SECARB PHASE III EARLY TEST CRANFIELD, MS

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Gulf Coast Carbon Center, Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin

Management of SECARB









Early Test

University of Texas at Austin



Bureau of Economic Geology

Gulf Coast Carbon Center

DRI Denbury Resources Inc

Sandia Technologies LLC

LBNL LLBL USGS
ORNL EPA QEA
U Mississippi Miss State

Schlumberger Carbon Services

Gulf Coast Carbon Center

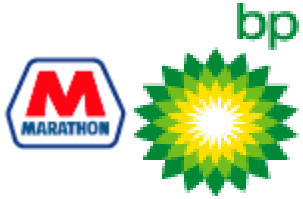


























Other SECARB tests

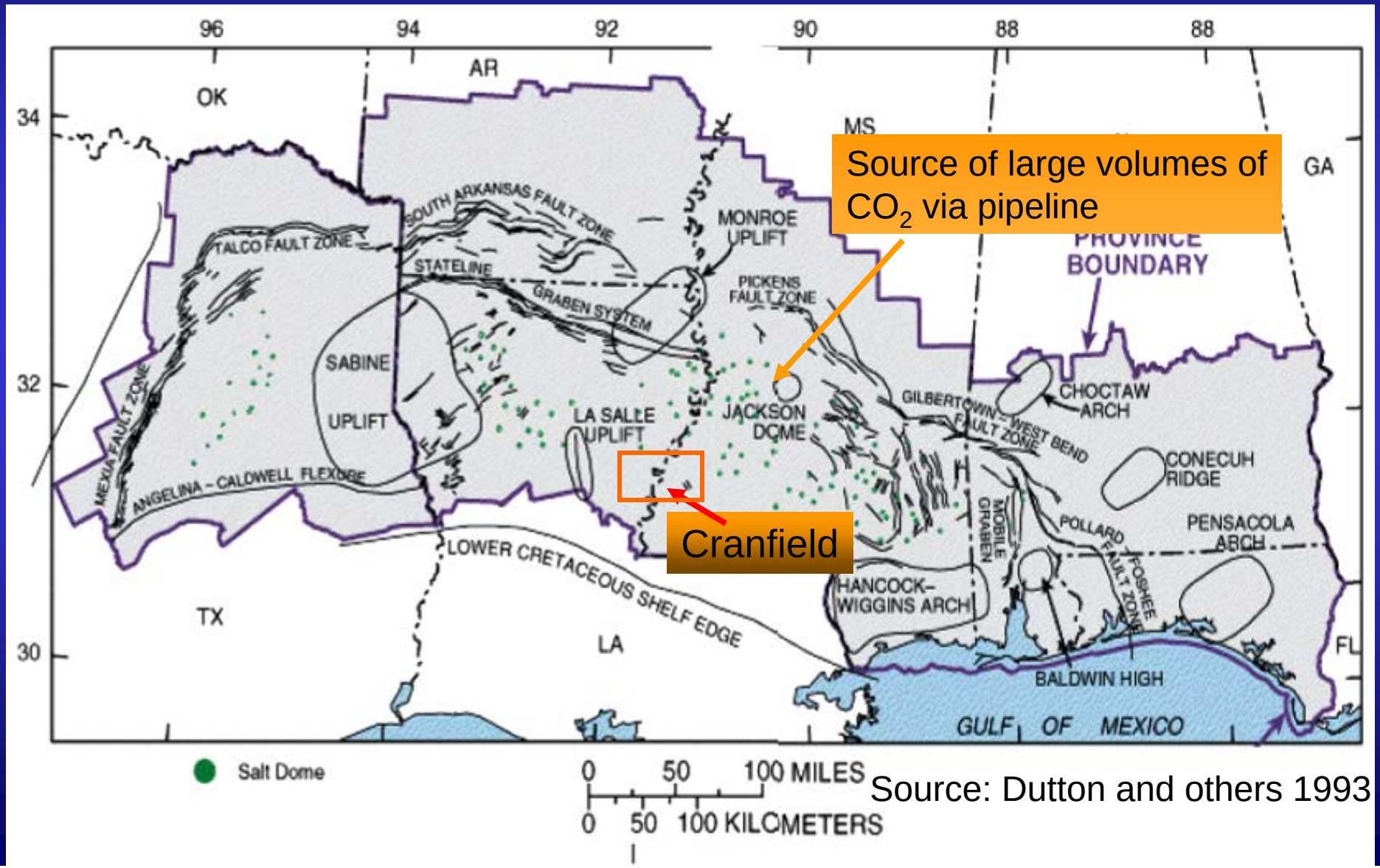
SECARB coal seam tests
Geological Survey of Alabama
Virginia Tech

SECARB Power Plant tests
EPRI
Southern Co
ARI

Overview

- **Background Information**
- **Phase III Design**
- **Summary**

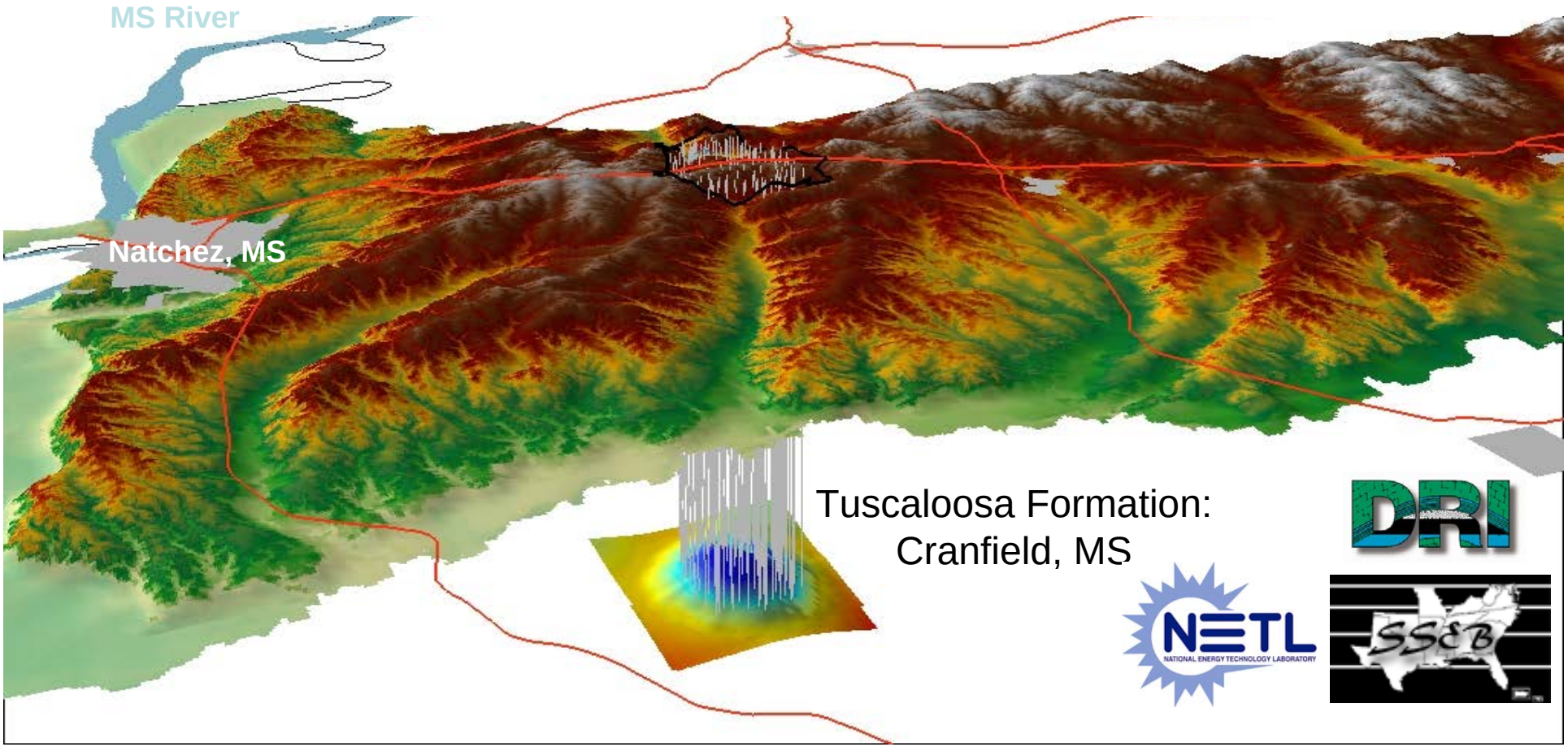
Upper Cretaceous Tuscaloosa-Woodbine Trend – Cranfield in Mississippi Salt Basin



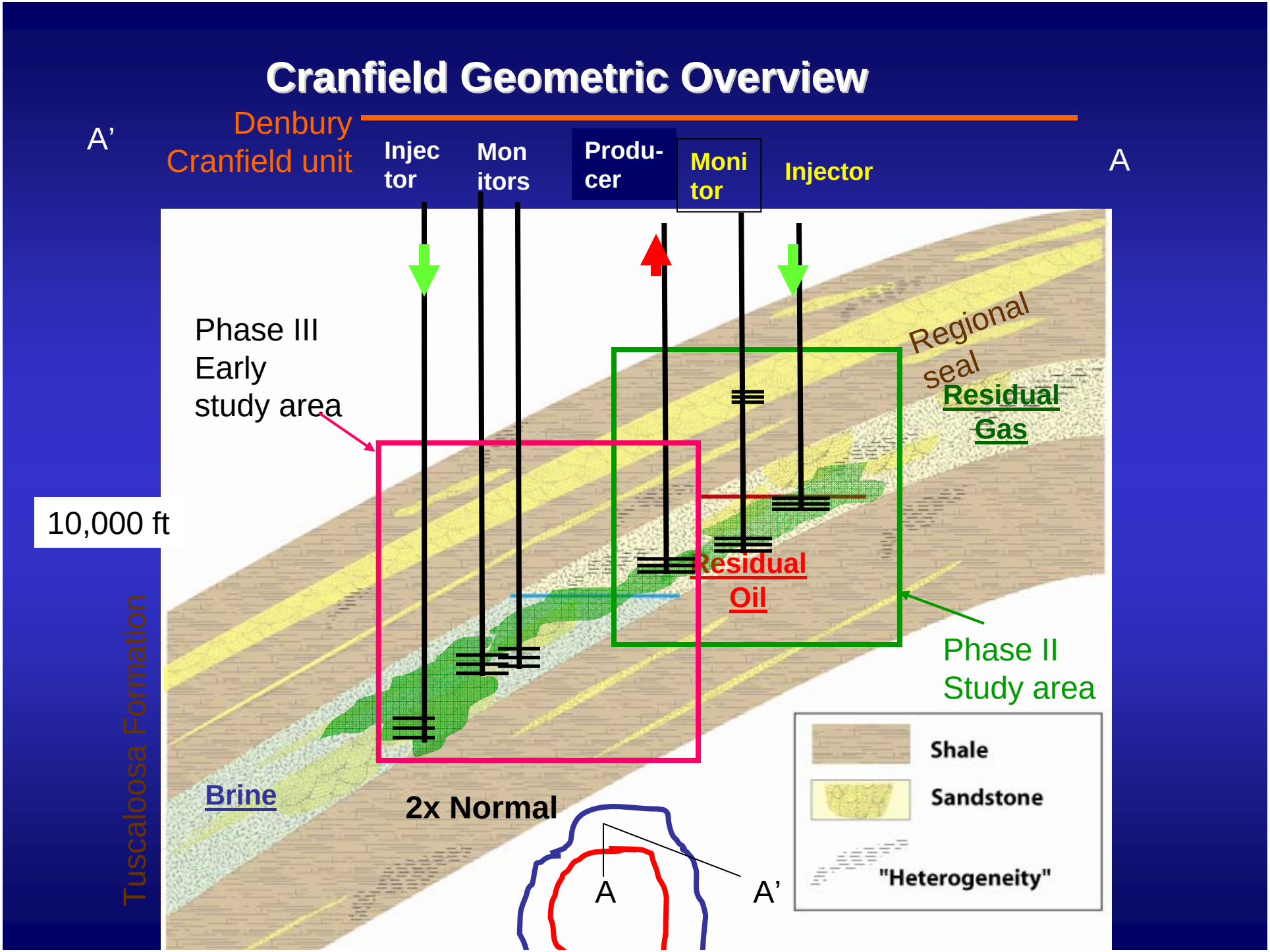
Source: Dutton and others 1993

Gulf Coast Stacked Storage Field Test

Phase 3: $36M, 2 observation wells, multiple injectors, 1 Mt/yr



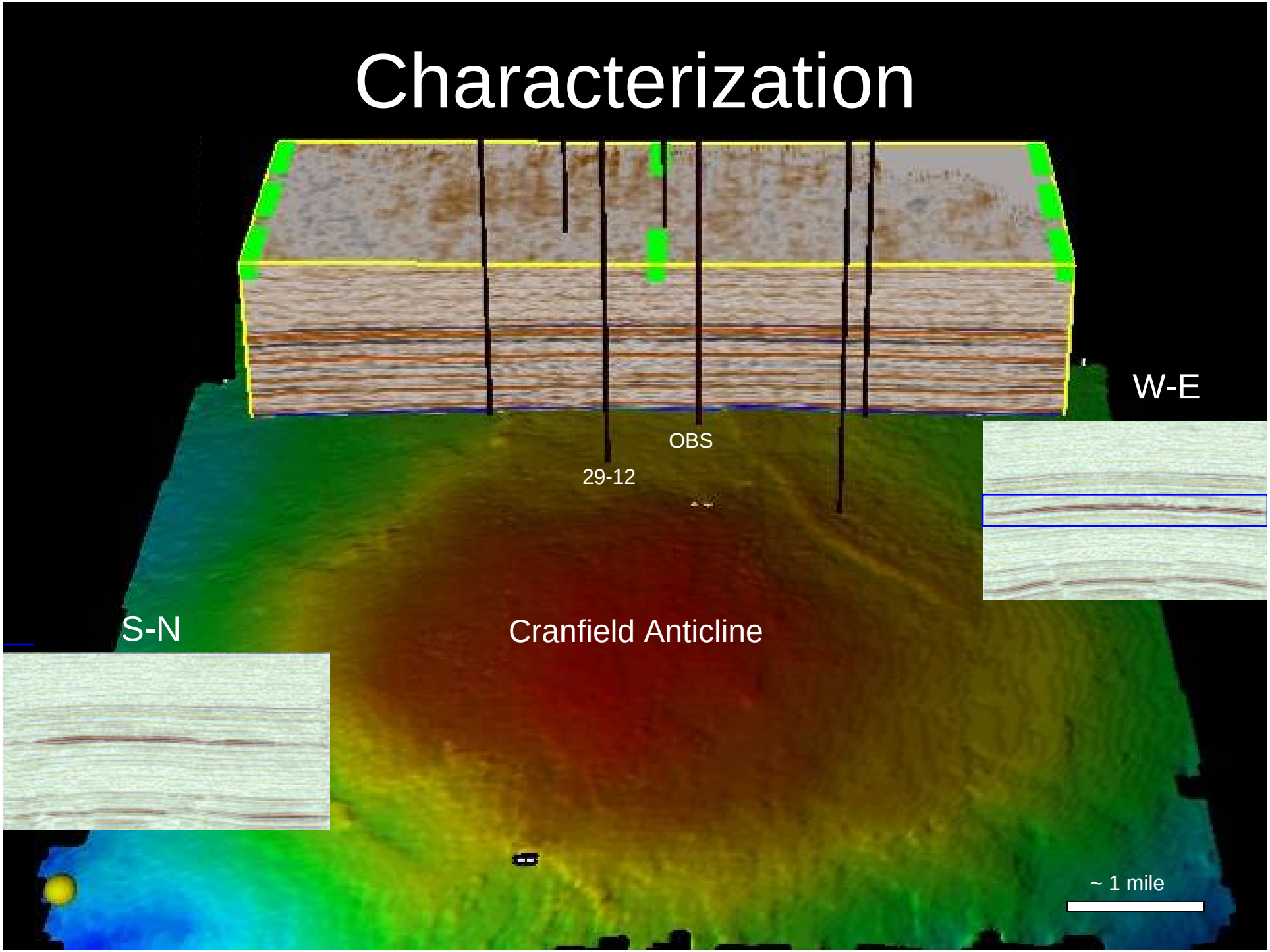
Cranfield Geometric Overview

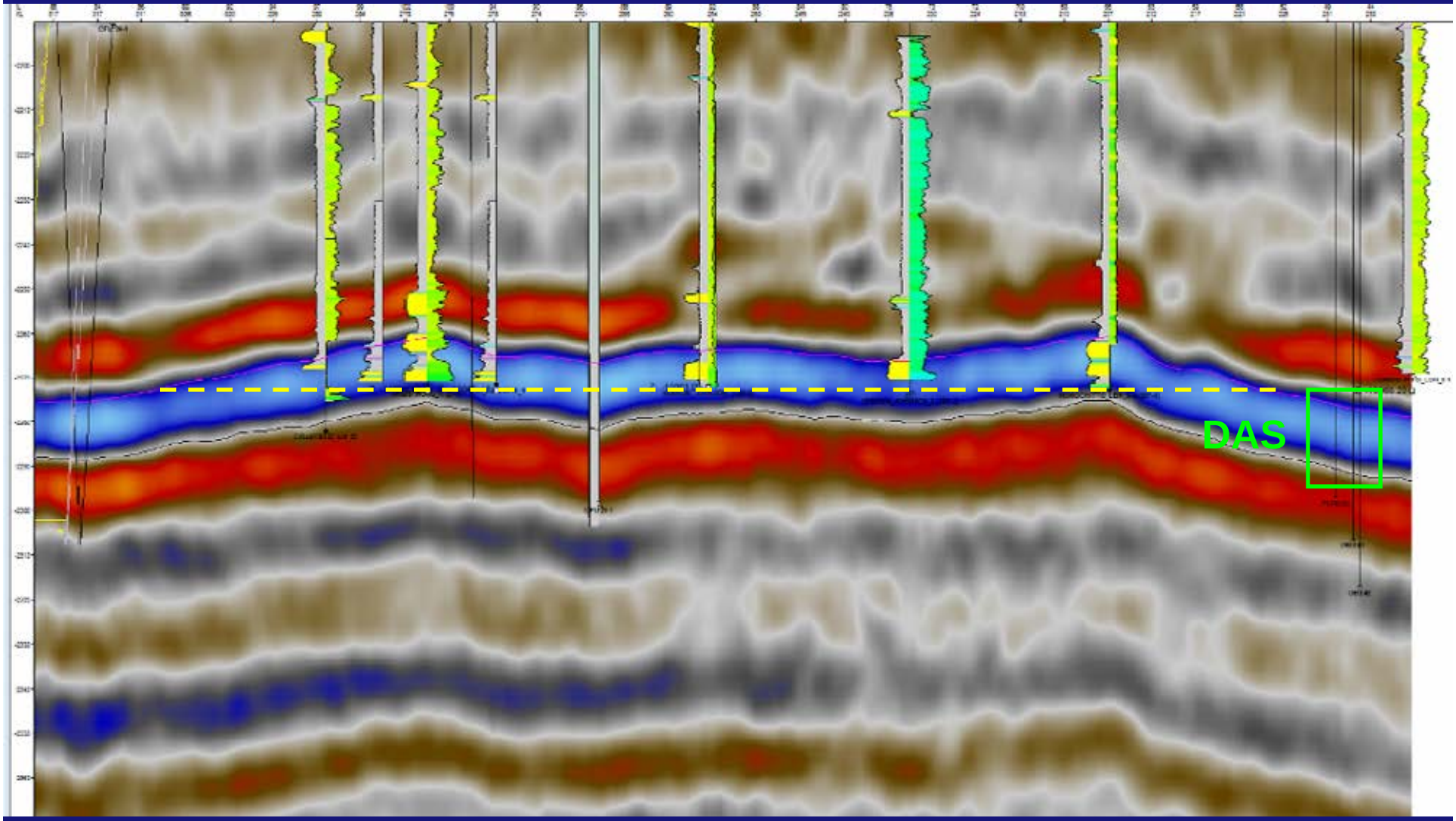


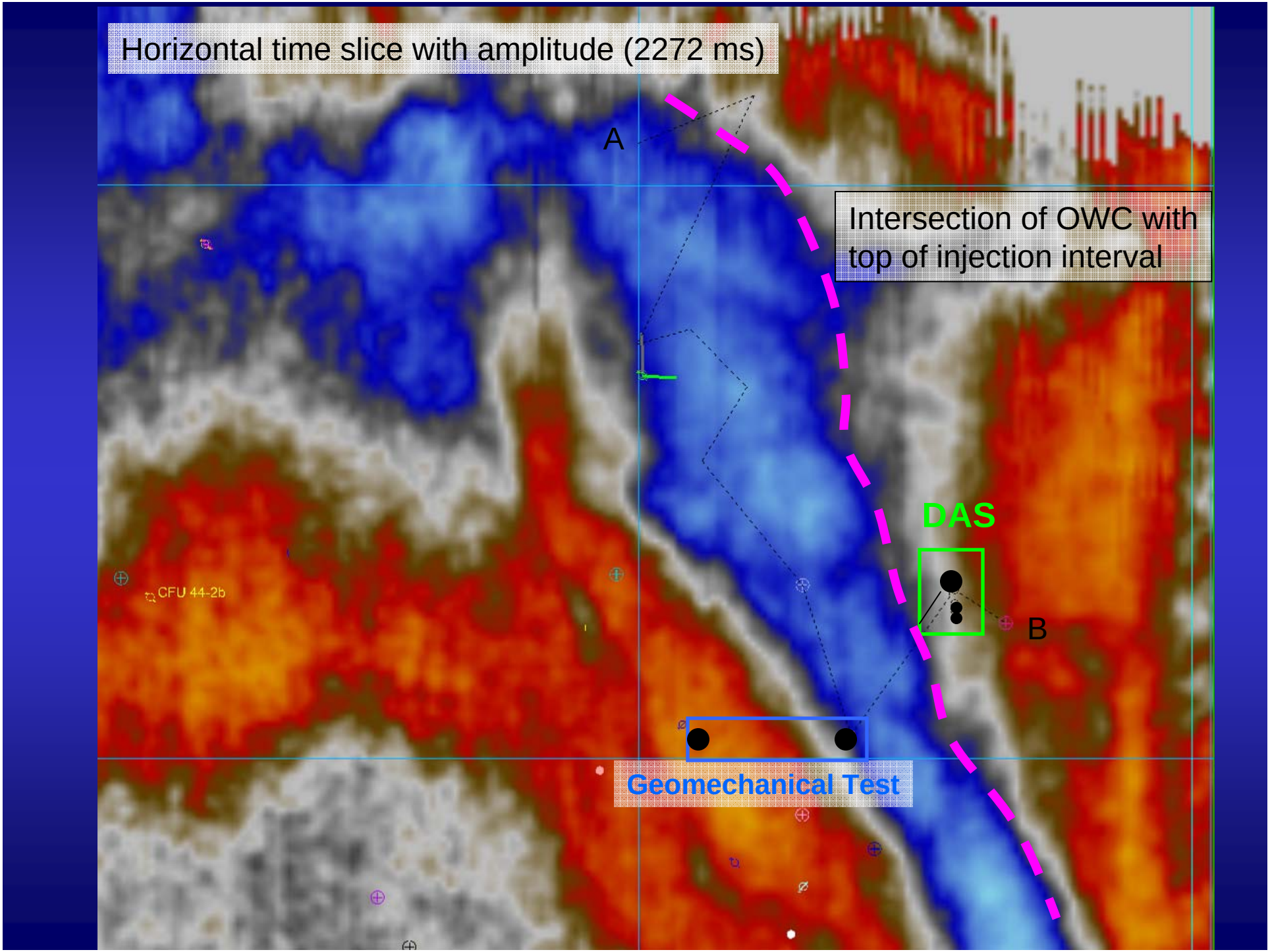
Phase III Design

- Two Observation Wells
  - CASSM
  - X-well tomography
  - ERT
  - Joint inversion (saturation, sweep efficiency)
  - Fluid sampling (U-tube)
  - Thermal response
  - Whole cores / core analyses
- Geomechanical Test
  - Paired Injection / Production
  - Downhole Microseismic & Tilt
  - In-zone / out-of-zone activity: pressure and fluid migration
- Far-Field Measurements
  - RST
  - BHP
  - BHT

Characterization

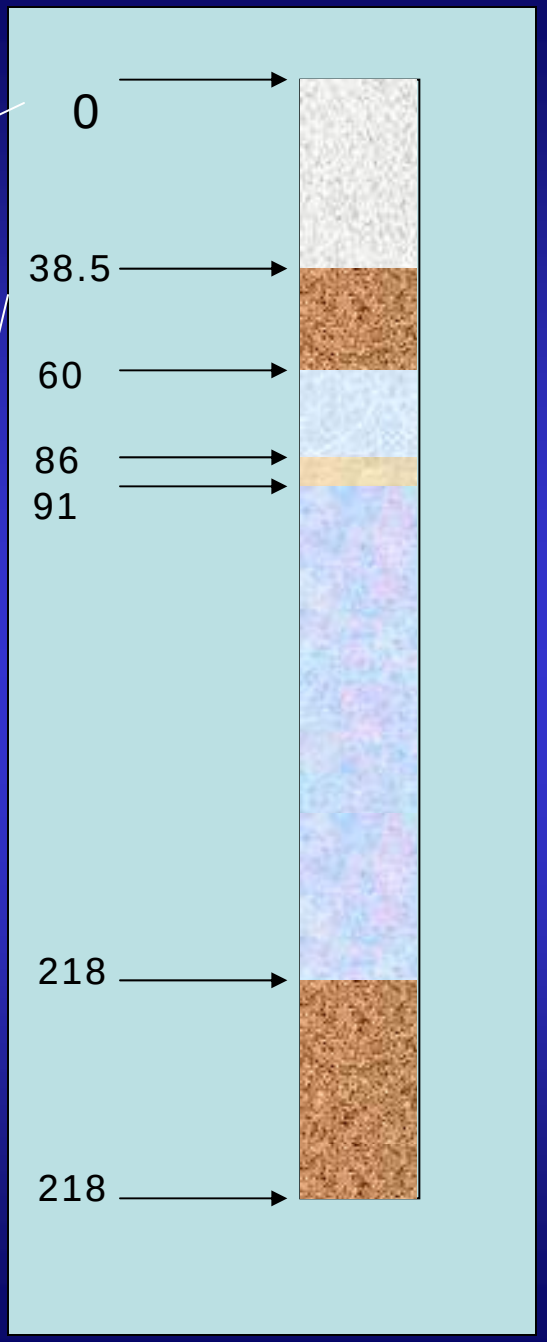



A
B
DAS


Horizontal time slice with amplitude (2272 ms)
A
Intersection of OWC with top of injection interval
DAS
B
CFU 44-2b
Geomechanical Test

Deep water table

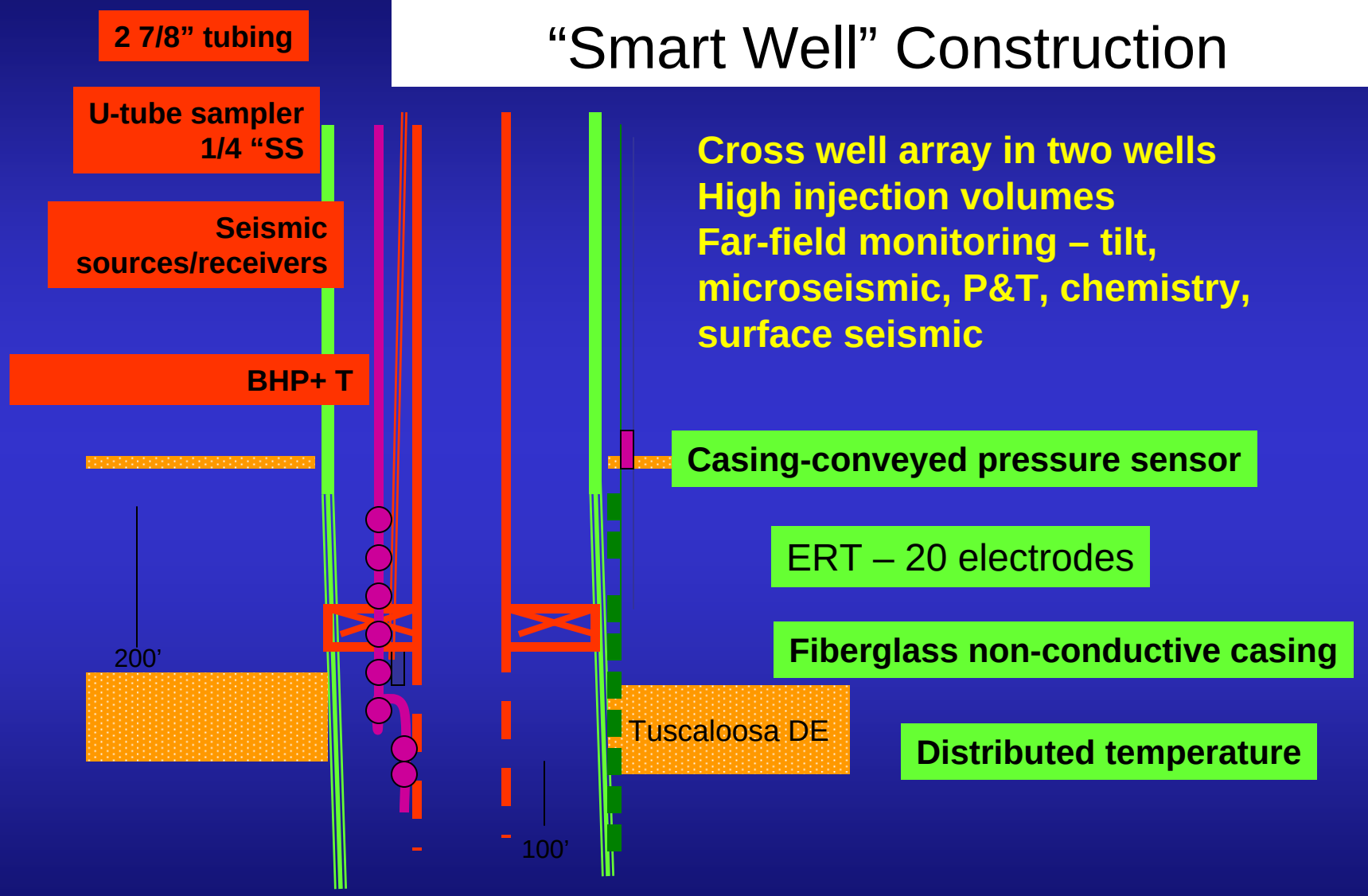




Scientific and Technical Objectives &Benefits

Objective	Anticipated Benefit
(1) Sweep efficiency brine system	• Well-quantified measure of how CO_2 occupies pore volumes
(2) Novel effort to account for volume and energy input	• Add rigor to pressure measurement for storage prediction
(3) Leakage though 1945 wells? Assess effectiveness of surface monitoring in a deep water table	• Challenge these technologies - Reliable leakage detection?

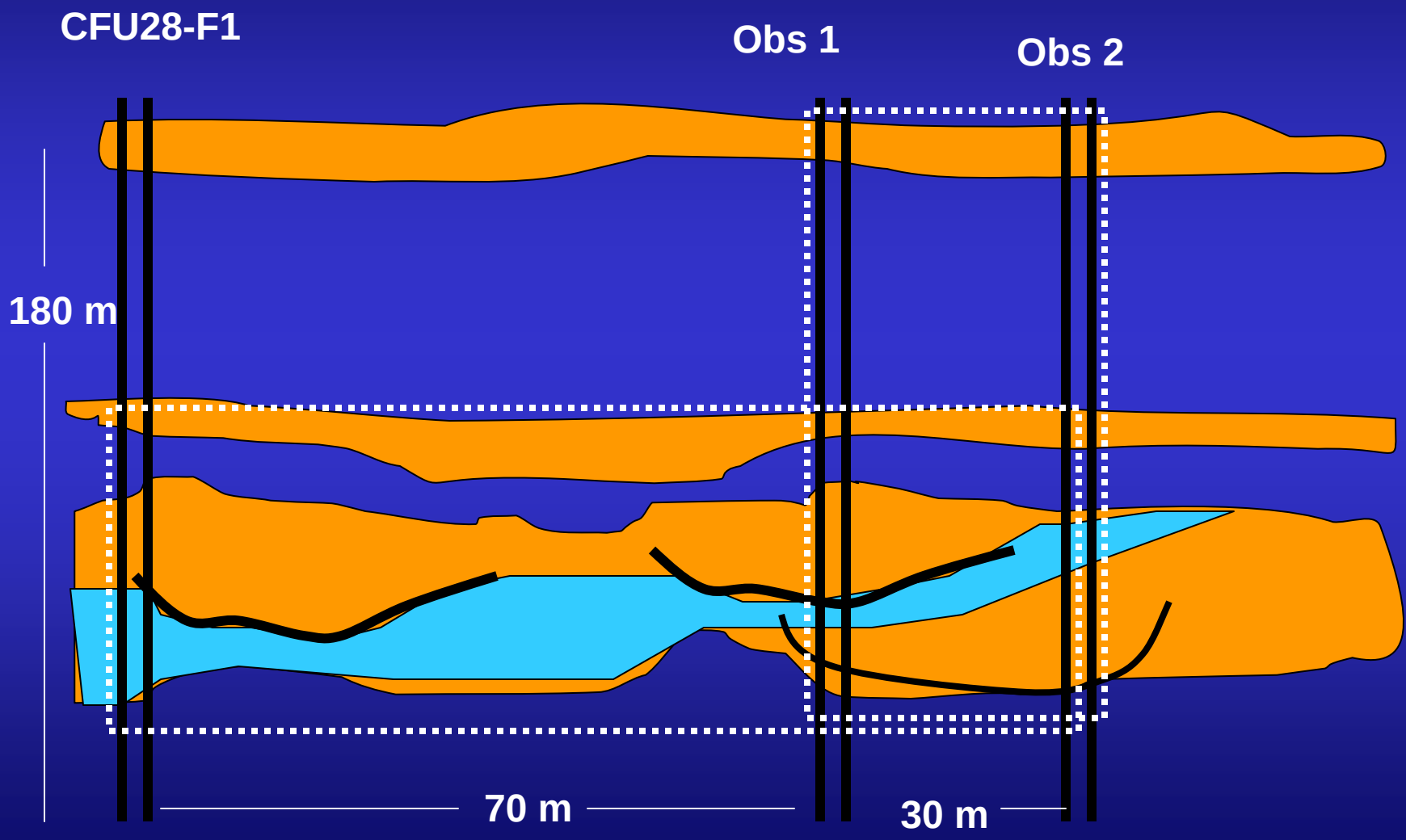
Planned Phase III Observation "Smart Well" Construction



Cross well array in two wells
High injection volumes
Far-field monitoring – tilt, microseismic, P&T, chemistry, surface seismic

BEG, LBNL, LLNL, USGS, ORNL, Pinnacle, QEA, Sandia Technologies

Planned Subsurface Measurements

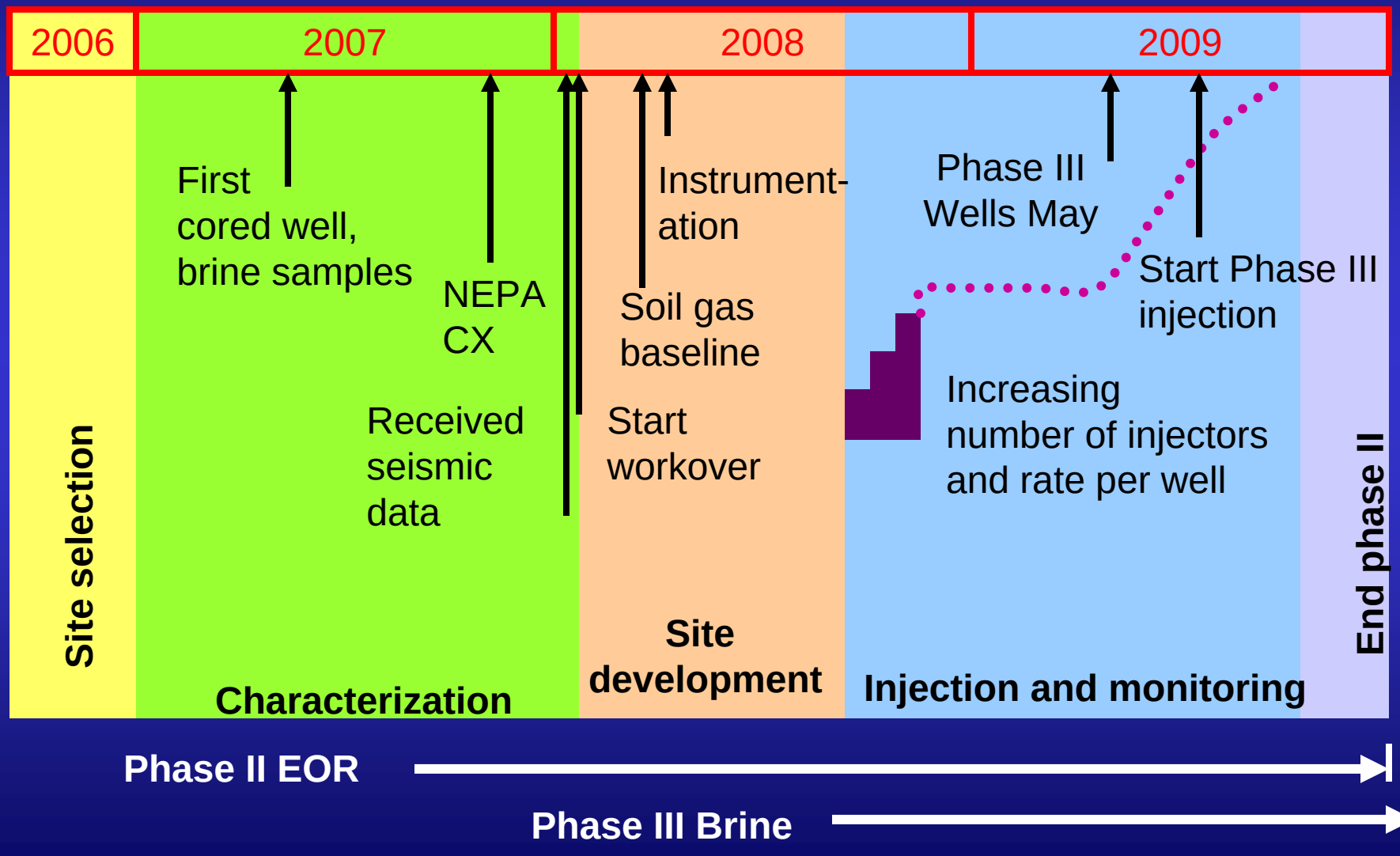


Phase III Summary

Currently Mid-May / Observation Well #1

- **Down-Dip Brine Injection**
- **Intensive Monitoring Campaign**
  - **Cross well**
  - **Geomechanical**
  - **Far Field**

Progress


2006
2007
2008
2009
First cored well, brine samples
NEPA CX
Received seismic data
Instrument-ation
Soil gas baseline
Start workover
Phase III Wells May
Start Phase III injection
Increasing number of injectors and rate per well
Site selection
Characterization
Site development
Injection and monitoring
End phase II
Phase II EOR
Phase III Brine

Cranfield Mississippi



SECARB Phase III Early Test at Cranfield



SECARB Stakeholders
March 9, 2010
Atlanta GA

Susan Hovorka
Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of Geoscience
The University of Texas at Austin



Cranfield "Early" Field Test Collaboration

Denbury Onshore LLC

Sandia Technologies LLC

LBNL
LLBL
USGS
ORNL
NETL
QEA
U Mississippi
Miss State
UTPGE
UT DoG
University Tennesse
BP
Princeton
Stanford

Gulf Coast Carbon Center Staff

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Rebecca Smyth
Sigrid Clift
Masoumeh Kordi
Stuart Coleman
Yihua Cai

BEG others

Tongwei Zhang
Jeff Paine
Bob Reedy
Robert Reed
Kitty Millican

Schlumberger Carbon Services

Pinnical Technologies

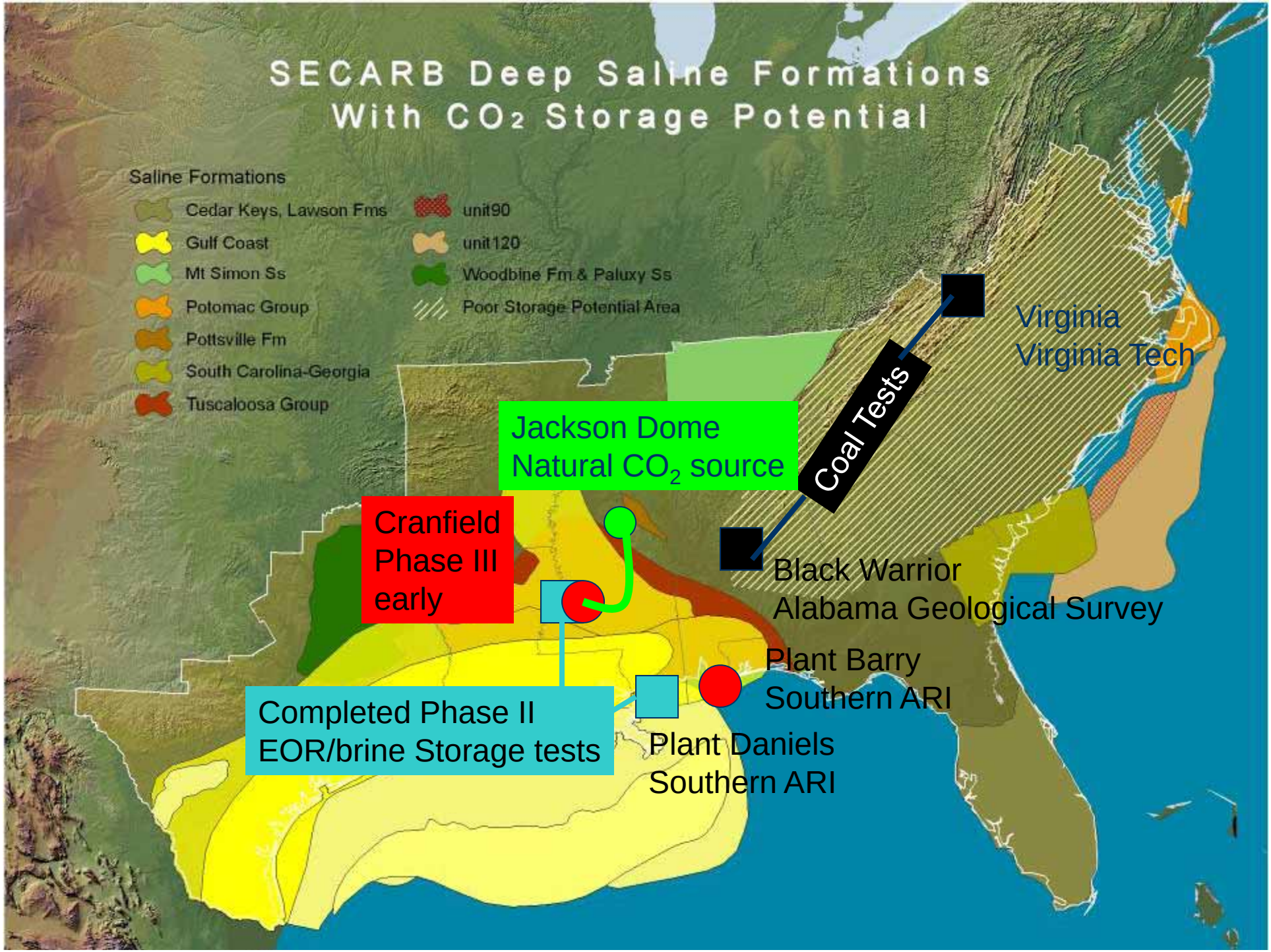
Gulf Coast Carbon Center Industrial Associates

Entergy
THE POWER OF PEOPLE
NRG
Schlumberger
LCRA
ENERGY • WATER • COMMUNITY SERVICES
Luminant
AUSTIN ENERGY
KINDER MORGAN
bp
MARATHON
Chevron
ConocoPhillips
Energy for tomorrow
ExxonMobil
Taking on the world's toughest energy challenges.
e
ENVIRONMENTAL DEFENSE
Saudi Aramco
The University of Texas at Austin
John A. & Katherine G.
JACKSON
SCHOOL OF GEOSCIENCES

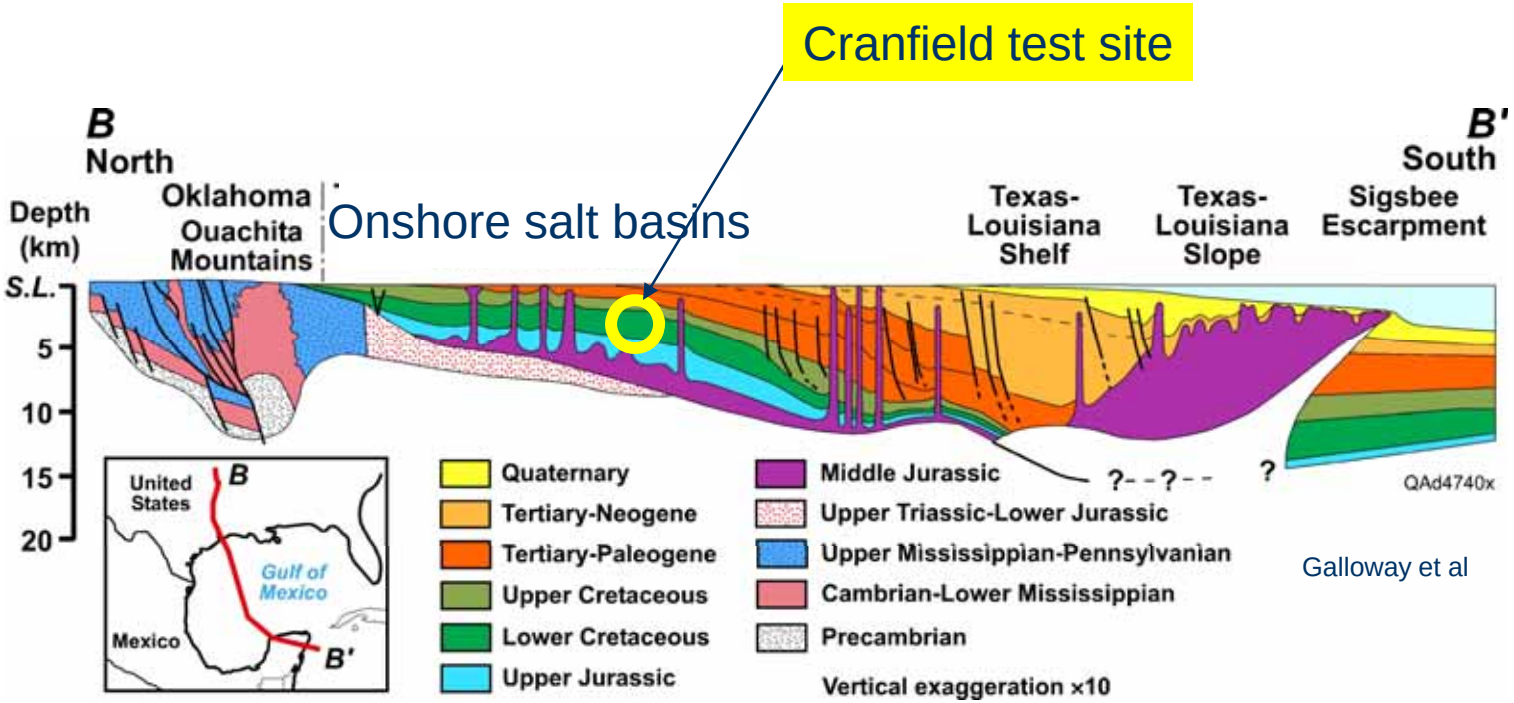
Interim Conclusions of Phase III Early Study at Cranfield

- Phase III 1 million ton/year rate achieved Dec 20, 2009
- Rate to be maintained >15 months
- Monitored with standard and novel approaches 30 months
  - 5 research areas
  - Tests of soil gas approaches in complex environments
  - Saturation change measured/monitored with multiple tools in complex flow field
  - First US use of Electrical Resistance Tomography (ERT) for sequestration
  - Quantification of dissolution
- Export to commercial EOR/sequestration projects

Gulf Coast Carbon Center


SECARB Deep Saline Formations
With CO_2 Storage Potential
Saline Formations
Cedar Keys, Lawson Fms
Gulf Coast
Mt Simon Ss
Potomac Group
Pottsville Fm
South Carolina-Georgia
Tuscaloosa Group
unit90
unit120
Woodbine Fm & Paluxy Ss
Poor Storage Potential Area
Virginia
Virginia Tech
Coal Tests
Jackson Dome
Natural CO_2 source
Cranfield
Phase III
early
Black Warrior
Alabama Geological Survey
Plant Barry
Southern ARI
Completed Phase II
EOR/brine Storage tests
Plant Daniels
Southern ARI

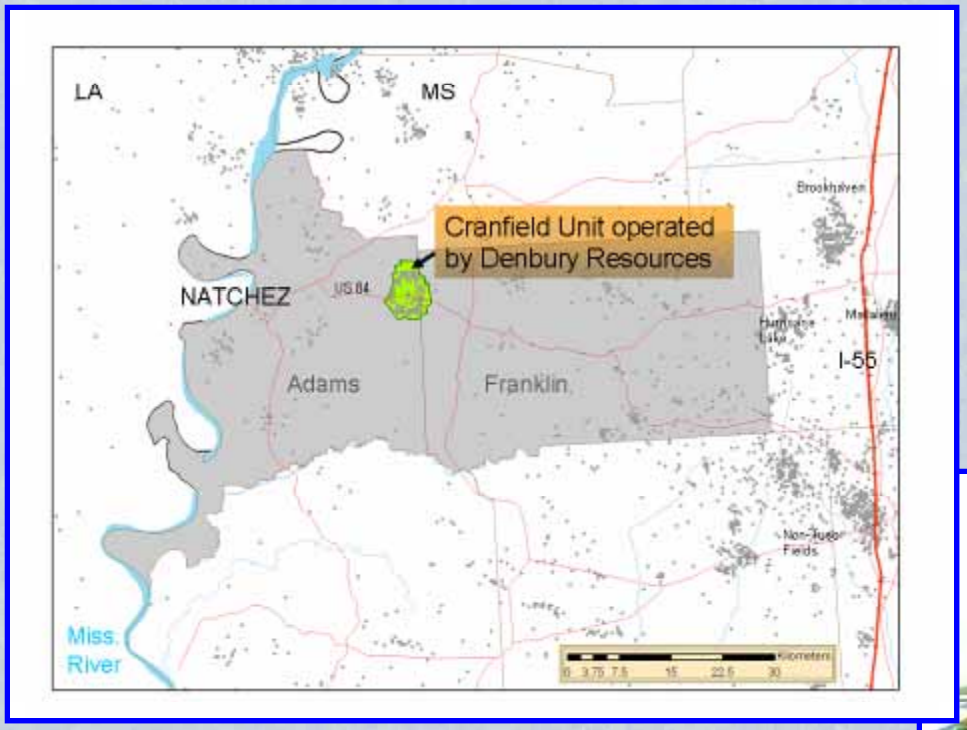
Natural CO_2 Available Now in large Volumes Shipped via Sonant Pipeline to Test Lower Part of the Gulf Coast Wedge



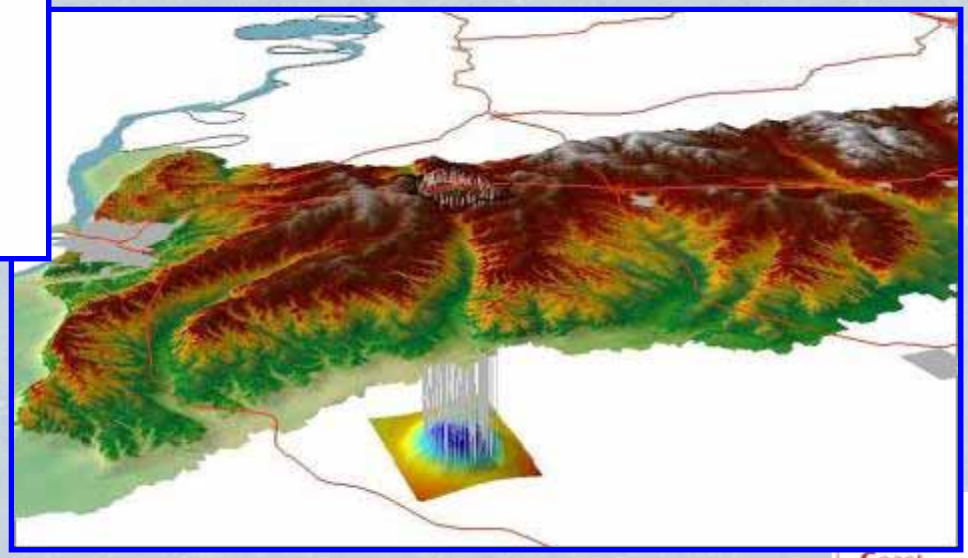
Relatively young sandstones with shale seals
Heterogeneous, high porosity sediments
Salt tectonics and growth faults
Heavy industry

} Characteristics of the Gulf Coast wedge

SECARB Early test: Cranfield, Mississippi

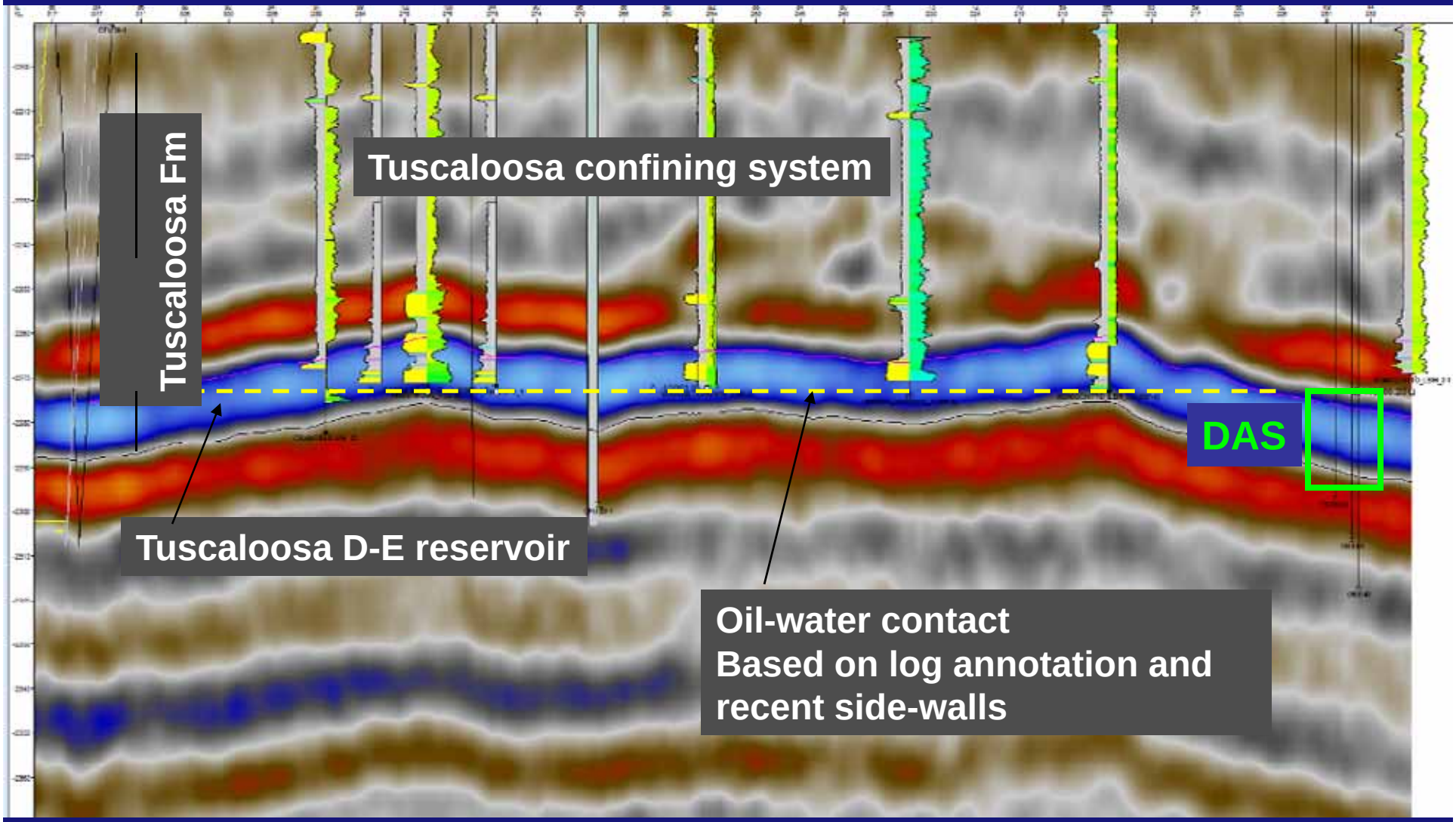


3,000 m depth (10,300 ft)
Gas cap, oil ring, downdip water leg
Original production in 1950's
Strong water drive
Shut in since 1965
Returned to near initial pressure
CO2-EOR initiated 2008 with coincident pressure monitoring
Downdip injection April 2009



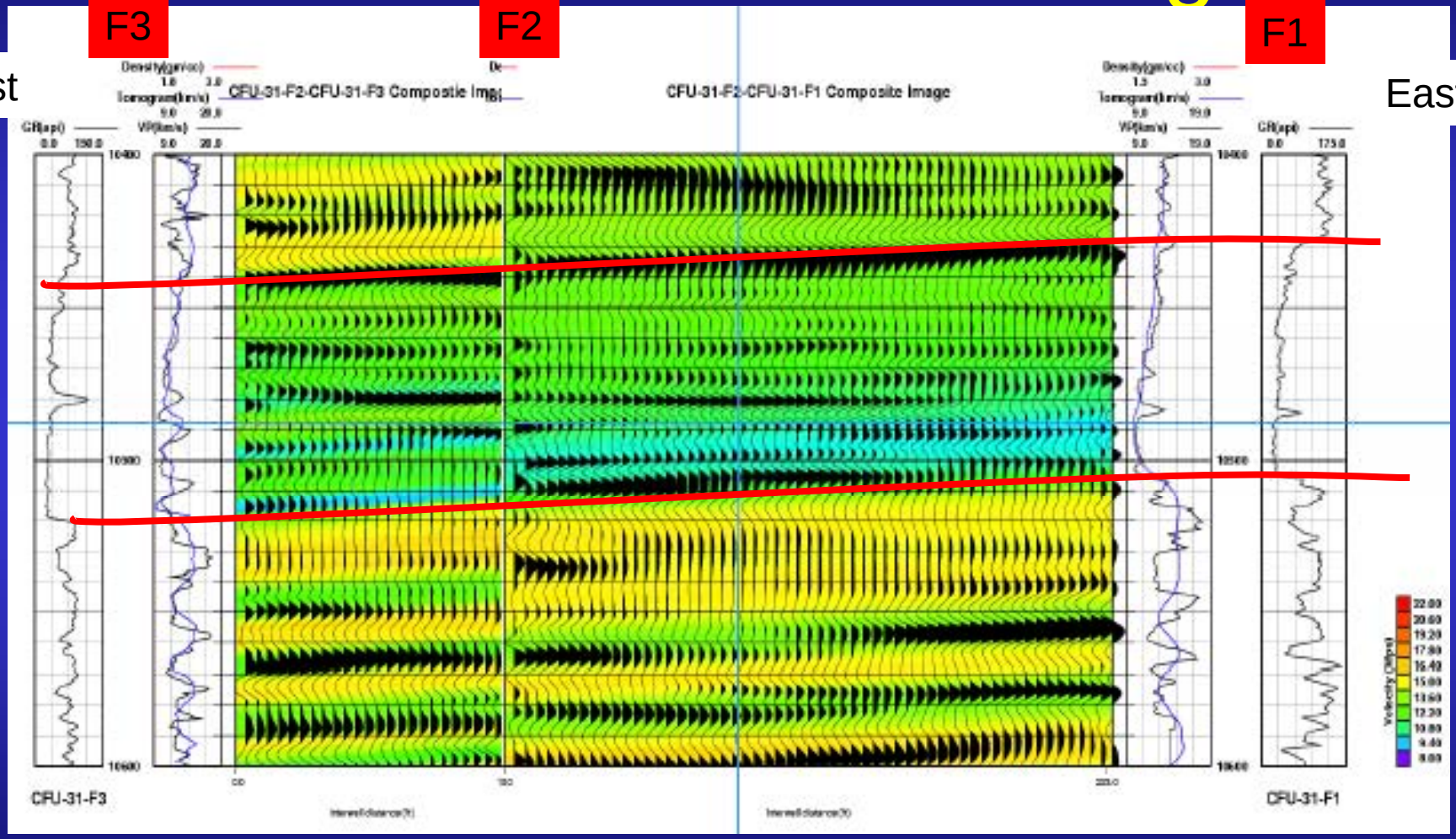
Coast Carbon Center

Location of the Phase III injection below oil-water contact



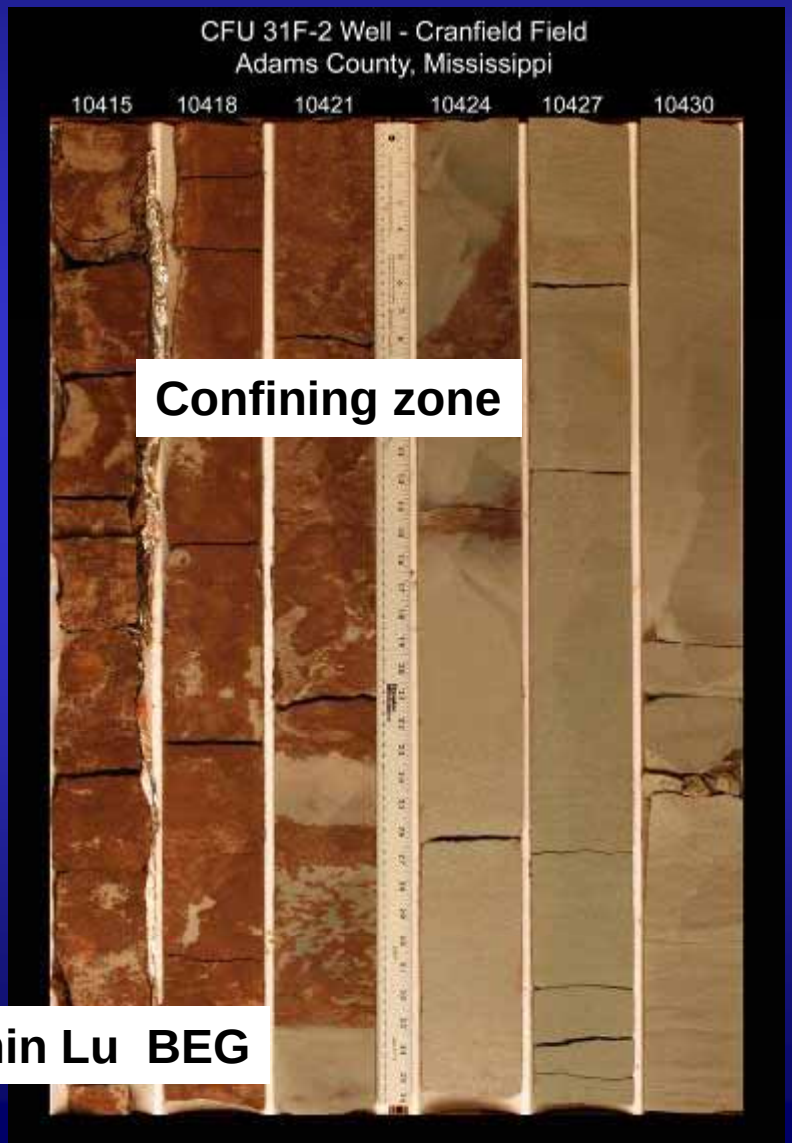
3D Denbury - interpretation Tip Meckel

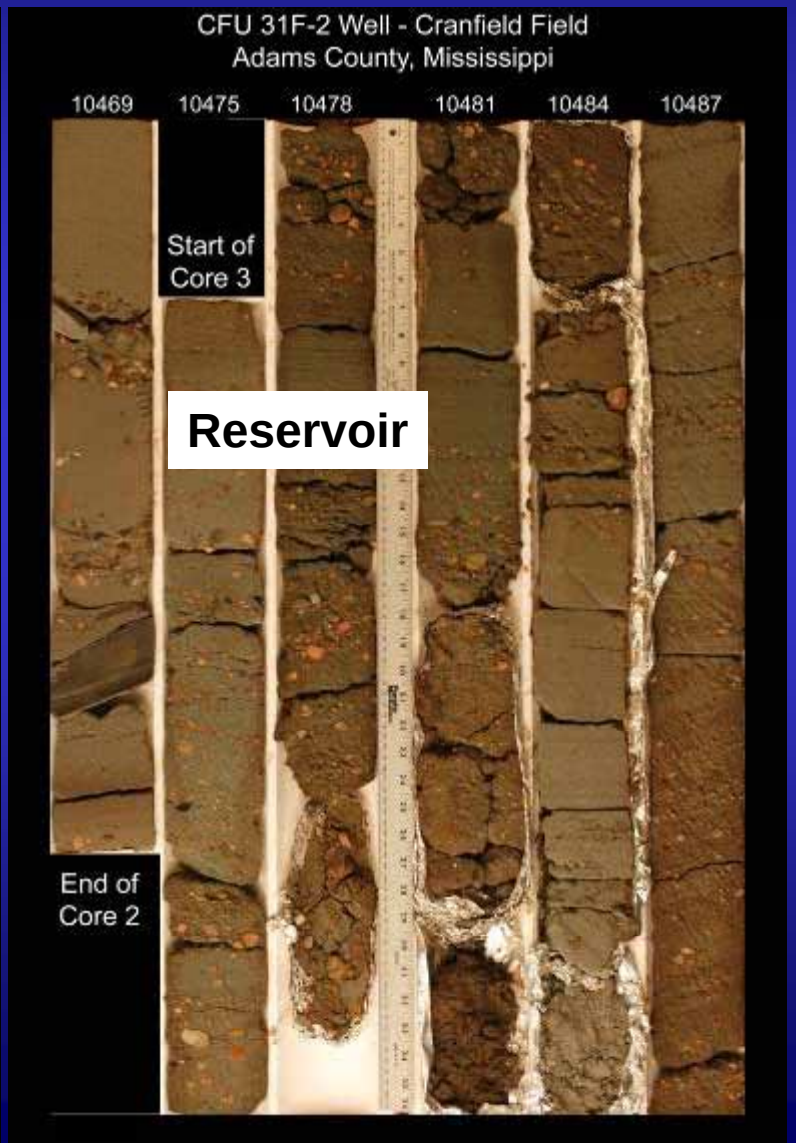
Baseline Cross Well tomogram



Z-Seis & Tom Daley Jonathan Franklin in review at LBNL

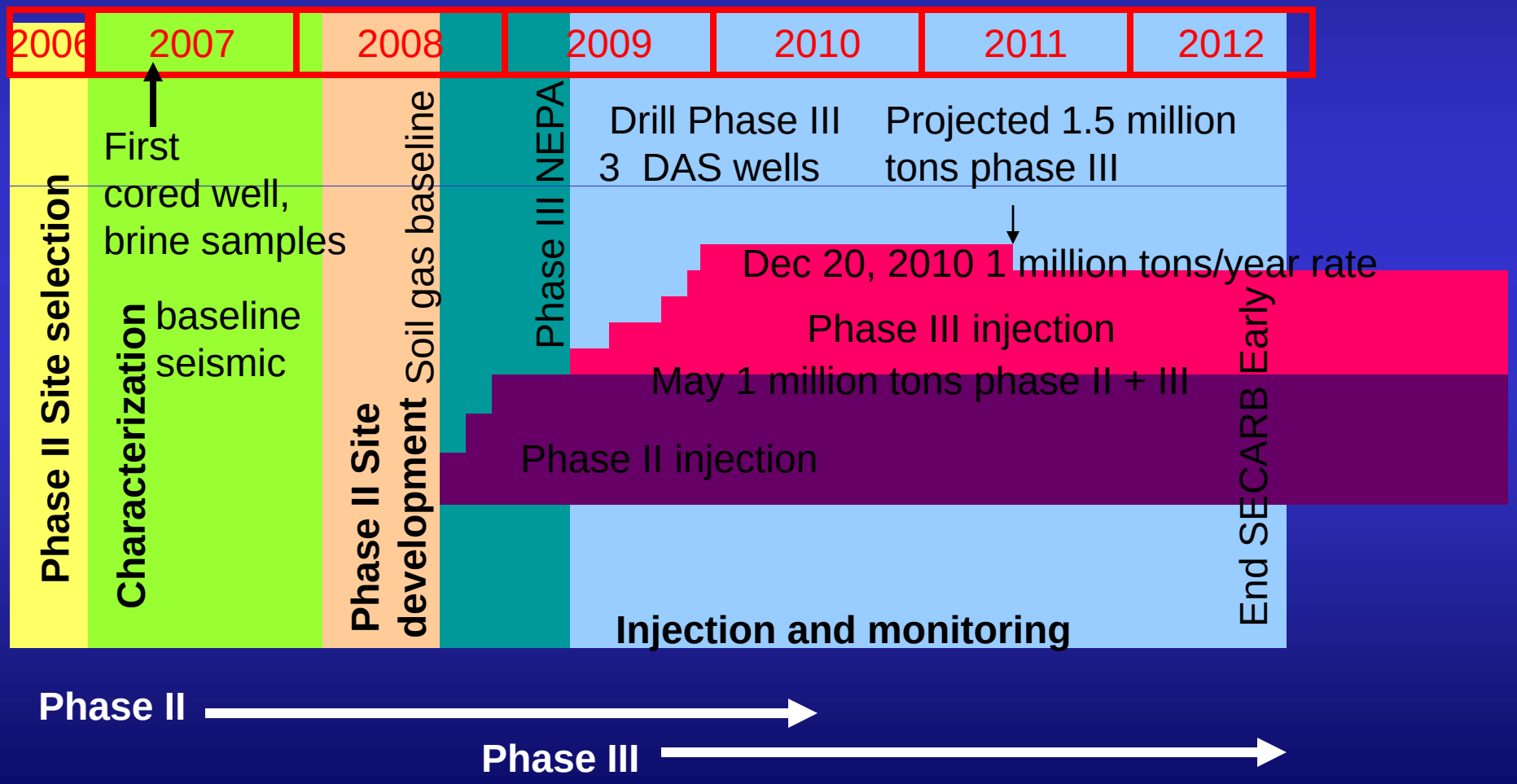
Upward fining fluvial sandstone and conglomerates of the lower Tuscaloosa Fm





Jiemin Lu BEG

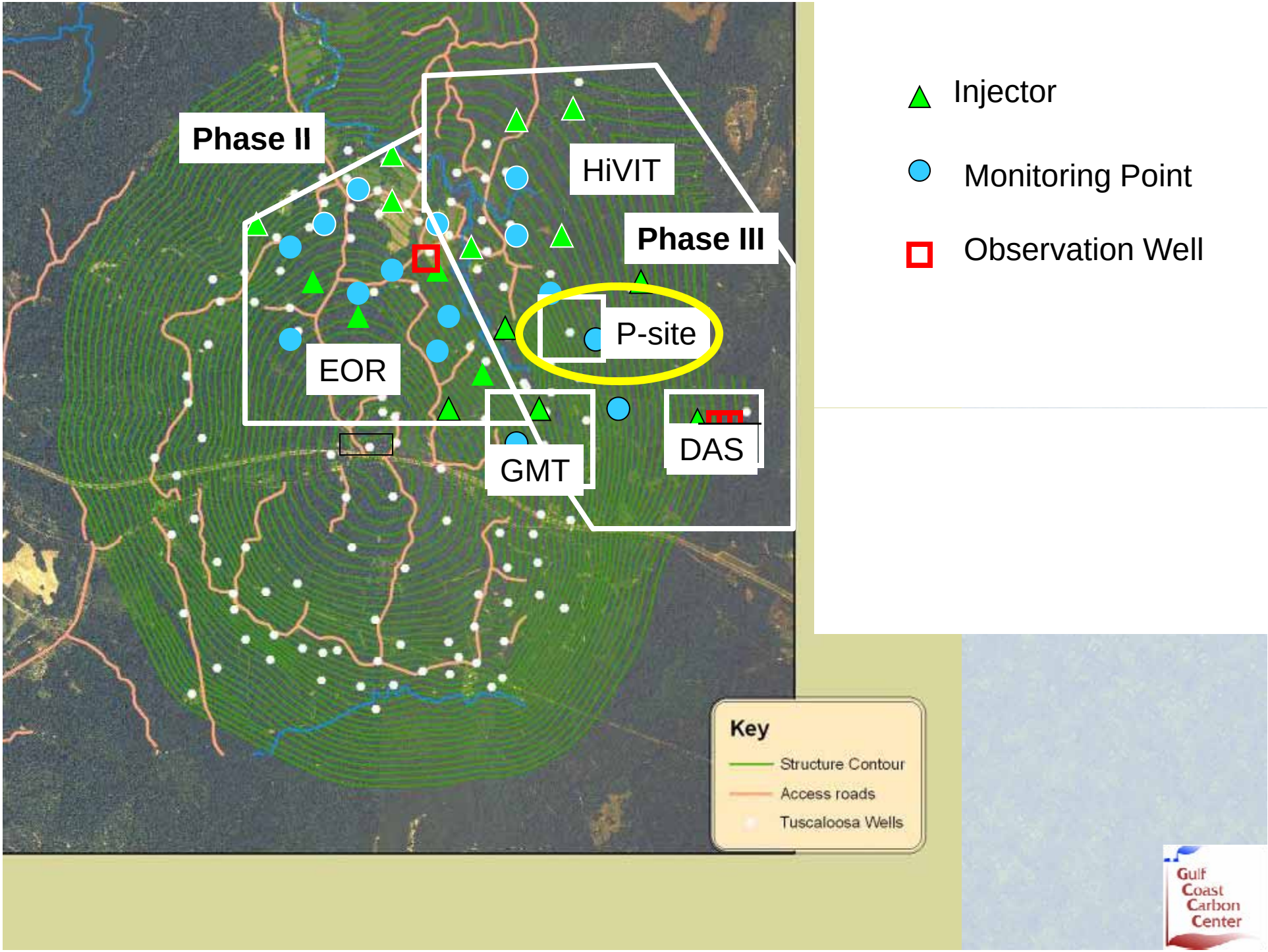
Progress


2006
2007
2008
2009
2010
2011
2012
Phase II Site selection
First cored well, brine samples
Characterization baseline seismic
Phase II Site development Soil gas baseline
Phase III NEPA
Drill Phase III 3 DAS wells
Projected 1.5 million tons phase III
Dec 20, 2010 1 million tons/year rate
Phase III injection
May 1 million tons phase II + III
Phase II injection
End SECARB Early
Injection and monitoring
Phase II
Phase III

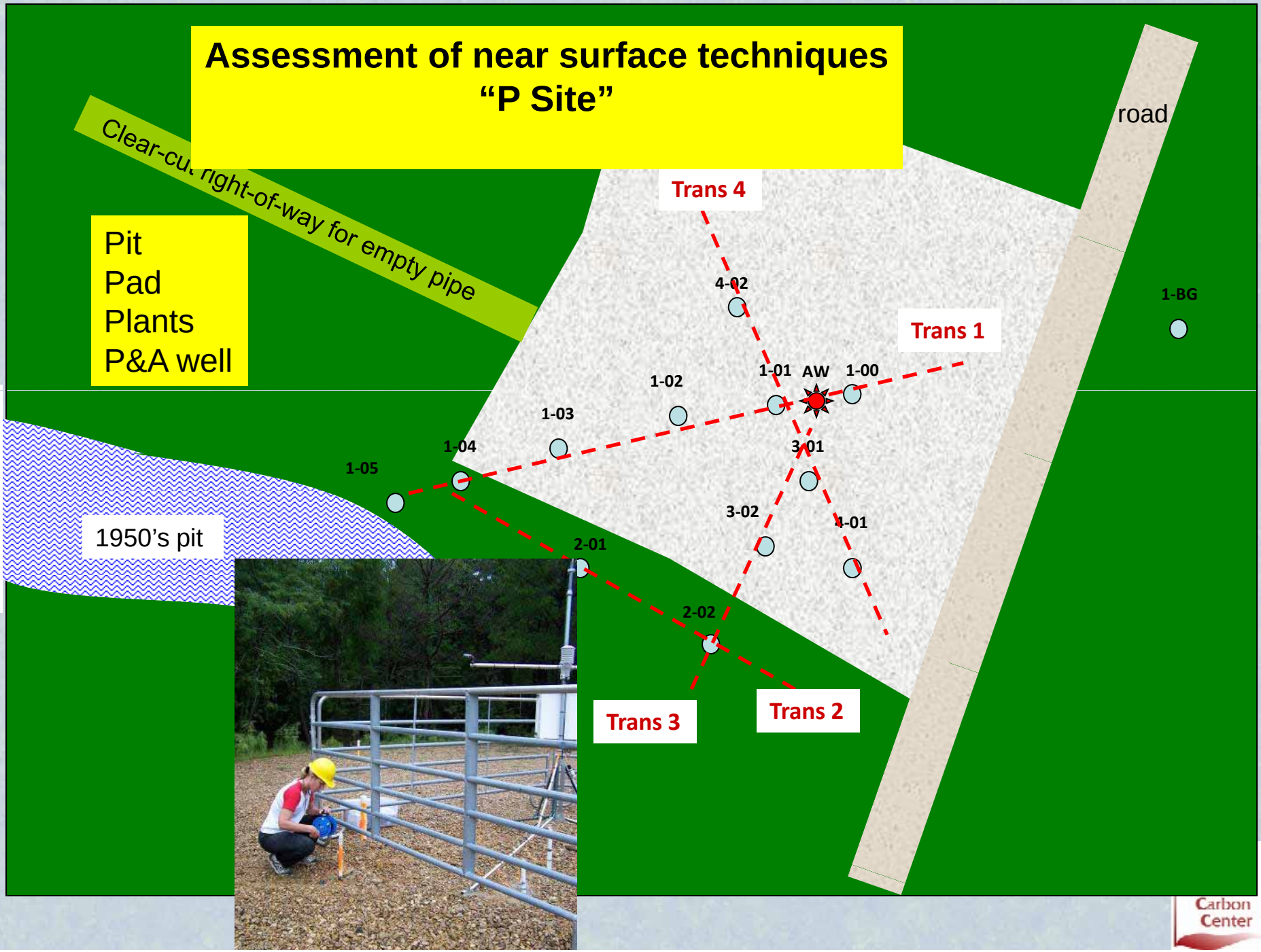
Phase III Research: Theoretical Approaches Through Commercialization

Commercial Deployment by Southern Co.

