Monitoring Geologic Storage of CO_2 for CCS to Document Permanence

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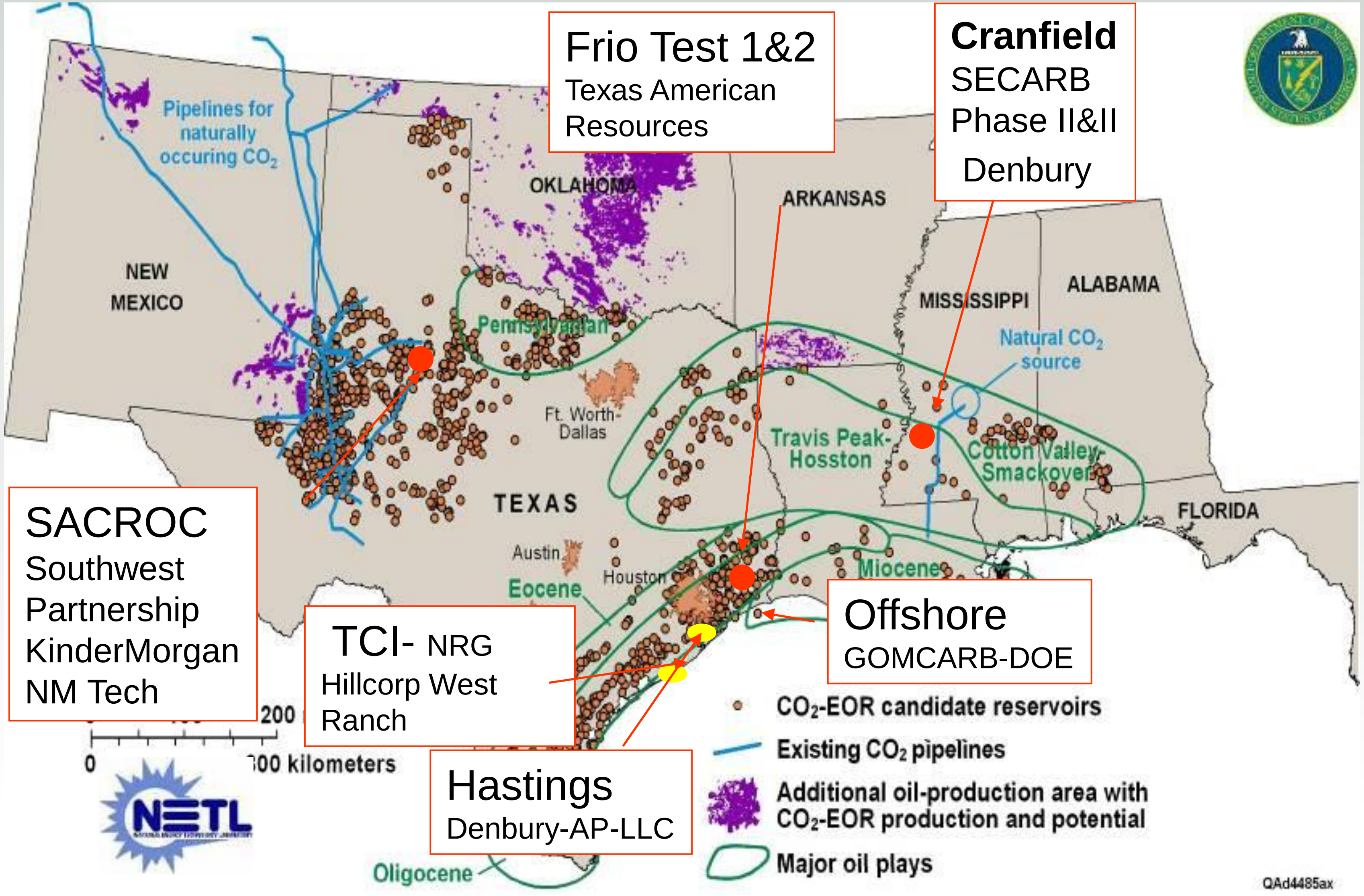
Geologic storage in deep saline formations Main Points:

- Large volume, high quality permanent storage of CO_2 to isolate it from the atmosphere.
- Confidence in the quality and permanence
  - site selection
  - modeling matching the capacity of the site to the rate and volumes of CO_2 to be injected
  - monitoring the response of the subsurface to injection to confirm the correctness of the model and make any during-operation corrections.

GCCC Field Research 2004 to 2020

- Founded in 1998
- Industrial Associates: Industry-academic program
- Conduct research and outreach in geologic storage technologies used to reduce emissions of CO_2
- Focus on very large volume storage in short time frames: Suitable geology where there is short term need.
- Field work and application oriented
- Stored approx. 11 Mt, monitored >100Mt and screened hundreds of sites



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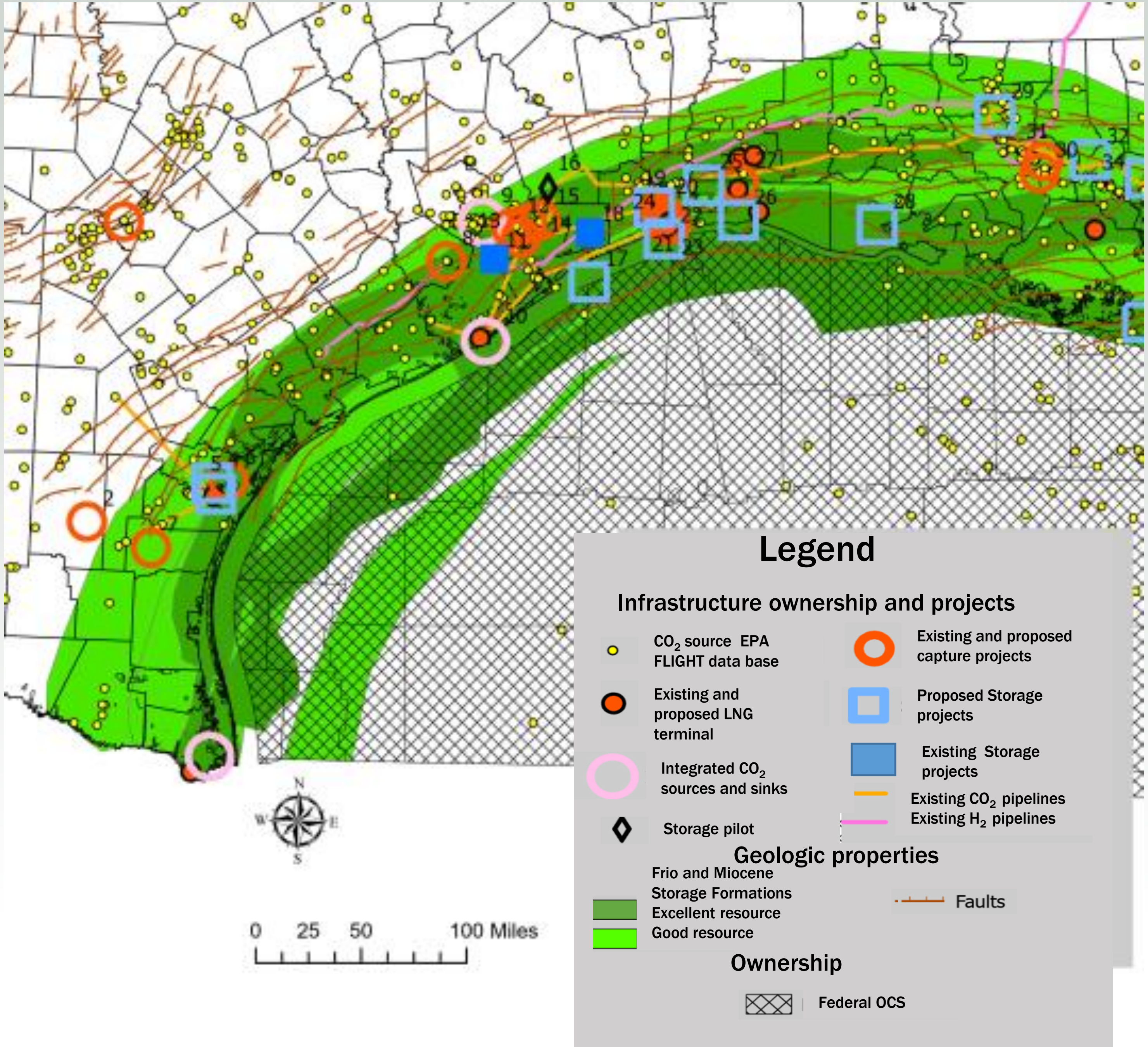
Announced CCUS Projects 1-2023



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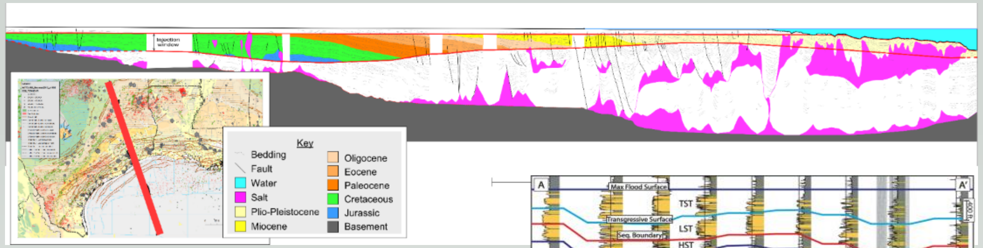
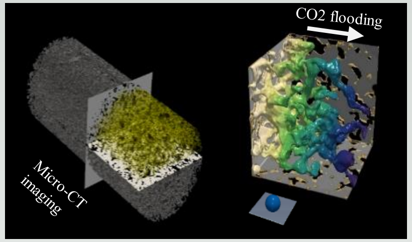
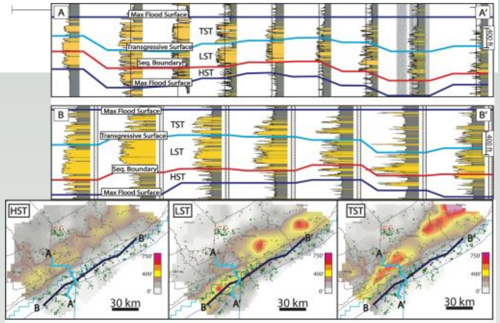
The Gulf Coast Carbon Center (GCCC) seeks to impact global levels of atmospheric carbon dioxide by:



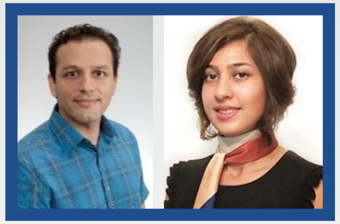




- Conducting studies on geological sequestration, retention and monitoring of CO_2 in the deep subsurface, focusing on the US Gulf Coast
- Educating the public about the process of geological CO_2 sequestration, the risks and mitigation measures associated with deployment
- Enabling the private sector to develop an economically viable industry to sequester CO_2 in the Gulf Coast region, across the US and ultimately globally

GCCC Research Staff

Fluid Flow Modeling



Seyyed Hosseini, Sahar Bakhshian

Surface/Deep Monitoring

Hailun Ni, Katherine Romanak, Susan Hovorka

Geologic Characterization

Carlos Uroza, Alex Bump, Timothy Meckel, Tucker Hentz, Mariana Olariu

Seismic Interpretation

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Economics and EJ

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Charles Jenkins CSIRO, Australia

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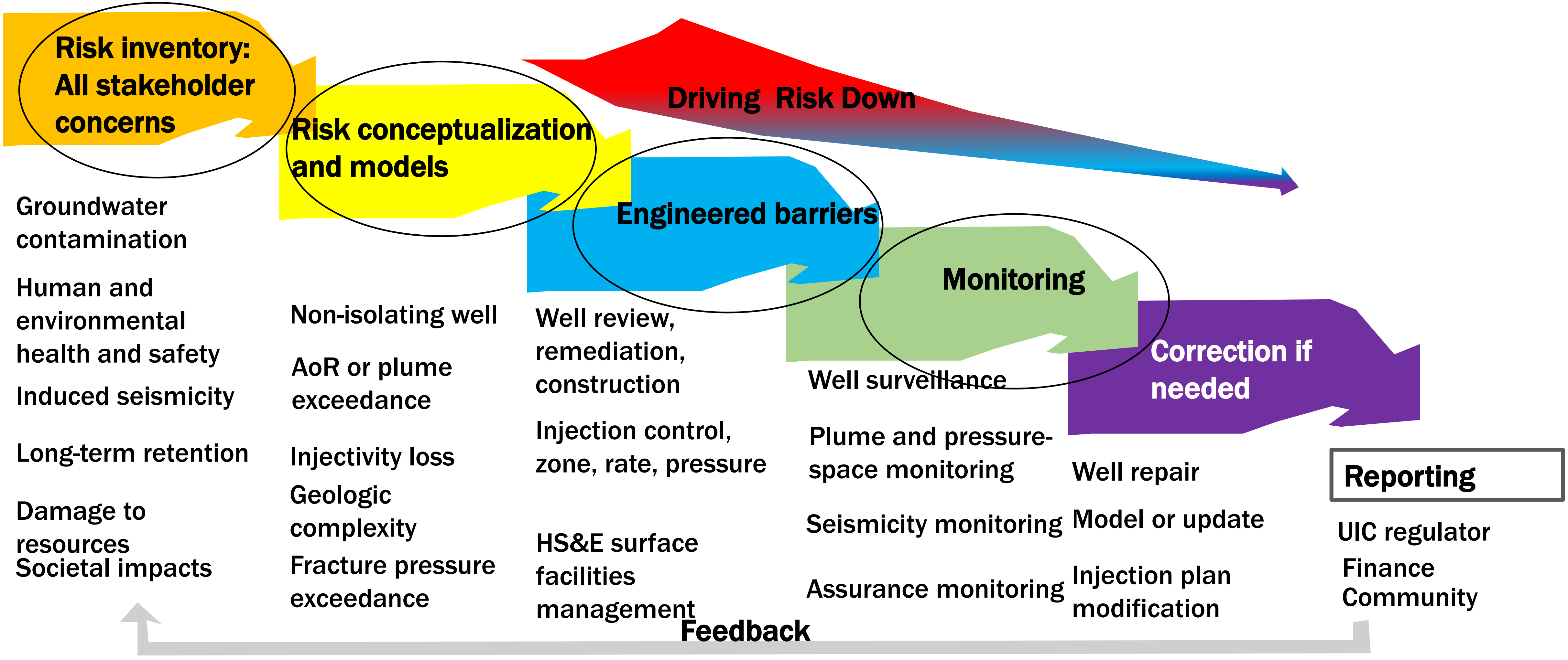
Geologic Storage is Intrinsically Secure

- Layered systems – multiple barriers
- Storage in porous media – trapping by capillary forces in pores throats
  - 20-60% is trapped in one volume
  - 100% will be trapped during migration via porus media
- Wells engineered to provide zonal isolation
  - Historic good performance

Monitoring is a double check on intrinsic storage value

Monitoring CO_2 Storage for Risk Avoidance



Purposes of Monitoring

1) Required by regulation – part of permit application and compliance
2) Monitoring to update fluid flow models
3) Monitoring to reduce risk

All three purposes are fundamentally motivated by risk reduction

focus on the idea of monitoring to systematically reduce project risks

High level material impact catalog

Impact	Monitoring
Capacity more limited than expected - pressure exceeds rock/well completion strength/ geomechanical stability field	Surface + at least intermittent downhole pressure at injection well
CO_2 plume grows beyond AOR encounters transmissive fault, fracture system non-isolating well, or impinges on another subsurface use	Monitor extent of CO_2, confirm model
Elevated pressure area grows beyond AOR and encounters transmissive fault, fracture system non-isolating well, or impinges on another subsurface use	Monitor extent of elevated pressure, confirm model
A transmissive feature (well or fracture set) within the AOR was missed or mischaracterized as isolating	Monitor potentially transmissive features within planned area of CO_2 plume and pressure elevation; Above-zone monitoring;
Induced seismicity	Monitor to confirm correct geomechanical model

Risk References

- Risk inventories
  - Expert elucidation
    - Frequency
    - Consequence
  - Features Events and processes (FEPS)
    - https://ieaghg.org/2-uncategorised/132-risk-scenarios-database
  - GCCSI – https://www.globalccsinstitute.com/resources/publications-reports-research/a-review-of-the-international-state-of-the-art-in-risk-assessment-guidelines-and-proposed-terminology-for-use-in-co2-geological-storage/
  - DNV RISKMAN - https://www.dnv.com/focus-areas/ccs/co2riskman.html

- Risk Management

  Bow-tie (used at Shell Quest CCS project)

  NRAP tools https://netl.doe.gov/node/2278

  https://netl.doe.gov/carbon-management/carbon-storage/strategic-program-support/best-practices-manuals

  Simple scientific-method workflow (presented here)

GCCC Scientific Method Monitoring Design (ALPMI)

Risk assessment method as usual

Quantify risks to define material impact

Specify magnitude, duration, location, rate of material impact

- Avoid subjective terms like safe and effective.
- E.g. : Specify mass of leakage at identified horizon or magnitude of seismicity.
- Specify certainty with which assurance is needed

Explicitly model unacceptable outcomes showing leakage cases.

