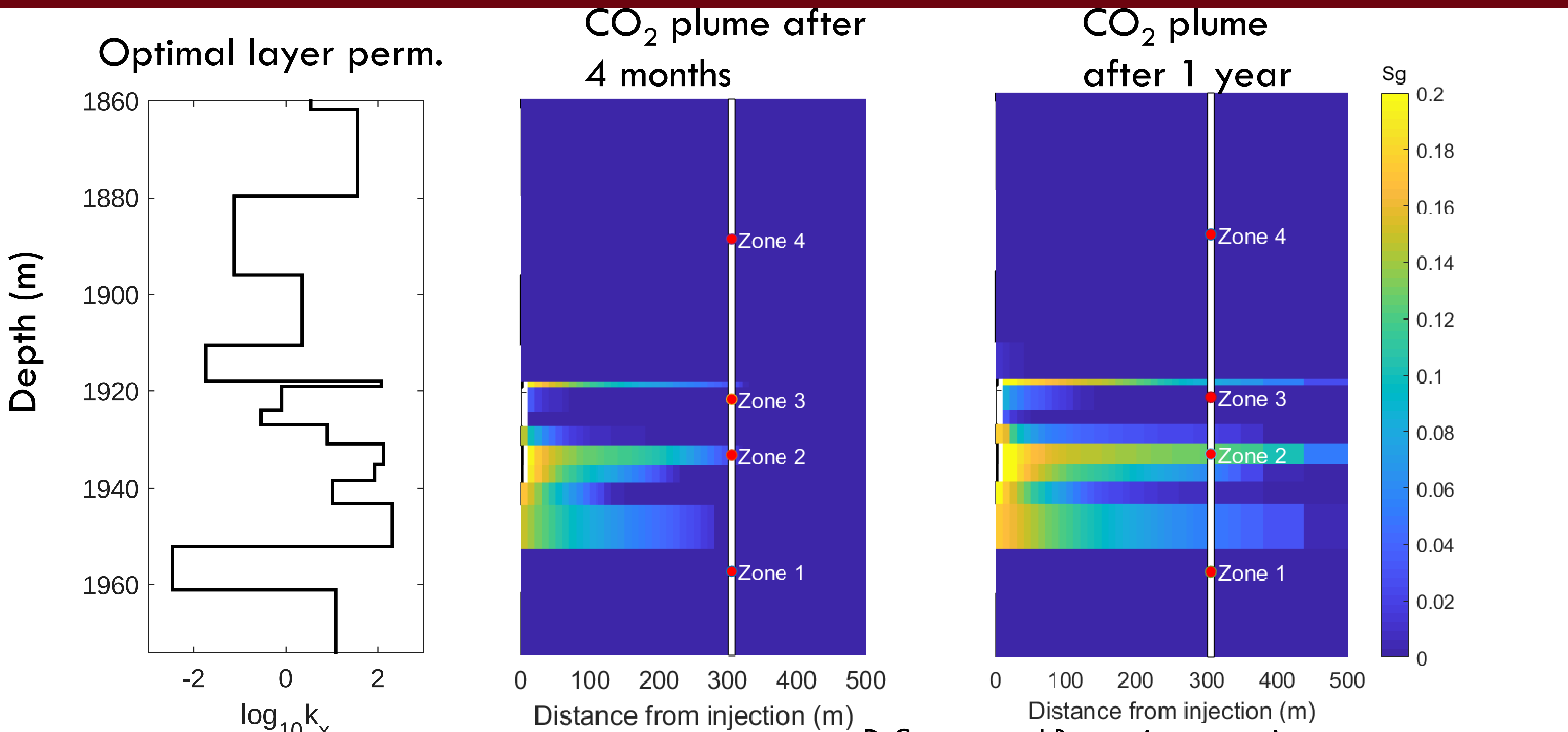
Couëslan et al. (2014)