Toward commercia-lization	Contingency plan Parsimonious public assurance monitoring	Subsurface perturbation predicted	
Hypothesis tested	CO_2 retained in-zone-document no leakage to air-no damage to water	CO_2 saturation correctly predicted by flow modeling	Pressure (flow plus deformation) correctly predicted by model
Field experiments	Surface monitoring: instrument verification Groundwater program CO_2 variation over time Above-zone acoustic monitoring (CASSM) & pressure monitoring	CO_2 saturation measured through time – acoustic impedance + resistivity Tomography and change through time 3- D time lapse surface/ VSP seismic Dissolution and saturation measured via tracer breakthrough and chromatography	Microseismic test, pressure mapping Acoustic response to pressure change over time
Theory and lab	Sensitivity of tools; saturated-vadose modeling of flux and tracers	Lab-based core response to EM and acoustic under various saturations, tracer behavior	Advanced simulation of reservoir pressure field


Phase II
HiVIT
Phase III
P-site
EOR
GMT
DAS
Injector
Monitoring Point
Observation Well
Key
Structure Contour
Access roads
Tuscaloosa Wells
Gulf Coast Carbon Center

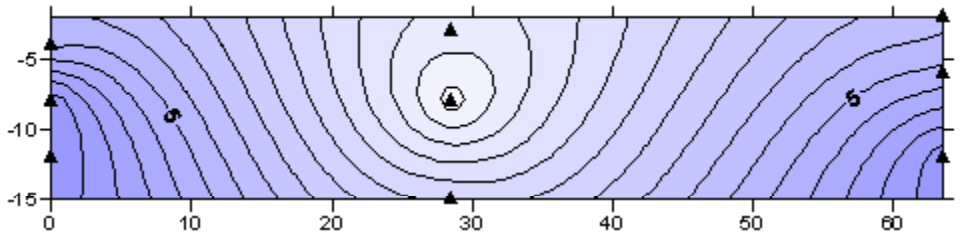
Assessment of near surface techniques "P Site"



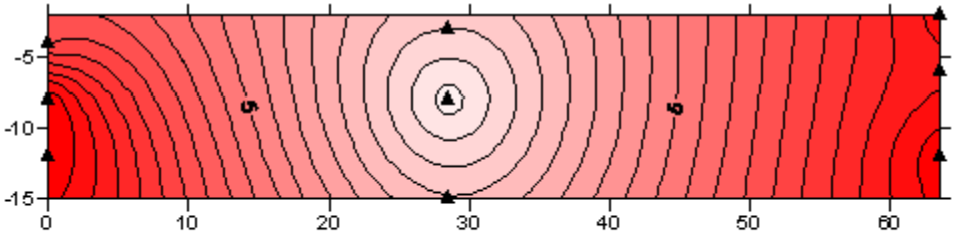
Carbon Center

Preliminary Soil Gas data

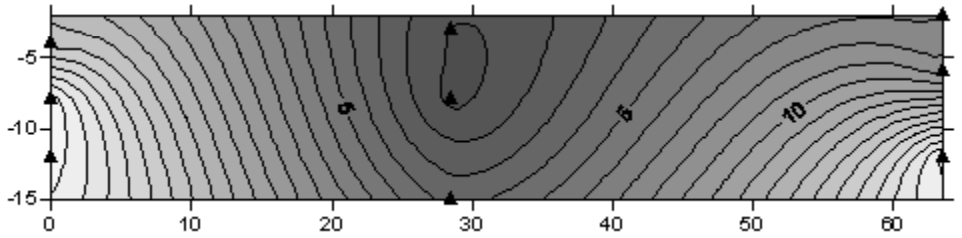
CO2 (vol %)



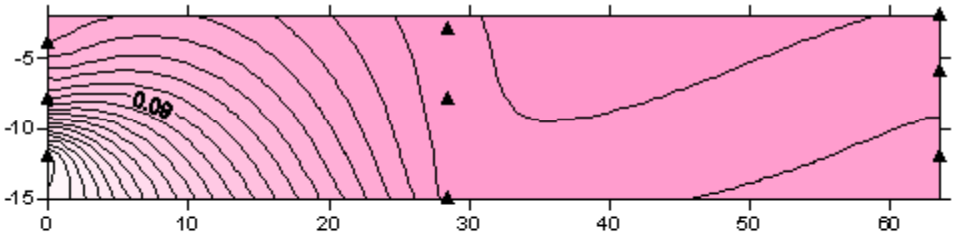
CH4 (vol %)



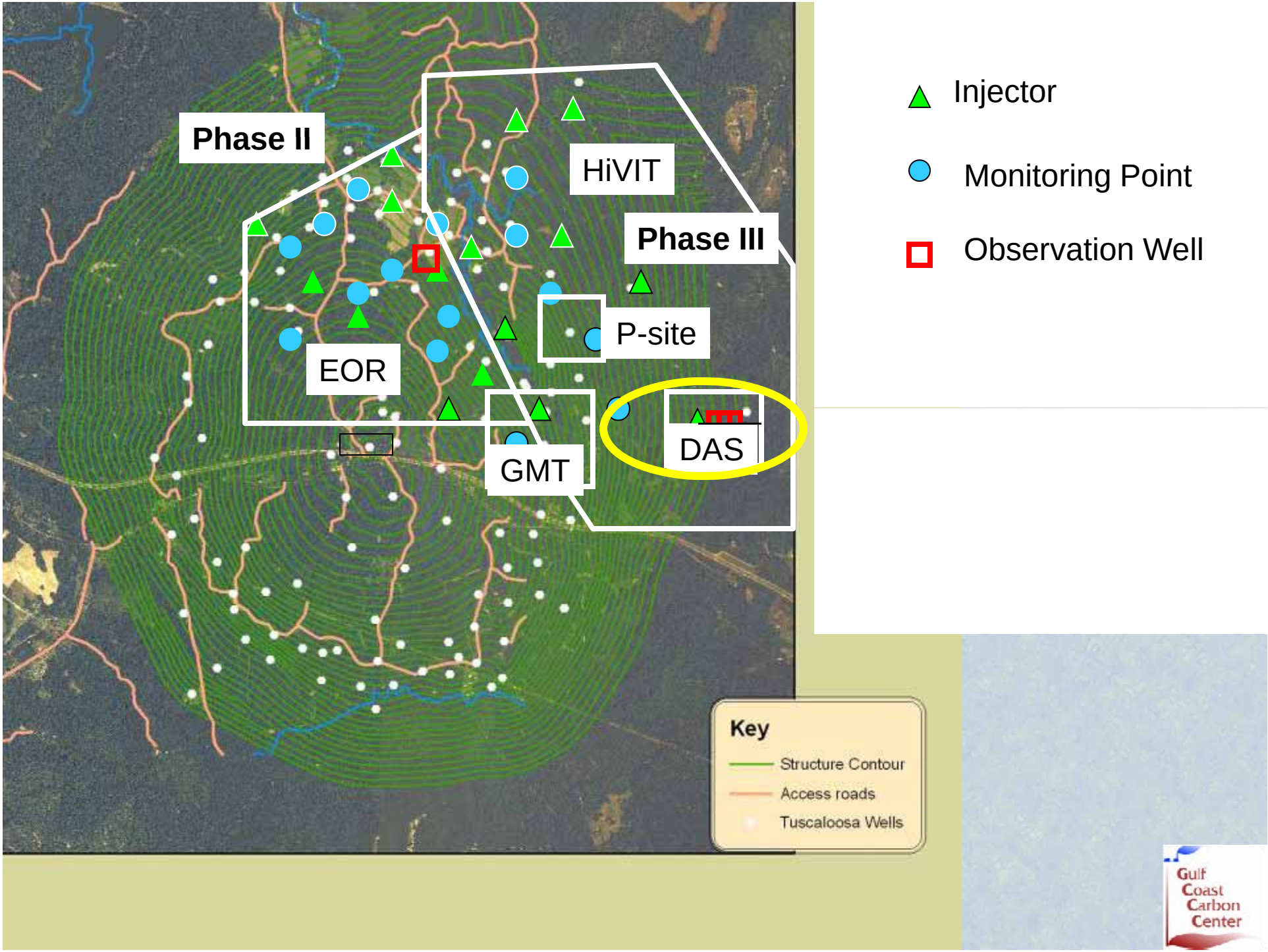
O2 (vol %)



Pressure
(inches H2O)

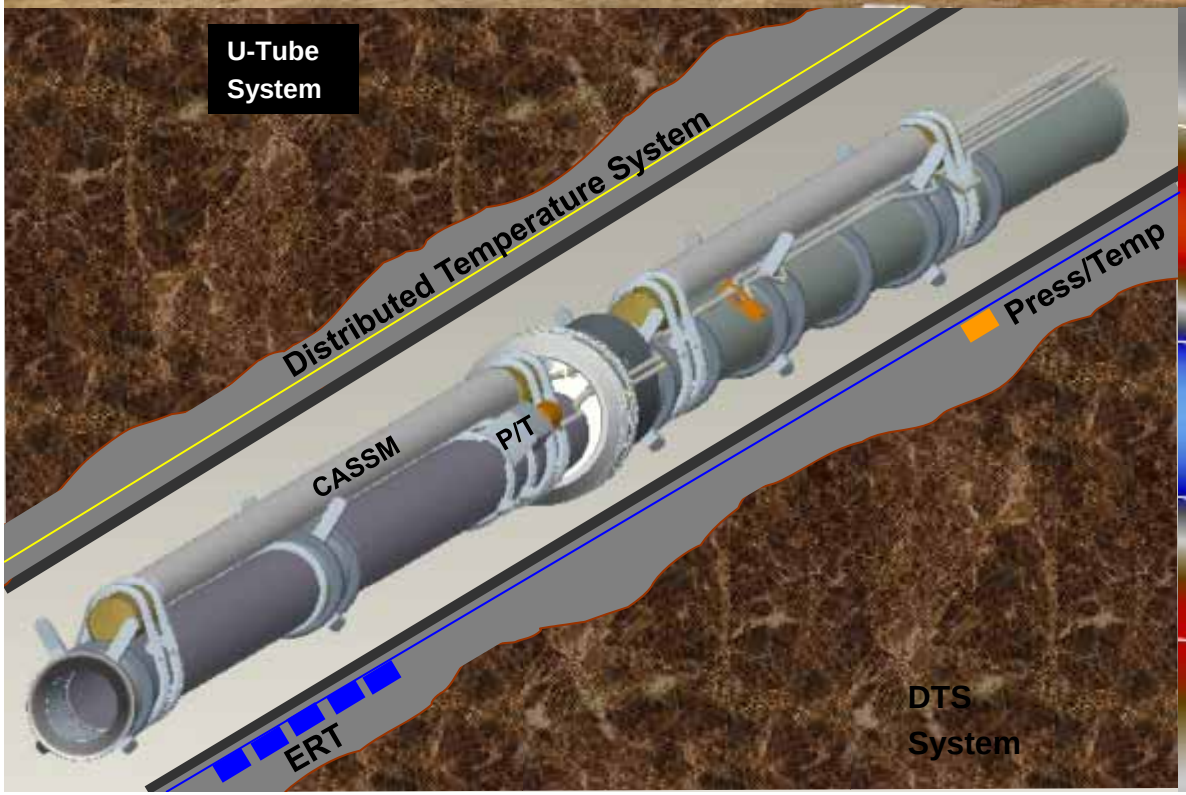


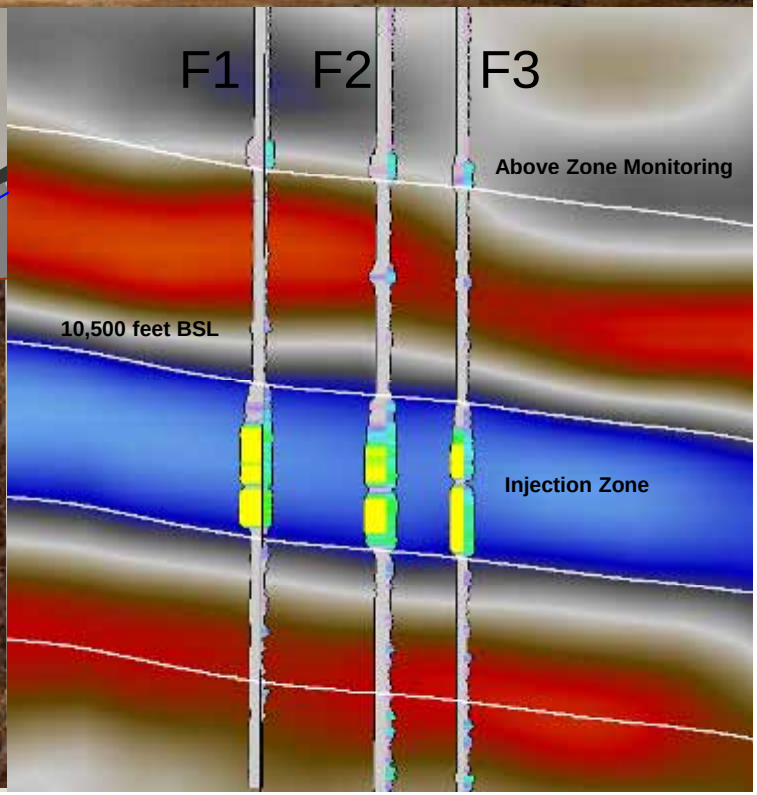
Gulf Coast Carbon Center


Phase II
HiVIT
Phase III
P-site
EOR
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Structure Contour
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Gulf Coast Carbon Center

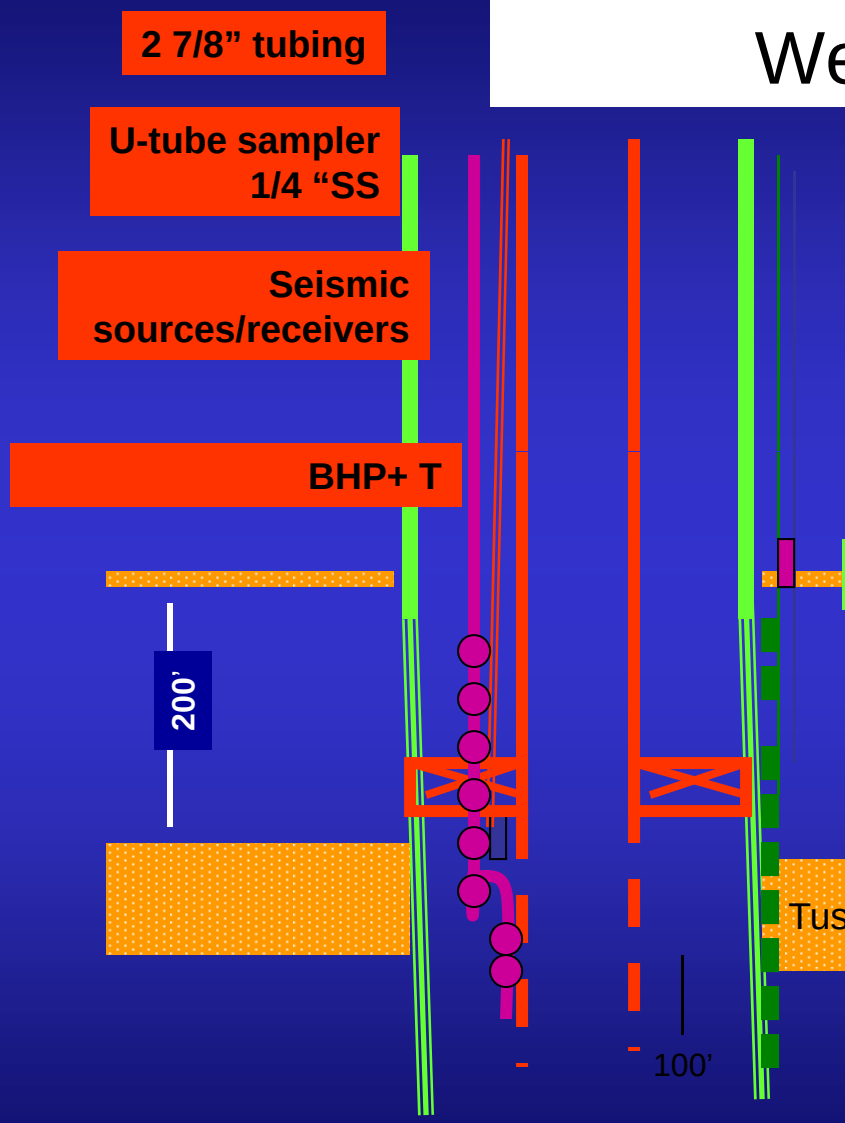
SECARB Phase 3
Cranfield, MS







Phase III Research Observation Well Construction 2X



Cross well array in two wells
High injection volumes
Far-field monitoring microseismic, P&T, chemistry, surface seismic

Casing-conveyed pressure sensor

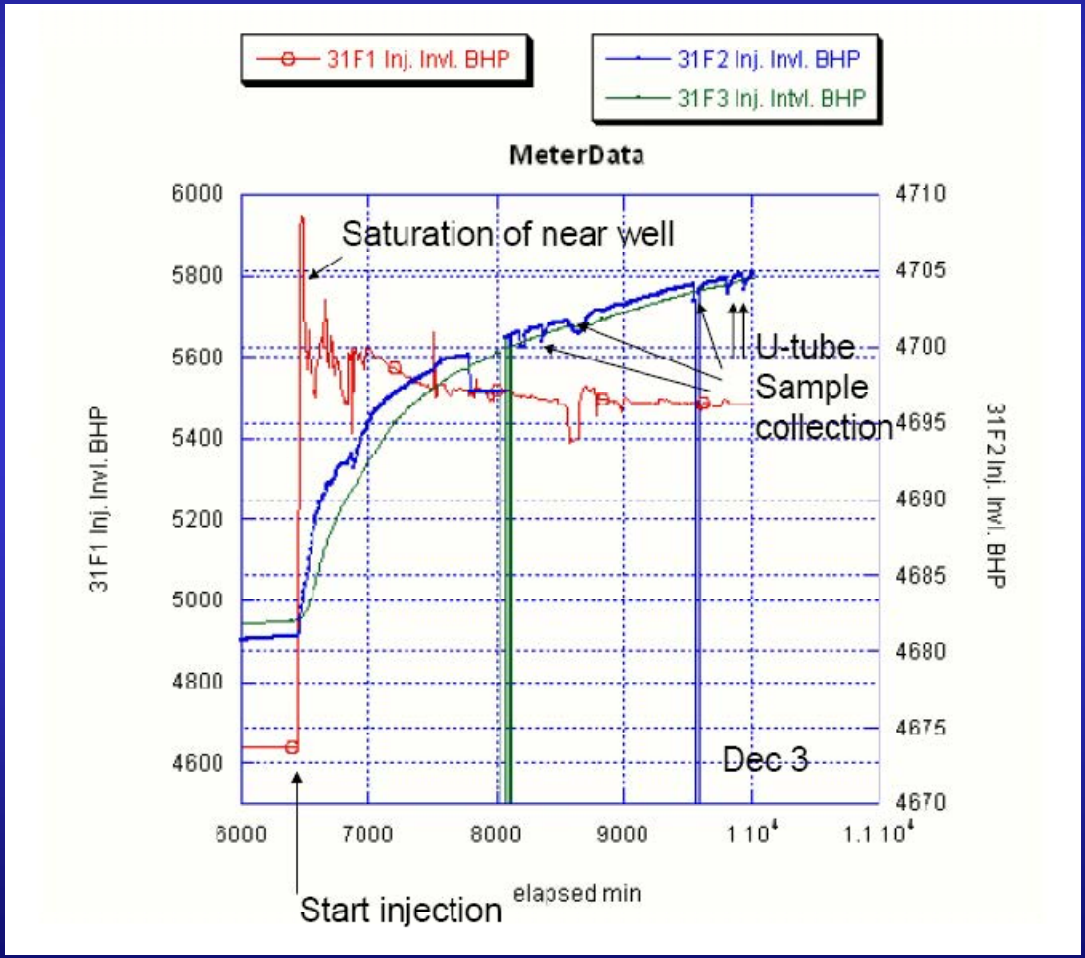
ERT – 20 electrodes

Fiberglass non-conductive casing

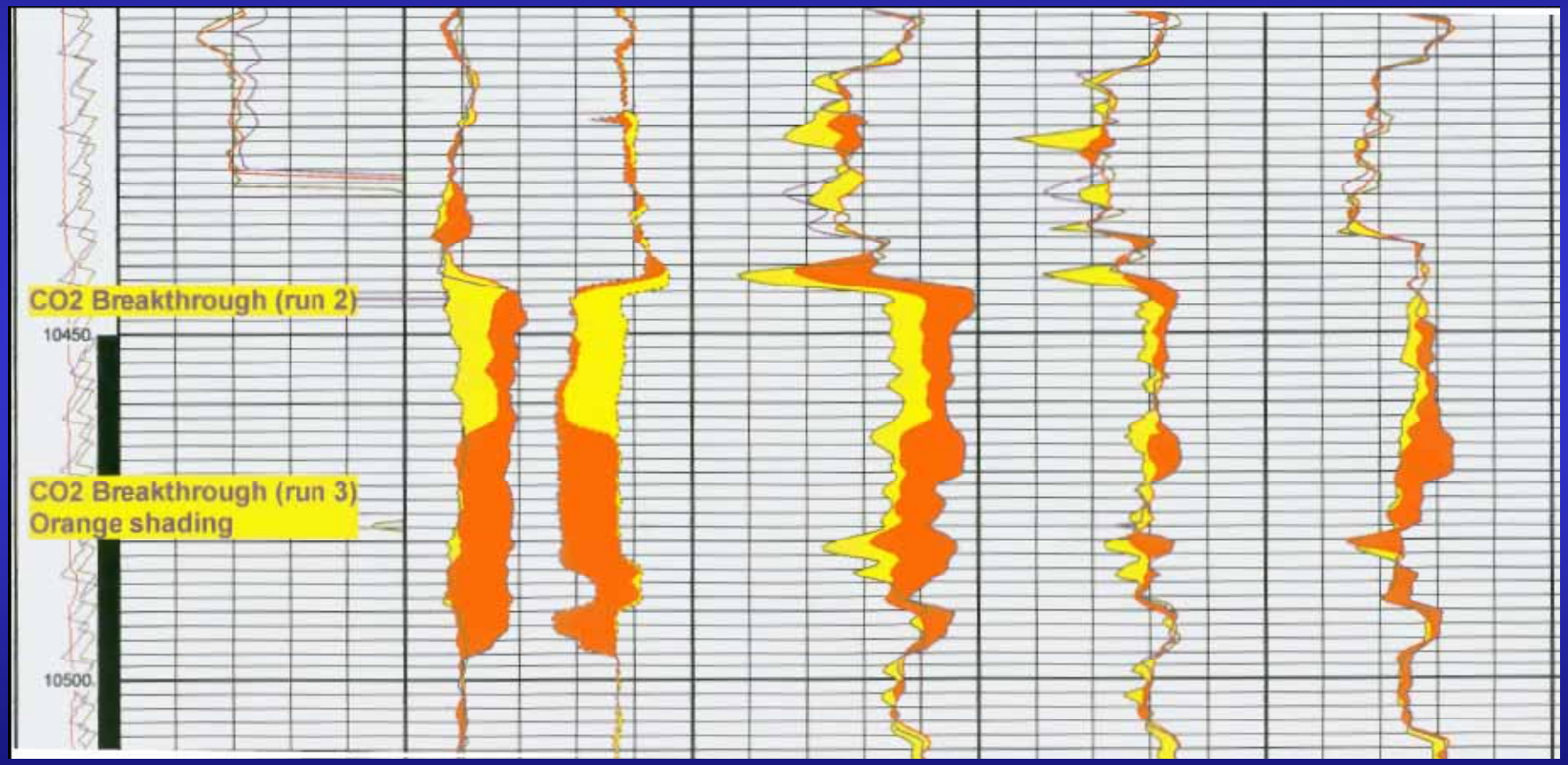
Distributed temperature and heater loop

BEG LBNL LLNL USGS ORNL Pinnacle QEA Sandia Technologies

Start injection at DAS Dec 1, 2009 1 Million ton/year rate in HiVITDec 20, 2009

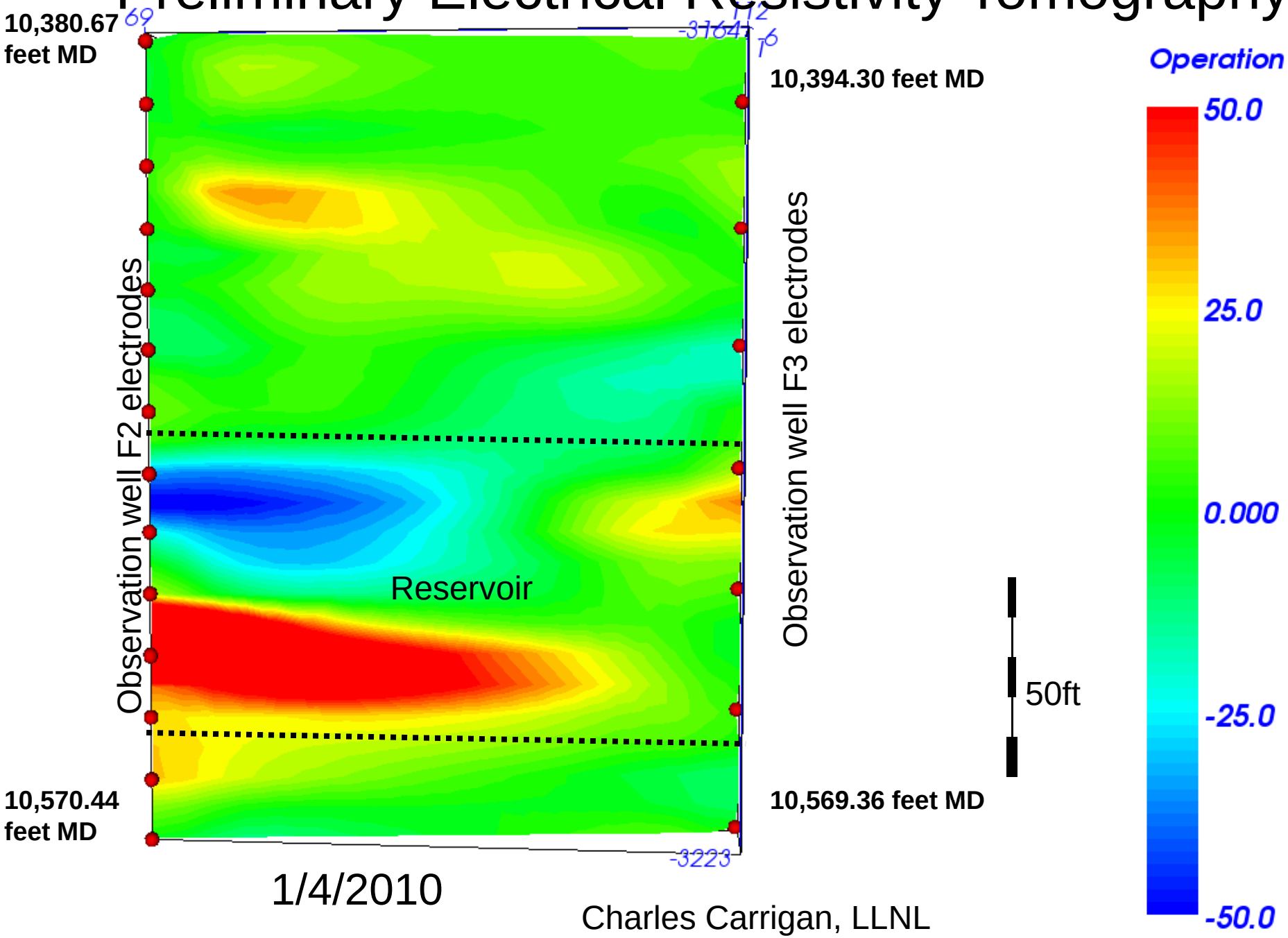


Preliminary interpretation Observation well F3 time laps RST (saturation) logs



Bob Butch Schlumberger Carbon Services

Preliminary Electrical Resistivity Tomography

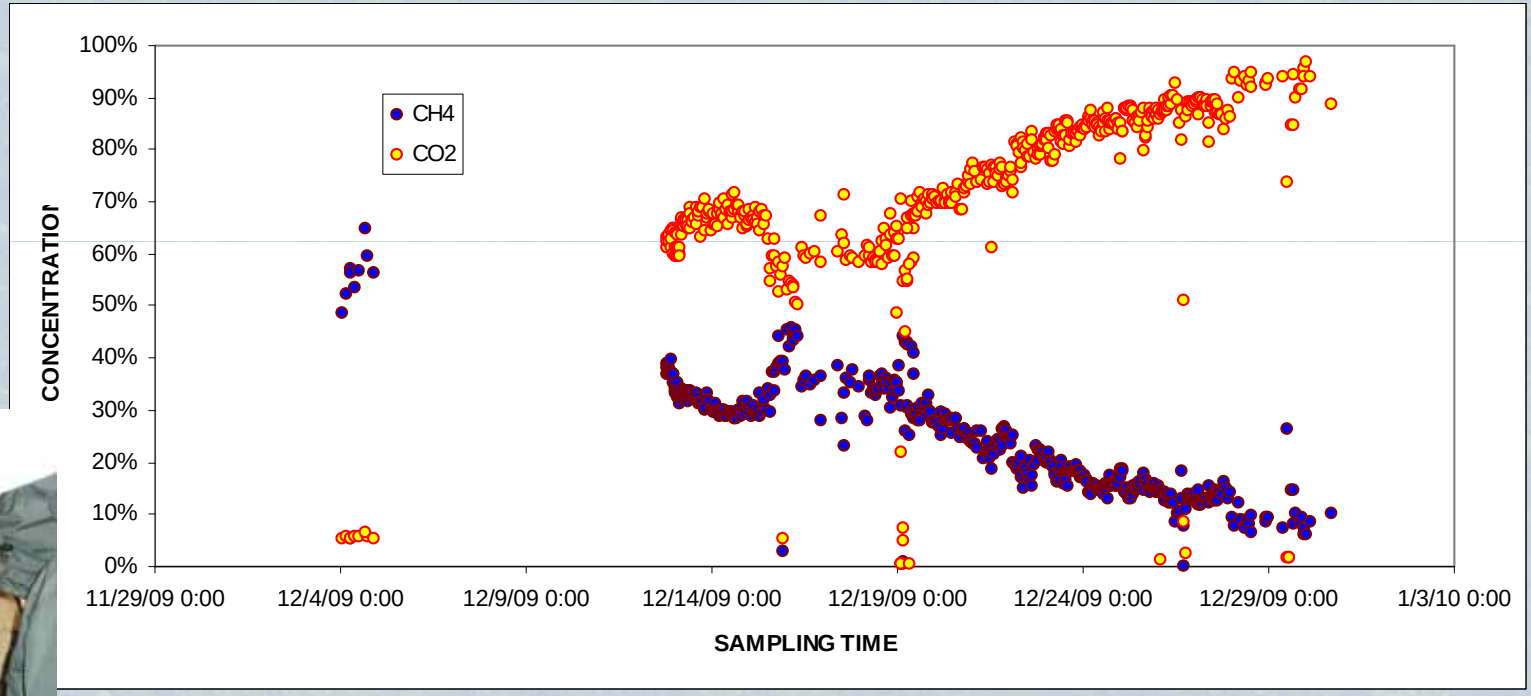


1/4/2010

Charles Carrigan, LLNL

High frequency fluid sampling via U-tube Data on flow processes

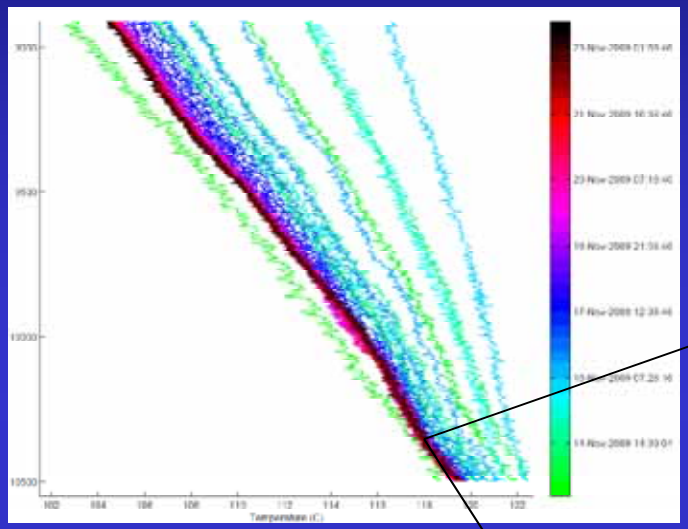


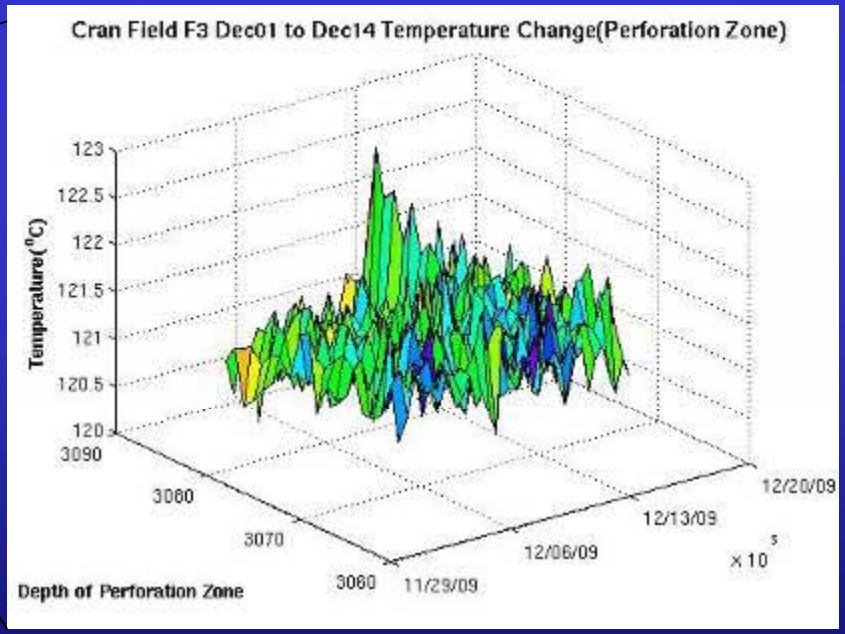


LBNL, USGS, ORNL, UTDoG

Gulf Coast Carbon Center

Distributed Temperature System





Barry Freifeld LBNL
and Yihua Cai BEG

Interim Conclusions of Phase III Early Study at Cranfield

- Phase III 1 million ton/year rate achieved Dec 20, 2009
- Rate to be maintained >15 months
- Monitored with standard and novel approaches 30 months
  - 5 research areas
  - Tests of soil gas approaches in complex environments
  - Saturation change measured/monitored with multiple tools in complex flow field
  - First US use of Electrical Resistance Tomography (ERT) for sequestration
  - Quantification of dissolution
  - More to come…
- Export to commercial EOR/sequestration projects

Gulf Coast Carbon Center

More information

- Field trip AAPG April 9-10
- Field trip and session IEA GHG R&D program Monitoring Network meeting May 6-8
- May 10-12 CCS meeting Pittsburg
  - 9 papers submitted
- updates on www.gulfcoastcarbon.org
  - Cranfield log, bookshelf

Gulf Coast Carbon Center

Update on Results of SECARB " Early" Test of Monitoring Large Volume Injection at Cranfield

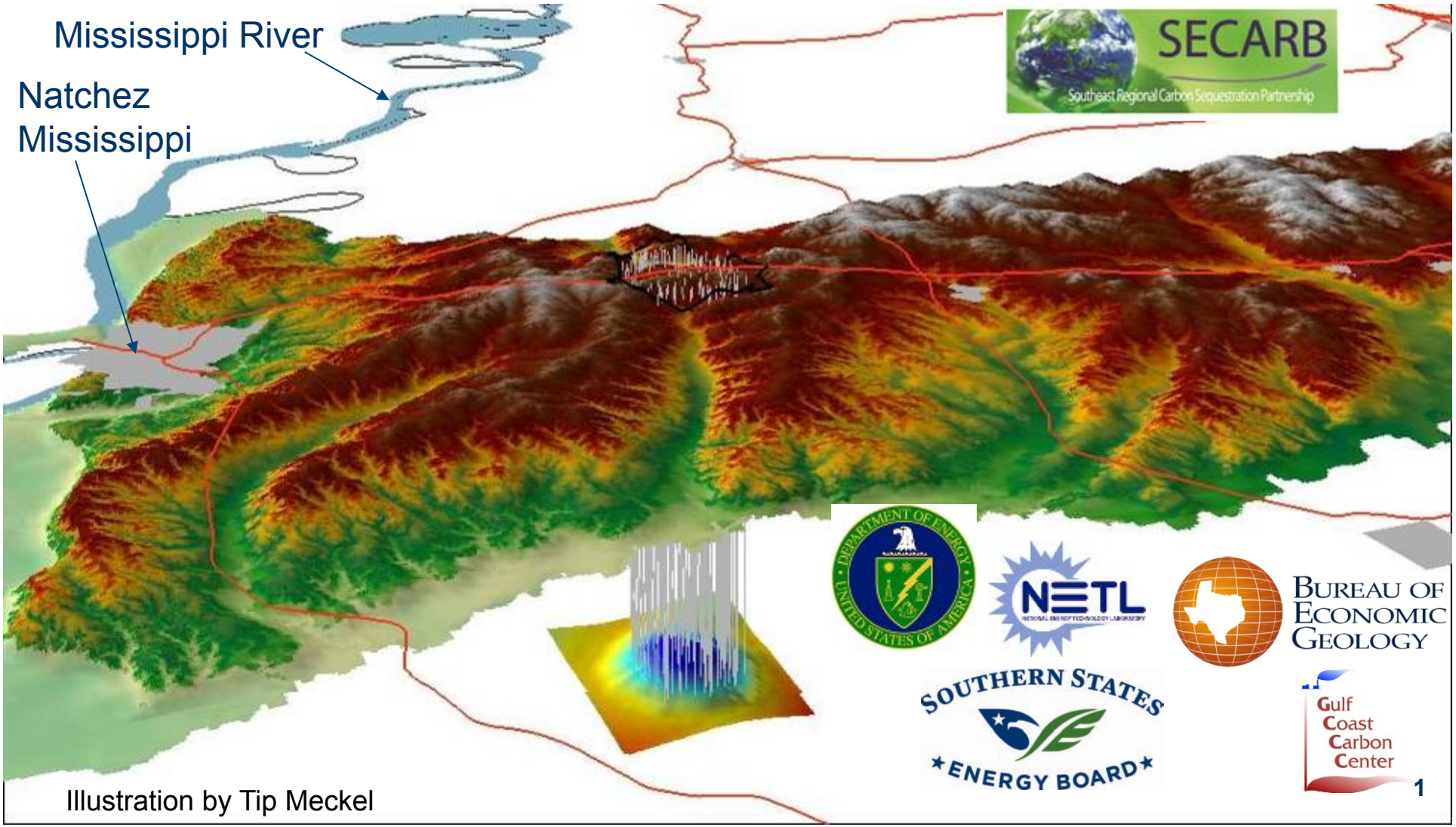


Illustration by Tip Meckel

Gulf Coast Carbon Center (GCCC)

BEG Team

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Sigrid Clift
Jiemin Lu
Seyyed Hosseini
Jong Won Choi
Vanessa Nunez
Khandaker Zahid
Carey King
students
Scott Tinker
Ian Duncan

Collaborators

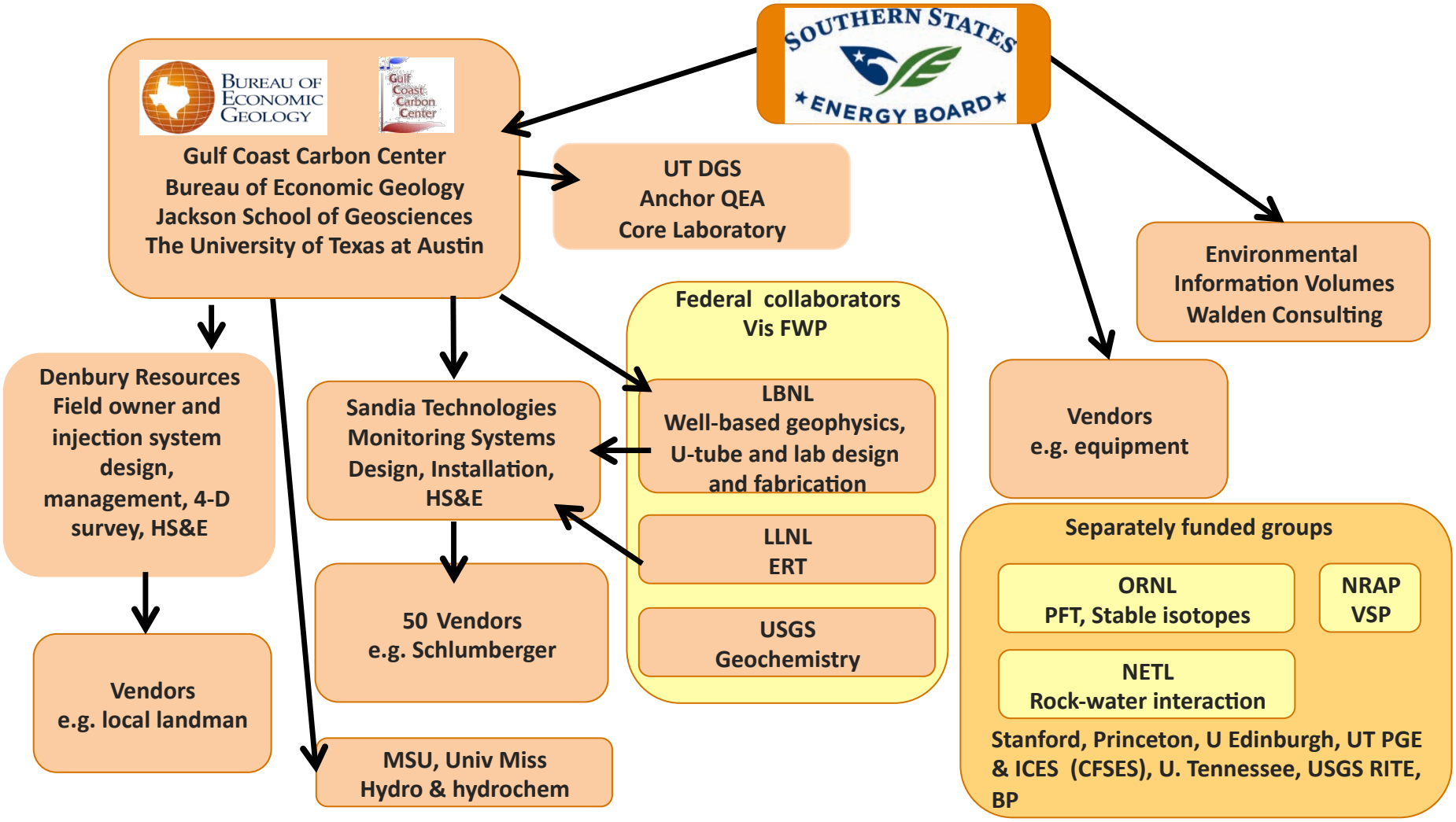
BEG- CEE
LBNL
LLNL
ORNL
USGS
New Mexico Tech
Mississippi State U
U of Mississippi
BP
ARI
SECARB
SWP
UT-PGE
UT- CCEP
UT- DGS
Univ Edinburgh

NETL: Bruce Brown
SSEB: Jerry Hill

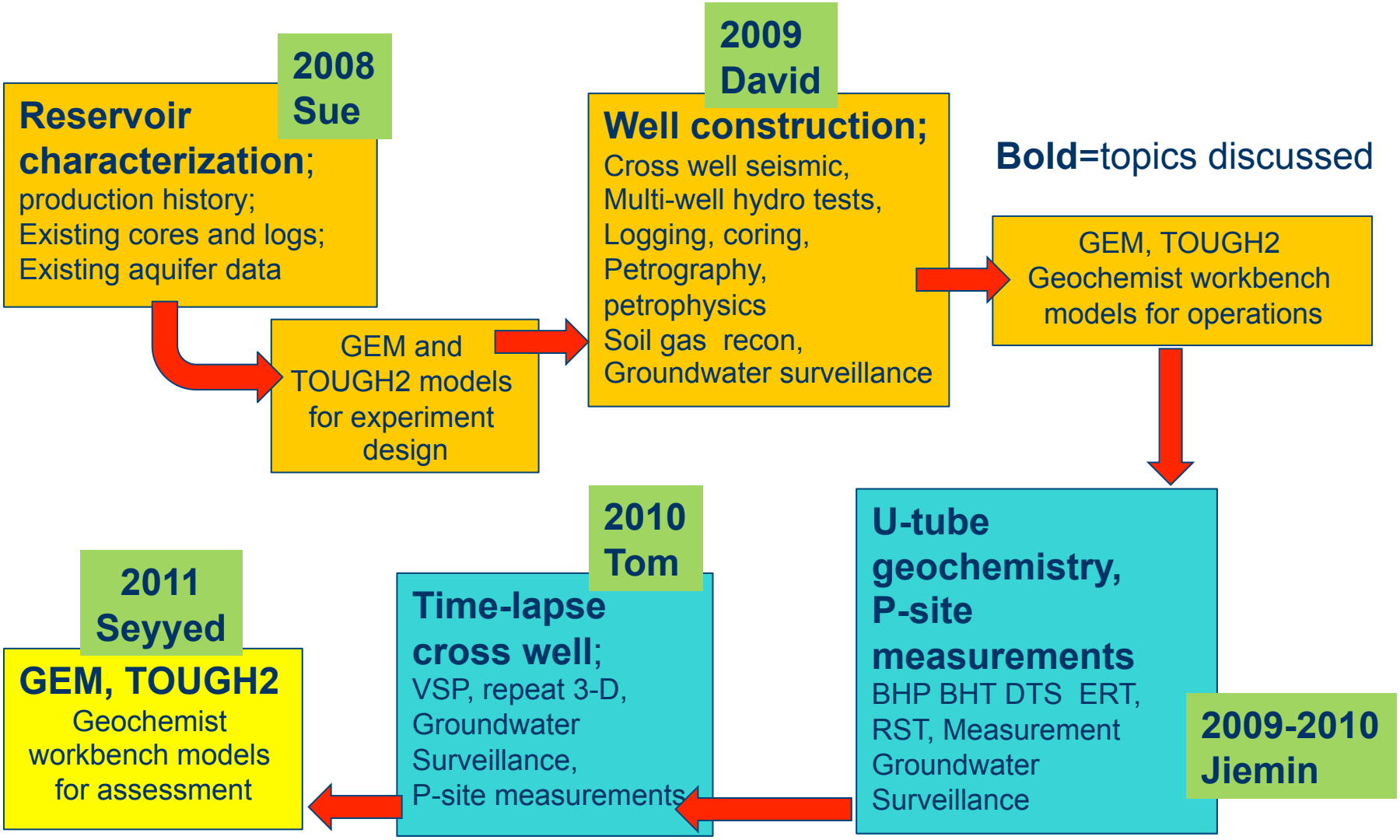
IA sponsors

New 2011
GE BG group

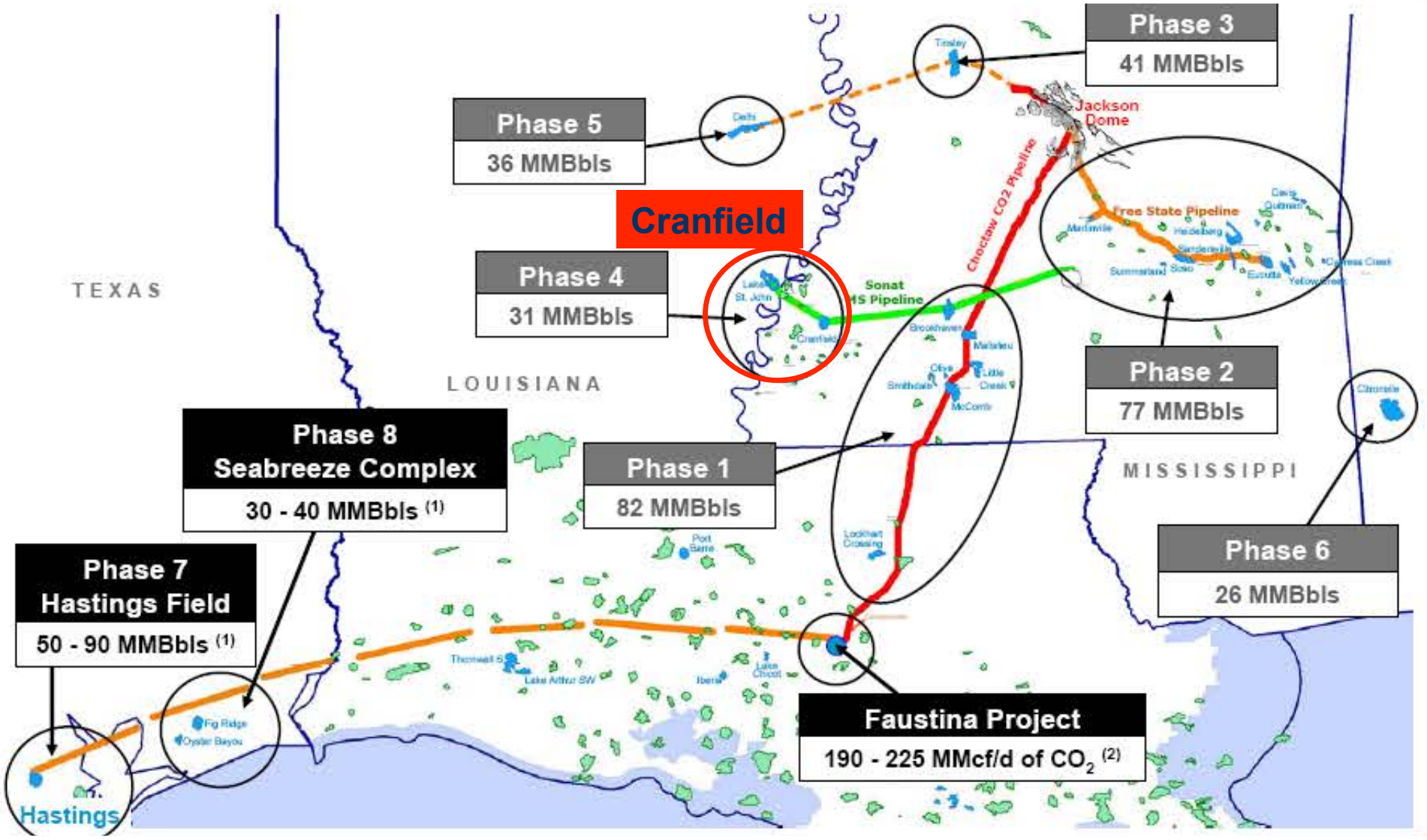
Early Test Organization Chart



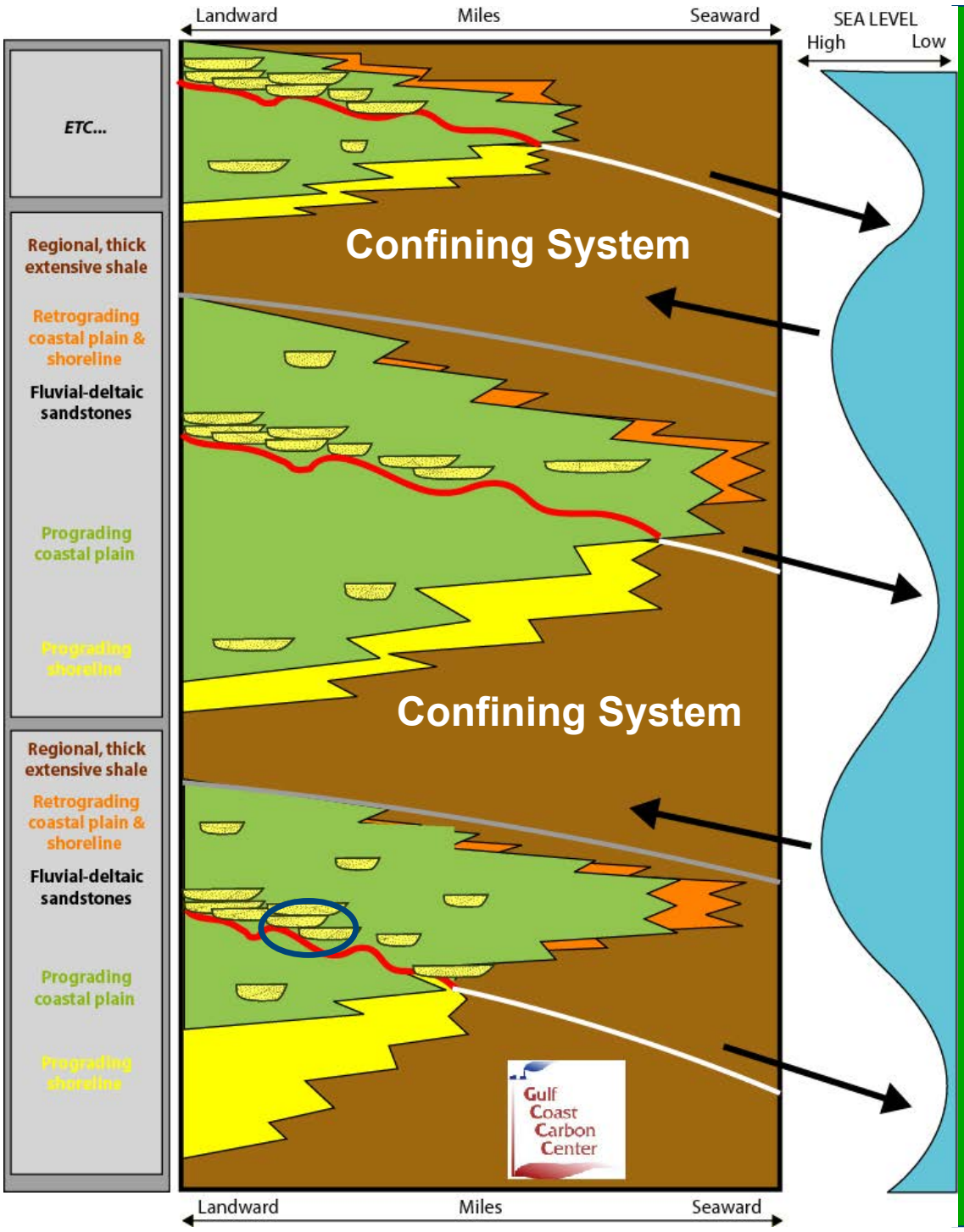
Early Test Workflow and Presentations



Source of CO_2 for Early Test



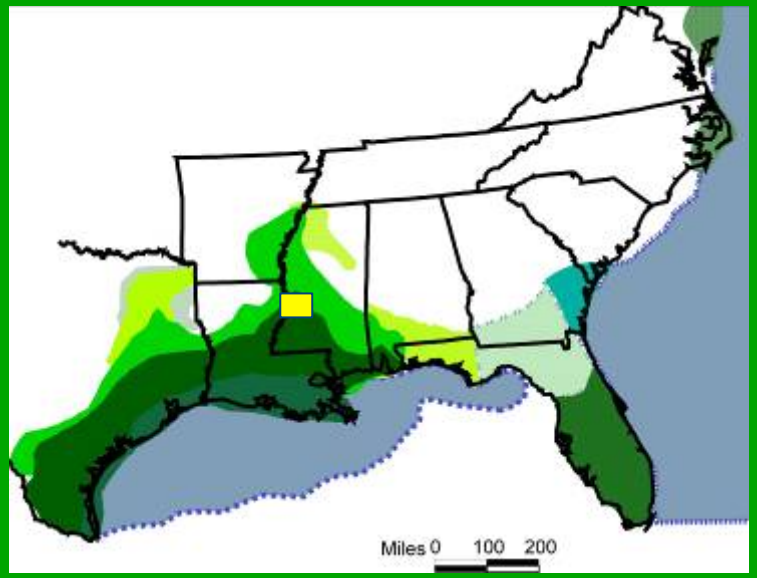
Courtesy of Denbury Resources, Inc.



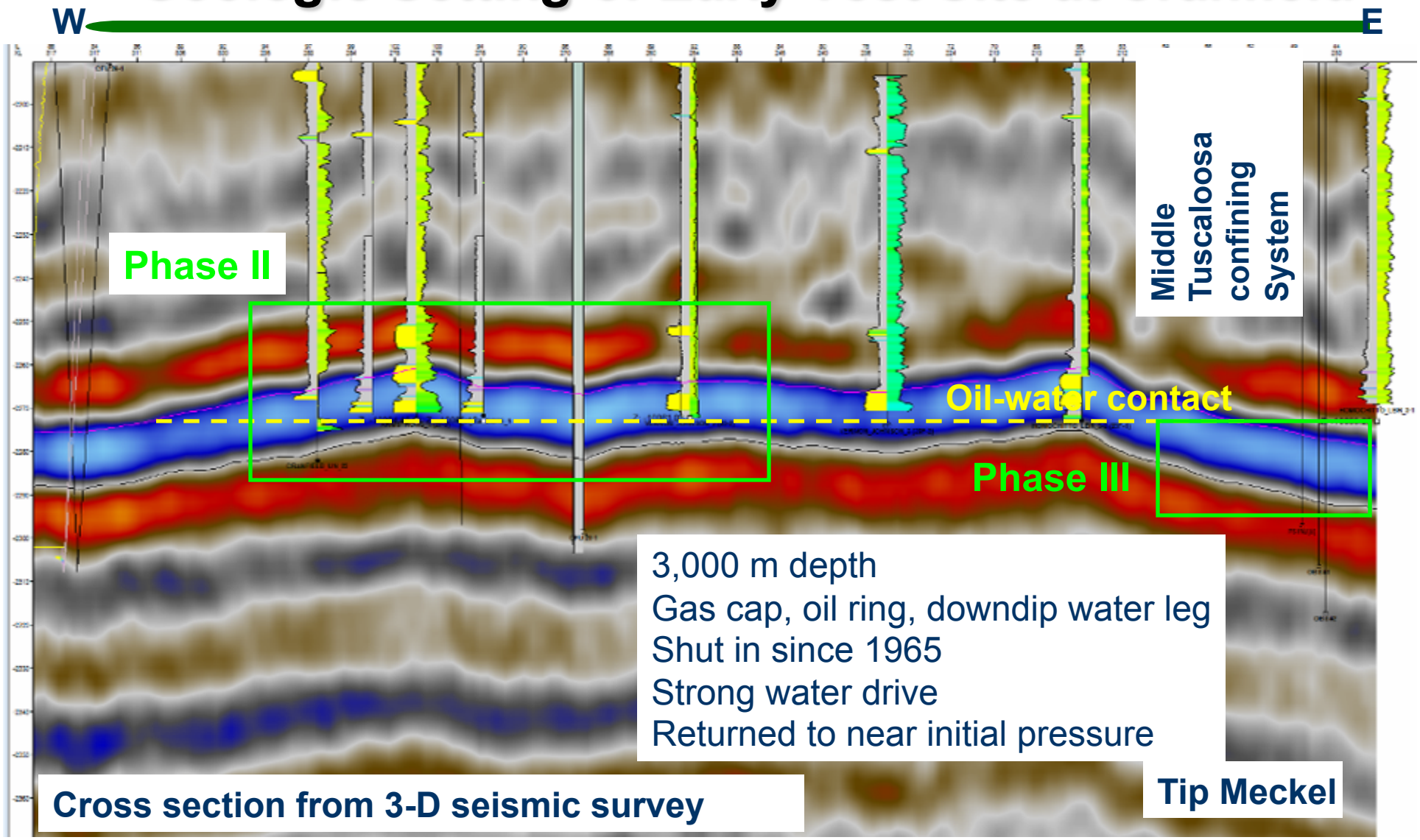
Regionally significant sequestration target for Early Test: Gulf Coast Wedge

Repetitive depositional units

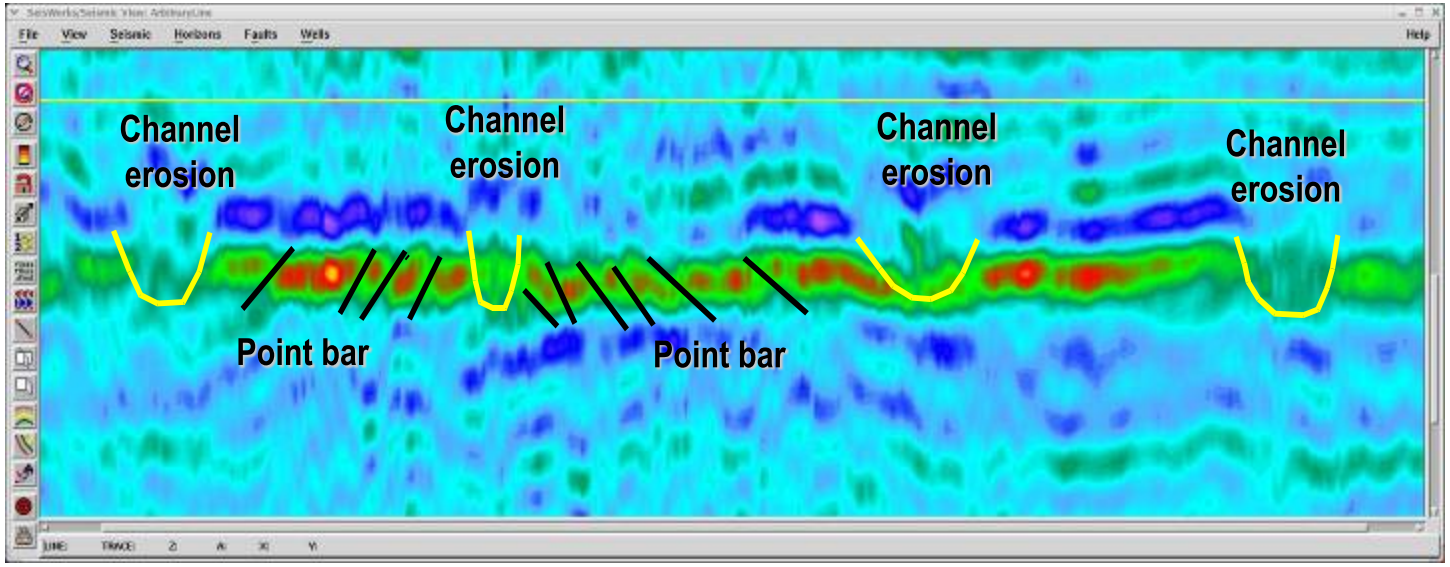
- **Results transferable to:**
  - **older and younger units**
  - **other parts of region**

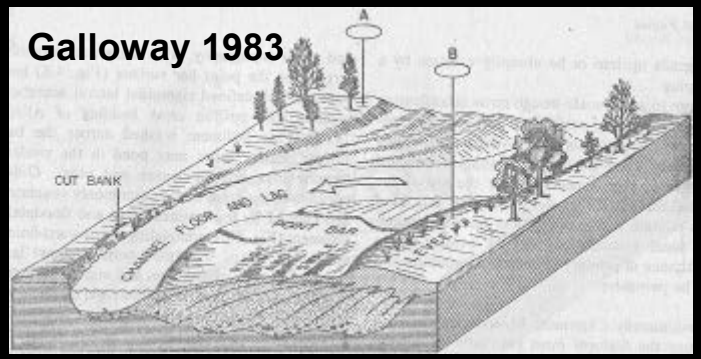


Geologic Setting of Early Test Site at Cranfield



Geologic Characteristics of Injection Zone





Meander fluvial model

Stratal slicing of 3-D volume
Hongliu Zeng

Interim Conclusions of Early Test

- Injection start July 2008
- 2.8 Million metric tons stored
- 1 million metric ton/year rate achieved Dec 2009
- Monitored with standard and novel approaches
  - History match pressure response
  - Above-Zone Monitoring Interval (AZMI)
  - Fluid flow measured/monitored with multiple tools in complex flow field
  - Quantification of dissolution
  - Knowledge sharing, outreach, risk assessment
- Export to commercial EOR/sequestration projects

(1) RCSP Program Goal

Predict storage capacities within +/- 30%

- Capacity and injectivity well known at project start.
- Advance understanding of efficiency of pore-volume occupancy (E factor).
- Measure saturation during multiphase plume evolution (completed).
- Increase predictive capabilities (underway through modeling).

(2) RCSP Program Goal

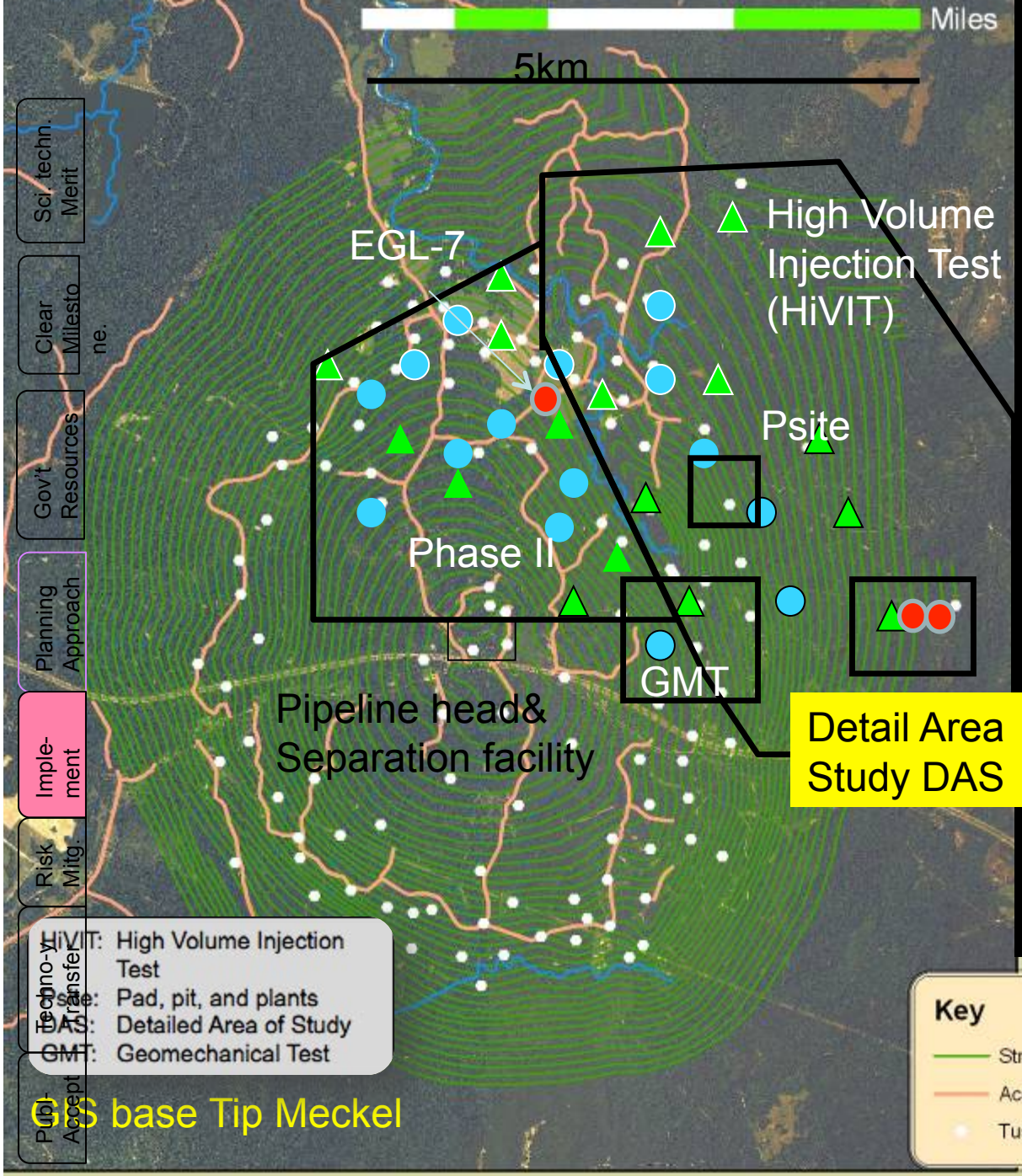
Evaluate protocols to demonstrate 99% CO_2 retained

- Permanence of geologic system well understood prior to test. Assess methods for documenting well performance.
- Measure changes above the injection zone along well, above zone monitoring interval (AZMI), and at surface (P site) over long times (underway).
- Plume confined by 4-way closure. Uncertainty – amount of radial flow (down dip/out of pattern).
- Completed certification framework assessment of leakage risk. Confirmed well performance as highest uncertainty and focus of monitoring research.

(3) RCSP Program Goal

Contribute Technical Expertise and Lessons Learned, Development of Best Practices Manuals

- Participated in developing BPMs for MVA, characterization, risk and reservoir modeling
- O&E in public and technical arenas.
- Hosted site visits, responses to local and trade media, Fact Sheets, website postings of project information.



Sci./techn. Merit

Clear Milestone.

Gov't Resources

Planning Approach

Imple-ment

Risk Mitg.

Techno-y Transfer

Pub-Accept

Five Study Areas

- Injector
- Producer (monitoring point)
- Observation Well

Bureau of Economic Geology

Gulf Coast Carbon Center

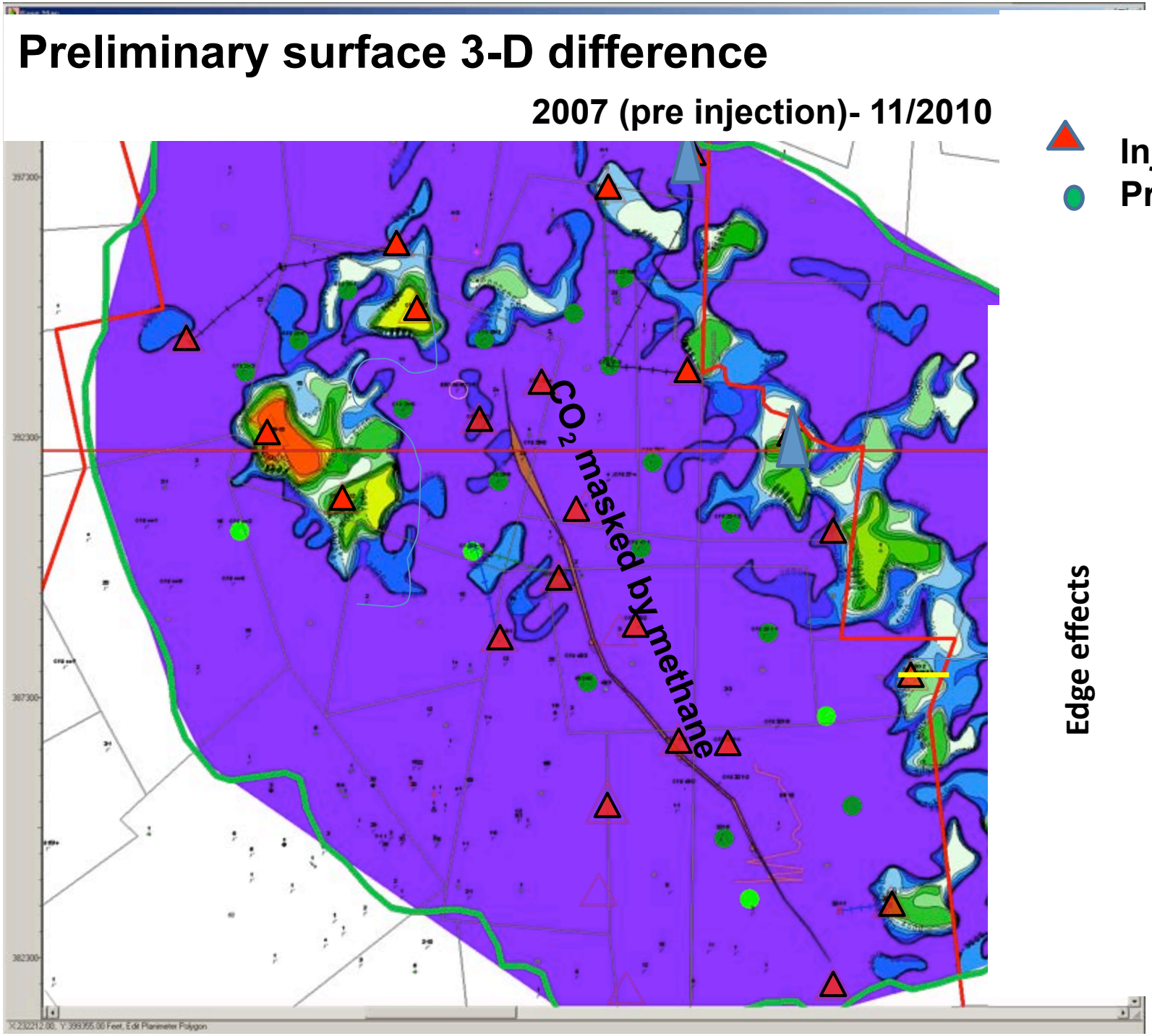
Early Test MVA Design

Area tested	Whole plume	Focus study
Atmosphere	Not tested	Not tested
Soil gas	Time-lapse surveys at active and P&A well pads	"P site" methodology assessment
Groundwater	Monitoring well at each injector	EGL-7 UM cored test well. Push-pull test
Shallow production	Not tested	Not tested
AZMI	Not tested	DAS pressure and EGL 7 pressure + fluids
Geo Mechanical test	Not tested	GMT-failed
Injection zone	Geochemistry breakthrough	DAS multi-well multi tool array

Extra slides for end

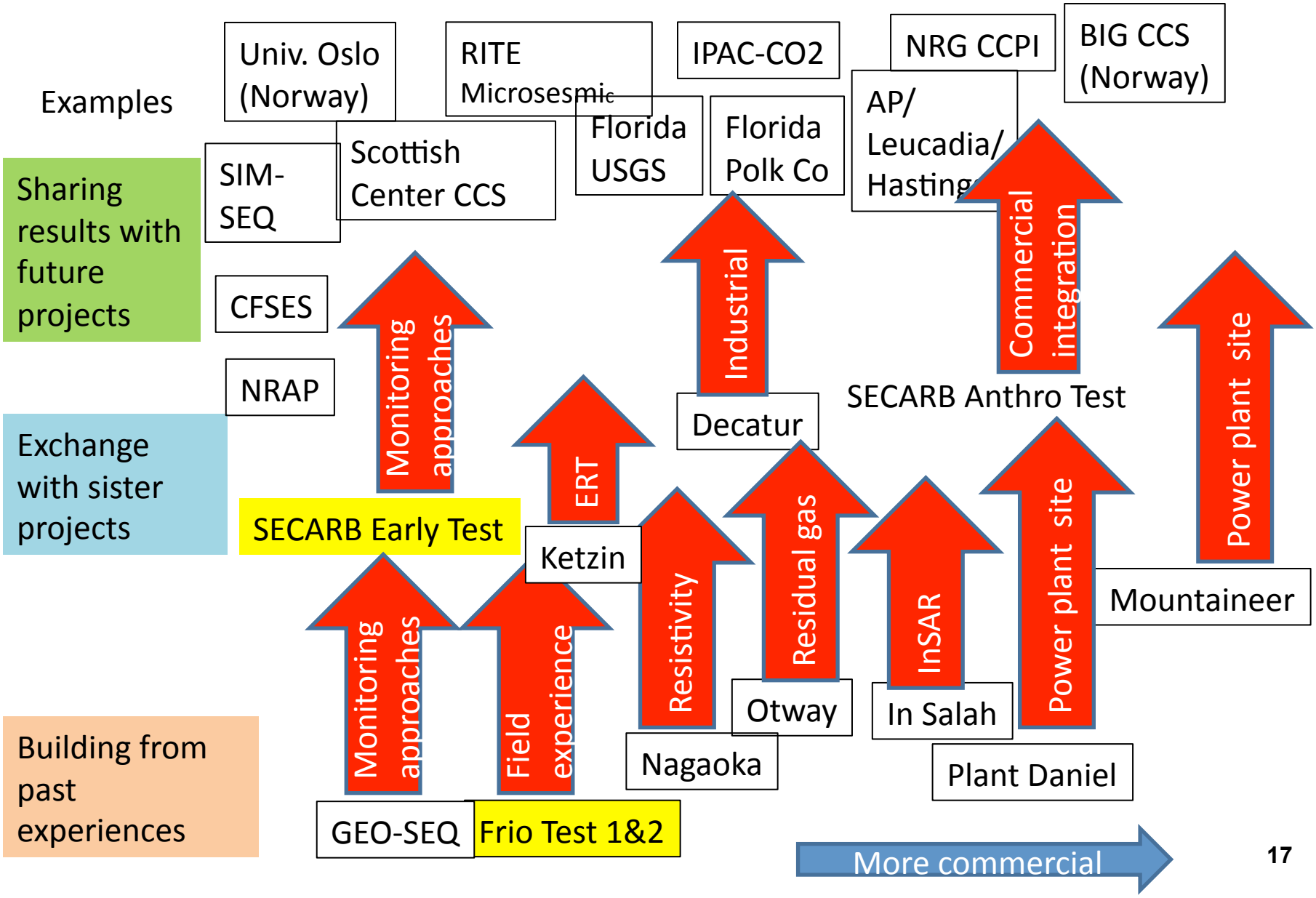
Preliminary surface 3-D difference

2007 (pre injection)- 11/2010



Early Test Knowledge Sharing

U.S. and International Programs



Interim Conclusions of Early Test

- Injection start July 2008
- 2.8 Million metric tons stored
- 1 million metric ton/year rate achieved Dec 2009
- Monitored with standard and novel approaches
  - History match pressure response
  - Above-Zone Monitoring Interval (AZMI)
  - Fluid flow measured/monitored with multiple tools in complex flow field
  - Quantification of dissolution
  - Knowledge sharing, outreach, risk assessment
- Export to commercial EOR/sequestration projects

Progress Update SECARB " Early" Test Monitoring 3.5 Million Tons at Cranfield

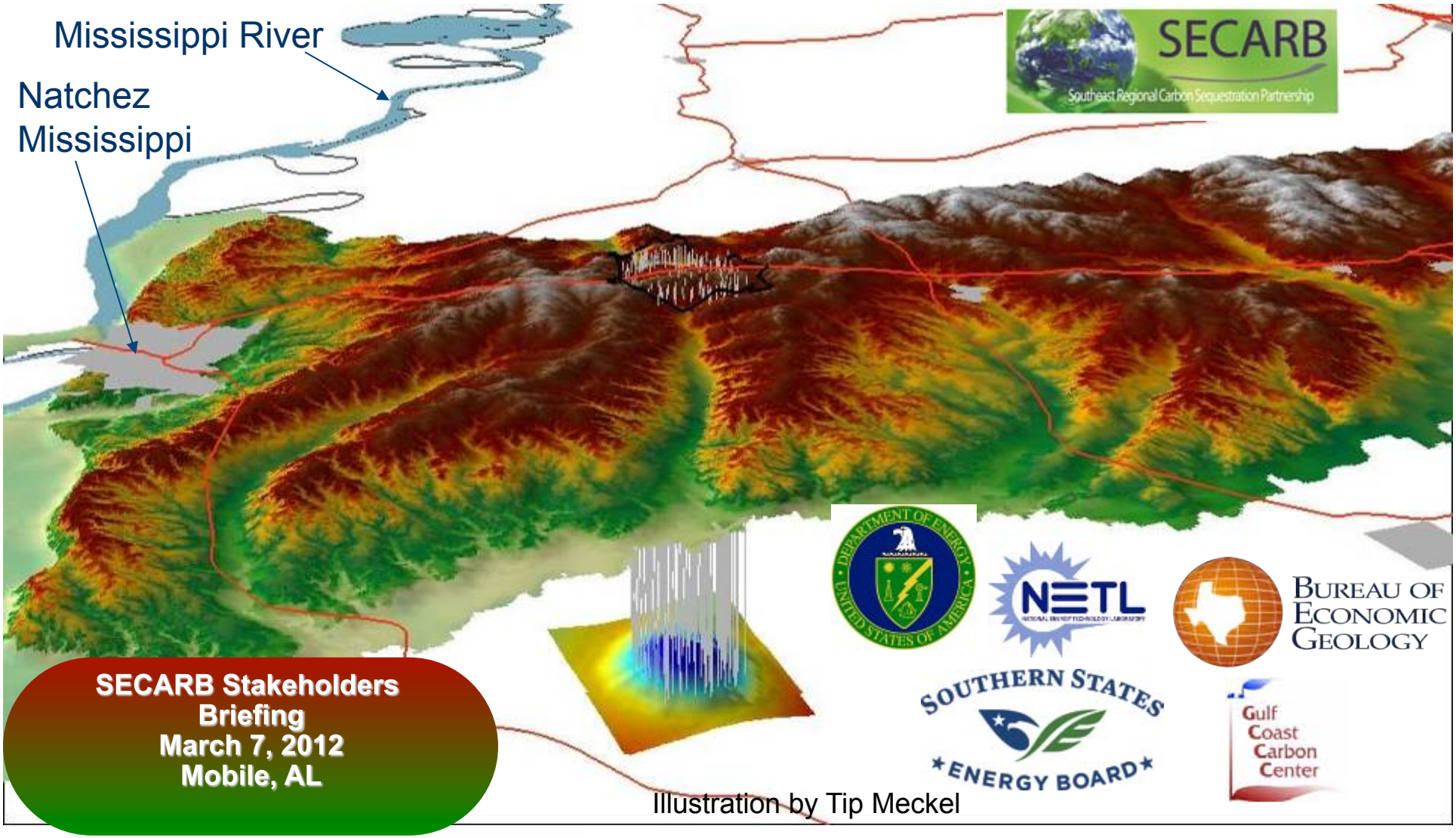


Illustration by Tip Meckel

Panel Overview

- Overview and updates – Susan Hovorka
  - Organization, design, status
  - Update – Modeling and pressure response
  - Update – geochemistry in reservoir and AZMI
  - Technical and public knowledge-sharing
  - Future opportunities - CCUS
- Update on Geophysics and lab activities– Tom Daley
- Update on near surface monitoring – Katherine Romanak

Gulf Coast Carbon Center

THE UNIVERSITY OF TEXAS AT AUSTIN
JACKSON SCHOOL OF GEOSCIENCES

BUREAU OF ECONOMIC GEOLOGY

Funding agency

NETL
NATIONAL ENERGY TECHNOLOGY LABORATORY

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

SECARB
Southeast Regional Carbon Sequestration Partnership

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Research Collaborators

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Sandia Technologies, LLC

USGS
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Curtin University
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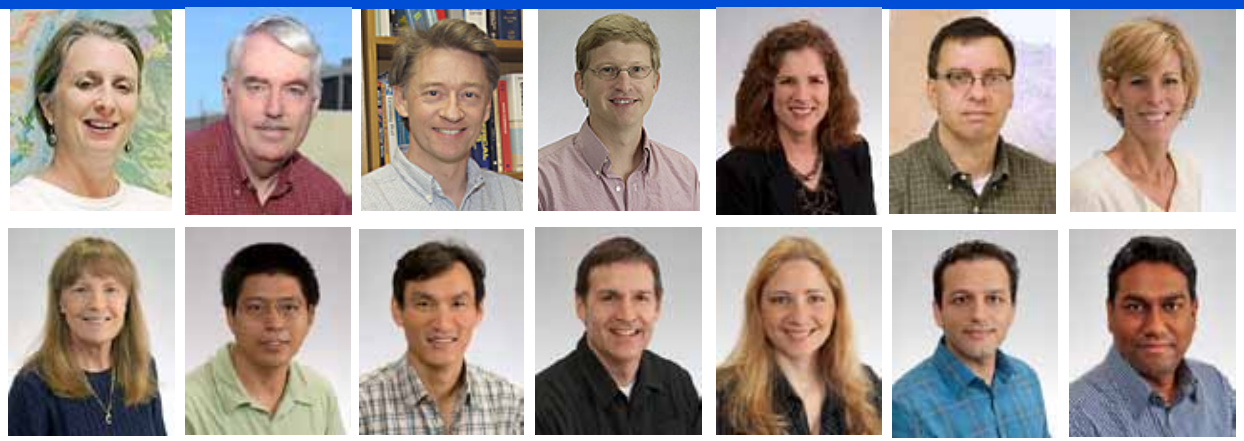
GE

ExxonMobil

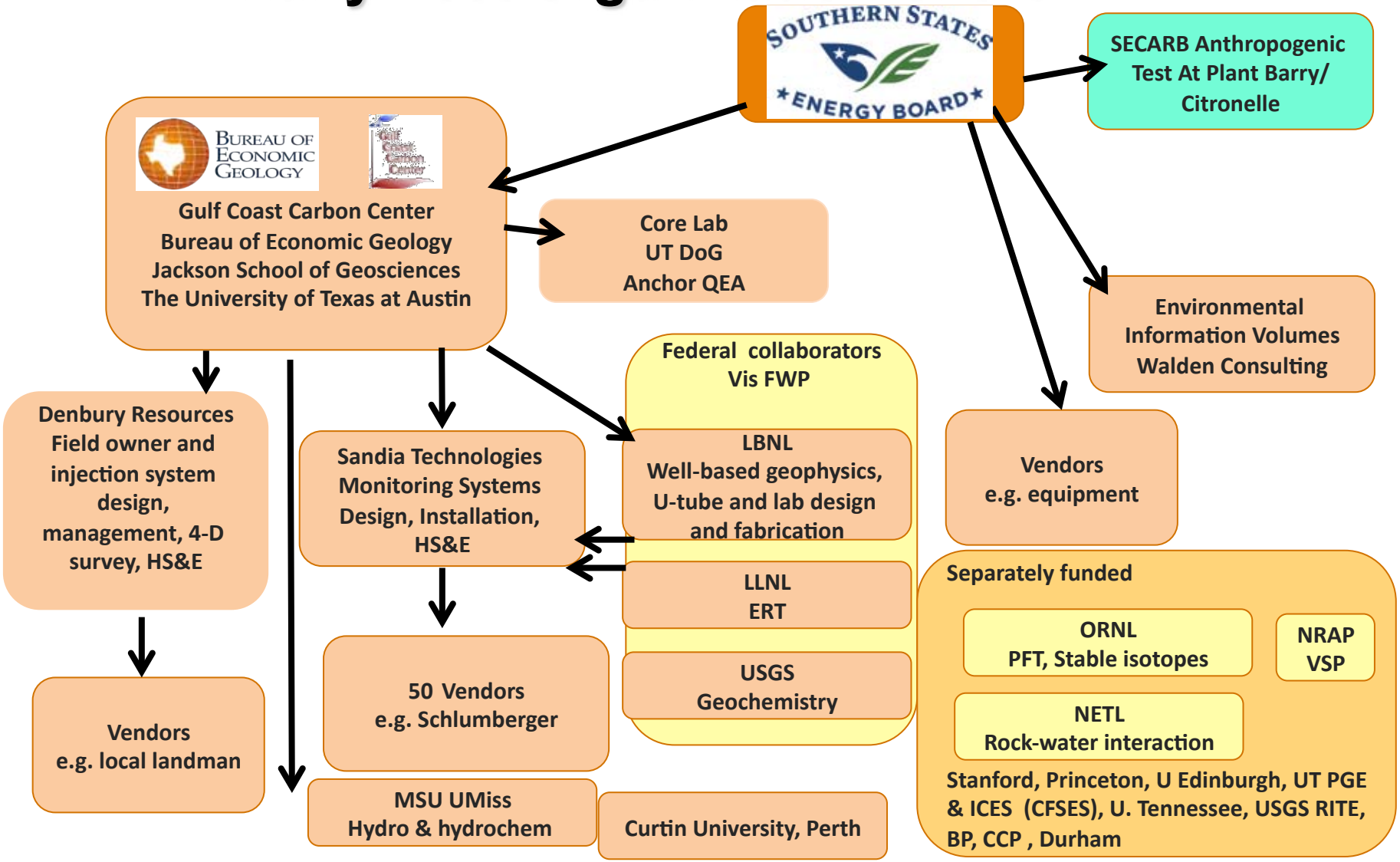
ارامكو السعودية
Saudi Aramco

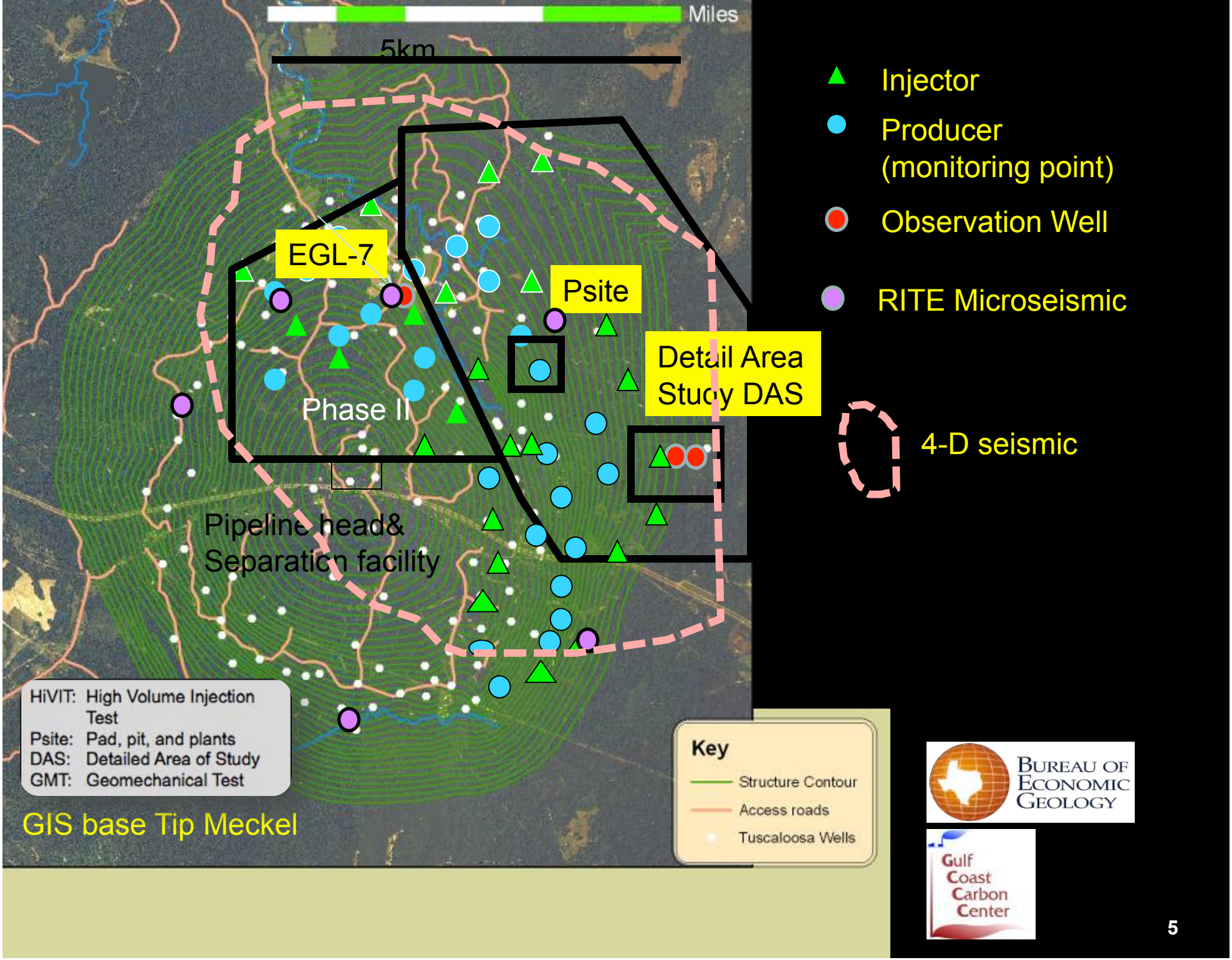
EDF
ENVIRONMENTAL DEFENSE FUND

STAFF

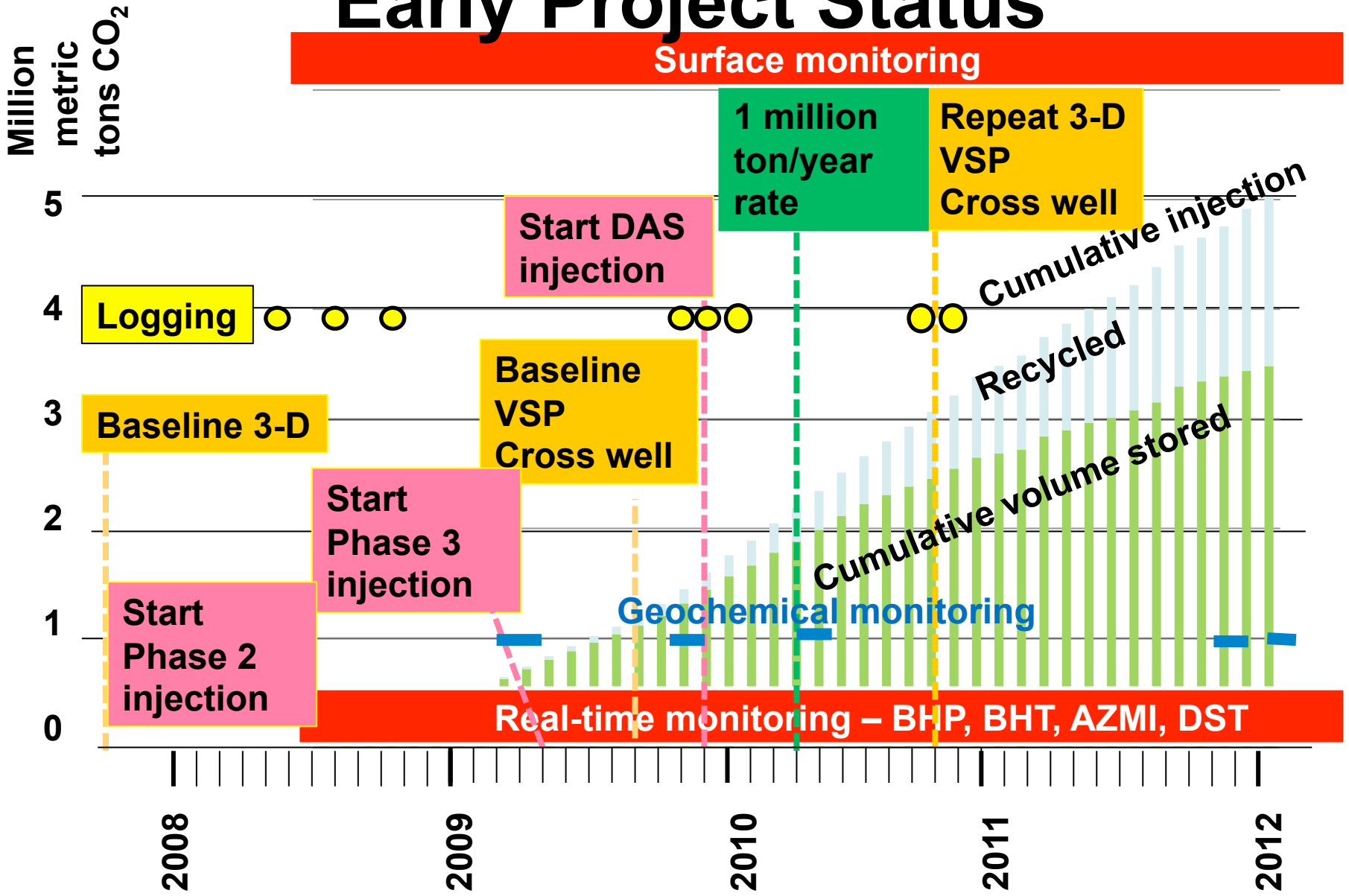


Early Test Organization Chart




Miles
5km
Injector
Producer
(monitoring point)
Observation Well
RITE Microseismic
4-D seismic
EGL-7
Psite
Detail Area
Study DAS
Phase II
Pipeline head&
Separation facility
HiVIT: High Volume Injection Test
Psite: Pad, pit, and plants
DAS: Detailed Area of Study
GMT: Geomechanical Test
Key
Structure Contour
Access roads
Tuscaloosa Wells
GIS base Tip Meckel
Bureau of Economic Geology
Gulf Coast Carbon Center

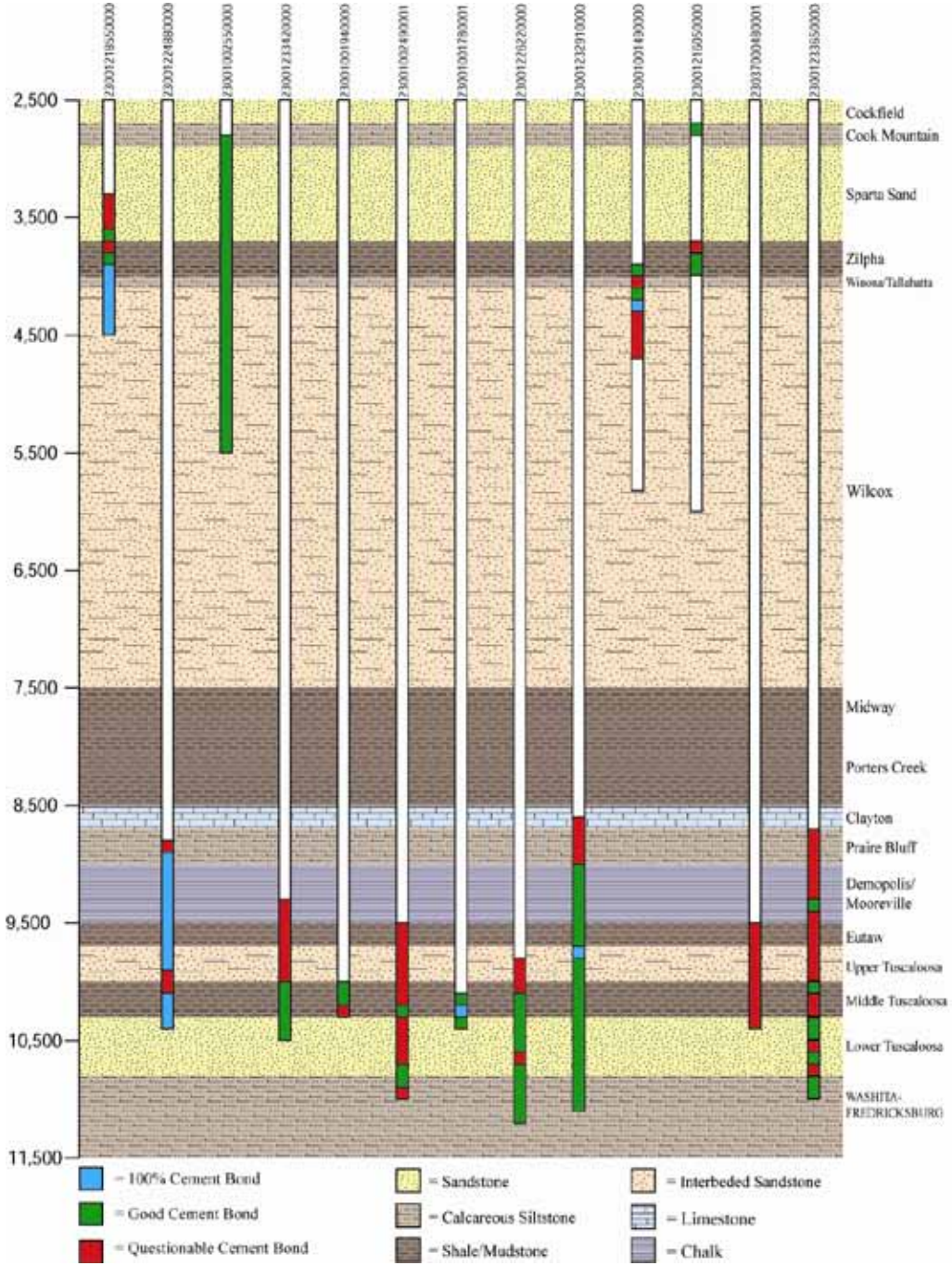
Early Project Status



RCSP program goal: Evaluate protocols to demonstrate that it is probable that 99% of CO_2 is retained

Permanence of geologic system well understood prior to test.