Model material impact scenarios

ALPMI uses models differently than the typical history matching the expected performance

Identify signals in the earth system that indicate or preferably precede material impact

This method down selects to consider only signals that may indicate material impact is occurring or may occur.

Approaches like those normally seismic survey design should be deployed for all modeling tools

Select monitoring tools that can detect these signals at required sensitivity

Forward modeling tool response is essential to developing the expected negative finding: "No material impact was detected by a system that could detect this impact."

This activity as traditionally conducted. Include all the expected components, such as attribution, updating as needed, feedback , etc..

Deploy tools and collected and analyze data

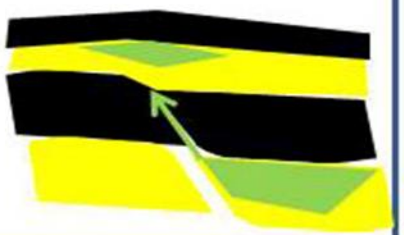
Only via this ALPMI process can a finding that the material impact did not occur be robustly documented

Report if material impact did/did not occur

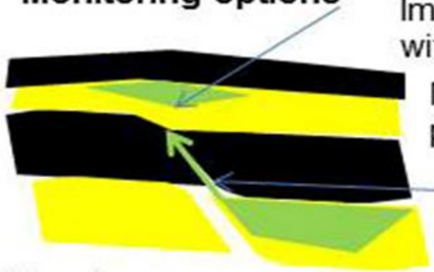
Scientific Method-Based Monitoring Example

Characterization Uncertainty: Fault-seal?

ALPMI

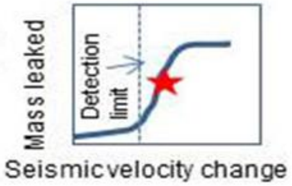


Monitoring options



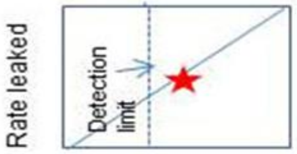
Test Sensitivity of Monitoring Options

Image free-phase leaked CO_2 with surface 4-D

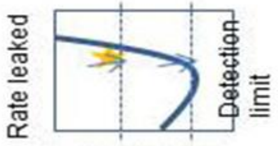


Change in rate pressure increase in reservoir

Measure change in pressure AZMI



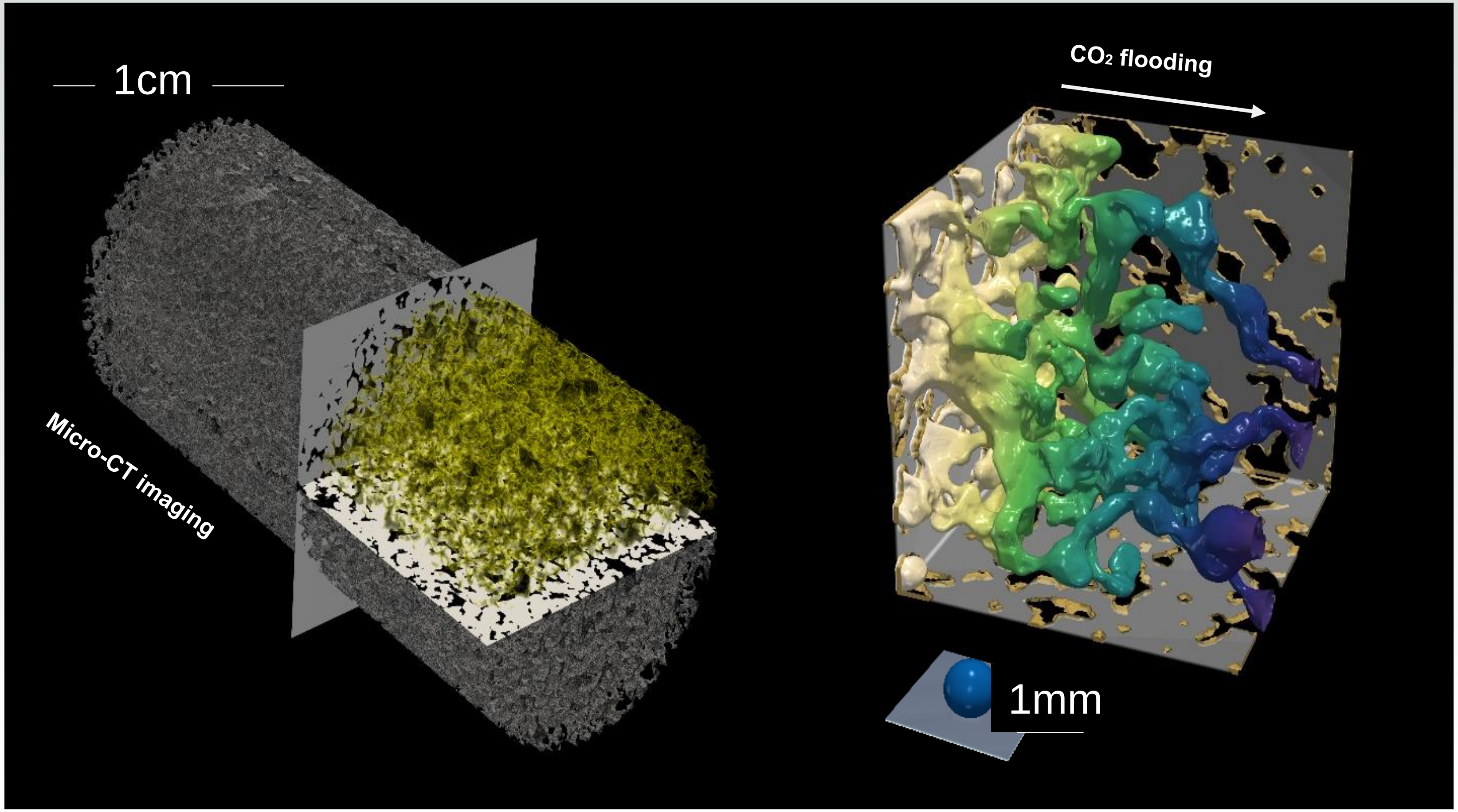
Temperature change along fault



Set triggers, stage monitoring options

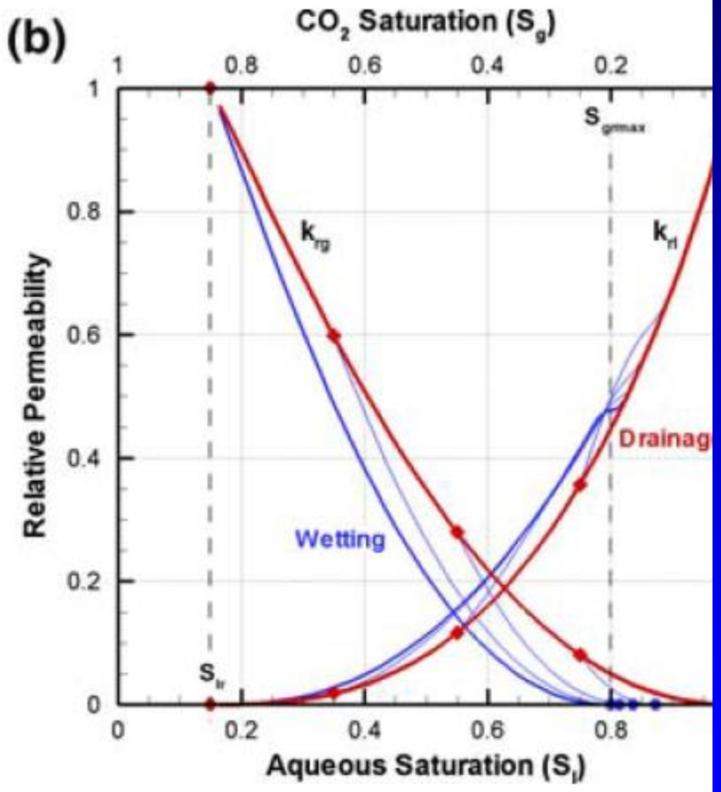
- Select microseismic as pre-failure trigger
- AZMI pressure as most sensitive trigger
- Select Image with surface 4- D and change in rate of pressure change in reservoir as post-trigger follow up.
- Decrease analysis of microseismic after pressure peaks and plateaus

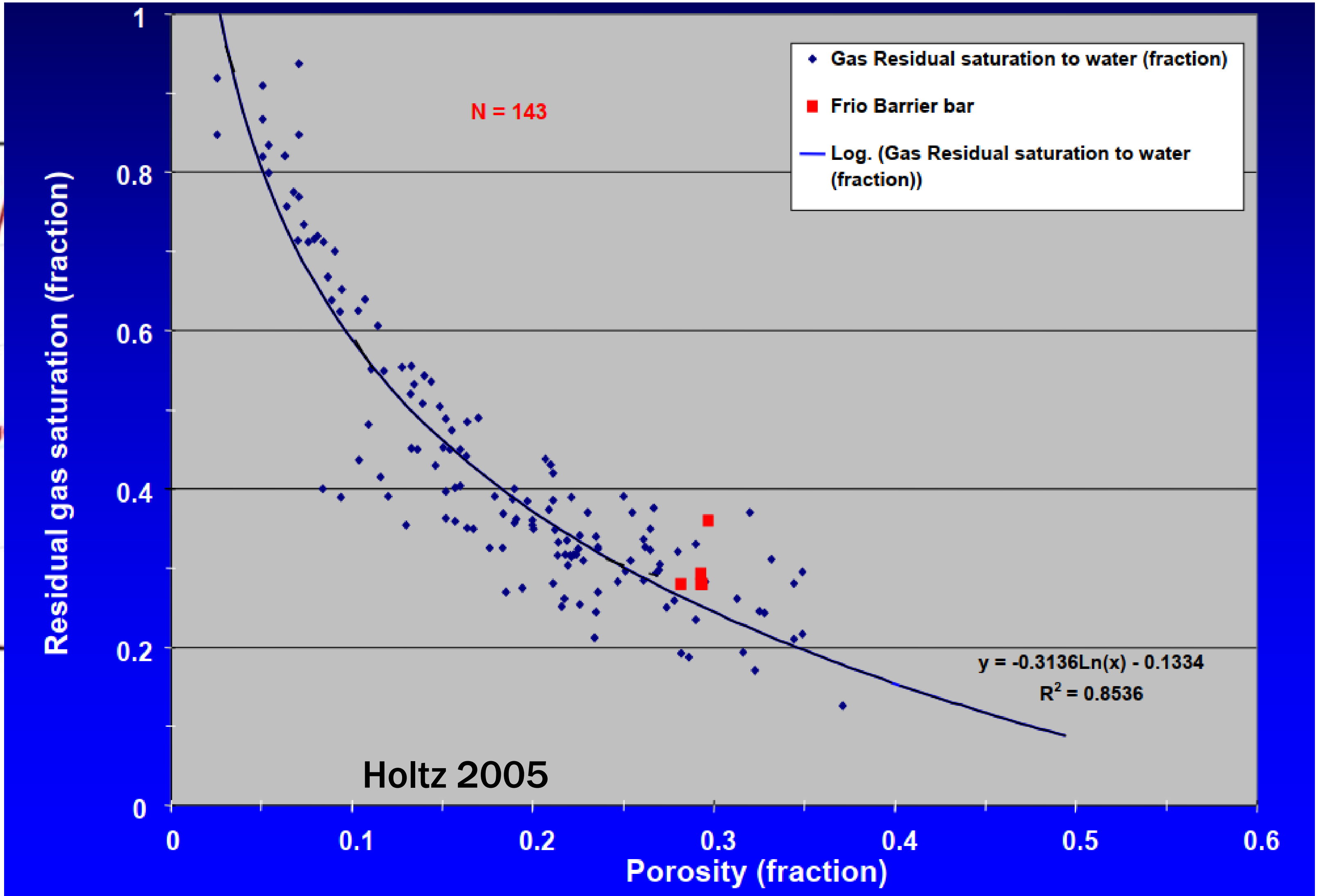
Rock volume that can be occupied by CO_2



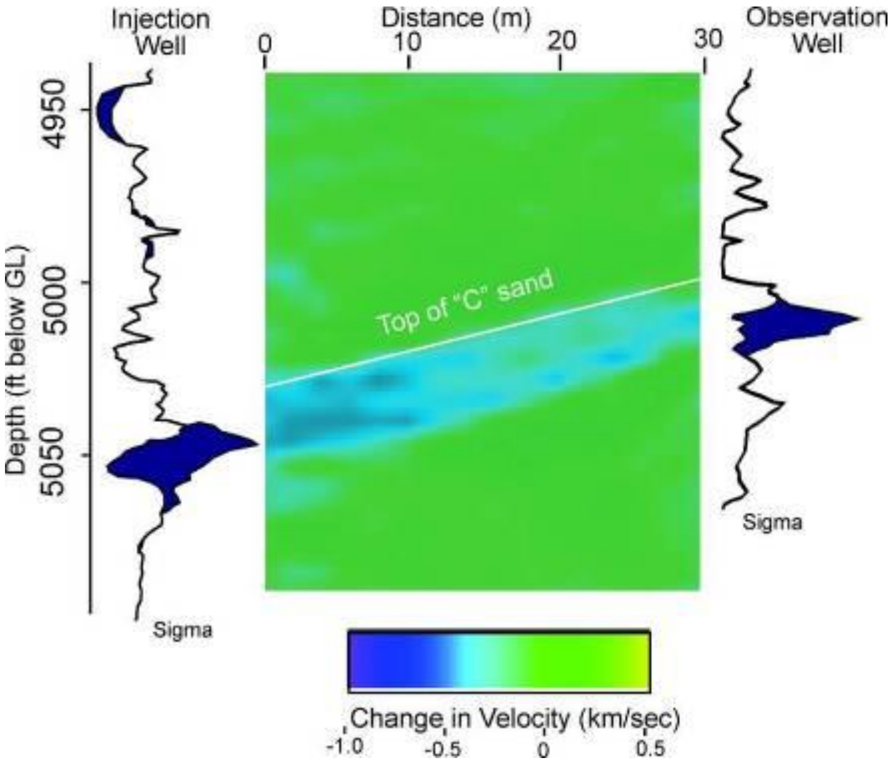
Sahar Bakhshian, GCCC, BEG, JSG, UT Austin