Automated Inversion of Pressure Data



D. Cameron and Benson, in preparation.

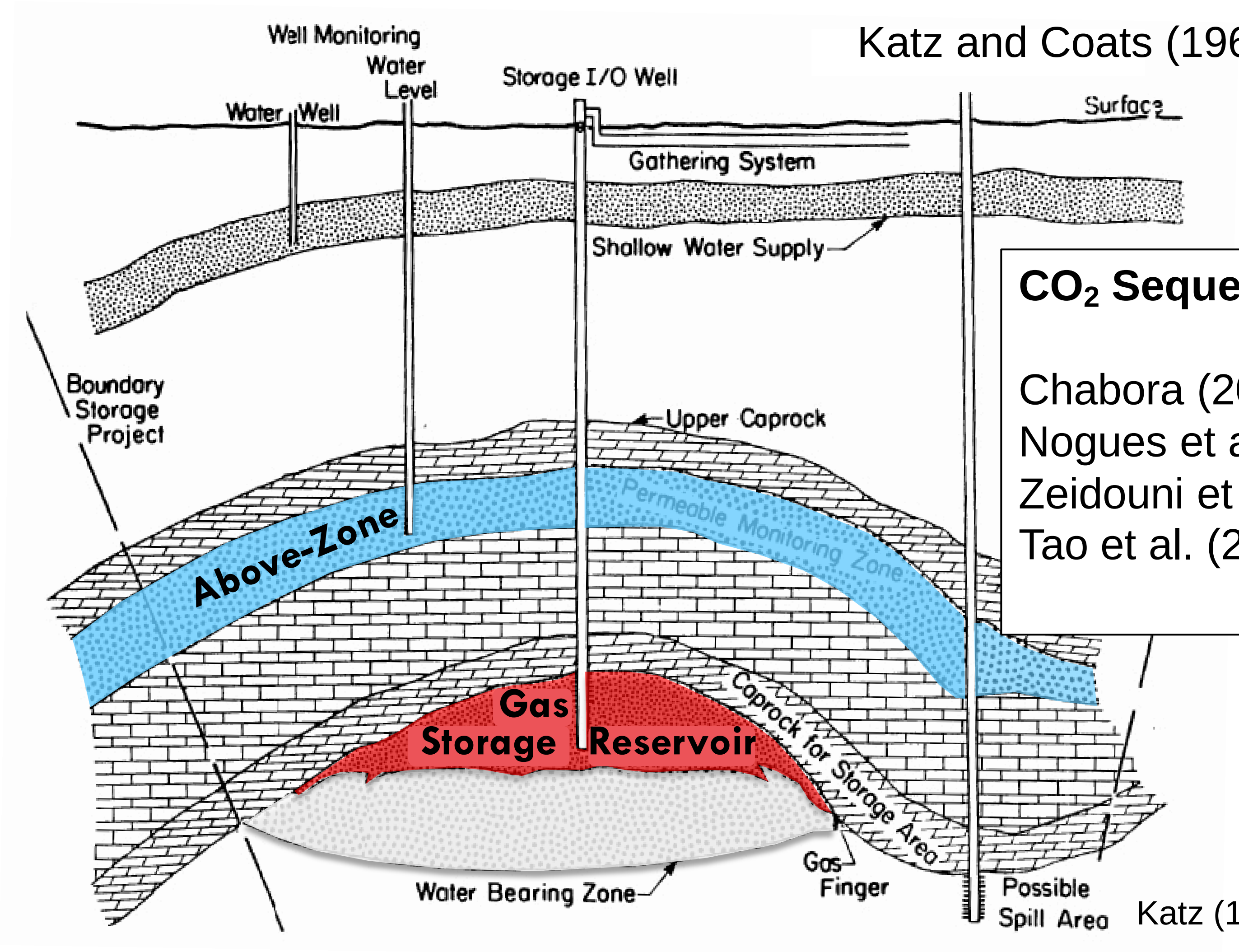
Automated Inversion Plume Migration Predictions



D. Cameron and Benson, in preparation.

Above-Zone Pressure Monitoring

Katz and Coats (1968)