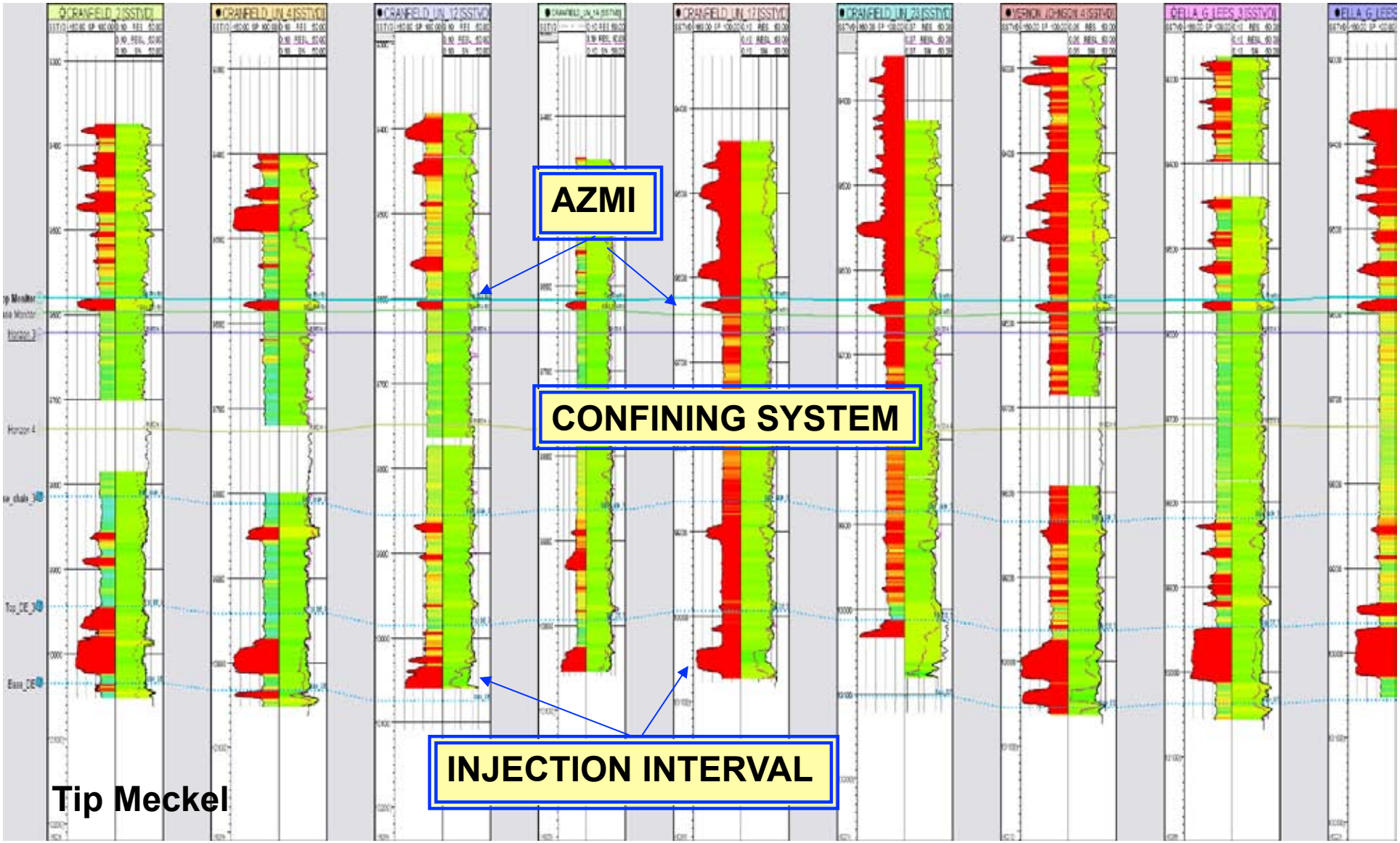
- Assessment of leakage risk.
  - Well performance is highest uncertainty and focus of monitoring research
- Conformance of flood in the injection zone
  - Pressure
  - Plume confined by 4-way closure.
    - Uncertainty – amount of radial flow (down dip/out of pattern)
- Measure changes above the injection zone
  - along well
  - above zone monitoring interval (AZMI)
  - Seismic response
  - at surface over long times



Evaluation of available Cement Bond Logs

Risk Assessment result – greatest leakage risk in unknown well rock-casing annulus bond

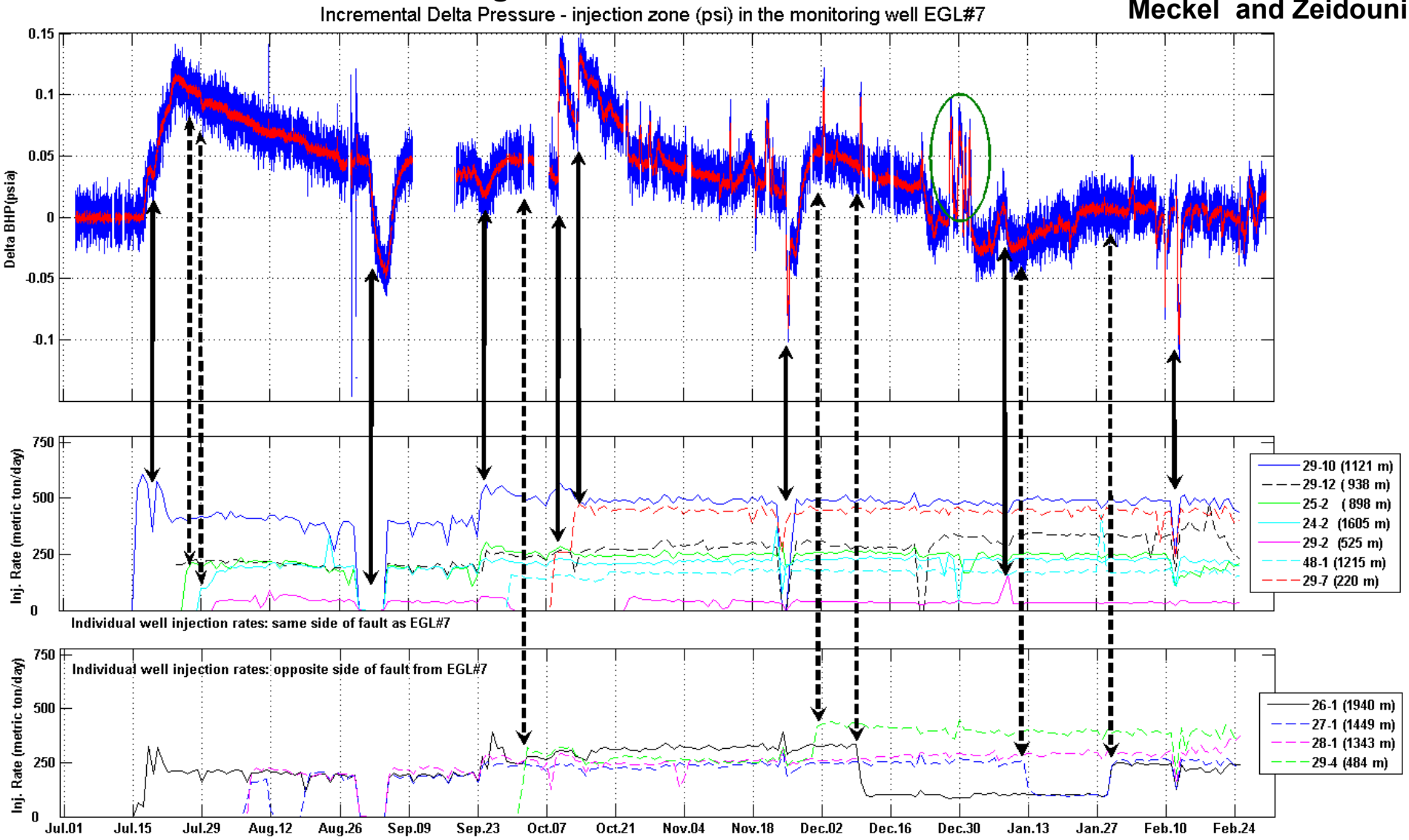
In-zone and AZMI pressure monitoring



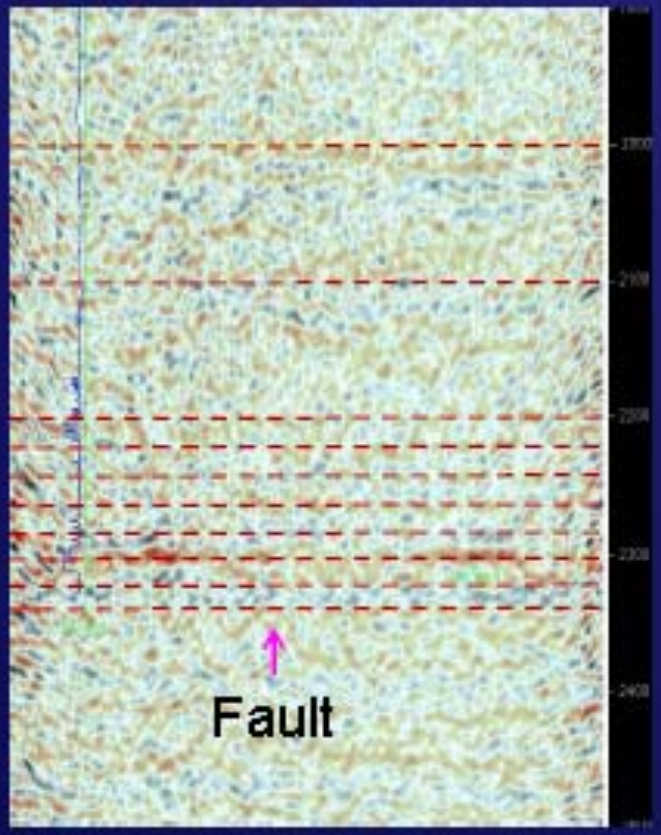
In Zone Continuous pressure data from dedicated monitoring well

- Large perturbations obvious
- Even small perturbations observable (100's tons/day flux from 1 km)
- Fault observed to be sealing

Meckel and Zeidouni

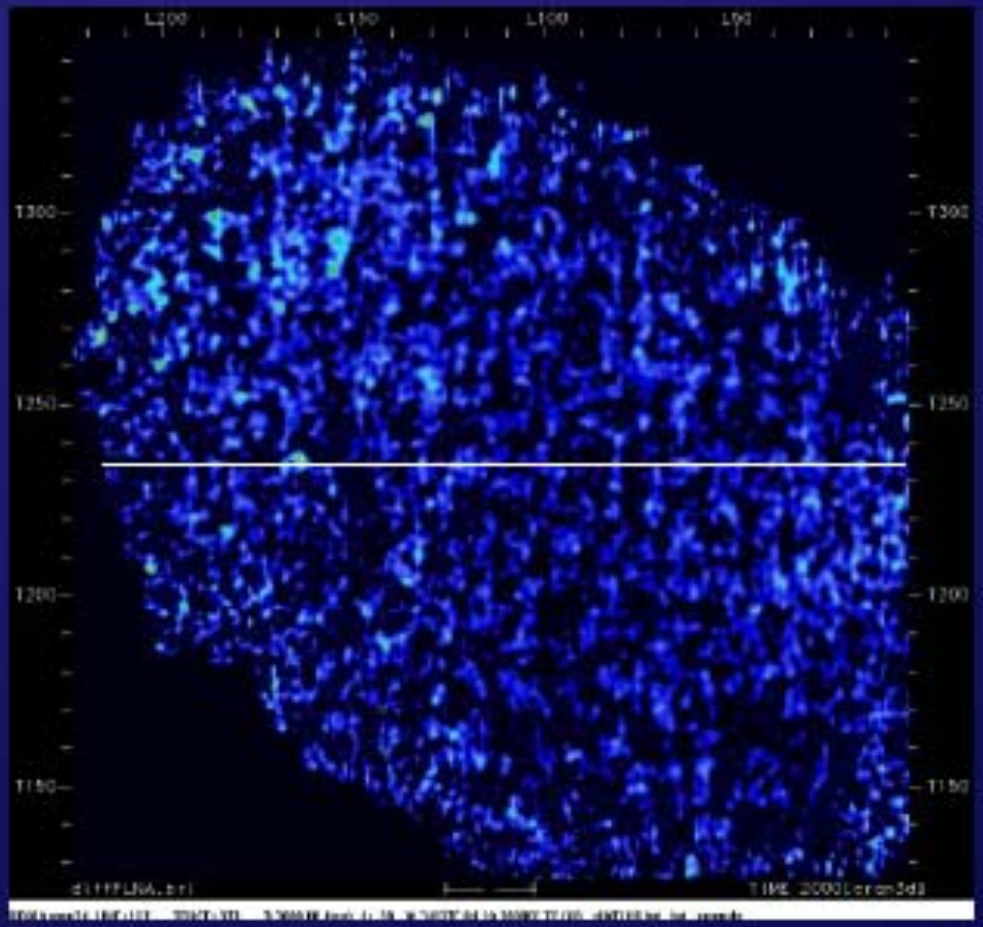


Stratal slices: there is no sign of leaking!

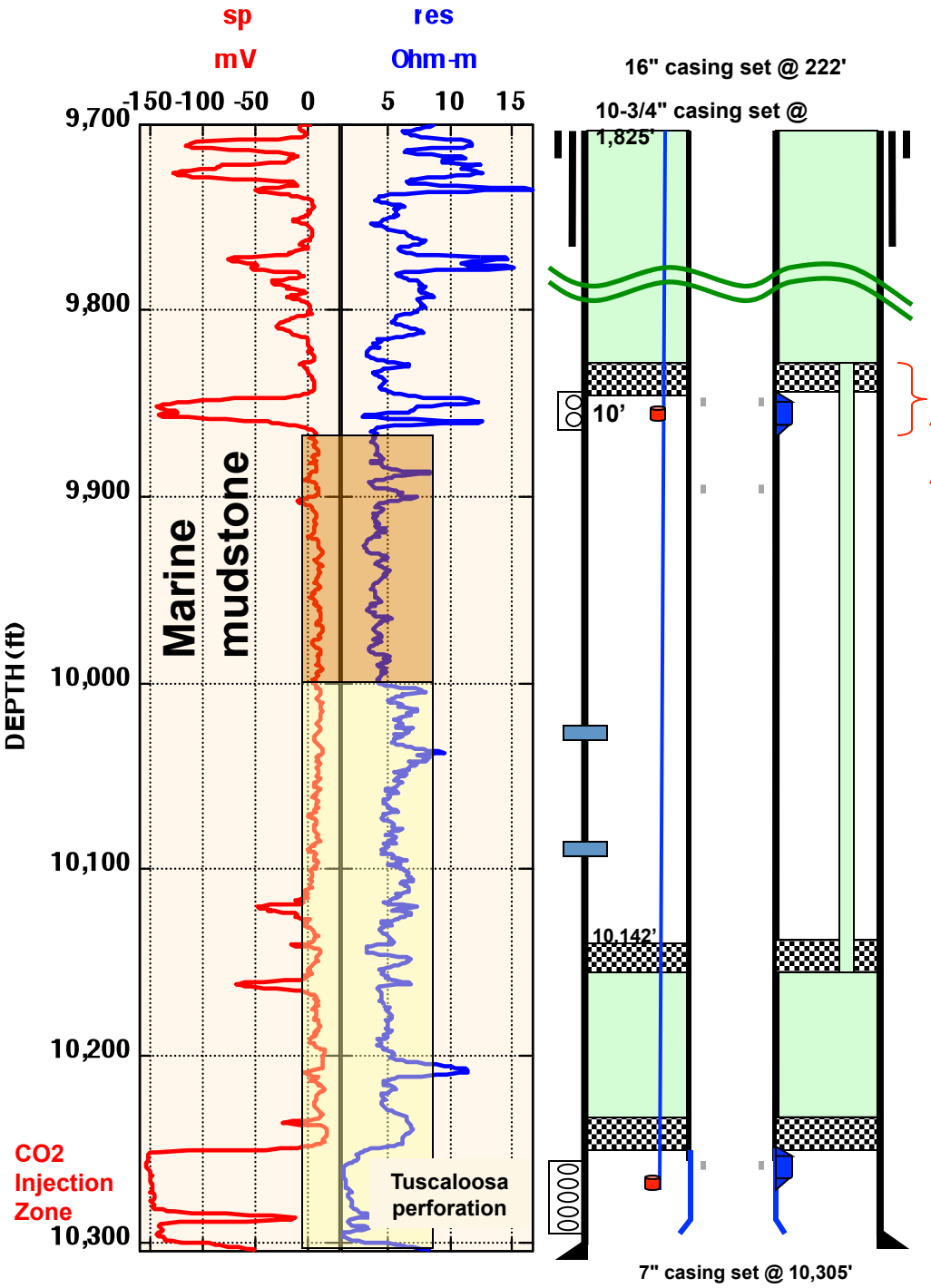


Cross-section flattened
Velocity difference

Velocity difference above zone



Initial result: Hongliu Zeng



AZMI
Above Zone Monitoring Interval

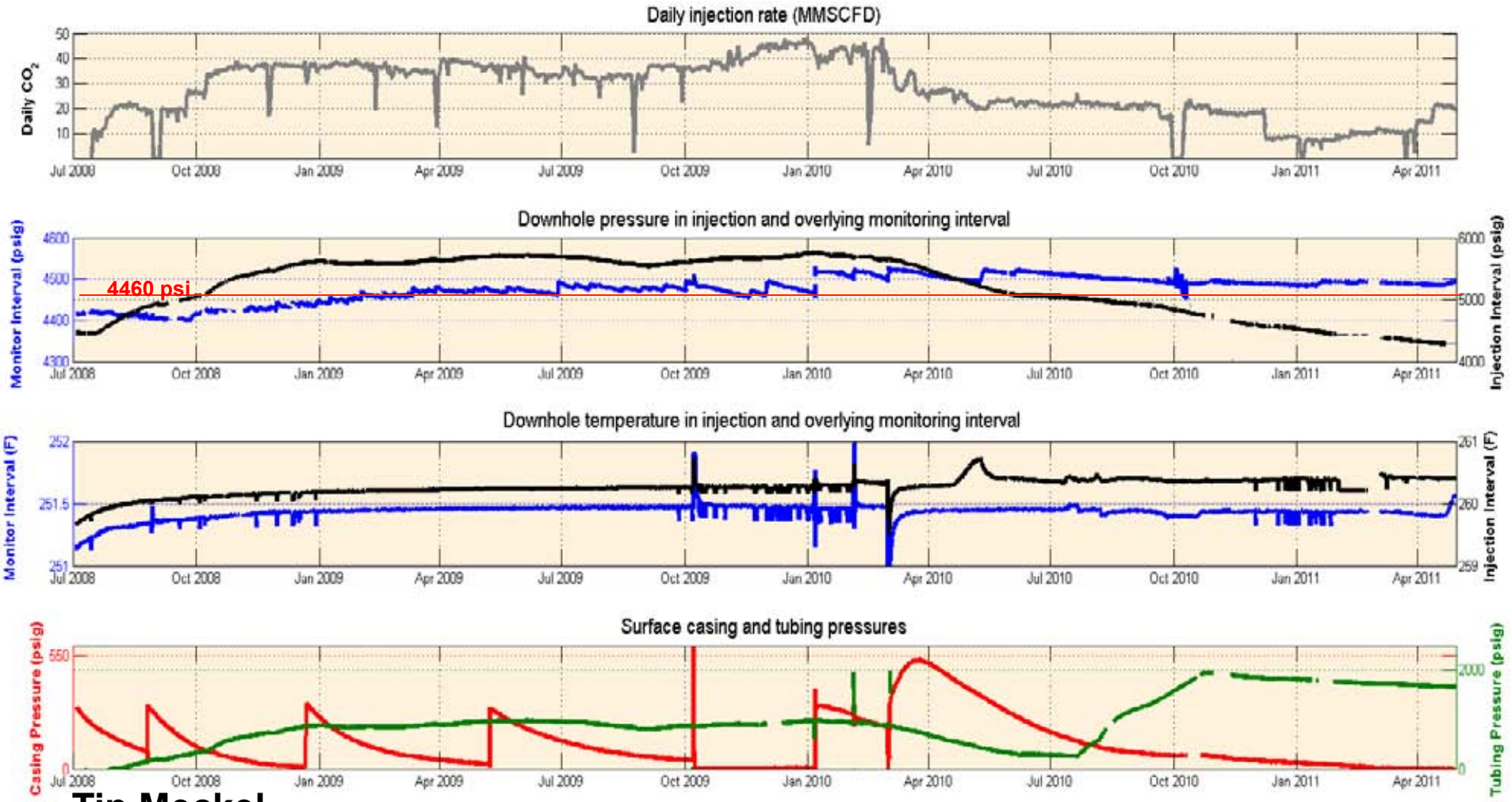
New analysis: Leakage not occurring along this well – integrated pressure-thermal analysis - Qing Tao UT PGE

Injection Zone

Tip Meckel

Continuous data series 3 years

Maximum sustained pressure differential ~1,200 psi / 80 bar / 8 MPa

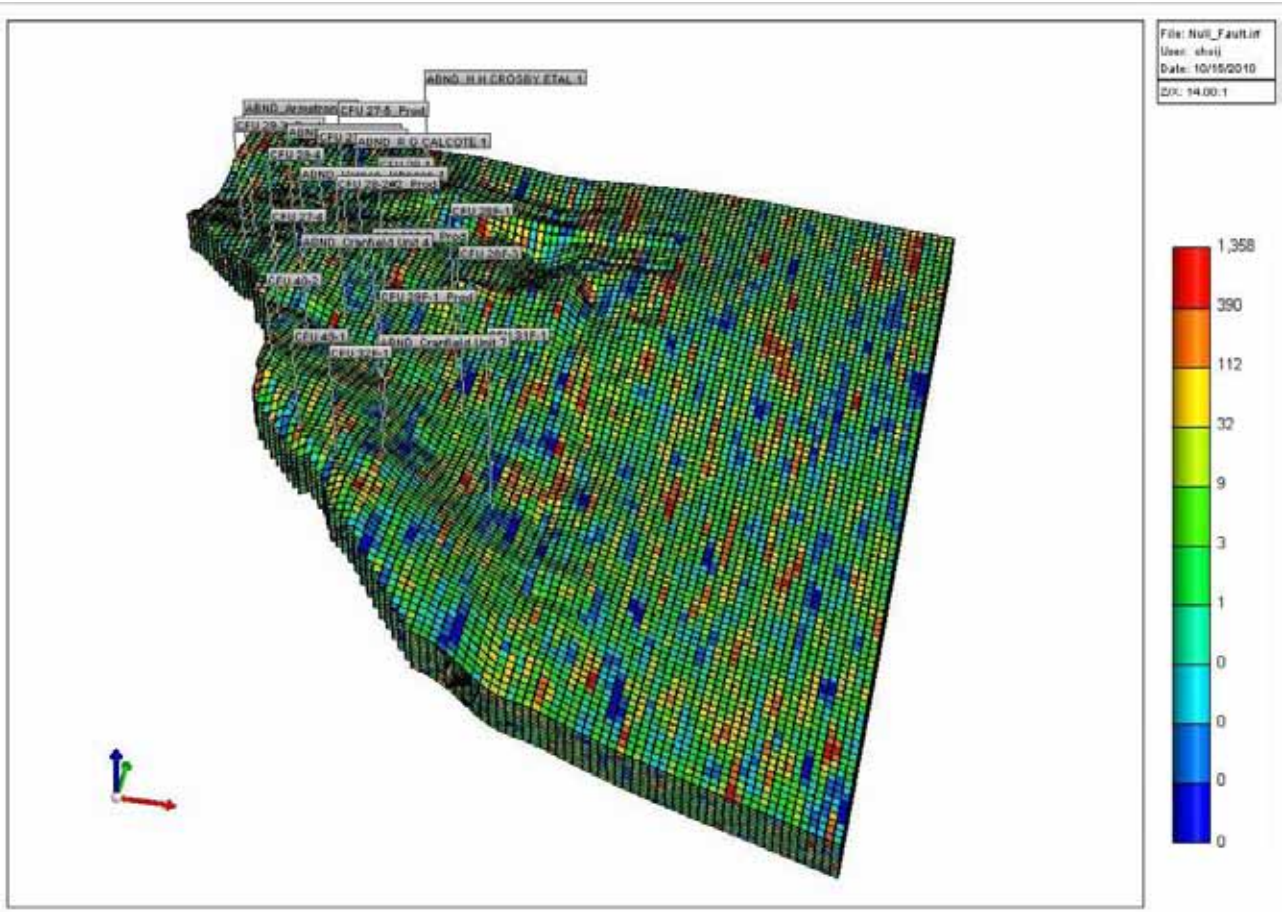


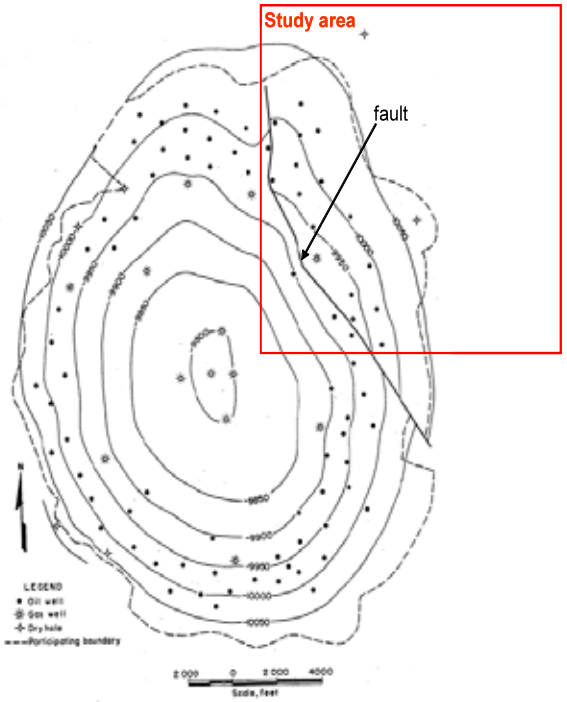
Tip Meckel

RCSP program goal:
Predict storage capacities within +/- 30%

- Capacity and injectivity well known at project start.
  - Open boundary conditions predicted during characterization are demonstrated by good model match.
  - CO_2 moved radially from injectors at the scale of the test (density contrast did not dominate)
- Advance understanding of efficiency of pore-volume occupancy (E factor)
  - Measure saturation during multiphase plume evolution Increase predictive capabilities (underway through modeling)
  - The plume continued to thicken over time, increasing capacity

DAS Simulation

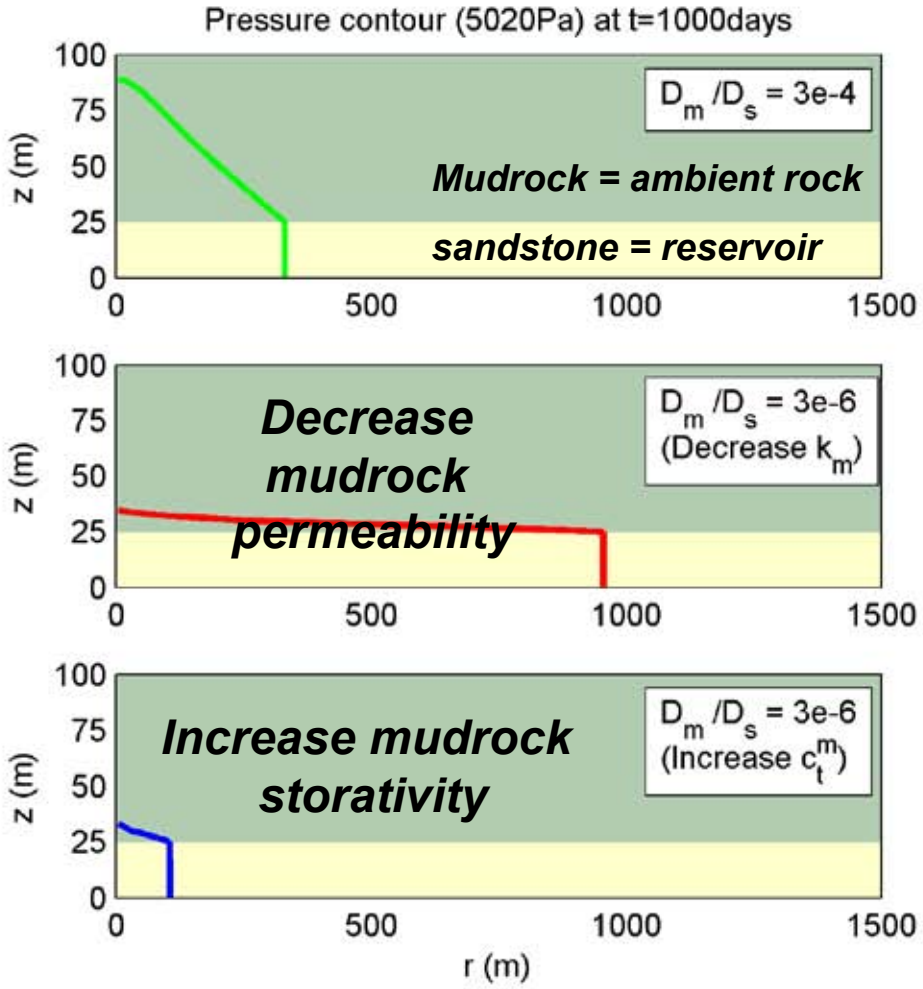




Role of the mudrock during CO_2 injection

- Pressure propagation is governed by ratios of mudrock/ sandstone permeability and storativity
- Permeable and compressible surrounding rock reduces pressure propagation within a reservoir

♪

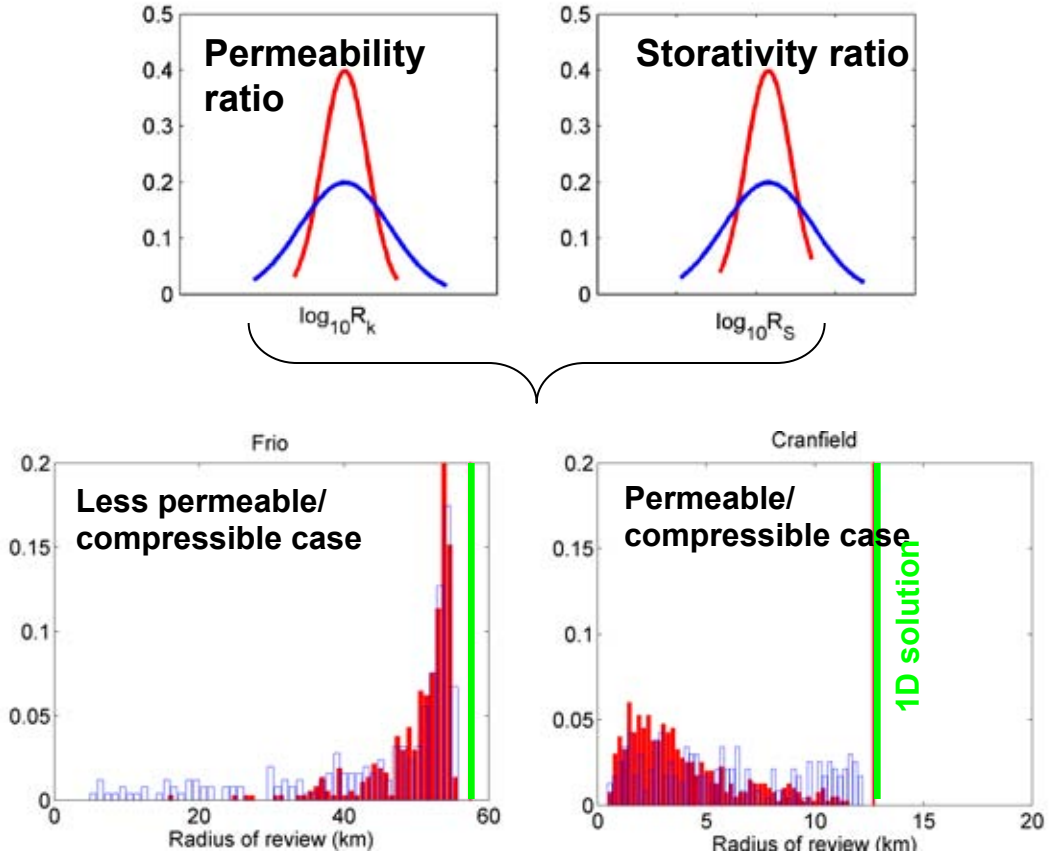


Kyungwon Chang UT DoGS

Continued…

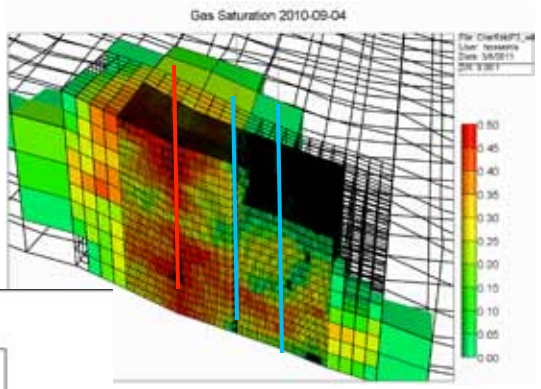
- **Area of Review (Area of pressure increase):**
  - Compressible/ permeable mudrock may reduce the radius of review
  - The uncertainty in mudrock properties leads to large variance in radius of review

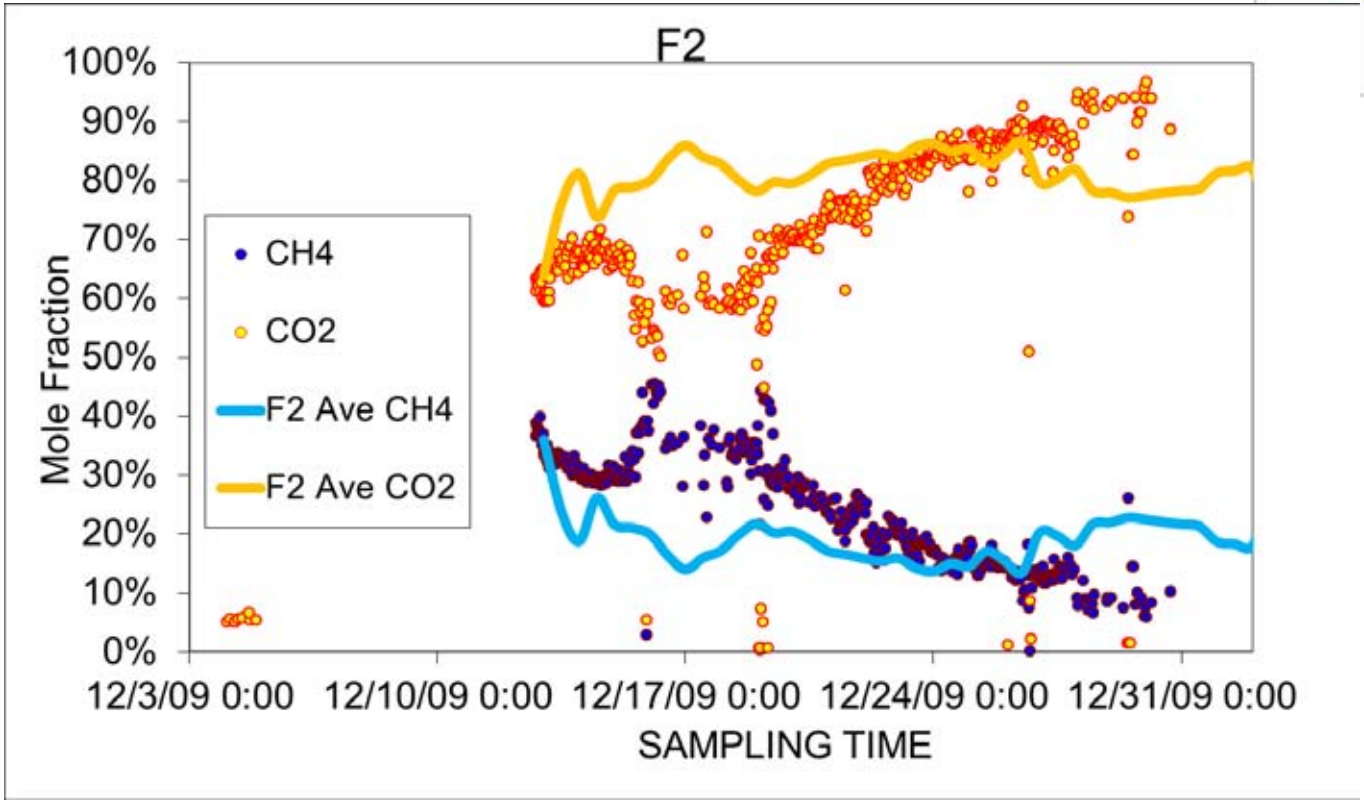
♪



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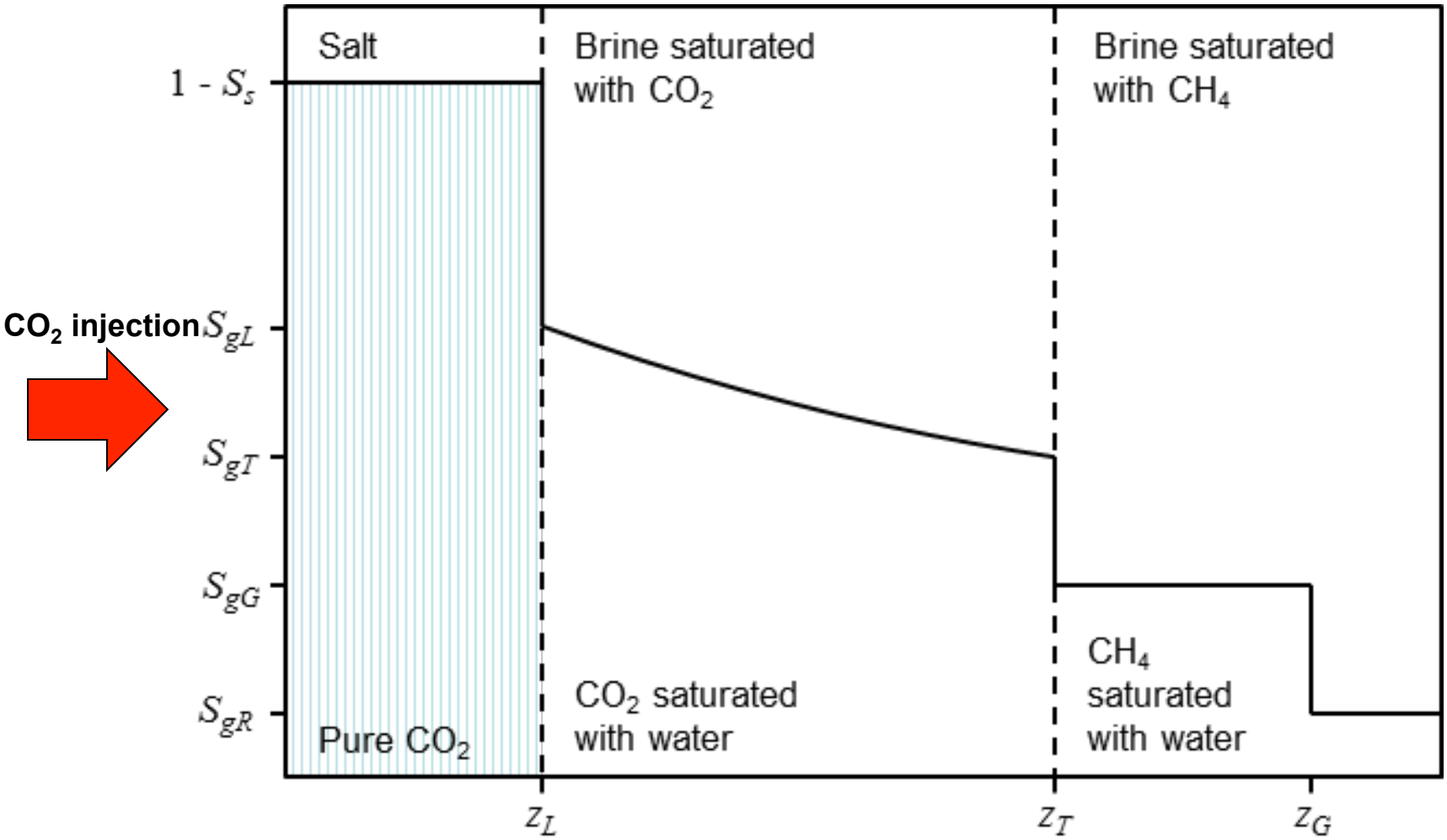
Residual methane effect on AOR and plume size





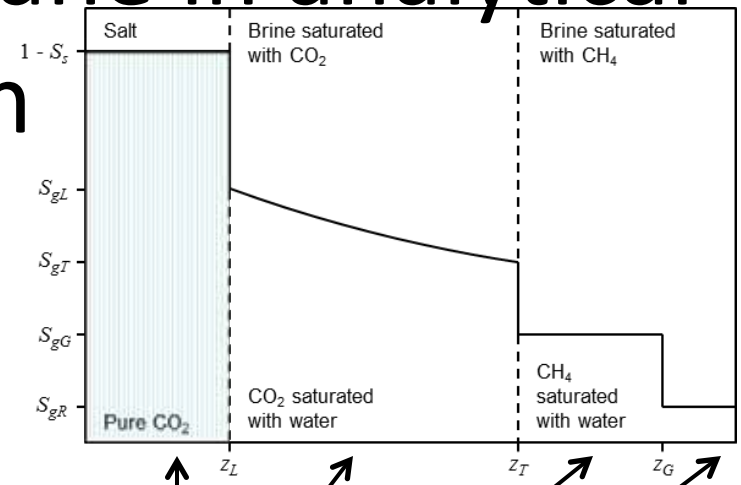
, U-tube-team; Seyyed Hosseini,

Significance of Methane Outgassing



Simon Matthias, Univ. Durham; Seyyed Hosseini, BEG

Effect of residual methane in analytical solution



- **Reduction of relative permeability**

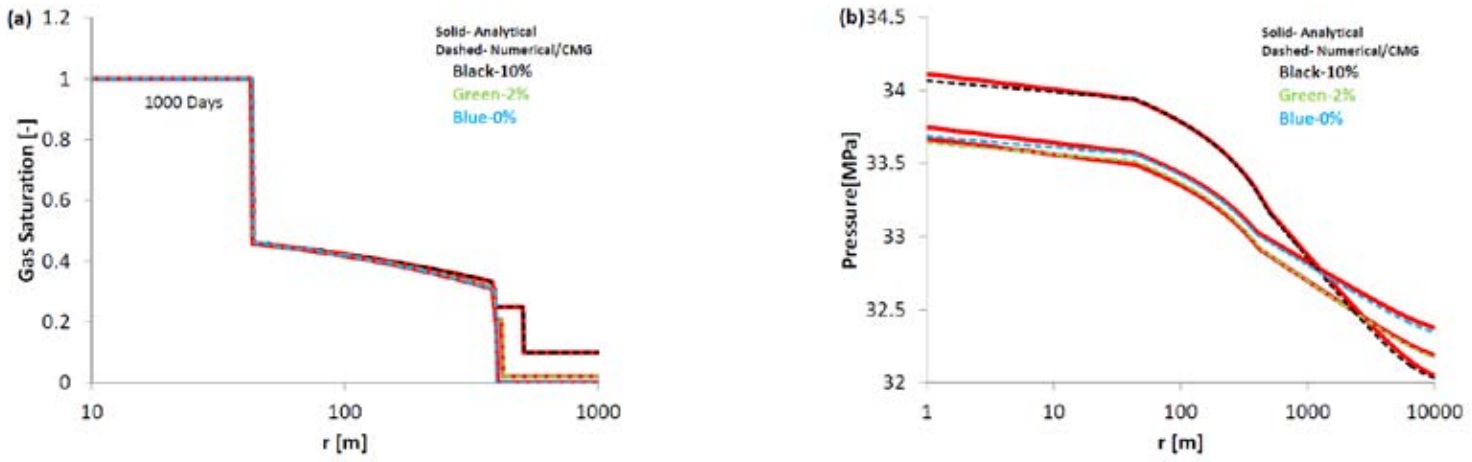
$$P - P_0 = \frac{M_0}{4\pi\rho_c H k} \begin{cases} \frac{\mu_c}{k_{rs}} \ln\left(\frac{z_T}{z}\right) + \mu_g q_{D2} F_3(z_T) + \mu_m q_{D3} F_2(z_L) + \frac{\mu_b q_{D3}}{k_{rb0}} F_1(z_G), & 0 \le z < z_T \\ \mu_g q_{D2} F_3(z) + \mu_m q_{D3} F_2(z_L) + \frac{\mu_b q_{D3}}{k_{rb0}} F_1(z_G), & z_T \le z \le z_L \\ \mu_m q_{D3} F_2(z) + \frac{\mu_b q_{D3}}{k_{rb0}} F_1(z_G), & z_L < z \le z_G \\ \frac{\mu_b q_{D3}}{k_{rb0}} F_1(z), & z > z_G \end{cases} \quad (49)$$

$$\alpha = \frac{M_0 \mu_b (c_r + (1 - S_{g3}) c_b + S_{g3} c_m)}{4\pi H \rho_c k}, \quad z_E = \frac{\pi \phi \rho_c H r_E^2}{M_0 t} \quad (53)$$

Simon Matthias, Univ. Durham;
Seyyed Hosseini, BEG

- **Increase of compressibility**

Sensitivity to initial residual gas amount



- At **higher** methane residual saturations it can:

1. Reduce the injectivity
2. Reduce the far-field pressure
3. Increase the plume size by 30%

Simon Matthias, Univ. Durham; Seyyed Hosseini, BEG

Knowledge Sharing

- UT Energy Forum
- UT Law School Continuing Education
- CSLF – Recognition of SECARB Early Test
- 10th Annual CCS conference (Pittsburg)
- IEA Monitoring network
- Trondheim CCS Conference
- Pew Center Accounting Framework
- Canadian Standards Association (CSA) carbon sequestration standards development
- CO2CARE – EU -post-closure research
- BIG CCS – Norwegian University Research program
- CCP Contingency Workshop
- EPA/LBNL Geologic Sequestration and Water workshop
- AEP Mountaineer – Geologic Expert Team
- Review EPA guidance documents
- UT CCS1
- STORE and SECARB-Ed training
- 29 Publications www.gulfcoastcarbon.org bookshelf
- Thesis and dissertations: 2 completed; 3underway

Future work

- Long-term monitoring- AZMI, groundwater, soil gas
- Complete cross- tool comparison
- Support other experiments
  - LBNL - CO2 geothermal
  - RITE - microseismic
  - Schlumberger cement analysis
  - Univ. Edinburgh noble gas study
  - SIM-SEQ
- Possible CCUS activities

Document storage permanence

Storage only saline green field

- Prove-up capacity
- Prove-up confinement

- Simple fluid – low solubility

- Few wells
- Historical uses?
- Evolving regulatory and legal framework
- Unknown public acceptance

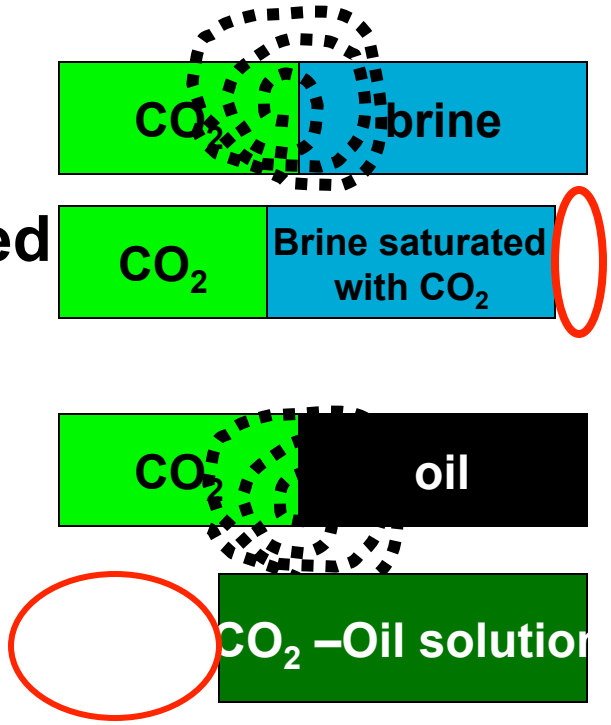
CCUS – EOR in brownfield

- Well-known capacity
- Well-demonstrated confinement
- Complex fluids, high solubility
- Many wells
- Complex history
  - Perturbation from past practices
- Mature regulatory and legal framework
- Good public acceptance

Role of Dissolution in Plume and Pressure Evolution CCS/CCUS

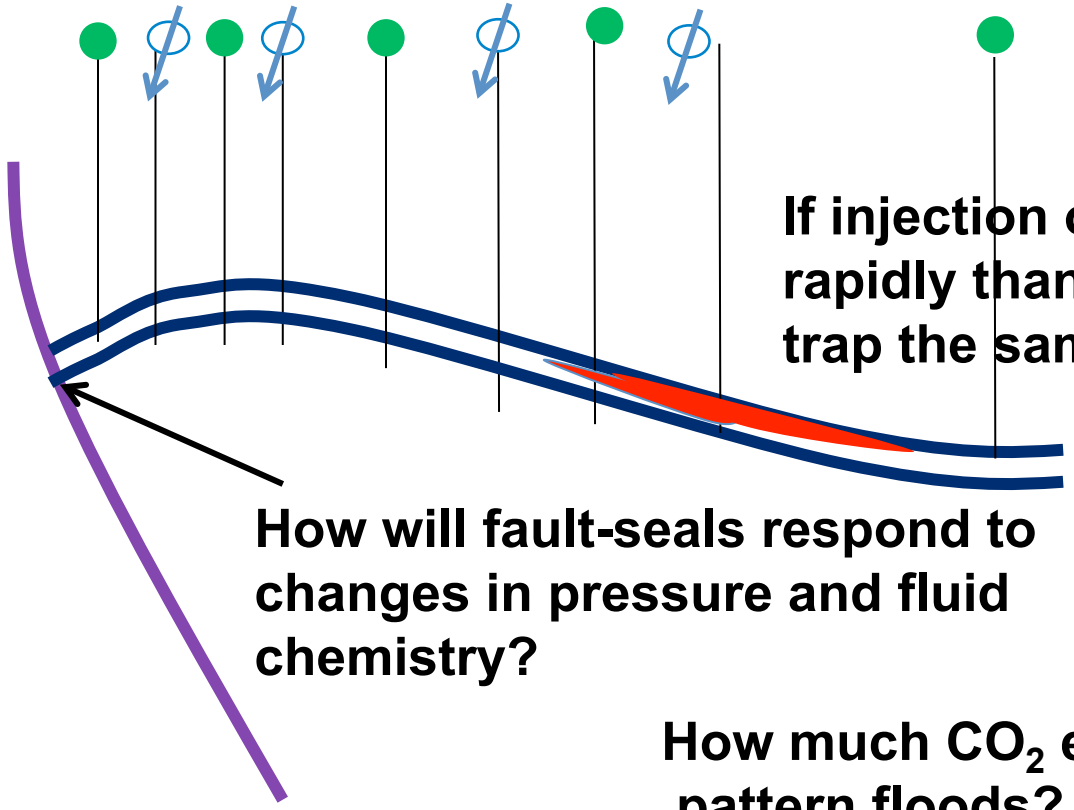
CO_2 injected into brine:
Minor dissolution: volume displaced
4% less than volume injected

CO_2 injected into oil:
Complete dissolution:
volume displaced
as much as 40% less than
volume injected



Less space occupied = enhanced security and lower pressure.

Is it always true that traps and seals that held oil will hold CO_2 ?



If injection occurs much more rapidly than charge, will it fill the trap the same way?

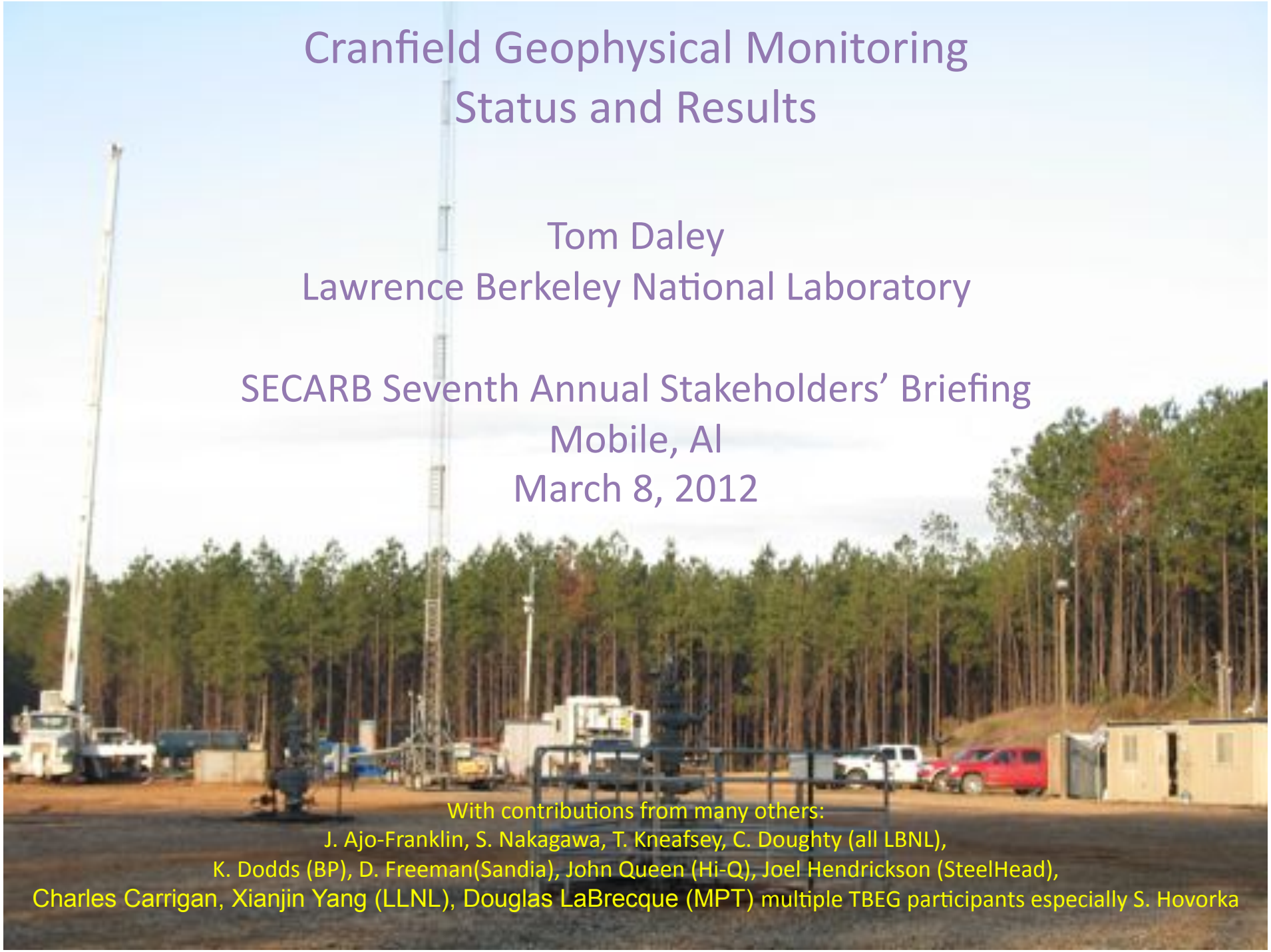
How will fault-seals respond to changes in pressure and fluid chemistry?

How much CO_2 escapes from pattern floods?

Cranfield Geophysical Monitoring Status and Results

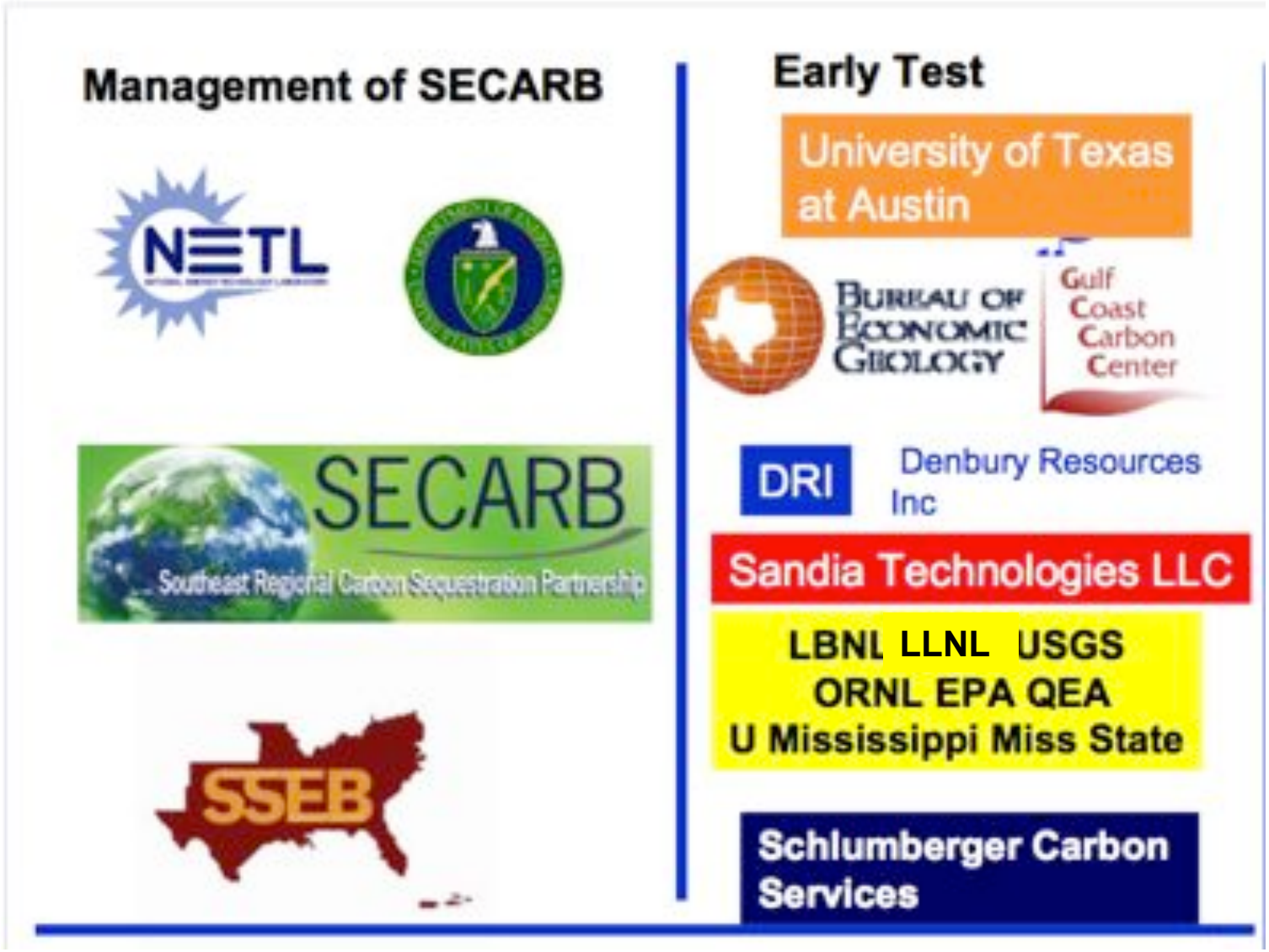
Tom Daley
Lawrence Berkeley National Laboratory

SECARB Seventh Annual Stakeholders' Briefing
Mobile, Al
March 8, 2012



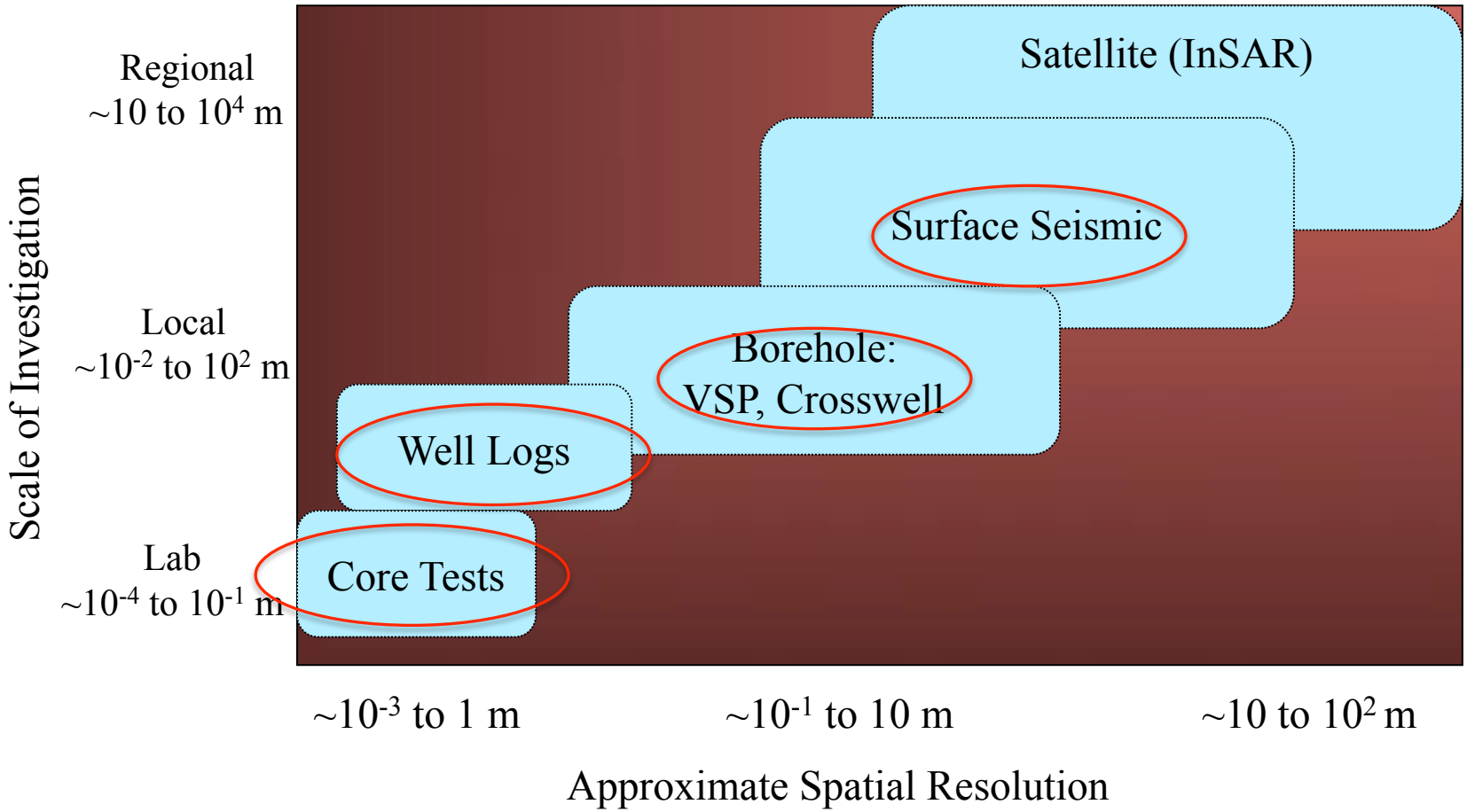
With contributions from many others:
J. Ajo-Franklin, S. Nakagawa, T. Kneafsey, C. Doughty (all LBNL),
K. Dodds (BP), D. Freeman(Sandia), John Queen (Hi-Q), Joel Hendrickson (SteelHead),
Charles Carrigan, Xianjin Yang (LLNL), Douglas LaBrecque (MPT) multiple TBEG participants especially S. Hovorka

Acknowledgements



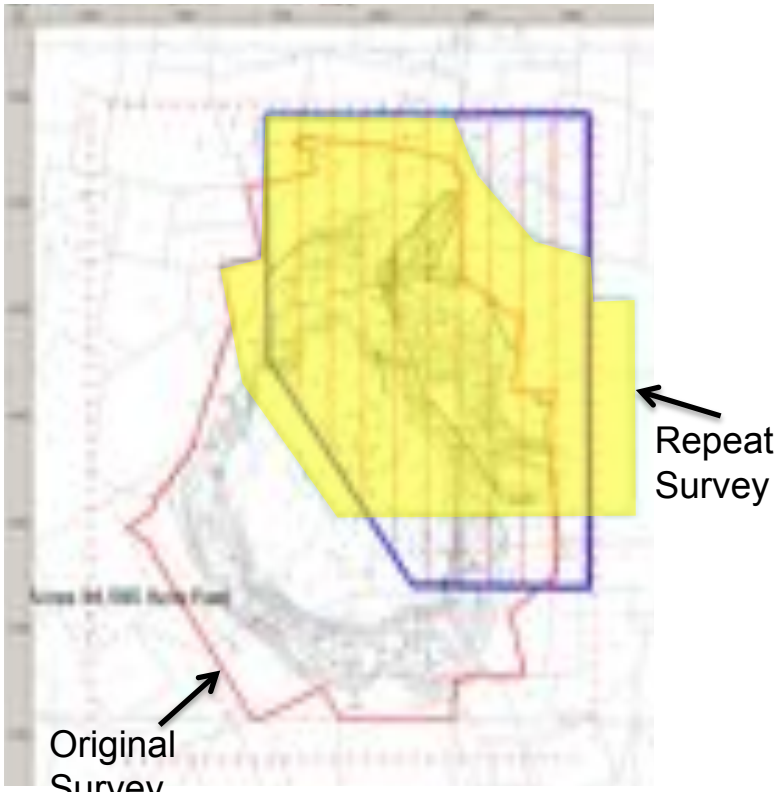
Geophysical Monitoring:

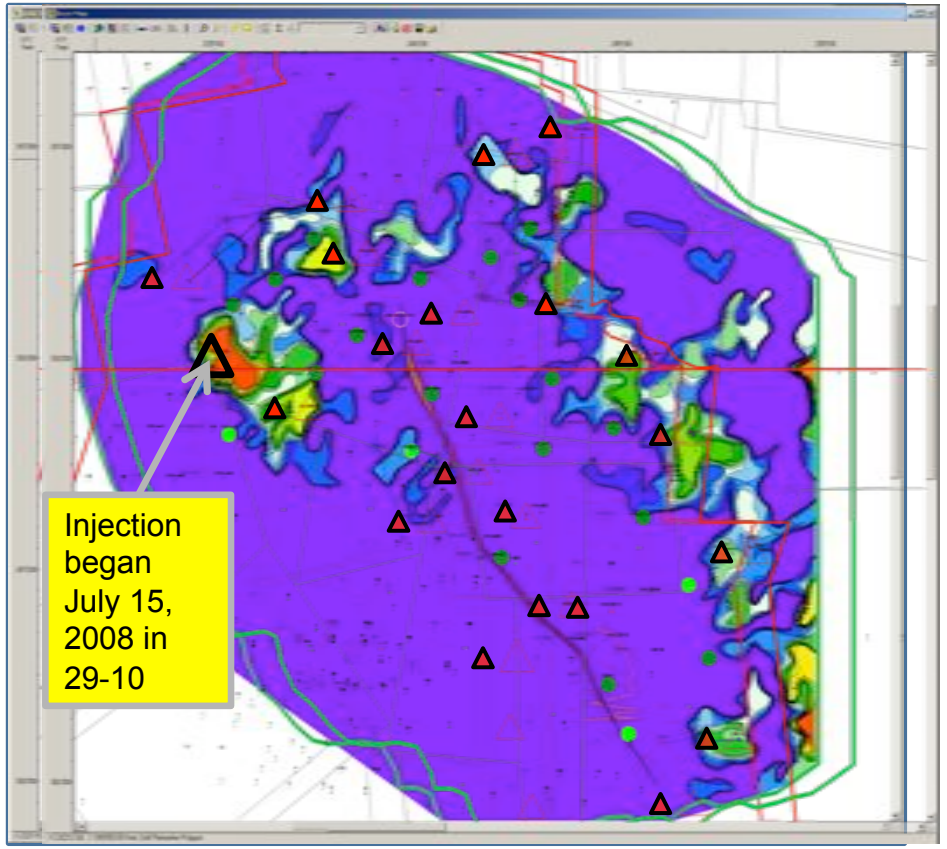
We want to 'see' the CO2, but also understand what we are seeing. =>
Integrate and quantitatively interpret geophysical data at varying scales



Acquired at Cranfield

4D Seismic: Change in Reservoir Reflection Amplitude

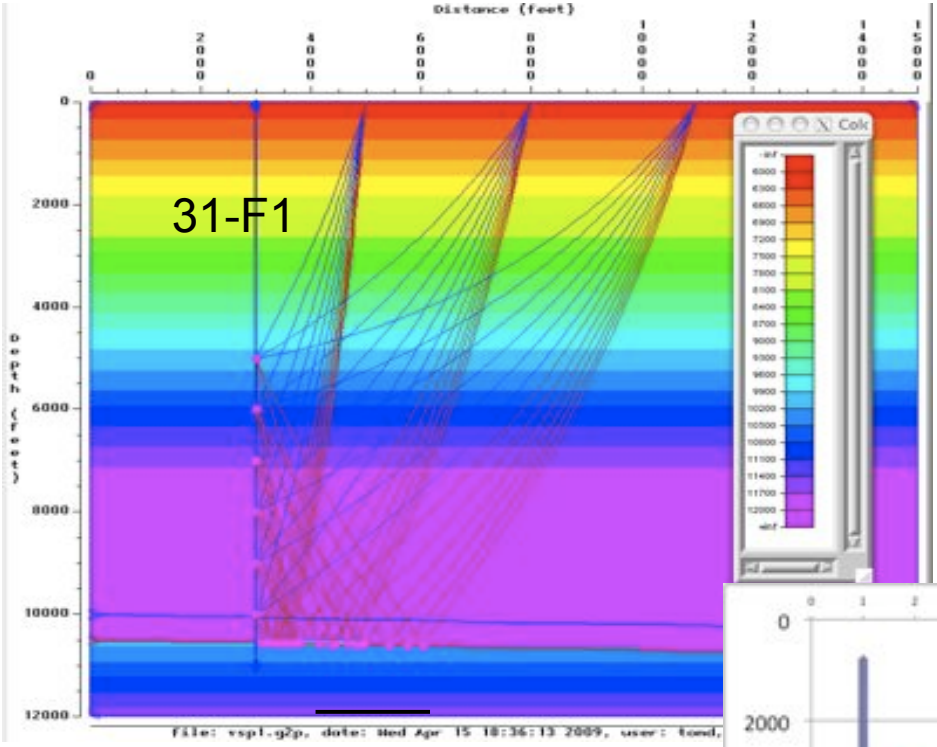




Courtesy J. Ditkof (TBEG) and Denbury

VSP Sep 2009/ Nov 2010

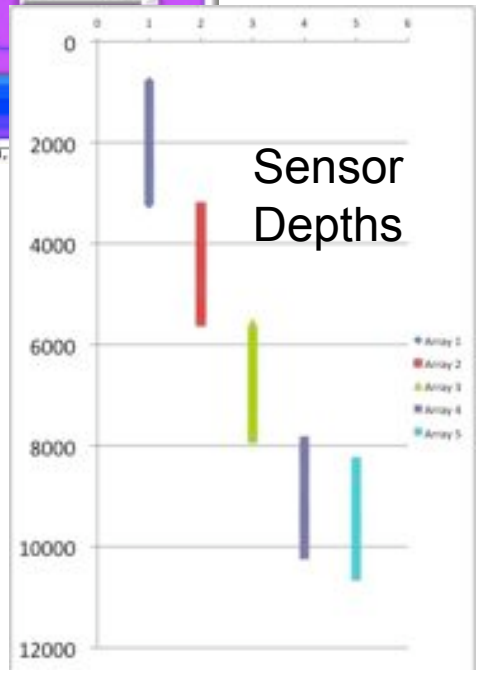




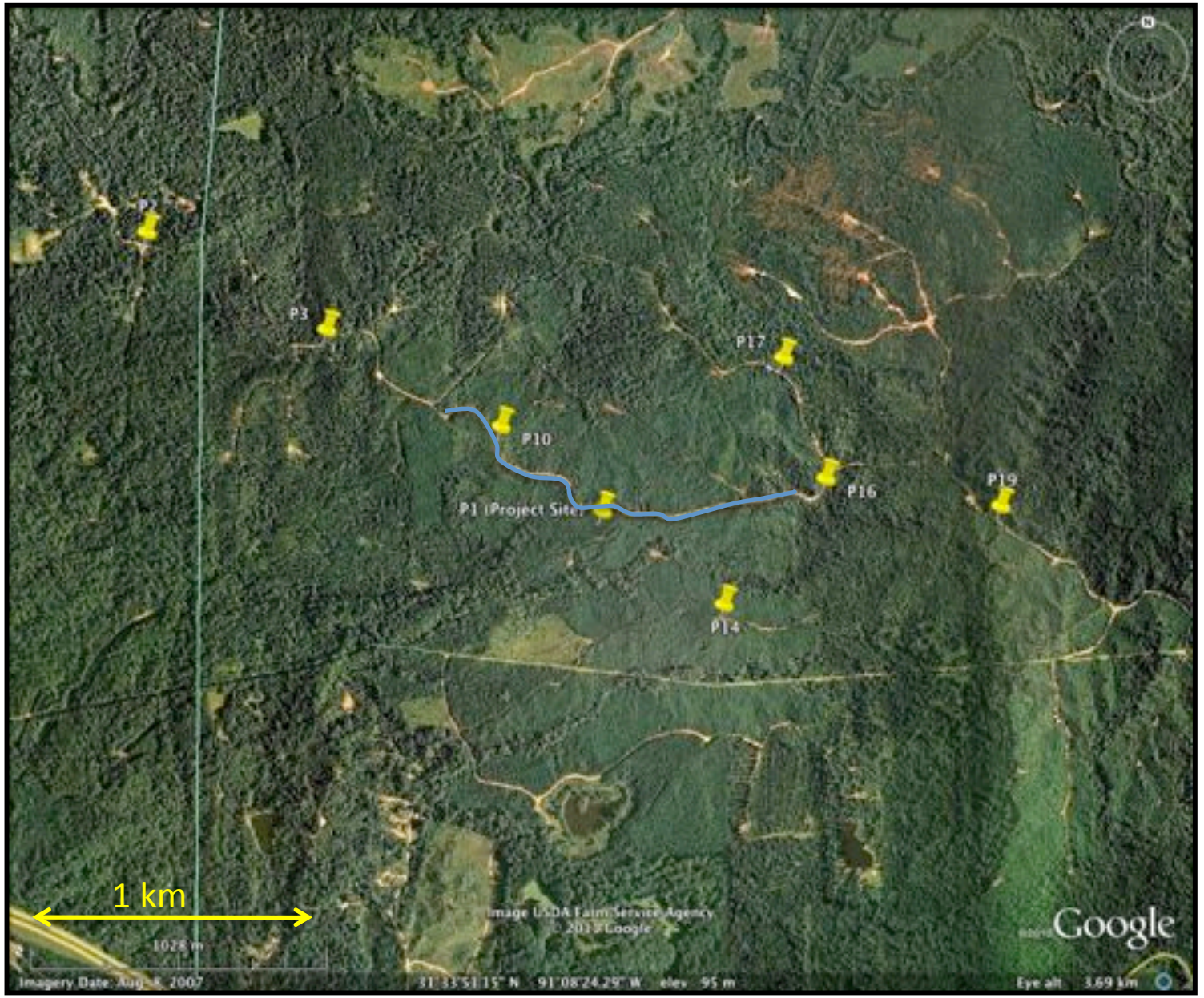


Acquisition by
Apex-HiPoint

Weight Drop Source

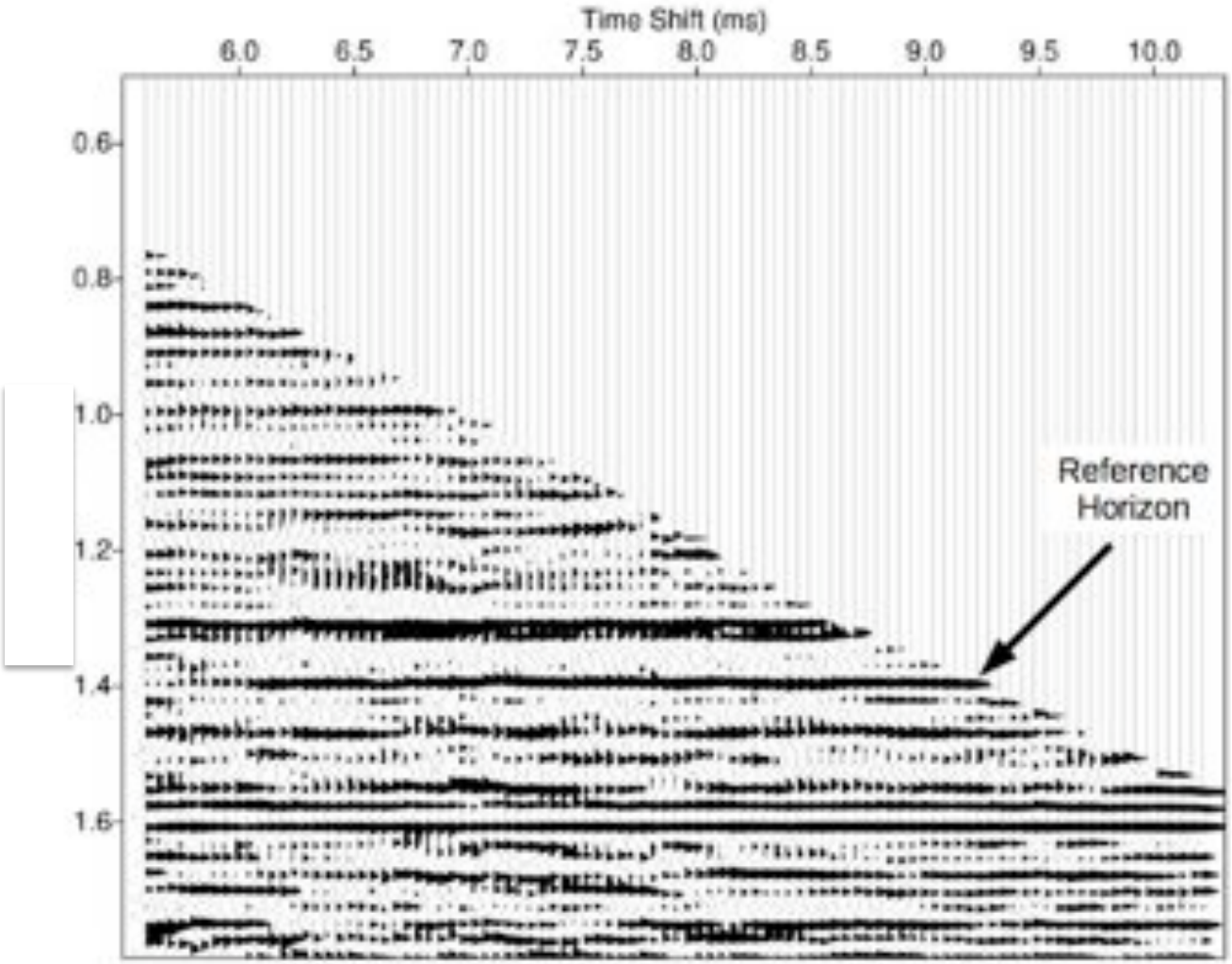


OVSP: Time-Lapse



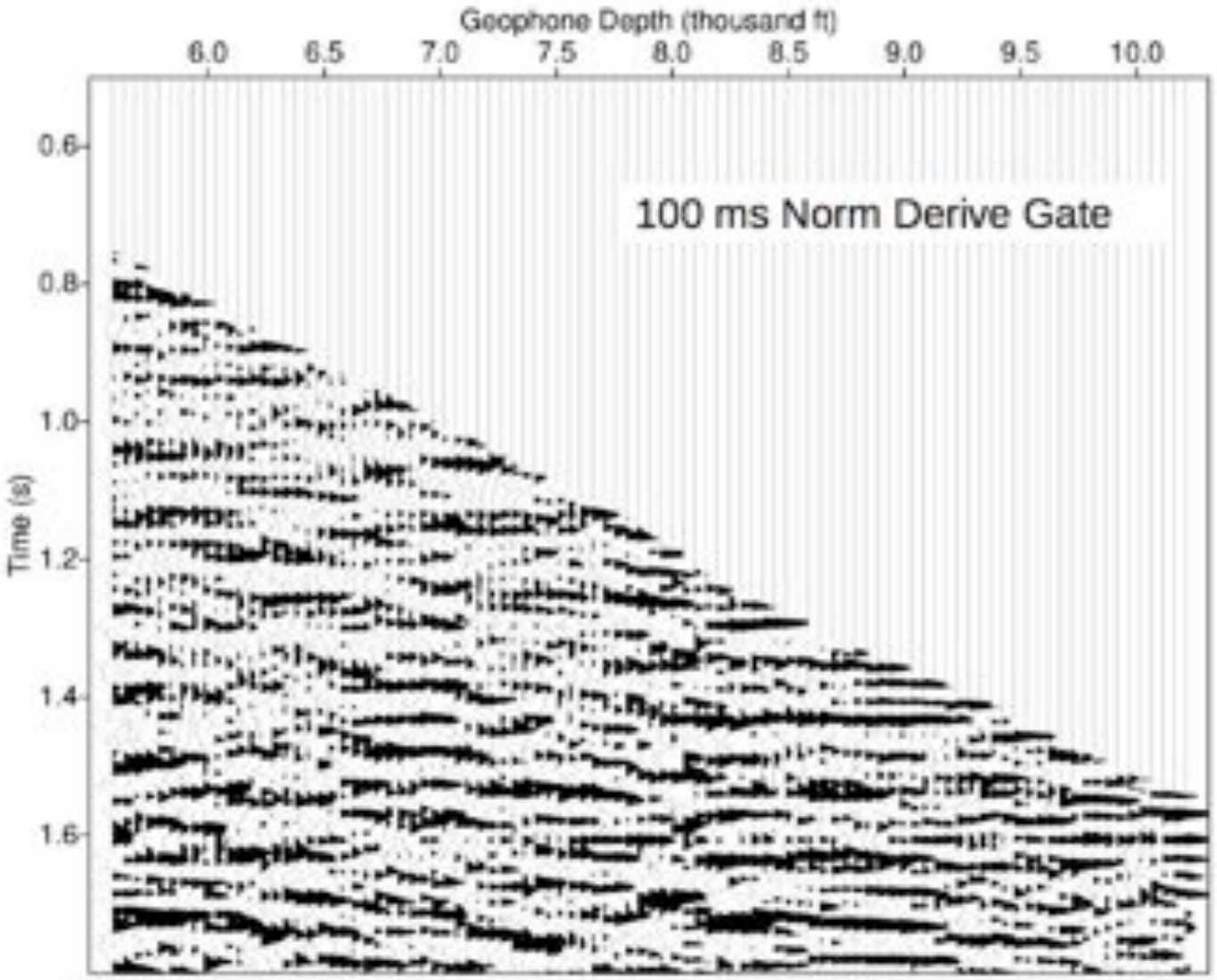
WVSP

SP 138 VSP Pre Data



From Hi-Q Geophysics & SteelHead

SP 138 VSP (Up Dip) – Time Lapse Change

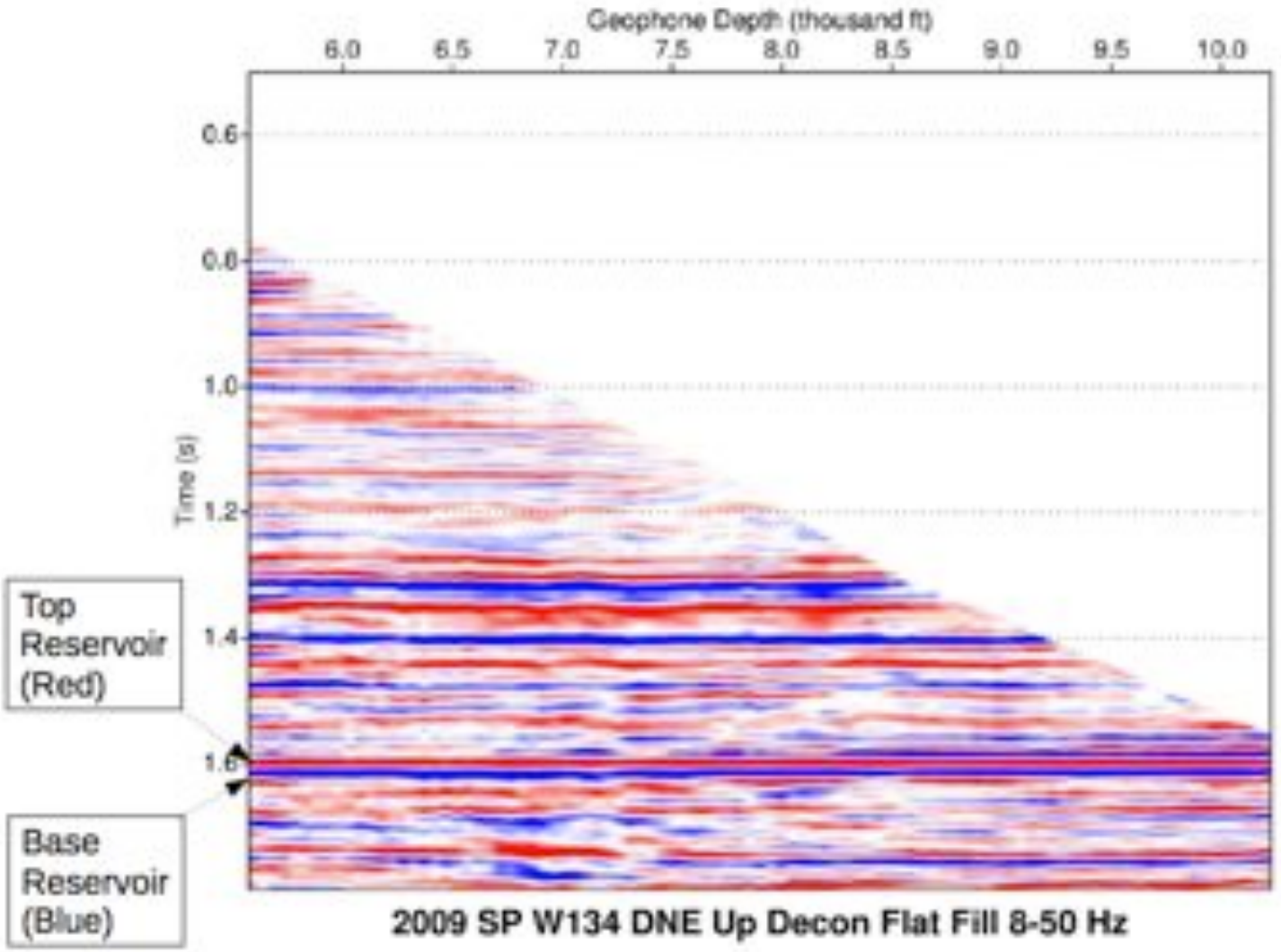


Reservoir

2010 SP W138 DNE Up Decon Flat Fill Tshift Enorm 8-50 Hz - 2009

J. Hendrickson (Steelhead)

VSP – Top and Base Reservoir Analysis

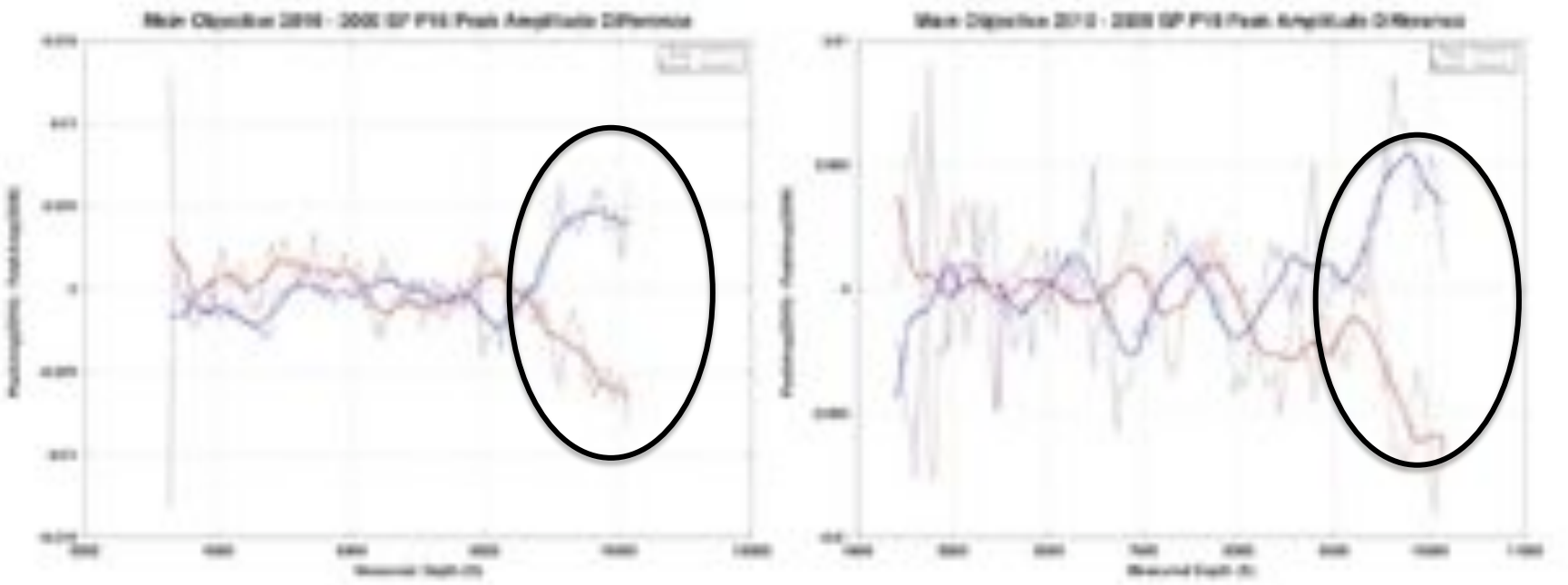


Reservoir

J. Hendrickson (Steelhead)

VSP – Downdip Response

Why so difficult to see?