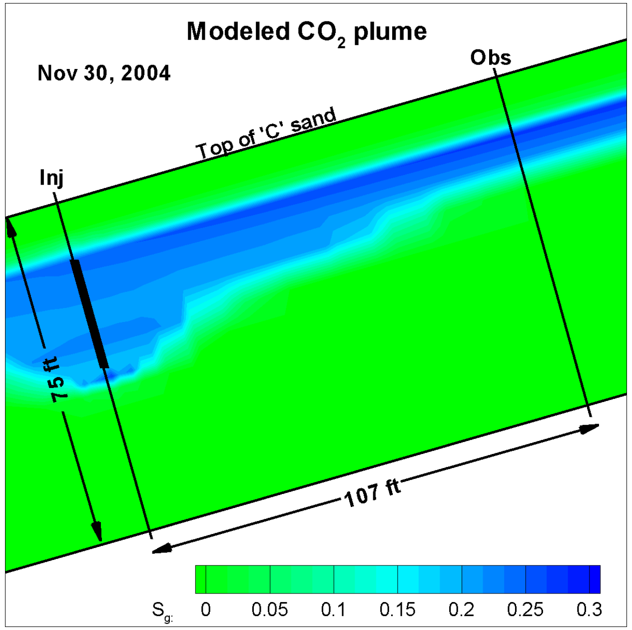
Two phase porous media hysteretic curves limit two phase flow





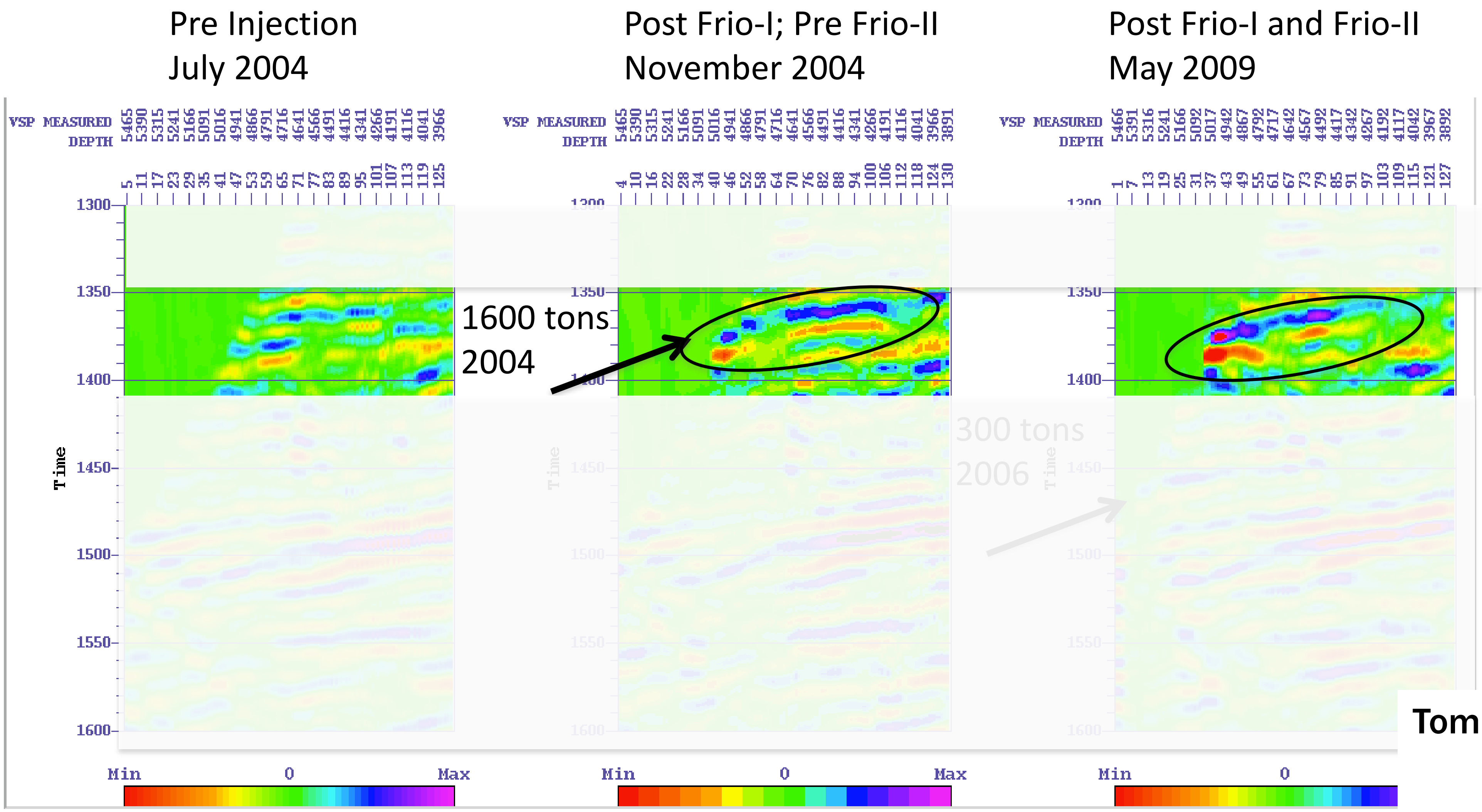
Post injection CO_2 Saturation Observed with Cross-well Seismic Tomography vs. Modeled





Tom Daley and Christine Doughty LBNL

Frio Time Lapse VSP: Reflection



Tom Daley LBNL

One year later, attempting to produce the CO_2 back – no success. CO_2 is underground but cannot be produced

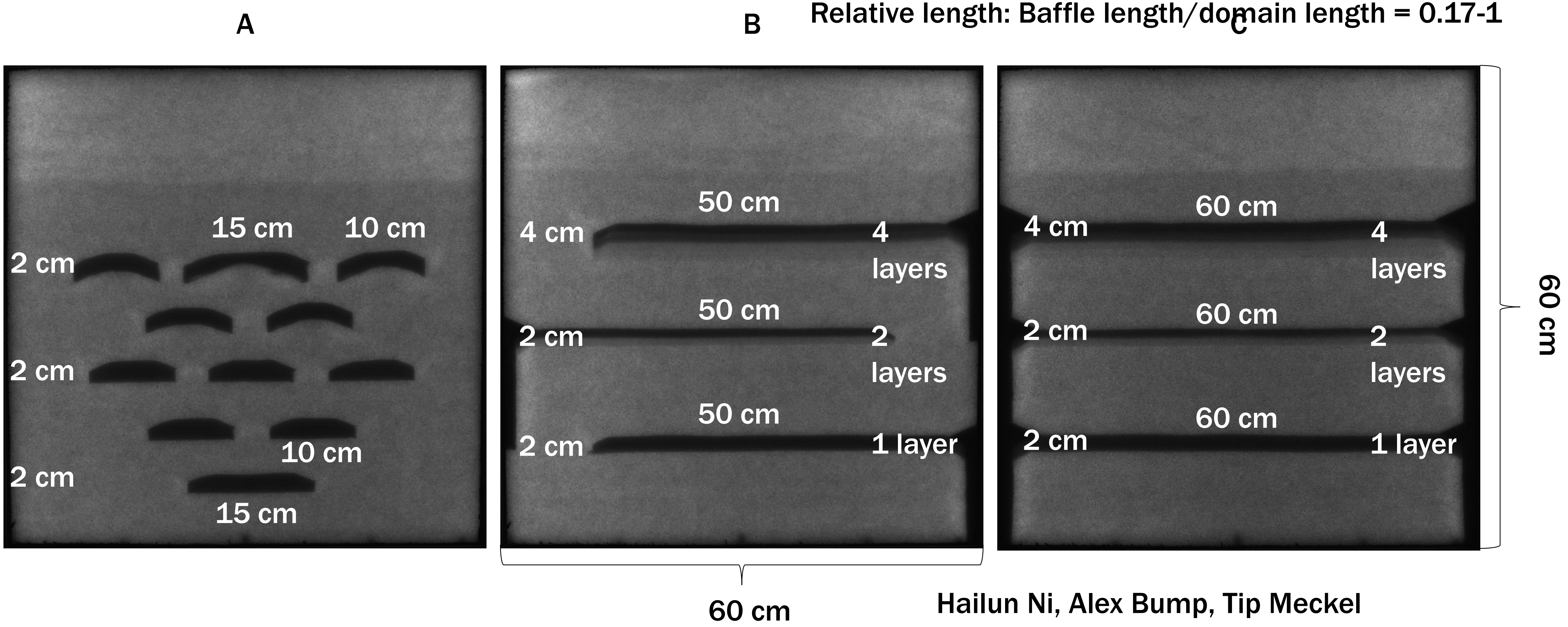
Limiting vertical flow – how good does the "seal" need to be