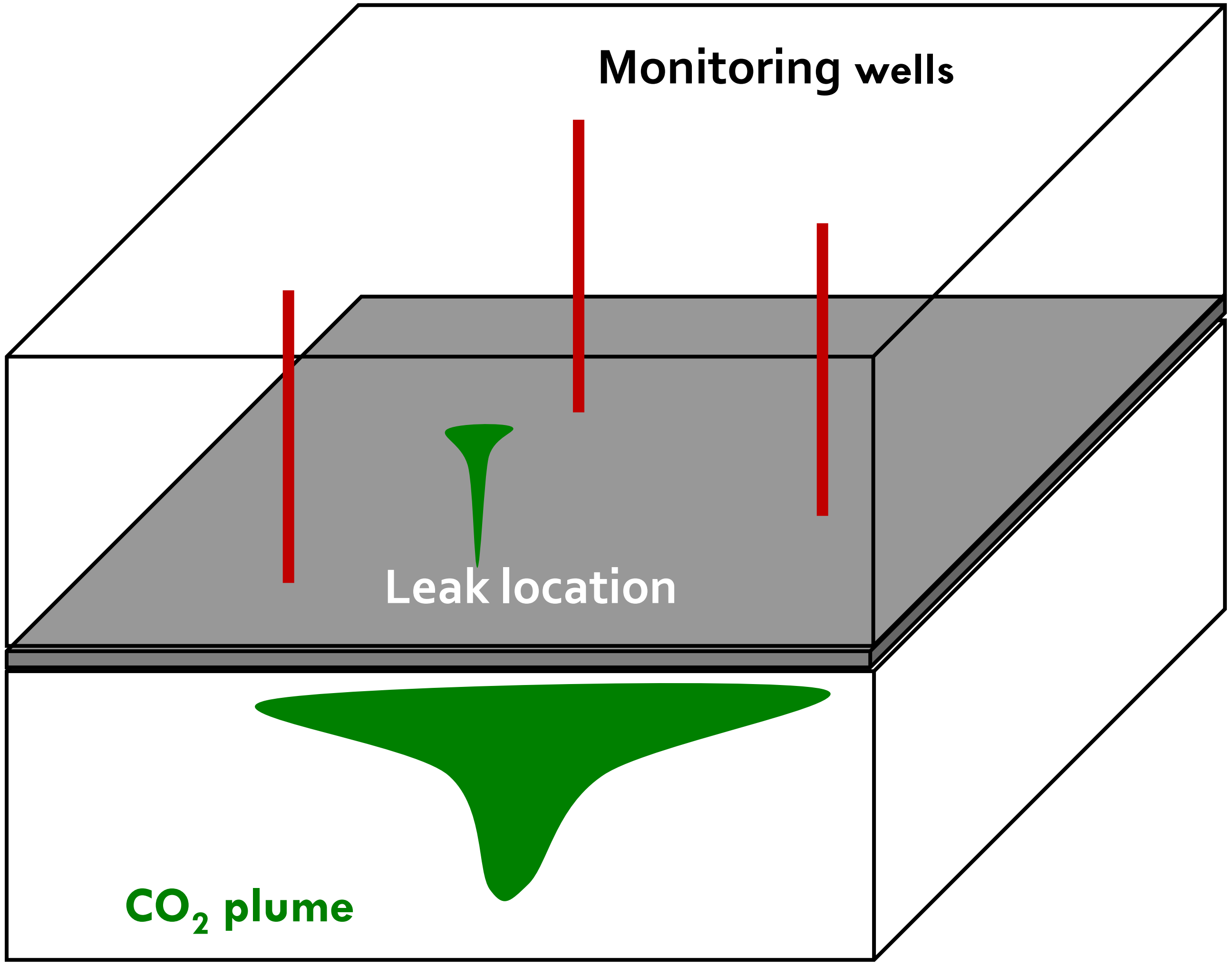


Katz (1971)

CO_2 Sequestration:

Chabora (2009)
Nogues et al. (2011)
Zeidouni et al. (2011)
Tao et al. (2012)