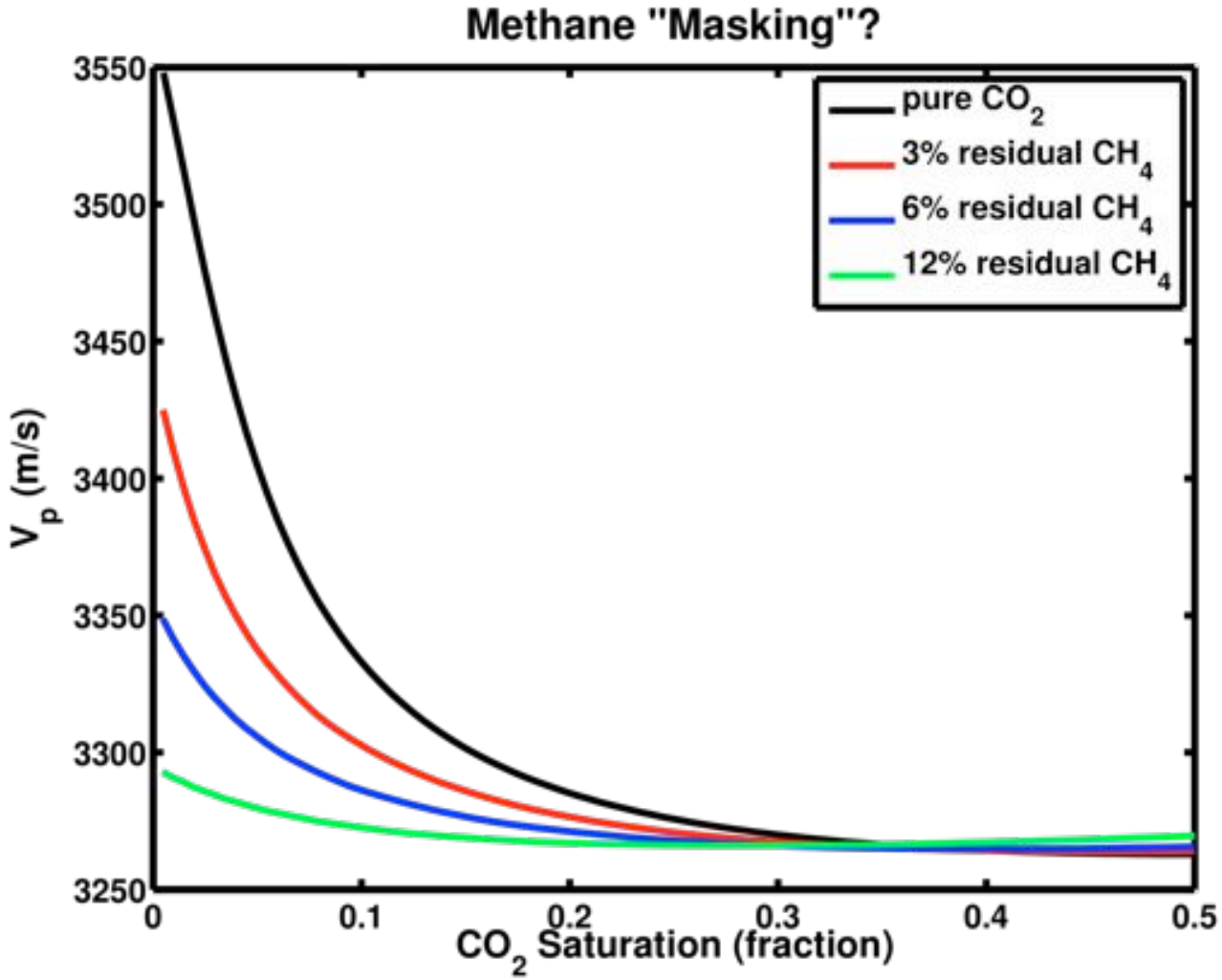


Offset from well

Offset from well

J. Hendrickson (Steelhead)

Petrophysical Modeling of Tusc. D/E at Surface Seismic Frequency (50 Hz)



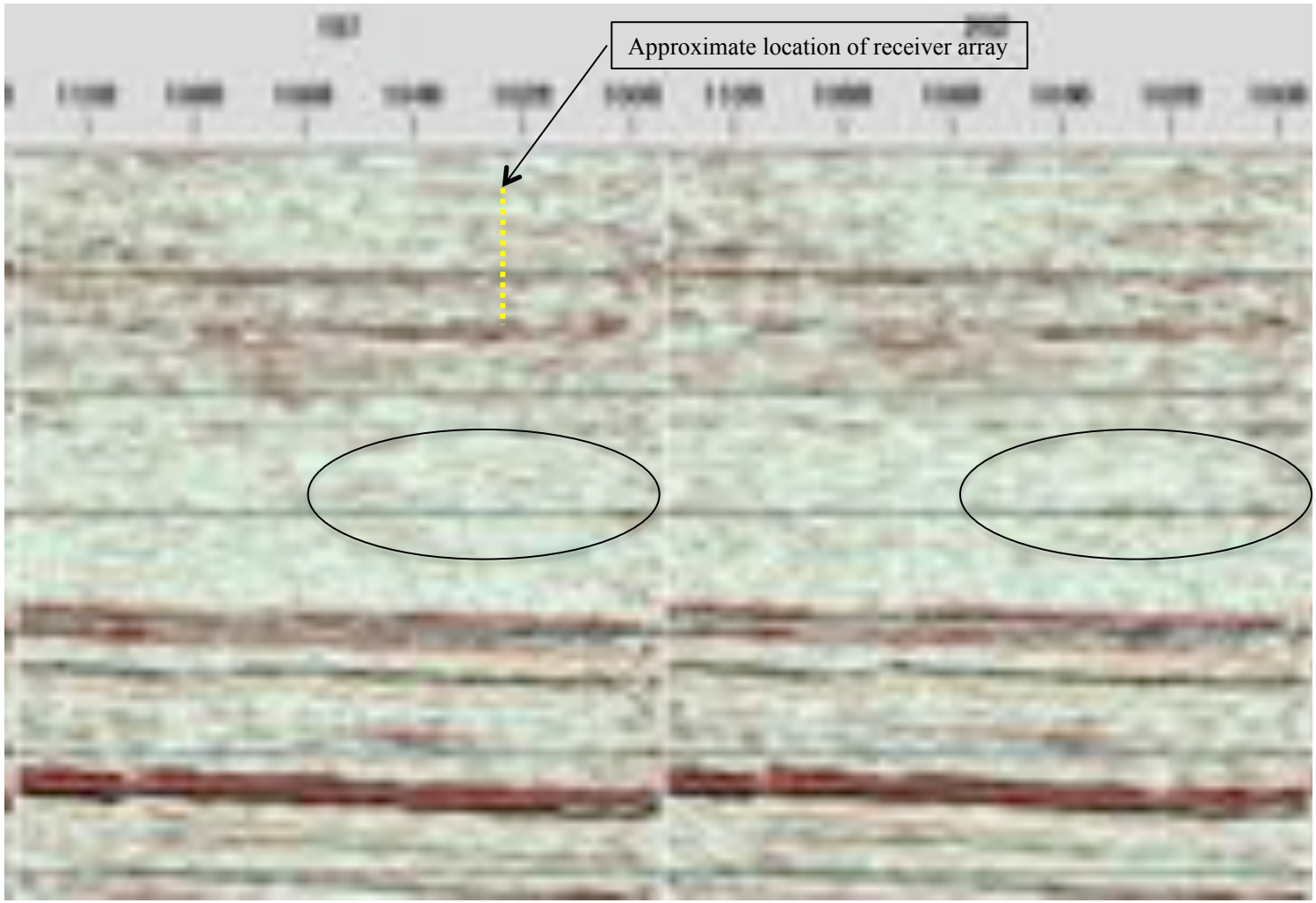
Predicted Velocity Decrease for CO2 Displacing Brine:

No Methane:
~300 m/s (9%)

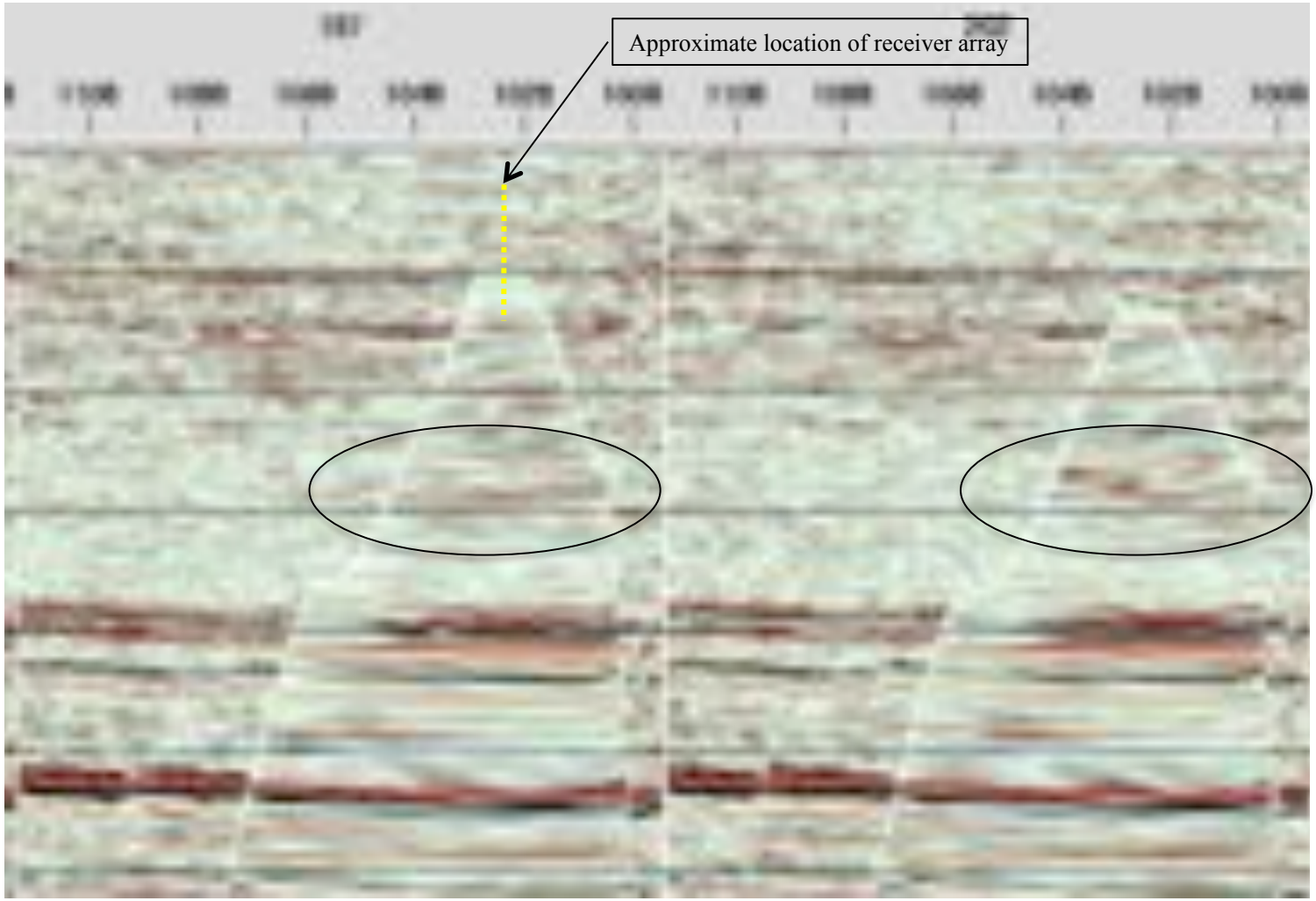
12% CH_4
20 m/s (0.5%)

J. Ajo-Franklin

Surface Seismic



3D-VSP and Surface Cube

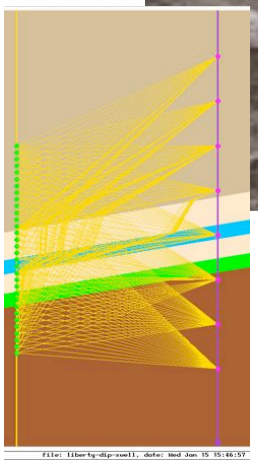


3D-VSP Collaborative with National Risk Assessment Partnership (NRAP)

-20 msec time shift applied to match surface data

Crosswell Scale: Seismic
Sep 2009 & Oct 2010





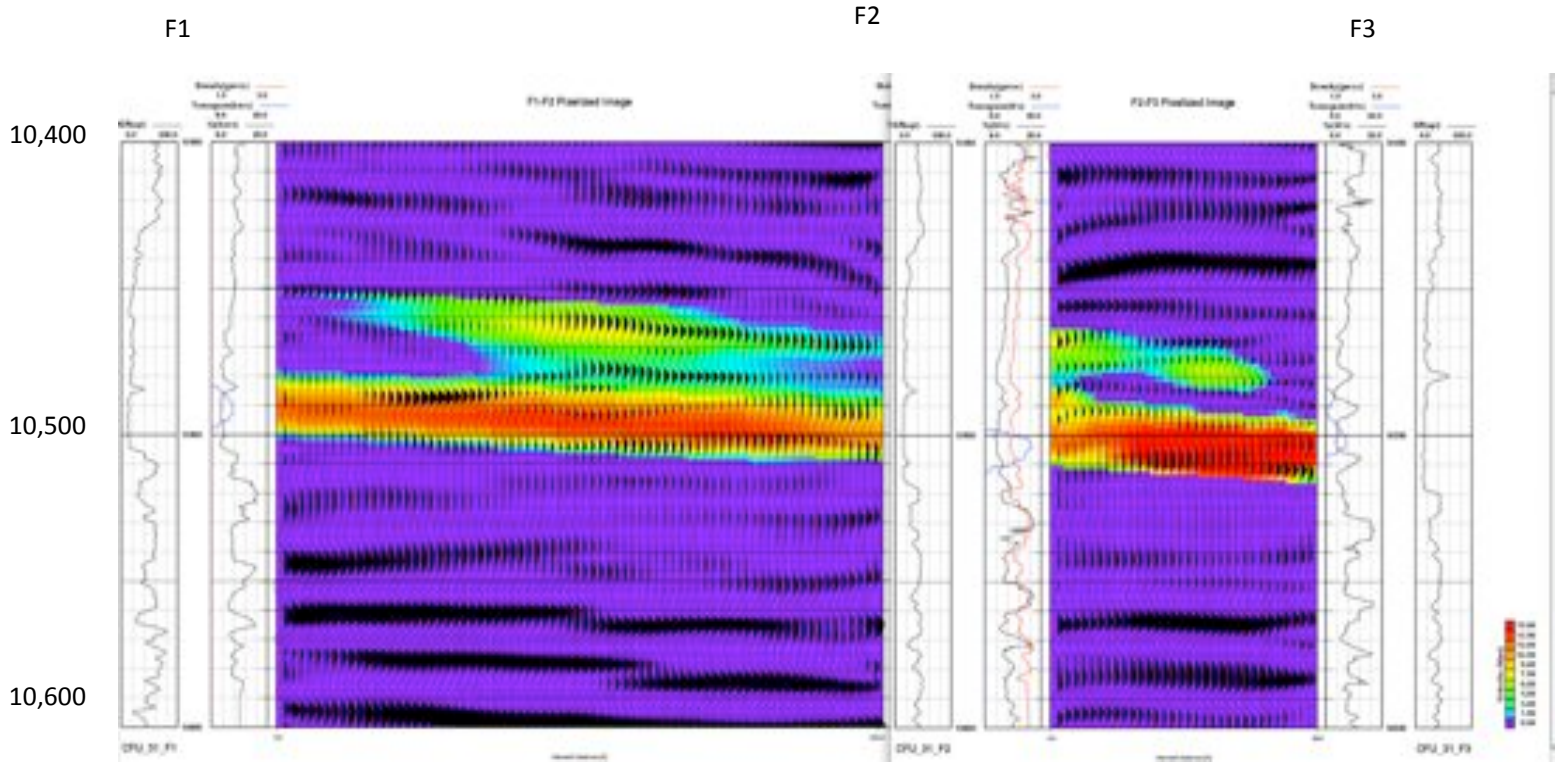


Hydrophone Sensors



Piezoelctric Source

Commercial Crosswell Seismic: Reflection Image and Velocity Tomography

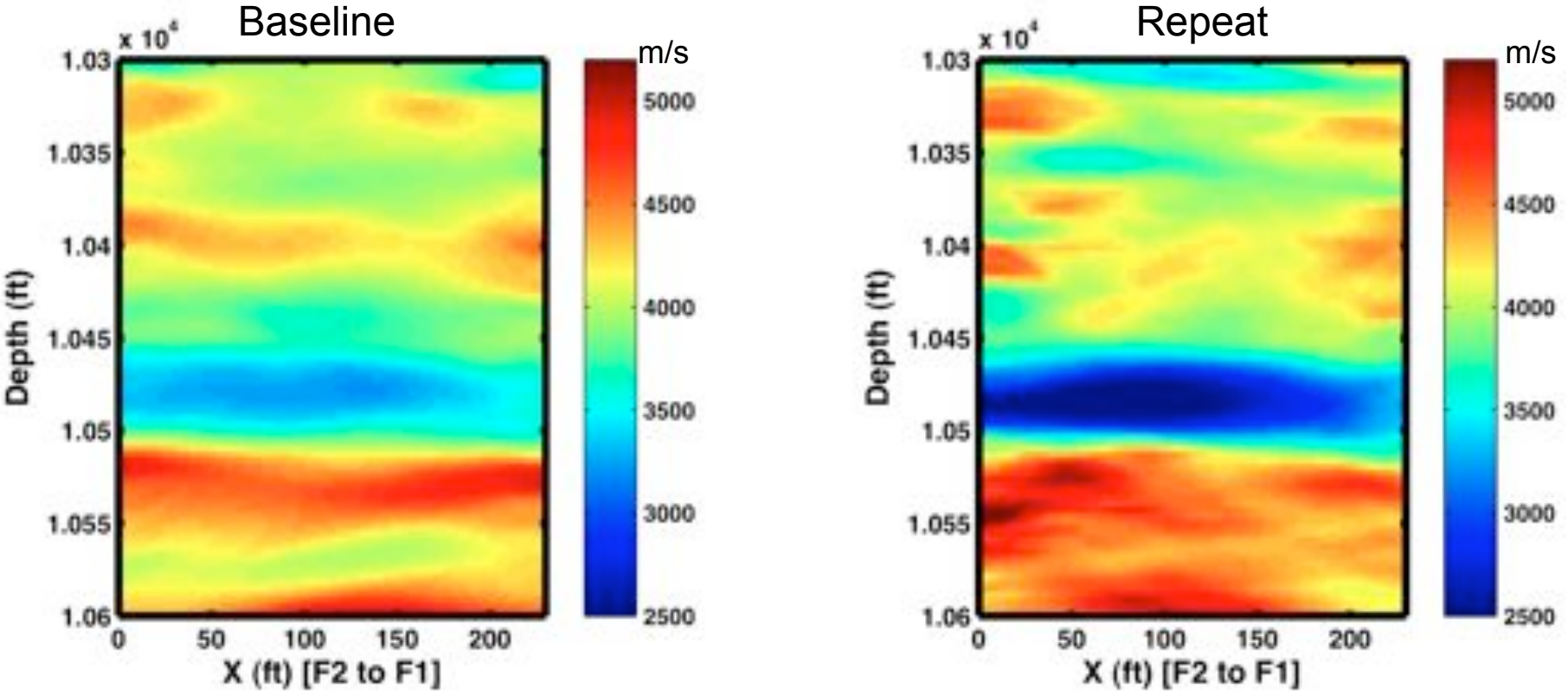


Time-Lapse Velocity Change in Color: Red = Slower

Post Injection Reflection (black)

Schlumberger

Velocity Tomography: LBNL Inversion F1 to F2



Maximum Seismic Velocity Change ~ 500-700 m/s
Theory = ~250 m/s

Note: Color scale reversed, Red=Faster

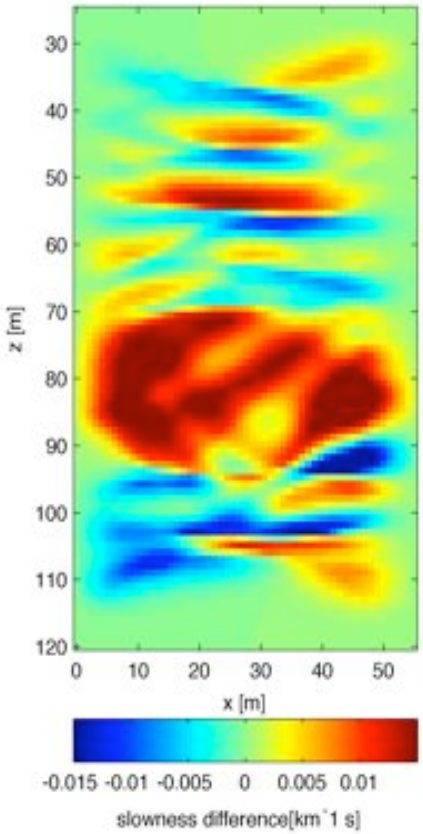
J. Ajo-Franklin (LBNL)

Velocity Tomography: LBNL Inversion F2-F3

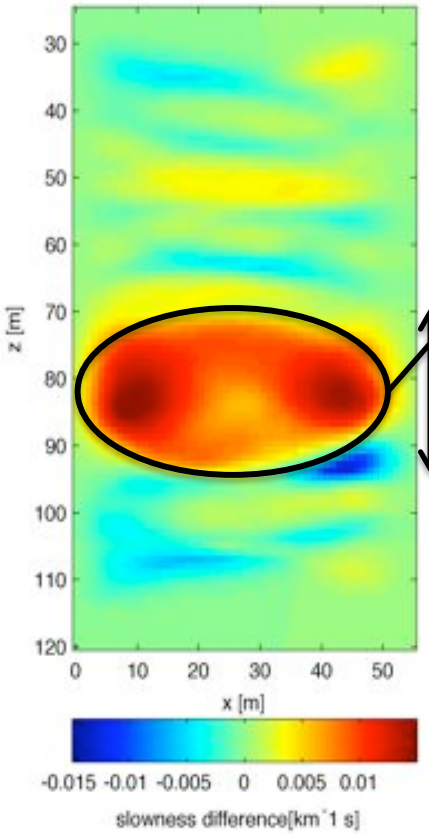
Analysis using various inversion strategies

Current estimate:
Δv=270 m/s,
but, range between 180 and 500 m/s!
Theory: ~250 m/s

Independent Inversion
Difference: Post-Pre



Invert directly for
Difference



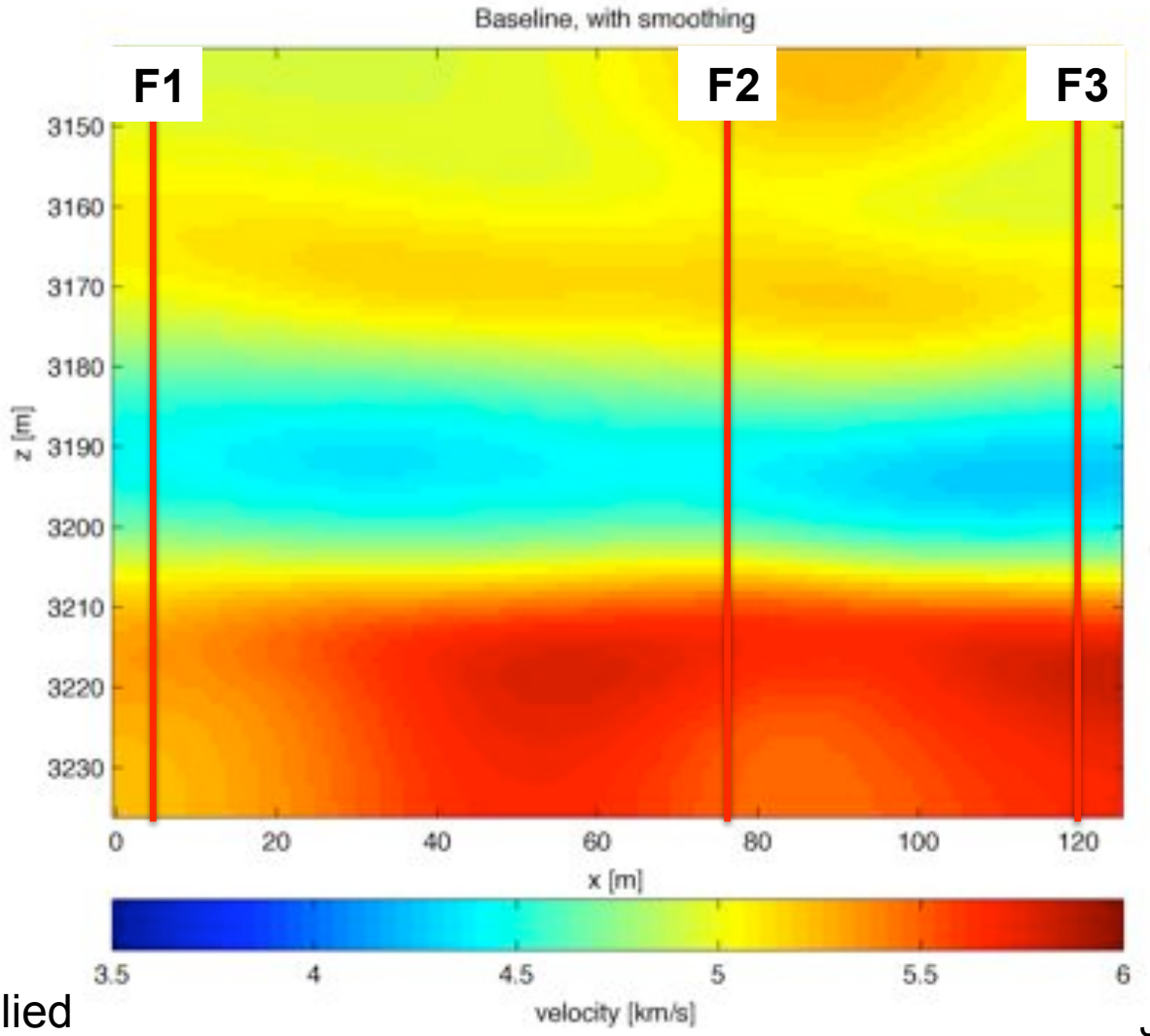
Note: Color scale reversed – Red=Slower

J. Doetsch (LBNL)

Tie the inversion: F1-F2-F3

Work in Progress: Pre-injection inversion of both planes together,

but => F2-F3 traveltimes scaled by 1.23

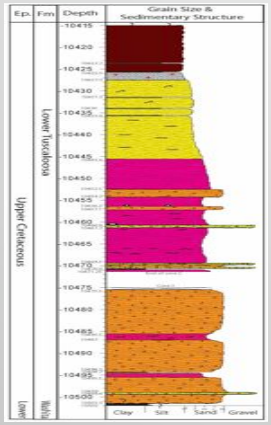


Perf. Interval

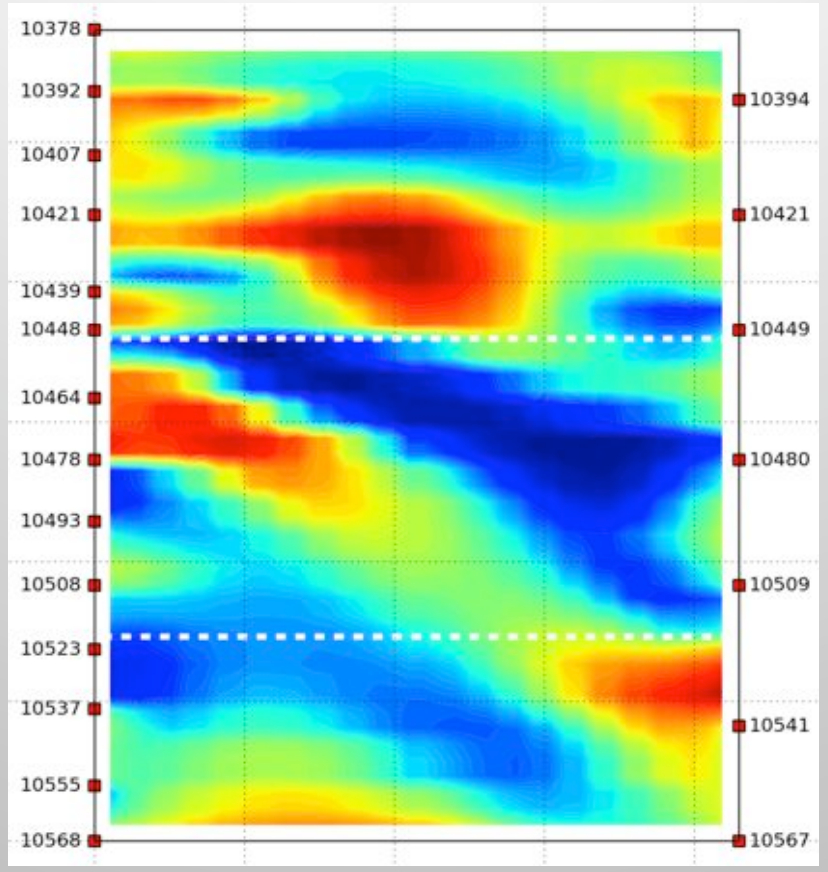
Smoothing operator applied

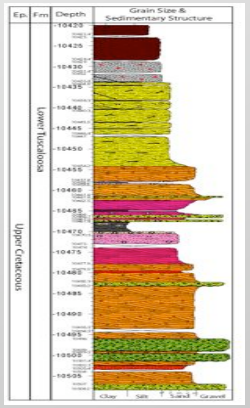
J. Doetsch (LBNL)

Baseline Resistivity Model



Core Log

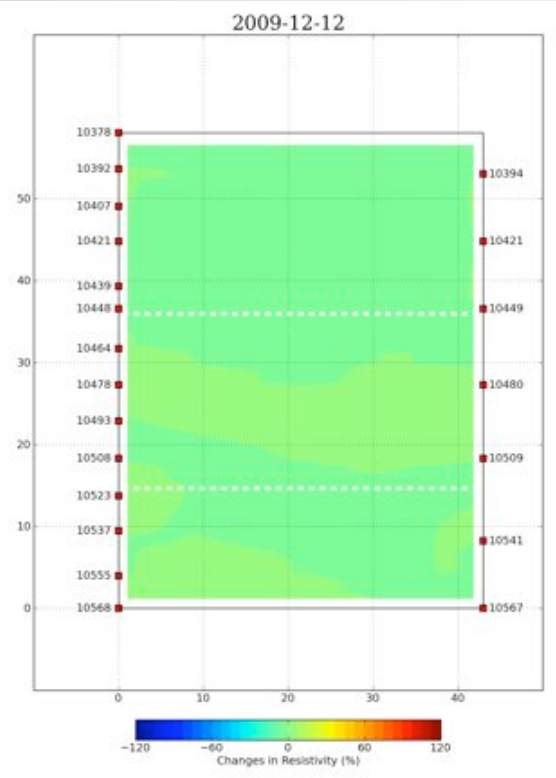


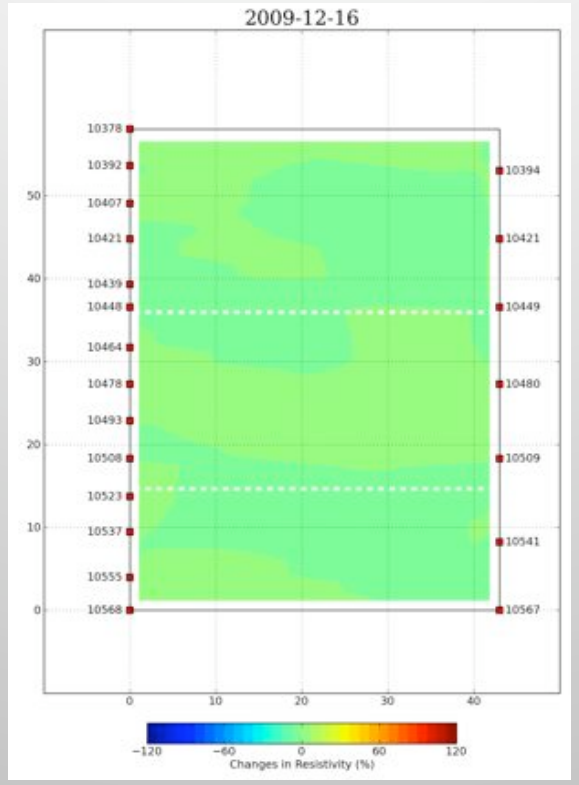


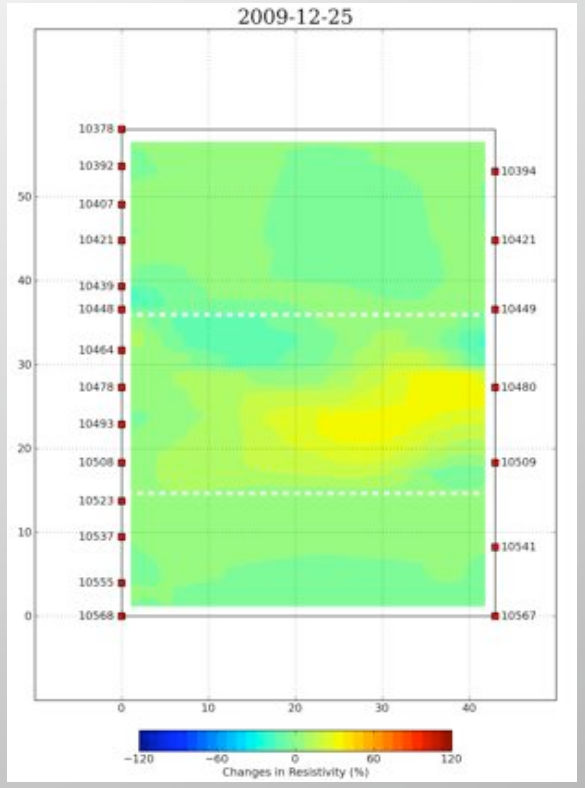
Core Log

Courtesy of C. Carrigan and X. Yang

Time Lapse Resistivity Changes







Initial CO_2 Breakthrough in F2

Initial CO_2 Breakthrough in F3

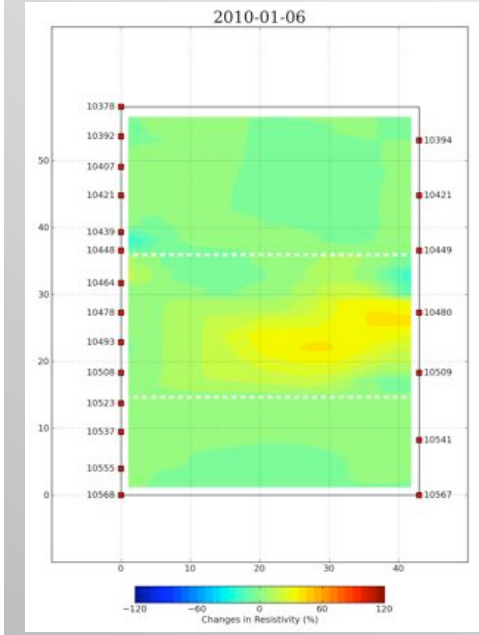
Courtesy of C. Carrigan and X. Yang

December 12

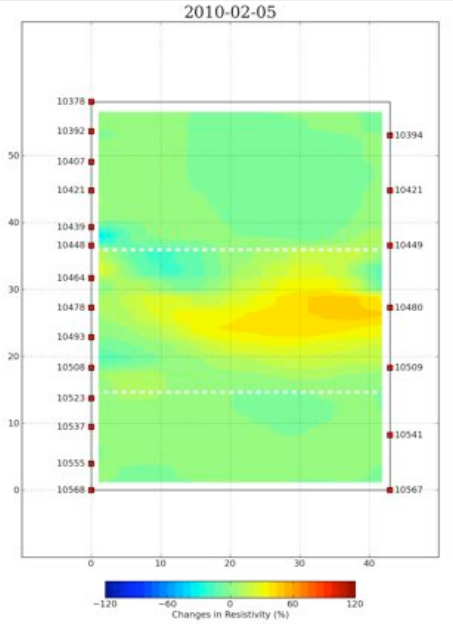
December 16

December 25

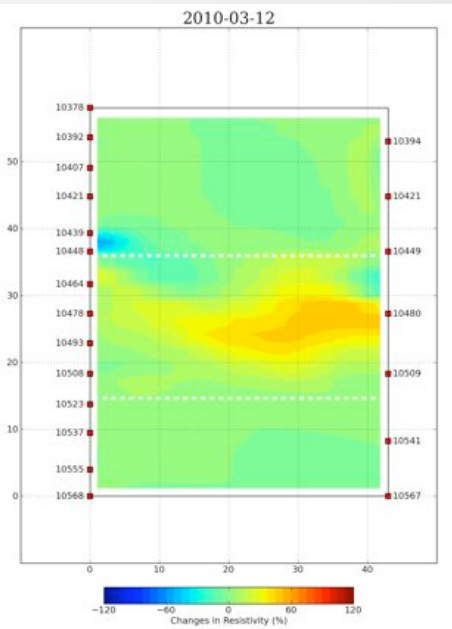
Time Lapse Resistivity Changes



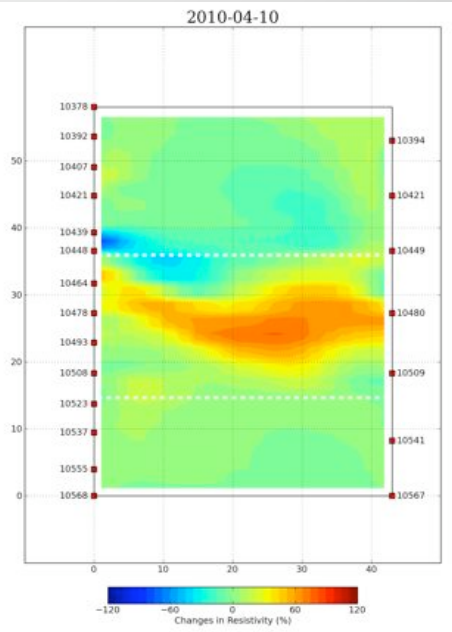
January



February



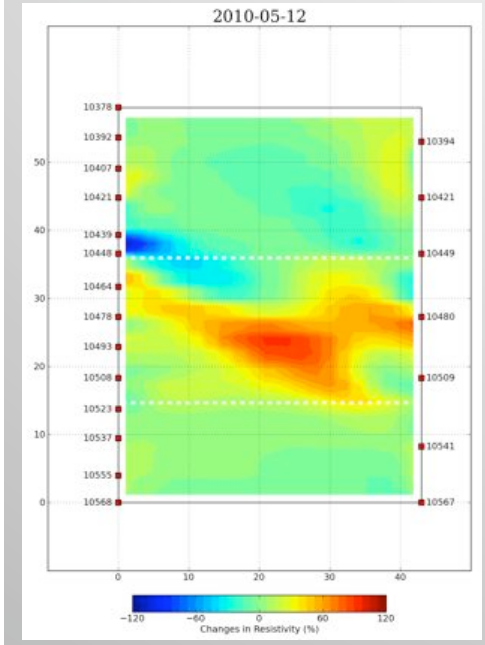
March



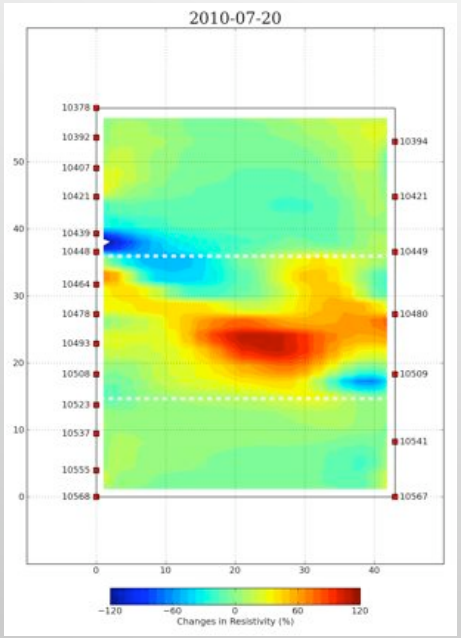
April

Courtesy of C. Carrigan and X. Yang

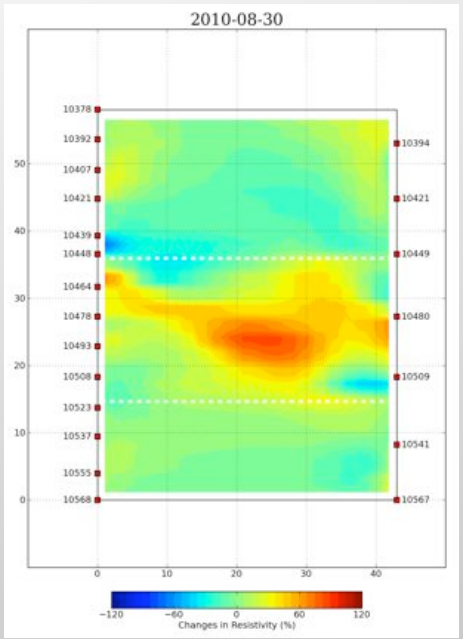
Time Lapse Resistivity Changes



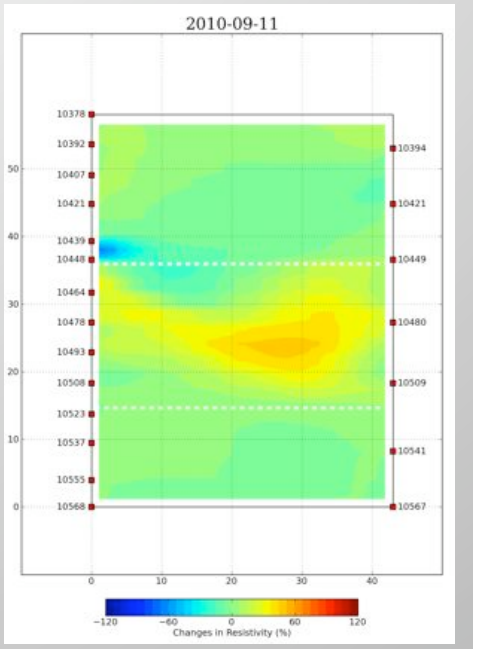
May



July



August

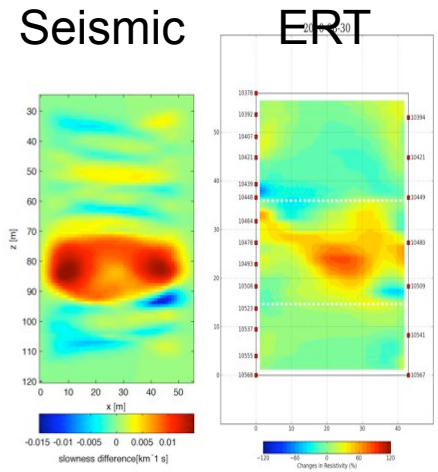


After Recompletion in September 2010

Courtesy of C. Carrigan and X. Yang

Joint inversion of multi-geophysical data and reservoir model

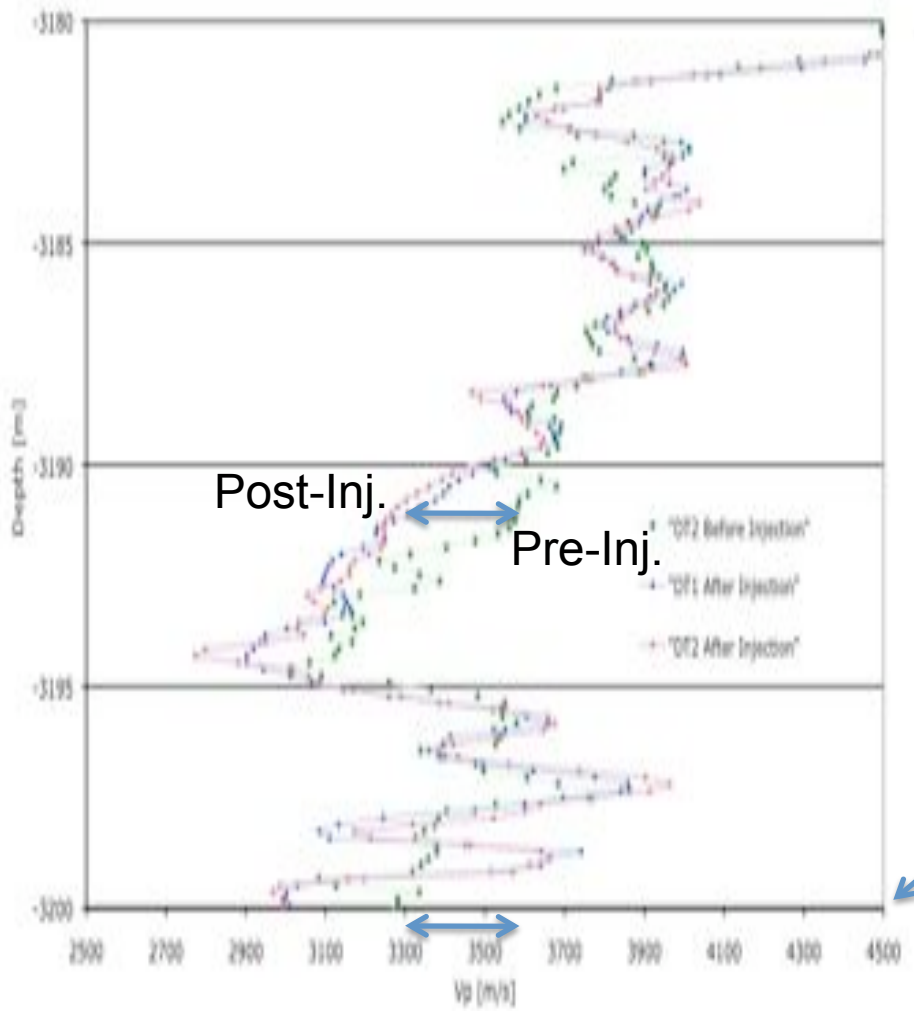
- Three approaches will be applied to time-lapse **crosswell seismic** and **electrical resistivity (ERT)** data from the Cranfield experiment:
  1) **Independent inversions**
  2) **Cross-gradient joint inversions**
  3) **Coupled hydrological-geophysical inversion** of time-lapse geophysical data (seismic and ERT) and hydrological data (CO_2, tracer data,…) with iTOUGH-2

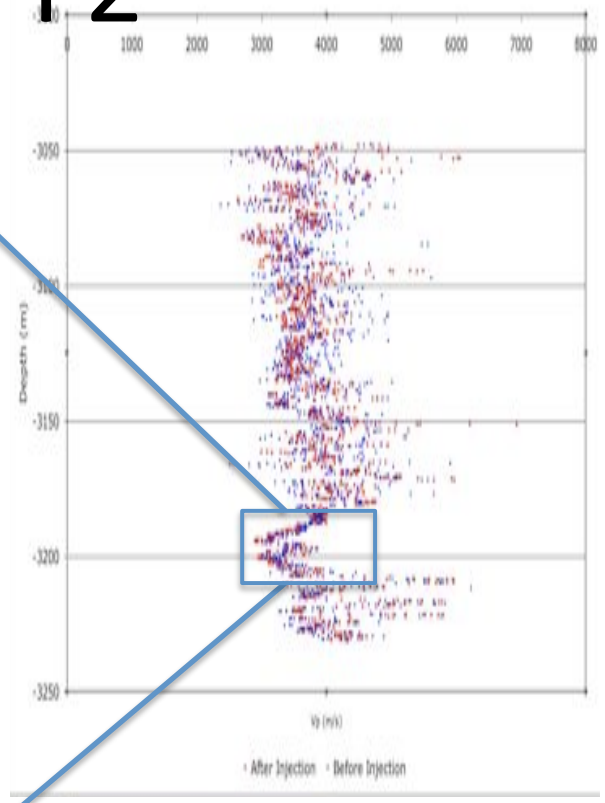


Supported by DOE's NRAP:

J. Doetsch, M.B. Kowalsky, C.Doughty (LBNL)
C. Carrigan, X. Yang (LLNL)

Well Logging Scale: Time-Lapse Sonic Log 31-F2

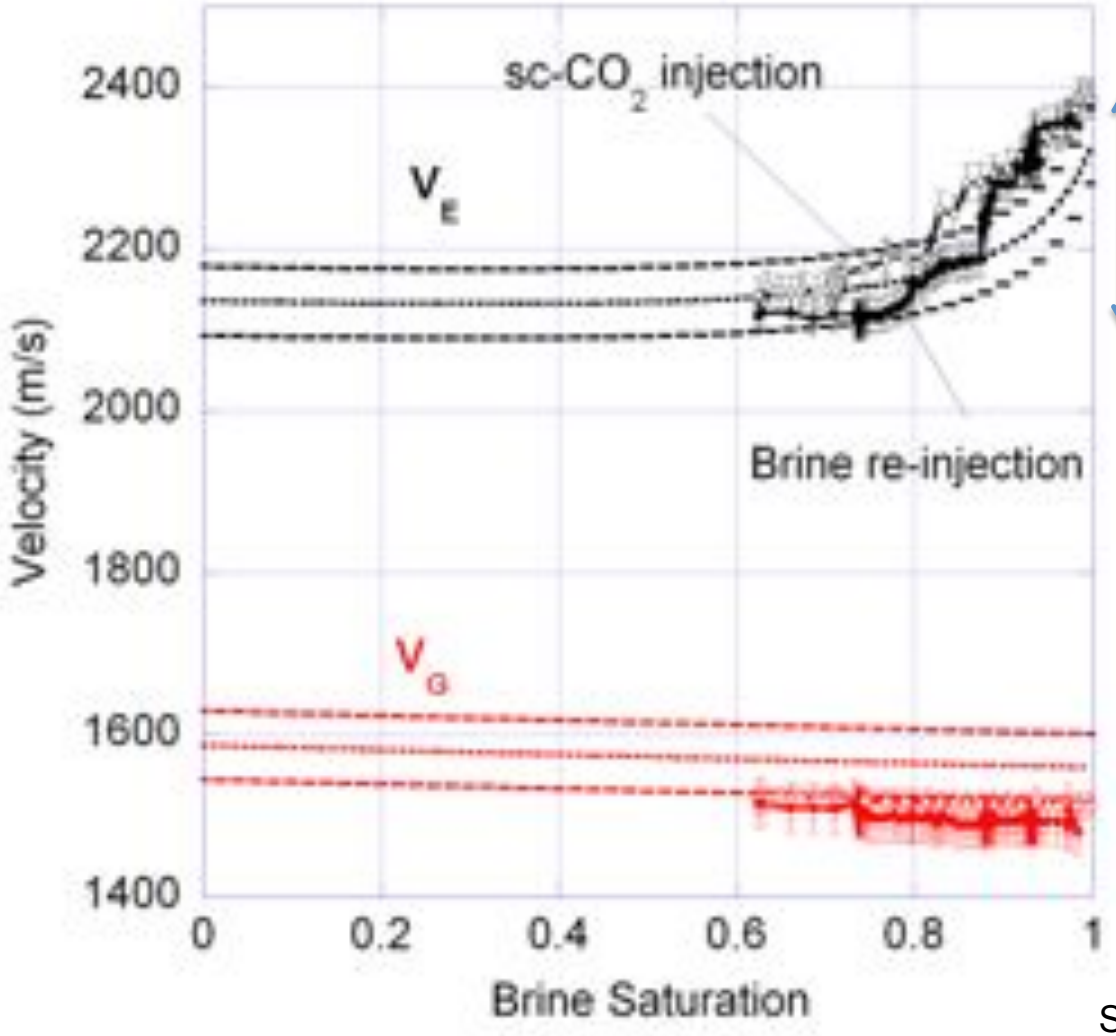




~250 m/s decrease in Seismic velocity

Schlumberger: Data and Processing

Core Scale: Lab Study at 1500 Hz

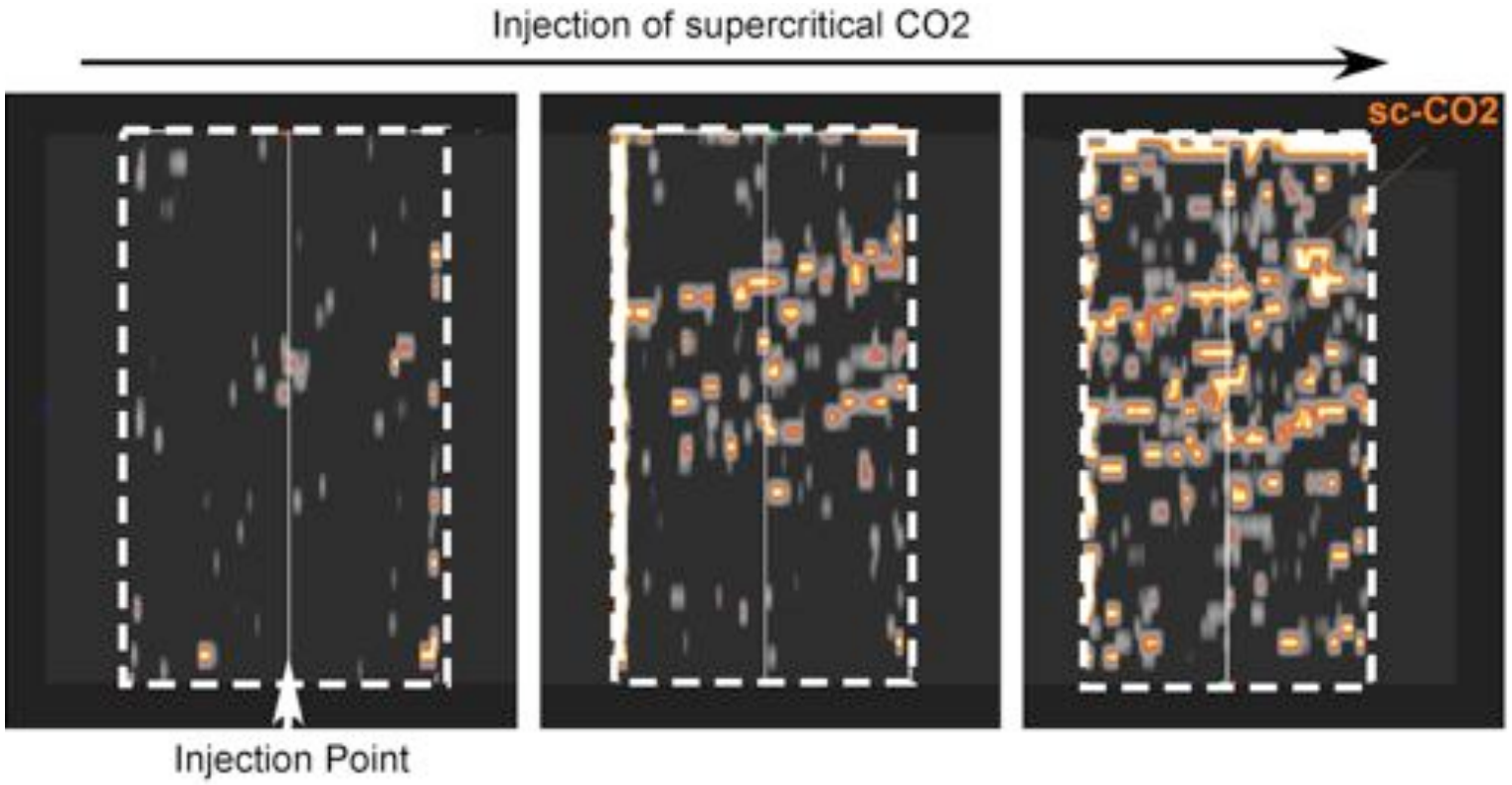


Max Change
~300 m/s

Seiji Nakagawa, LBNL

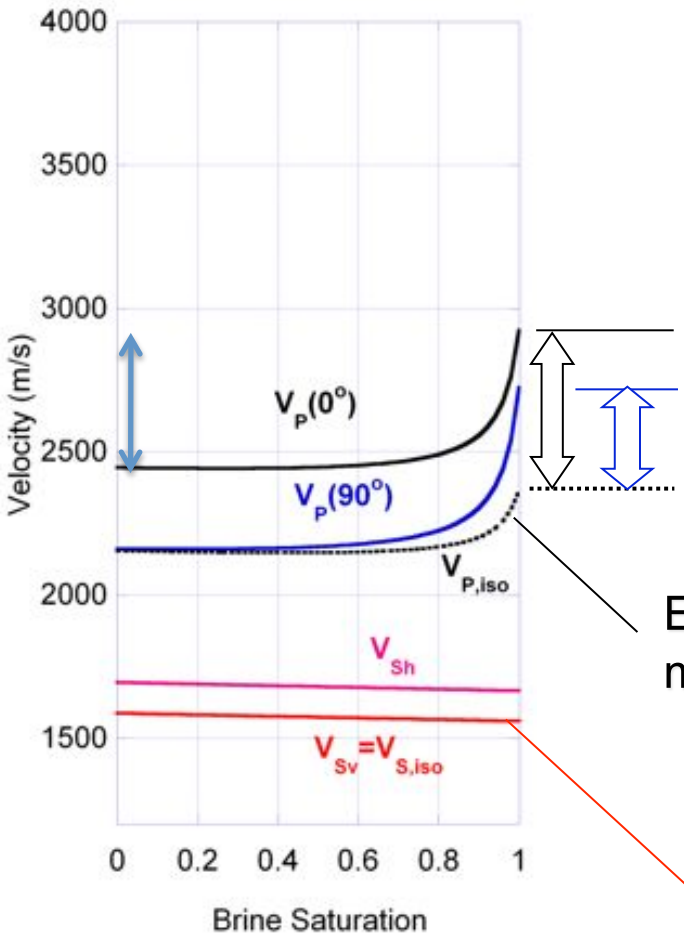
Tuscaloosa Core CAT Scanning To Image CO2

- strong structural anisotropy of the rock



Tim Kneafsey, LBNL

Affect of Seismic Anisotropy on Core Study



Two directions of measurement

~500 m/s Difference

~300 m/s Difference

Error in "**assuming**" the material is isotropic

Isotropic S-wave velocity is exactly the Vsv

Seiji Nakagawa, LBNL

Summary

- Multi-Scale Geophysical Monitoring
  - Time Lapse Data: 3D surface, OVSP, Crosswell Seismic, Gravity
  - Continuous Data: ERT can detect CO2; gives daily-to-weekly updates
- Seismic monitoring is varying with scale
  - Inconsistent change at large and intermediate scale (surface and VSP data) - Hypothesis that Methane is 'masking' CO2
  - Velocity change more consistent at DAS site with crosswell scale and log scale
    - xwell: ~270 m/s; log: ~250 m/s; Core: ~250m/s; Theory: ~250 m/s w/o CH4
  - Important physics being seen at core scale (anisotropy, frequency dependence)
- Plans
  - Improved analysis of 4D surface seismic
  - Continue processing of OVSP, 3D VSP and crosswell seismic
  - integrate geophysics (crosswell ERT and seisimic) with reservoir model to improve model predictions

Thank You - Questions?



Large Volume CO_2 Injection at Cranfield, Early Field Test of the SECARB Phase III: Near-Surface Monitoring

C. Yang, K.D. Romanak, S. D. Hovorka; R. Trevino;
The University of Texas at Austin;
R.M. Holt, University of Mississippi;
J. Lindner, L. Smith, F. Roeckner, Y. Xia, J. Rickerts;
Mississippi State University;

7th Annual
Stakeholders' Briefing
March 7, 2012

100 Years of Scientific Impact
1909-2009

Acknowledgements















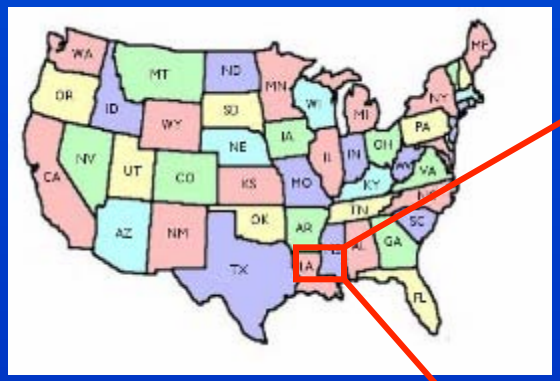






www.gulfcoastcarbon.org

Cranfield, Mississippi



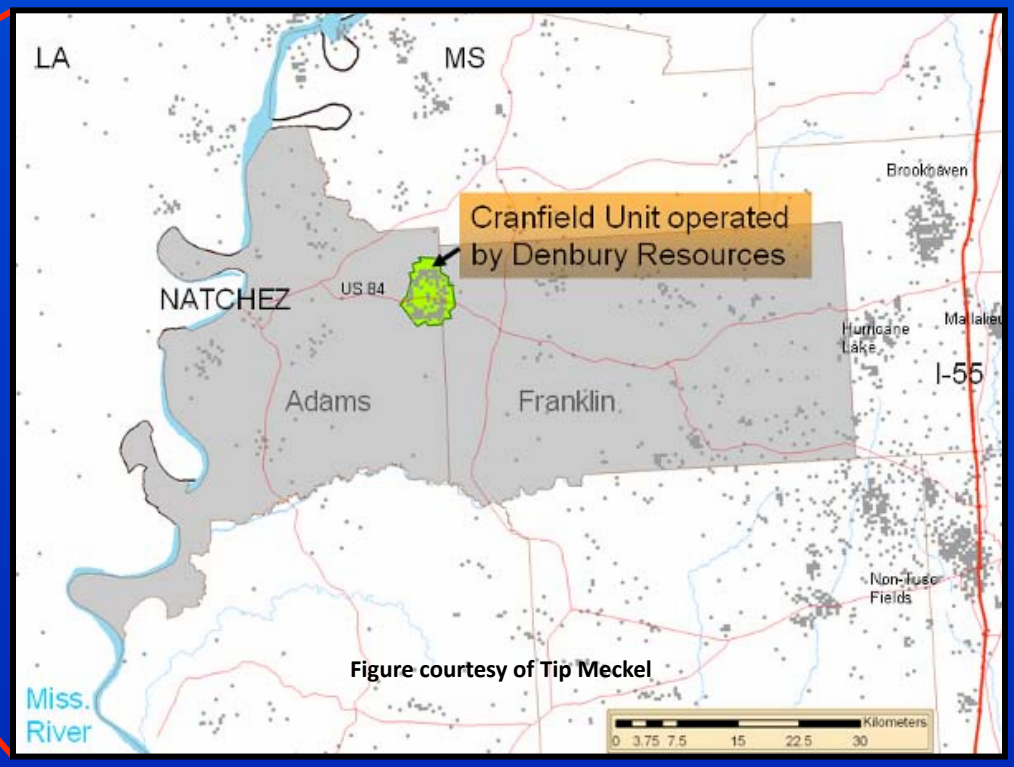
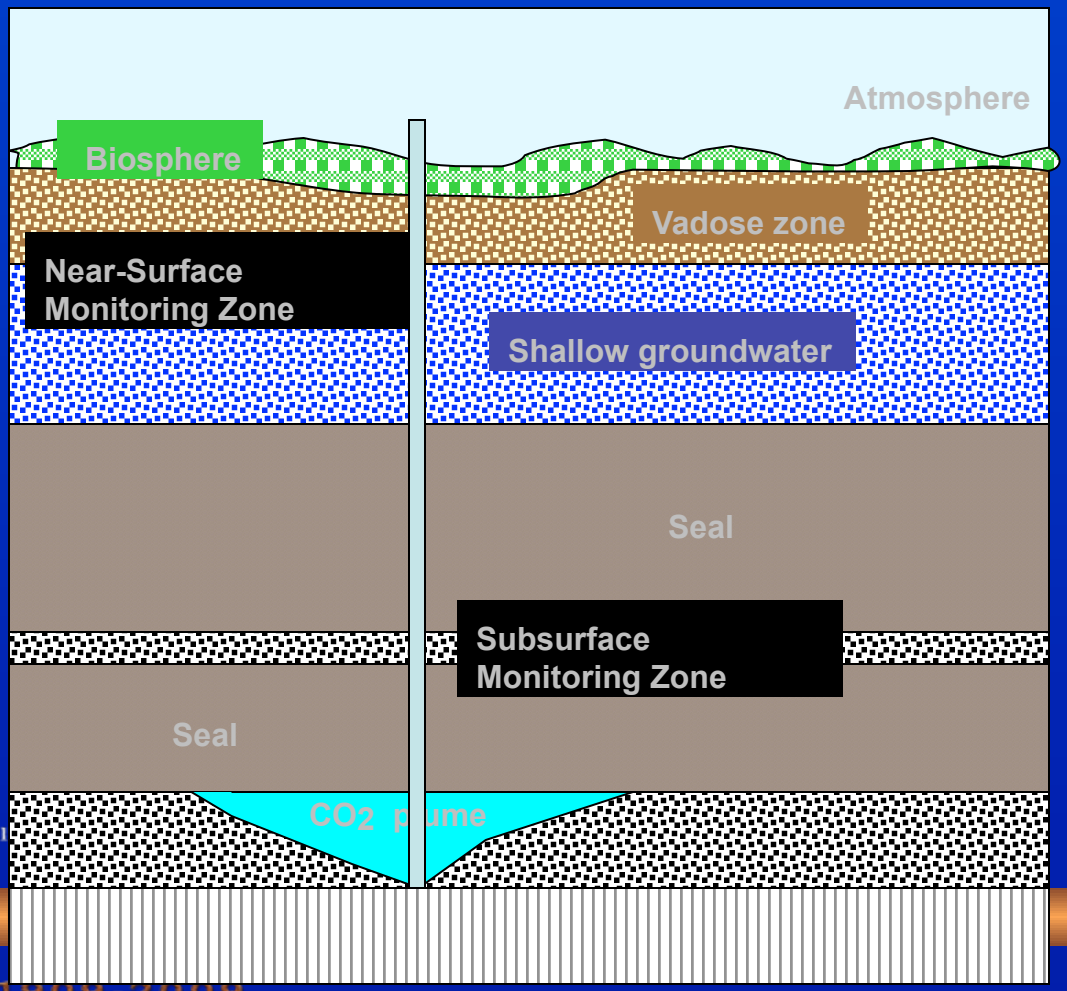


Figure courtesy of Tip Meckel

- Located 15 miles east of Natchez, MS
- Owned and operated by Denbury Resources
- Injection of CO_2 for EOR since 2008

Near-surface Monitoring

- Shallow groundwater monitoring
- Soil gas monitoring (P-site)



Objective

Assess near-surface monitoring technologies for leakage detection at a CO_2 sequestration site

Address environmental variability in the near-surface

Potential Geochemical Outcomes in a Shallow Aquifer

- CO_2 dissolution into groundwater
  - Possible mineral dissolution

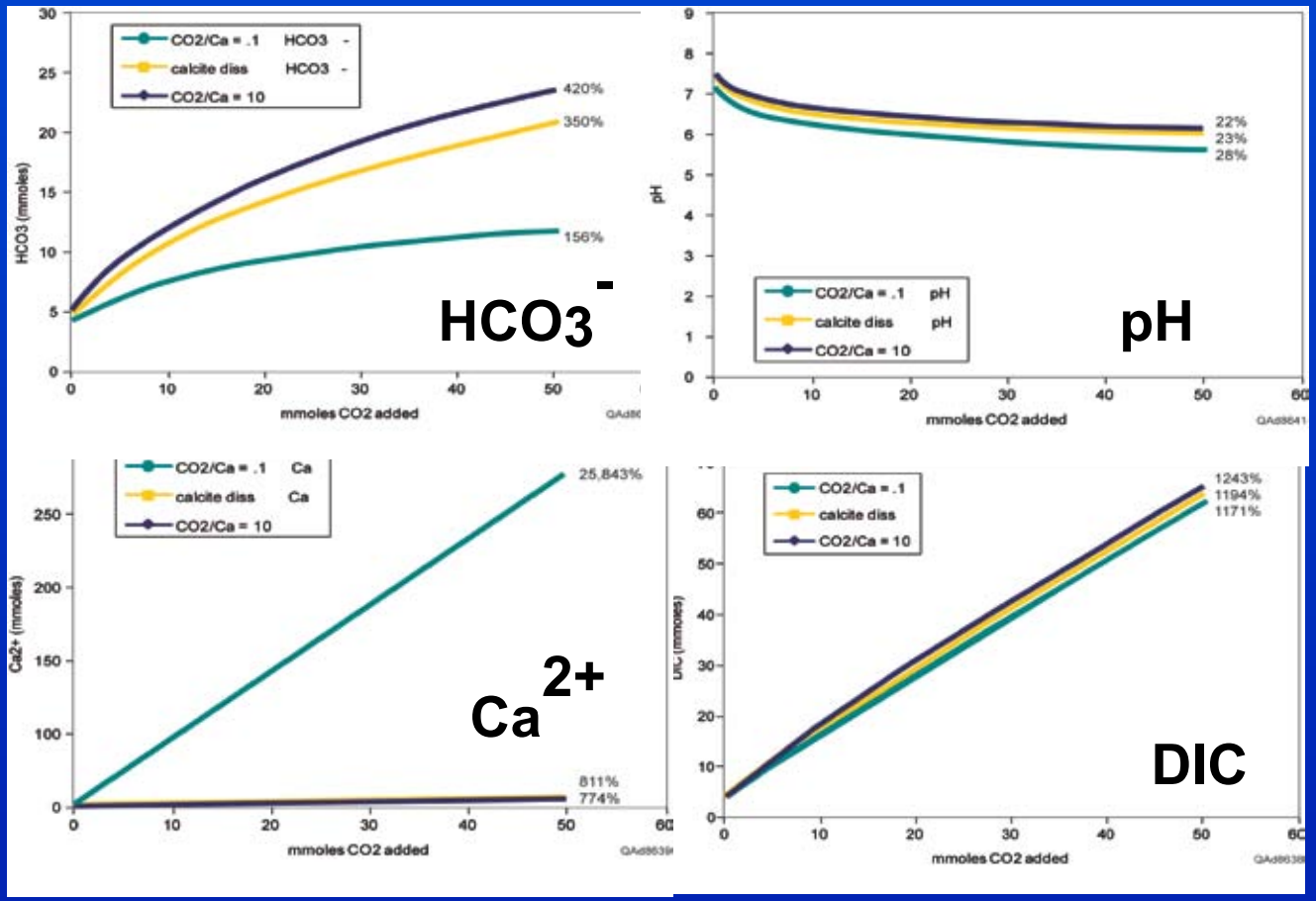
$$H_2O + CaCO_3 + CO_2 \rightarrow 2HCO_3^- + Ca^{2+}$$

- Potential effects on mobilization of trace metals (Fe, Pb, As…)

Geochemical parameters for detecting CO_2 leakage

pH, HCO_3-, Ca^{2+}, DIC, $\delta^{13}C$, trace metals

Global Monitoring Parameters



Romanak et. al., International Journal of Greenhouse Gas Control, Jan 2012

Groundwater Monitoring Strategy

Characterize shallow groundwater geochemistry

Identify a set of geochemical parameters for detecting CO_2 leakage

Test and validation

- Numerical modeling
- Lab experiments
- Field experiments (Push-pull tests)

Application

Groundwater chemistry monitoring for detecting CO_2 leakage

Groundwater Geochemistry

Nine field trips for groundwater sampling since August, 2008

Measured pH, temperature, alkalinity, water level

Cations:

Ag, Al, As, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Pb, Se, Zn

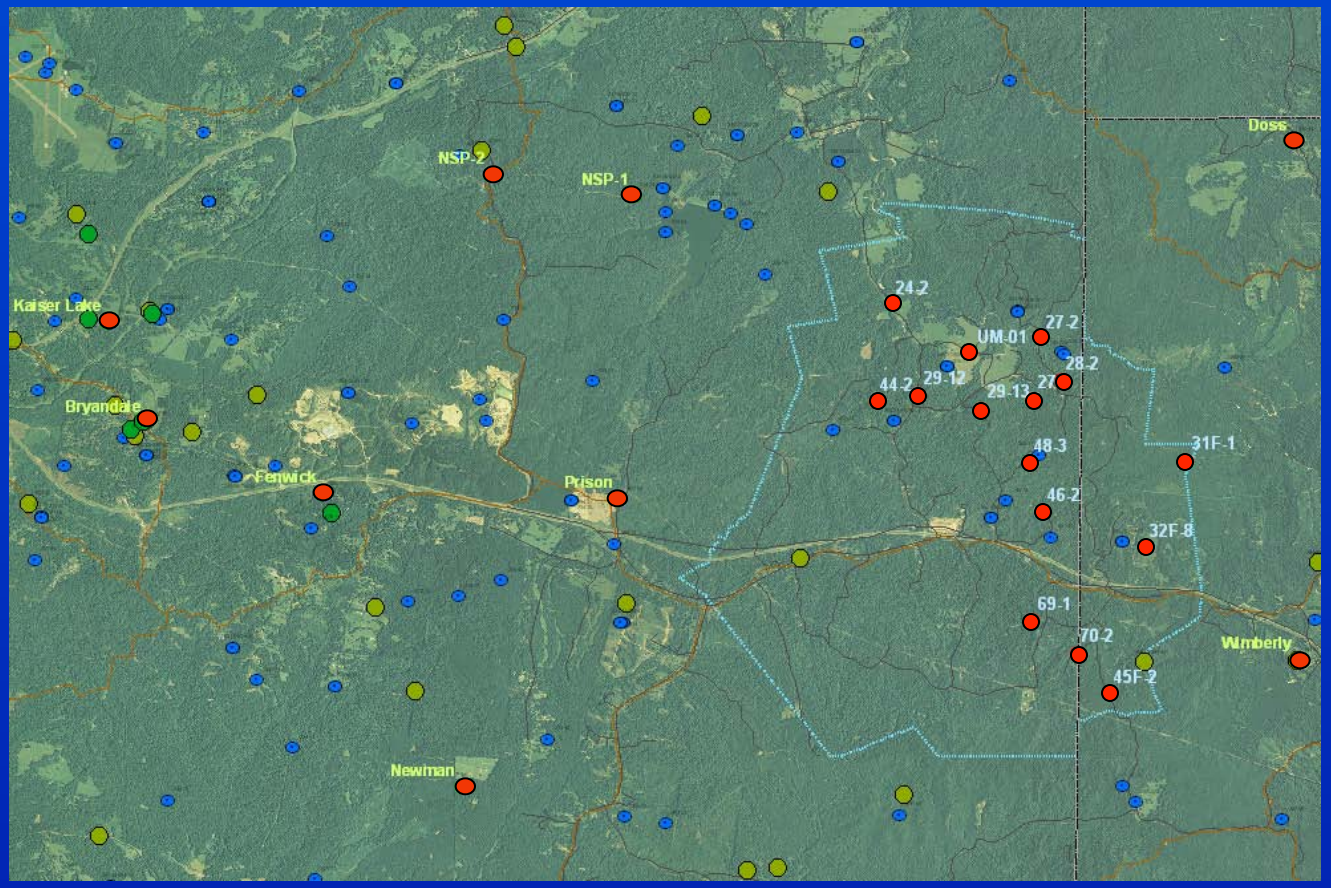
Anions:

F-, Cl-, SO42-, Br-, NO3-, PO43-

TOC, TIC

VOC

δC13



"makeup" wells

Private wells

Wells surveyed by USGS

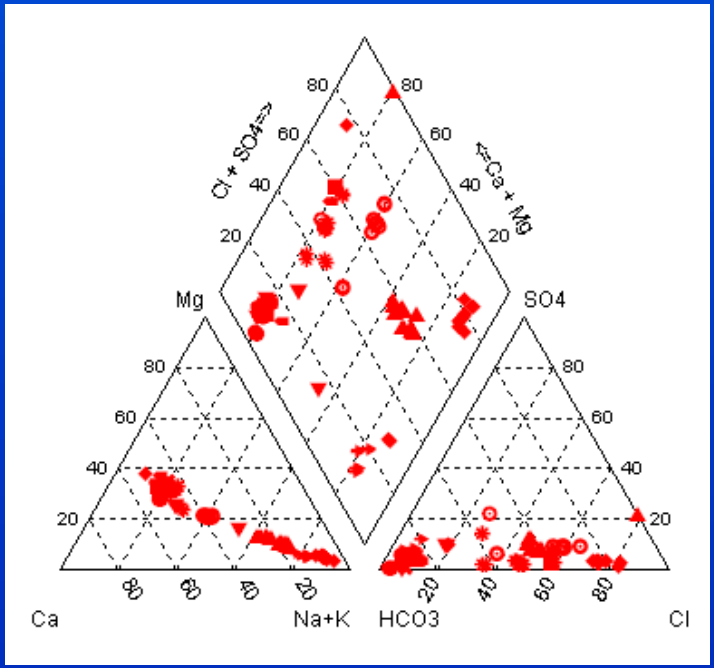
Public wells

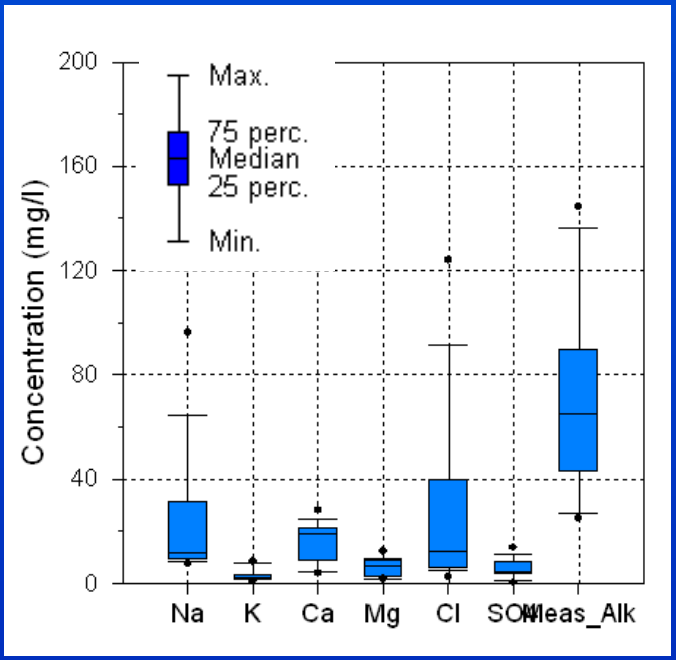
100 Years of Scientific Impact

1909-2009

Bureau of Economic Geology

Groundwater Geochemistry





Groundwater types mainly are Na-Cl, Ca-Na-HCO3, and Ca-Na-HCO3-Cl

Na and Cl concentrations show variations

Metals	Fe (mg/L)	Ba (mg/L)	Pb (ug/L)	Zn (mg/L)	Mn (mg/L)	Cd (ug/L)	Cu (ug/L)
Maximum	17.04	0.237	65	2.625	0.71	6	6

- **Other metals are non-detectable, such as As**

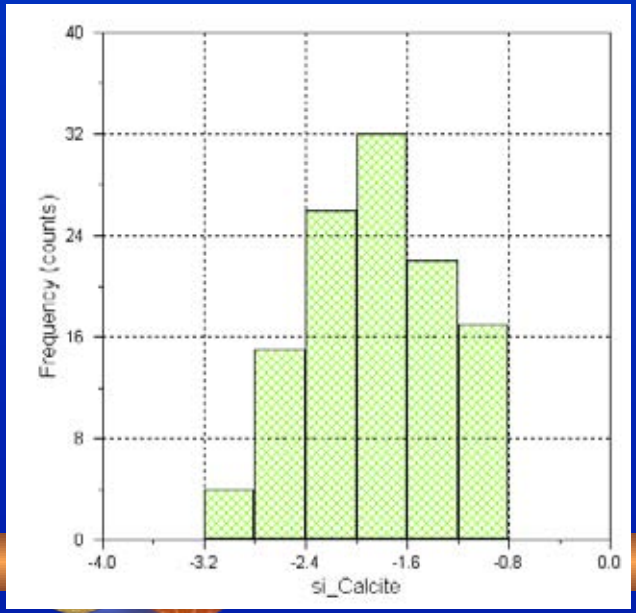
Groundwater Geochemistry

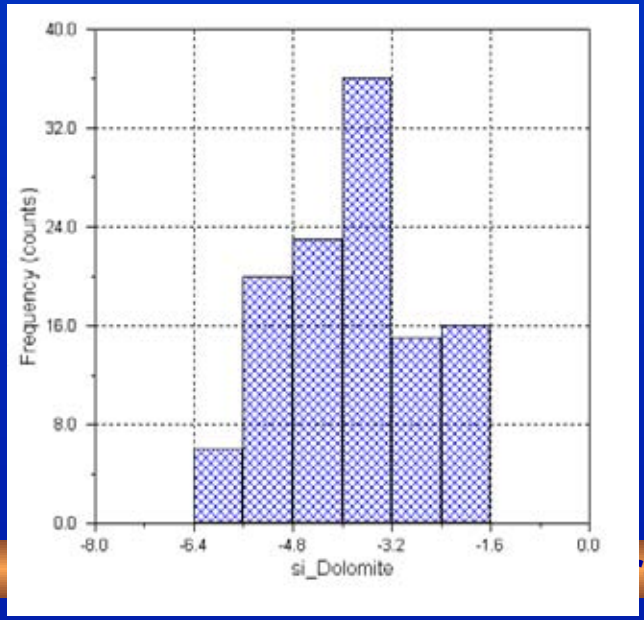
Mineralogy of the sediments





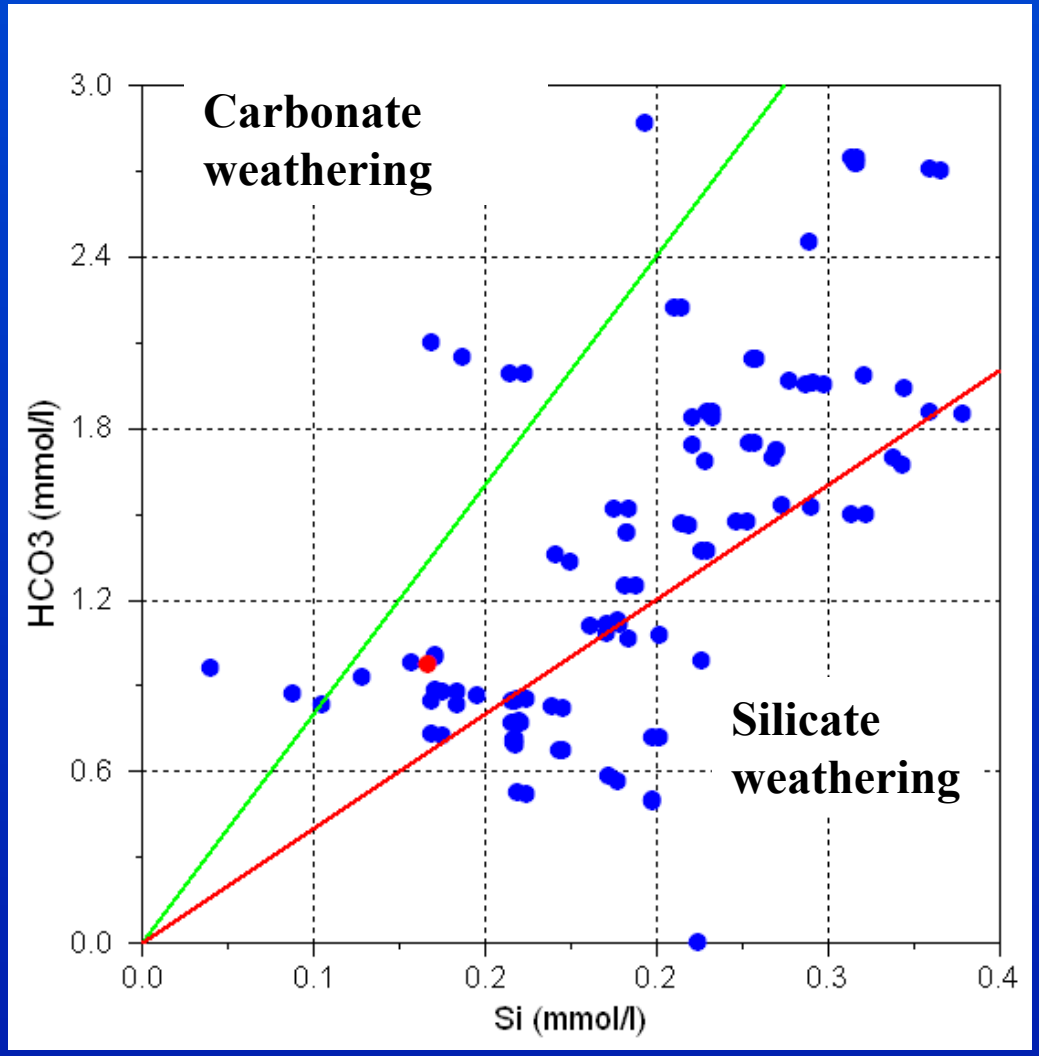
- **Preliminary XRD and SEM analyses indicate the shallow aquifer sediments are mainly silicate minerals**



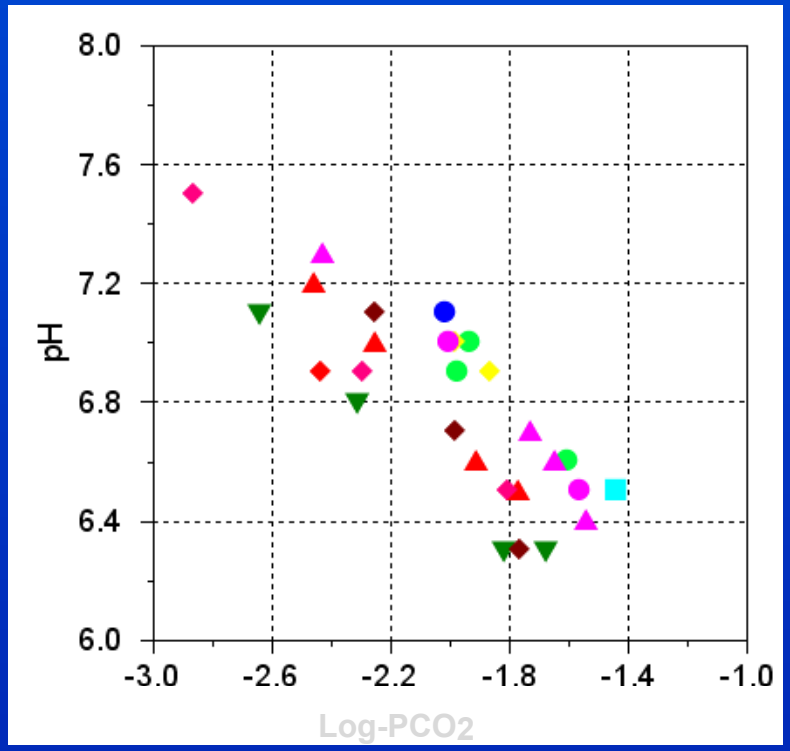


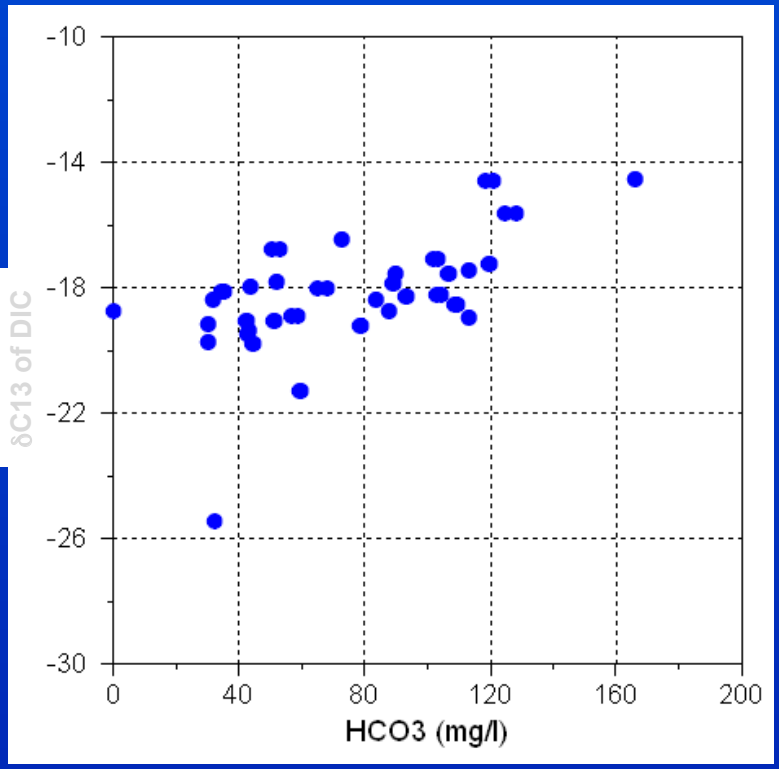
- **Groundwater is undersaturated with respect to carbonate minerals (calcite and dolomite**