Layer properties

Capillary entry pressure contrast: Matrix/barrier = 0.5-0.8

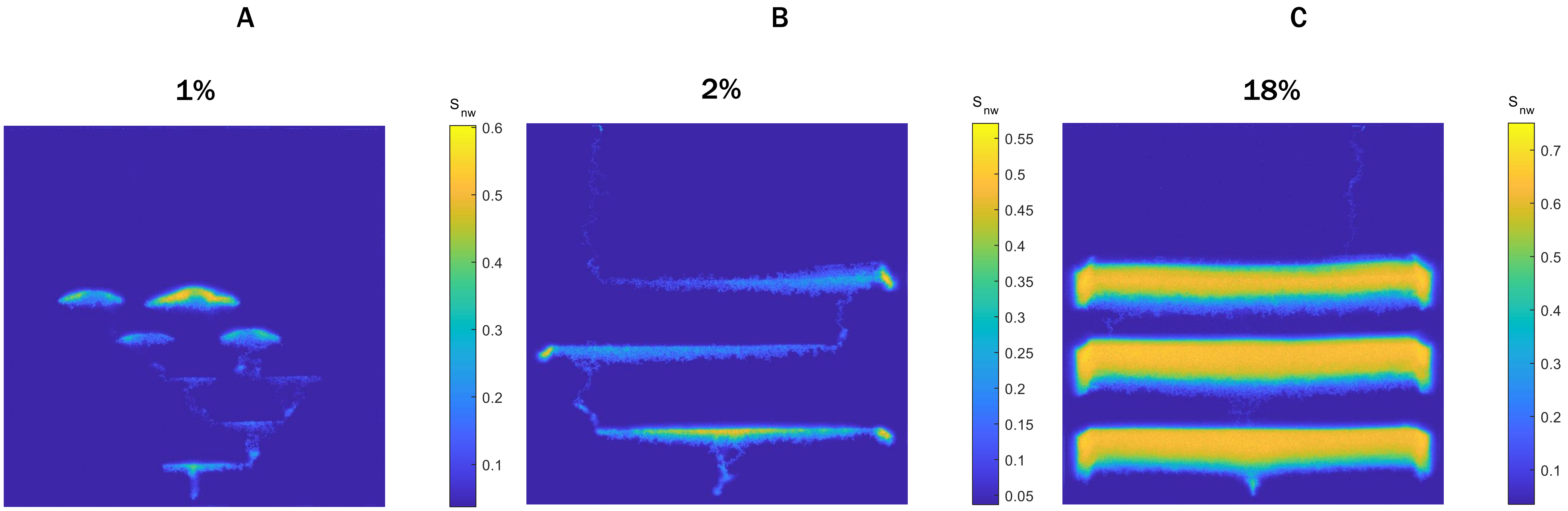
Aspect ratio: Length/width = 5-30

Relative length: Baffle length/domain length = 0.17-1



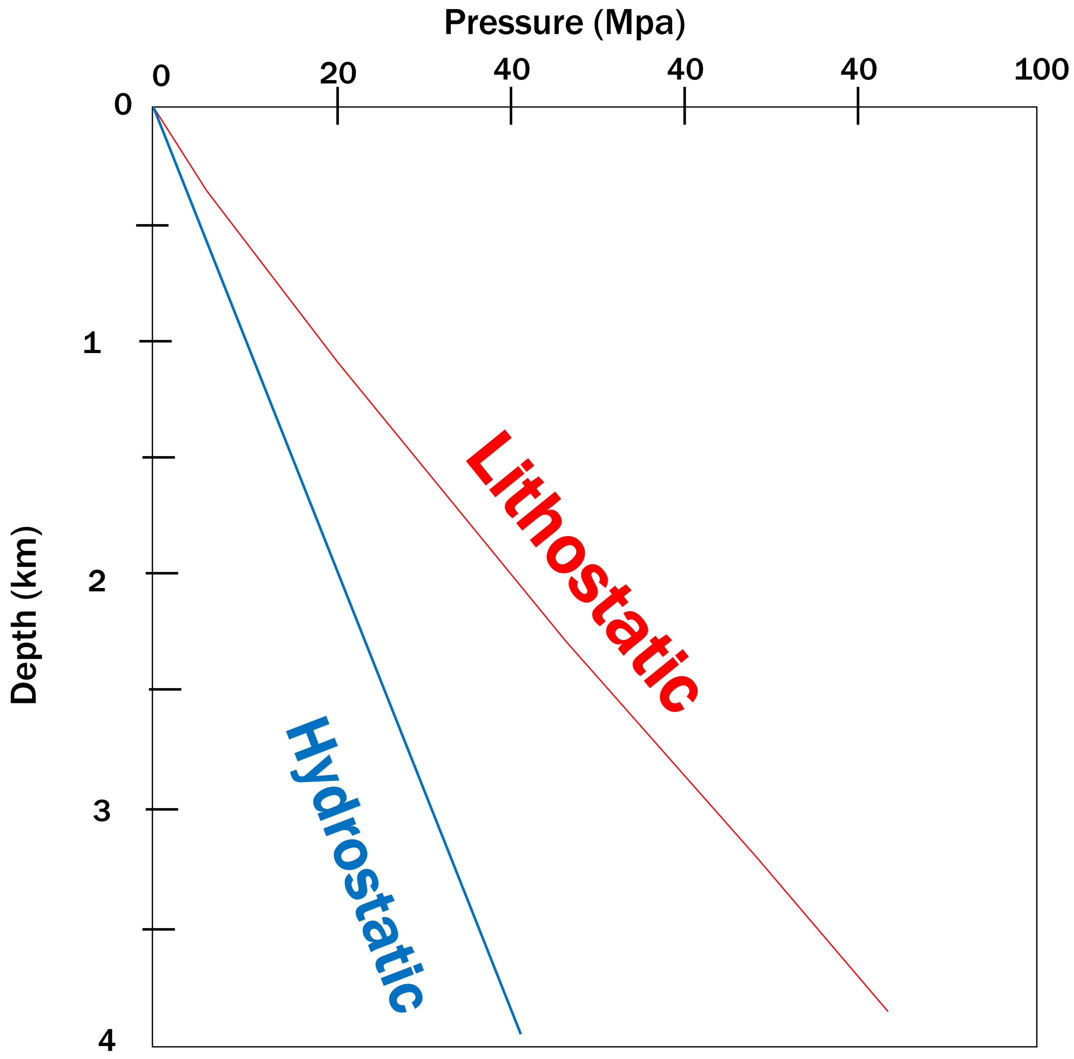
Hailun Ni, Alex Bump, Tip Meckel

Capilary Barriers are Effective



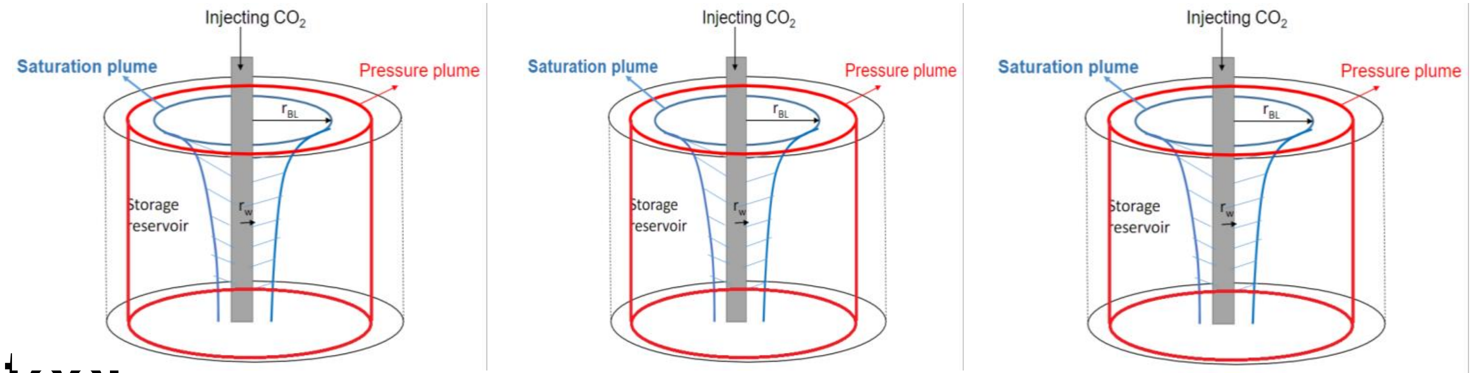
Hailun Ni, Alex Bump, Tip Meckel

Capacity for injection is limited by pressure increase



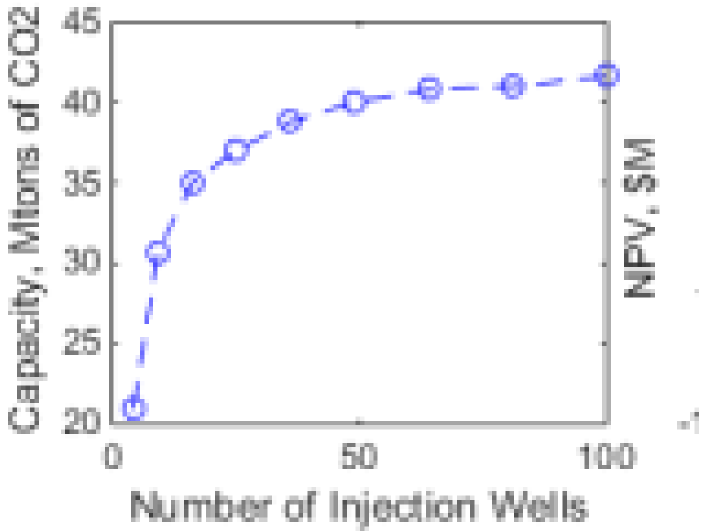
Capacity in context of climate mitigation (large volumes removed now!)

- The commodity of value is pressure space



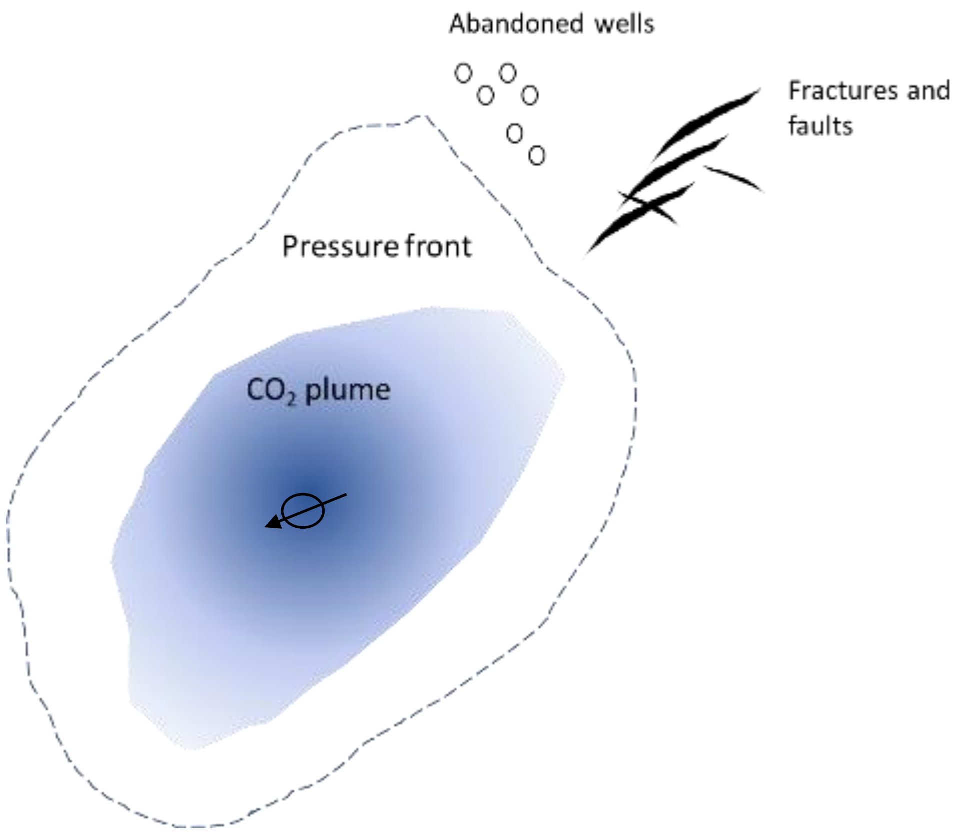
- EASI –tool

https://www.beg.utexas.edu/gccc/research/easitool



Deep Subsurface Verification

- Flow simulation models predict the extent of the CO_2 plume and elevated pressure.
- Ensures no wells or faults (main leakage risk) are intersected.
  - Risk is CO_2 or brine leakage to surface
- The surface projection of this area defines the area of environmental monitoring.
- During the project, plume behavior is monitored for performance and flow simulations are history-matched and updated.



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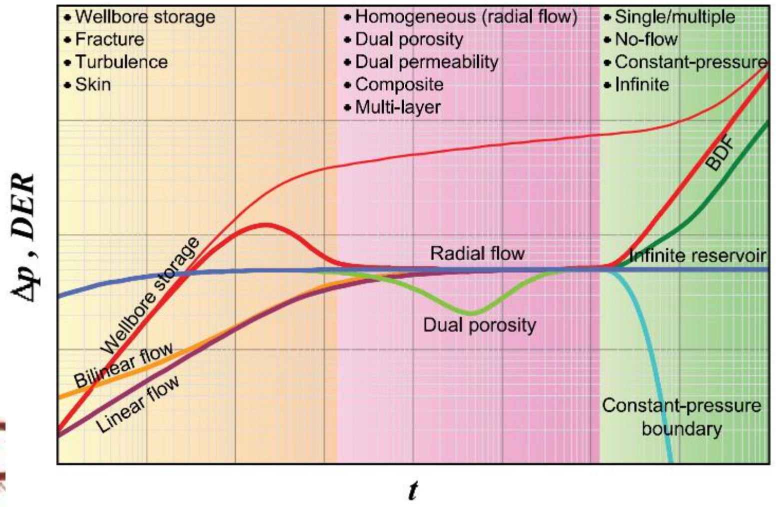
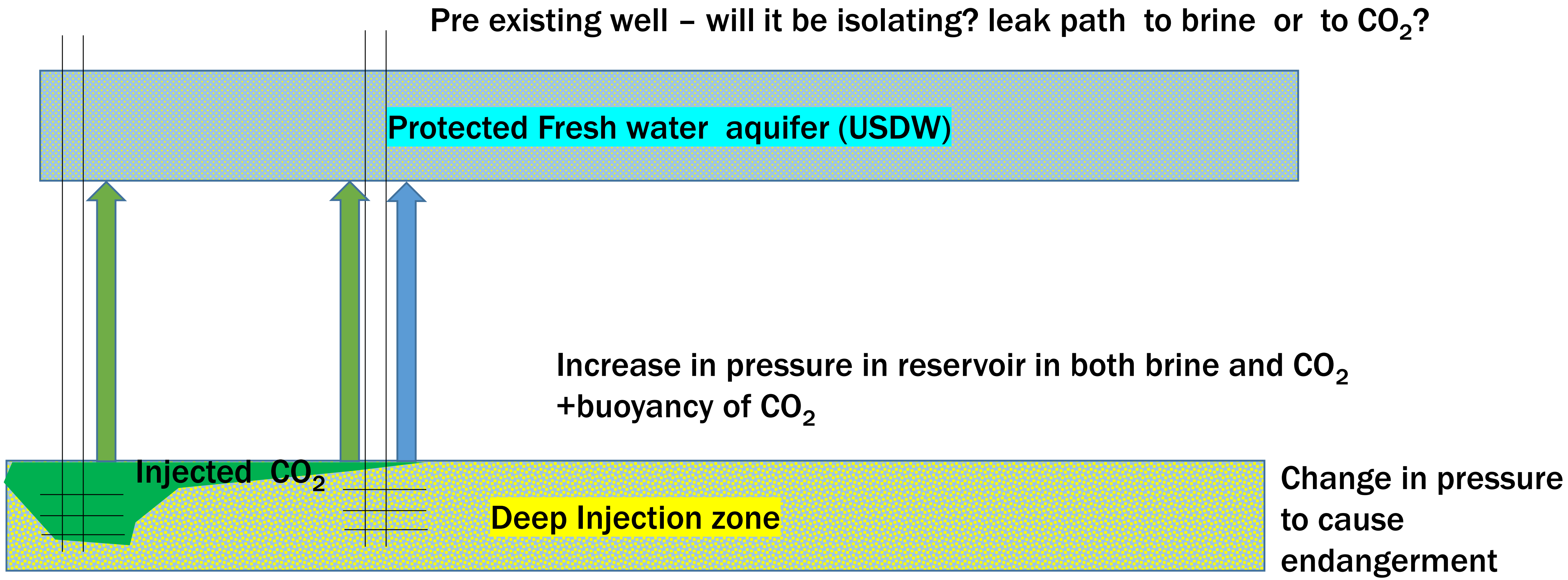
Pulsed Pressure

- Injection – fall-off tests – required in US permitting
- Boundary conditions
- Distinctive signals to isolate response
- Time-lapse change in fluid compressibility - novel method to track CO_2 substitution for brine, geometry



Pressure-data curves used in formation characterization (source: www.fekete.com).

Injection Can Lift Fluids to Surface via Transmissive Pathways



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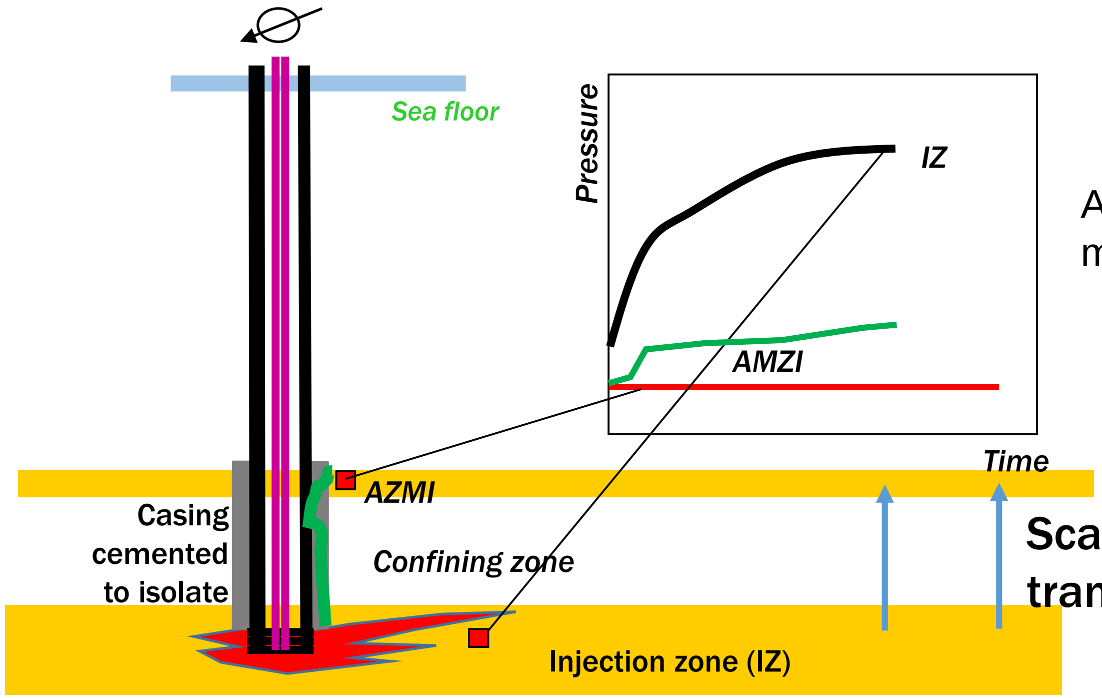
Case example - Leakage behind casing in an area of many wells

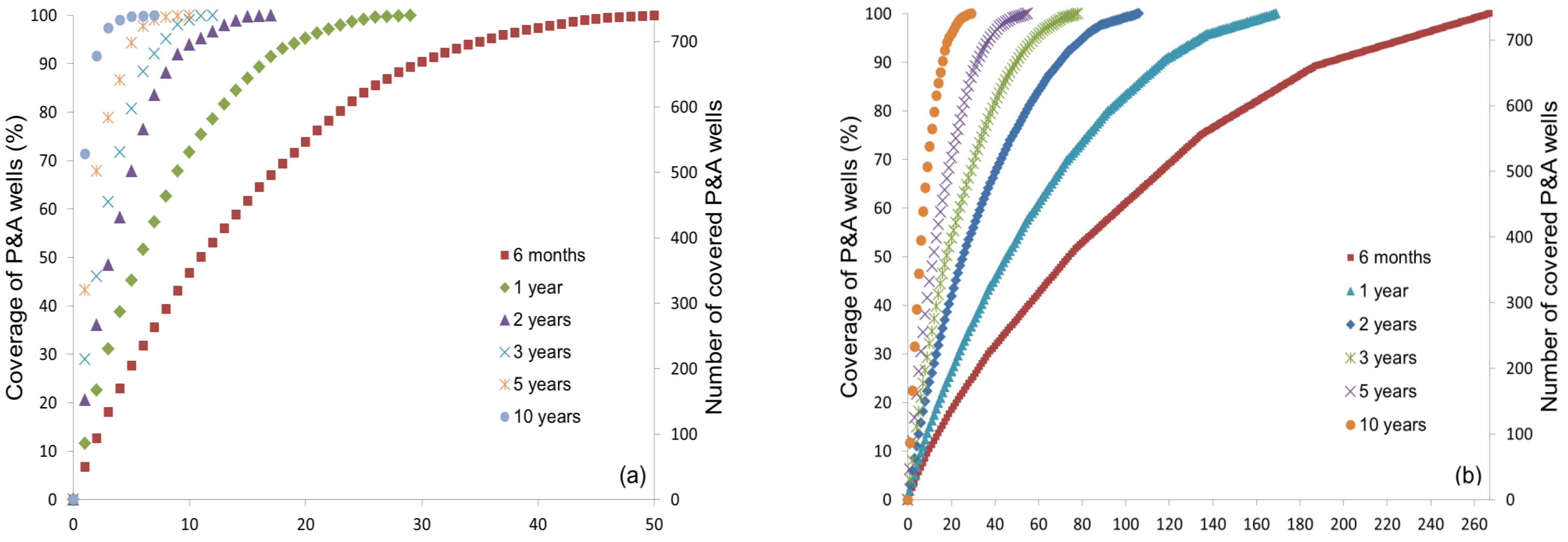
Above-Zone pressure monitoring – no leakage



Above-Zone pressure monitoring

Scattered existing wells, transmissive fractures

Why Pressure Not Chemistry for Deep Subsurface Monitoring?