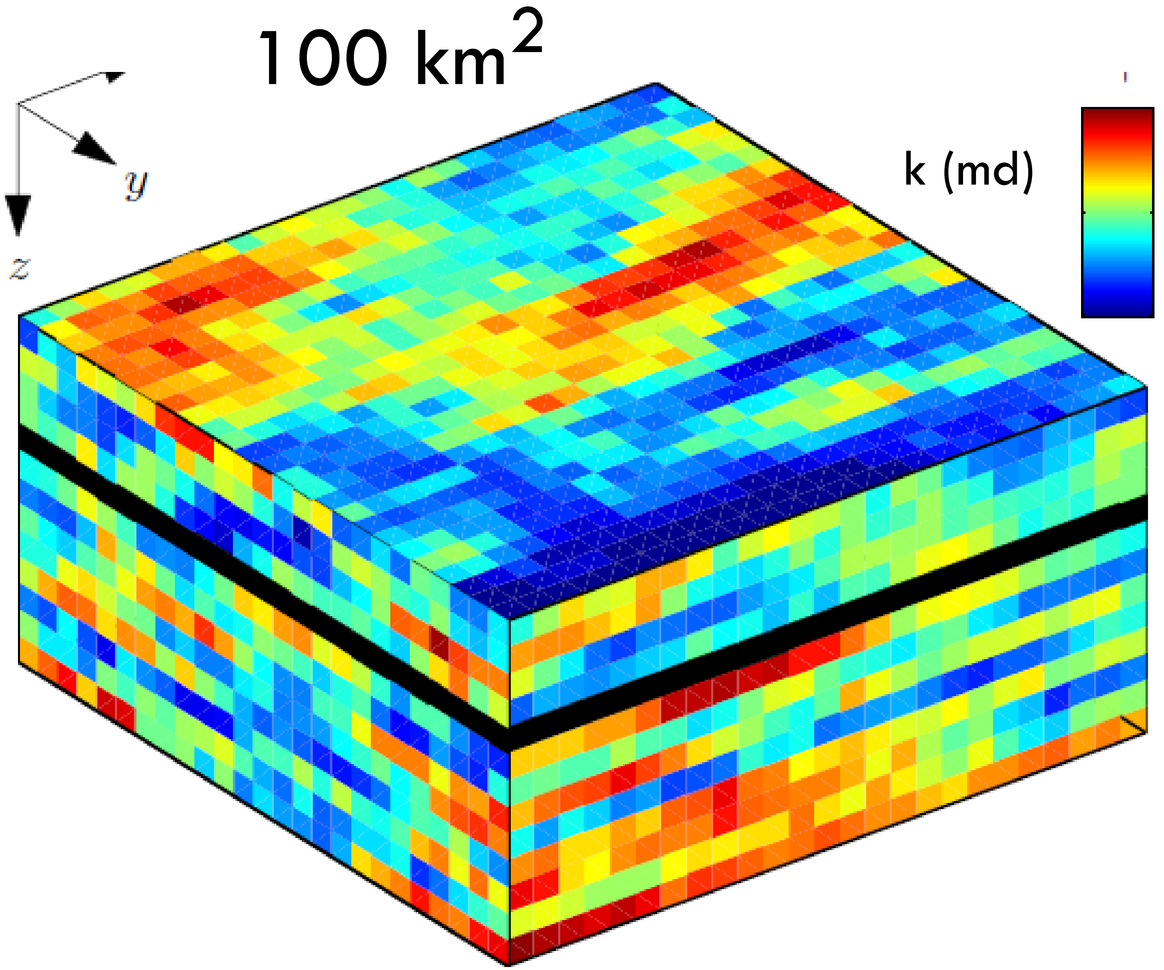
Above Zone Pressure Monitoring for Leakage