Groundwater Geochemistry



Groundwater geochemistry

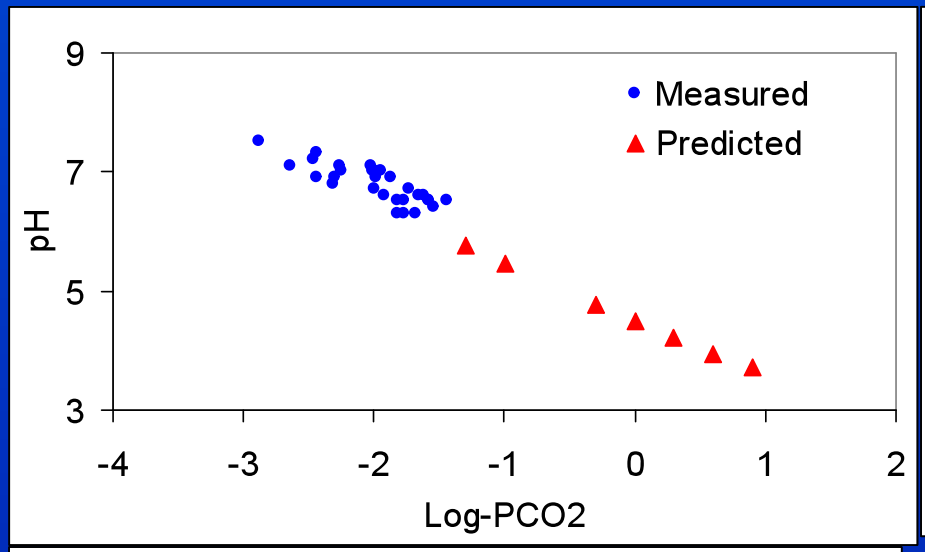


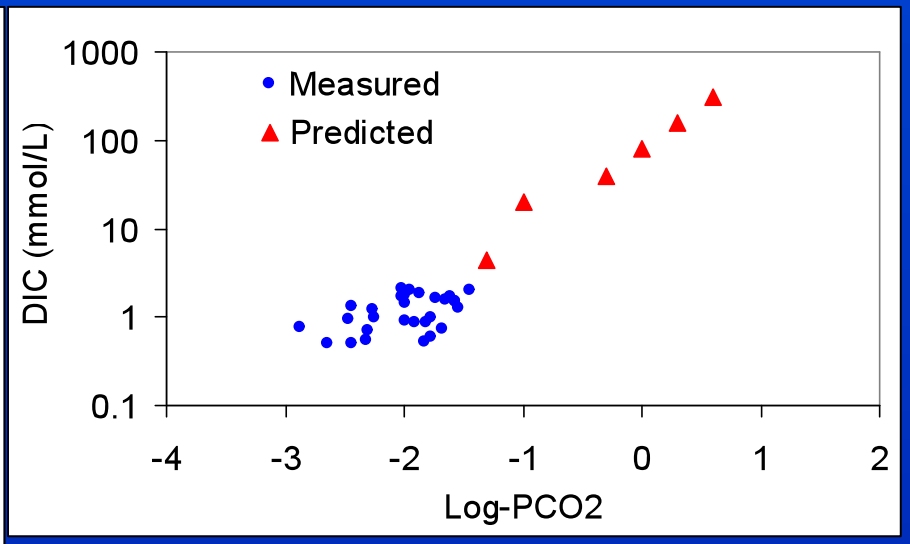


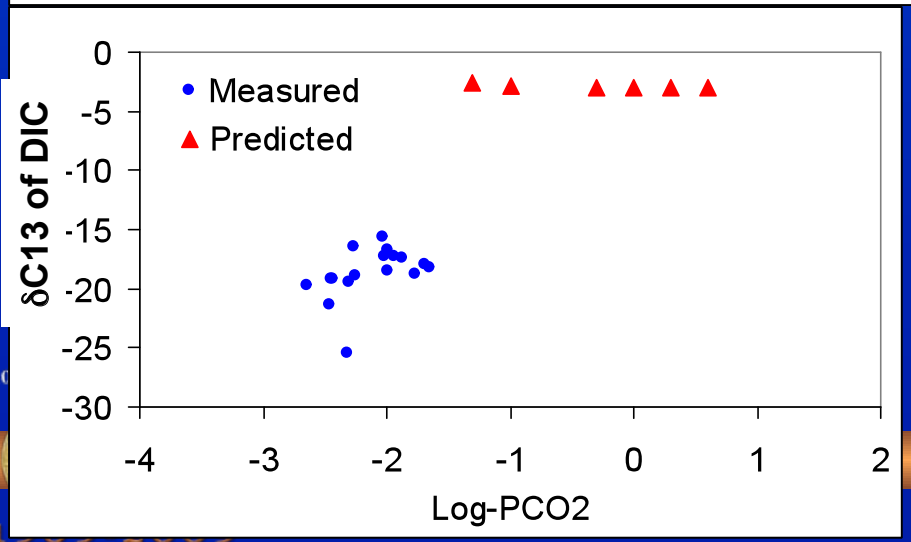
- pH shows good linear relationship with log-PCO_2
- δC13 of dissolved inorganic carbon (DIC) ranges from -14‰ to -26 ‰

Test and validation

Geochemical modeling







Simulating CO_2 leakage into the Cranfield-type shallow aquifers as CO_2 pressure builds up:

- **pH will be lowered**
- **DIC will increase**
- **δC13 of DIC will approach -3‰, the value of δC13 of CO_2 injected**

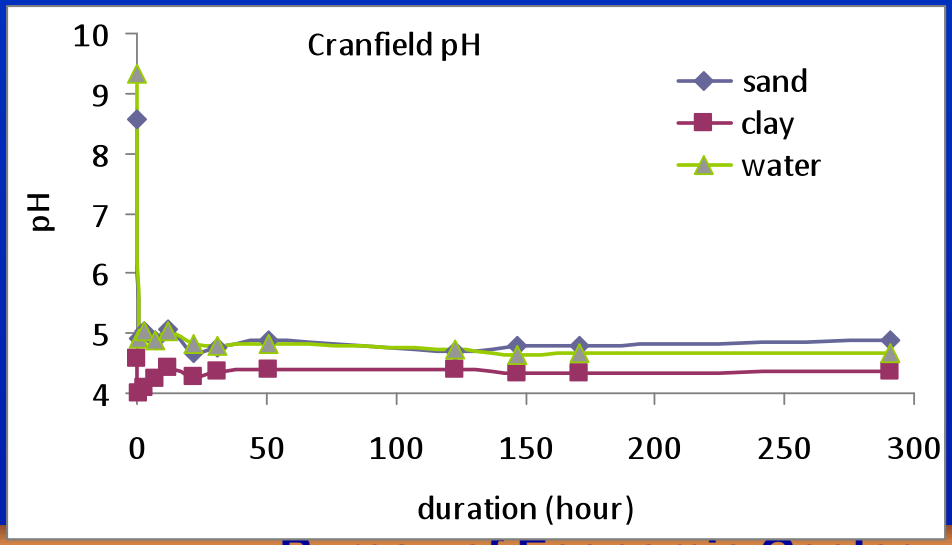
Test and validation

Water-Rock-CO2 interaction lab experiments



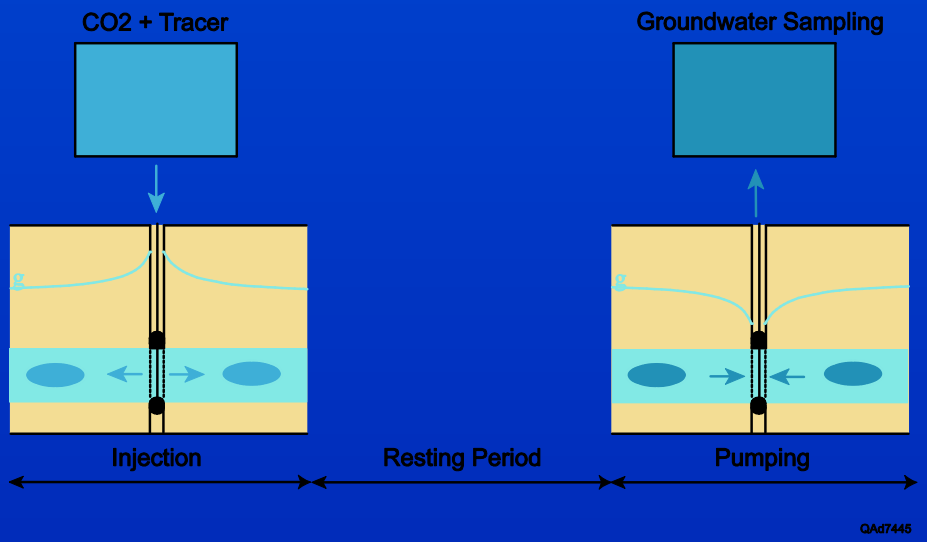
Three batches:
Rock samples from

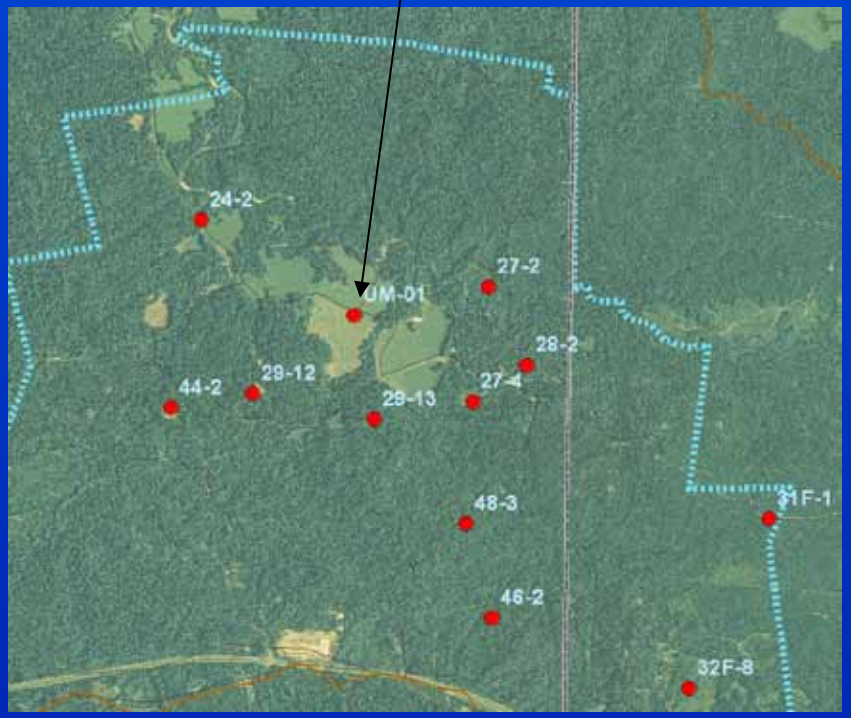
- aquitard
- aquifer
- control with no rock



Test and Validation

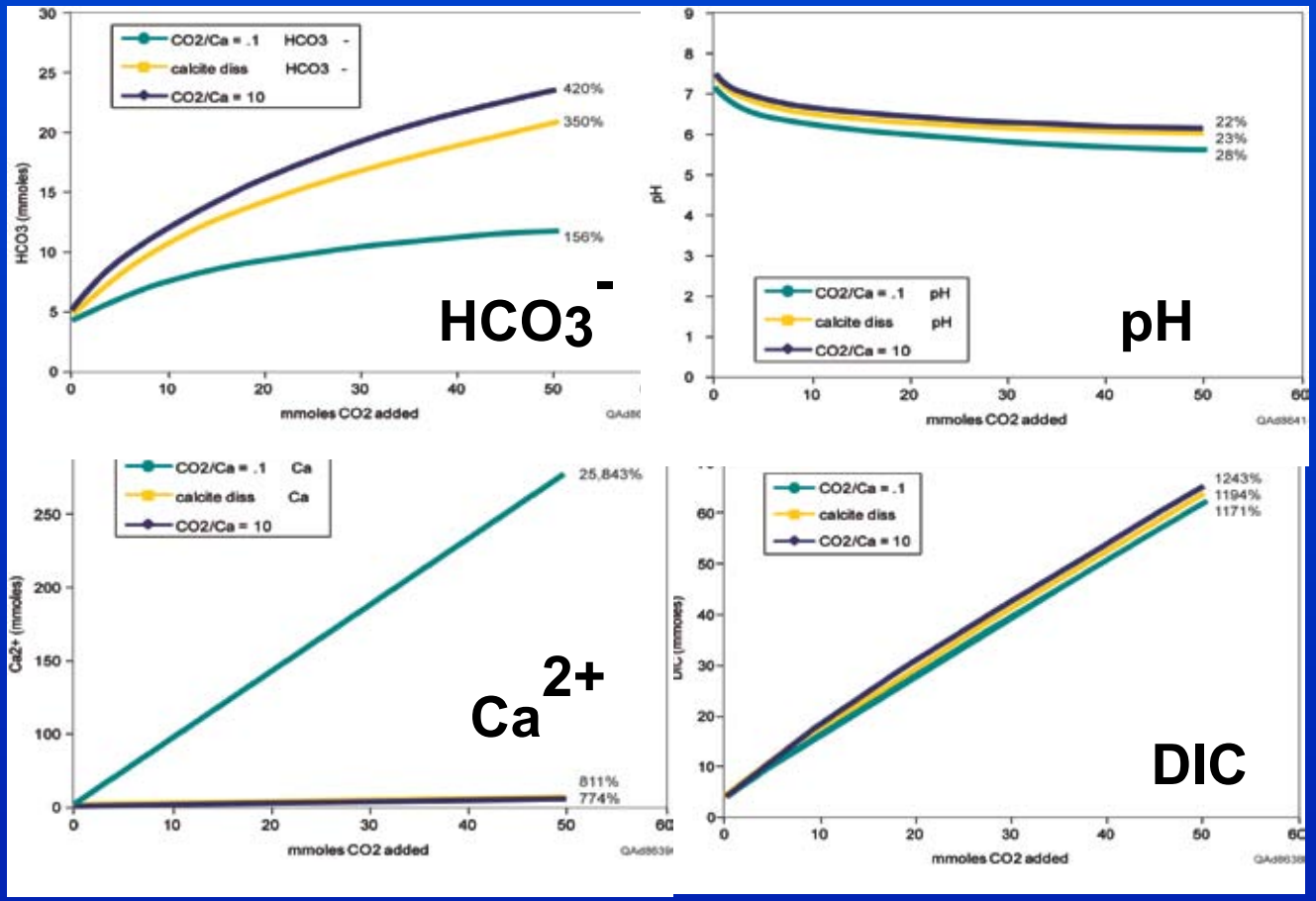
Push Pull Tests





- Depth of the well: 240 ft to surface
- Depth of water: 90 ft to surface
- The well is screened at the 180 to 240 ft

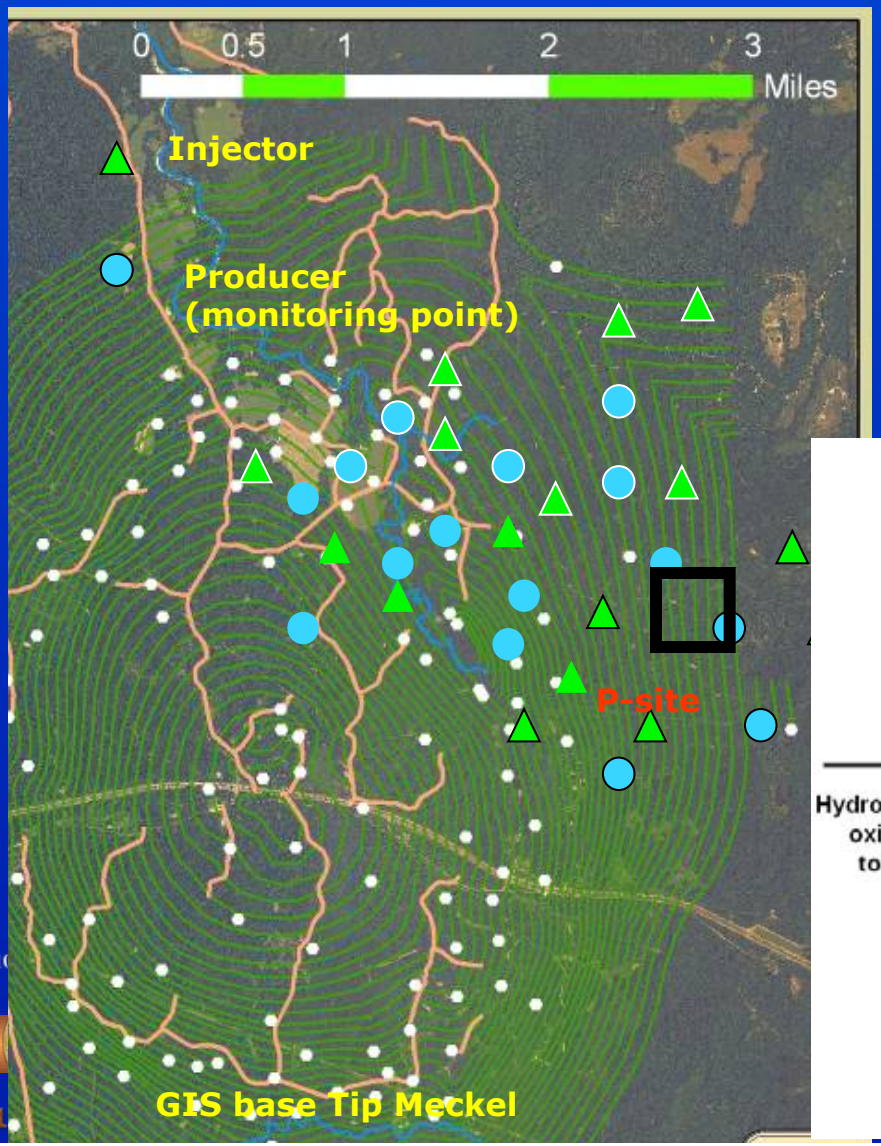
Global Monitoring Parameters



Romanak et. al., International Journal of Greenhouse Gas Control, Jan 2012

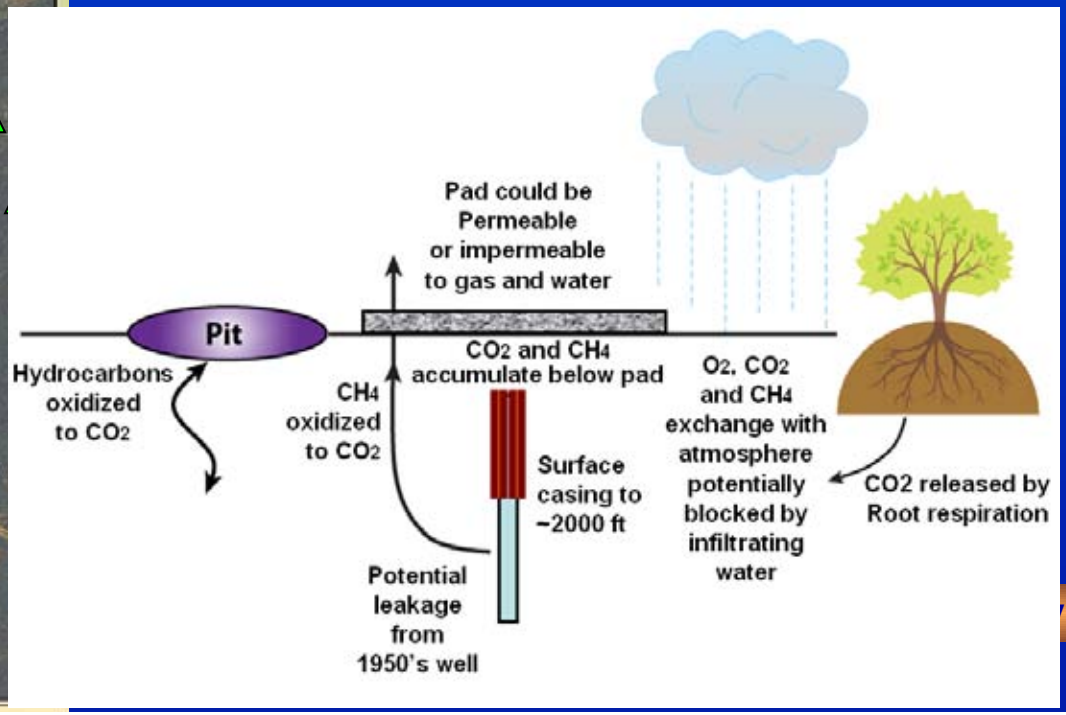
P-site Soil Gas

- Potential leakage pathway: Abandoned wells



P-site

- **Pit**
- **Pad**
- **Plants**
- **Plugged & abandoned well**



Near-surface Observatory

- Weather station
- Underground sensors for measuring soil temperature, matric potential, water content, CO_2 concentrations, etc

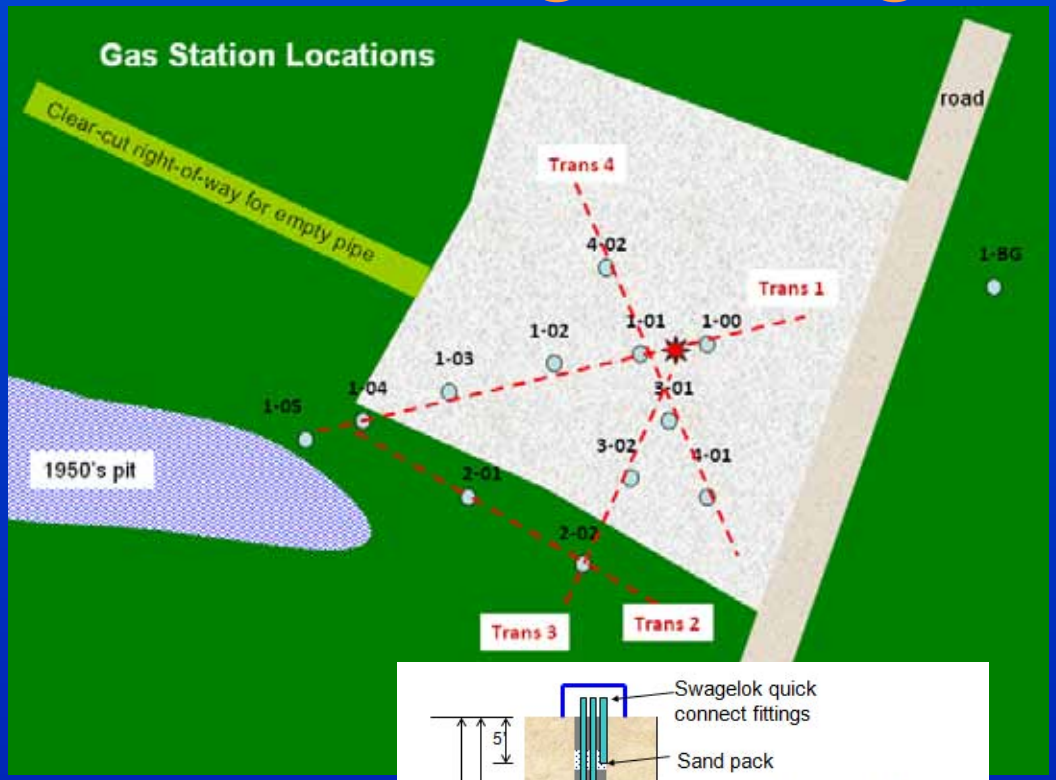






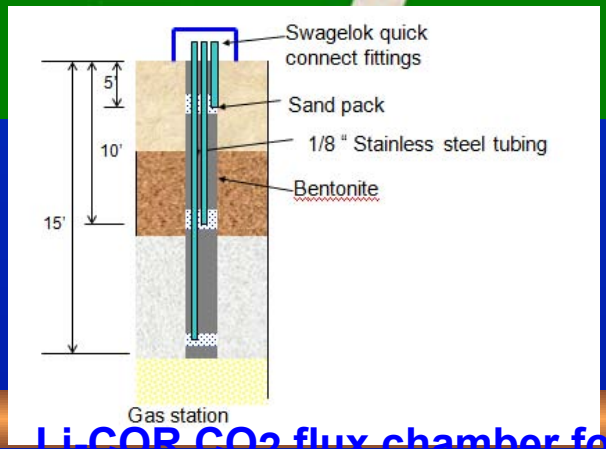


Soil gas composition measured through soil gas stations



- 4 transects
- 12 stations
- 36 wells
- Measure soil gas compositions (N2, CH4, O2, CO2) using GC



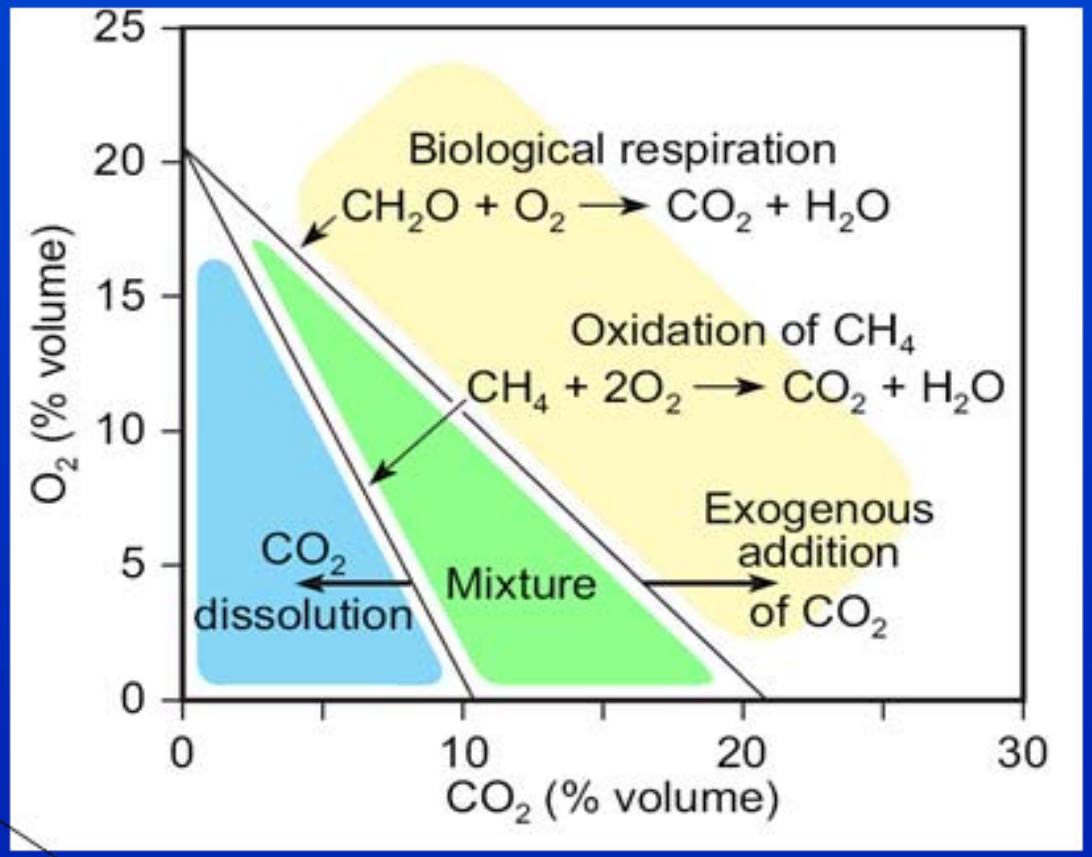


- Li-COR CO_2 flux chamber for CO_2 flux measurements

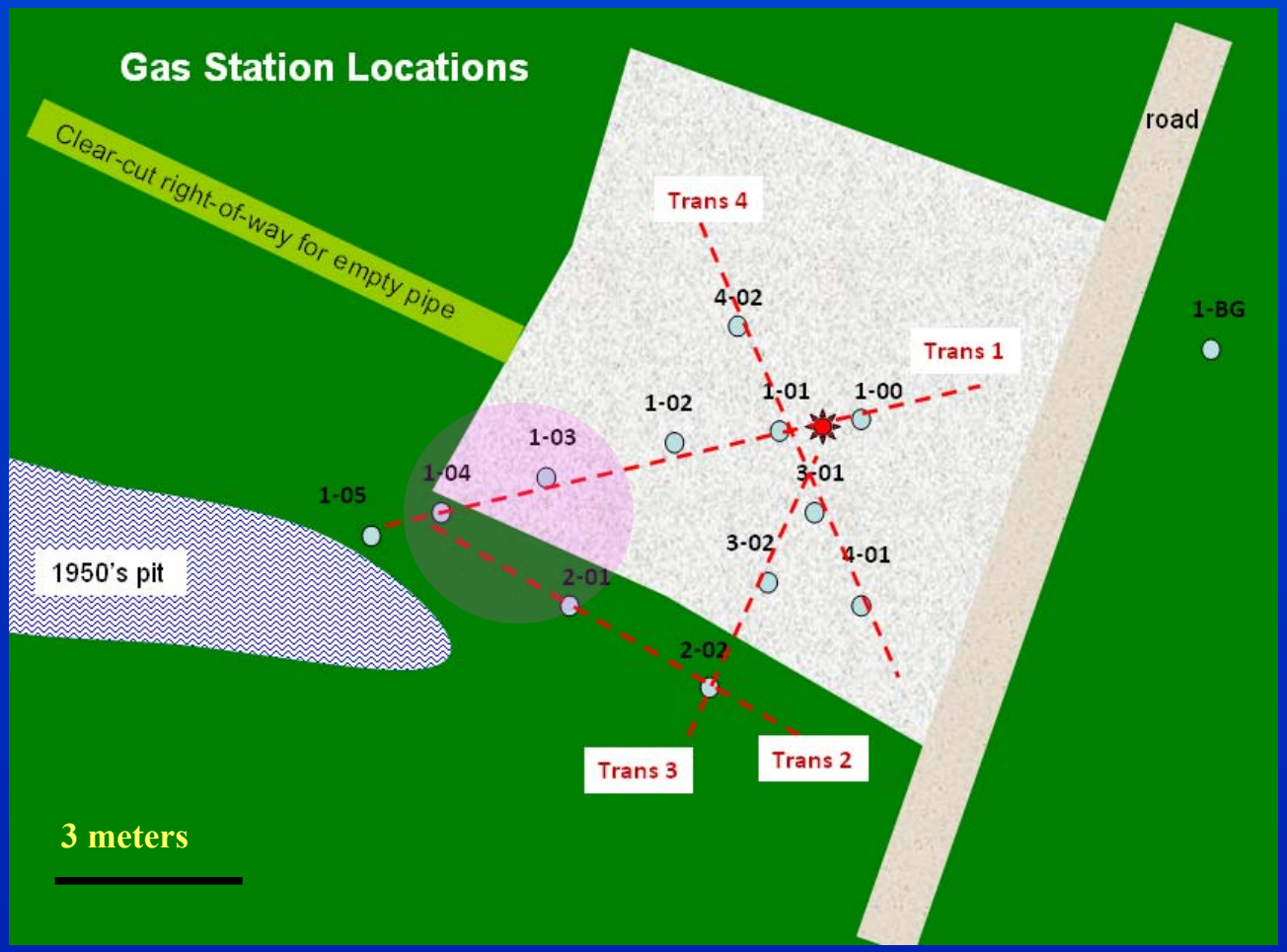
Process Based Method for Near Surface Leakage Detection

Uses gas concentration relationships to understand process.

Requires no background measurements



Fixed Soil-Gas Monitoring



4 transects
12 stations
36 wells

7 sampling trips
Sept, 2009 –
Feb, 2011

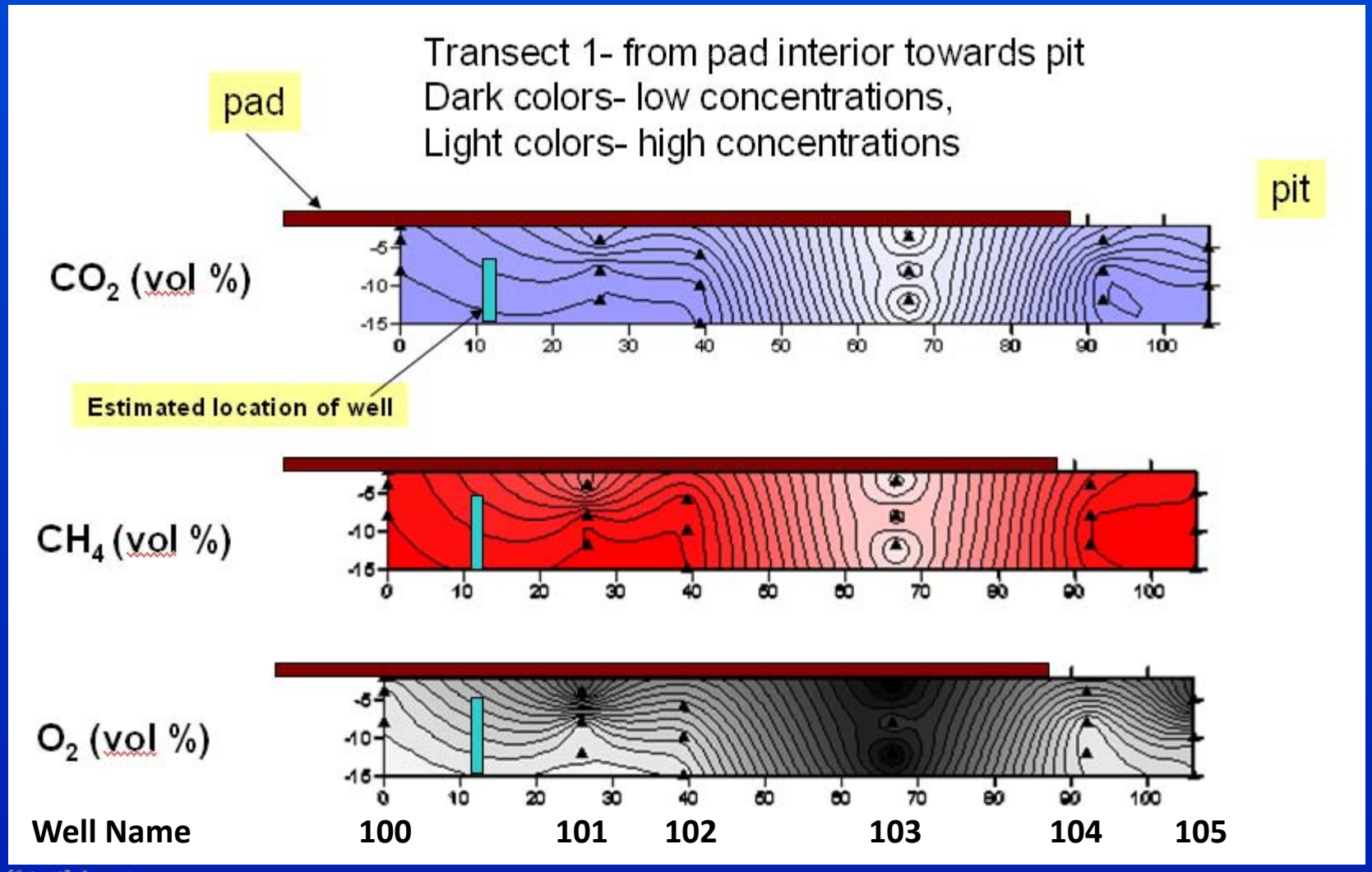
$CH_4 \leq 34$ vol. %

$CO_2 \leq 45$ vol. %

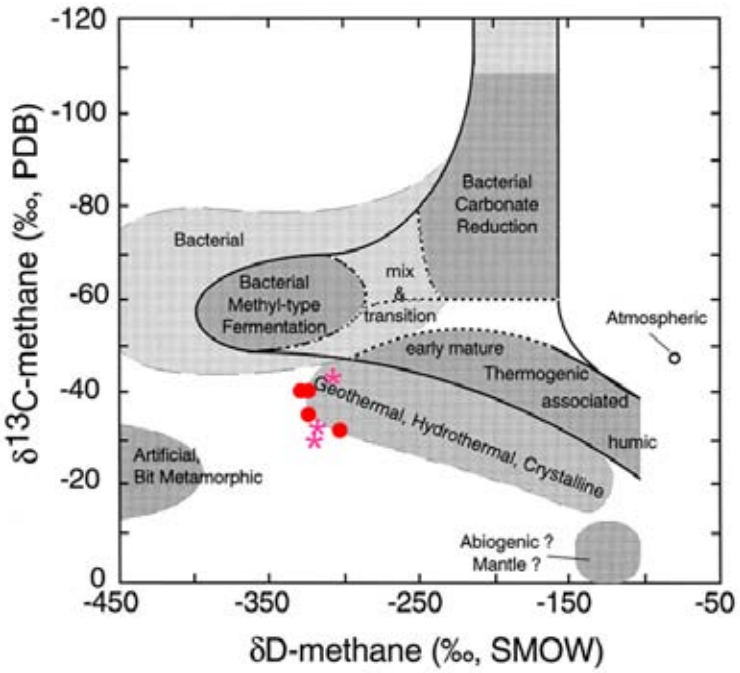
N_2 42-85%

O_2 2- 21%

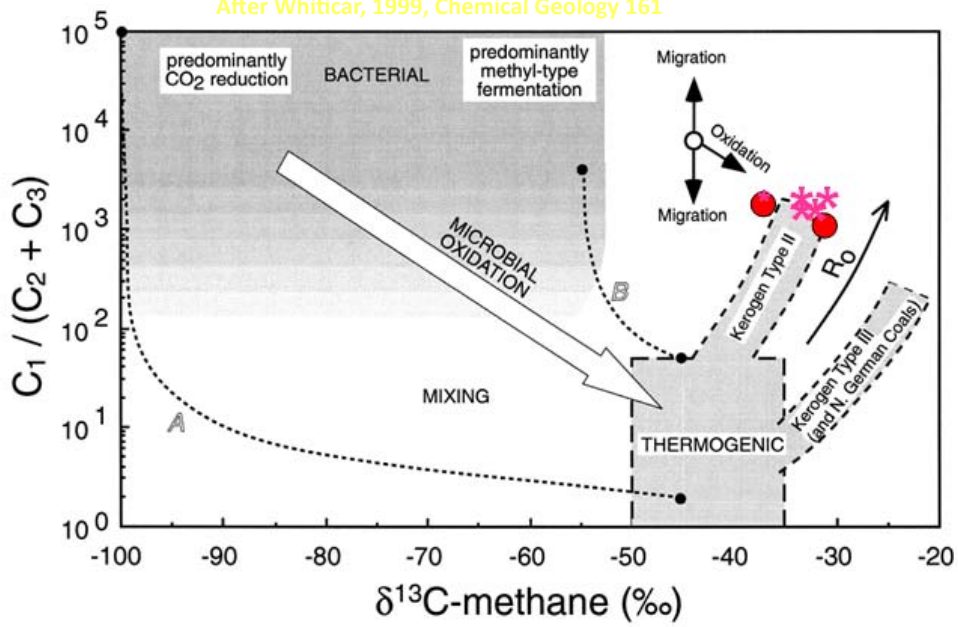
Gas Concentration Gradients



Methane Source Identification



After Whiticar, 1999, Chemical Geology 161



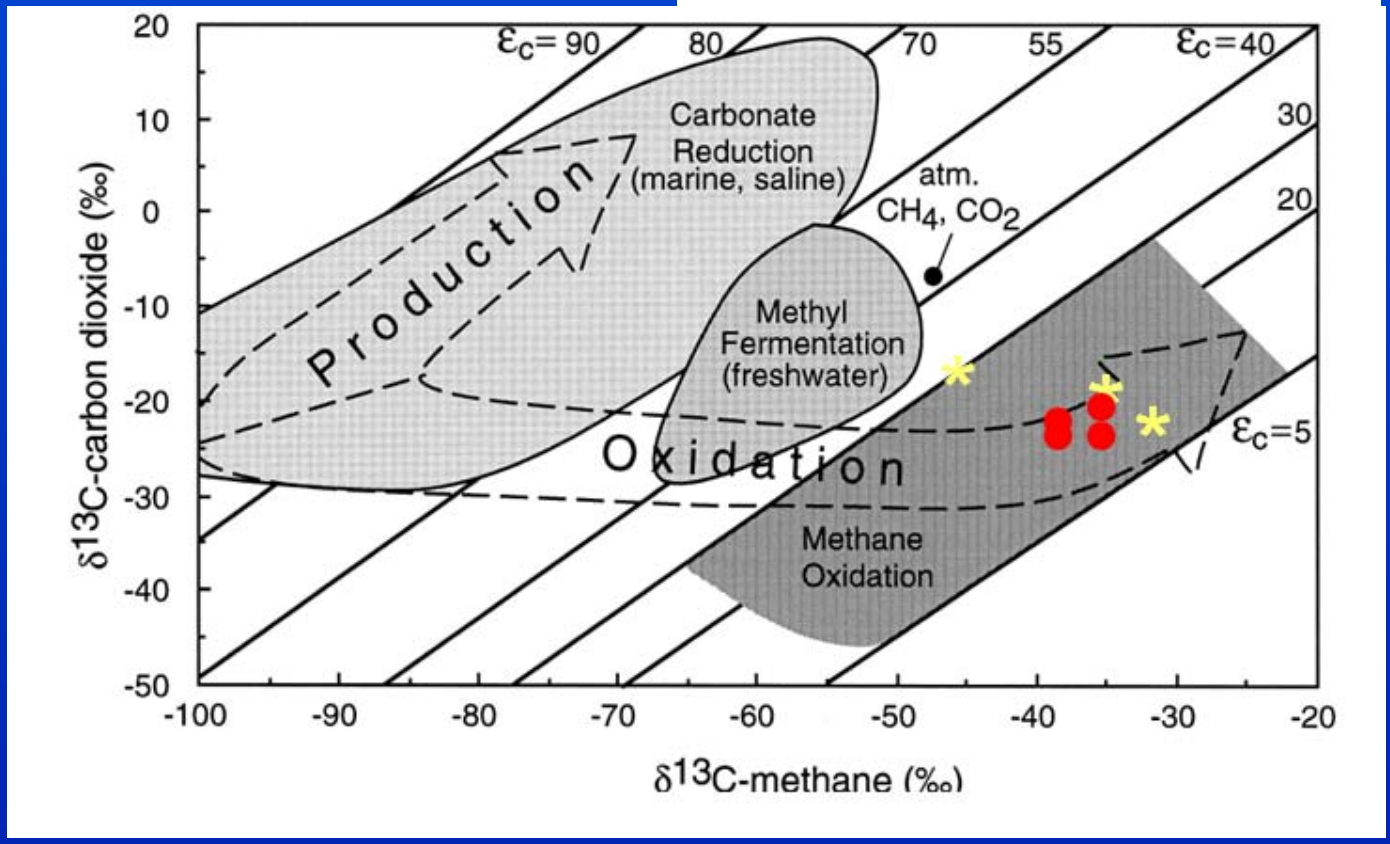
- Thermogenic
- Kerogen Type II
- Signifies oil and gas reservoir

QUESTION:
Field-wide seepage or leakage from well?

*

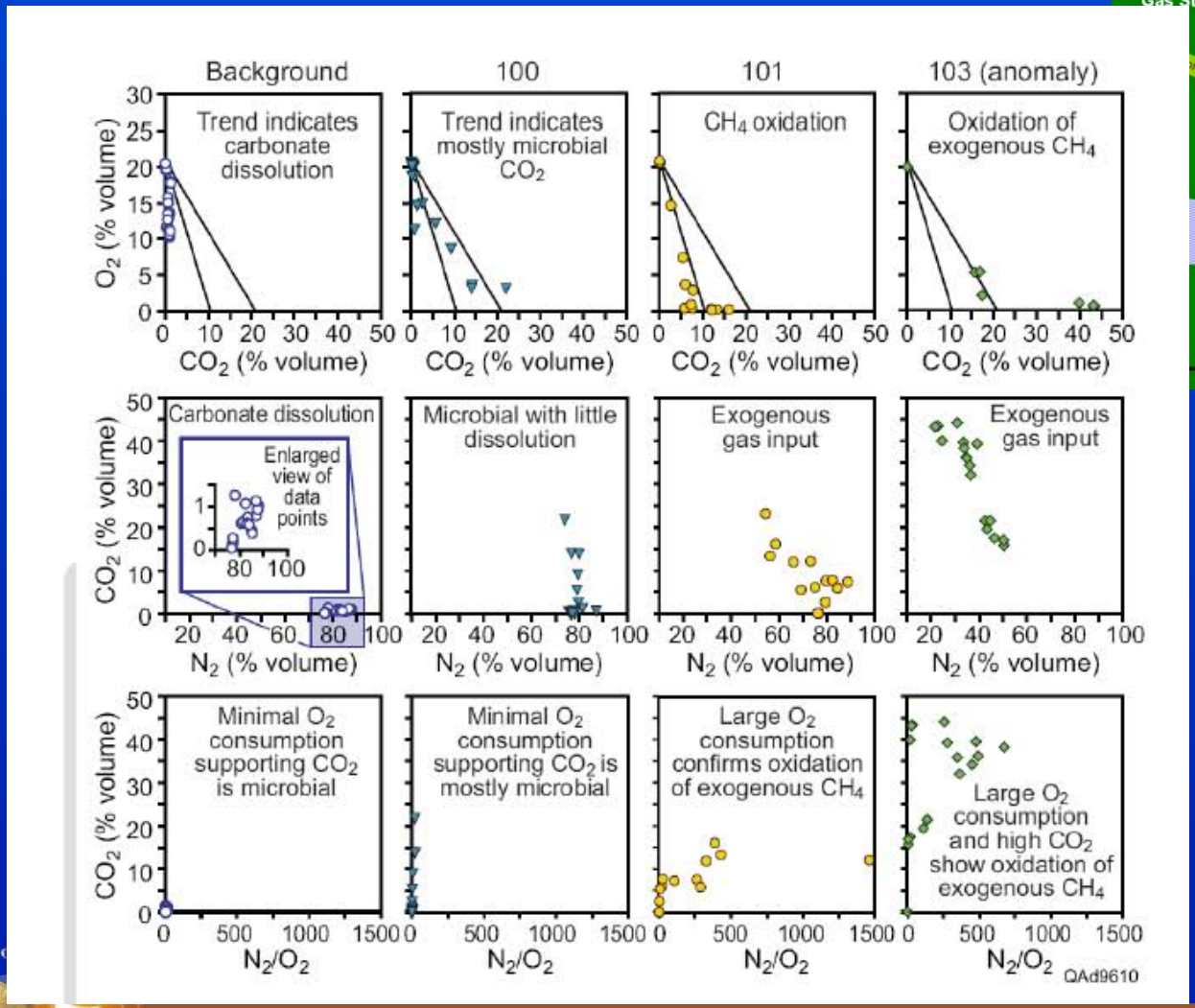
CO_2 Source Identification

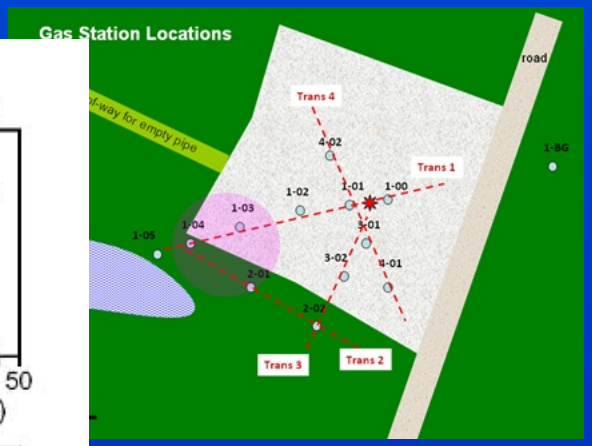
After Whiticar, 1999, Chemical Geology 161



- **Methane oxidation**

Validation of Process Based Method: CCUS Setting





Summary

- A four-step working procedure (characterization, selection, verification and application) is used for conducting shallow groundwater monitoring at the Cranfield site
- Characterization of shallow groundwater indicates mostly silicate minerals control shallow aquifer geochemistry with little influence from carbonate minerals.
- .The utility of various geochemical monitoring parameters is being tested and validated in many environments through hydrologic characterization, lab experiments, geochemical modeling, and field experiments
- Dissolved inorganic carbon (DIC) is proposed as a global monitoring parameter

Summary

- Soil-gas monitoring was conducted at the P-site by measuring soil CO_2 concentrations, flux and soil-gas compositions.
  - CO_2 and CH_4 at the site are “anomalously” high.
  - The source of CH_4 appears to be thermogenic, kerogen type II which is indicative of an oil & gas reservoir.
  - The source of CO_2 from oxidation of CH_4.
  - Currently not proven if the CH_4 is from the well or general seepage from the reservoir

Summary

- Soil CO_2 concentration measurements may be insufficient for CO_2 leakage detection.
- Soil gas composition measurements may be more reliable than CO_2 concentration measurements alone.
- A new *Process-Based* approach to near surface leakage detection is proposed and was successfully tested at Cranfield.

Contact Information

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Shallow Groundwater Study at the Cranfield site

Changbing Yang
Susan Hovorka
Other team members
Gulf Coast Carbon Center
Bureau of Economic Geology
The University of Texas at Austin
March 12, 2013

Acknowledgements

- This material is based upon work supported by the U.S. Department of Energy National Energy Technology Laboratory.
- Cost share and research support provided by SECARB/SSEB Carbon Management Partners.



Cranfield, Mississippi

- Located 15 miles east of Natchez, MS
- The oil field discovered in 1940s and abandoned in 1960s

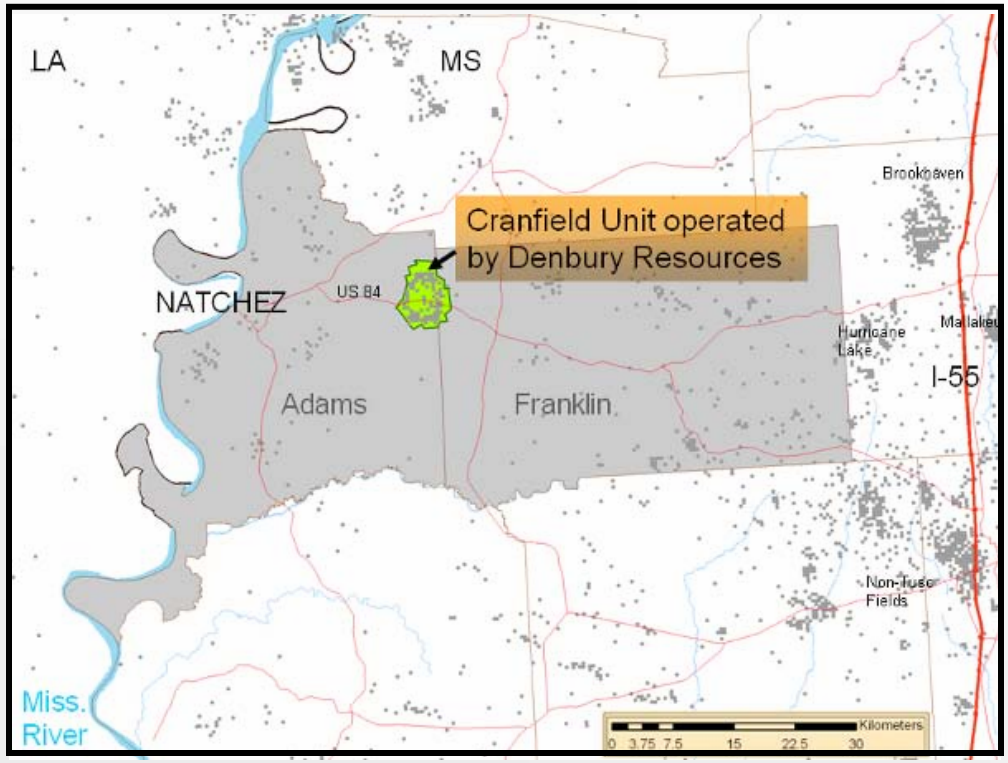
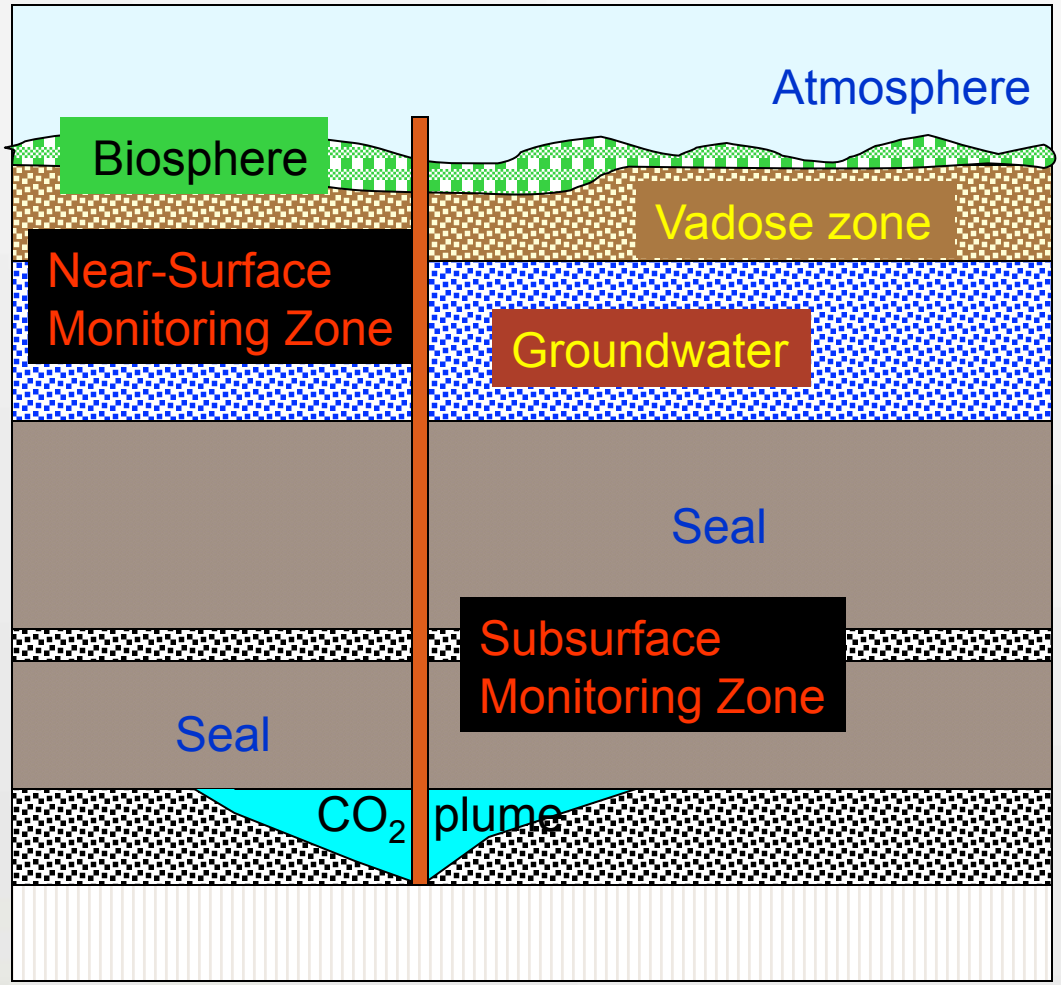


Figure courtesy of Tip Meckel

- Currently owned and operated by Denbury Resources
- Injection of CO_2 for EOR since 2008



Objectives

- To evaluate plausibility of groundwater chemistry monitoring for detecting CO_2 leakage
- To assess potential impacts of groundwater quality in case of CO_2 leakage

Stepwise groundwater monitoring strategy

Step 1. Characterize shallow groundwater chemistry and mineralogy of aquifer sediments

Step 2. Identify a set of geochemical parameters for detecting CO_2 leakage

Step 3. Test & validation

- Numerical modeling
- Lab experiments
- Field controlled-release experiments (Push-pull tests)

Step 4. Application

Groundwater chemistry monitoring for detecting CO_2 leakage

Research team

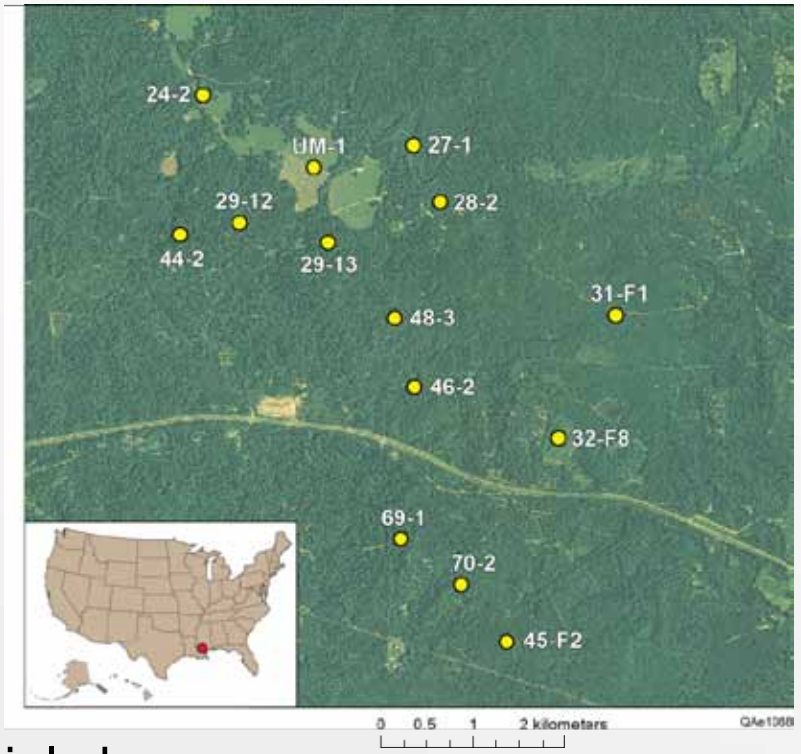
- Main participants
  - Bureau of Economic Geology (BEG)
    - Data analysis
    - Lab experiments
    - Field controlled-release tests
    - Numerical modeling
  - University of Mississippi
    - Groundwater sampling
  - Mississippi State University
    - Water chemistry analysis
  - Anchor QEA
    - Reactive transport modeling in a regional shallow aquifer

Tasks completed

- Characterization of groundwater chemistry at the Cranfield shallow aquifer
- Lab batch experiments of water-rock-CO_2 interactions
- Field controlled-release tests at the Cranfield site
- Numerical modeling

Characterization of groundwater chemistry

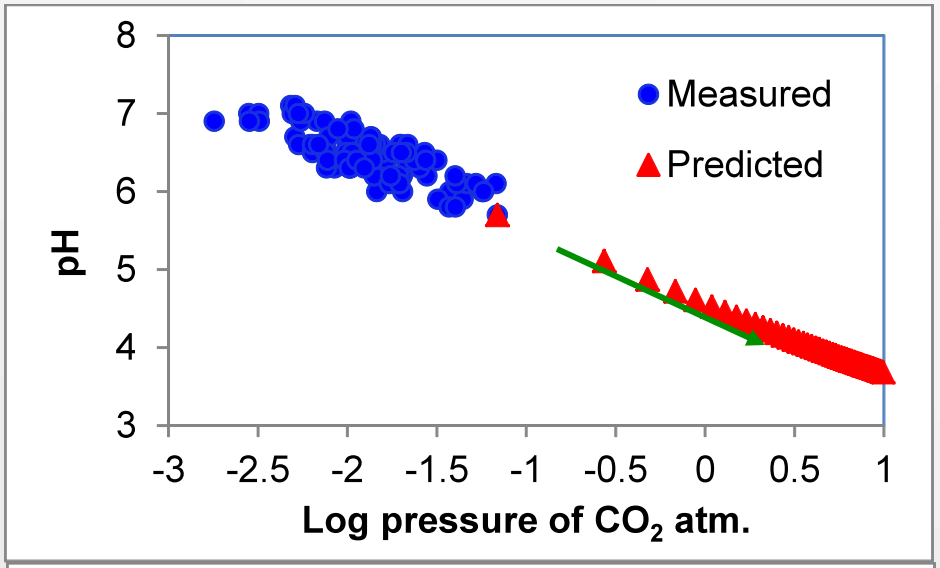
- 10 field campaigns for groundwater sampling since August, 2008
  - On-site measurements: pH, temperature, alkalinity, water level
  - Lab analysis: Ag, Al, As, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Pb, Se, Zn, F^-, Cl^-, SO_4^{2-}, Br^-, NO_3^-, PO_4^{3-}, TOC, DIC, pH, Alkalinity, VOC, δC13 of DIC

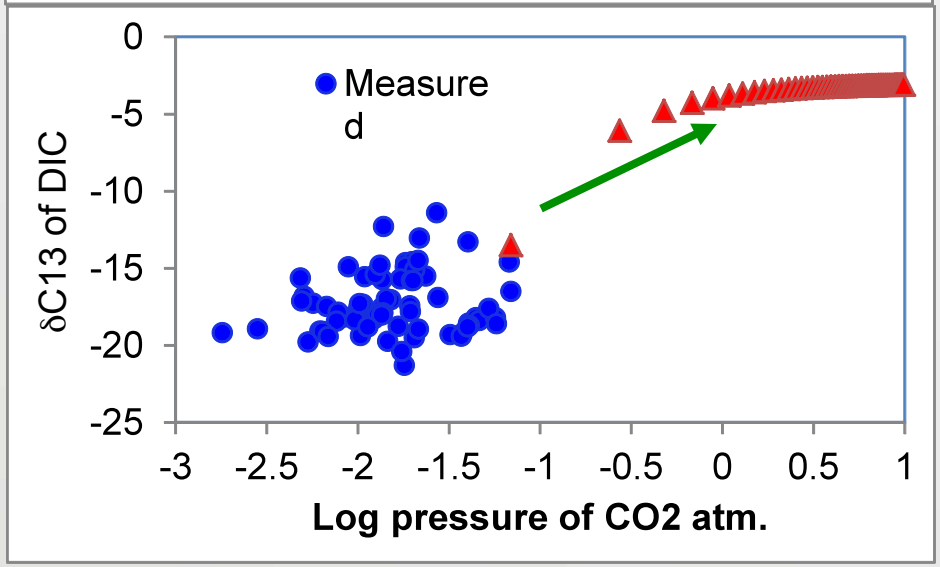


- X-RD analysis of sedimentary samples indicates that silicates and clay minerals are dominant
- Groundwater chemistry dominated mainly by silicate mineral weathering
- Carbonate parameters (e.g., DIC), pH, and δC13 of DIC may be used for detecting CO_2 leakage at the Cranfield site

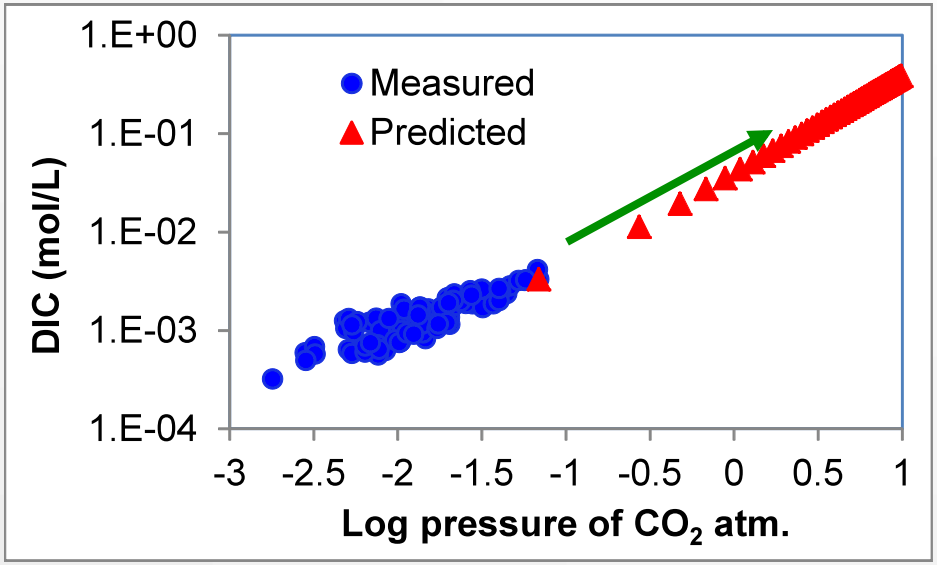
Changbing Yang, Katherine Romanak, Susan Hovorka, Rober Holt, Jeff Lindner, and Ramon Trevino, Near-surface monitoring of large-volume CO2 injection at Cranfield: early field test of SECARB phase III, SPE Journal, in Press

Numerical Modeling





Geochemical modeling



Simulating CO_2 leakage into the Cranfield-type shallow aquifers as CO_2 pressure builds up:

- pH will be lowered
- DIC will increase
- δC13 of DIC will approach -3‰, the value of δC13 of CO_2 injected

Laboratory batch experiments of water-rock-CO_2 interactions

To understand responses of groundwater chemistry to CO_2 leakage under laboratory conditions

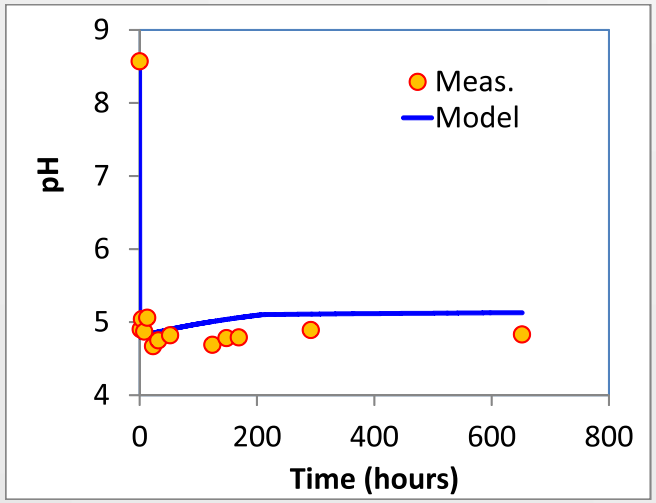
- 106 g of sedimentary samples and 420 ml groundwater from the Cranfield shallow aquifer
- bubbled with Ar for a week, then with CO_2 for ~half year



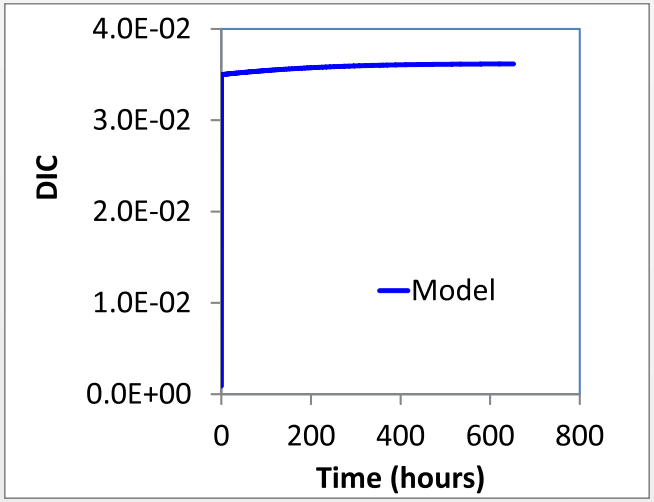
Laboratory batch experiments of water-rock-CO_2 interactions

Results

pH



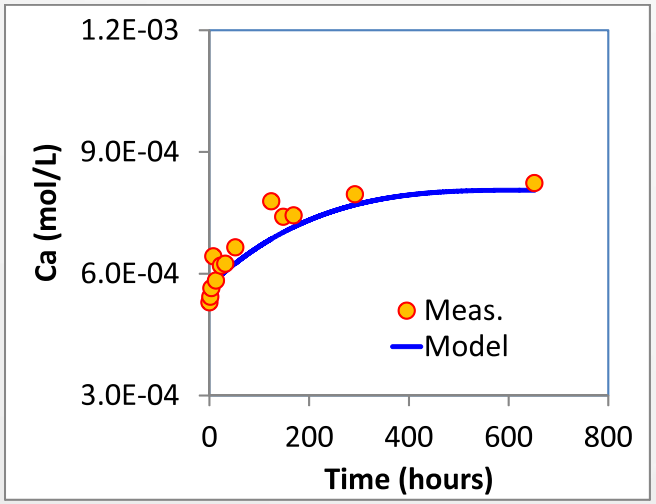
DIC

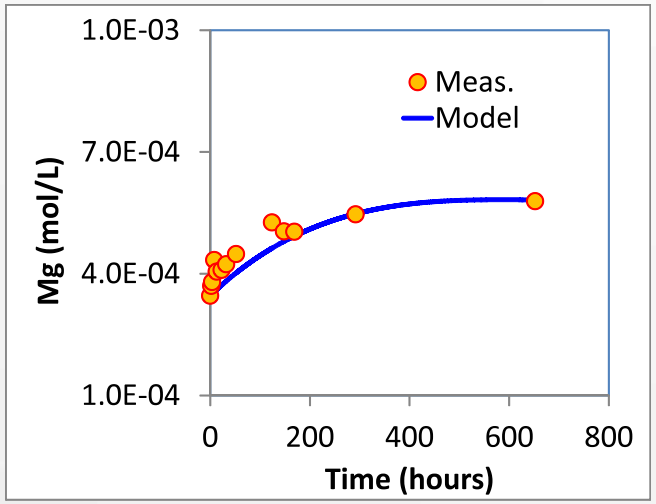


Laboratory batch experiments of water-rock-CO_2 interactions

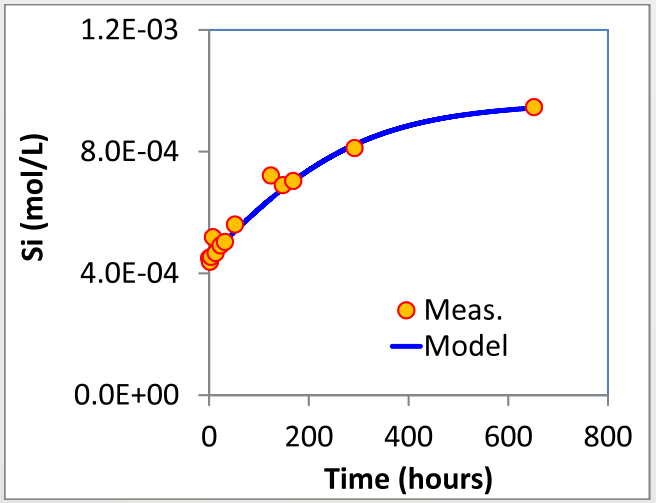
Results

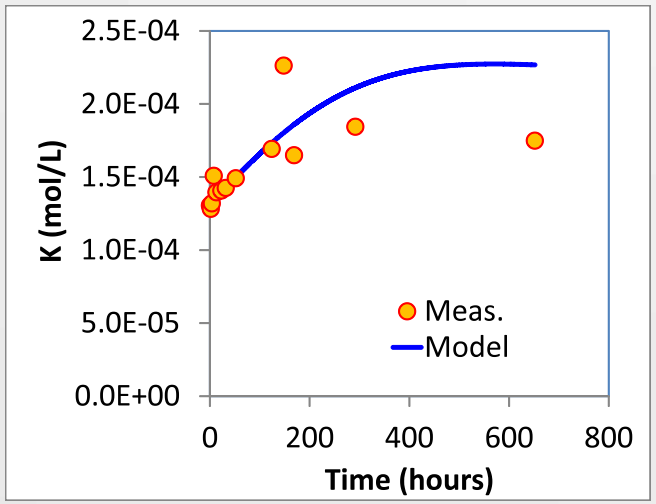
Carbonates dissolution





Silicates dissolution



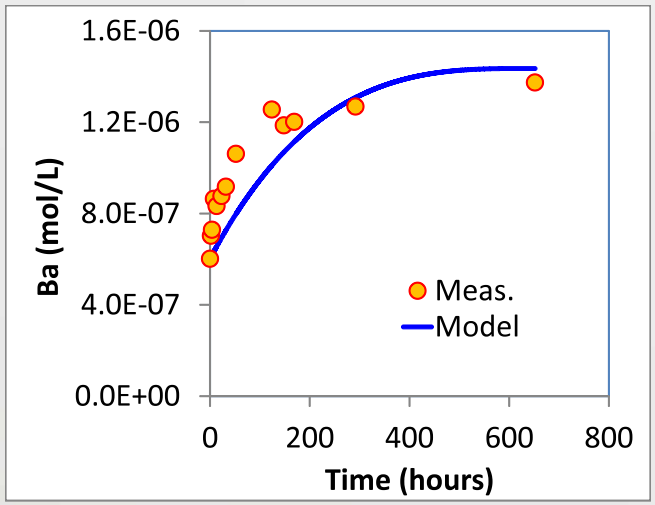


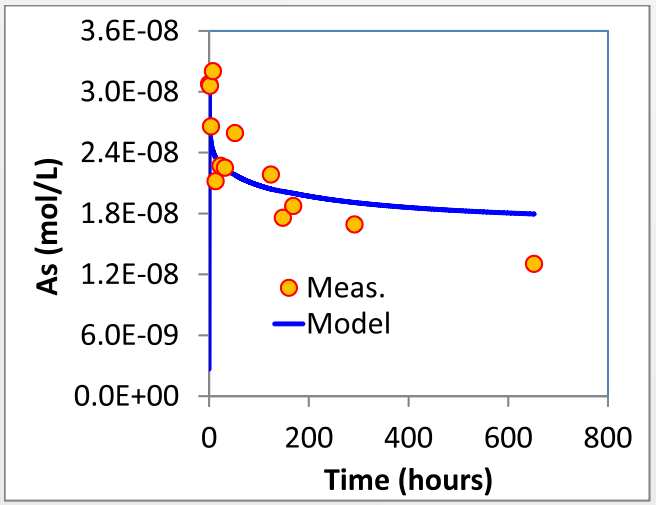
Laboratory batch experiments of water-rock-CO_2 interactions

Results

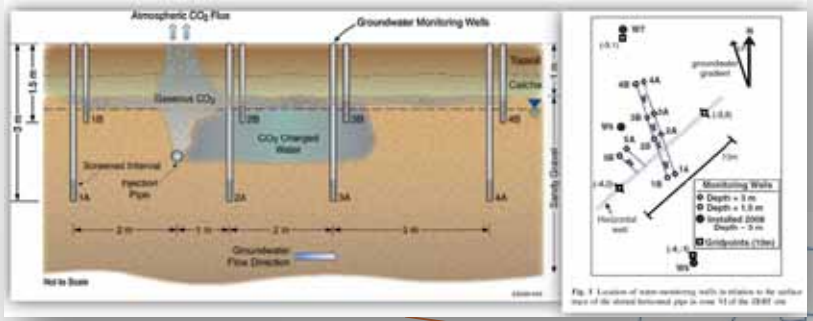
Mobilization of trace metals dominated by two mechanisms

- Carbonate dissolution, such as Ba, Mn, Sr
- Desorption/adsorption, such as As, Pb



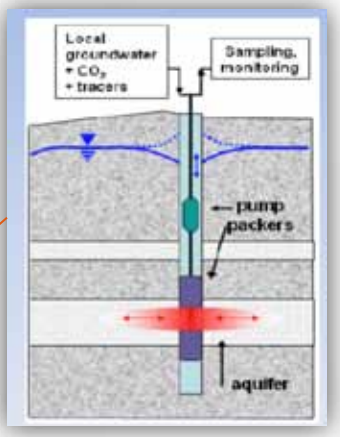


Field controlled-release experiments



Kharaka et al. (2010)
Zheng et al. (2012)

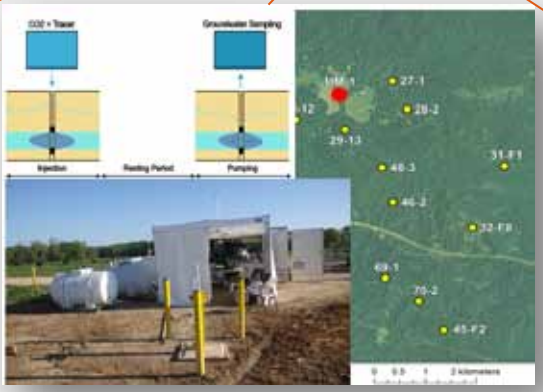




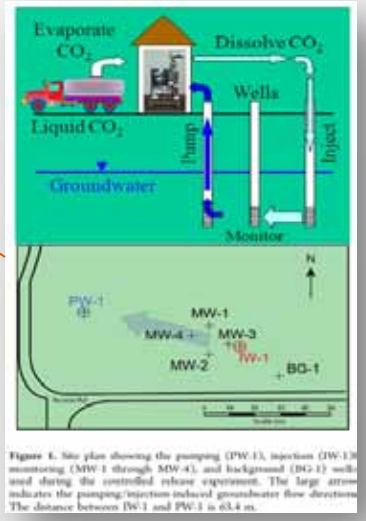
Q. Yang et al. (2013), Newark Basin



Mickler et al. (in preparation),
Yang et al. (in preparation)



Yang et al. (2013)

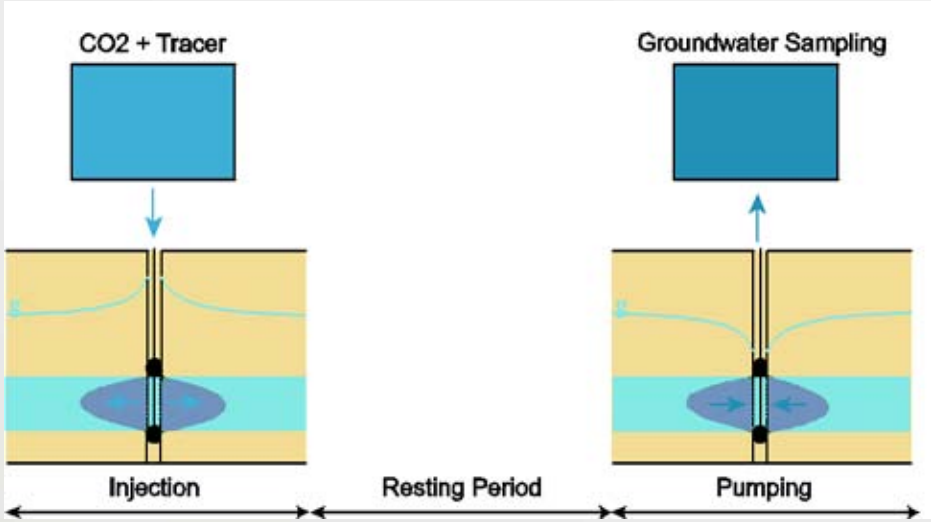


Trautz et al. (2012, 2013)

Field controlled-release experiments

Single well push-pull test

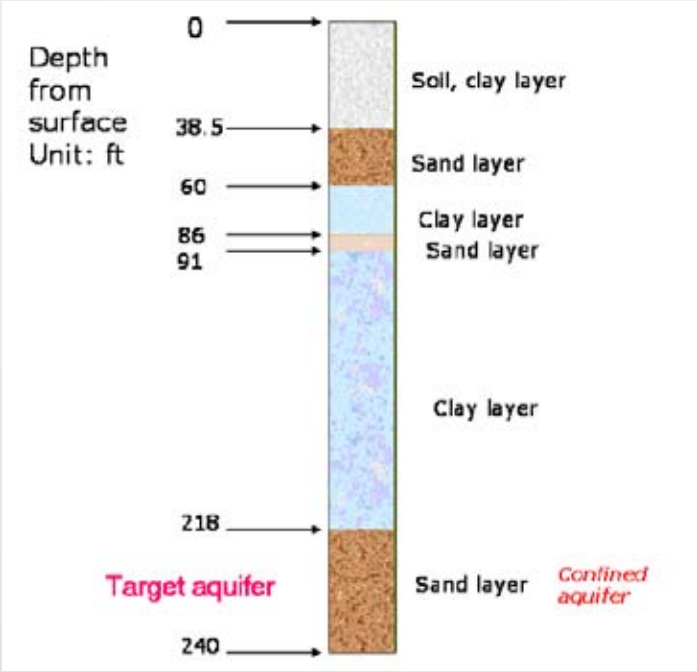
- The injection phase: inject groundwater saturated with CO_2 into the target aquifer
- The resting phase: let injected water react with aquifer sediments
- The pulling phase: pump groundwater continuously for collecting water samples

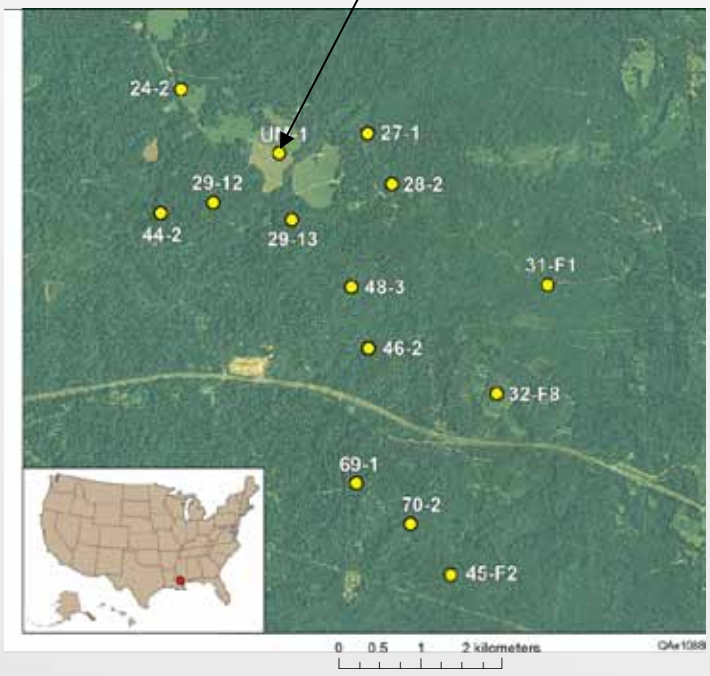


Field controlled-release experiments

Single well push-pull test

- The well was drilled in Nov. 2008
- The well was completed with 2” PVC and screened at the 180 to 240 ft
- Depth of the well: 240 ft to surface
- Depth of water level: 90 ft to surface





Field controlled-release experiments

Single well push-pull test





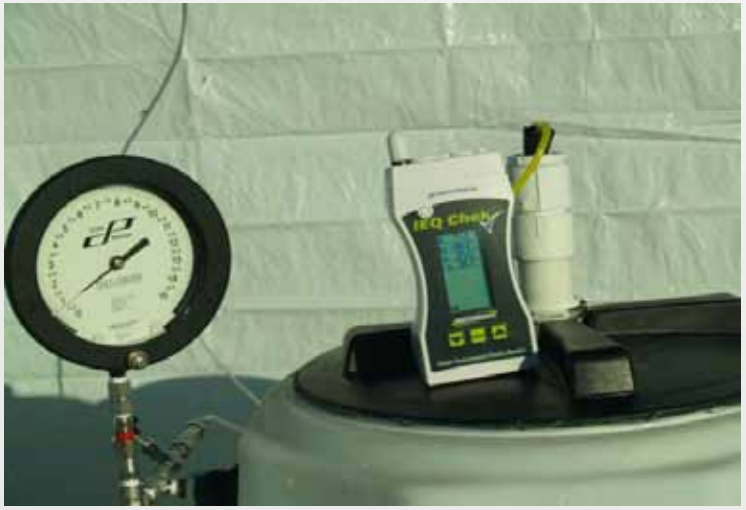
Field controlled-release experiments

Single well push-pull test









Field controlled-release experiments

Single well push-pull test

- ✓ The injection phase:
  Injection started at ~7:00 pm, March 23
  Total 3825 L water injected during 8 hours
- ✓ The resting phase:
  ~55 hours
- ✓ The pulling phase:
  Pumping started at ~9:10 am, March 26
  ~15142 L groundwater pumped out during ~11 hours

Onsite measurements

- ✓ pH, alkalinity
  conductivity
  temperature

Water samples

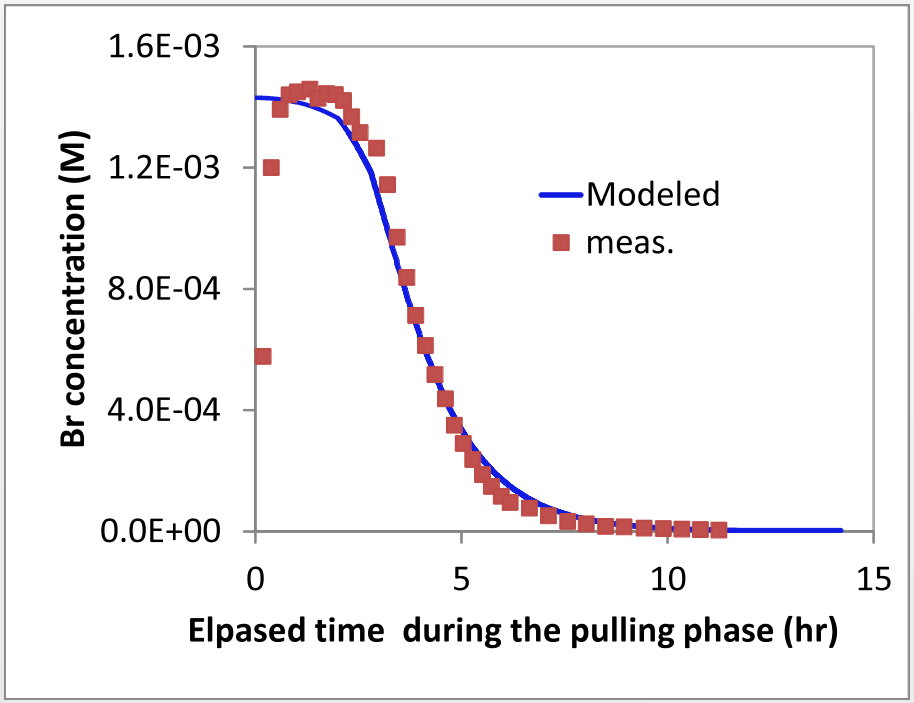
- ✓ IC analysis
- ✓ ICP-MS analysis
- ✓ DIC and stable carbon isotope of DIC

Field controlled-release experiments

Single well push-pull test

Results

- Breakthrough of Br inj.: 1.43 mmol/l, bkg: ~0

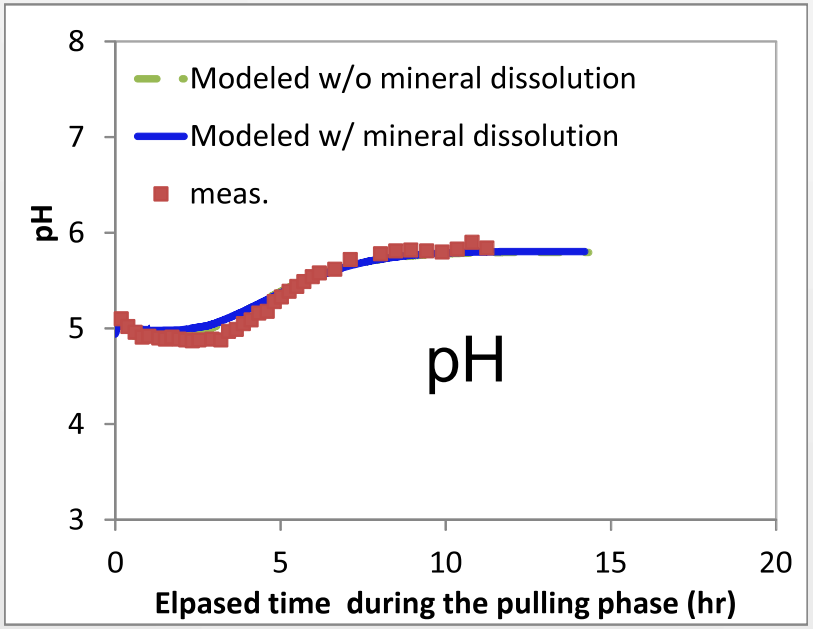


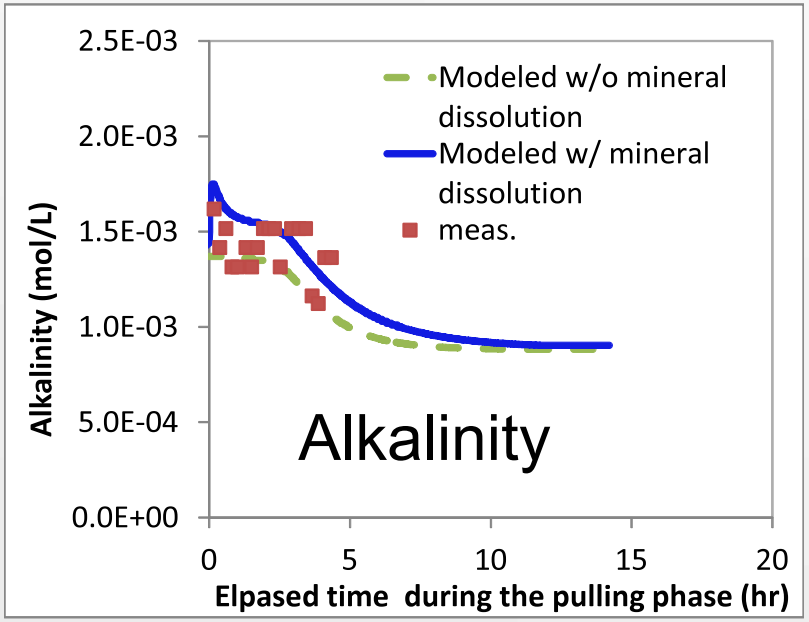
Changbing Yang, Pat Mickler, Robert Reedy, Bridget R. Scanlon, Katherine D. Romanak, J.P. Nicot, Susan D. Hovorka, Ramon Trevino, Toti Larson, Single-Well Push-Pull Test for Assessing Potential Impacts of CO2 Leakage on Groundwater Quality in a Shallow Gulf Coast aquifer in Cranfield, Mississippi, International Journal of Greenhouse Gas Control, in press.