Number of monitoring well measuring pressure

Number of monitoring well measuring chemistry

Find a leak much faster and with fewer wells with pressure

Behnaz Bolhassani UT Austin MS thesis

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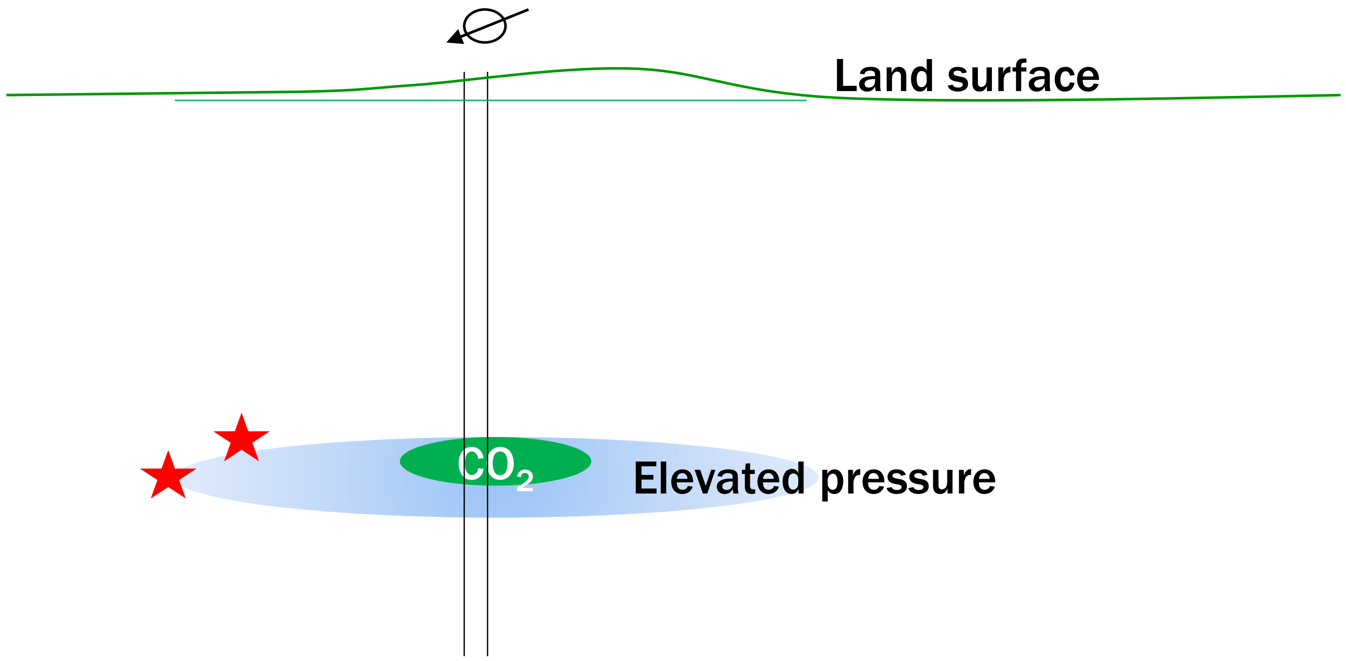
Limits and Comments on Pressure as a Monitoring Tool

- Direct measurements require wells – balance data value against expense and risk
- Pressure is diffusive – signal over wide area
  - Need multi-wells an analysis to locate signal (see new work at Otway project Australia)
- Well completion important – connect to zone to be assessed. Avoid well storage issues.
  - Don’t have mature way to complete multiple zones
  - On casing deployments?
  - Multi-packer?
  - Fiber?

Indirect Measurements of Pressure

- Tilt at surface
  - Tilt meters
  - INSAR – See In Salah CO_2 injection
- Induced seismicity –
  - Events triggered as pressure changes reach sensitive features. See Decatur

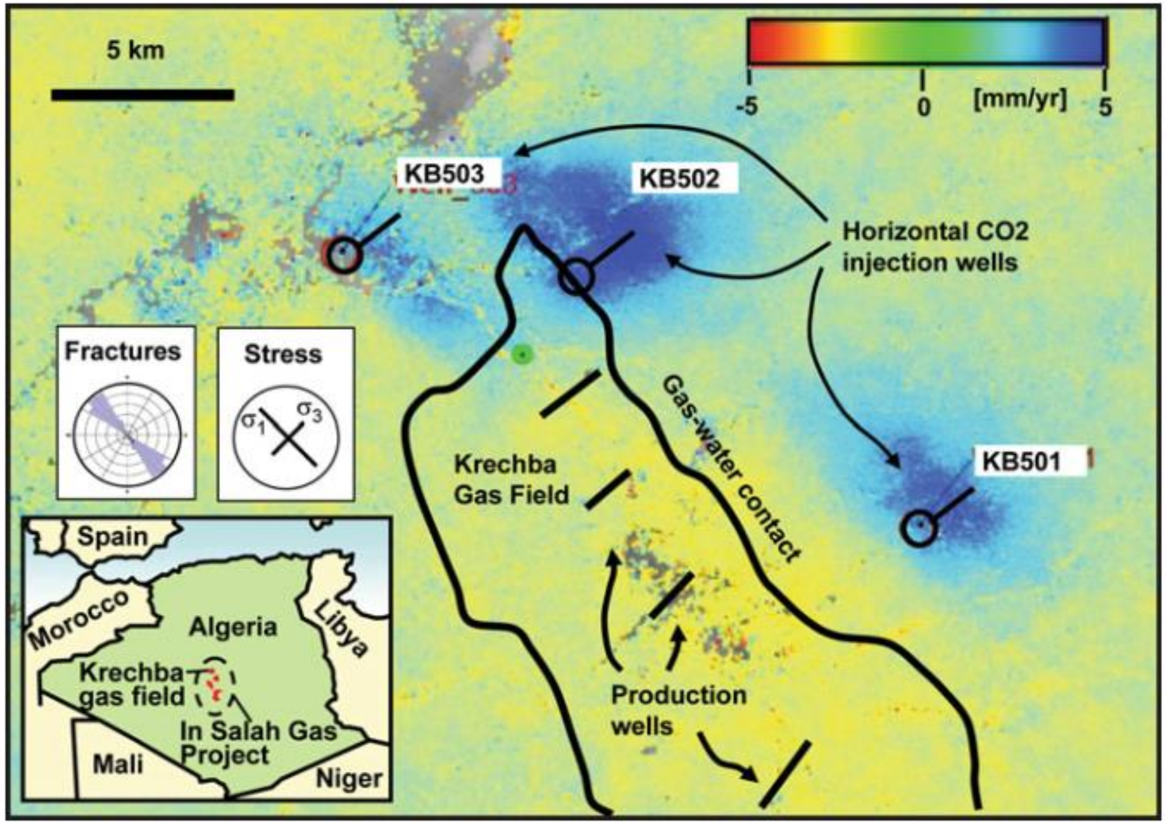


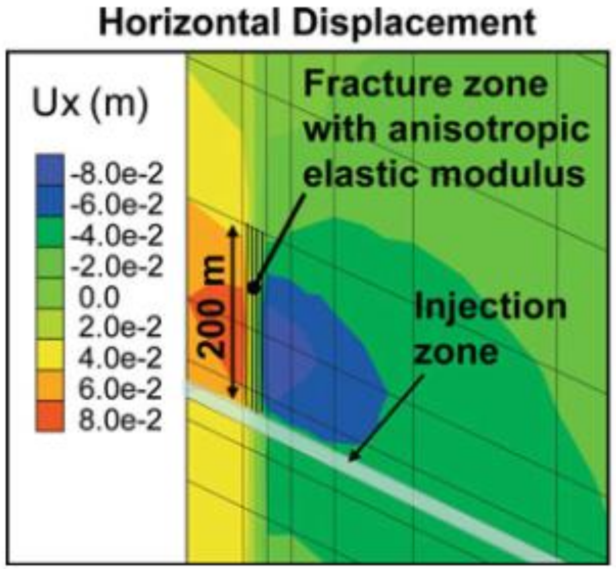
- Seismic response to pressure – stiffer rocks (discussed at Snøhvit below)

Surface deformation showing pressure leakage signal

In Salah, Algeria

Fig. 2 InSAR data for average distance change (close to vertical displacement) evaluated by Tele-Rilevamento Europa (TRE) from August 2004 though March 2007. Fracture orientation rose diagram from Iding and Ringrose (2010), and stress orientations evaluated by Geosciences Ltd, UK (Darling 2006). Cold (*green* to *blue*) colors with positive values indicate uplift, whereas hot (*green* to *red*) indicate subsidence





Forward geomechanical model

Rutqvist, 2012; Geotech Geol 30:525–551
DOI 10.1007/s10706-011-9491-0

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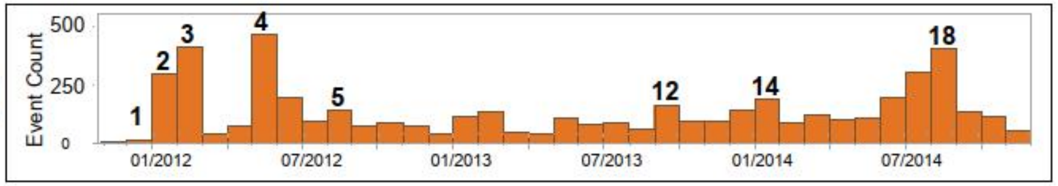
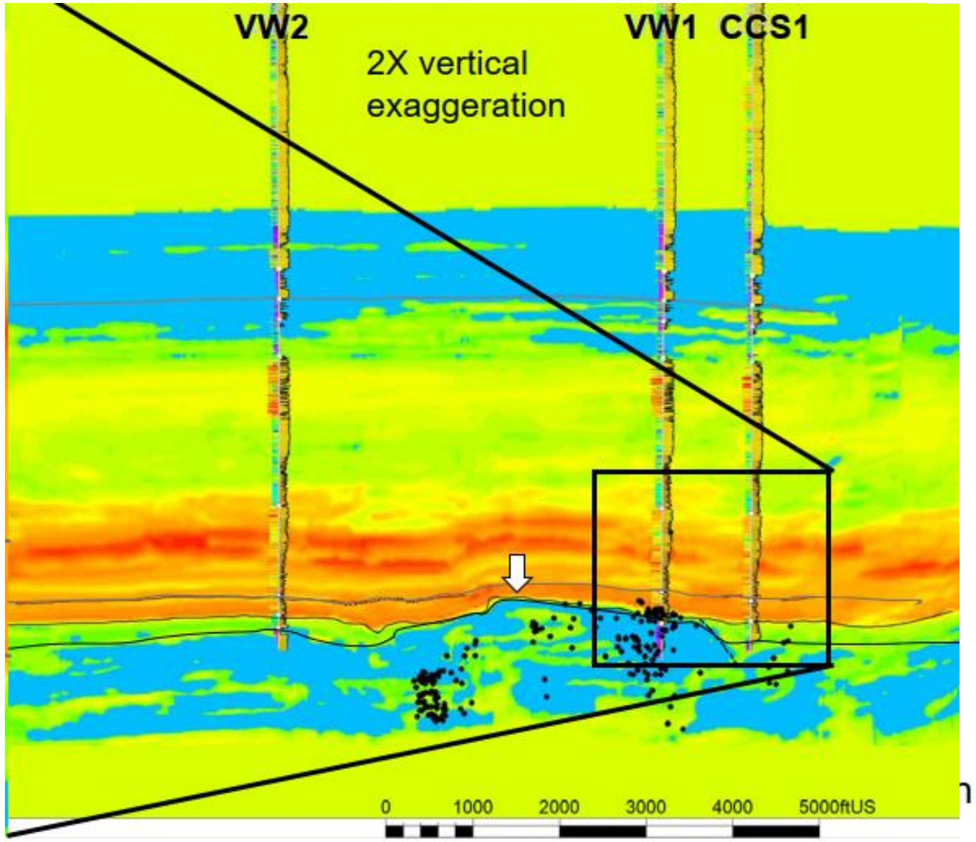
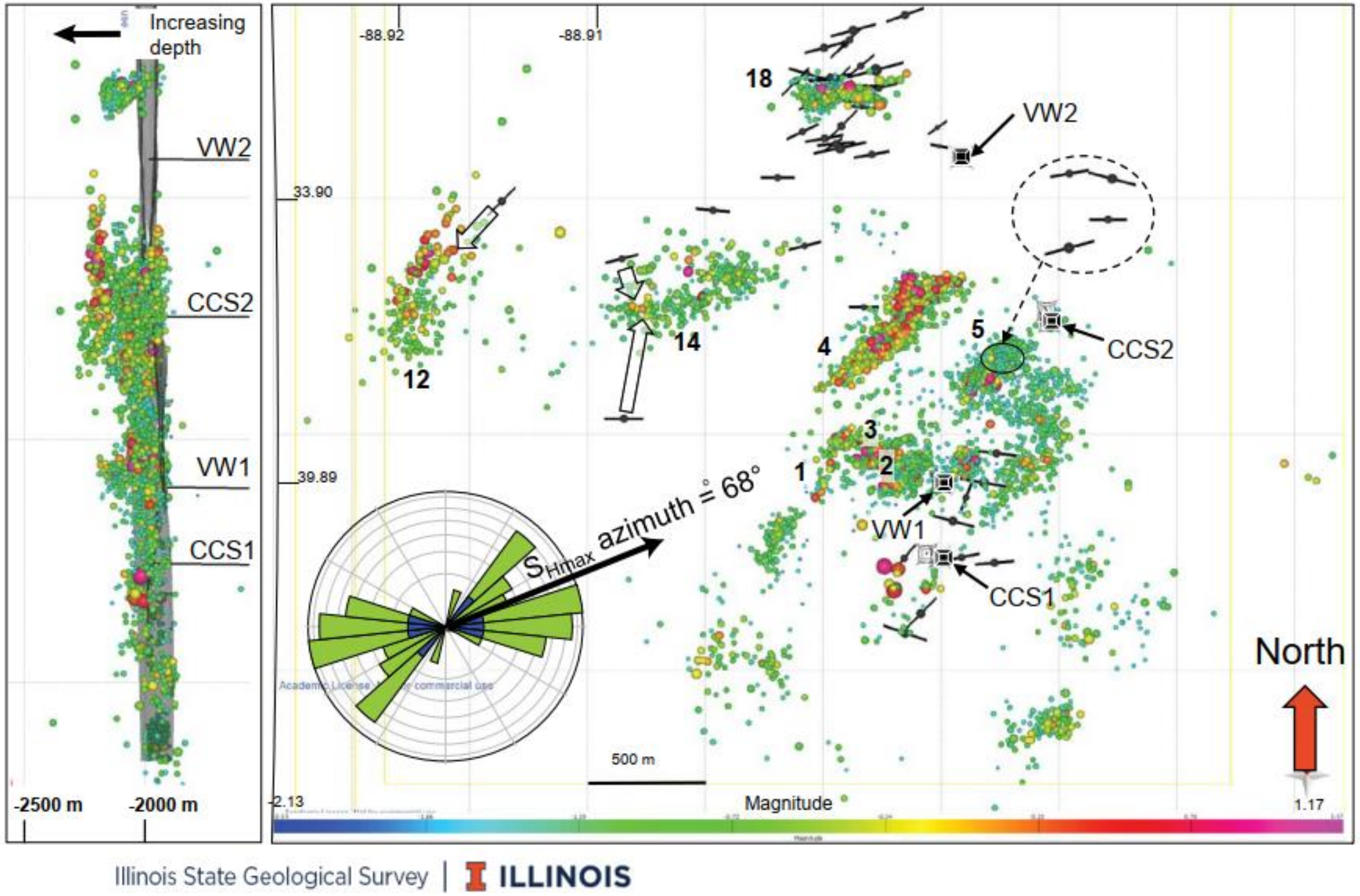
Low Magnitude Seismicity – Tracking Pressure Illinois Basin Decatur Project