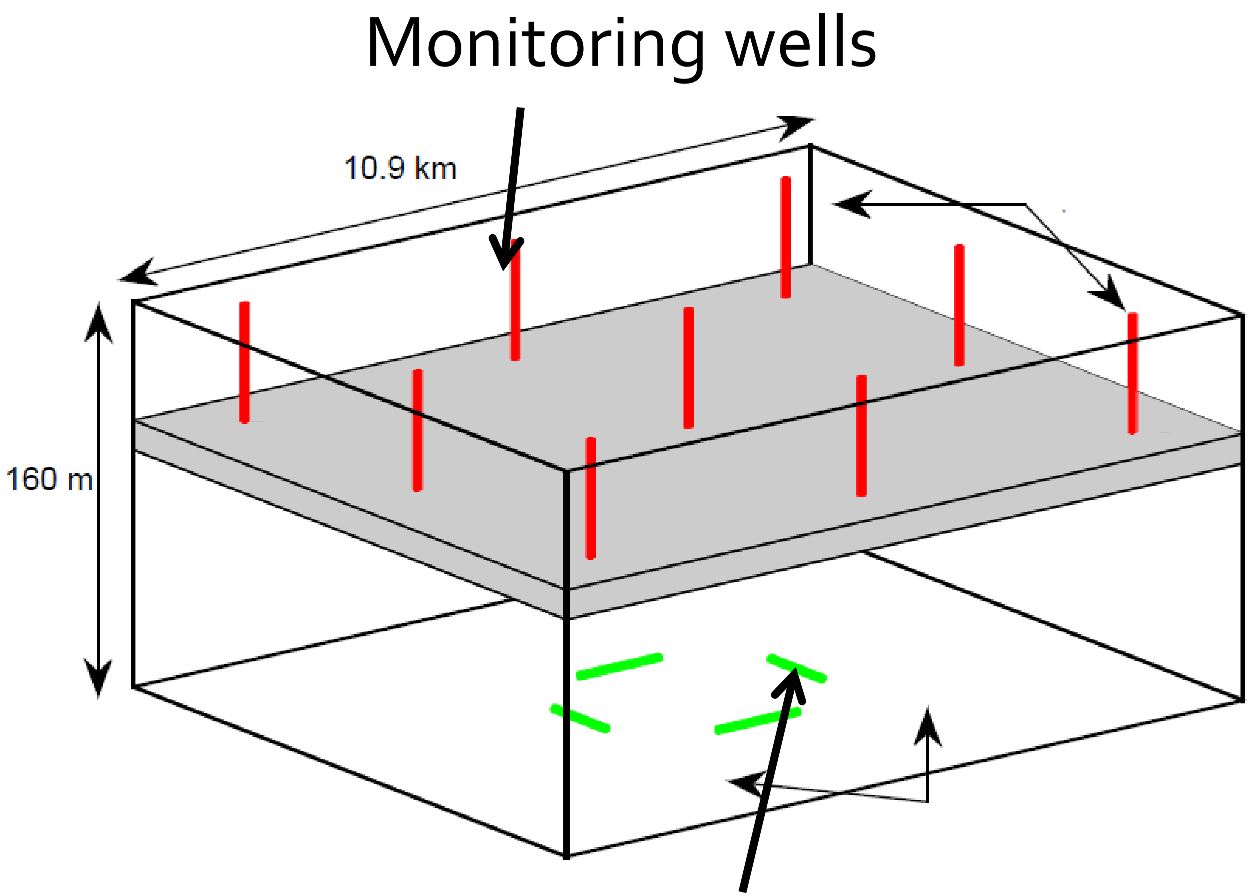
- Where is the leak?
- How much is leaking?

[Cameron, D. A., Durlofsky, L. J., Benson, S. M, 2016]