Field controlled-release experiments

Single well push-pull test

Results



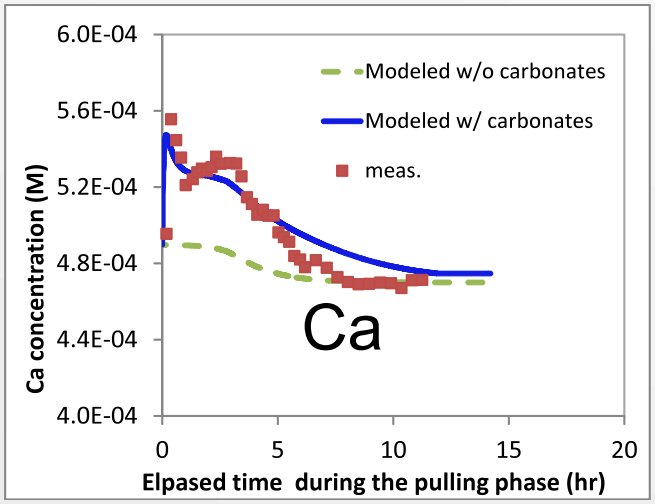


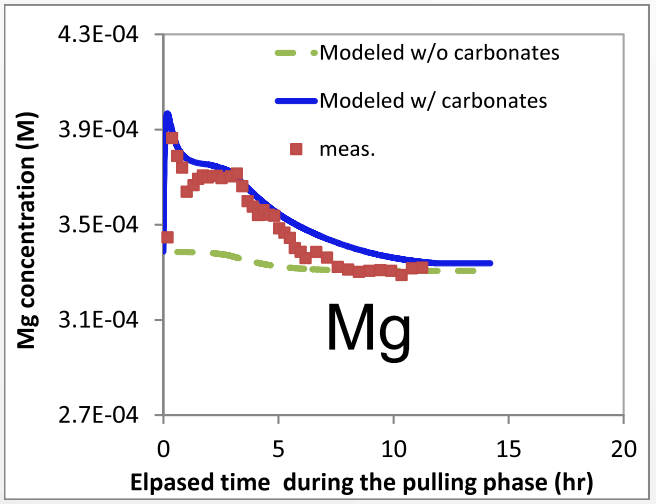
Field controlled-release experiments

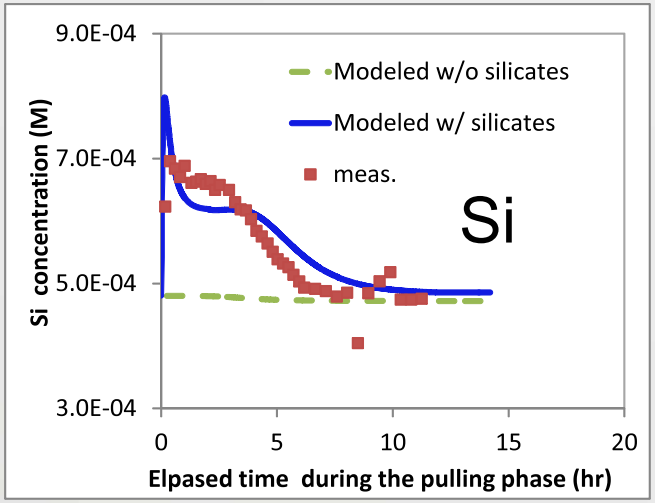
Results

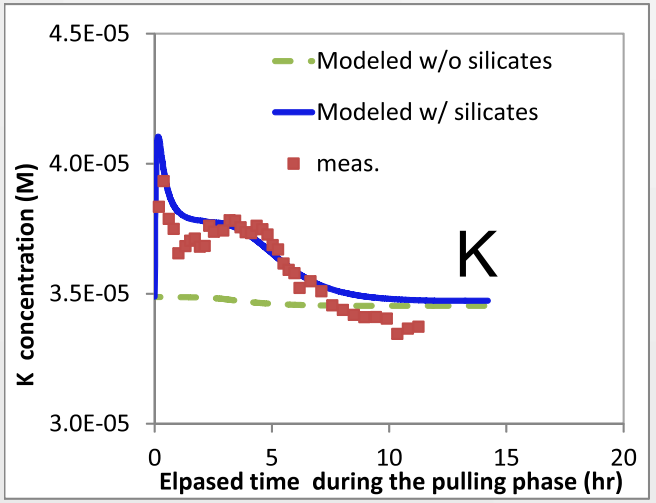
Single well push-pull test

- Carbonate dissolution
- Dissolution of silicates







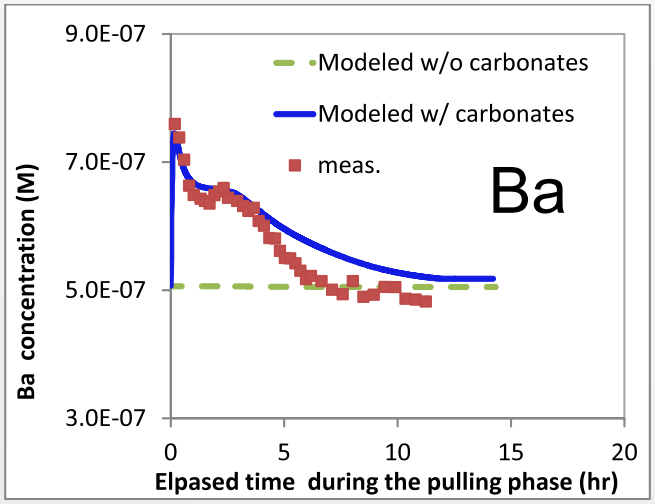


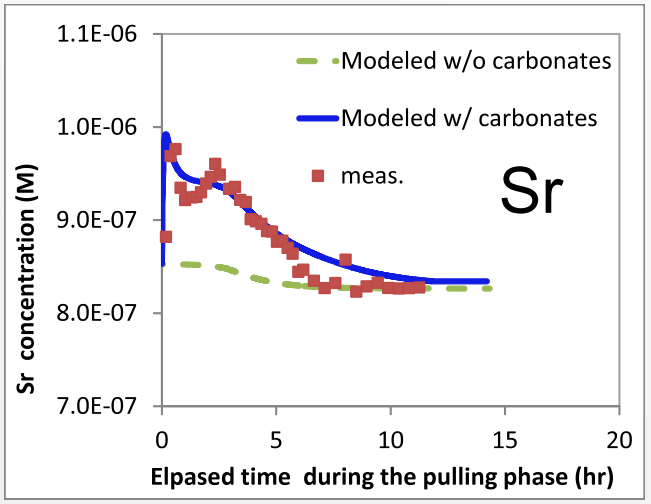
Field controlled-release experiments

Single well push-pull test

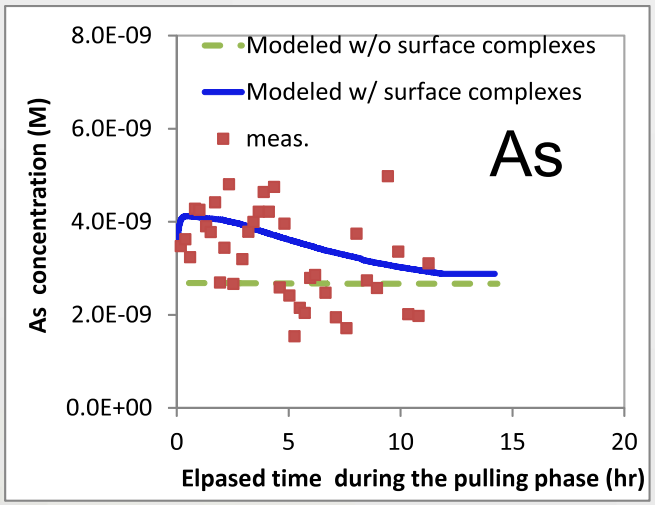
Mobilization of trace metals

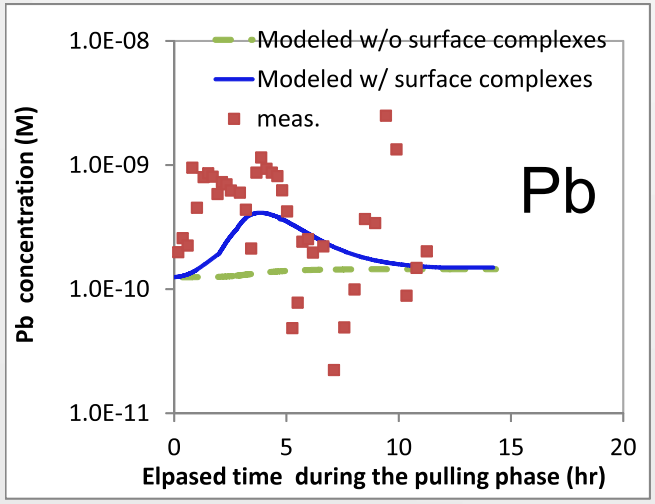
- Carbonate dissolution





- Adsorption/ desorption





Field controlled-release experiments

Comparison of maximum concentrations observed in push-pull test with concentration measurements from 14 wells at Cranfield shallow aquifer

Ions	Unit	Max Conc.	Statistics of concentration measurements	
			Min	Max
pH	-	**5.0**	**5.3**	**7.5**
Alkalinity	mg $CaCO_3$/L	80.9	30.0	154.3
DIC[8]	mmol/L C	**35.25**	**1.3**	**5.5**
Ca	mg/L	22.3	4.0	27.9
Mg	mg/L	9.4	1.6	10.2
K	mg/L	1.5	1.1	8.4
Na	mg/L	-	7.6	74.3
Si	mg/L	19.5	1.9	23.0
Ba	µg/L	104.3	10.0	258.0
Cu	µg/L	0.9	<3.0	34.0
Fe	mg/L	0.2	<0.007	11.2
Mn	µg/L	13.4	1.0	708.0
Zn	µg/L	20.2	3.0	1187.0

Summary

- Groundwater chemistry at the Cranfield shallow aquifer appears to be dominated by silicate mineral weathering;
- Batch experiments, the field controlled-release test, and numerical modeling show that DIC and pH are sensitive to CO_2 leakage and may be used for detecting CO_2 leakage at the Cranfield shallow aquifer;
- Dominant geochemical processes for ion mobilization include dissolution of carbonates and silicates, desorption/adsorption;
- No obvious degradation in groundwater quality was observed in the batch experiments and the field test;

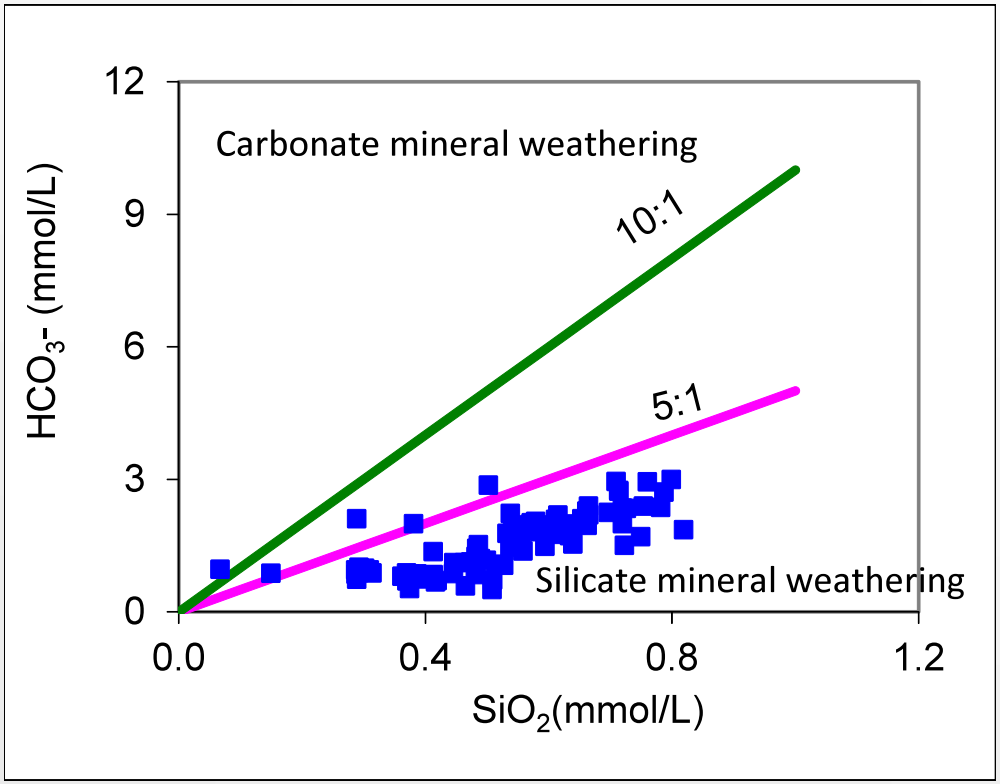
Summary

- Maximum concentrations of trace metals observed, such as As and Pb, are much less than the EPA contamination levels;
- Single well push-pull test appears to be a convenient field controlled-release test for assessing potential impacts of CO_2 leakage on drinking groundwater resources;
- Stepwise monitoring strategy used for groundwater study at the Cranfield site may be applied to other sites;
- The combined use of laboratory batch experiments, field controlled-release tests, and reactive transport models provide a comprehensive evaluation of potential impacts of CO_2 leakage on groundwater chemistry.

Supplementary slides

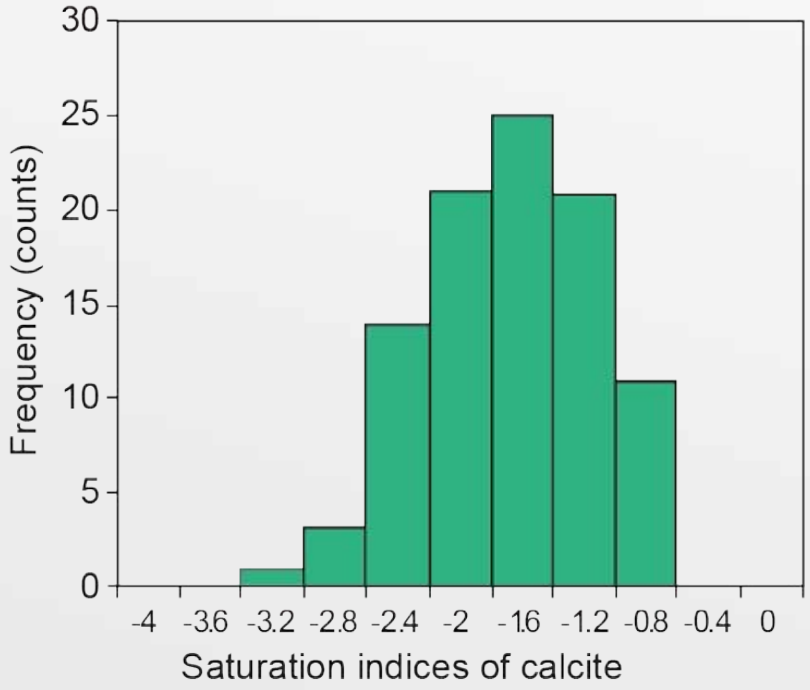
Characterization of Groundwater Geochemistry (3/6)

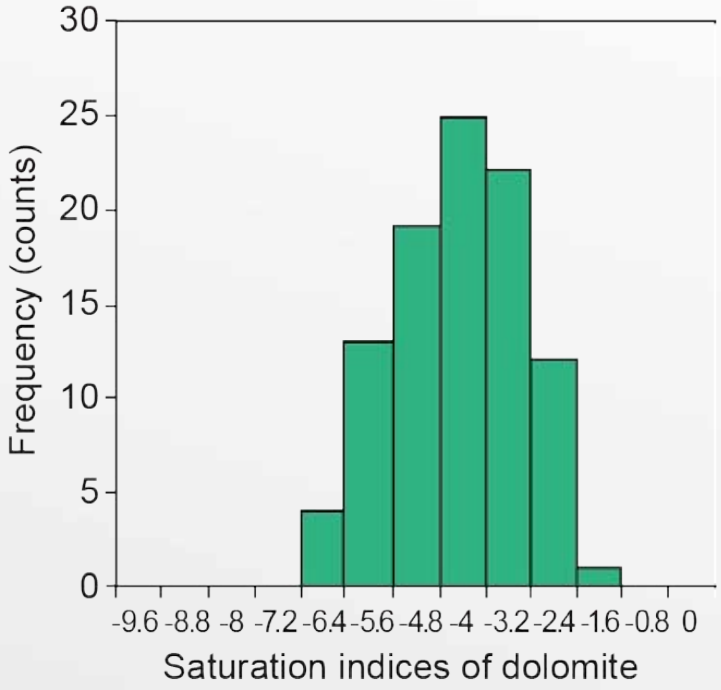
- HCO_3/Si>10: water chemistry is dominated by carbonate mineral weathering
- HCO_3/Si<5: water chemistry is dominated by silicate mineral weathering



Hounslow, A. 1995. Water Quality Data: Analysis and Interpretation. New York, New York: Lewis Publishers.

Characterization of Groundwater Geochemistry (4/6)

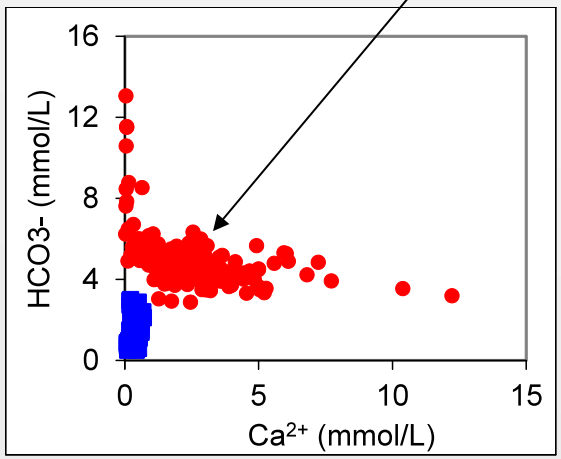


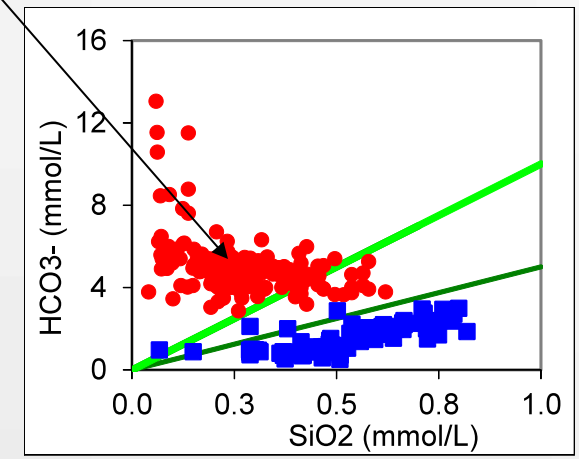


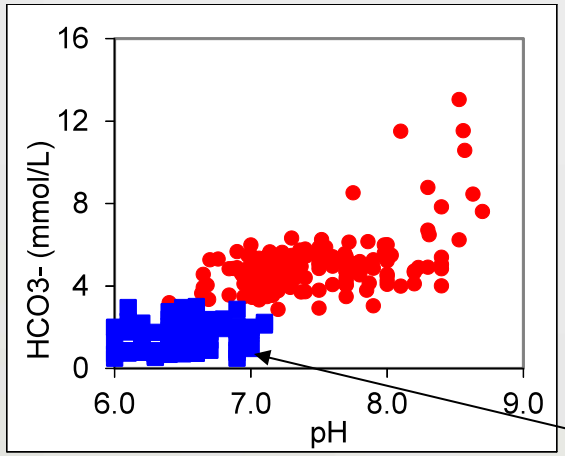
- Carbonate mineral saturation indices show that carbonate minerals (calcite and dolomite) are under saturated with respect to groundwater

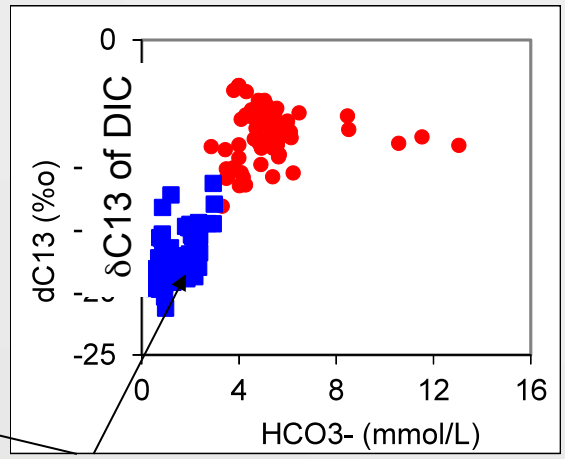
Characterization of Groundwater Geochemistry (6/6)

SACROC









Cranfield

SACROC aquifer sediments contain carbonate minerals

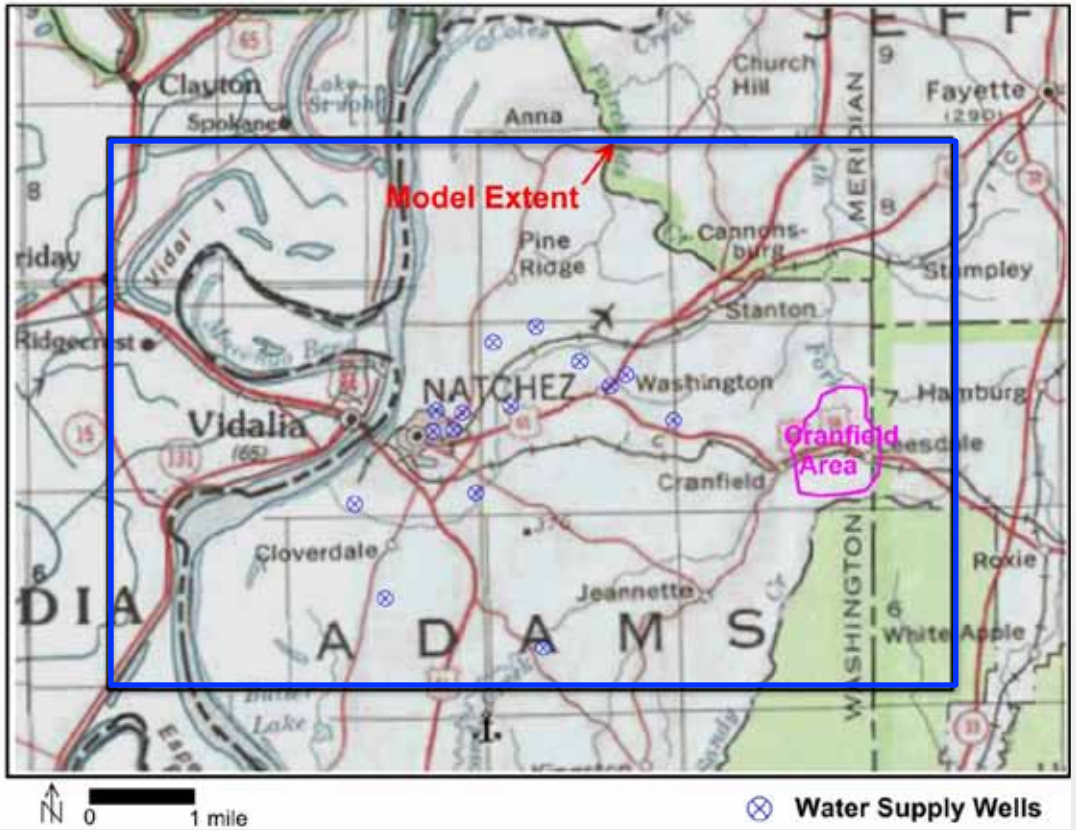
Cranfield aquifer sediments without carbonate minerals

Numerical Modeling

- Regional scale
- Fixed head boundary based on USGS water level data
- Production at pumping wells based on USGS data
- Worst scenarios for CO_2 leak
- Model tool: MODFLOW, MT3D, PHREEQC

Reactive transport modeling

By Anchor QEA



Geochemical processes if CO_2 has leaked into a shallow aquifer

- CO_2 dissolution into groundwater

  $CO_2 + H_2O \rightarrow H_2CO_3$ $H_2CO_3 \rightarrow H^+ + HCO_3^-$ $HCO_3^- \rightarrow H^+ + CO_3^{2-}$

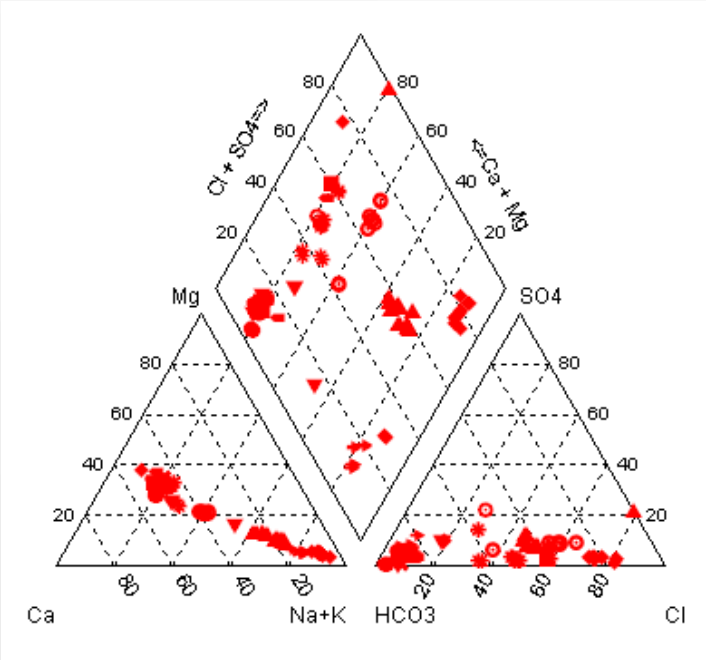
- Mineral dissolution

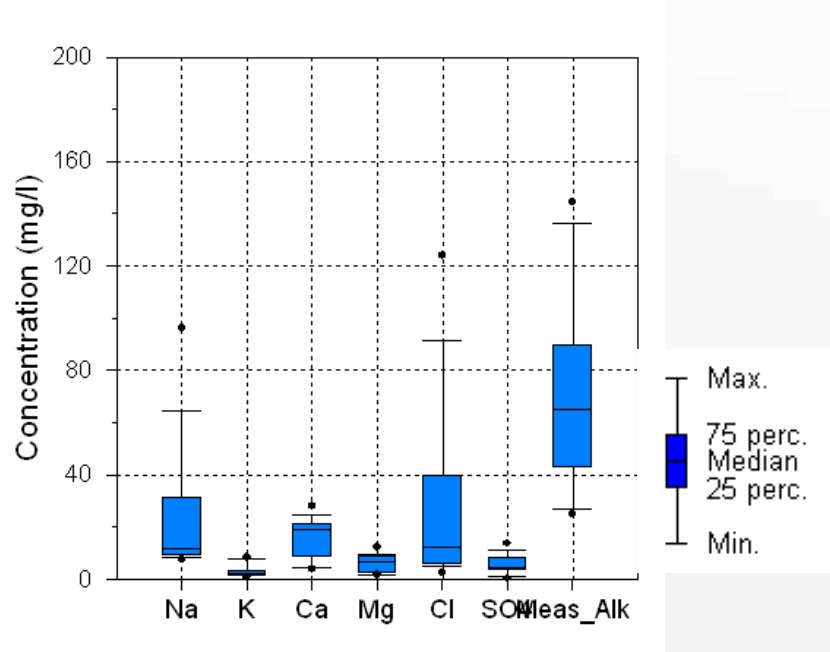
  $H_2O + CaCO_3 + CO_2 \rightarrow 2HCO_3^- + Ca^{2+}$

- Mobilization of trace metals (Fe, Mn, Pb, Zn, U, As, Cd, Sr,…)

- Redox (oxidation-reduction)

Characterization of Groundwater Geochemistry





- Groundwater types mainly are Na-Cl, Ca-Na-HCO3, and Ca-Na-HCO3-Cl
- Na and Cl concentrations show variations

Maximum concentrations of trace elements observed at Cranfield shallow aquifer (as of March 2012)

Trace metals	Ba	Cd	Cr	Cu	Fe	Mn	Pb	Zn
Maximum concentration (ppm)	0.258	0.004	0.003	0.034	11.17	0.71	0.065	1.19

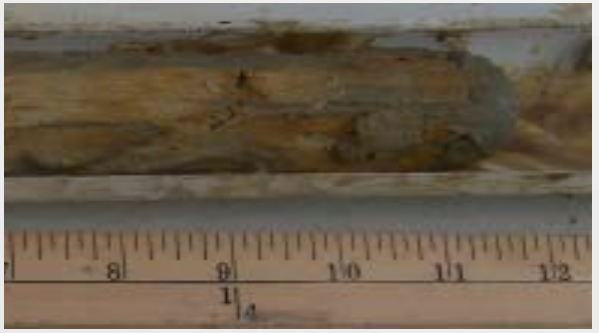
Characterization of Groundwater Geochemistry

- Calculated saturation indices of calcite and dolomite are under saturated with respect to groundwater
- Ratios of HCO_3/Si < than 10
- $\delta^{13}C$ of DIC ranges from -14‰ to -26‰

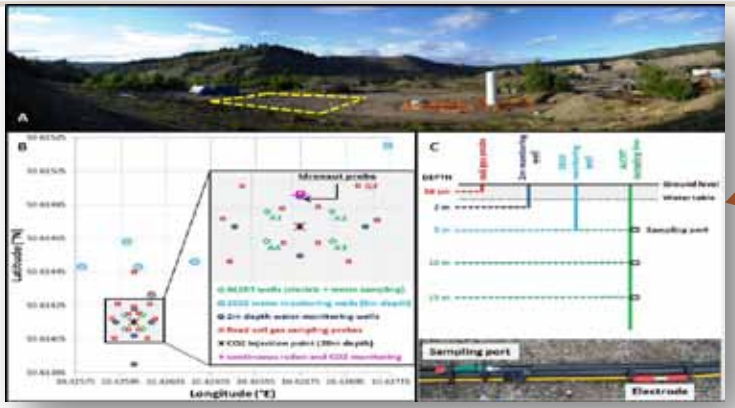


Mineral compositions of aquifer sediment

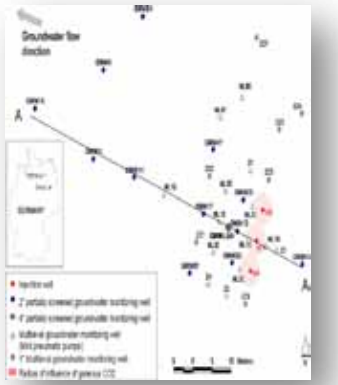
Depth (m)	Quartz	Microcline	Illite	Kaolinite	Albite
61.26	38.76	17.5	19.74	20.85	3.15
67.97	81.86	9.26	1.64	5	2.24
69.49	59.35	17.27	2.79	18.16	2.43
70.10	32.84	18.46	14.39	32.96	1.35
71.02	50.93	20.91	5.31	21.76	1.09



THE UNIVERSITY OF TEXAS AT AUSTIN







Gal et al. (2013)

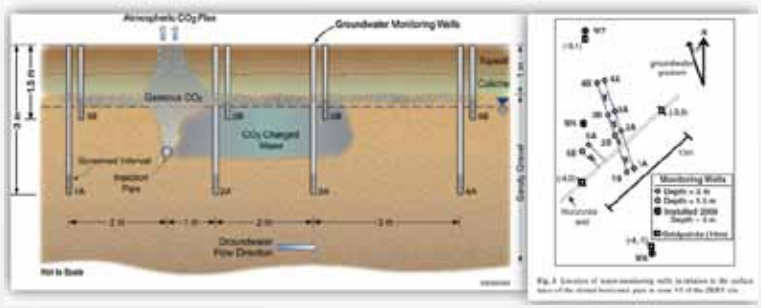
- Fluvial-glacial deposits;
- Gaseous CO_2 injected for ~6 days at the interval ~20 m;
- Groundwater samples at different depths, in-situ continuous monitoring.

- Major findings:
  Injection of CO_2 induced pH/alk changes and also chemical variations both in time and space; Even well-characterized, natural deposits makes identification of CO_2 leakage challenging.

Peter et al. (2012)

- Medium to course sand, silt;
- Gaseous CO_2 injection into three wells for ~10 days at the interval ~18 m;
- Groundwater samples at different depths, geo-electrical measurements, multi-parameter probes.

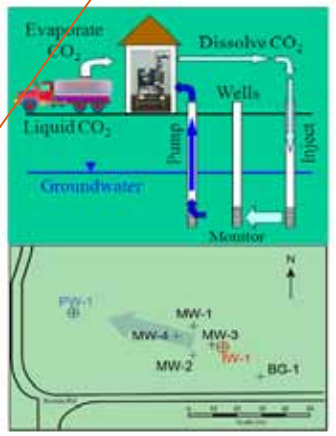
- Major findings:
  DIC (Dissolved Inorganic Carbon) increased and pH decreases due to CO_2 injection; Release of major cations and trace elements was observed; Lab DIC measurements are less reliable than values obtained by multiparameter probes or by field titration and pH measurements



Kharaka et al. (2010), Zheng et al. (2012)

- Injection interval: 2-3 m;
- Sandy gravel;
- Gaseous CO_2 through horizontal pipe for ~ 1 month;
- Onsite pH, Eh, EC, T; groundwater samples for major ions & trace elements, DOC, BTEX;
- Major findings:
  pH, alkalinity, and EC show systematic change;
  Major ions and some trace elements show obvious increase in concentration;
  Pb and As show very minor increase which may be related to exchange reactions.





Trautz et al. (2012, 2013)

- Injection interval: 47-55m;
- Gray-green fine grained silty sand;
- Groundwater saturated with CO_2 for ~5 months;
- Groundwater samples, in-situ logging, complexly spaced electrical methods.

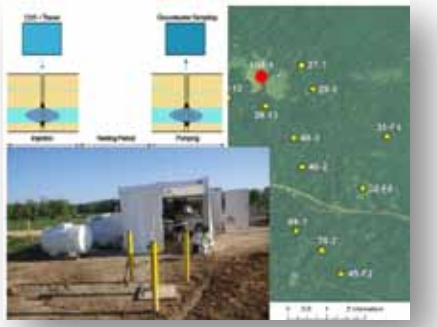
- Major findings:
  pH shows 3 unit drops;
  As and Pb are below detection limit;
  Some ions (Ba, Ca, Cr, Sr, Mg, Mn, Fe) show a pulse response.



Mickler et al. (2012), Yang et al. (2013)



- Injection interval: 2.5-6 m;
- Fine, silty sand with abundant carbonates;
- Groundwater saturated with CO_2, injection for ~ 1 hr;
- Onsite pH, Eh, EC, T, Alk, Groundwater samples for major ions & trace elements.
- Major findings:
  Lower pH leads to carbonates dissolution;
  Trace elements were mobilized from aquifer materials, however, lower than EPA MCLs;
  Increases in Ca & alkalinity are significant.

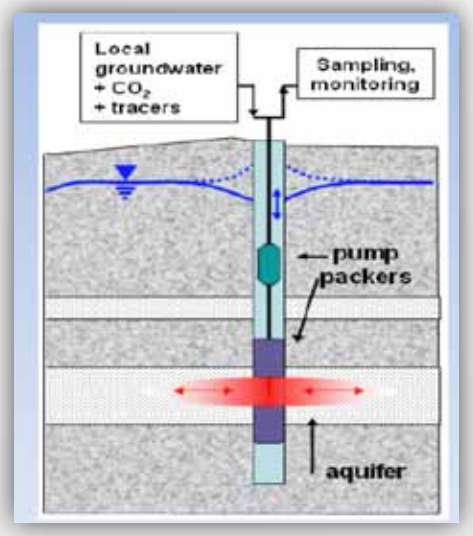


Yang et al. (2013)

- Injection interval: 66-73 m;
- Fine sand, silty sand;
- Groundwater saturated with CO_2 injection for ~8 hrs;
- Onsite, pH, Eh, EC, T, Alk; Groundwater samples.
- Major findings:
  Conc. of major ions elevated during mineral dissolutions; moblization of some trace elements come from carbonates dissolution; As and Pb show minor increases but much smaller than EPA MCLs; Dissolution of small amount of carbonates may be significant to mobilization of trace elements

- Field Tests (Single well)

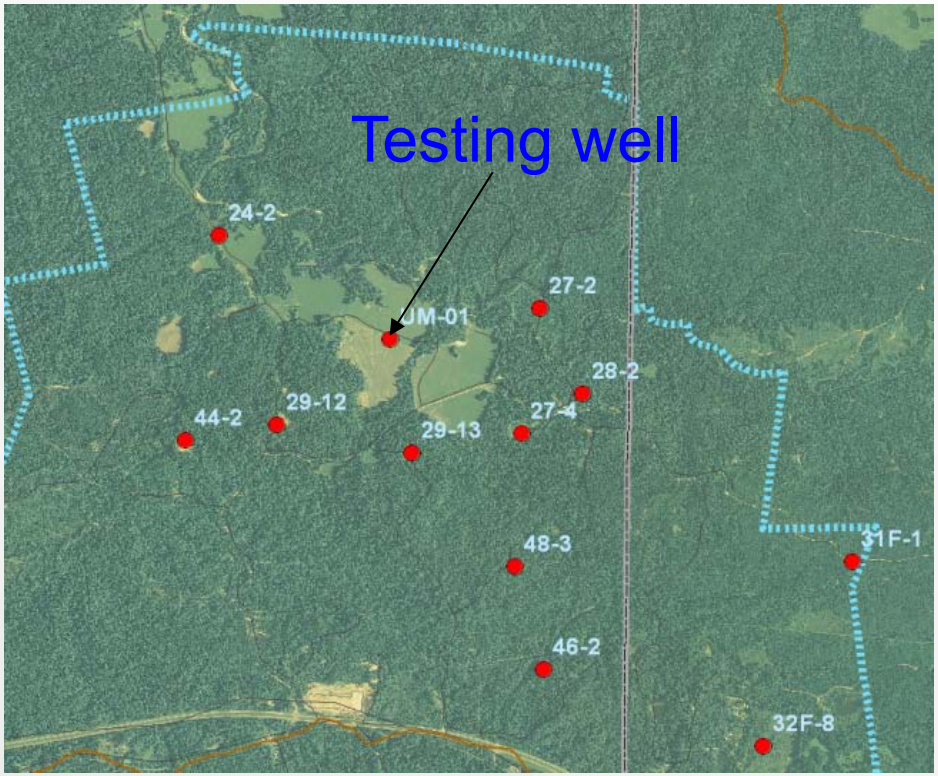


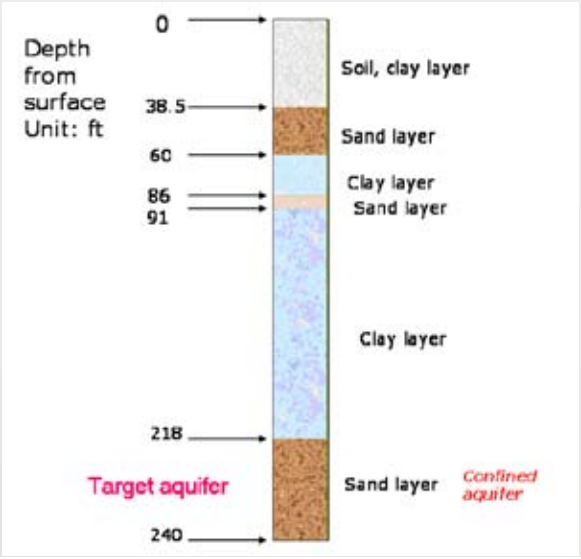


Q. Yang et al. (2013), Newark Basin, US

- Injection interval: 362-366 m;
- Fractured sandstone;
- Groundwater saturated with CO_2, injection for ~ 10 hr;
- Onsite pH, Eh, EC, T, Alk; Groundwater sampled for major ions & trace elements.
- Major conclusions:
  Lower pH causes mobilization of trace elements.

- The well was drilled in Nov. 2008
- The well was completed with 2” PVC and screened at the 180 to 240 ft
- Depth of the well: 240 ft to surface
- Depth of water level: 90 ft to surface





Mineral compositions of aquifer sediment

Depth (m)	Quartz	Microcline	Illite	Kaolinite	Albite
61.26	38.76	17.5	19.74	20.85	3.15
67.97	81.86	9.26	1.64	5	2.24
69.49	59.35	17.27	2.79	18.16	2.43
70.10	32.84	18.46	14.39	32.96	1.35
71.02	50.93	20.91	5.31	21.76	1.09

Subsurface Monitoring Studies: Results and Integration

Tom Daley

Lawrence Berkeley National Laboratory

with contributions from many on the Cranfield team

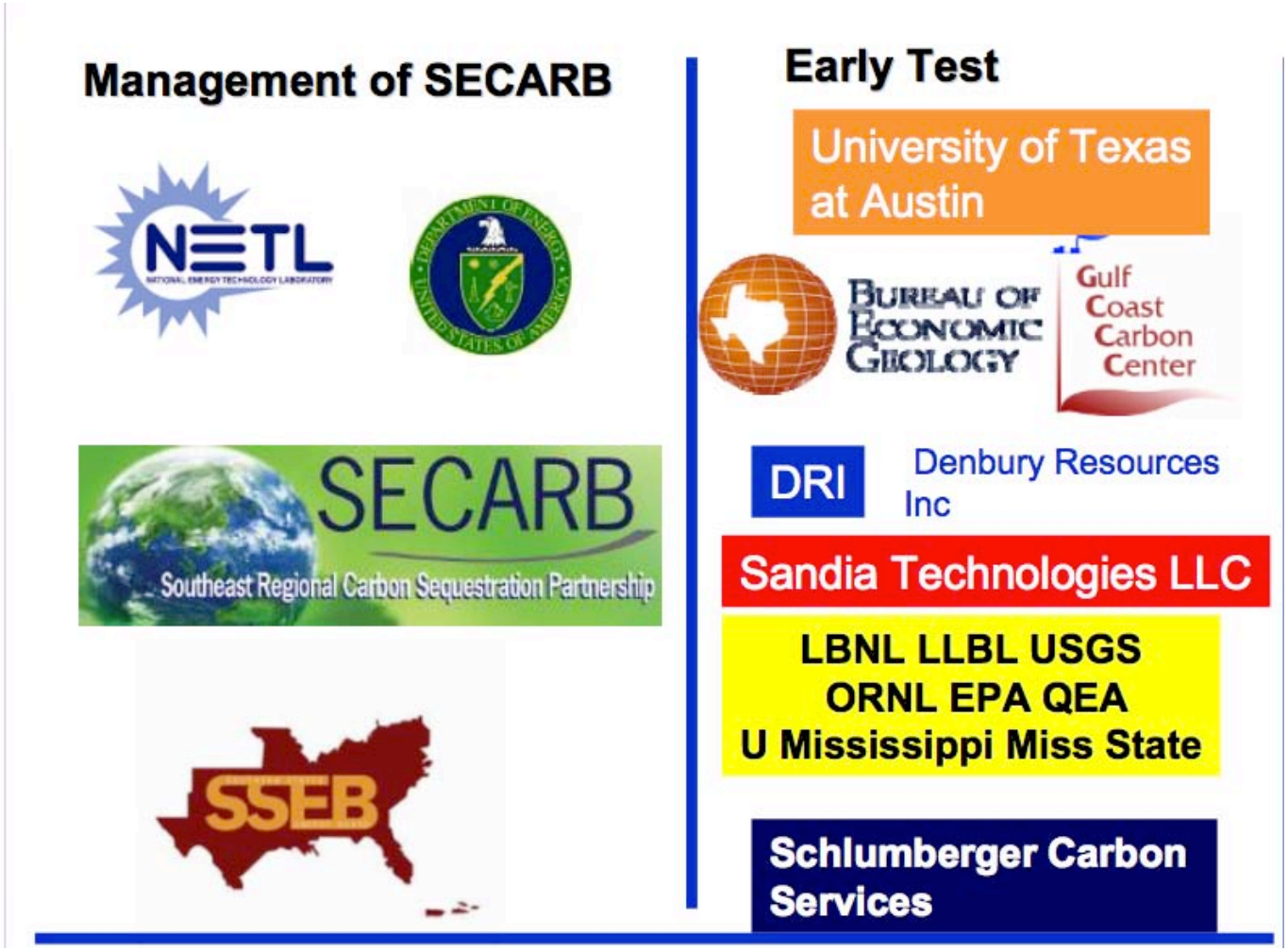
March 12, 2013

Acknowledgements

- This material is based upon work supported by the U.S. Department of Energy National Energy Technology Laboratory.
- Cost share and research support provided by SECARB/SSEB Carbon Management Partners.
- Anthropogenic Test CO_2 Capture Unit funded separately by Southern Company and partners.



Acknowledgements
Cranfield Eary Test (DAS Site)

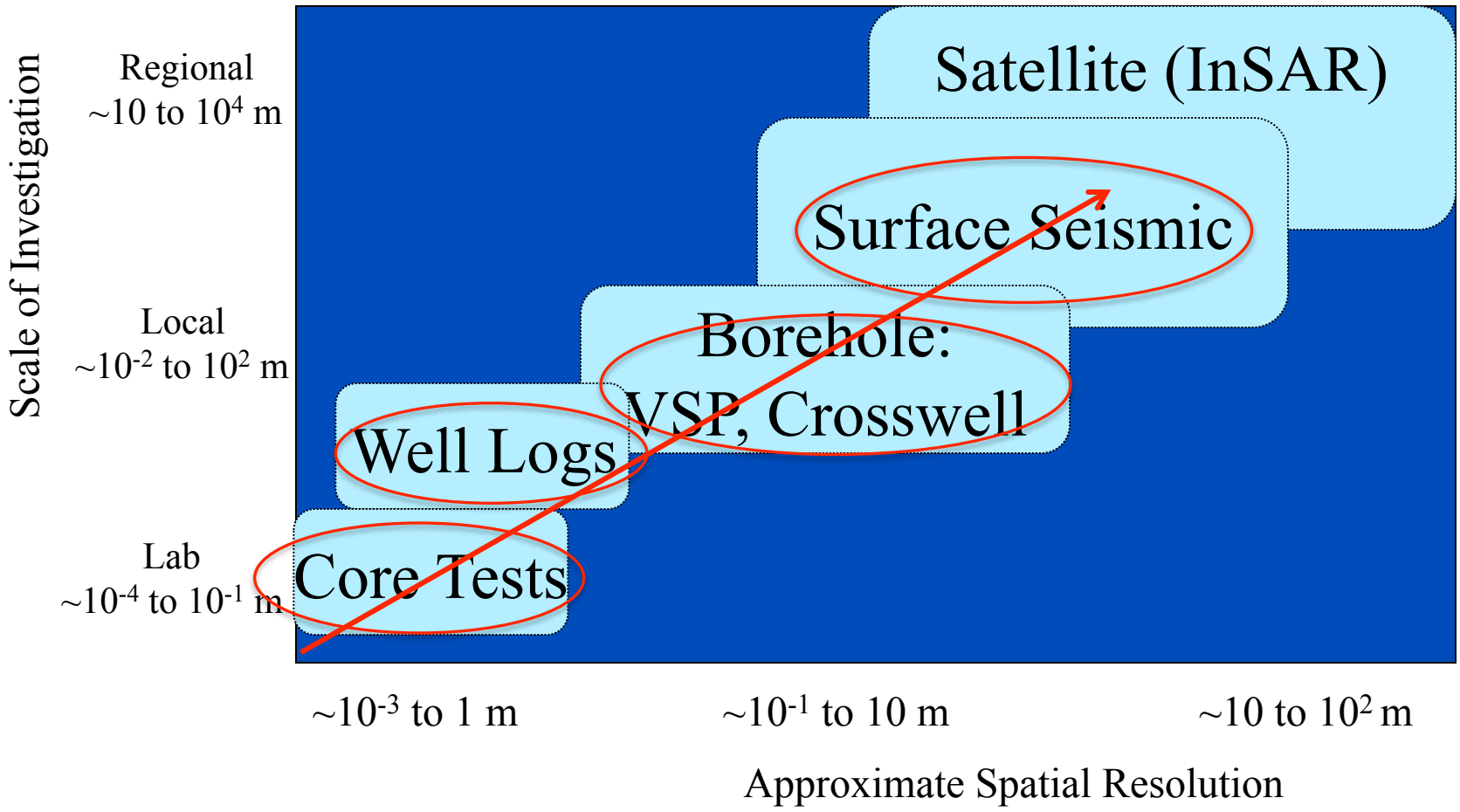


Outline

- **Overview of Project Design Concept**
  - Geophysical monitoring across scales
- **Specific and Integrated Monitoring Results**
  - Theory, Core Imaging and Measurements
  - Time Lapse Monitoring
    - ERT/Fluid Sampling/Detail Reservoir Model
    - Sonic Logging
    - Crosswell Seismic
    - Vertical Seismic Profile (VSP): Time Lapse
    - 4D Surface Seismic

Cranfield Monitoring:

We want to Integrate and quantitatively interpret geophysical data at varying scales



Acquired at Cranfield

Petrophysical Modeling of Tuscaloosa D/E:

Result: Predict ~ 300 m/s (9%) Velocity Decrease for CO2 Displacing Brine (no CH_4)

What affects the seismic response calculation?

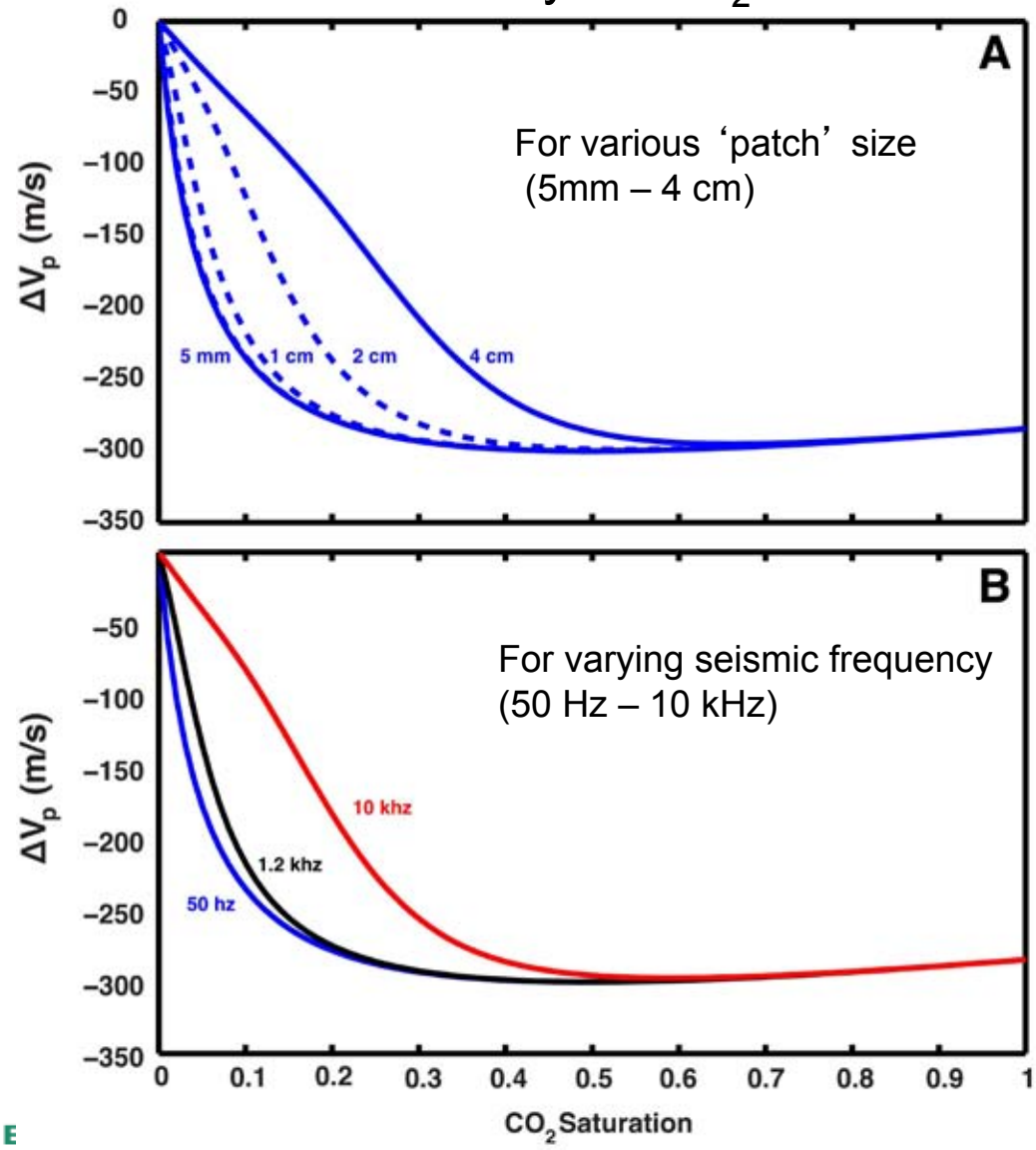
"Patch Size", Frequency,

pressure, temperature, brine properties, matrix properties (density, moduli of grains), clay percentage and clay properties, porosity, CO2 property model, CH4 property model

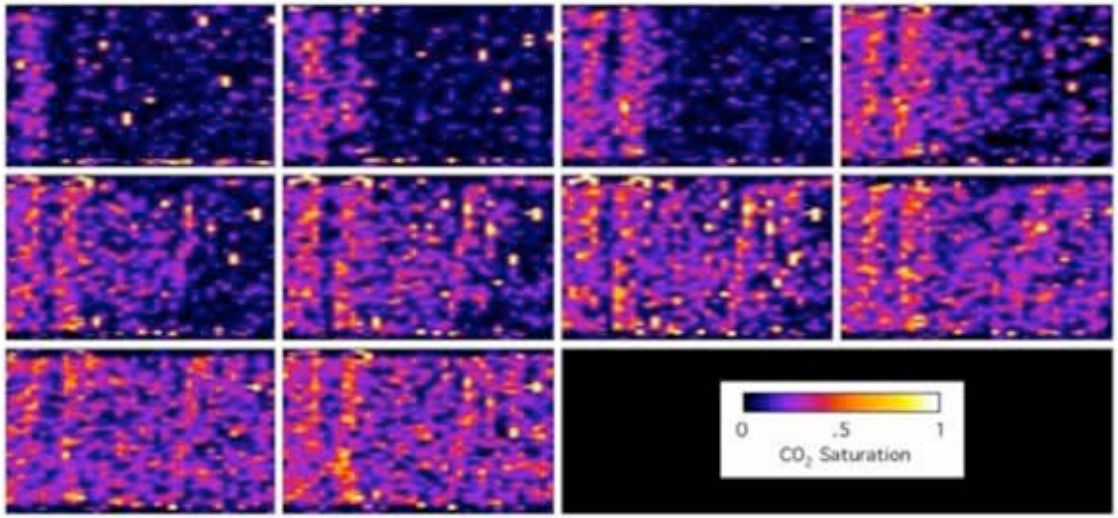
Variation within reservoir:
10470 ft core data predicts larger change than 10465' core.

Ajo-Franklin, et al, 2013 IJGCC, in press.

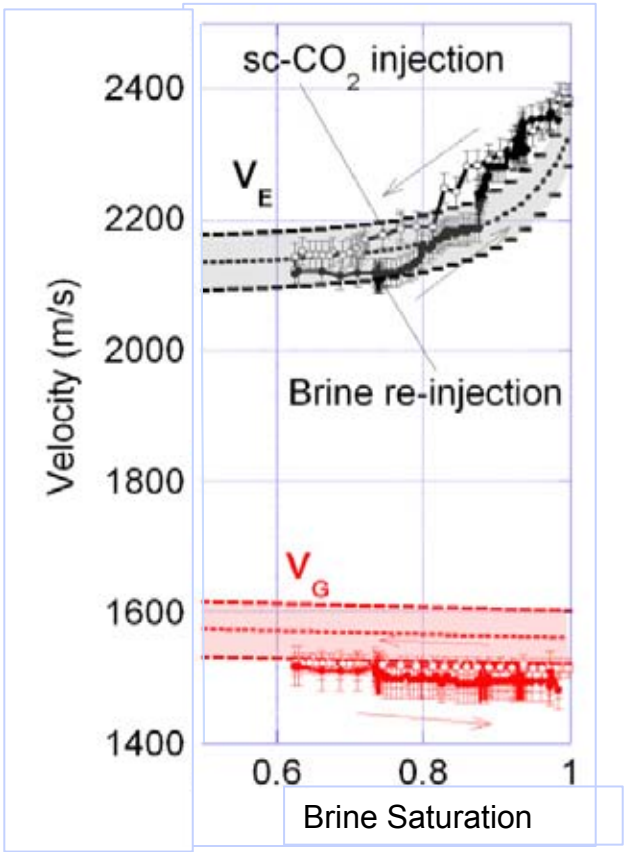
P-wave Velocity vs CO_2 Saturation



Tuscaloosa Core – Measurement of Fundamental Properties

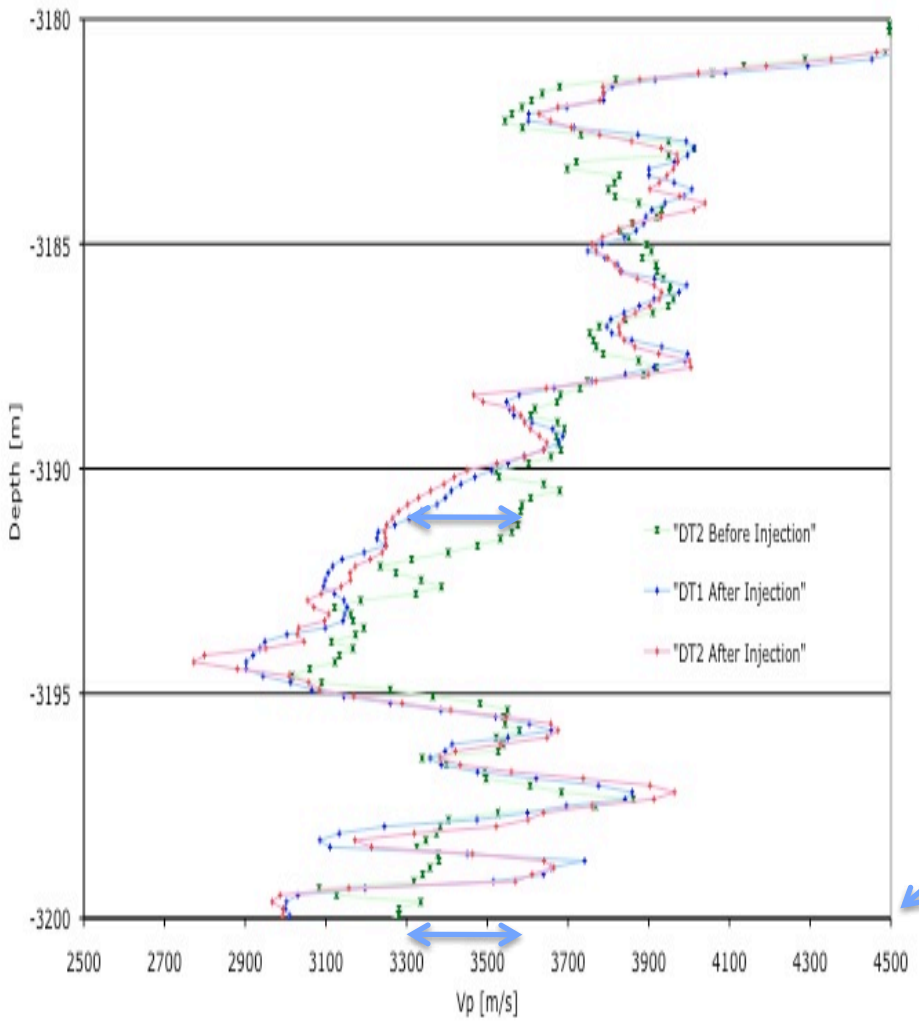


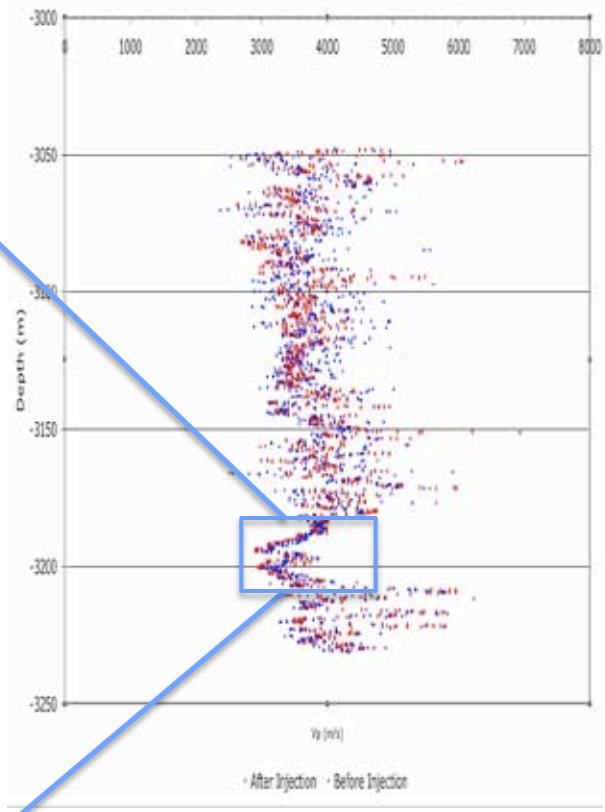
Nakagawa, et al, 2013,
Geophysical Prospecting



- **Results:**
- **Estimate ~ 300 m/s change in velocity**
- **Measure seismic velocity vs CO_2 saturation**
  - **Estimate patch size (~1 cm) limited by core size (~2 cm)**
- **Strong structural anisotropy of the rock**

Well Logging Scale: Time-Lapse Sonic Log 31-F2





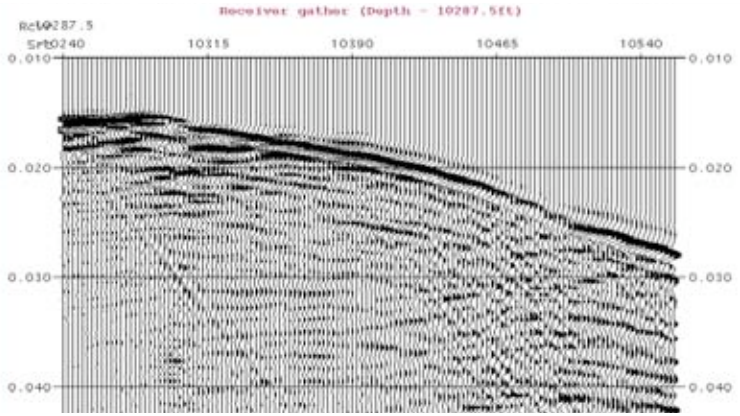
Result:
~250 m/s decrease in Seismic velocity

Schlumberger: Data and Processing

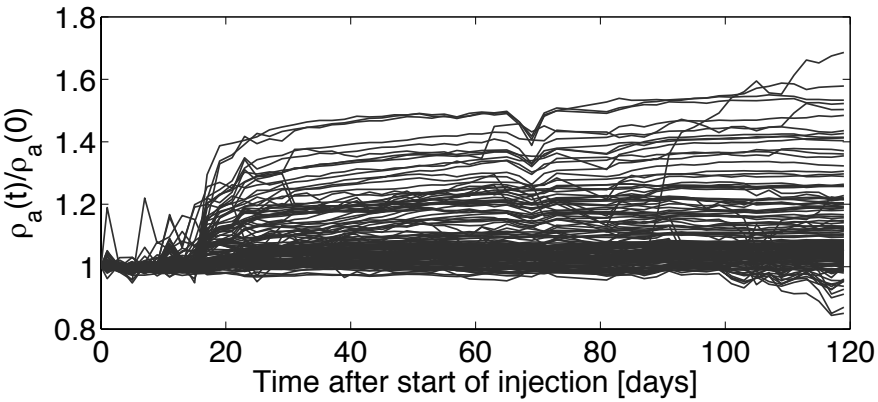
Crosswell Scale: Seismic and ERT Data

- **Crosswell Seismic data**
  - — **Baseline and post-injection (9 months after start of injection)**
  - — **Best data set between F2-F3**
- **Electrical resistance (ERT) data**
  - — **21 electrodes in F2 and F3**
  - — **Continuously acquired data for 300 days**
    - **Best-quality data for first 120 days of injection**

Crosswell Seismograms



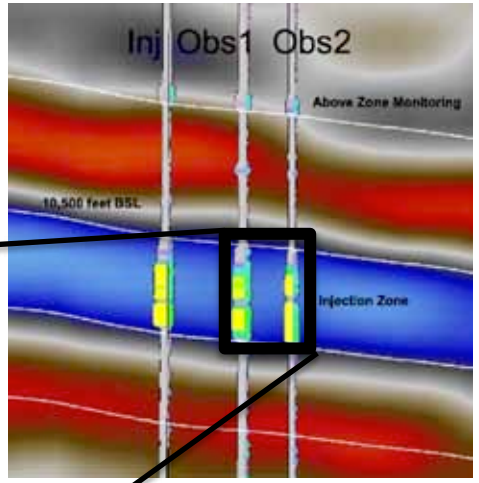
Crosswell Resistivity

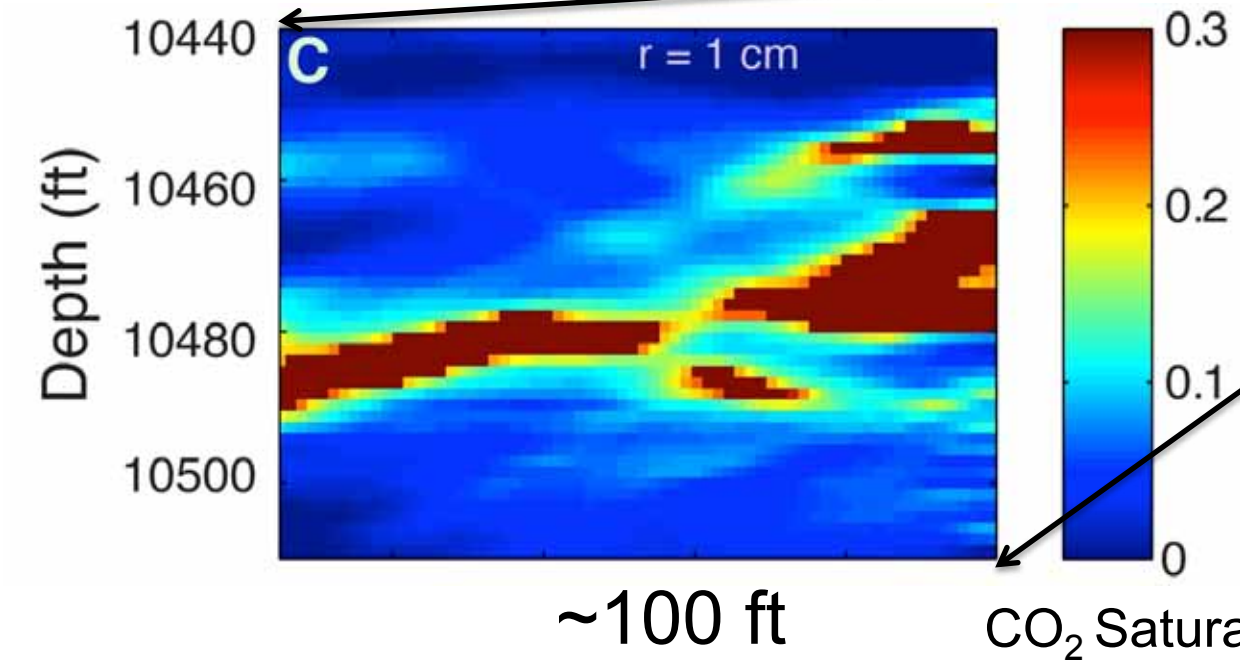


Time Lapse Crosswell Seismic Result: Maximize Resolution of CO2 Saturation

- 'Compactness' Constraint on Inversion:
- Very high resolution, but still have uncertainty converting to saturation
- 'Patchy' Model (use 1 cm patch size)

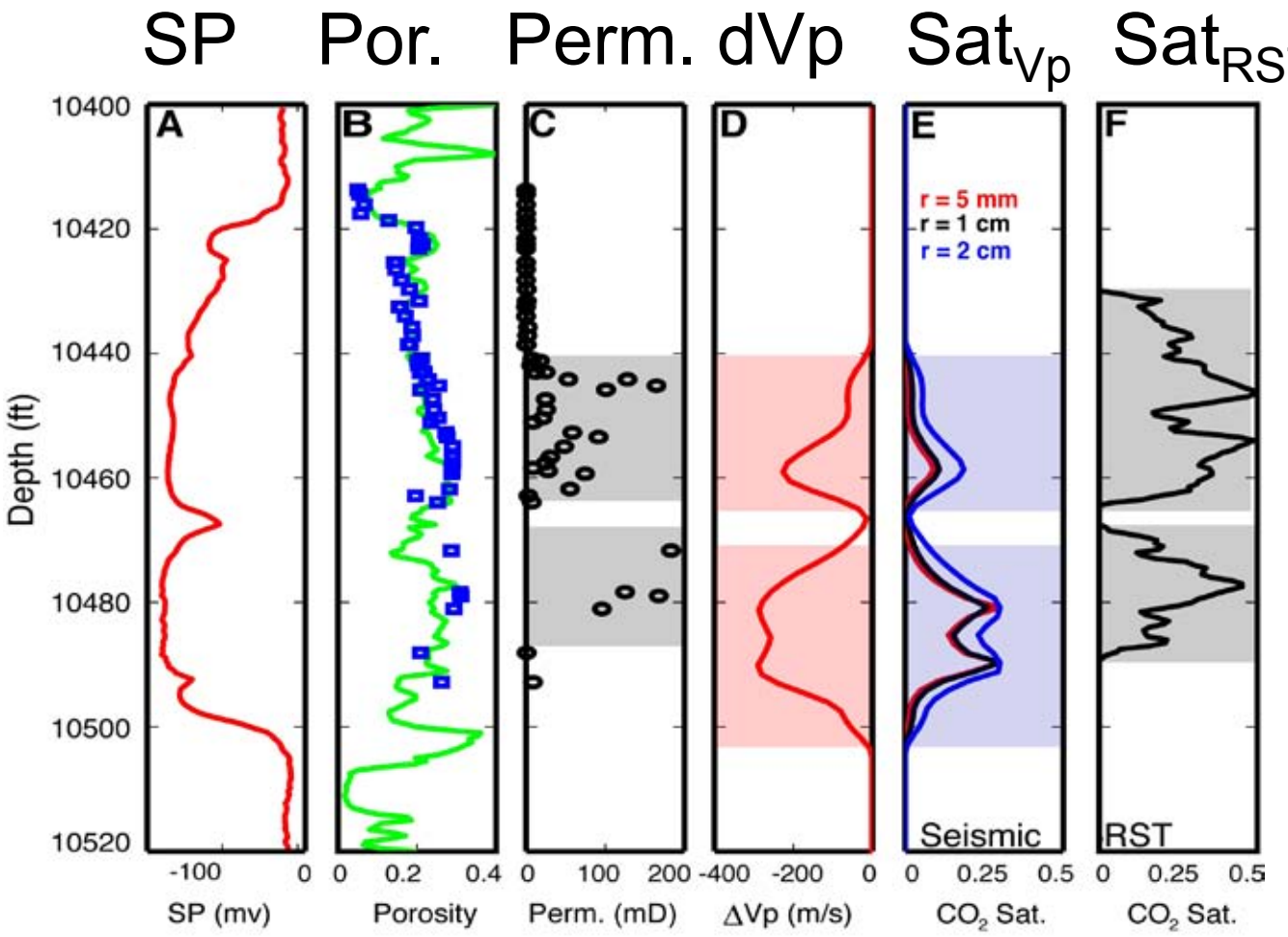
Surface Seismic





Ajo-Franklin, et al, 2013 IJGCC, in press.

Comparison of Data (Core, Log, Xwell)

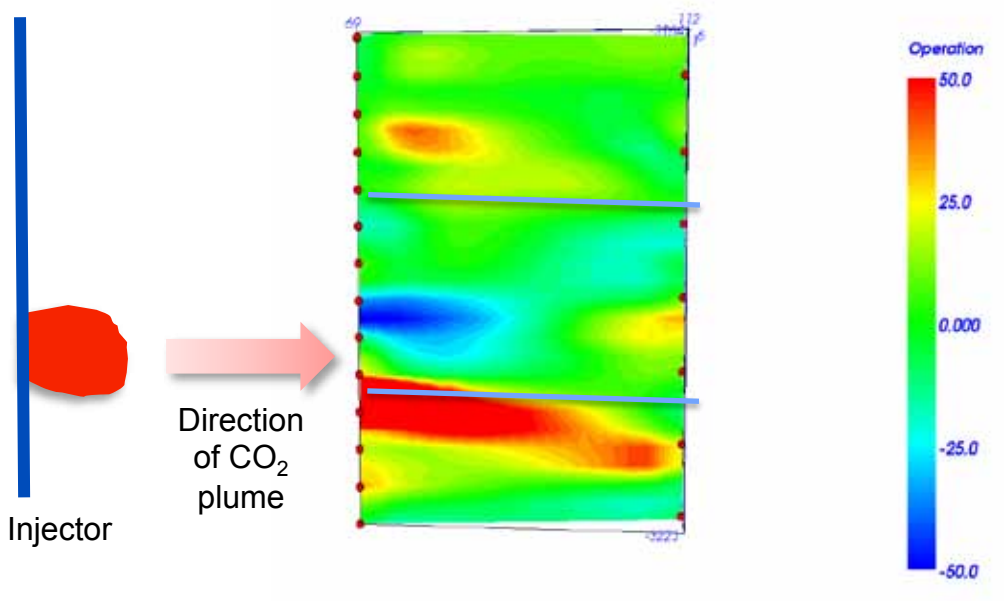


Ajo-Franklin, et al, 2013 IJGCC, in press.

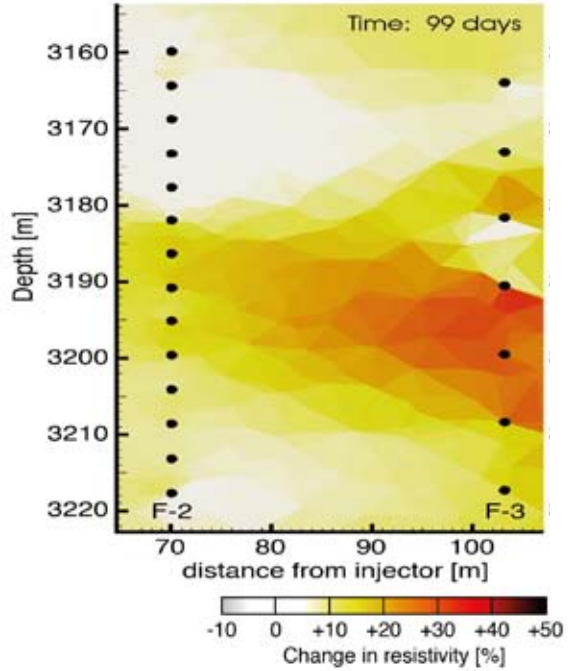
Time-Lapse Electrical Resistance Tomography (ERT)

Result:

- Real-time monitoring
- Data processing improved estimate of time-lapse change



Carrigan, et al, 2009; CCS conference.



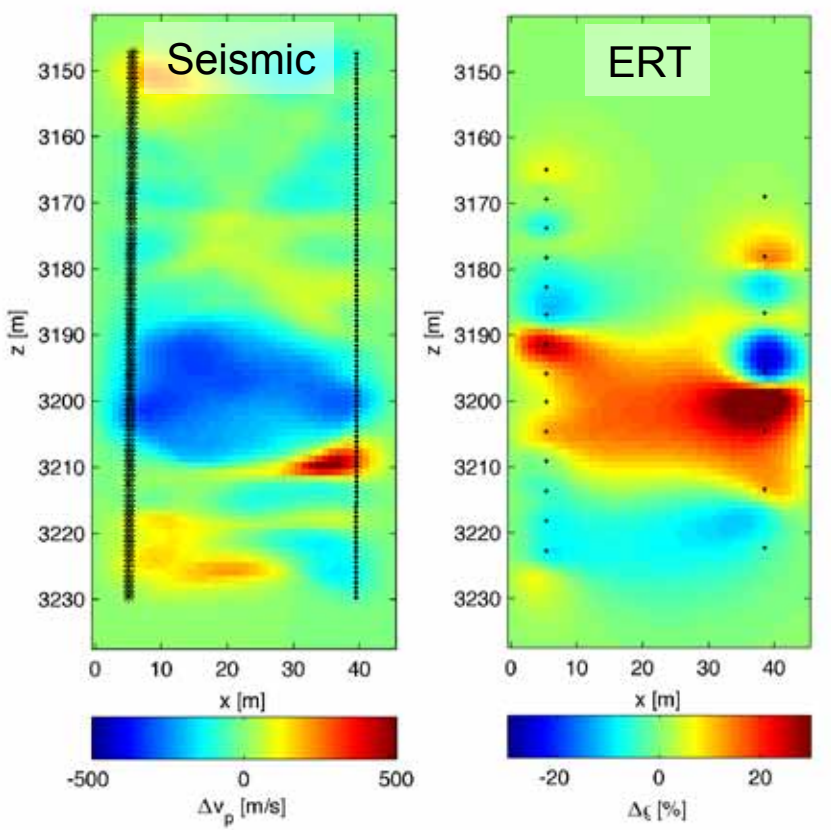
Doetsch, et al, 2013, IJGCC Submitted

Latest Results: Carrigan, C.R., Yang, X., Labrecque, B., 2013. ERT monitoring at the Cranfield CO2 injection site. Int. J. Greenh. Gas Control,

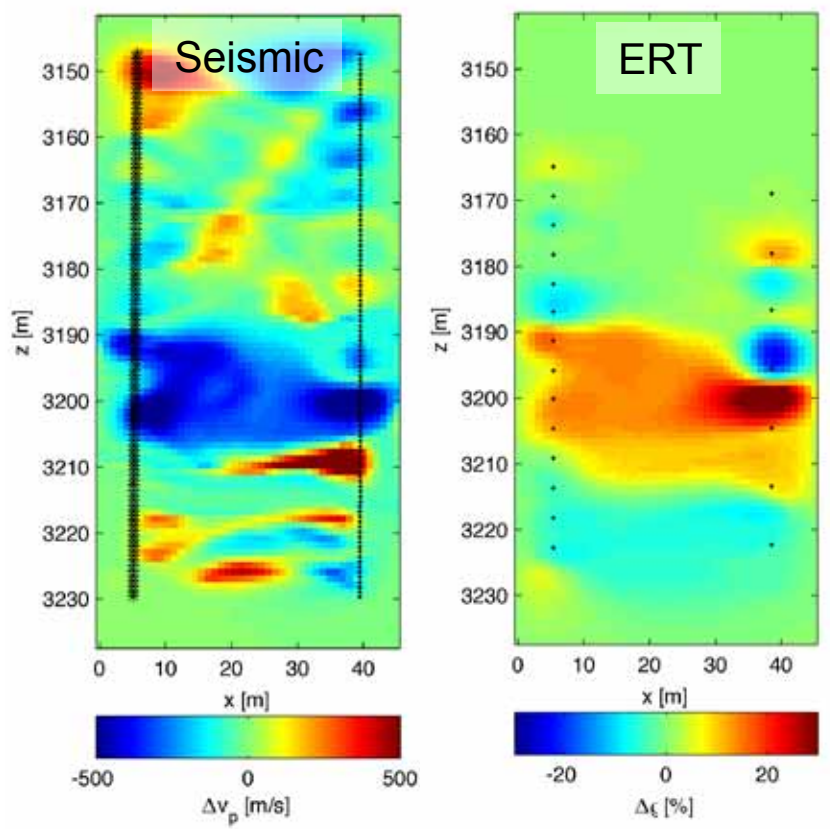
Individual and Joint time-lapse Seismic and ERT inversion

- **Invert for change in seismic velocity and in resistivity (same author)**
- **Result: model that 'best' fits both data sets – est. saturation 7-15%**

Individual inversions



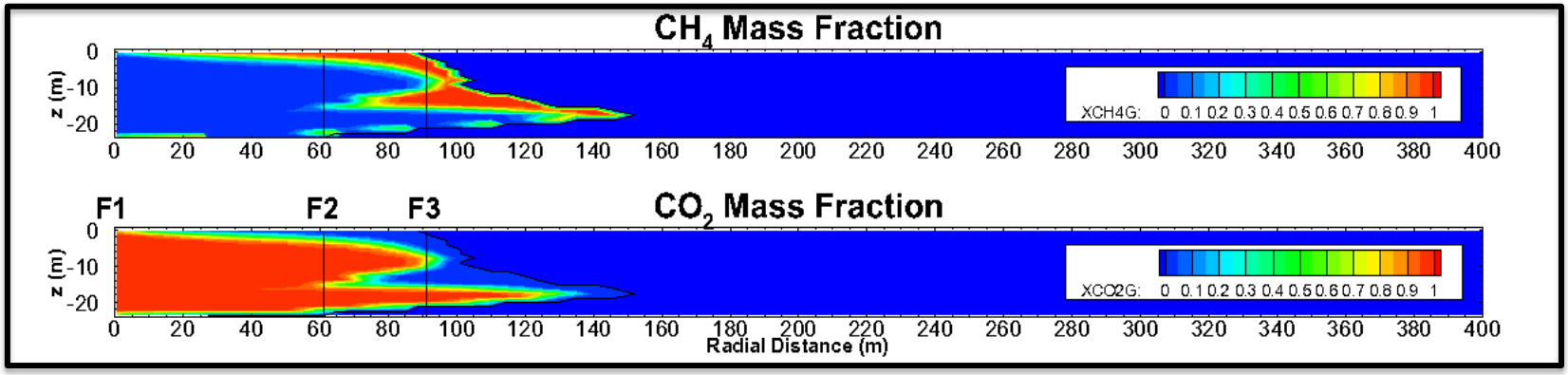
Joint inversion

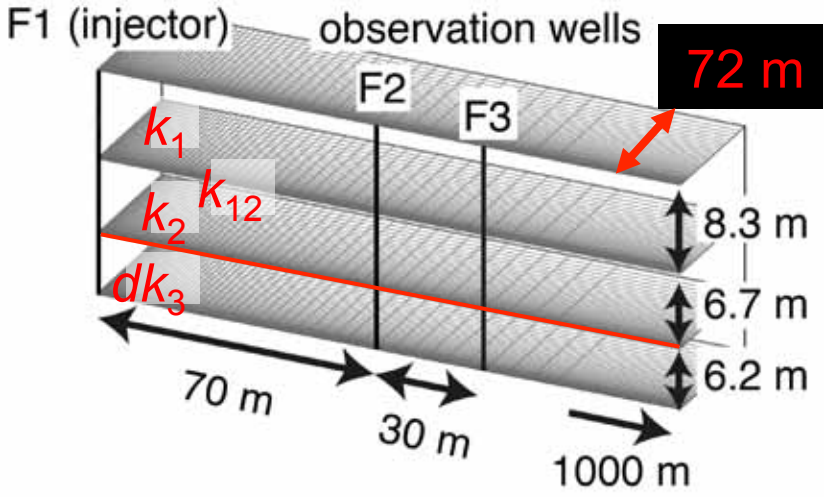


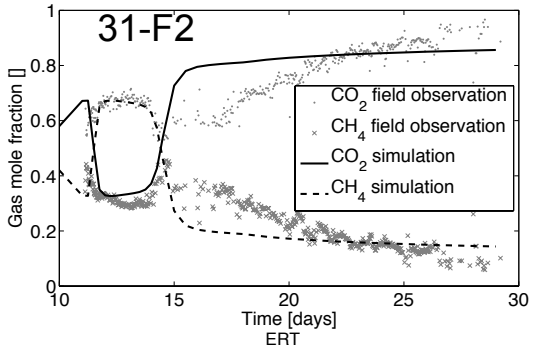
Doetsch, et al, 2012, AGU Annual Meeting

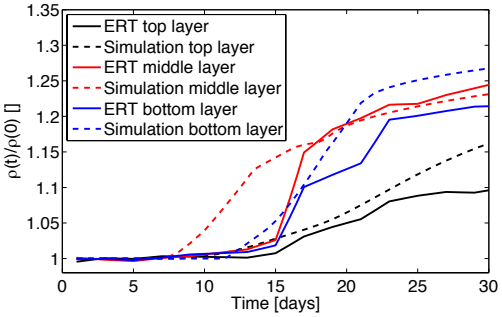
Joint Inversion of Gas Breakthrough and ERT using Detailed Reservoir Model

Model at 60 days (C. Doughty LBNL)









Result: Estimate 72 m wide channel.