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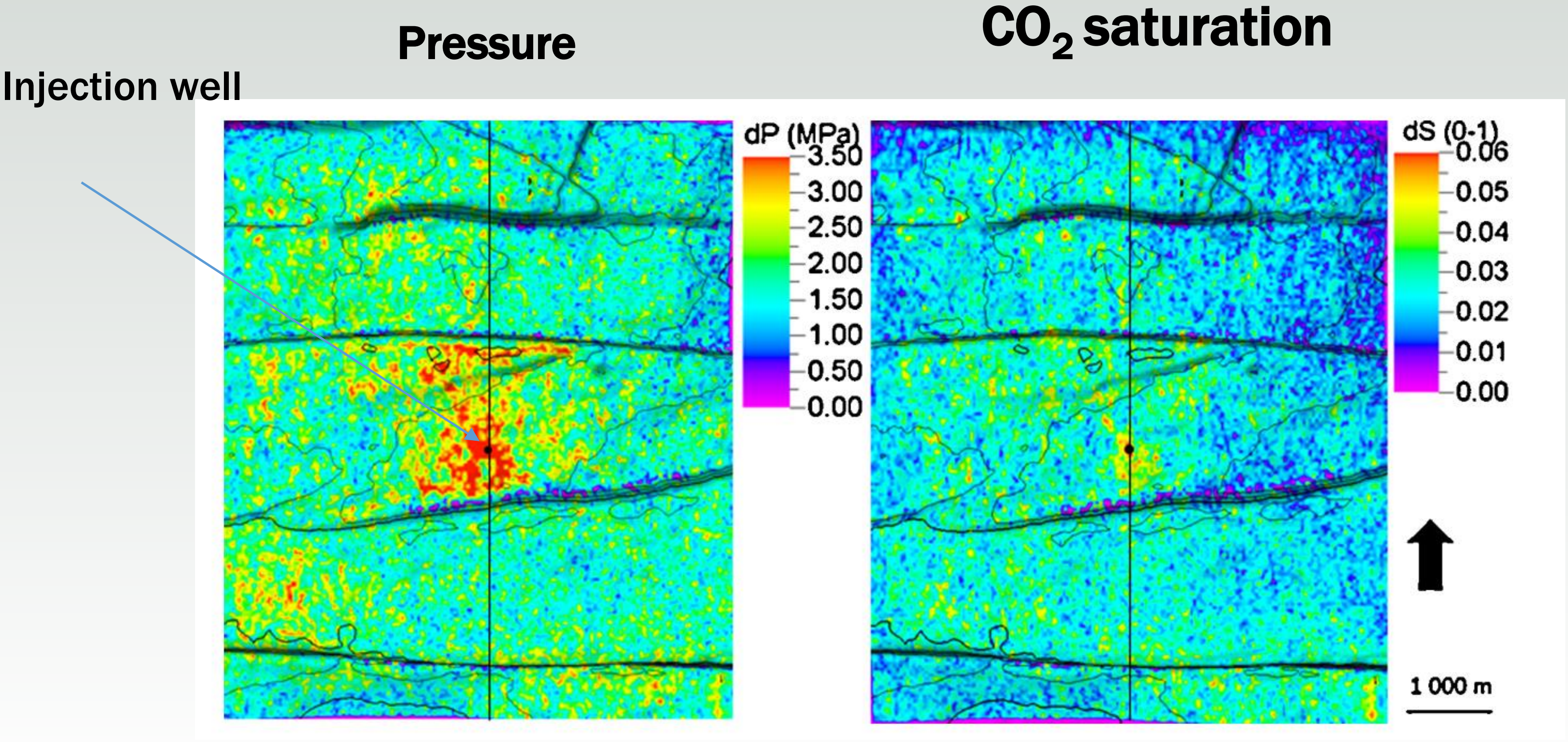
Sherilyn Williams-Stroud, Illinois State Geological Survey, 2020 talk to Risk Network

Example from Snøhvit

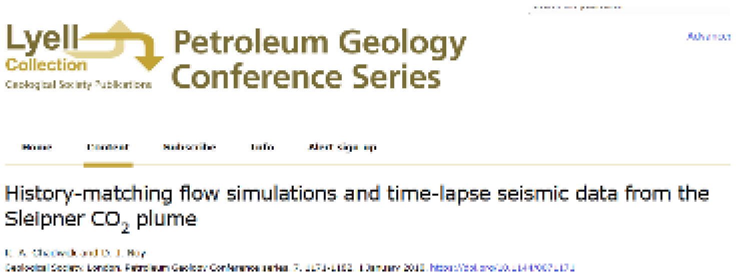
Equinor, Barents Sea



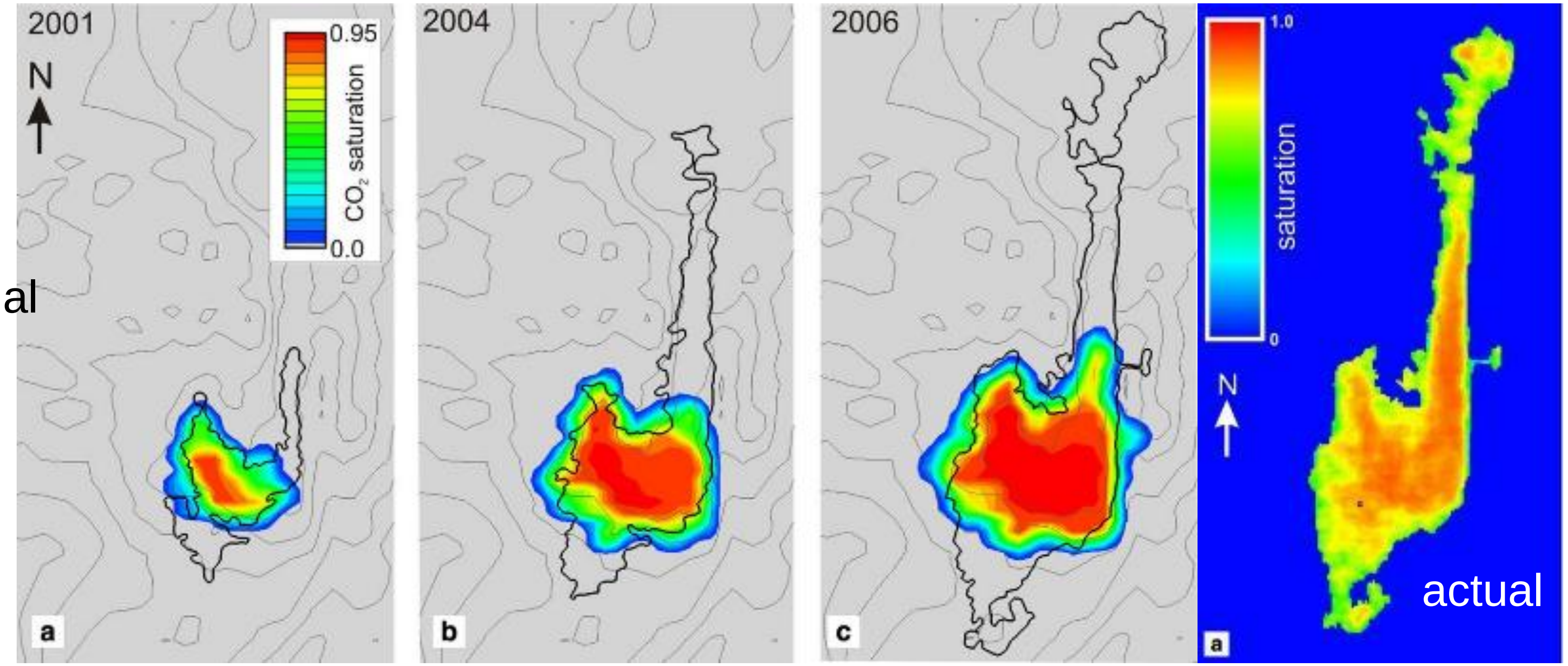
RMS amplitude on inverted pressure and saturation cubes

Grude et al 2014 Int J. GHG Control v.27

History matching beautiful seismic survey



Color = model
Black line = actual



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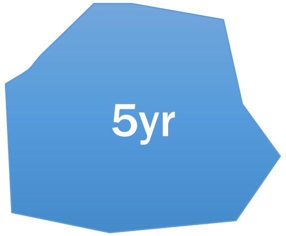
ALPMI Approach to Plume Migration

Predicted plume footprint year 5 of >5% CO_2 saturation in zone



Measured plume footprint year 5 of >5% CO_2 saturation in zone

Match to model OK or not OK?

Environmental Monitoring is Important

- Stakeholders have difficulty understanding geological CO_2 storage
- Environmental monitoring is the interface between the public and the project
  - What will happen if it leaks?
- Stakeholder assurance is imperative
- Therefore we must accept the challenge of meeting expectations
- In US Environmental “baseline” of groundwater and at administrators discretion soil air and other elements is required – use this requirement to characterize environments that might be perturbed during the project.

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Attribution: Response to observed events

- A key part of planning a monitoring approach.
- Attribution: does a detected signal indicate a material impact?
  - Incident – something has happened in operation that has damaging potential
  - Allegation - something observed that may/may not be material
- Monitoring plan needs to have response in place to signal detection

- See definitions in Dixon and Romanak, 2015 https://doi.org/10.1016/j.ijggc.2015.05.029

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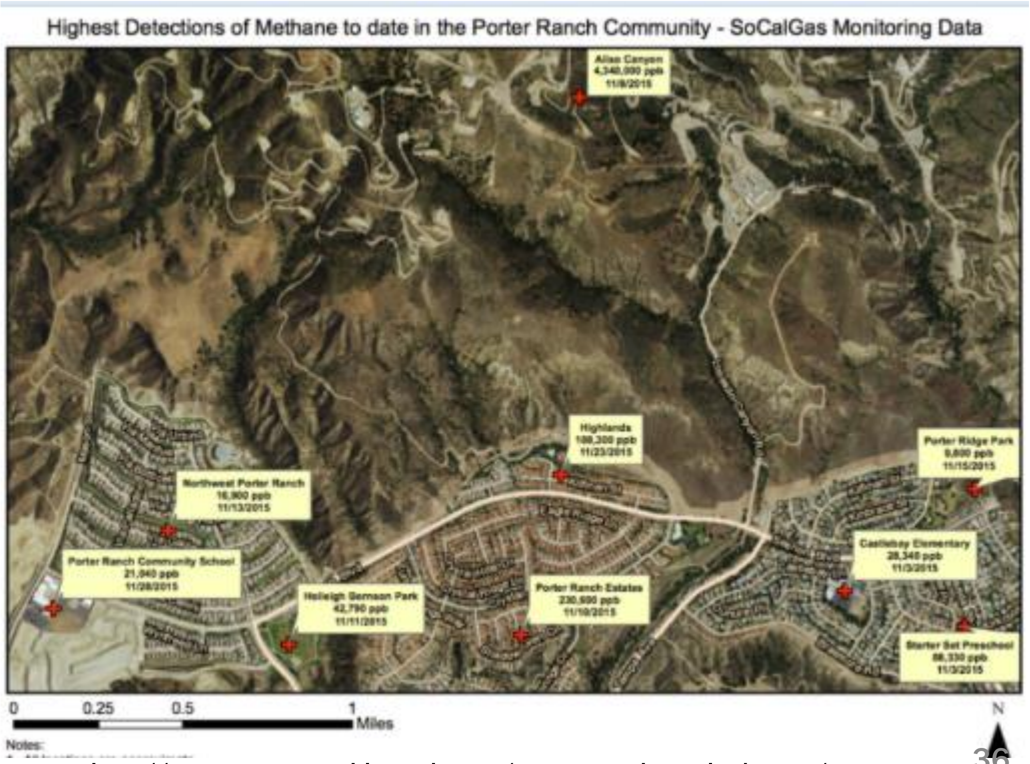
Industrial Analog – Well Release

- Aliso Canyon Natural Gas leak
- Los Angeles, CA, USA
- Well blowout at underground gas storage facility
- October 23, 2015 - February 11, 2016
- 91,000 metric tons of methane gas.
- Seepage sites are unpredictable and far from blowout well.

http://www.ibtimes.com/aliso-canyon-gas-leak-caused-largest-us-methane-release-ever-study-2324001



Source: http://www.porterranchlawsuit.com/porter-ranch-gas-leak-map/

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"Baselines" in Groundwater are Shifting Upwards

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Geochimica et Cosmochimica Acta 72 (2008) 5581–5599

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Increasing shallow groundwater CO_2 and limestone weathering, Konza Prairie, USA