Heterogeneous Model and Monitoring Wells



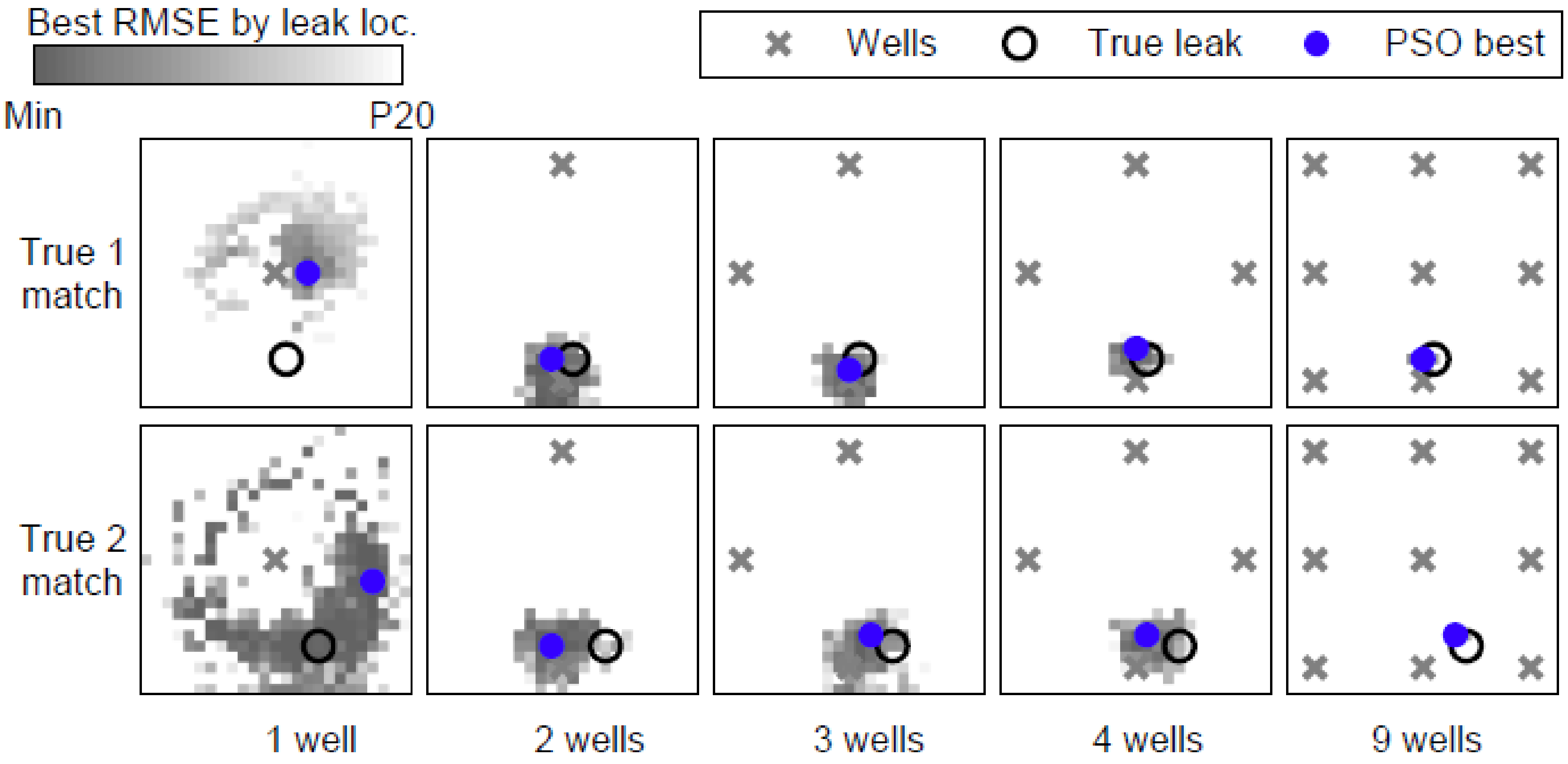
Simulation model



Five Scenarios Tested

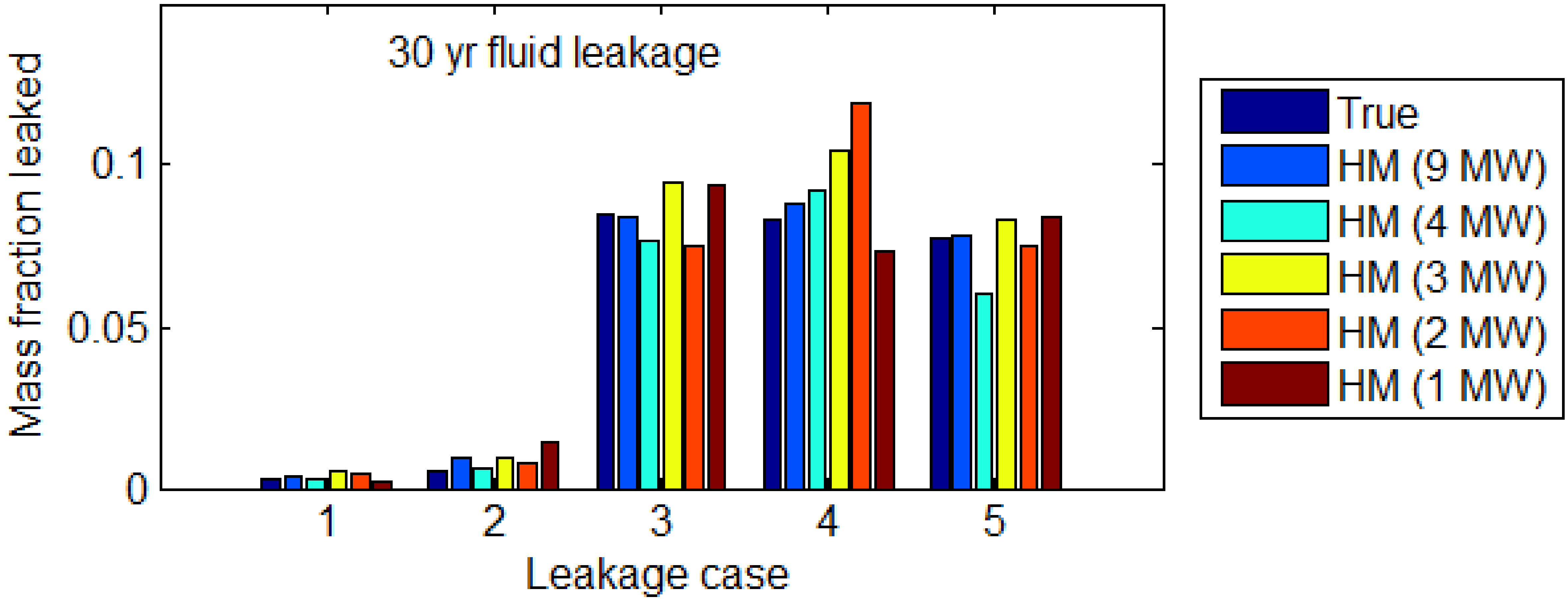
	500-yr CO_2 leakage	30-yr brine leakage
True 1	0.7%	0.3%
True 2	3.3%	0.5%
True 3	7.5%	8.5%
True 4	13%	8.3%
True 5	23%	7.8%