Doetsch, et al, 2013, IJGCC Submitted

Vertical Seismic Profile (VSP)

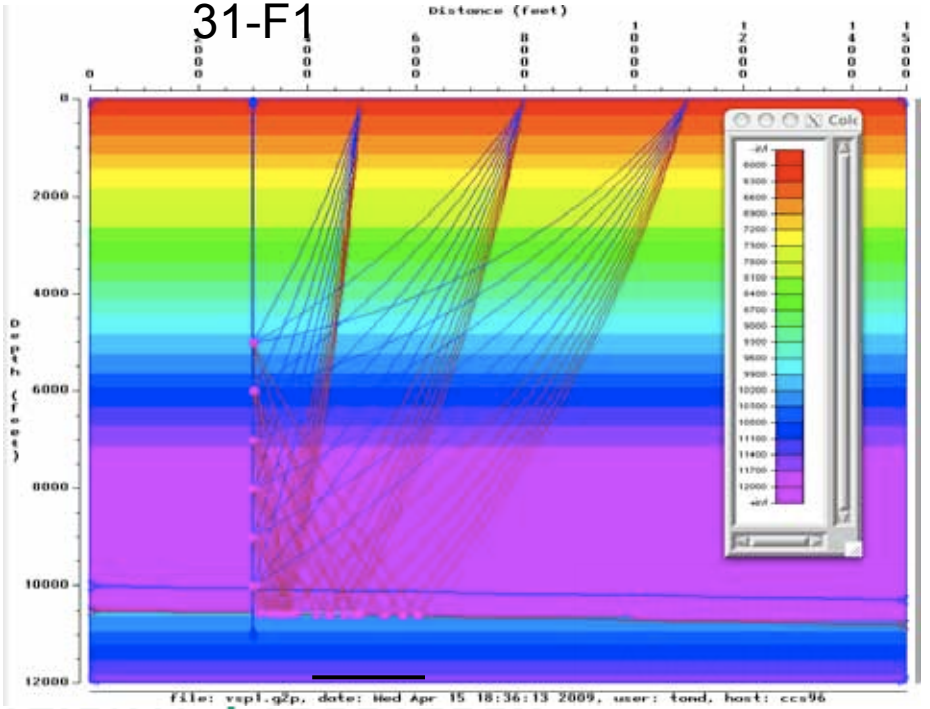




- 2 Surveys:
  - Time-Lapse OVSP 2009/2010
  - 3D-VSP 2010

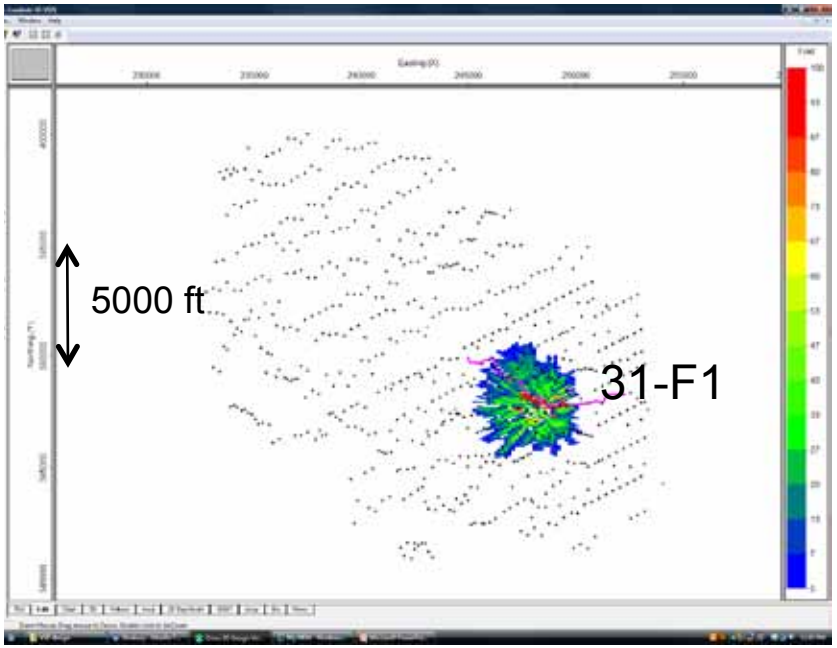
Design Modeling

31-F1



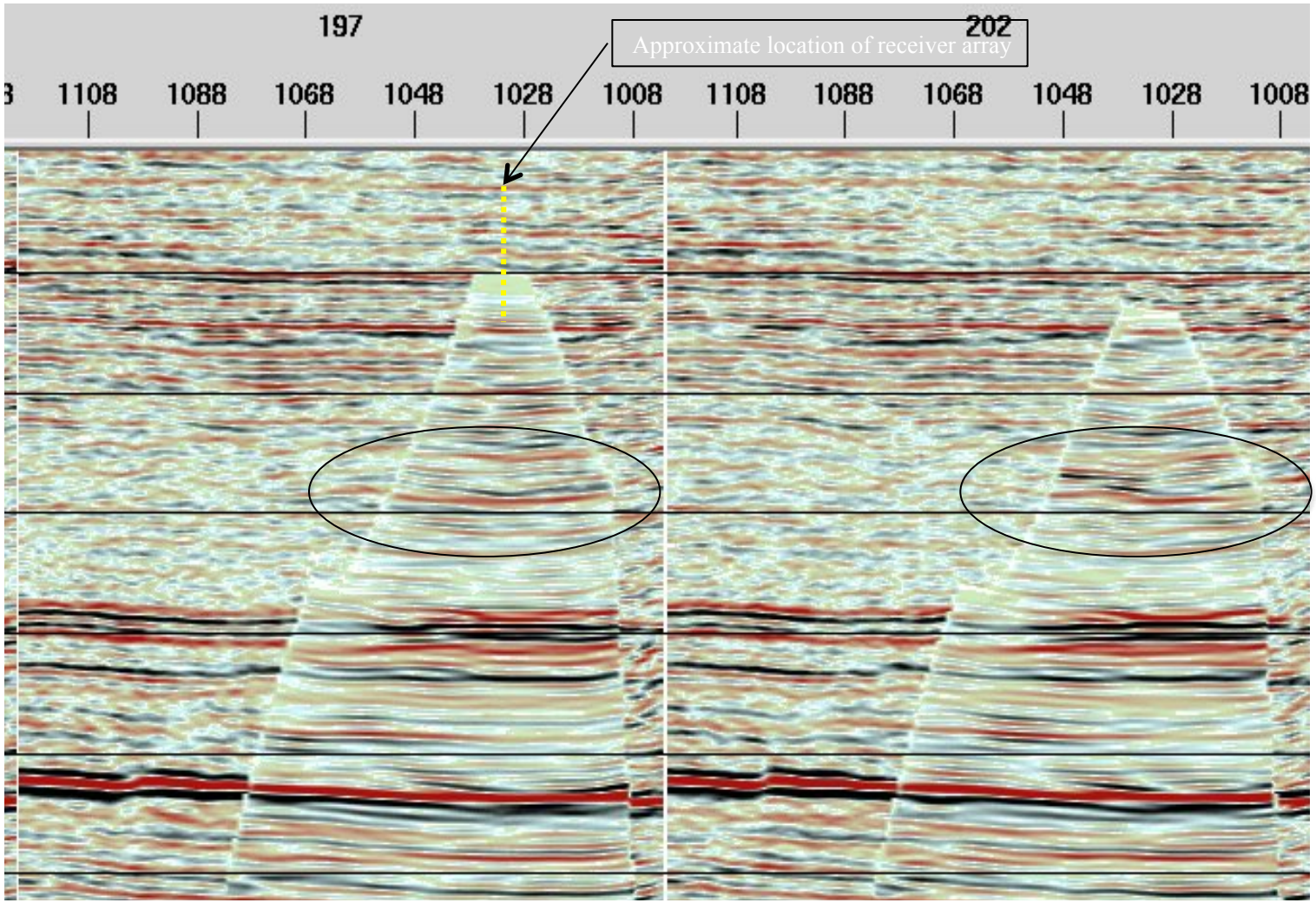
3D-VSP (~750 source points)

- **Resolution quantification for seismic data (3D-VSP)**
  - —Acquire and analyze 3D VSP at Cranfield to compare/quantify spatial resolution with 3D surface seismic
  - —Supported by DOE's NRAP Program



Plan View

3D-VSP and Surface Cube

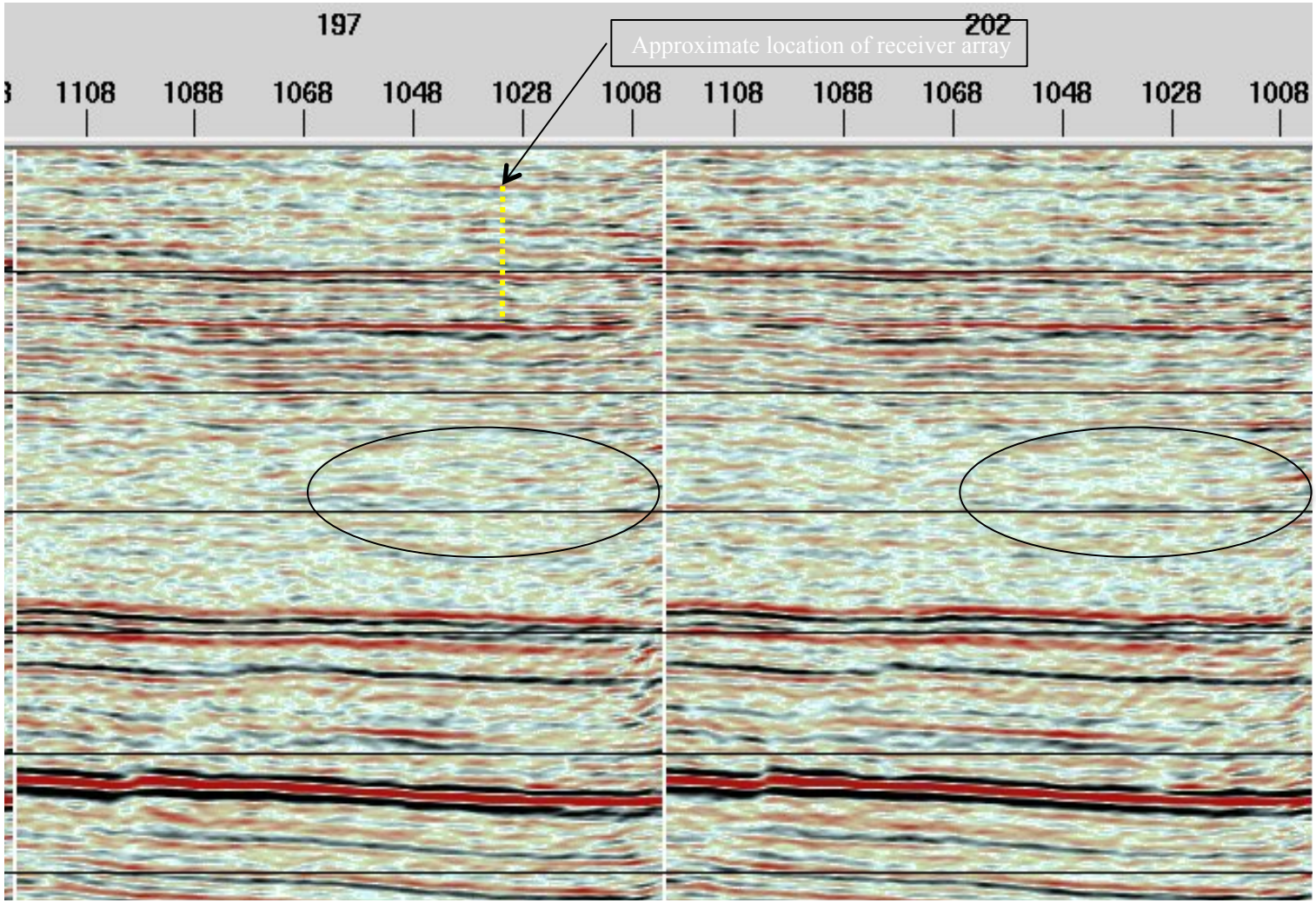


Reservoir

Result: Improved image near well

-20 msec time shift applied to match surface data

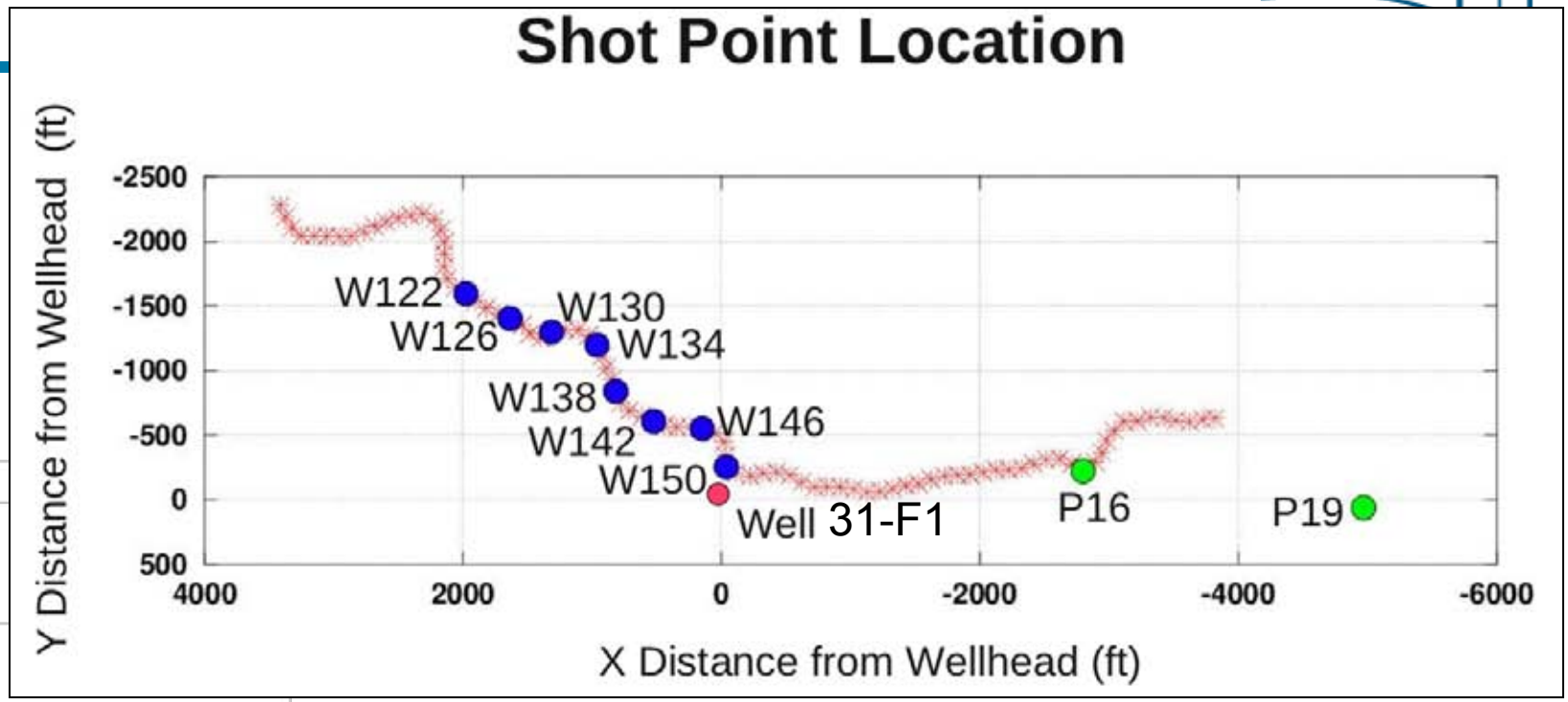
Surface Seismic

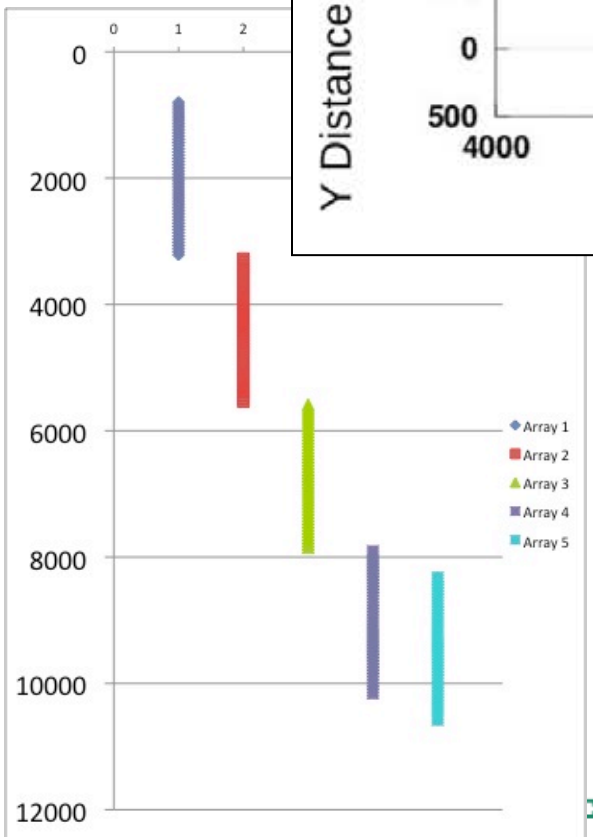


Reservoir

Result: Improved image near well

Time Lapse Offset VSP at 31-F1

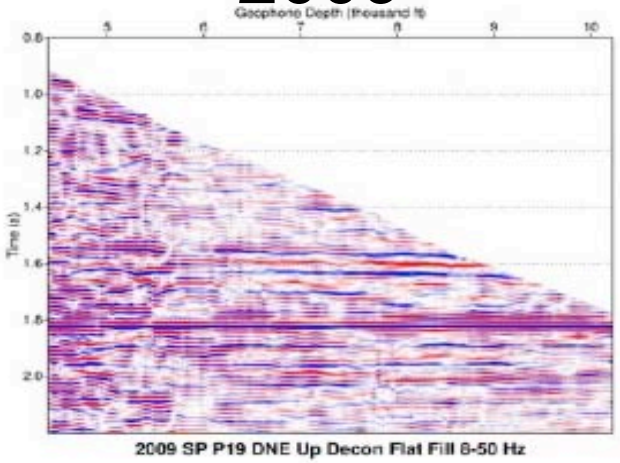




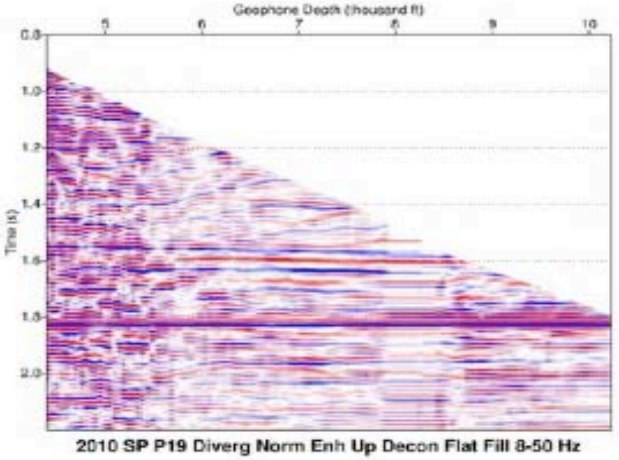
Well 31-F1 Sensor Depths – 50 3C levels per 'toolstring' Most Source Points only had 2 toolstrings recorded

OVSP: Example Shot Point
Result: Change in zone – but 'noisy'

2009

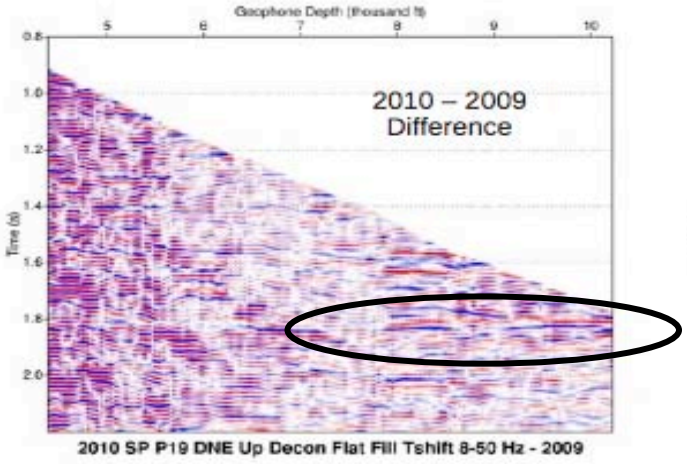


2010

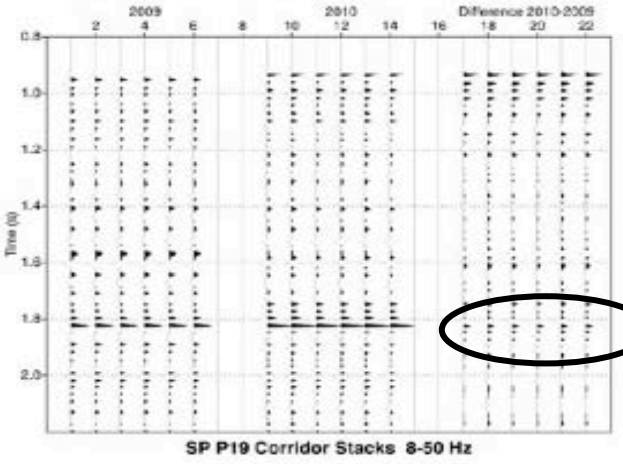


Reservoir

Difference

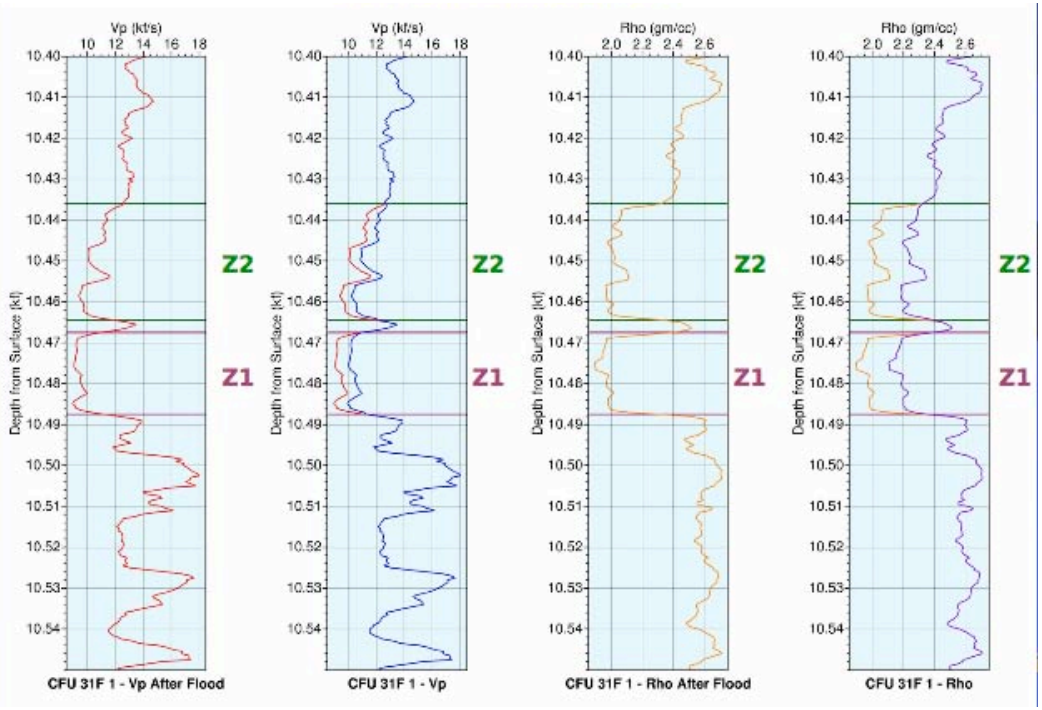


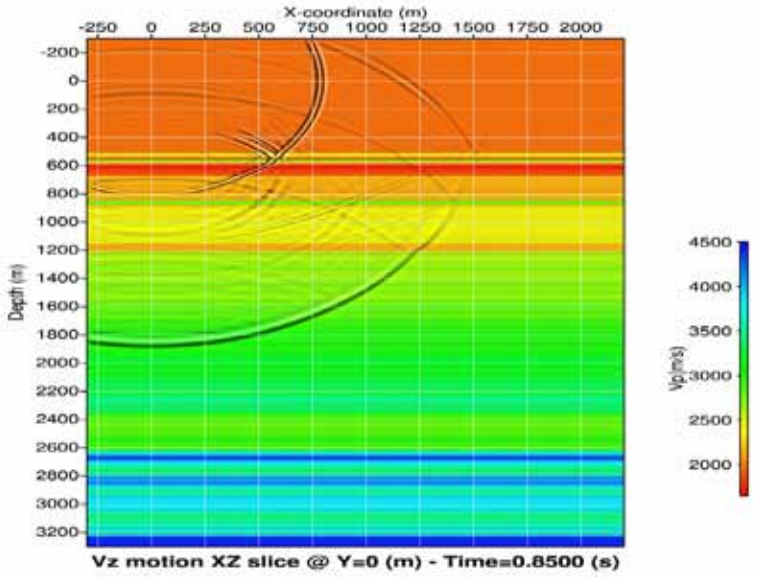
Corridor Stack

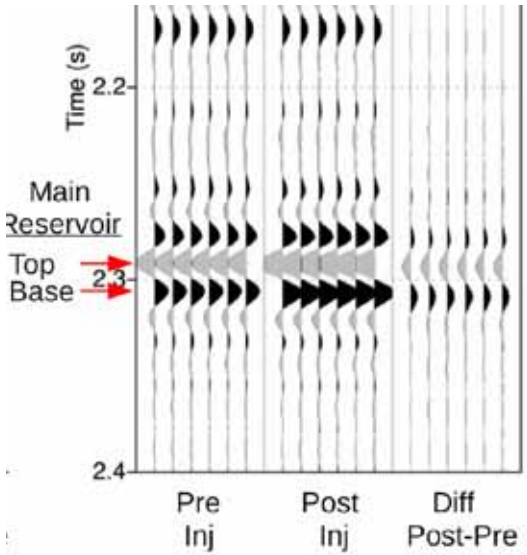


Difference

Integration: Use Logs and Crosswell results to model VSP



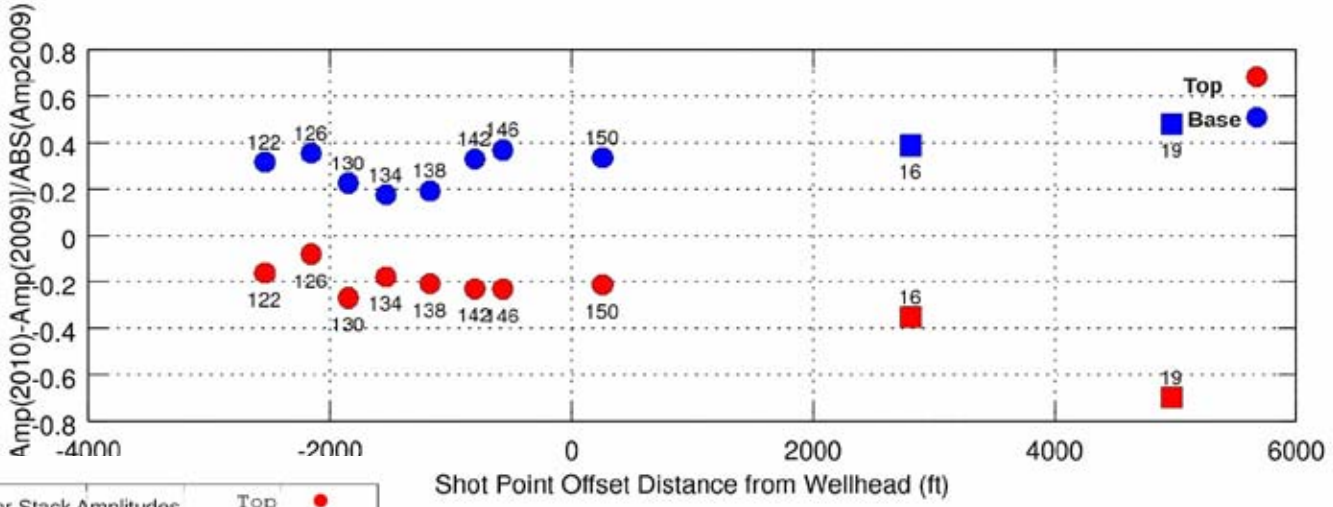


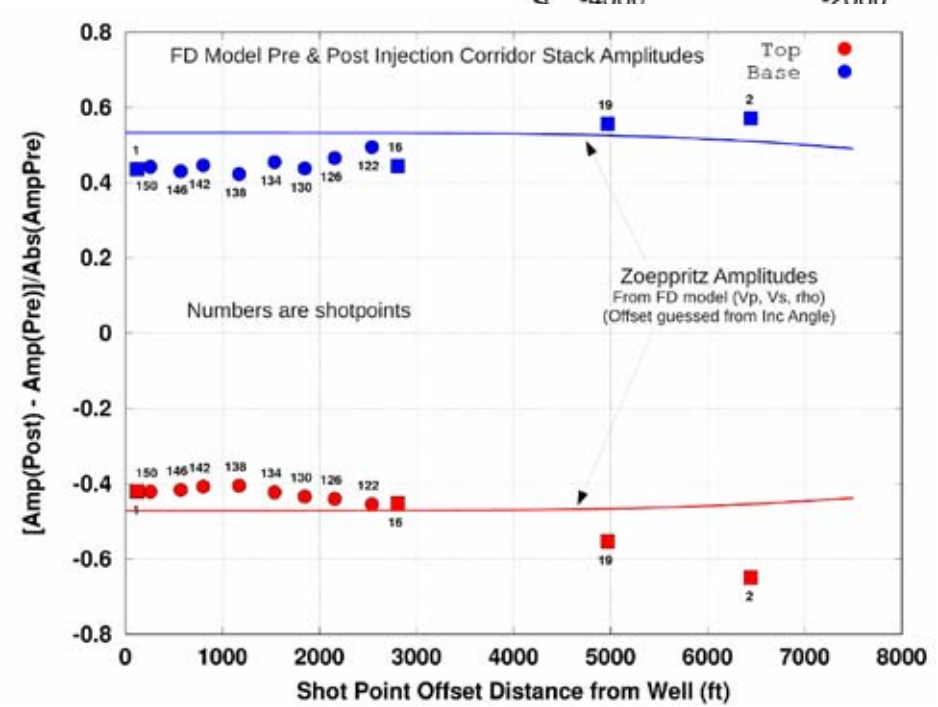


Modeling Result:
Should see separate response from top and base of reservoir

Result: Data matches Model

Data





Model (and theory): Expected change in amplitude

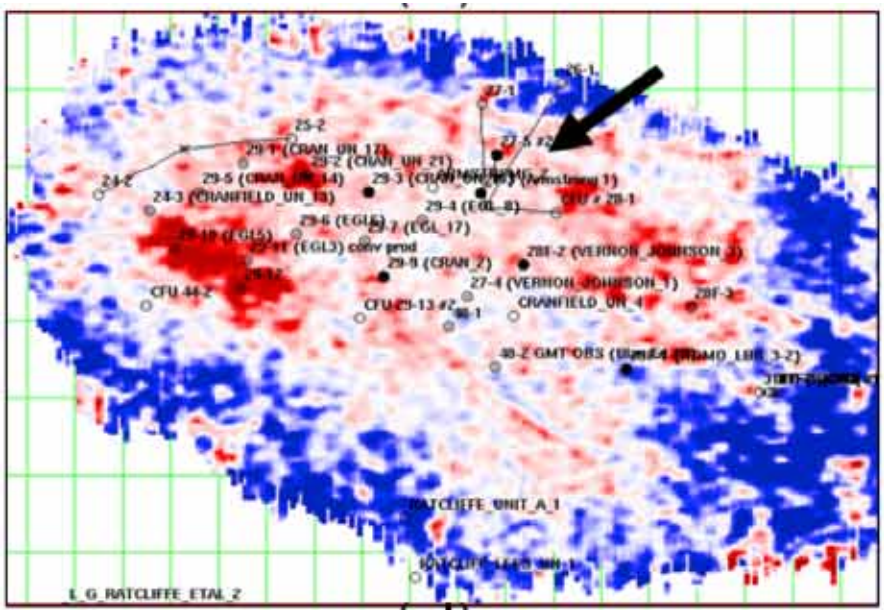
VSP Conclusions

- Change in reflection amplitude for both top and base of reservoir is indicator of CO2 despite poor T.L. repeatability
- Corridor stacks are robust and consistent, but seeing lateral variation is hampered by poor repeatability
  - —Time Shifts variable with depth – *'ignore' time shift*
- Modelling based on observed change in crosswell velocity tomography agrees with field data
  - — model used post injection with larger change than actually observed, and has larger amplitude change than field data
- ***Time Lapse VSP result (data and modeling) could be used to aid interpretation of 4D seismic***

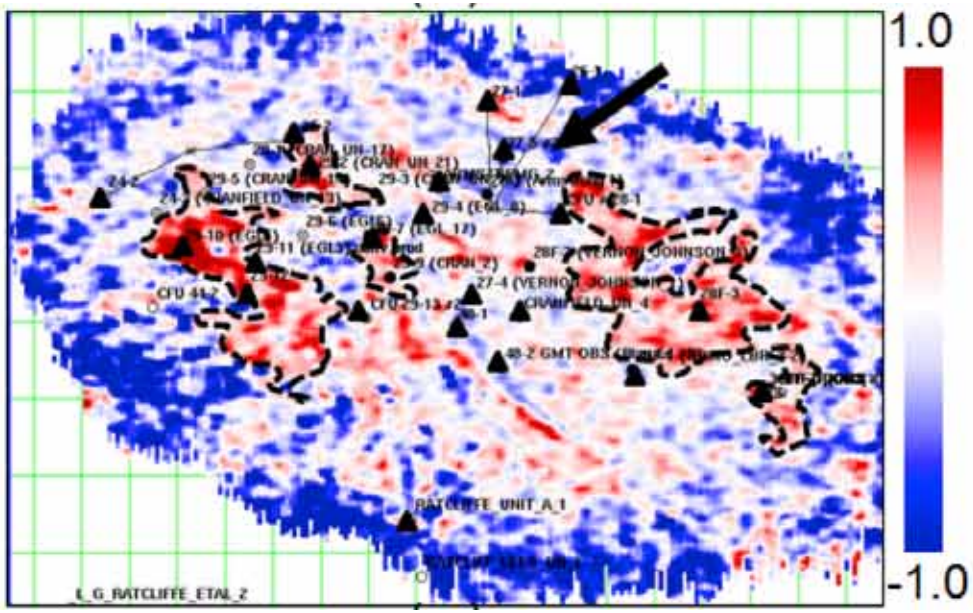
4D Surface Seismic

- **Continued reprocessing to improve result**
- **<u>remove time change</u> to improve amplitude change**

Before



After



Rui Zhang, UT Austin, now at LBNL

Summary and Conclusions

- Multiple monitoring techniques tried at Cranfield DAS site
  - R&D testing not commercial application
- Crosswell seismic has provided high resolution estimate of CO2 saturation distribution
- Multiple data sets are integrated to find a 'best fit' solution for CO2 saturation
  - Seismic, ERT, U-tube fluid sampling, reservoir model
- VSP has determined magnitude of reflection change
  - Detect CO2 and tie to model
  - Repeatability too poor for mapping
- Data integration
  - improve confidence in results
  - Improve saturation estimate
- At 4D surface seismic can detect and map CO_2 induced changes, but – not yet saturation
  - 4D seismic is improving and still has potential improvement from VSP and other smaller scale studies
- **Goal for Future Work: Improve ability to estimate saturation from 4D surface seismic**

Schlumberger
Carbon Services



Review of the Petrophysics for the Cranfield Phase III Project

Michael Carney – Subsurface Technical Manager

Schlumberger Carbon Services

12 March 2013

Schlumberger
Carbon Services

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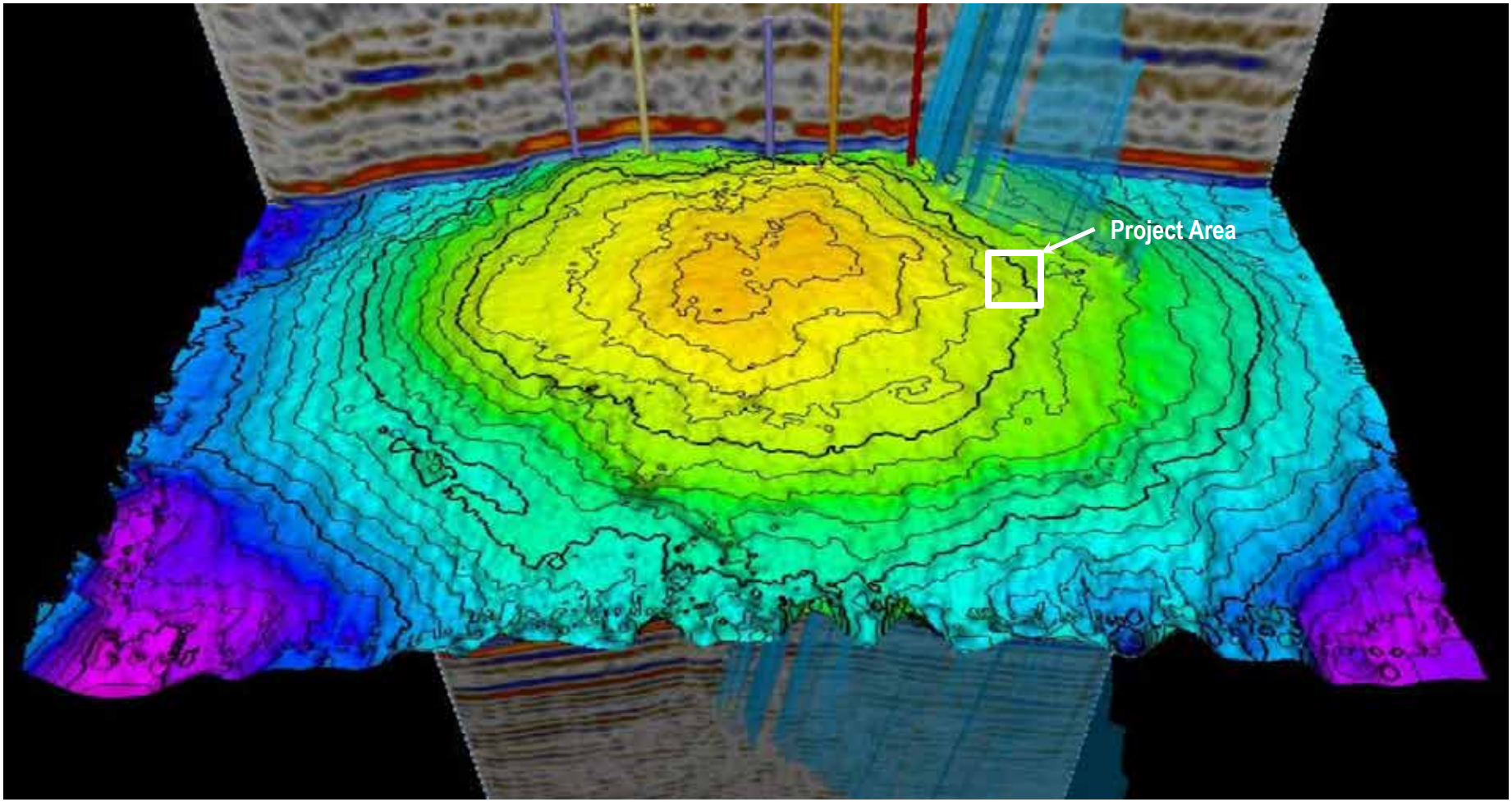
Presentation Overview

Schlumberger
Carbon Services

- Project Overview
- Summary of Data
- Interpretation Results
- Discussion on the Integration, Results and “What it all means”

Regional Overview of Cranfield

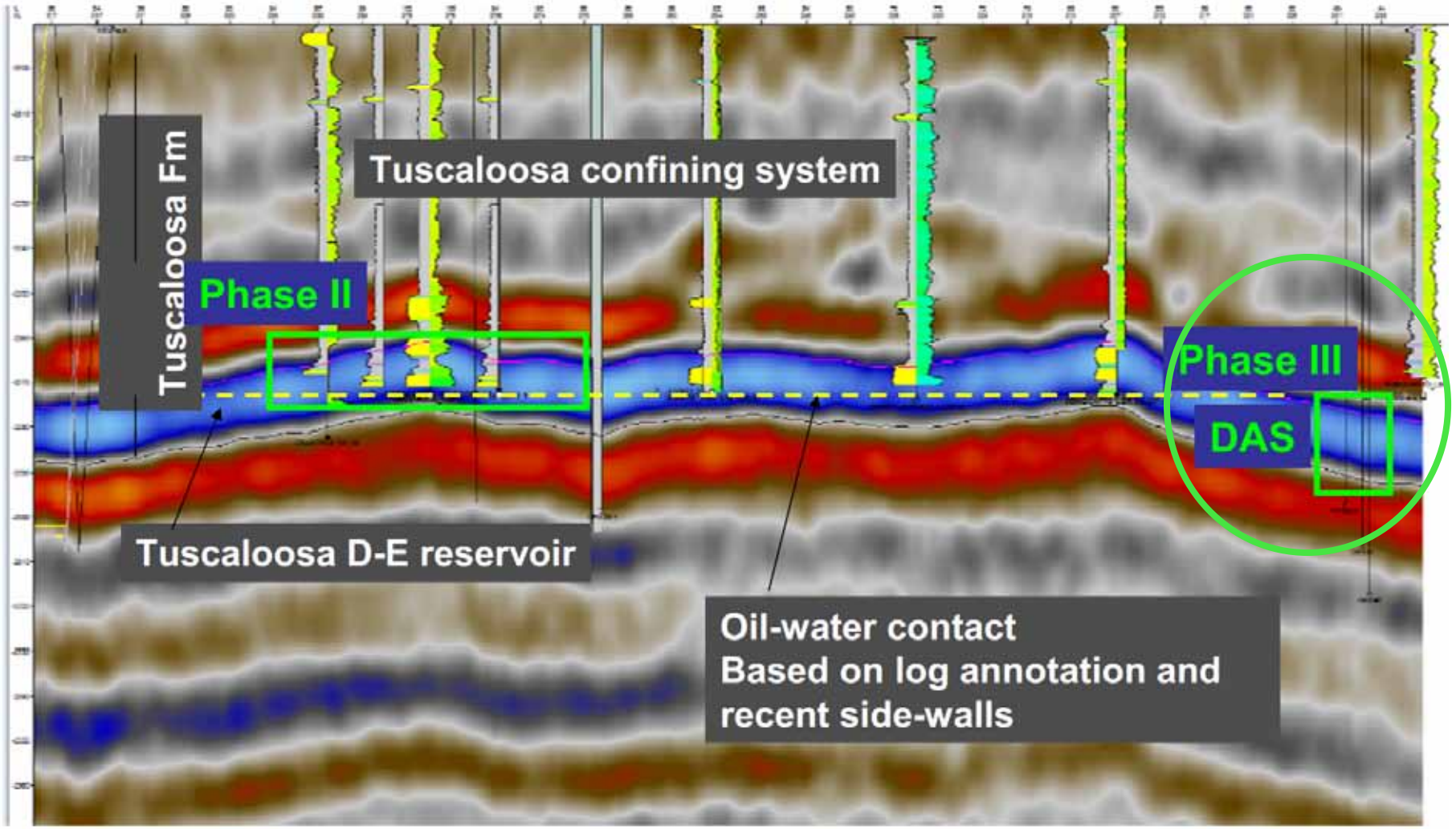
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Cranfield Cross Section

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Carbon Services

West East

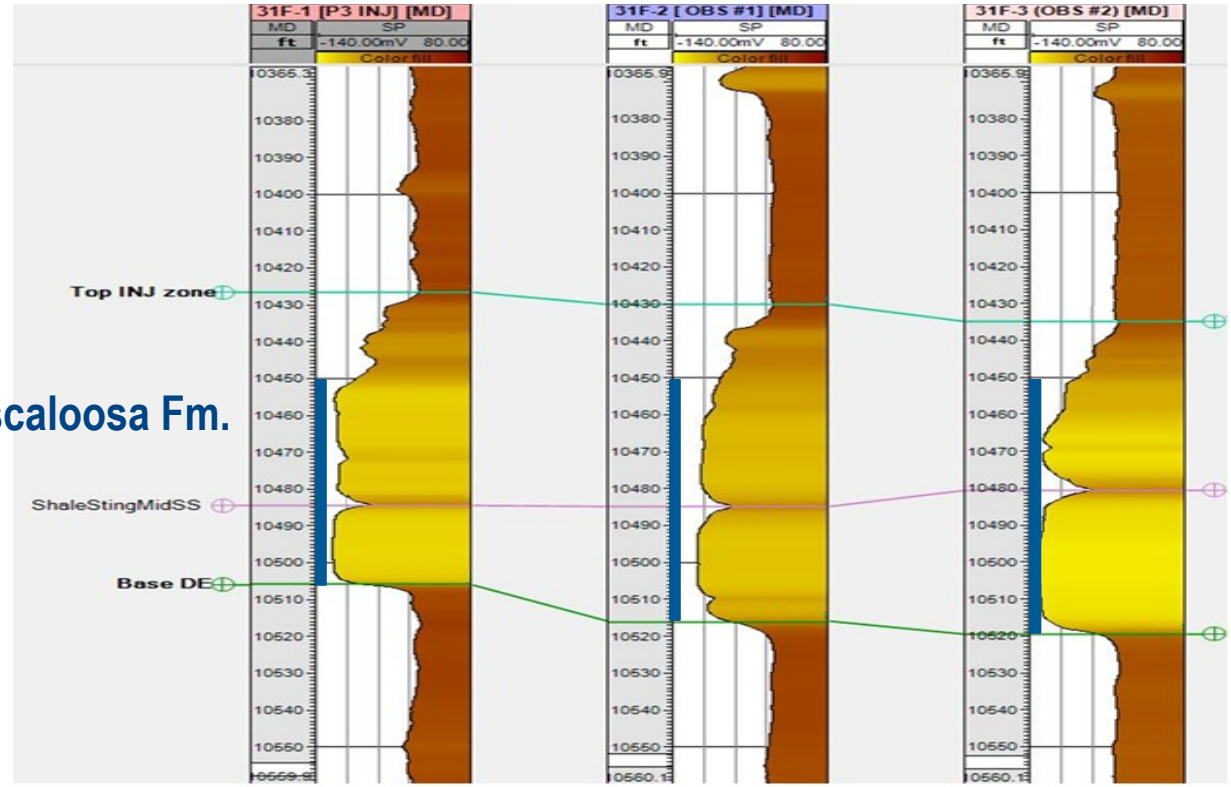


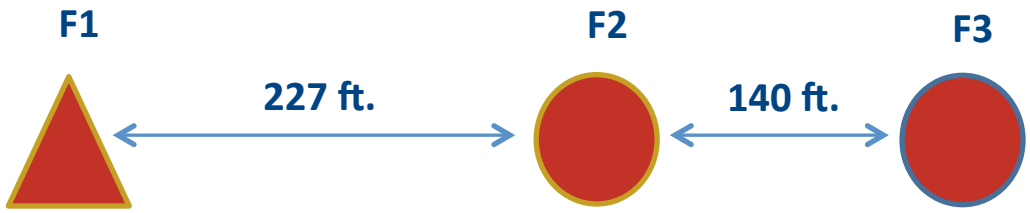
CFU Detail Area of Study Well Configuration

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West

East





F2 & F3 are 2° down dip of F1

Logging Program – Cranfield Phase III DAS

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Openhole Logging:

	CFU 31 F#1	CFU 31 F#2	CFU 31 F#3
Date	Jun 6, 2009	Aug 18, 2009	Jul 10, 2009
Logs run	Platform Express* Sonic Scanner*	Platform Express CMR*, Sonic Scanner	Platform Express Sonic Scanner
Other data		Core	Core

Cased Hole Logging:

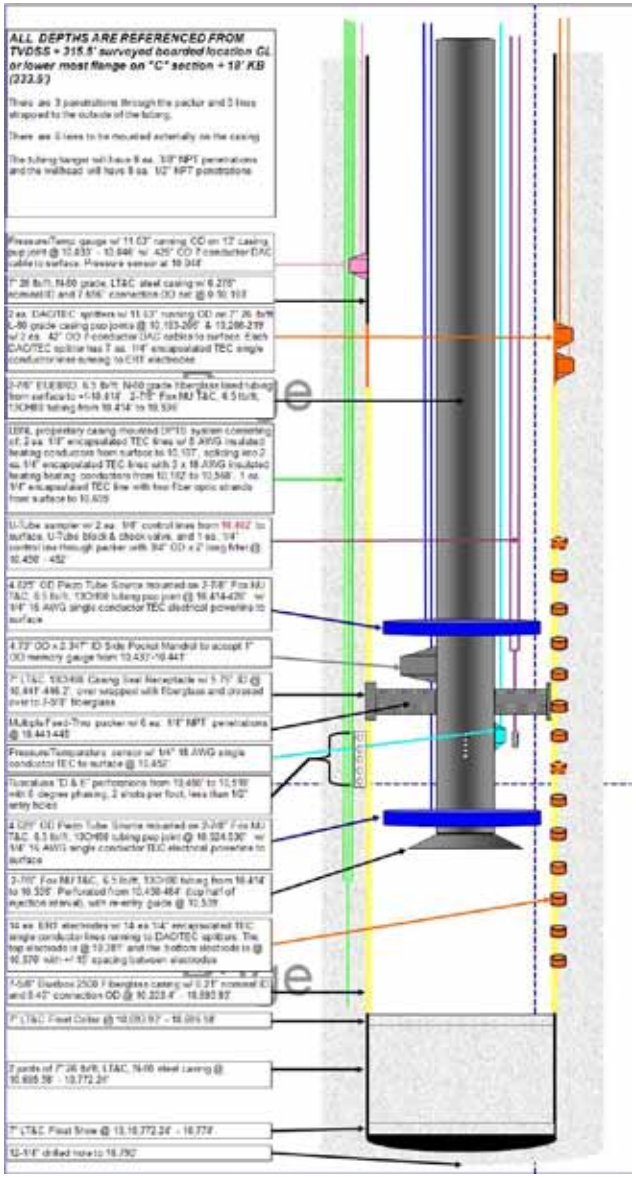
A base RST* reservoir saturation tool log was run in all 3 wells. Starting on 12/1/09, 250 tons/day of CO_2 were injected into F1. On 12/19/09 the rate was increased to 500 tons/day. Injection continued for nine months. RST logs were made during the injection period as follows:

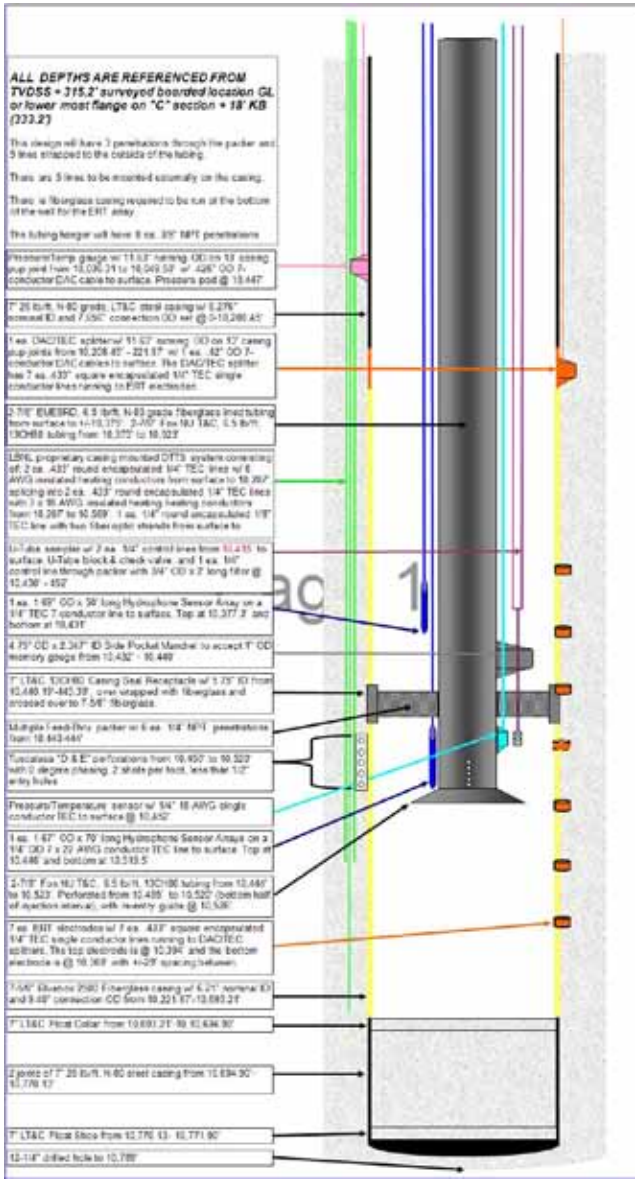
	CFU 31 F#1	CFU 31 F#2	CFU 31 F#3
Cemet Eval	CBL	USIT/CBL+AIT	USIT/CBL+AIT
RST 1 (base):	11/30/09	11/27/09	12/12/09
RST 2:	N/A	12/15/09	12/15/09
RST 3:	N/A	12/30/09	12/30/09
RST 4:	9/7/2010	9/9/2010	9/8/2010
After Killing Well		AIT, Sonic	AIT, Sonic

Observation Well Construction

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CFU 31 F#2

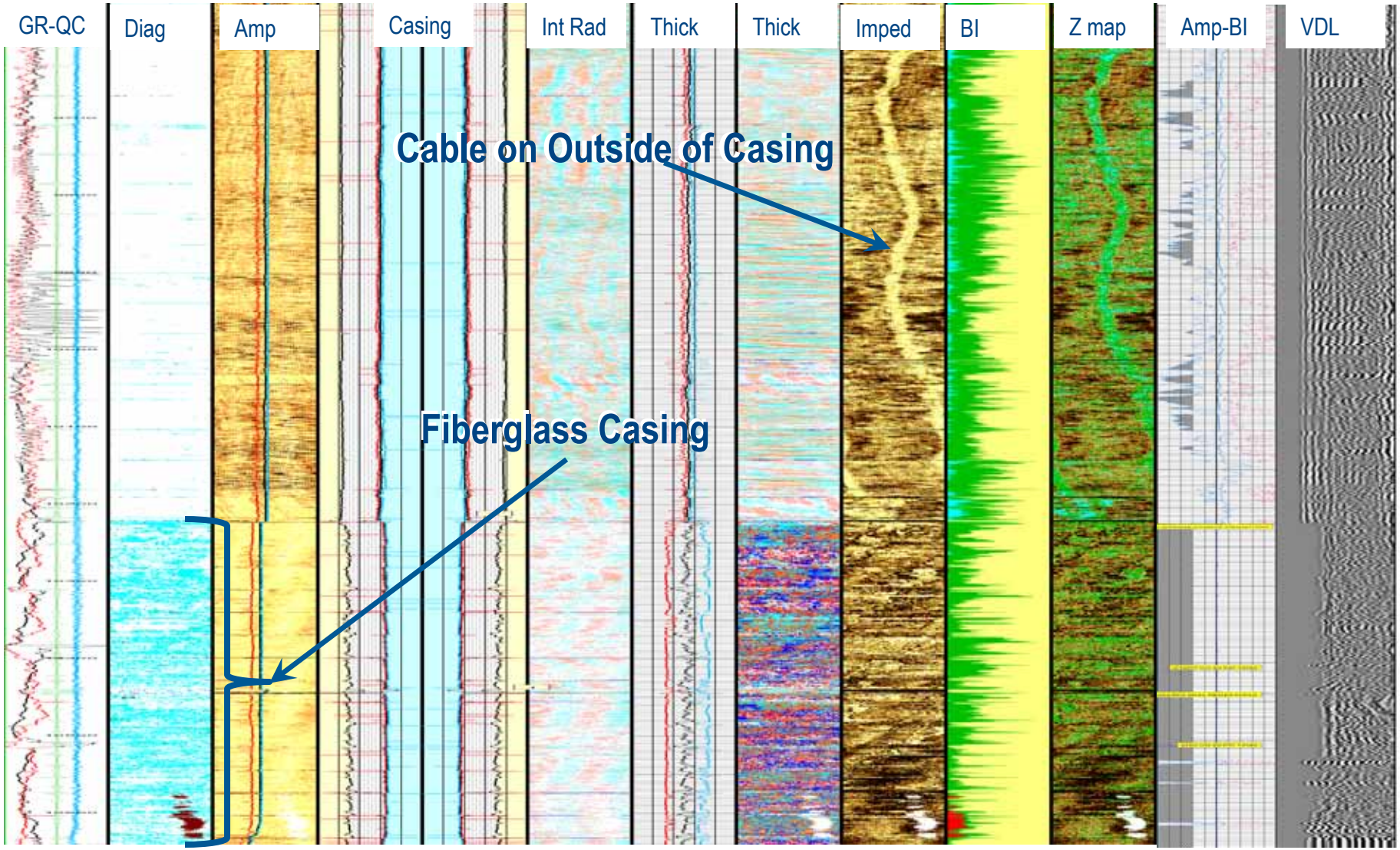




CFU 31 F#3

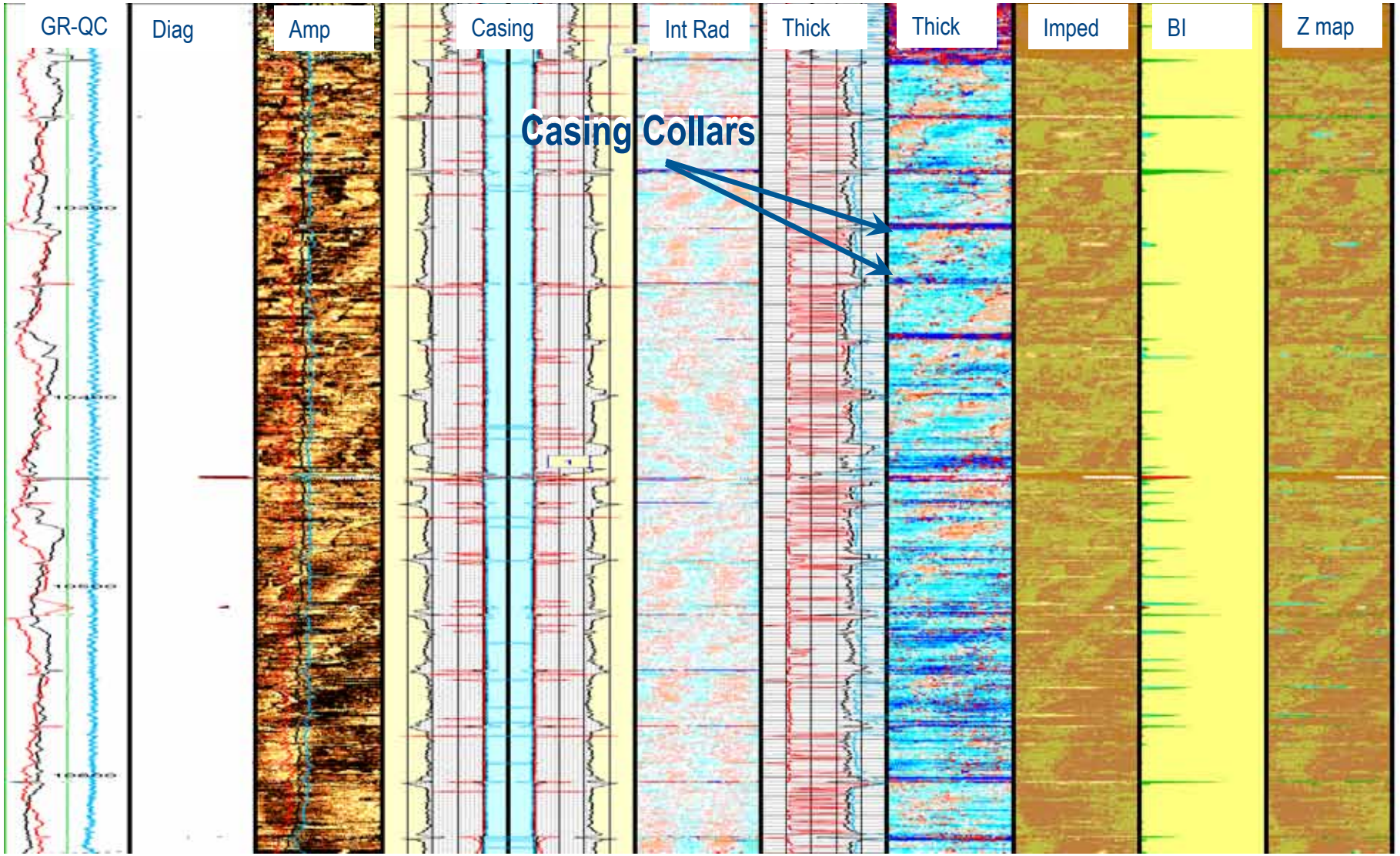
USIT & CBL – Standard Processing (9,550'-10,640')
CFU 31 F#2

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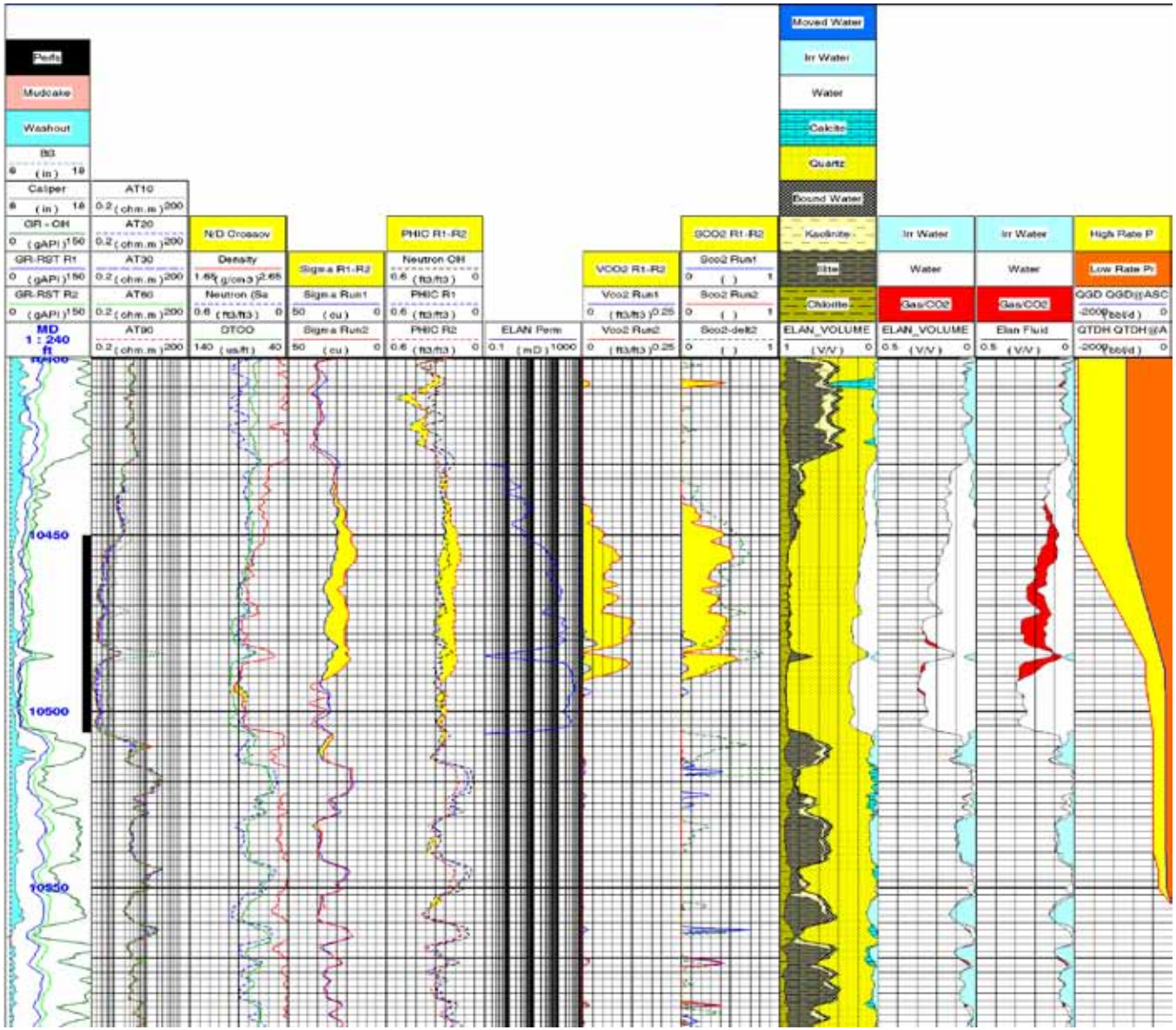
USIT – Fiberglass Processing CFU 31 F#2

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Carbon Services



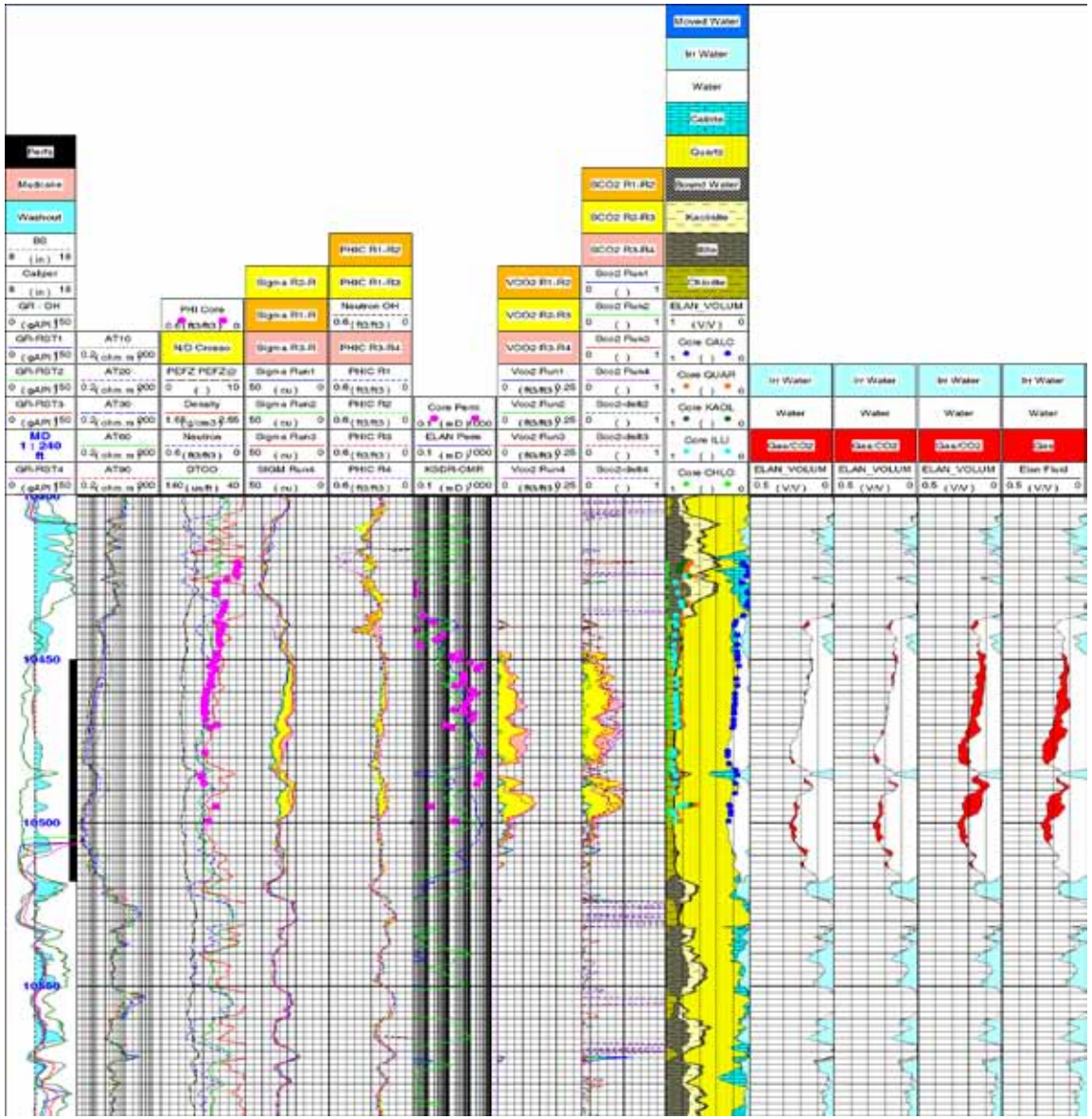
Injection Well – CFU 31 – F#1

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Carbon Services



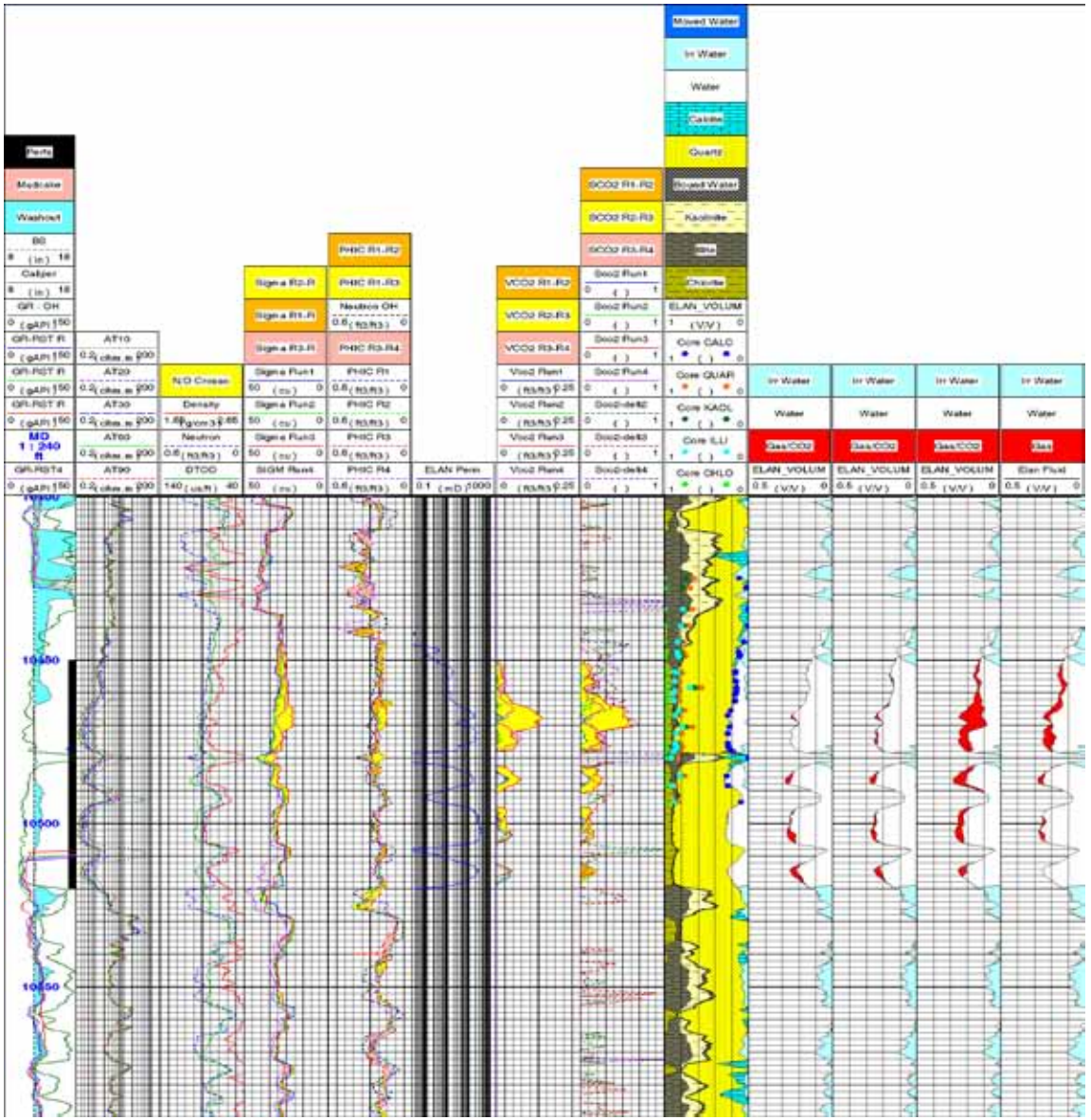
Closest Observation Well – CFU 31–F#2

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Carbon Services



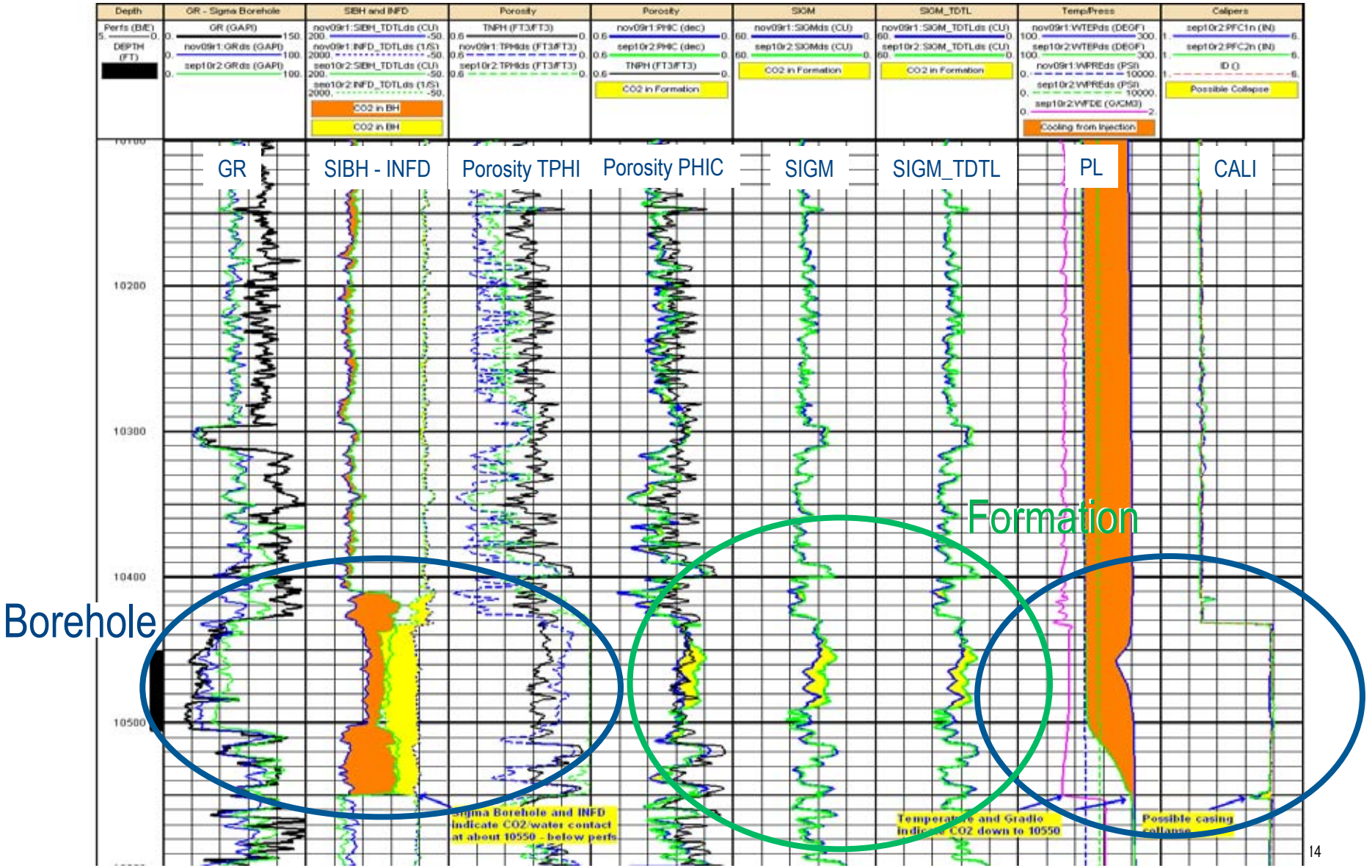
Far Observation Well – CFU 31 F#3

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Carbon Services



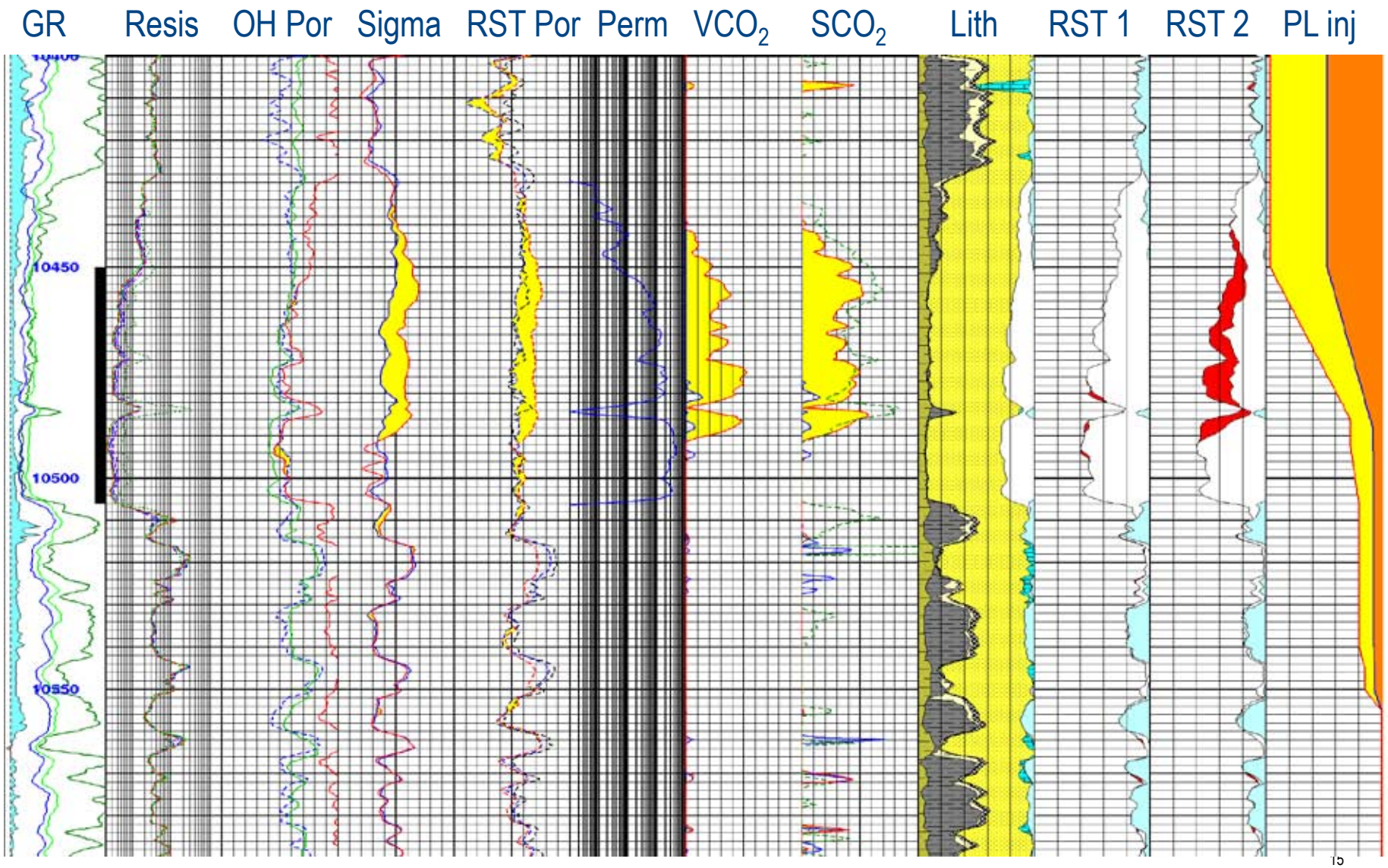
CFU 31 – F#1 Data Overlay

Schlumberger Carbon Services



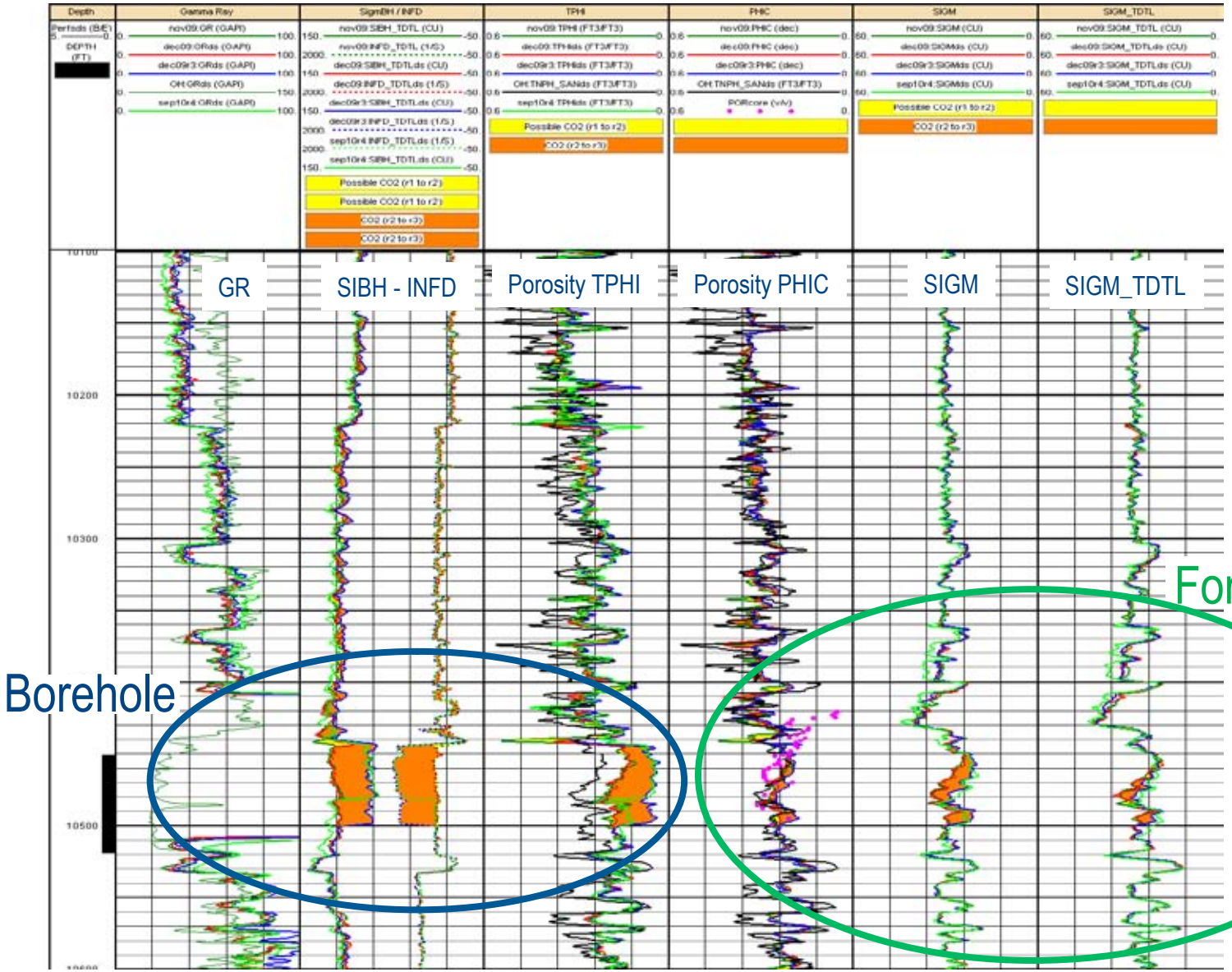
CFU 31 – F#1 Data Analysis

Schlumberger
Carbon Services



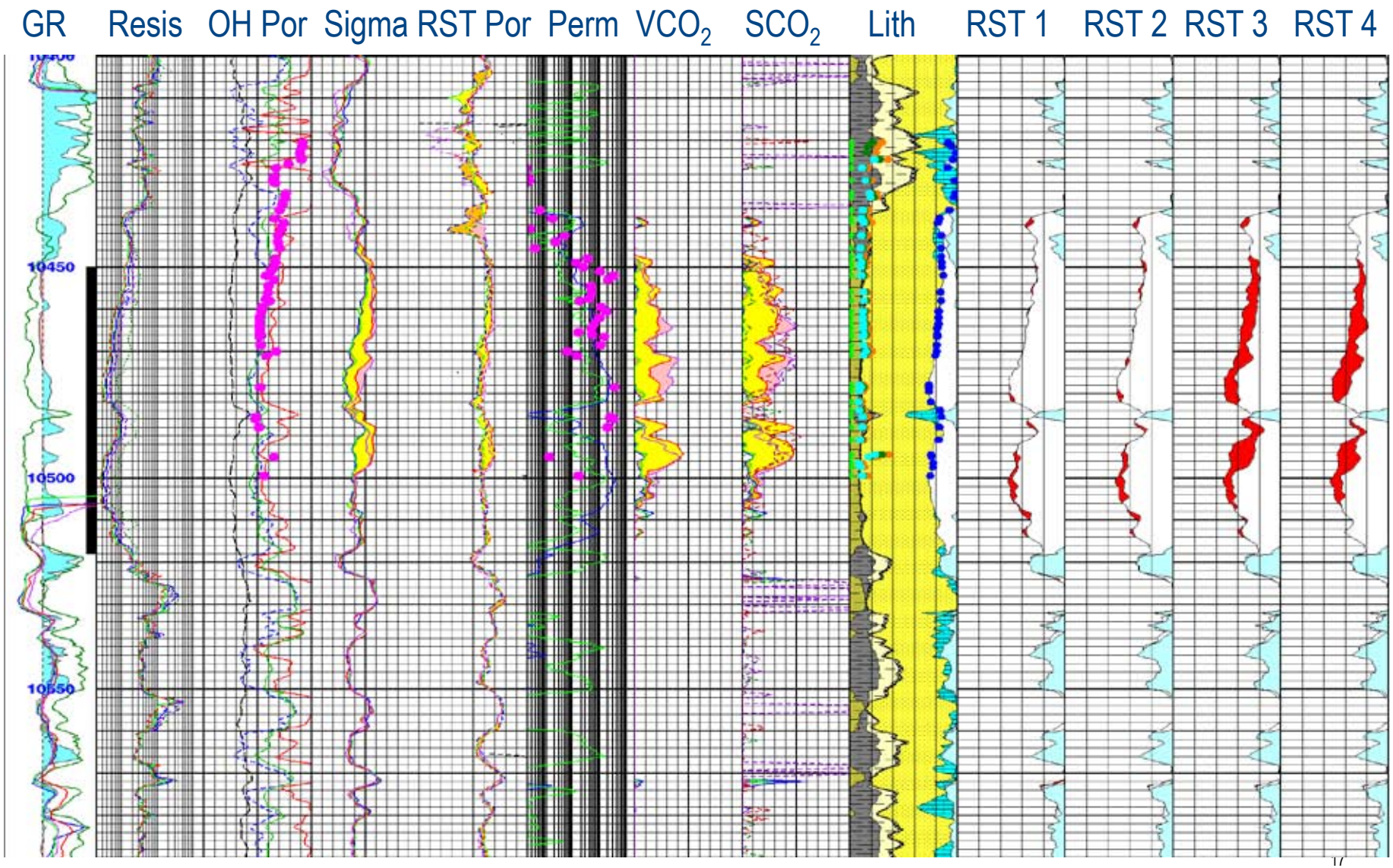
CFU 31 – F#2 Data Overlay

Schlumberger
Carbon Services



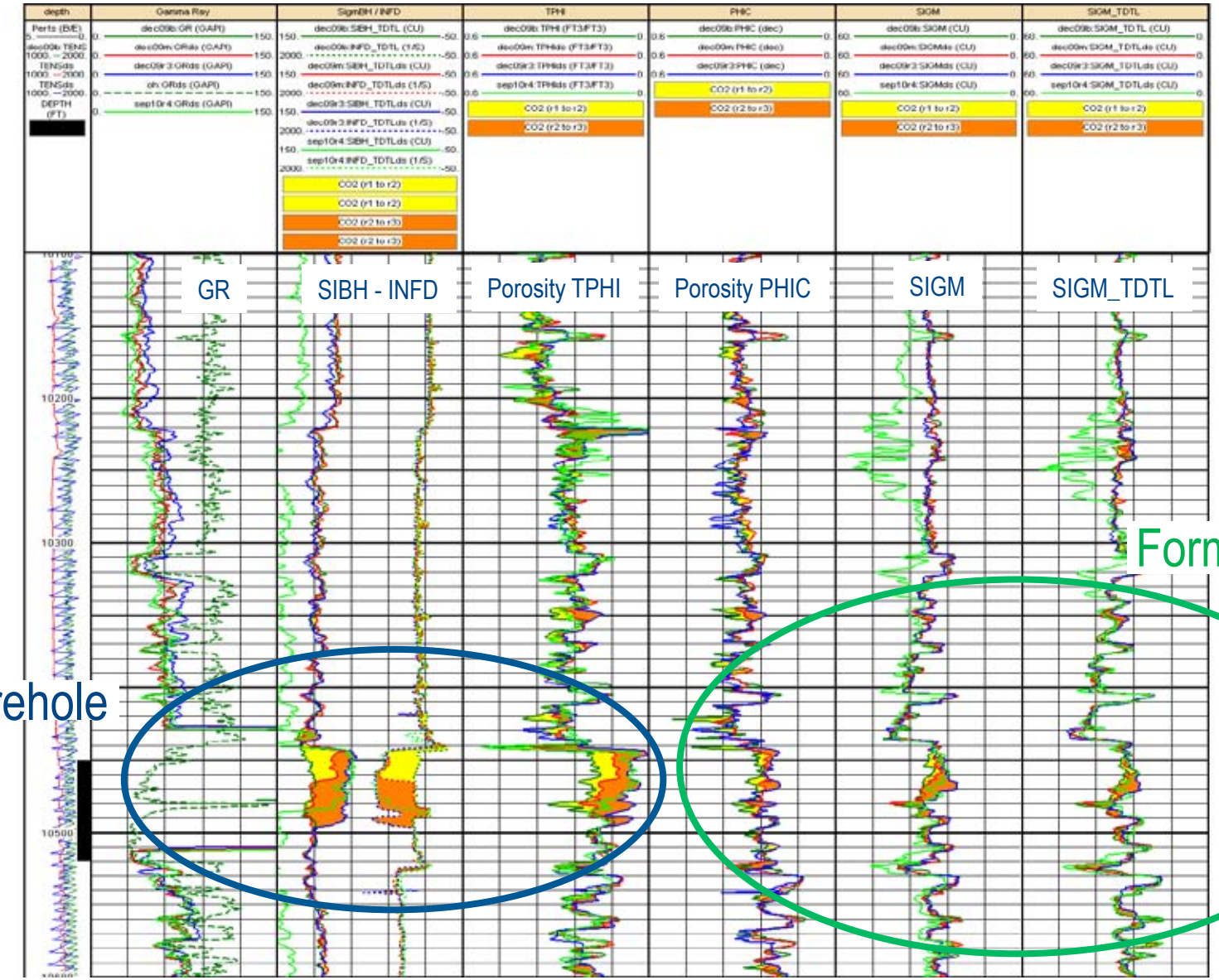
CFU 31 – F#2 Data Analysis

Schlumberger
Carbon Services



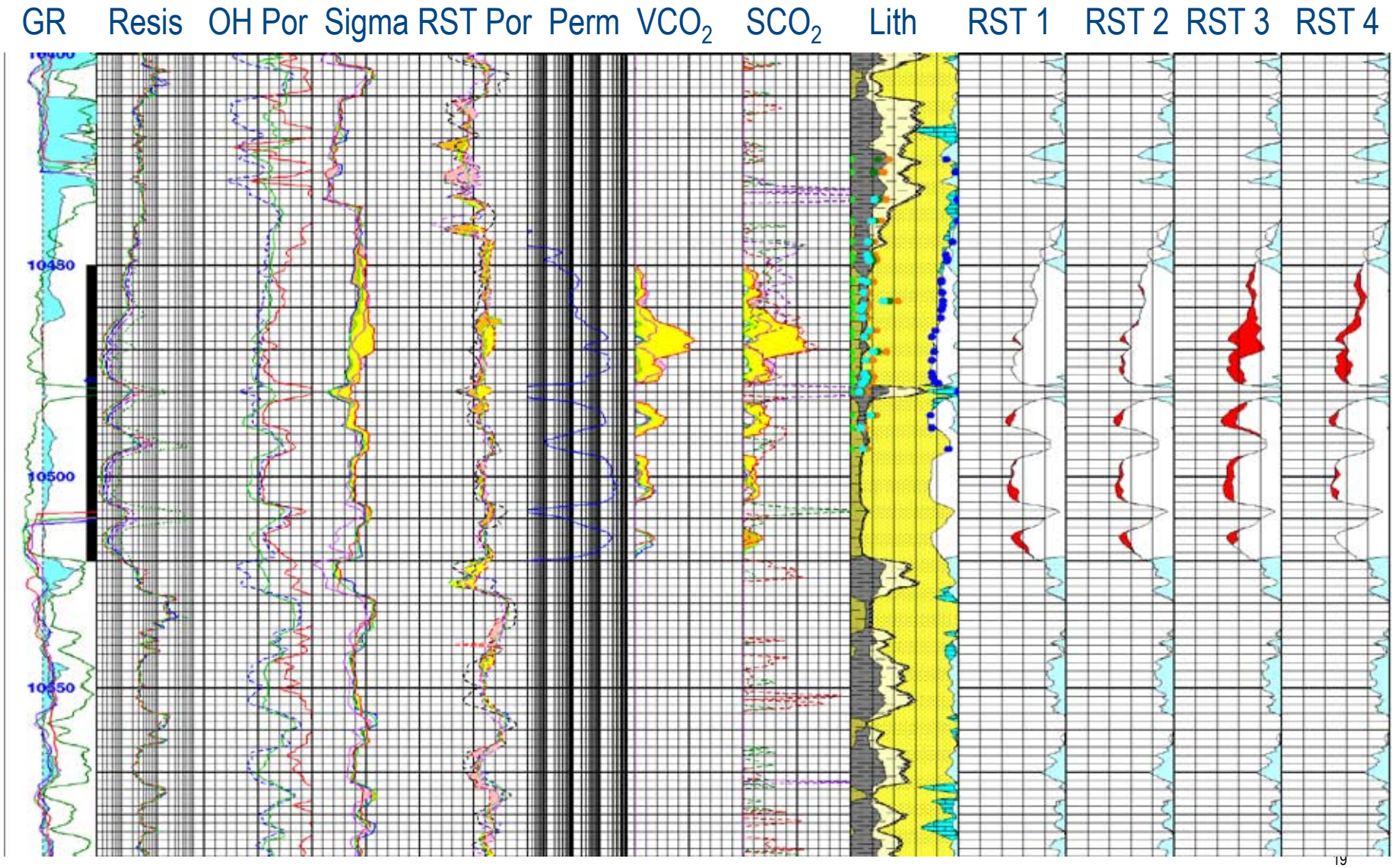
CFU 31 – F#3 Data Overlay

Schlumberger
Carbon Services



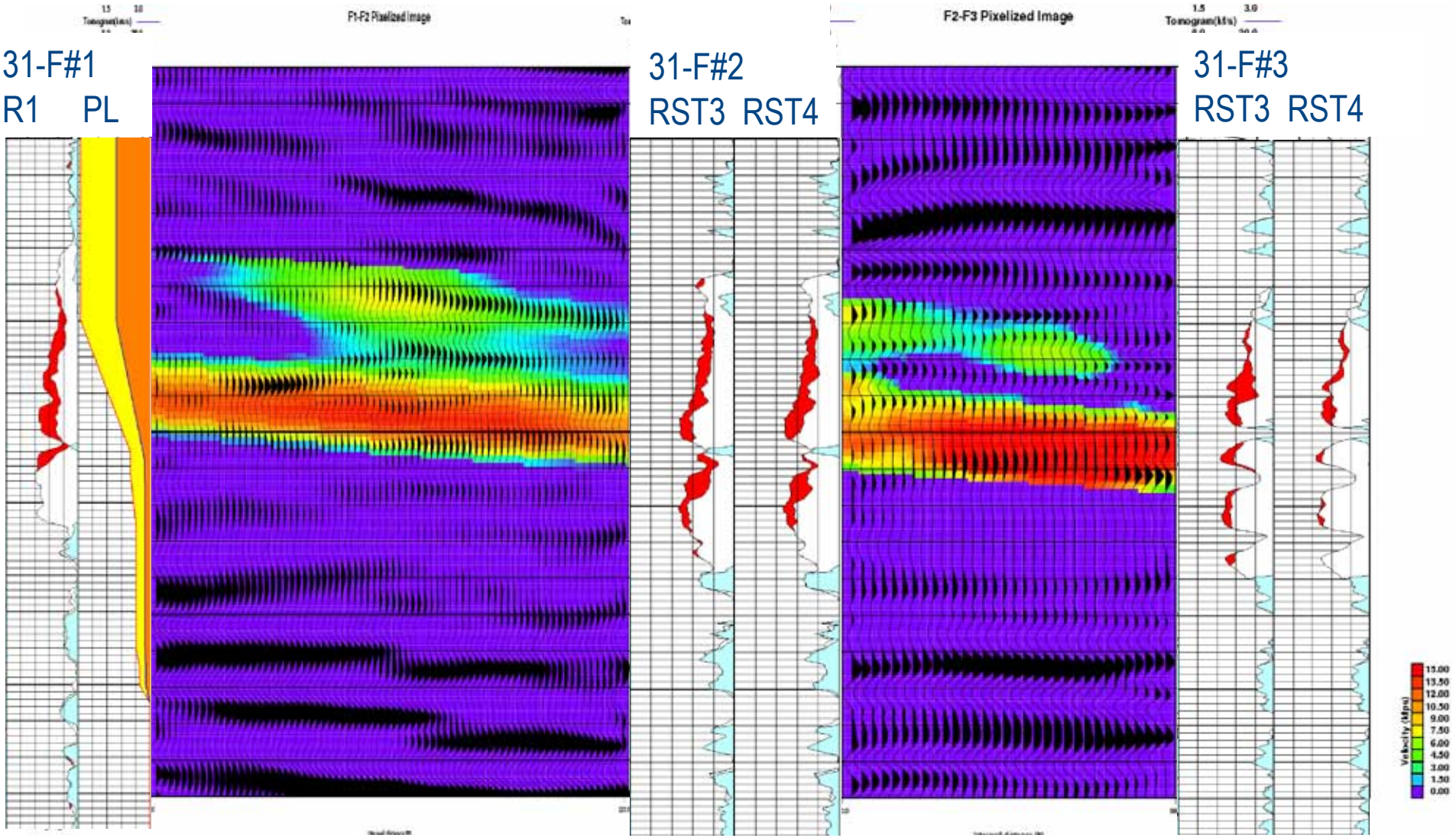
CFU 31 – F#3 Data Analysis

Schlumberger
Carbon Services



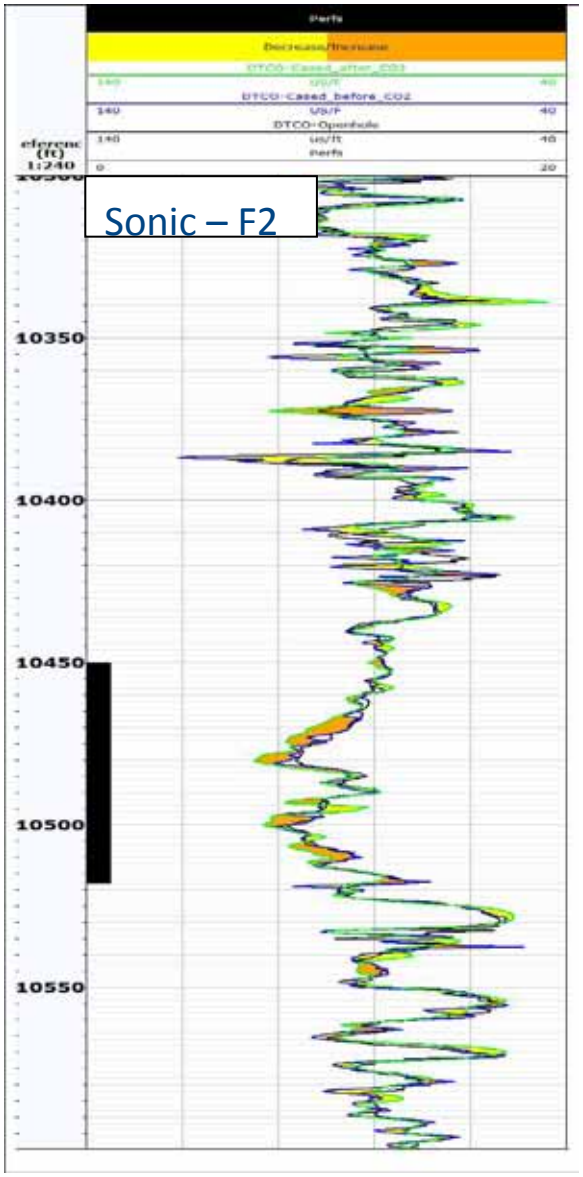
Cranfield – Cross Well Seismic with RST

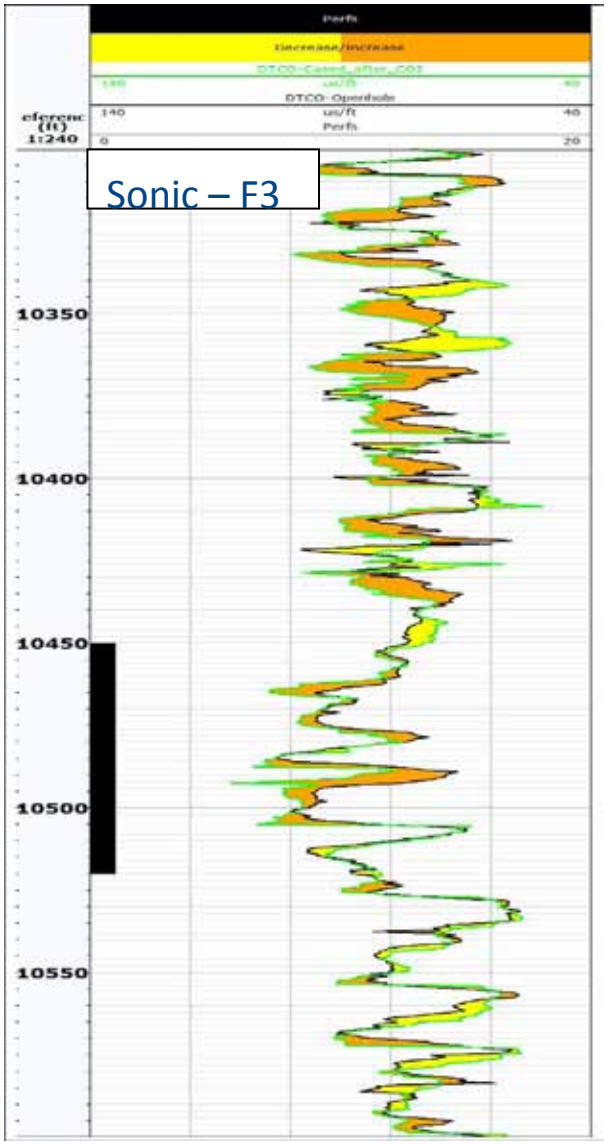
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Carbon Services