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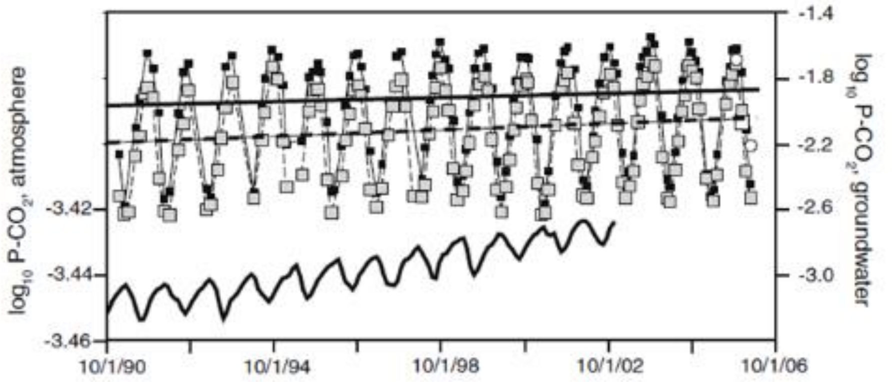
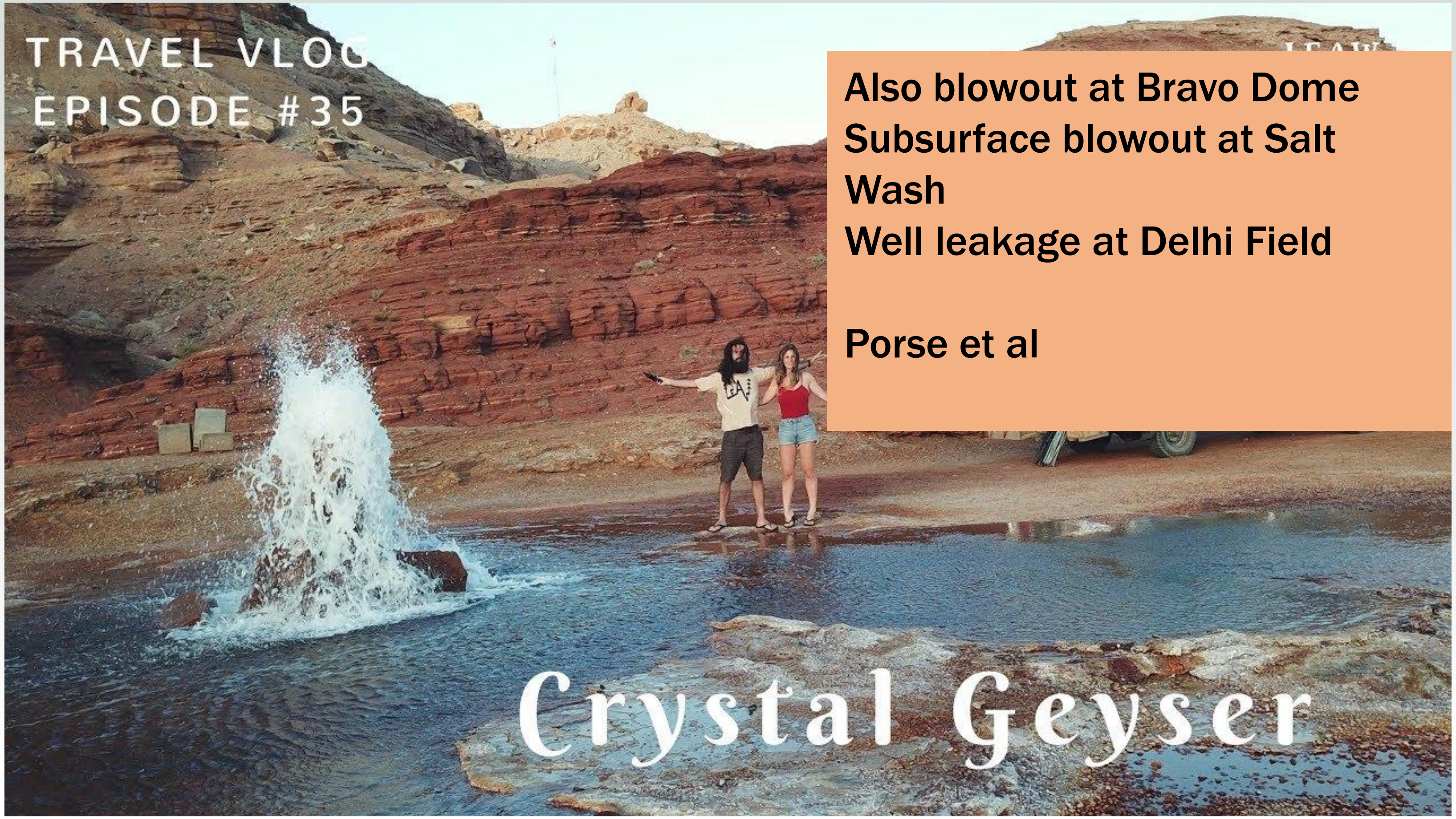


Increased dissolution of CO_2 in groundwater and associated mineral dissolution

What if something went wrong....



Also blowout at Bravo Dome
Subsurface blowout at Salt Wash
Well leakage at Delhi Field

Porse et al

Experience with non-retention

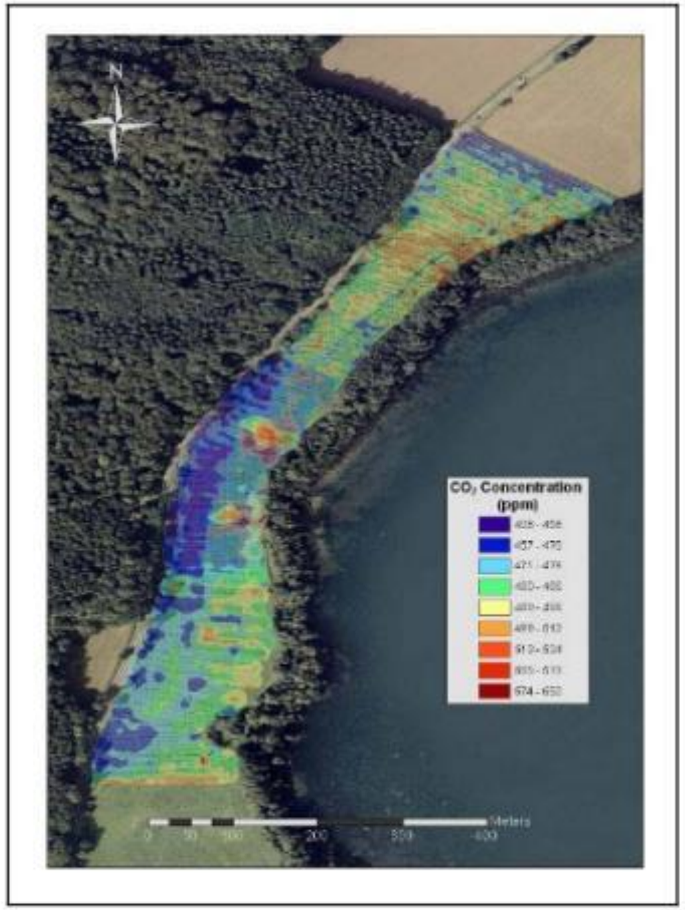
Sulfur Mt oil seeks Ventura County

https://cikeys.com/uncategorized/oil-seeps-101/

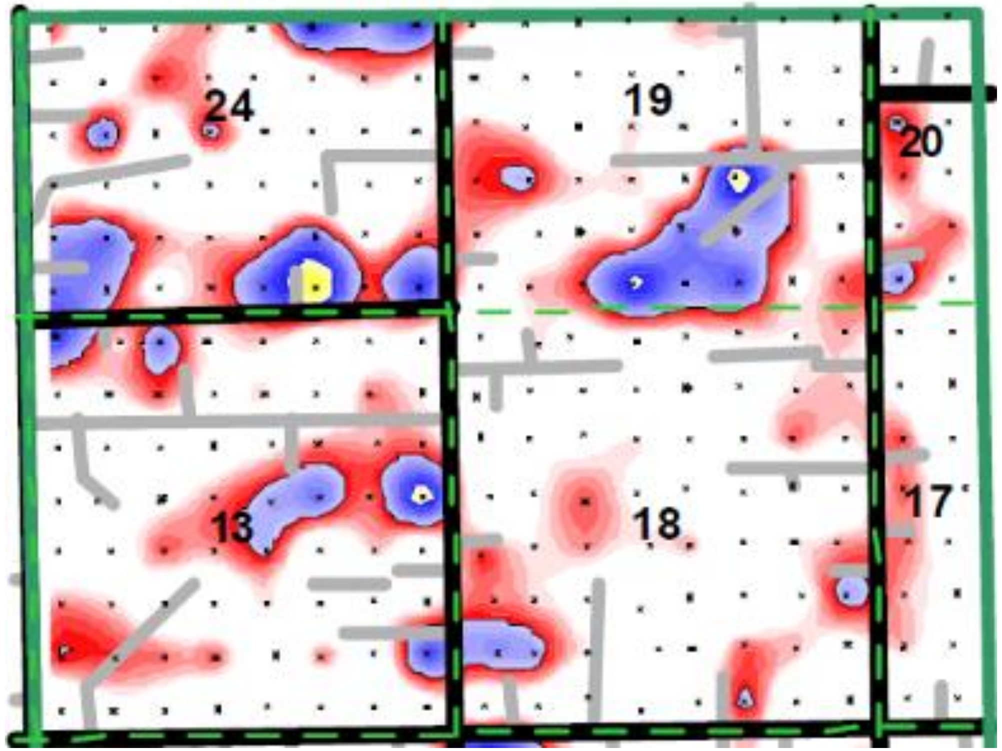
CO_2 Spatial as Well as Temporal Variability:

which one is Leakage?

A)



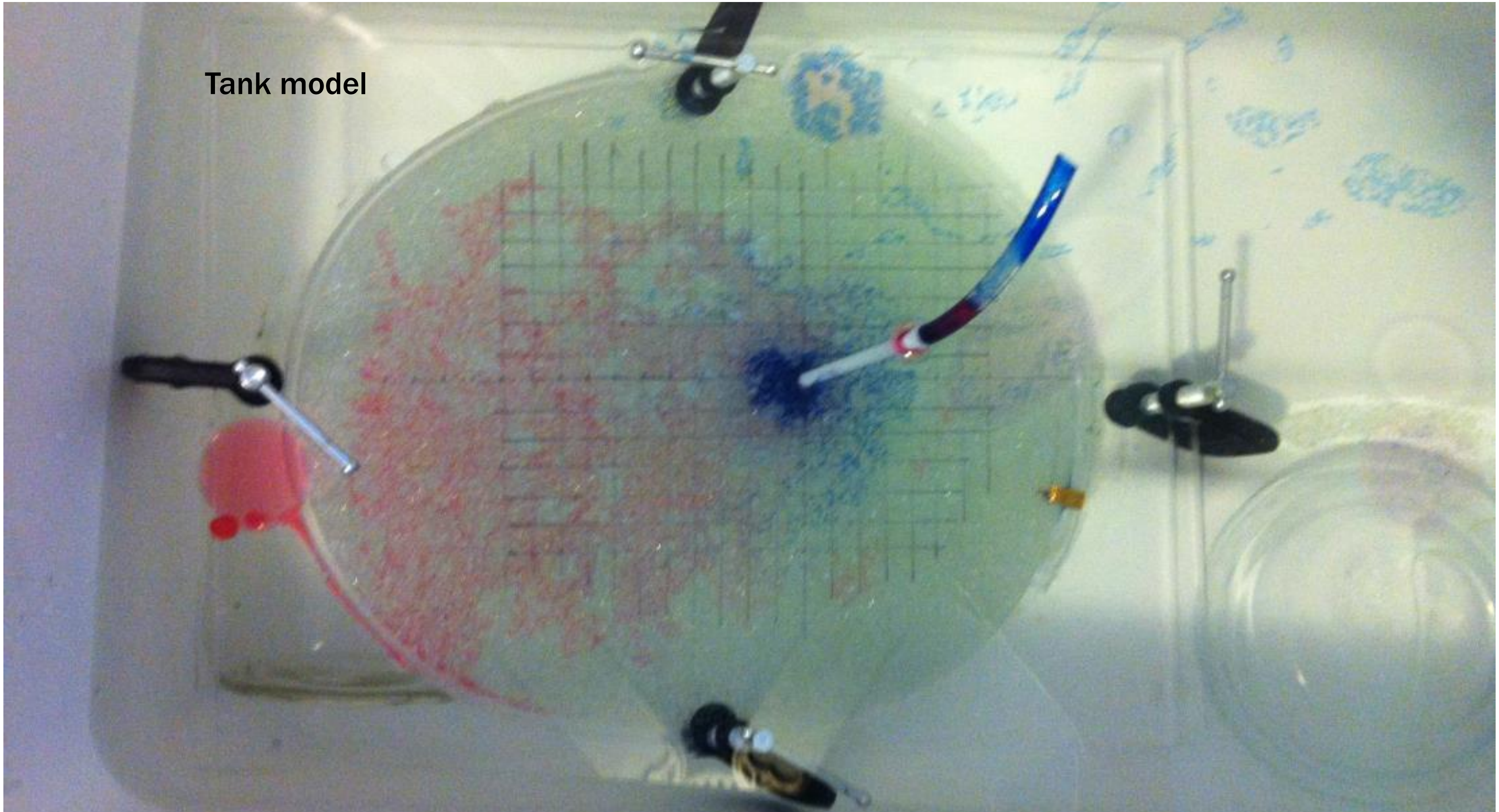
B) CO2 flux (g/m2/d) - October 2005



Walking traverses over gas vents at Latera with the ground surface measurement system (infrared analyzer) measuring CO2 concentrations (Jones et al. 2009)

Weyburn soil-gas grid: 14 km^2, 200 m spacing. Jones et al., 2006, Soil Gas Monitoring at the Weyburn Unit in 2005