Simulations Indicate Above Zone Monitoring is Highly Effective

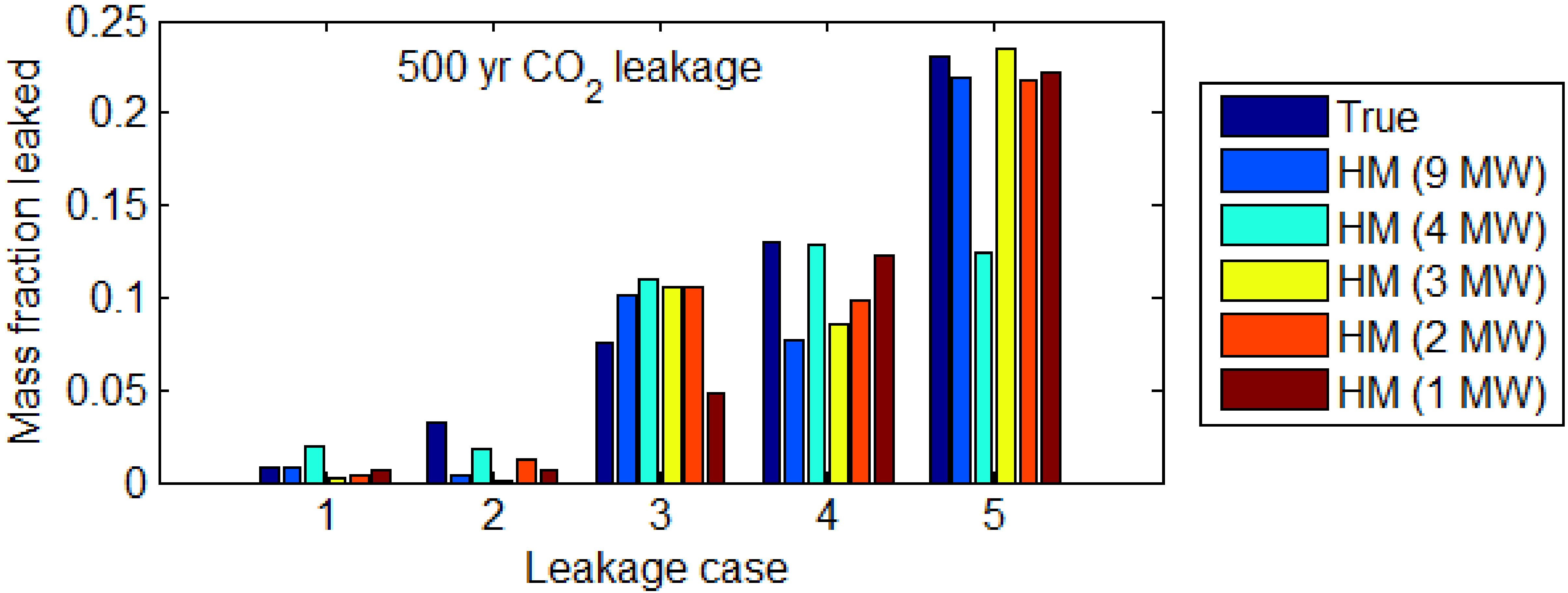


- Leak detection occurs quickly (< 1 year)
- Leakage location detection requires 3 wells

Fluid Leakage: 30 years



500 Year CO_2 Leakage



Final thoughts

Benefits of monitoring >> costs

- Difficult to quantitatively assess benefits for monitoring
  - Financial risk mitigation from leakage or damages
  - Societal engagement and transparency
  - License to operate
- Many monitoring techniques are available
  - Need to develop integrated packages with highest value
  - While, keeping costs low
- Real time awareness of project status a priority
  - Permanently emplaced arrays of sensors (pressure, seismometers)
  - Automated data inversion and interpretation