How to build a case for perminance
Step 1 Model all the failures



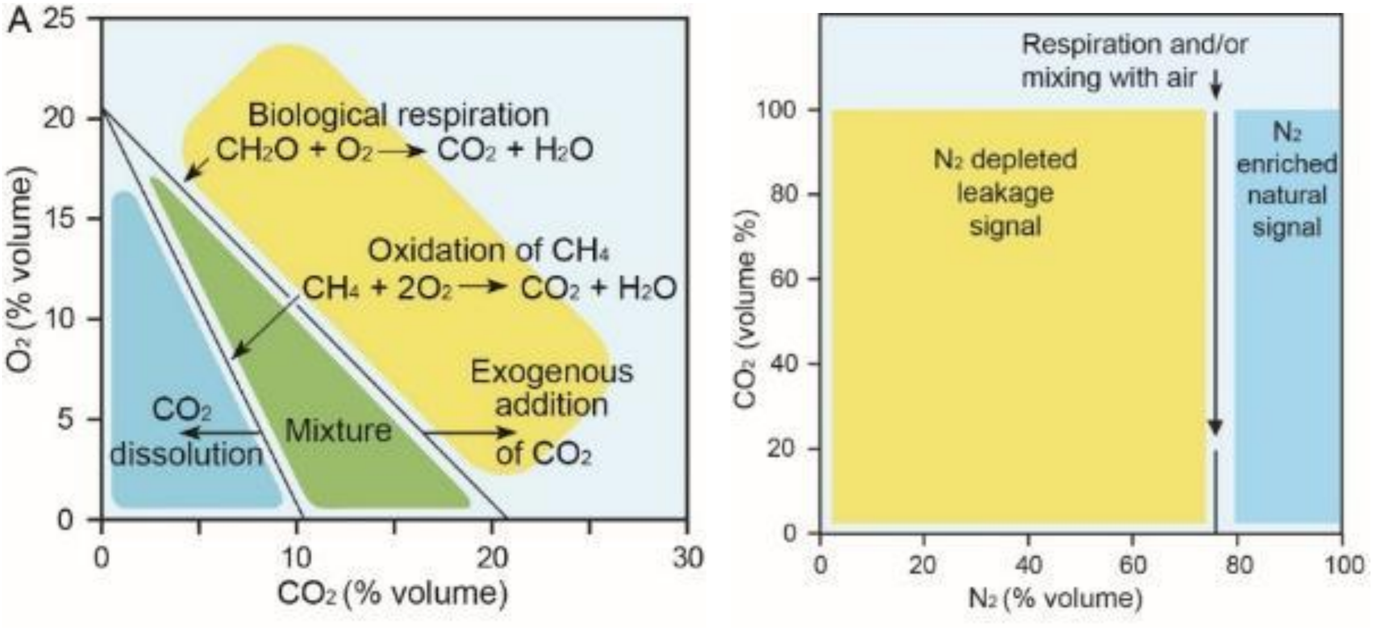
Attribution-Incident-Allegation

Change of mind-set from Environmental Monitoring of Contaminated Sites

- Contaminated site – plume from a release is present
  - Make measurements to assess release, damages, guide remediation, assess succeed of remediation
- CO_2 storage site
  - Expecting no release – prepare to prove a negative – ALPMI process setting up leakage hypotheses
  - However, prepare for incident or allegation
  - Guides collection of pre-injection data – A substitute for “baseline”

Process-Based Soil Gas Ratios

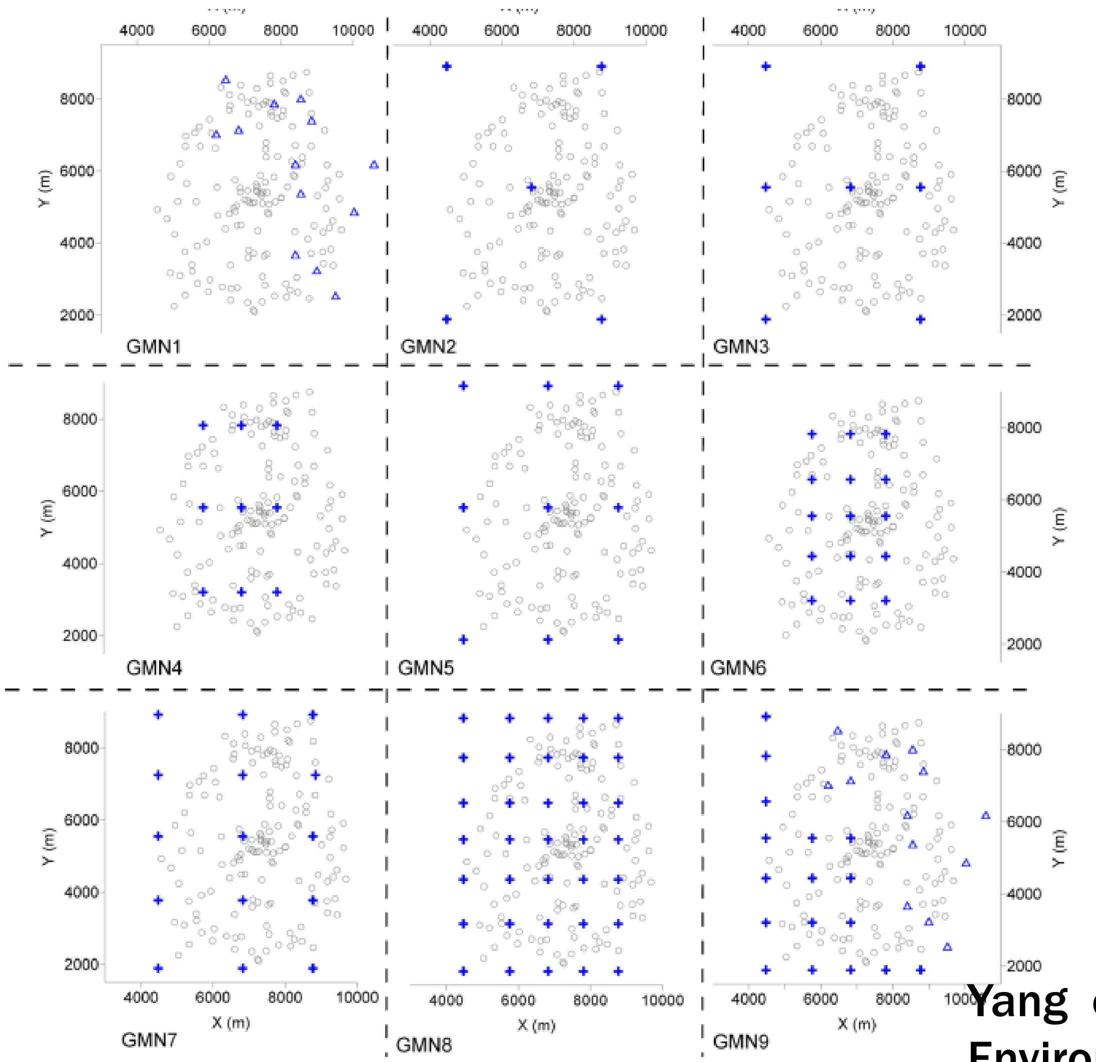
- Uses simple gas relationships to identify **processes.**
  - Biologic respiration
  - Methane oxidation
  - Dissolution
  - Leakage
- No need for years of background.
- Method can be applied in any environment regardless of variability



Romanak et al., 2012, Geophysical Research Letters, *39* (15).
Romanak et al., 2014, International Journal of Greenhouse Gas Control, 30, 42-57
Dixon and Romanak, 2015, *International Journal of Greenhouse Gas Control*, *41*, 29-40

Testing Groundwater Monitoring Networks –

Reactive Transport in Gulf Coast Aquifer
How many groundwater wells are enough?



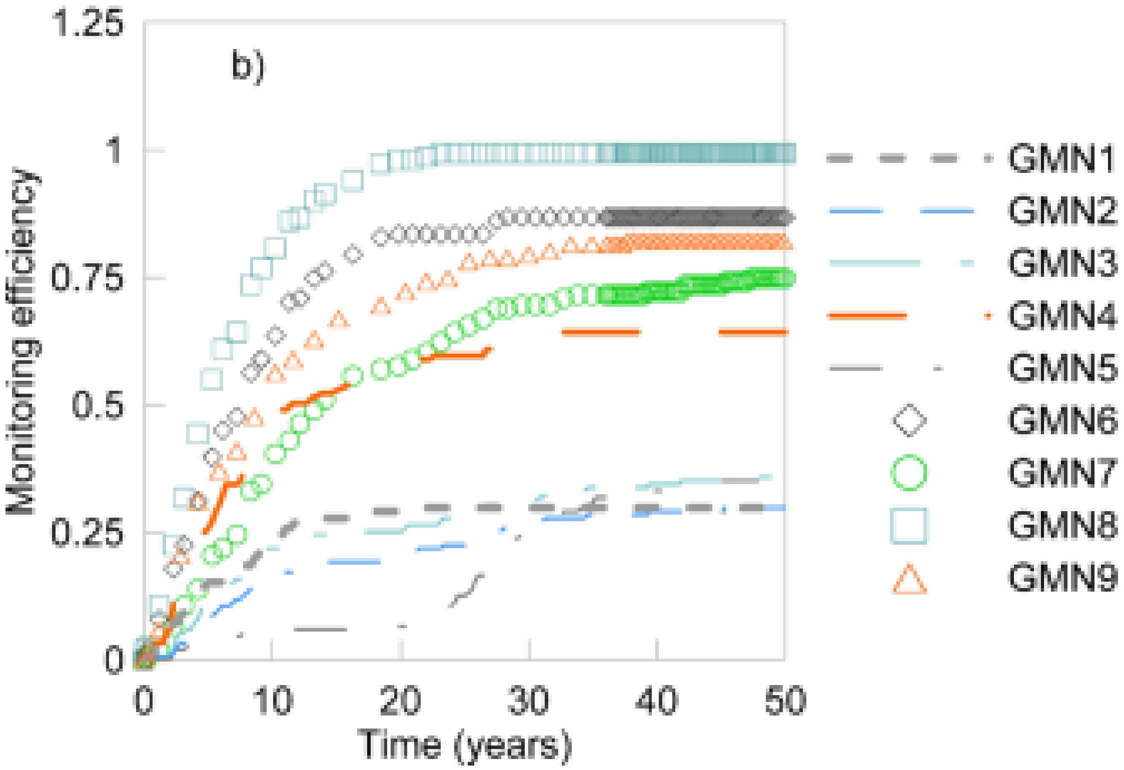
○ Penetration – possible leakage risk

● Groundwater monitoring network

500m

Yang et al. DOI: 10.1021/acs.est.5b01574
Environ. Sci. Technol. 2015, 49, 8887−8898

Answer – None of them!



100 tones/year leaked at any well – efficiency of detection with best constituent – dissolved CO_2 , with 35 groundwater monitoring wells, takes decades to detect leakage even with well density of 0.87 wells/km2

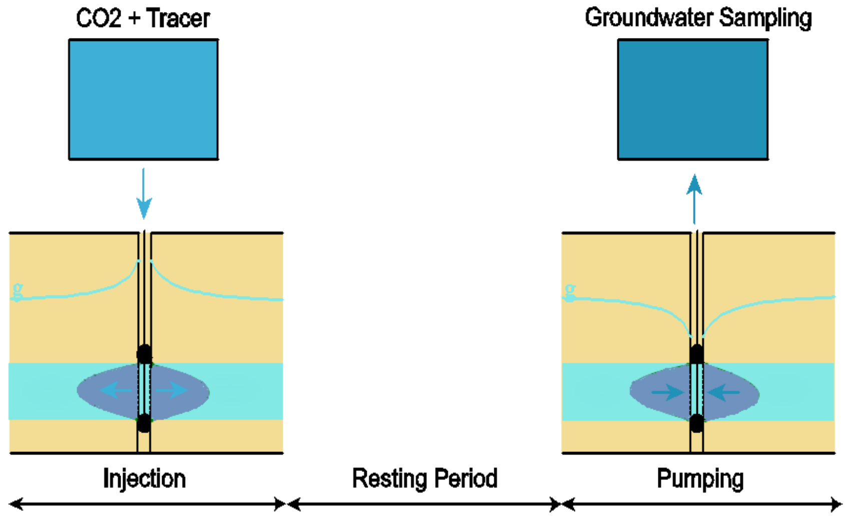
Yang et al. DOI: 10.1021/acs.est.5b01574
Environ. Sci. Technol. 2015, 49, 8887−8898

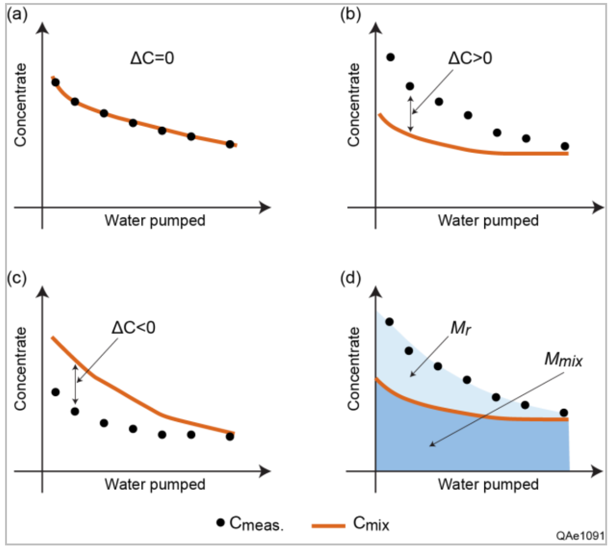
Examples of Constituents that separate deep fluids from shallow ground water and surface water

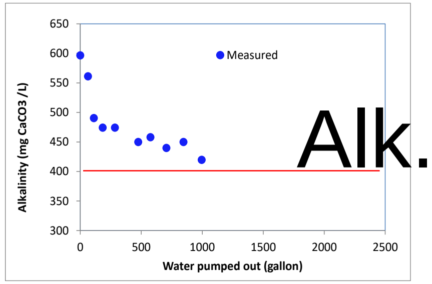
Deep	Shallow
Saline water	Fresh water
Na-Cl SO_4 H_2S	Bicarbonate?
Strong rock-water interaction	what cations?
Cl/Br ratio?	Limited rock-water interaction
Noble gasses He	other natural tracers
other natural tracers	
Thermogenic hydrocarbons (Bernard 1978)	Biogenic hydrocarbons
Light ^{13}C isotopes	Heavy ^{13}C isotopes
Higher hydrocarbons (ethane C2 butane C3)	Mostly methane (C1)

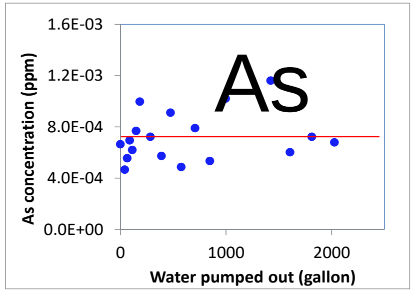
GCCC GULF COAST CARBON CENTER
BUREAU OF ECONOMIC GEOLOGY

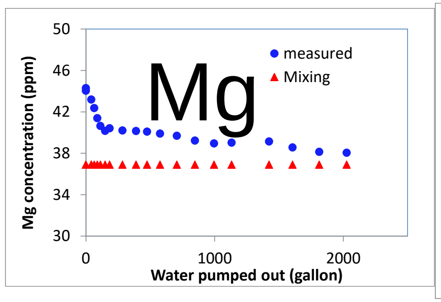
Try it and see – controlled release experiments

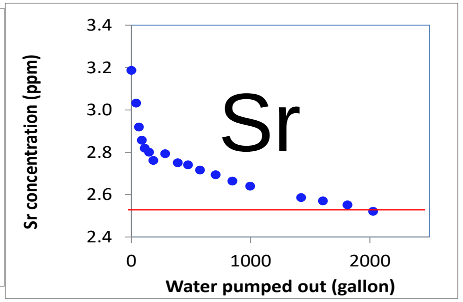












We fail to get much response from low MCL constituents

Yang, Changbing, et al, 2013 Water Research Foundation Web Report #4265

Storage is intrinsically secure – monitoring can be used to increase confidence

- 50 years experience with CO_2 injection for Enhanced Oil Recovery
  - Leakage and other risk is known and small see https://www.rrc.texas.gov/oil-and-gas/compliance-enforcement/blowouts-and-well-control/
- Dozens of monitored CO2 storage projects demonstrate viability
- Monitoring tools available to provide increased confidence

Main points

- Fluid and CO_2 storage in deep saline formations (porous media) is an old art – success/failure rate known, low, non-catastrophic
- Retention driven by:
  - Depth
  - Layering
  - Porous media hysteretic effects
  - Site selection
- Oversight and monitoring
  - 1) support value
  - 2) reduce uncertainty