Pre/Post Sonic Comparison

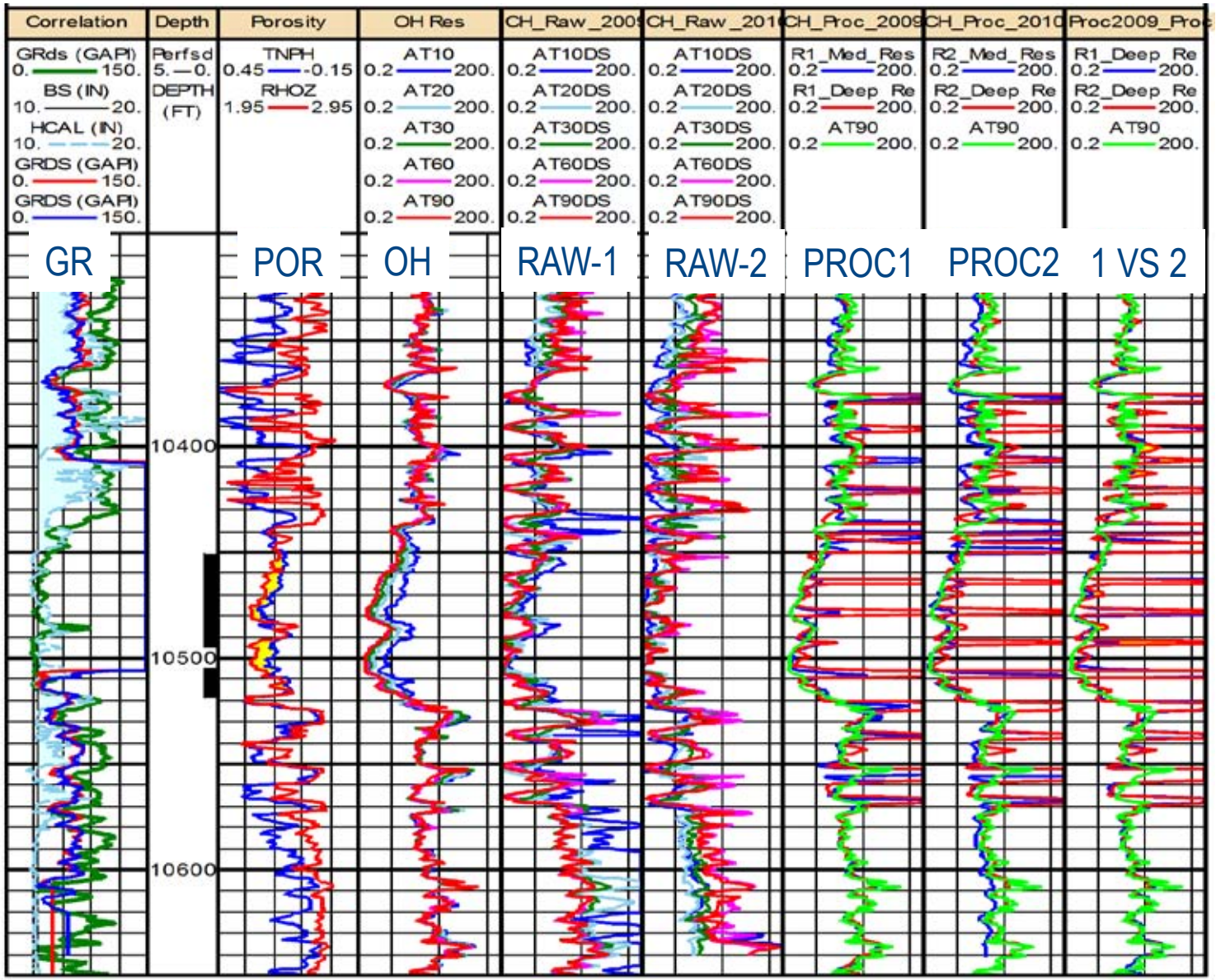
Schlumberger
Carbon Services





CFU 31 – F#2 Pre/Post AIT Comparison

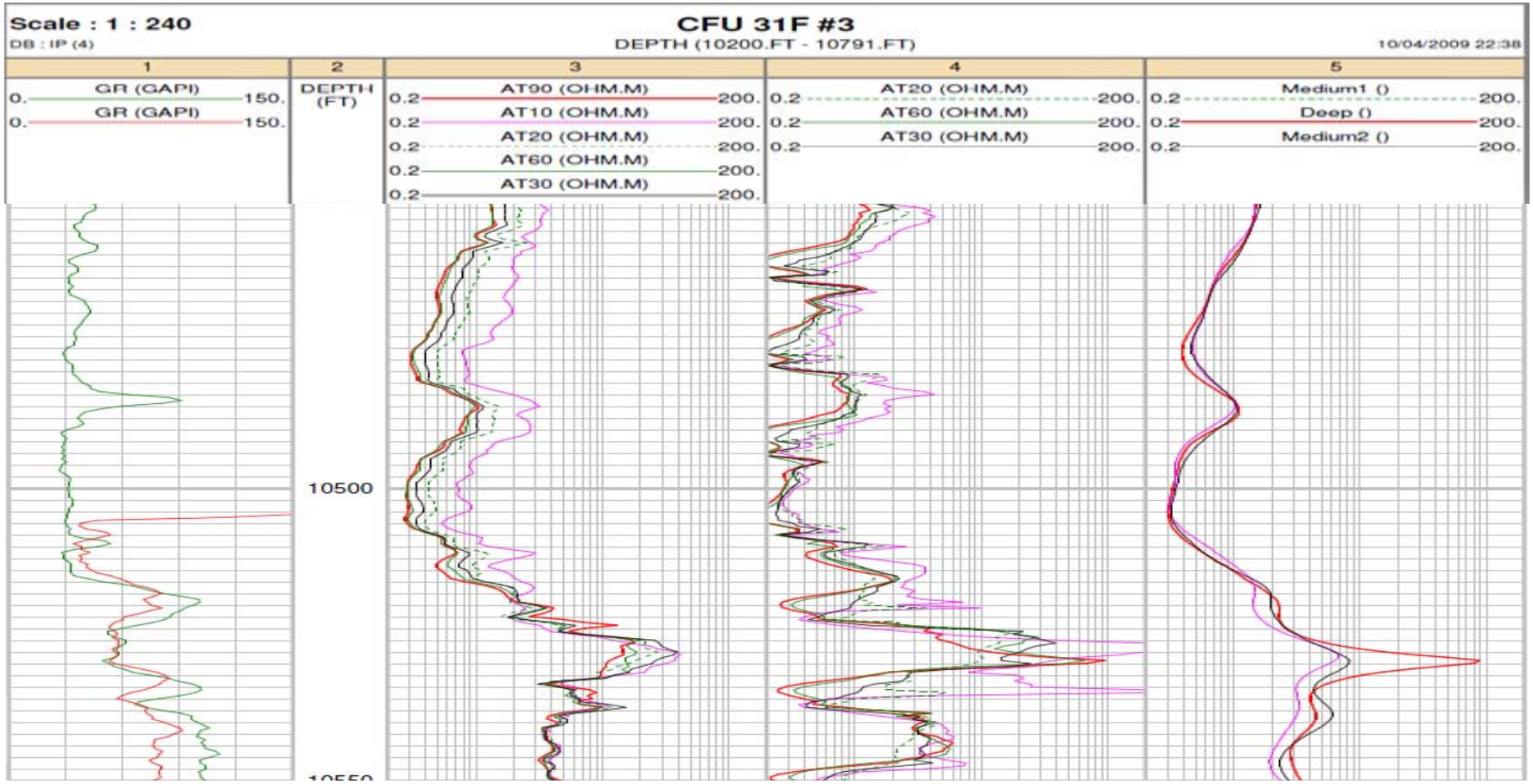
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Initial AIT Reprocessing

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Open Hole | Case Hole Field | Cased Hole Re-processed



Conclusions

Schlumberger Carbon Services

- RST Results
  - $\sum$ measurement is able to identify and quantify changes in saturations of all fluids in the formation.
  - C/O measurement may provide additional information but carries additional expense and time.
  - Borehole measurements in $\sum$ mode provide information on fluid contacts in the wellbore.
- PL measurements run during injection provided valuable information on injection profile.
- Sonic data quality is in question – possible problems with additional hardware in wellbore and injecting kill fluids into formation.
- AIT data quality is in question due to electrodes and additional hardware in wellbore as well as injecting kill fluids into formation

Lessons Learned

Schlumberger Carbon Services

- There is an obvious casing leak below the injection zone.
- Trying to do too much in a single well causes problems
- The data is supportive across technologies
- Killing the wells was should be avoided
- The real world is different from research

Acknowledgements

- This material is based upon work supported by the U.S. Department of Energy National Energy Technology Laboratory.
- Cost share and research support provided by SECARB/SSEB Carbon Management Partners.
- Anthropogenic Test CO_2 Capture Unit funded separately by Southern Company and partners.



THE UNIVERSITY OF TEXAS AT AUSTIN

WHAT STARTS HERE CHANGES THE WORLD

BUREAU OF ECONOMIC GEOLOGY

Gulf Coast Carbon Center

Geomechanics at Cranfield

March 5th, 2014

Seunghee Kim, Ph.D.
Bureau of Economic Geology
The University of Texas at Austin

SECARB
Southeast Regional Carbon Sequestration Partnership

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1. Pressure monitoring in AZMI

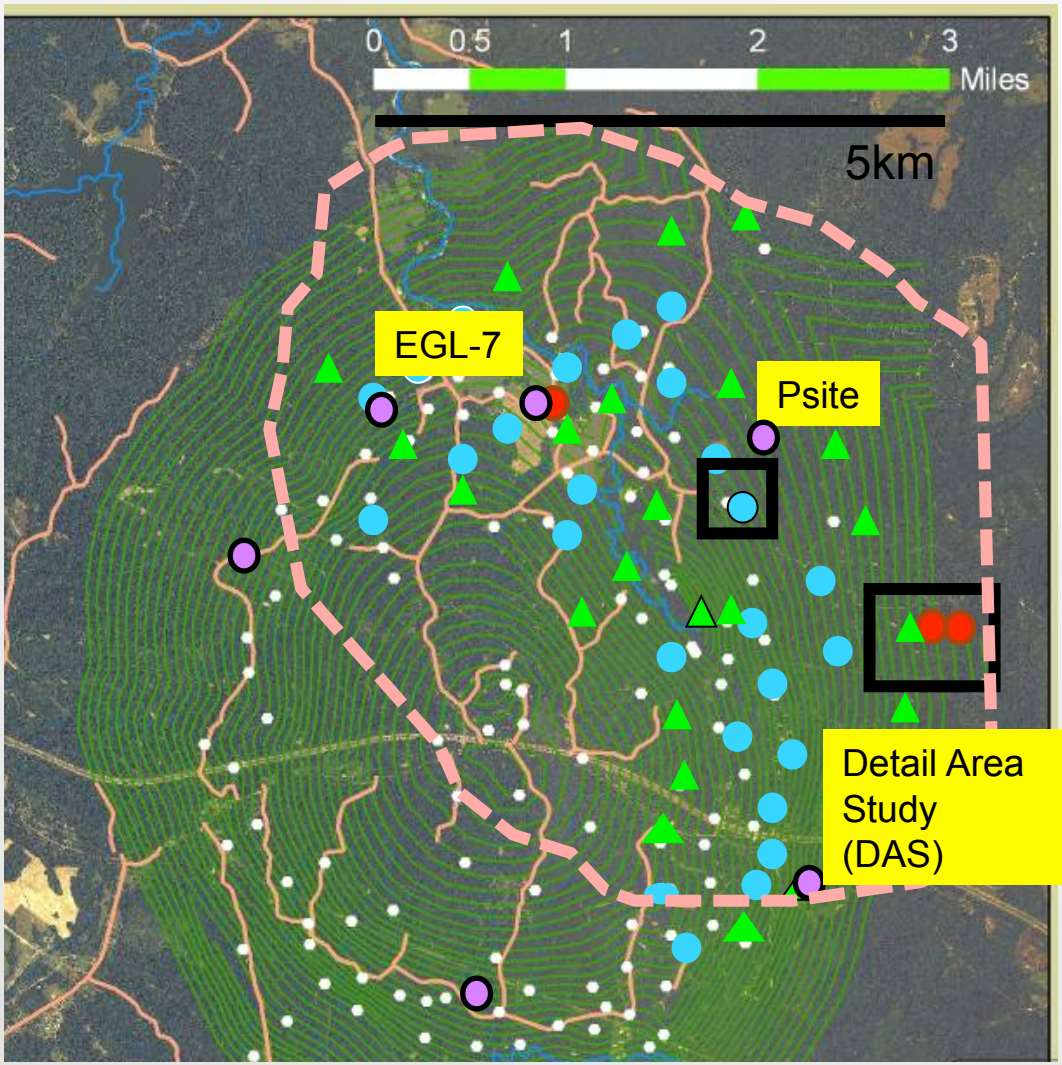
2. Maximum sustainable pressure limit

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1. Pressure monitoring in AZMI

2. Maximum sustainable pressure limit

Monitoring Layout - Cranfield



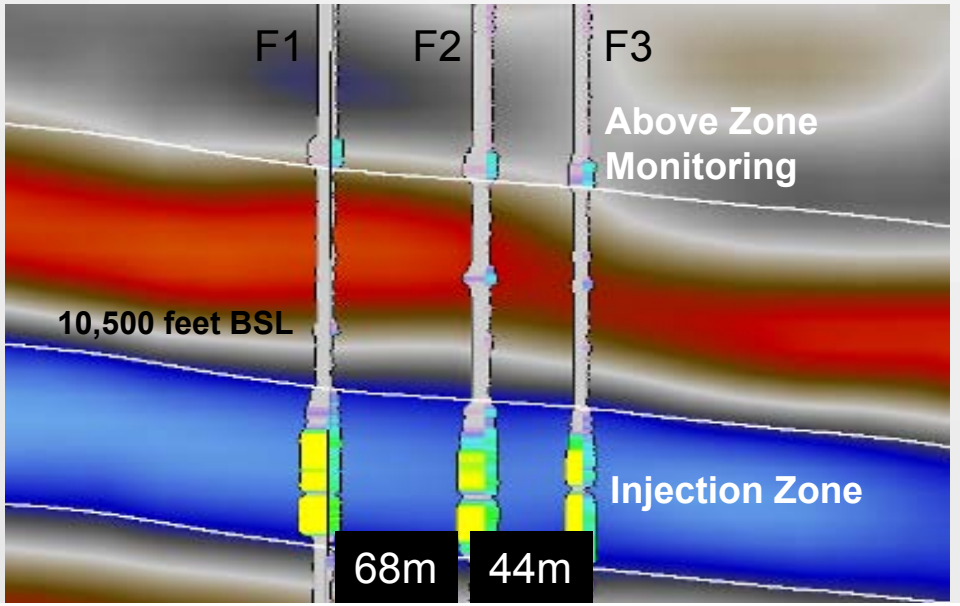
- Injector
- Producer (monitoring point)
- Observation Well
- RITE Microseismic
- 4-D seismic

GIS base Tip Meckel, BEG

DAS (Detail Area Study)

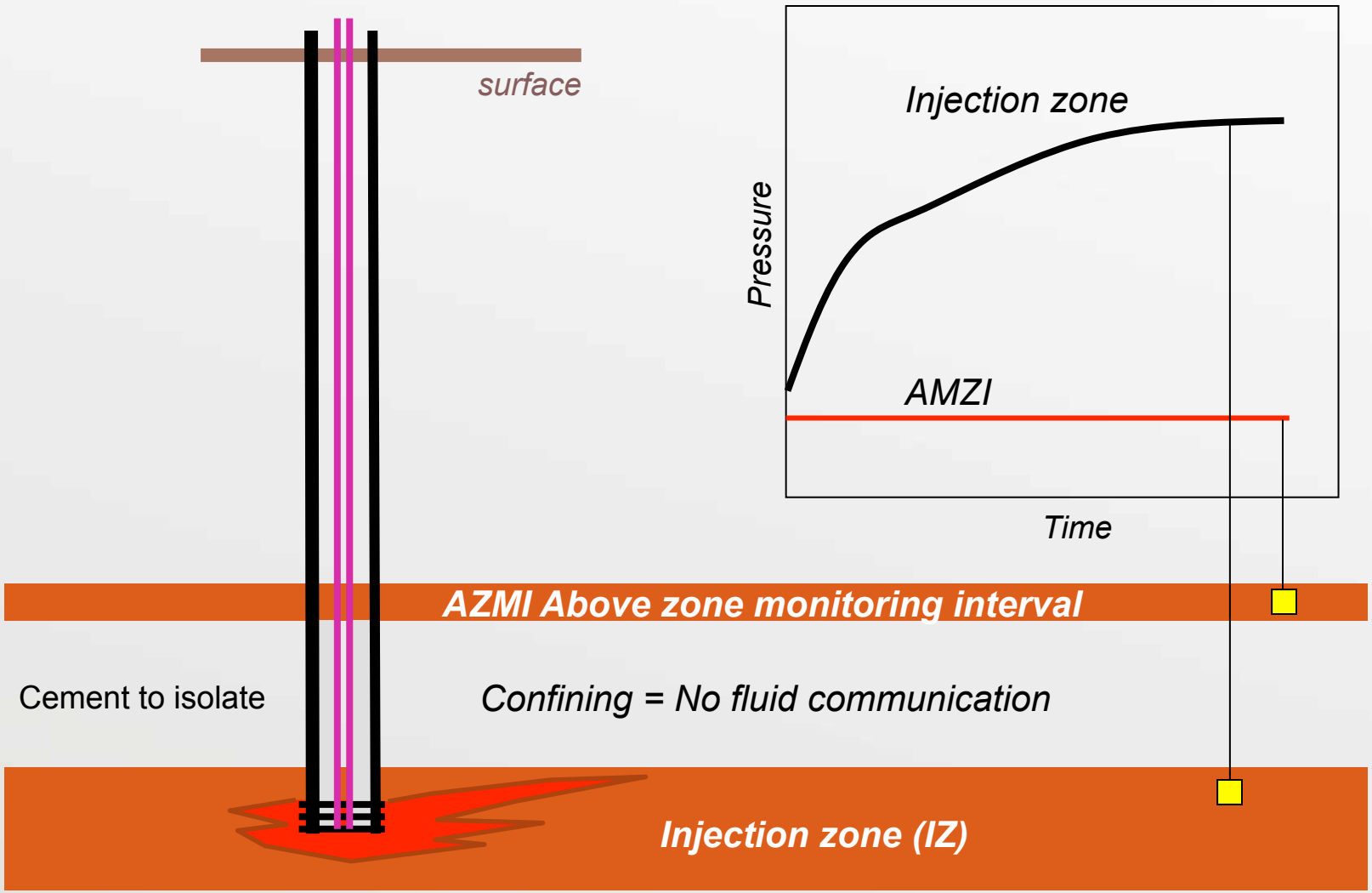


- Closely spaced wells
- "Window"
  - Flow in complex reservoir
- Sweep efficiency
  - RST
  - Seismic velocity
  - Electric resistivity
  - Borehole gravity

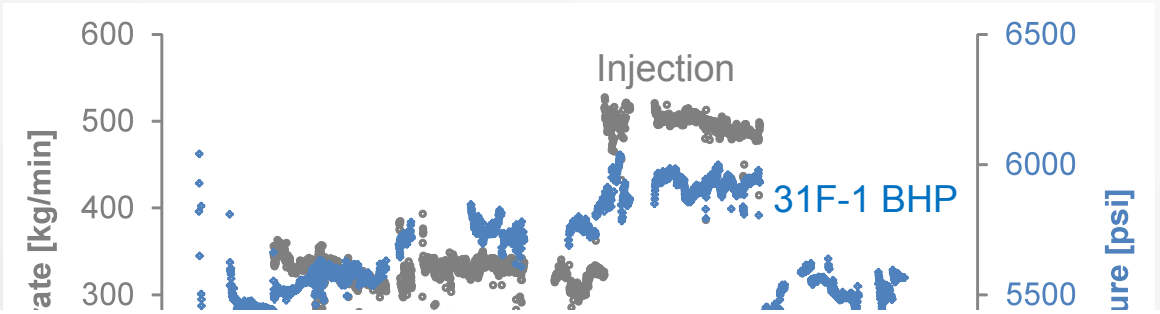


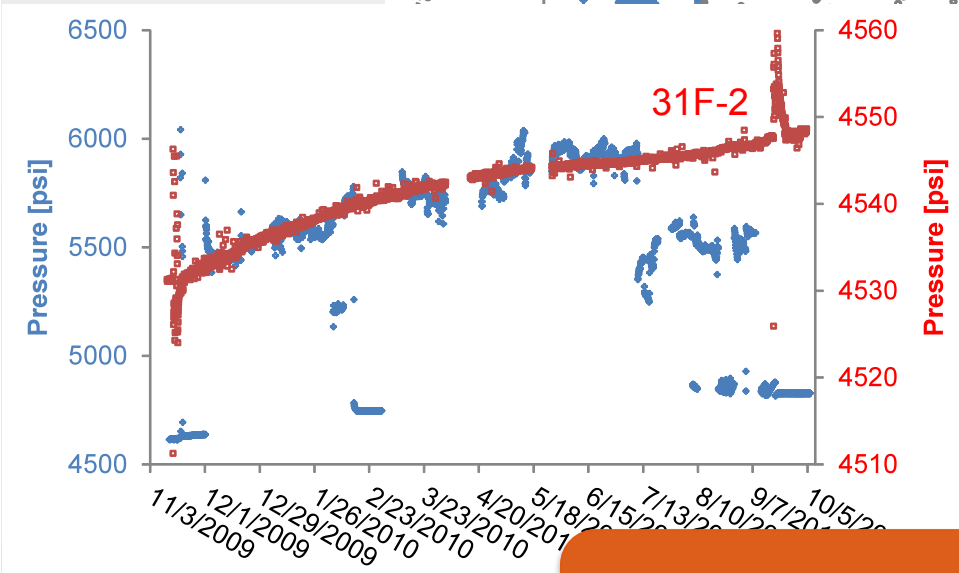
Petrel model by Tip Meckel, BEG

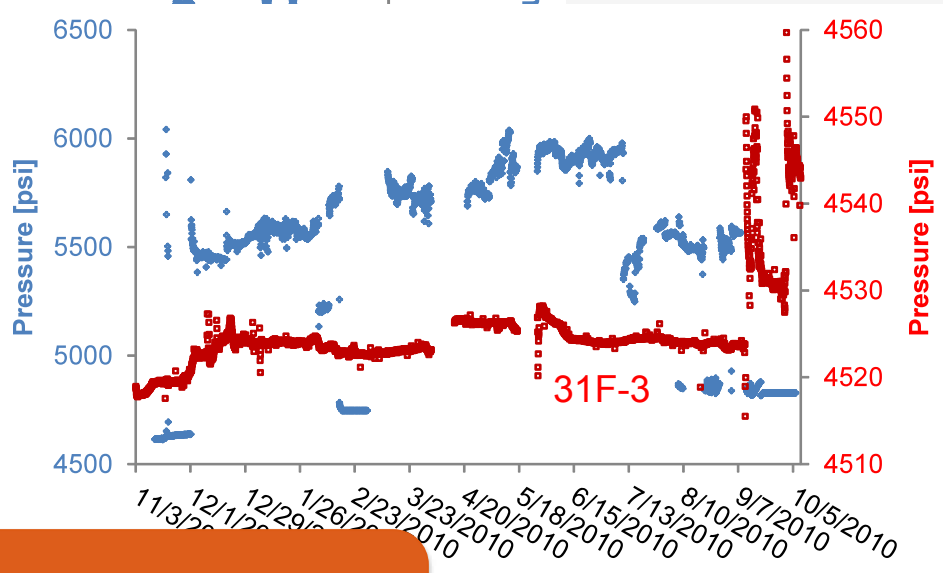
Pressure Monitoring in AZMI



Field Data - DAS, Cranfield







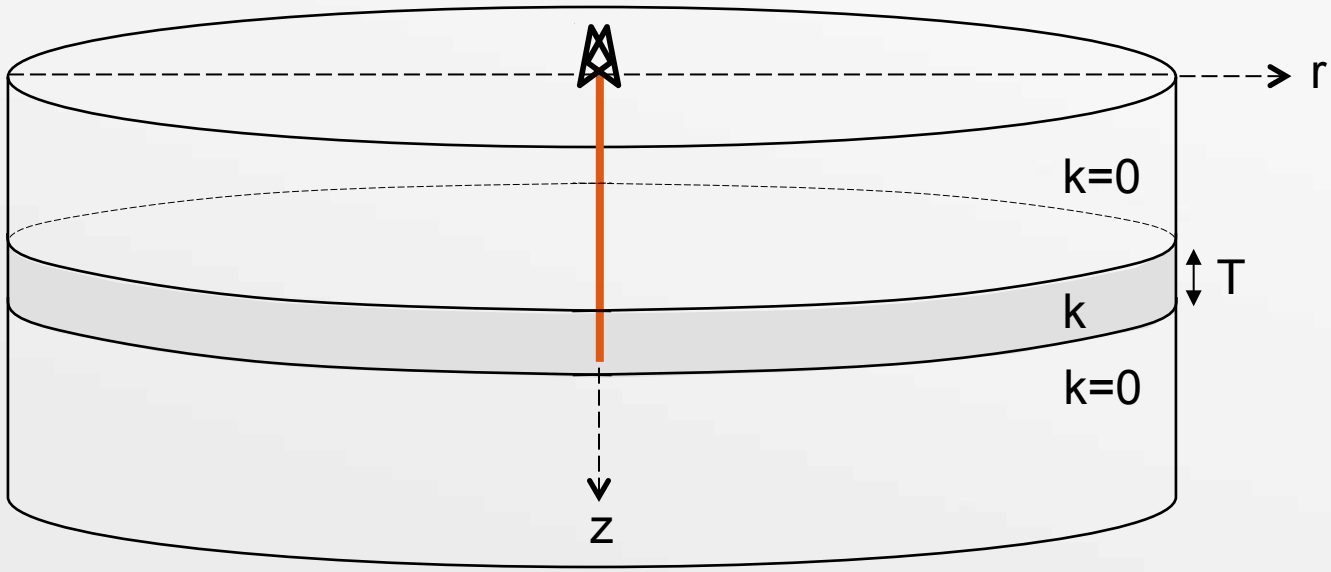
Q1: Pressure in AZMI
Q2: Pressure in Injection Zone

Analytical Approach



- Conventional geomechanics: pore pressure → stress → strain → displacement
  - Diffusive transport is very slow for caprock
- Poroelasticity: displacement → strain → stress → pore pressure
  - Can be used to predict: 1) pore pressure change in AZMI
    2) displacement

Assumptions



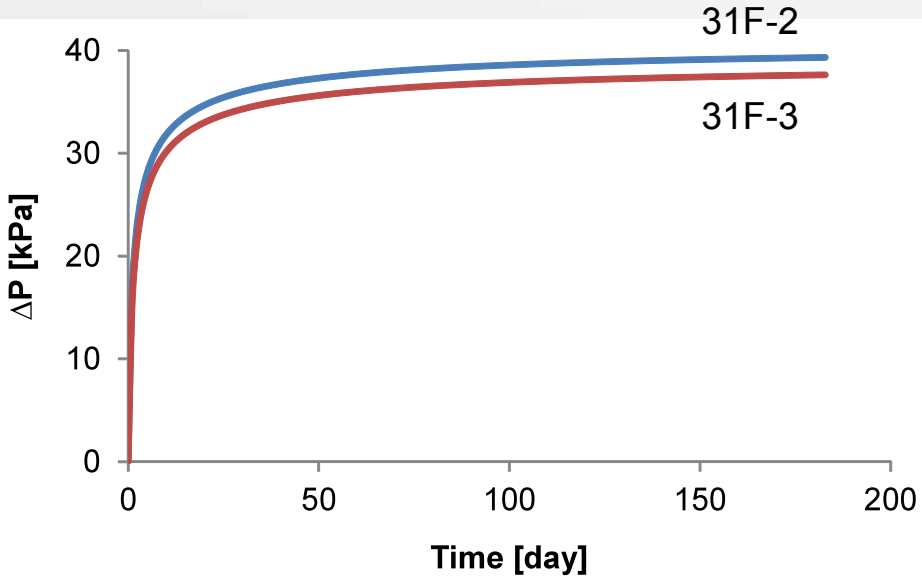
- Linear, isotropic, poroelastic material (one set of parameters, except permeability)
- Analytical solution: coupling of one direction only (pore pressure → deformation)
- Axisymmetric ($\varepsilon_{\theta\theta}$=0)
- Single phase flow & constant injection rate
- Isothermal

Segall, 1992

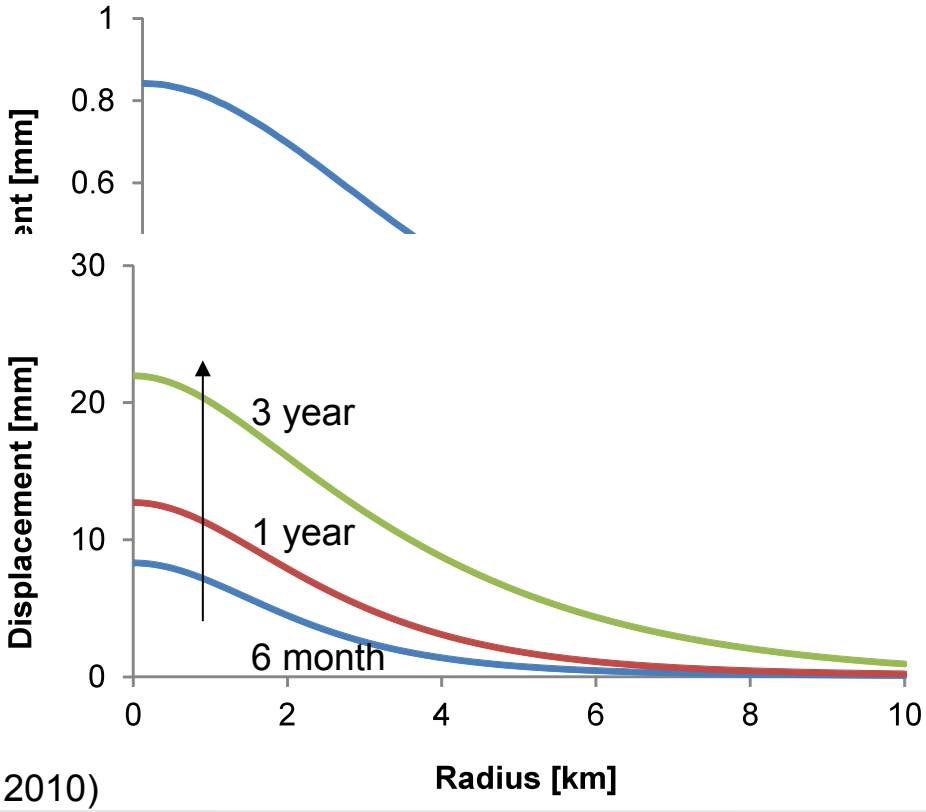
*Assumption: 1-D deformation

Results

- Pore pressure in AZMI*



- Vertical displacement at surface

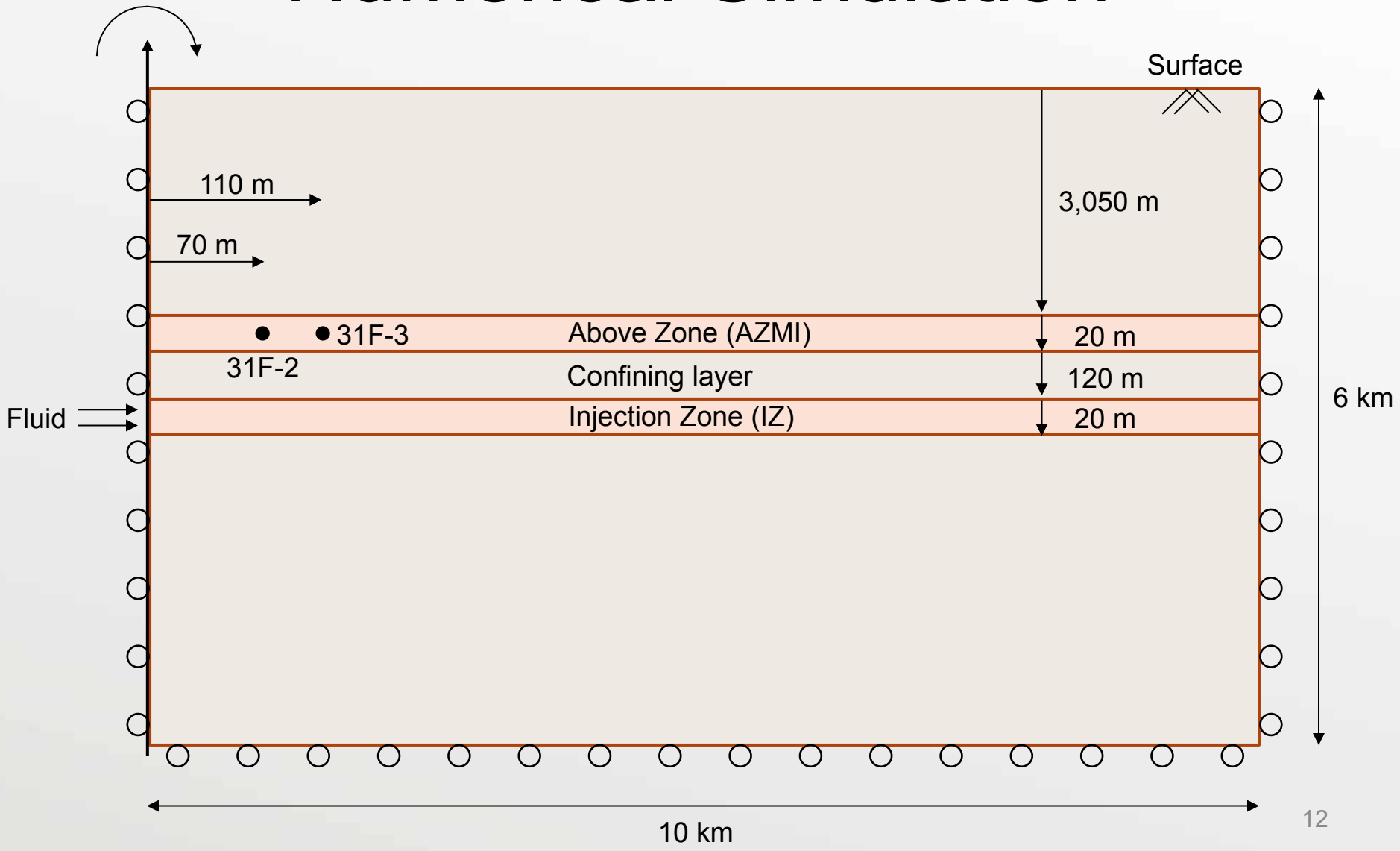


5~10mm/year – In Salah CO_2 Storage project
(Q=0.5~1 $MtCO_2$/year, 20m thick IZ at ~1.8km, Rutqvist, 2010)

Summary – Analytical Approach

- Advantages
  - Easy to implement
  - Fast first-order estimation
  - Sensitivity analysis & Monte-Carlo simulation
- Disadvantages
  - One set of material properties
  - Coupling of one direction

Numerical Simulation



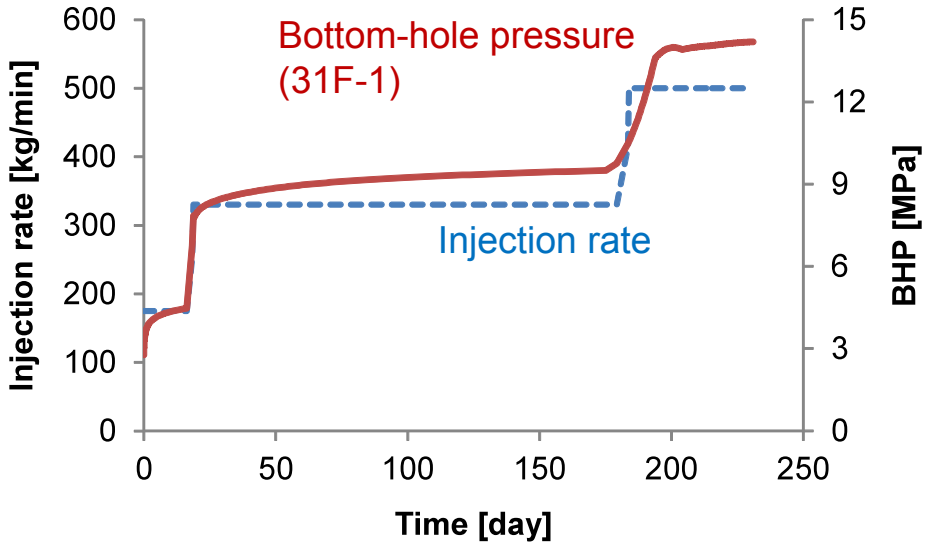
Parameters

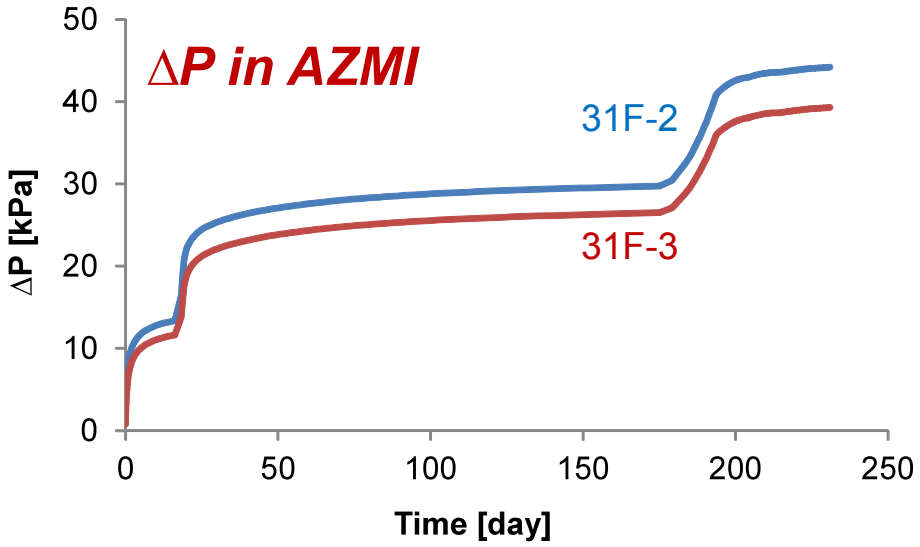
Property	Symbol	Value	
Young's modulus	E	17.5GPa (IZ)	30GPa (Cap)
Poisson's ratio	ν	0.15	0.3
Drained bulk density	ρ_d	2650kg/m^3	2000kg/m^3
Porosity	ϕ	0.25	0.1
Biot coefficient	α	1	1
Bulk modulus of fluid	K_f	2.2GPa	
Density of fluid	ρ_f	1000kg/m^3	
Viscosity of fluid	μ	0.001Pa · s	
Permeability	k	64md	1nd
Injection rate	Q	175→330→500kg/min	
Radius of the injection well	r_w	0.07m	
Thickness of the injection zone & AZMI	T_w	20m	
Depth of the injection layer	D_w	3200m	
Depth of the AZMI monitoring point	D_{AZMI}	3060m	
Distance of the AZMI monitoring point from the injection well	r_{AZMI}	70m (31F-2) & 110m (31F-3)	
Simulation time	t_{total}	200day	

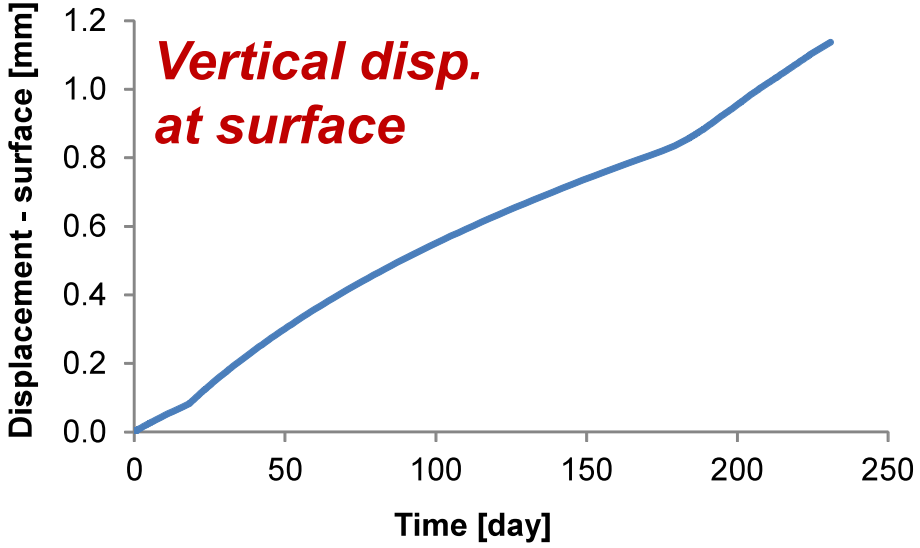
Cranfield data (BEG); Ajo-Franklin et al. (2013)

Match to Field

- Injection Rate & BHP

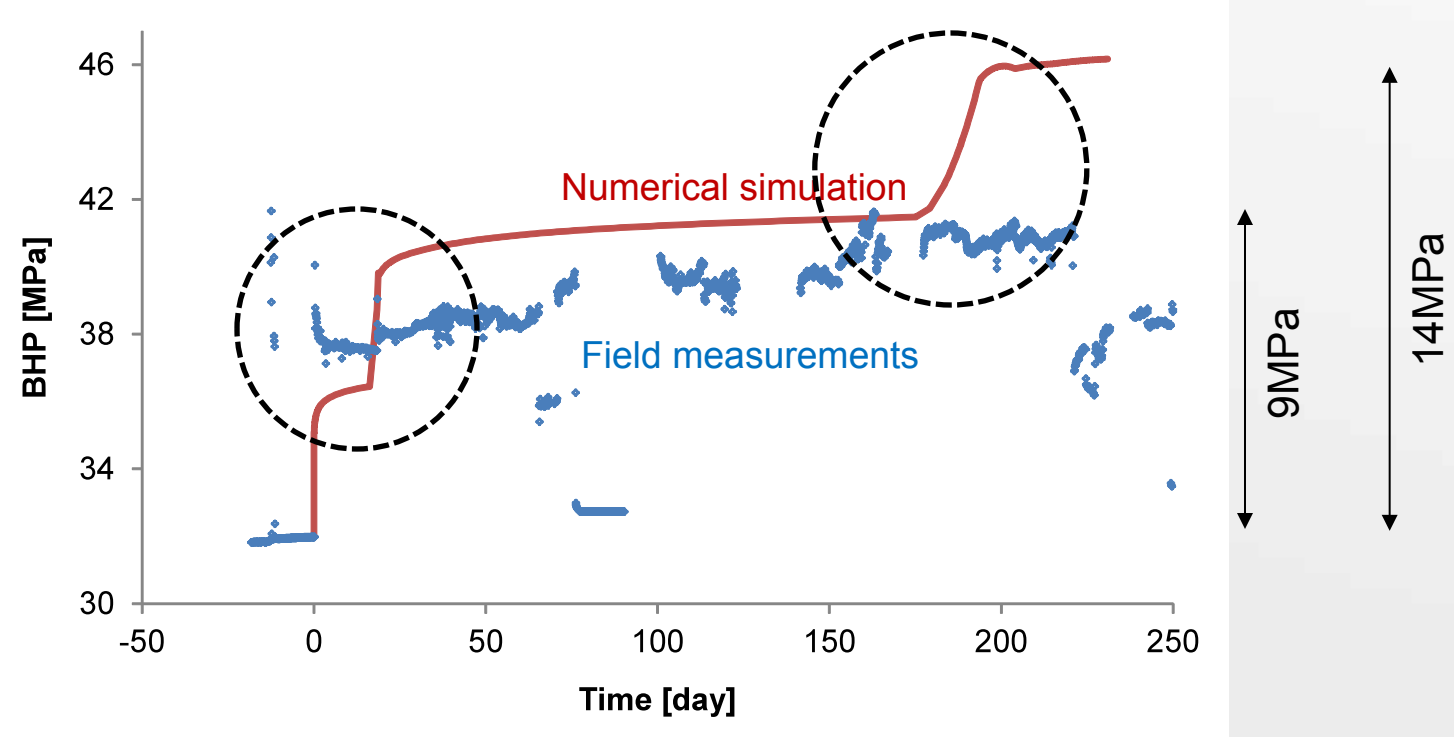






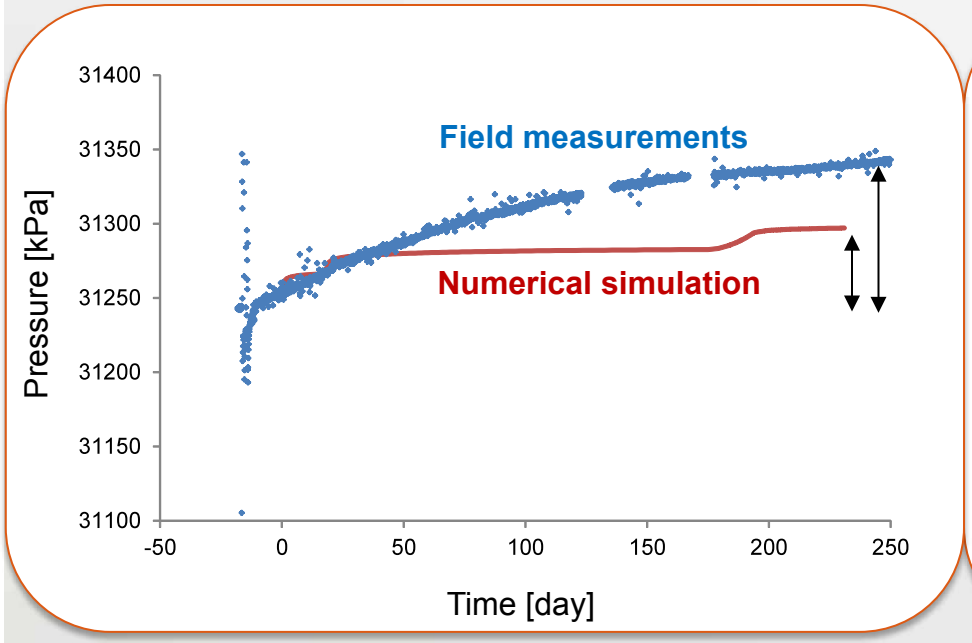
Revisit - Field Data (1/3)

- 31F-1 Inj. Well: Bottom Hole Pressure

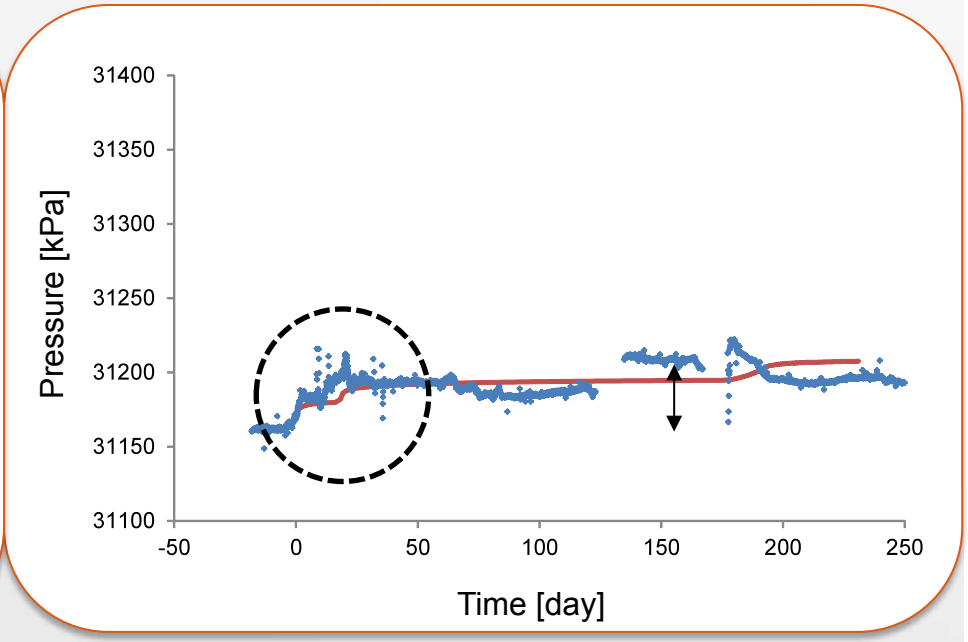


Revisit - Field Data (2/3)

- 31F2 Mon. Well: Pressure

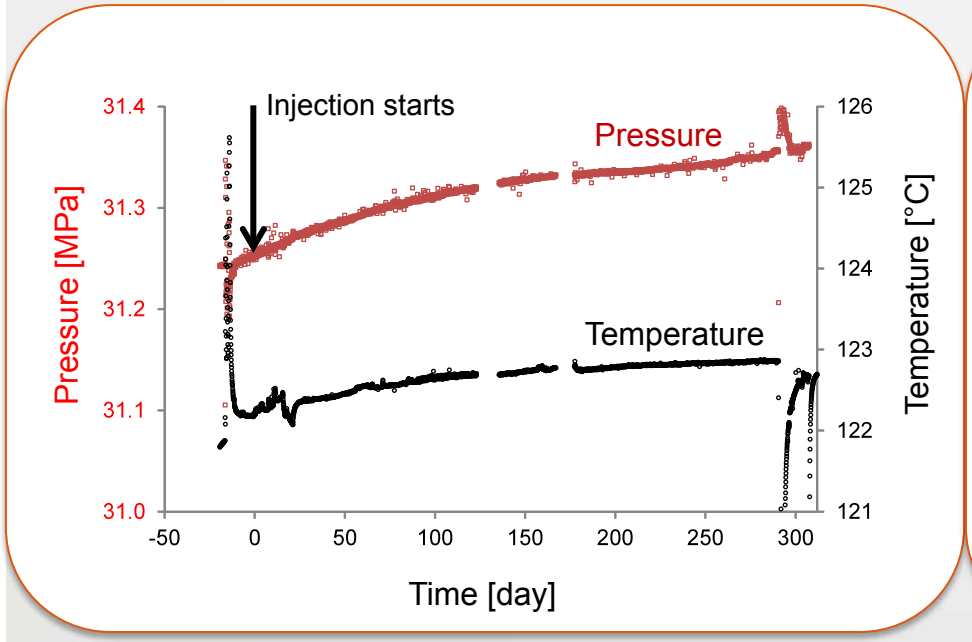


- 31F3 Mon. Well: Pressure



Revisit - Field Data (3/3)

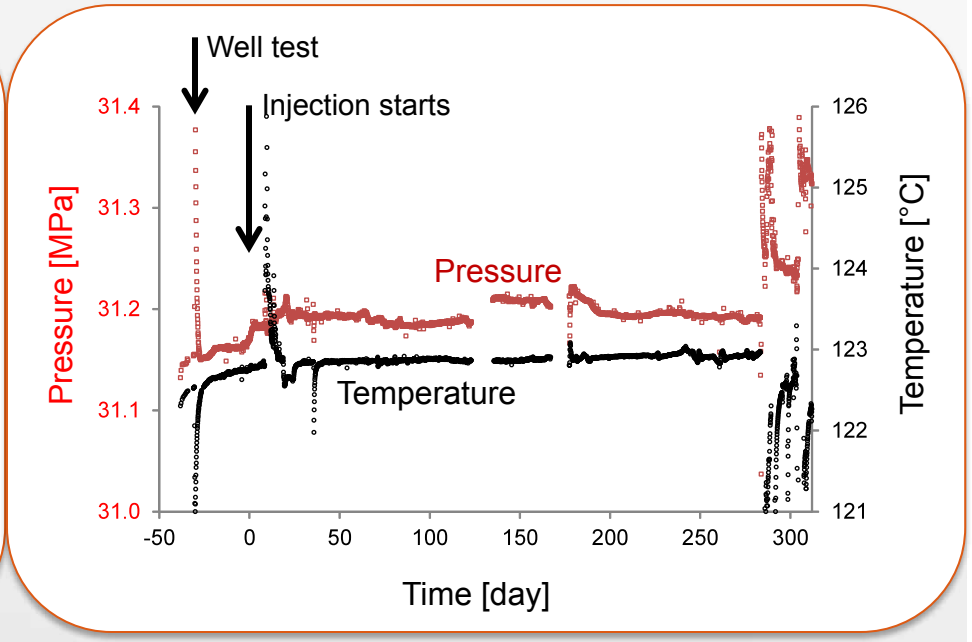
- 31F2 Mon. Well: P&T



- Pressure increase: 80kPa>40kPa
- Thermal increase

→ Migration of brine + Geomechanics

- 31F3 Mon. Well: P&T

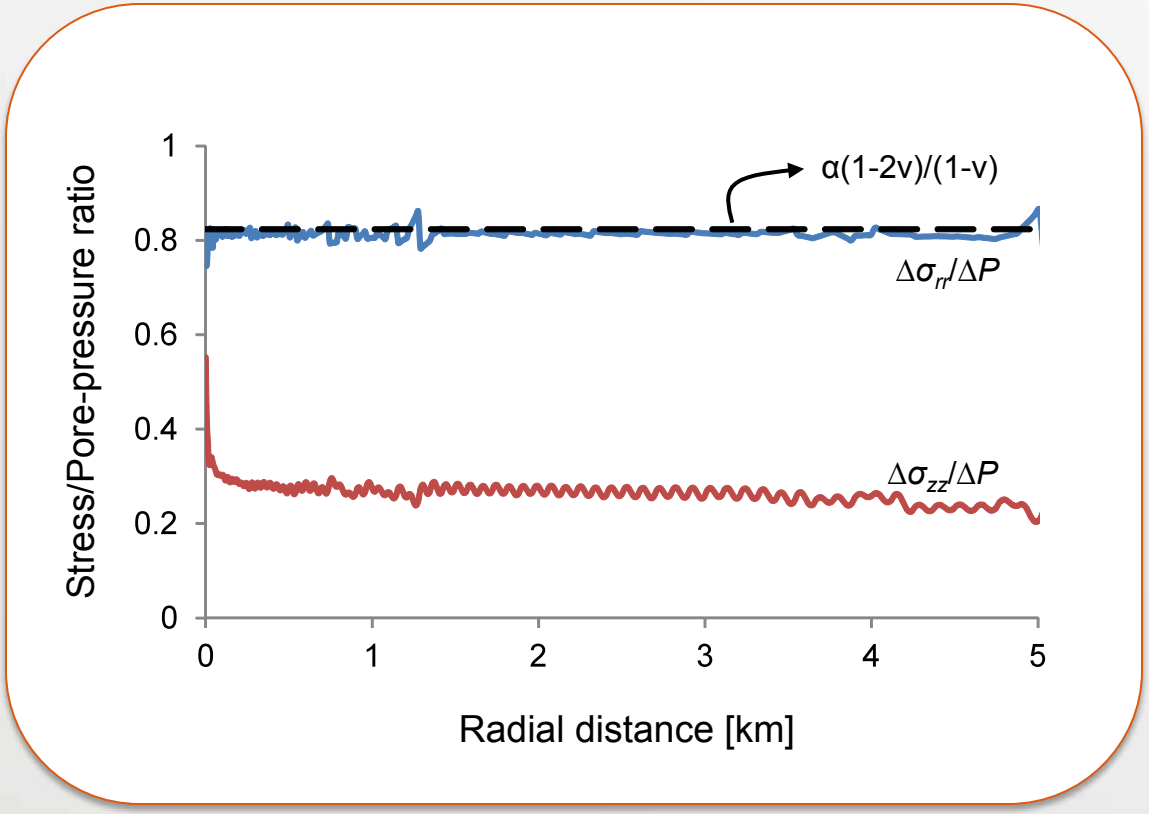


- Agreement in pressure increase
- No thermal change

→ Poroelastic effect

Additional Observation

- Pore pressure/stress coupling:



Summary

- Numerical simulation
  - Full coupling of fluid flow-poroelasticity
  - Versatile & Close to field conditions
- Pressure monitoring in AZMI at DAS, Cranfield
  - Simulation: ΔP=45kPa (31F-2), 40kPa (31F-3)
  - Field: Δ80kPa & Δ1°C (31F-2) & Δ40kPa (31F-3)
  - Interpretation: 31F-2 vs. 31F-3
  - Possible perturbation in field data

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1. Pressure monitoring in AZMI

2. Maximum sustainable pressure limit

Introduction

Federal requirements under the underground injection control (UIC) program for carbon dioxide (CO_2) geological sequestration (GS) wells (2010):

"Injection pressure limitations: EPA proposed that owners or operators limit injection pressure such that pressure in the injection zone does NOT exceed 90% of the ***fracture pressure*** of the injection zone, and that injection may not initiate new fractures or propagate existing fractures."

"The ***calculated fracture pressure*** -and therefore, the injection pressure limit- are based on site-specific geologic and geomechanical data collected during the site characterization process…"

- Reports on induced-seismicity: National Research Council (2012), IEAGHG (2013)

Maximum Pressure Limit

***Pressure Limit* for:**

1. Reactivation of existing fractures (or faults)
2. Tensile fracture (hydraulic fracture)
3. Shear failure of intact rock



Need information such as:

1. Initial state of stresses (vertical, horizontal, pore pressure,…)
2. Rock properties (fracture angle, friction, cohesion,…)
3. ***Pore pressure/stress coupling***
4. ***Thermal stress effect***

Pore Pressure/Stress Coupling

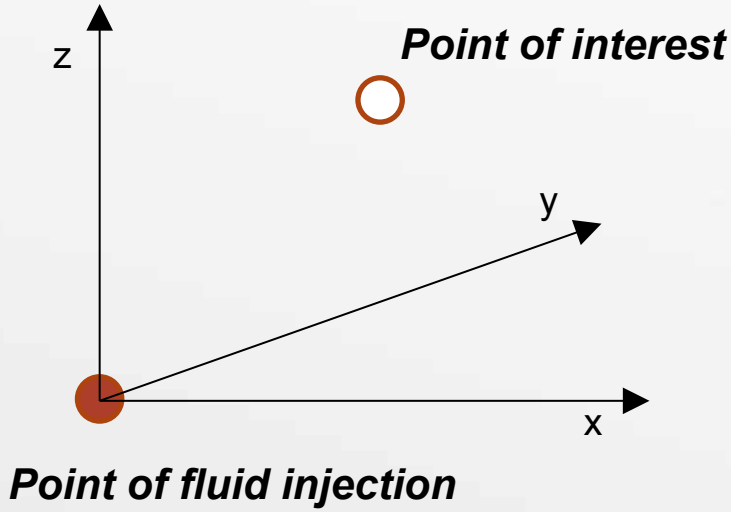
-Literature: Pore Pressure/Stress Coupling from Oil Production Sites

Area	$\Delta\sigma_h/\Delta P$	Source
Scotian Shelf, Canada	0.76	(1)
North West Shelf, Australia	0.75	(2)
Gannnet Fields, North Sea	0.60	(2)
Vicksburg Formation, South Texas	0.48	(3)
Ekofisk Field, North Sea	0.8	(4)
Wytch Farm Field, UK	0.65	(5)
US Gulf Coast	0.46	(6)

Elastic deformation in a porous rock ↔ Coupling in ***pore pressure*** & ***stress***

(1) Bell (1990), (2) Hillis (2000), (3) Salz (1977), (4) Teufel et al. (1991), (5) Addis (1977), (6) Breckels and Van Eek. (1982)

Theoretical Background



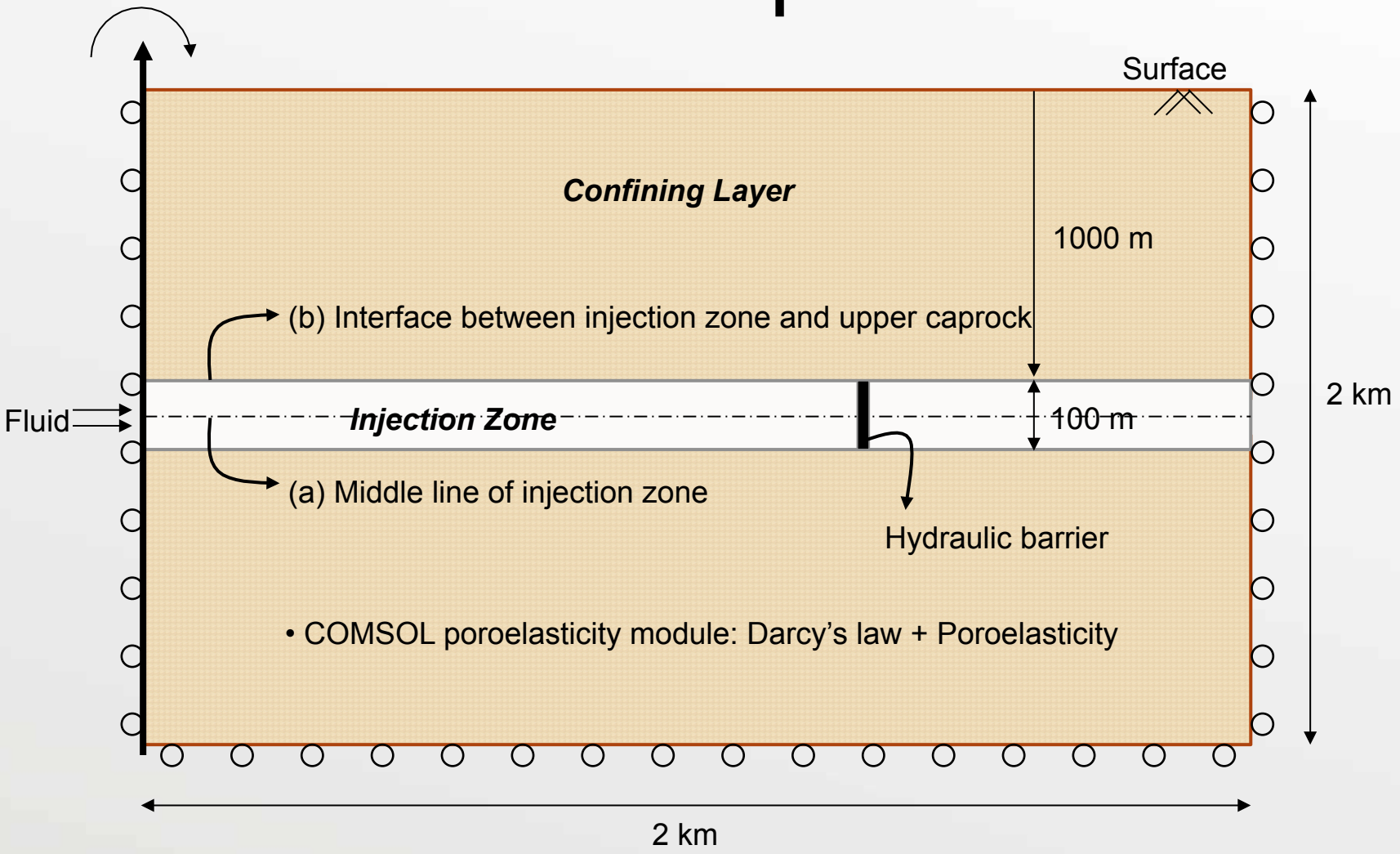
- For a continuous injection (homogenous media):

$$\frac{\Delta\sigma_{ij}(x,t)}{\Delta P(x,t)} = \frac{\alpha(1-2\nu)\{\delta_{ij}[erfc((1/2)\xi - (2/\xi^2)g(\xi)] + (x_i x_j / r^2)[erfc((1/2)\xi + (6/\xi^2)g(\xi)]\}}{2(1-\nu)erfc((1/2)\xi)}$$

Where, $r=(x_k \cdot x_k)^{1/2}$; $\xi = r/(c \cdot t)^{1/2}$; $erfc(z)=1-erf(z)$
α: Biot coefficient; ν: Poisson's ratio
c: hydraulic diffusivity

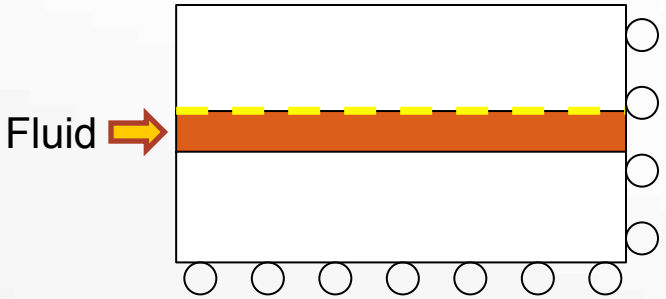
Rudnicki (1986); Altmann et al. (2010)

Numerical Experiments

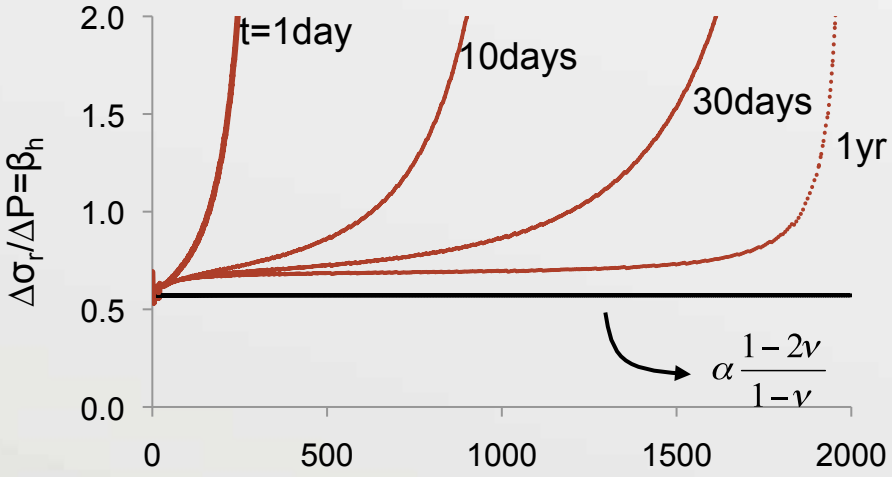


- Parameters: 1) Material properties
  2) Boundary condition (and hydraulic barrier)

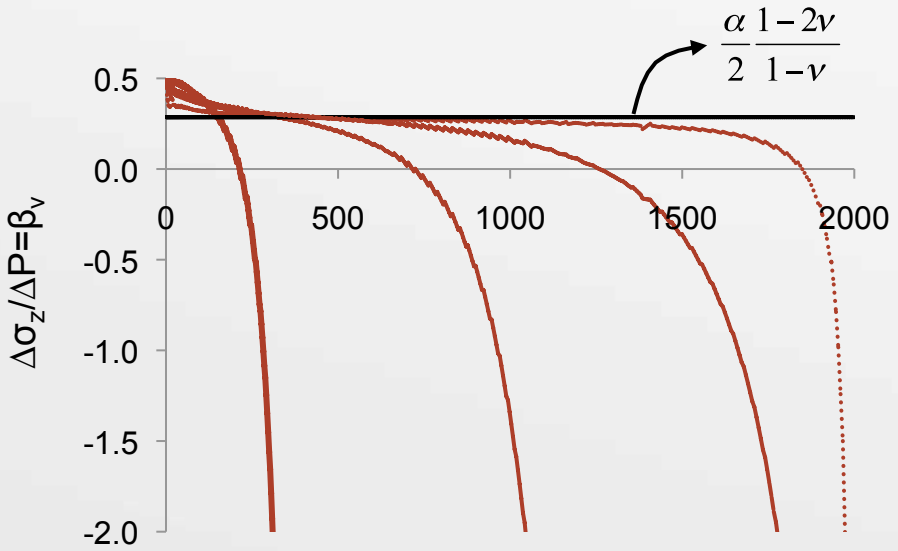
Result



- Radial stress/pore pressure



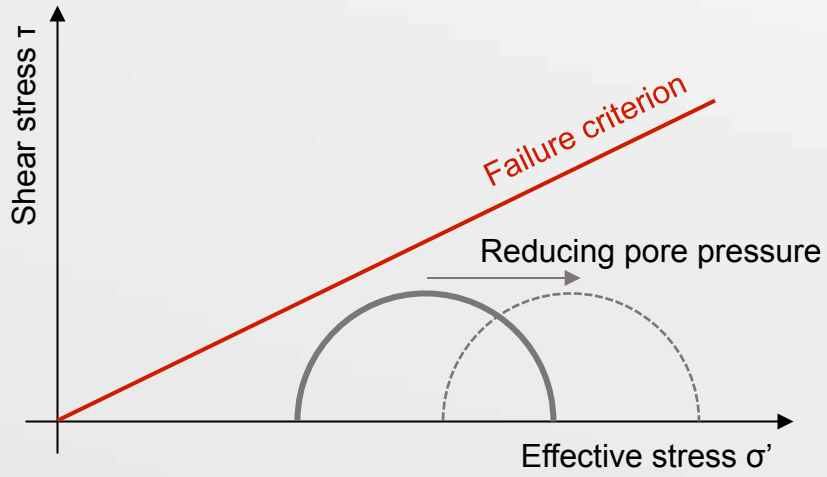
- Vertical stress/pore pressure



Implications - Fluid Extraction

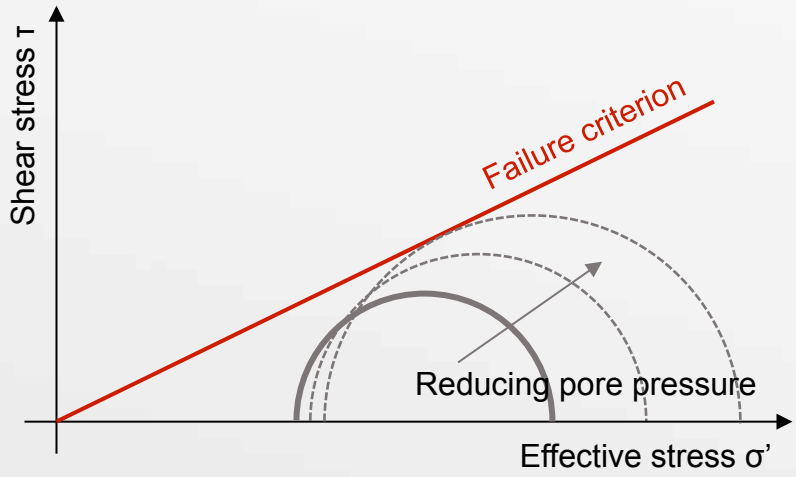
- Changes in the state of stresses

(a) Traditional approach



- Moves farther away from shear failure

(b) Consider $\Delta\sigma/\Delta P$ coupling

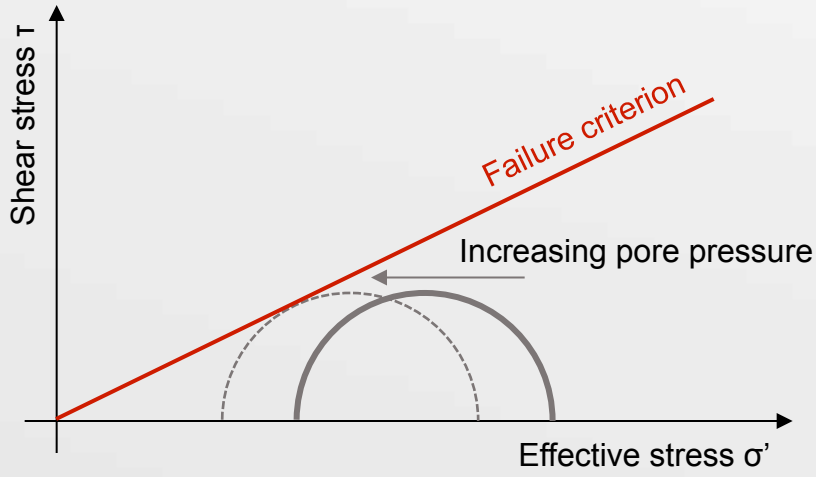


- Approaches toward shear failure

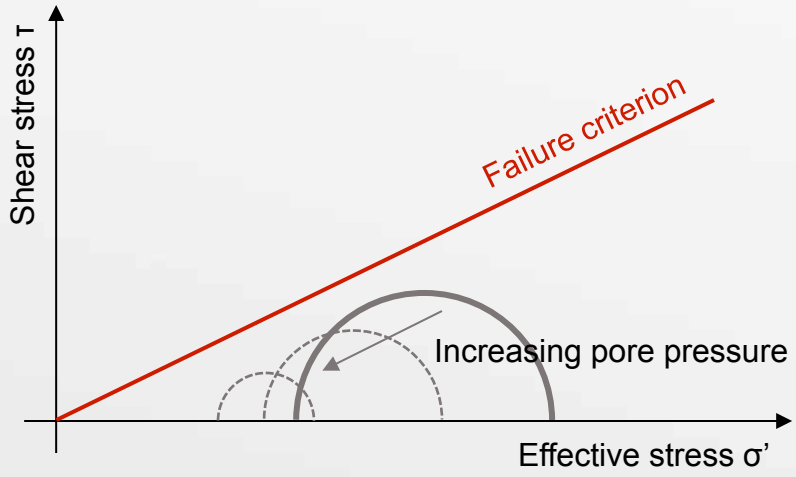
Implications - Fluid Injection

- Changes in the state of stresses

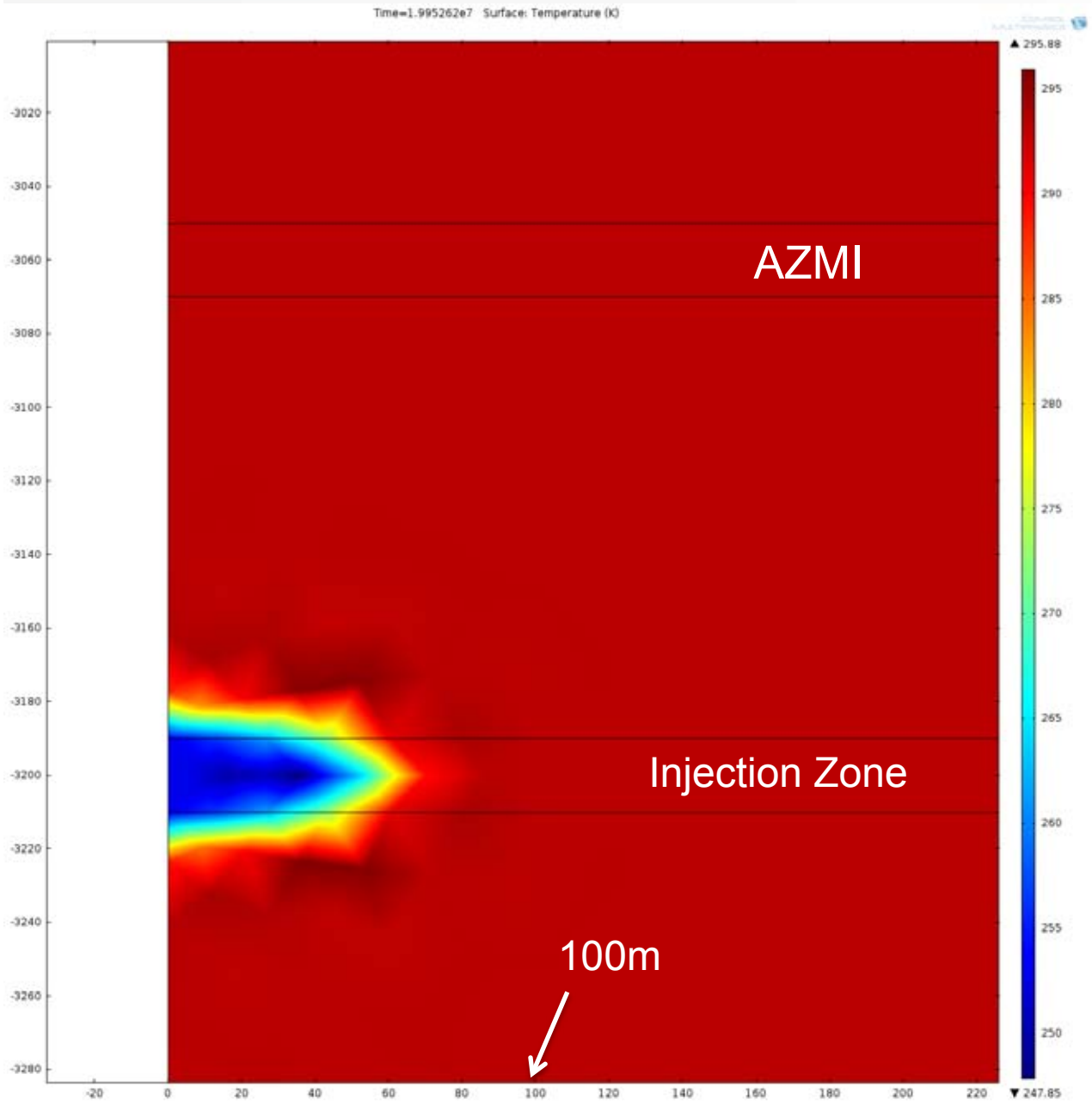
(a) Traditional approach



(b) Consider $\Delta\sigma/\Delta P$ coupling

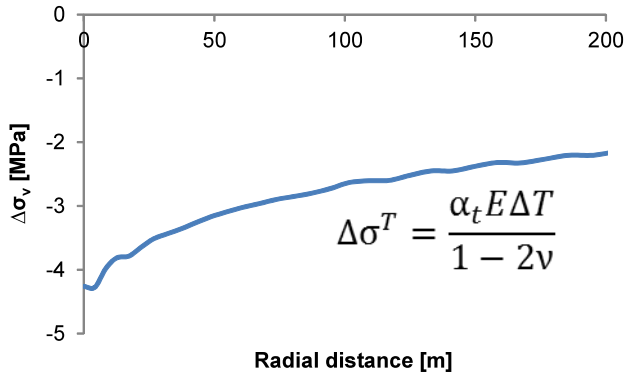


- May <u>underestimate</u> for maximum pressure limit

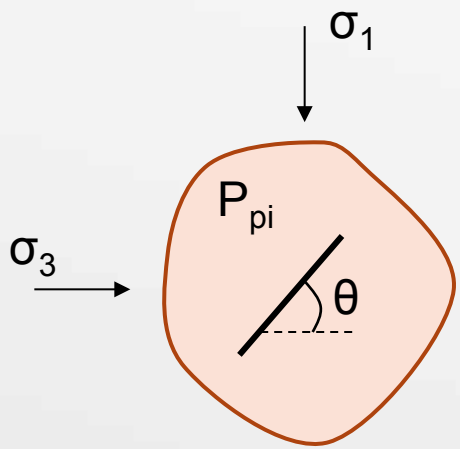


Thermal Stress Effect

Decrease in stress



Maximum Pressure Limit



1. Initial state of stresses: σ_1, σ_3, K, P_{pi}
2. Rock properties: μ_f, θ, E, v
3. Pore pressure/stress coupling: β_h, β_v
4. Thermal stress effect: α_T, ΔT

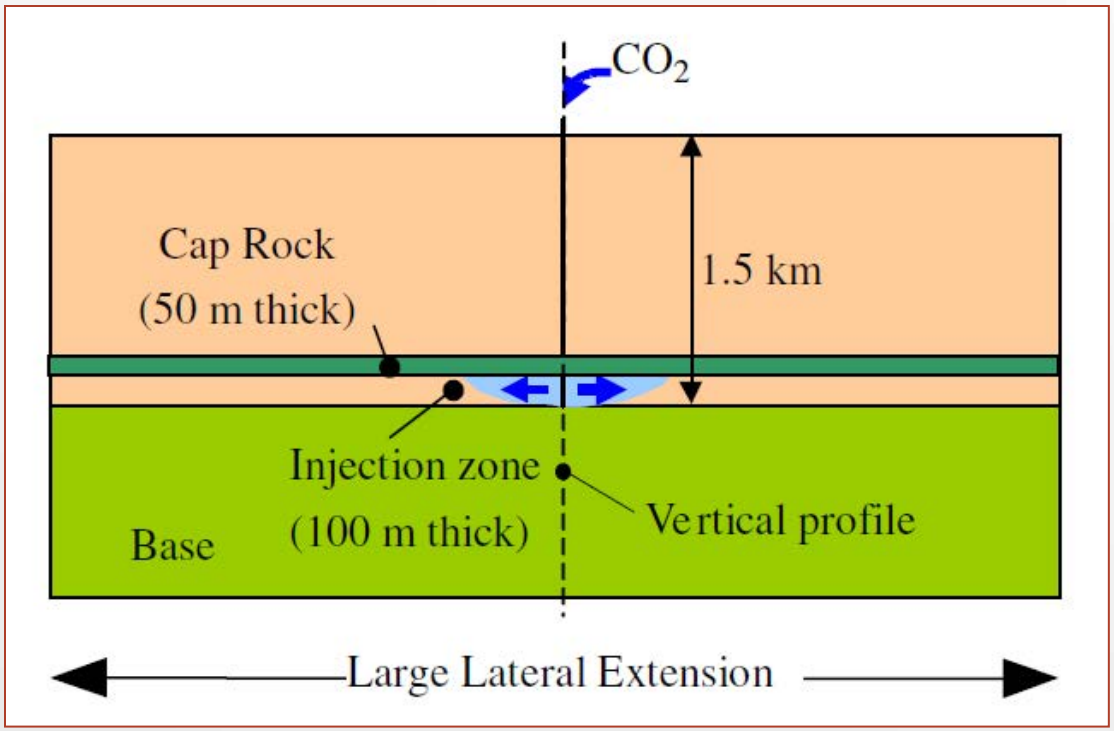
$$P_{max} = \frac{1}{\left[2\alpha - \beta_v - \beta_h - (\beta_v - \beta_h)cos2\theta + (\beta_v - \beta_h)\frac{sin2\theta}{\mu_f}\right]} \cdot$$

$$[\{(1+K) + (1-K)cos2\theta - (1-K)\frac{sin2\theta}{\mu_f}\}\sigma_{v0}$$

$$-\left\{(\beta_v + \beta_h) + (\beta_v - \beta_h)cos2\theta - (\beta_v - \beta_h)\frac{sin2\theta}{\mu_f}\right\}P_{pi} - \frac{2\alpha_T E\Delta T}{(1-2v)}]$$

Normal-fault regime

Application



v=0.25
α=1
σ_{h0}/σ_{v0}=0.7
Rutqvist et al. (2007)

- Shear-slip analysis using TOUGH2-FLAC: ΔP_{max}**=13.3MPa** (Rutqvist et al. 2007)
- Traditional approach: ΔP_{max}=4.3MPa; Simplified poroelastic method: ΔP_{max}=48.3MPa
- ***This method: ΔP_{max}=13.5MPa***

Summary

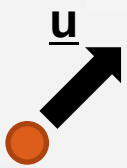
- CO_2 Injection: Change in pore pressure ΔP is coupled with change in stress $\Delta\sigma$.
- Asymptotic value: $\Delta\sigma_r/\Delta P \approx \alpha\cdot(1-2v)/(1-v)$, $\Delta\sigma_z/\Delta P \approx 0.5\Delta\sigma_r/\Delta P$.
    - Biot coefficient α and Poisson's ratio v: Determine asymptotic values.
    - Boltzmann variable $\xi = r/(c\cdot t)^{1/2}$: Affects spatio-temporal evolution.
- Inhomogeneity & structural complexity: Better to do numerical simulation for $\Delta\sigma/\Delta P$.
- Incorporation of all $\Delta\sigma/\Delta P \rightarrow$ Reliable maximum sustainable pressure limit ΔP_{max}.
    - Traditional approach: may underestimate.
    - Simplified poroelastic analysis: may overestimate.

Thank you!

Question?

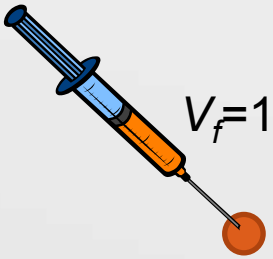
Theory (1/2)

- Green's function $g_i(\underline{x}, \underline{\xi})$:



(x_1, x_2, x_3)

Response at a point $\underline{x}$ due to a unit impulse at a point $\underline{\xi}$



Theory (2/2)

- Analytical computation:

1) Injection: Diffusion equation

$$c\nabla^2(\Delta m) = \partial(\Delta m)/\partial t$$

2) Displacement & Strain:

$$u_i(x,t) = \frac{\alpha}{G}\int p(\xi,t)g_i(x,\xi)dV_\xi$$

3) Stress: constitutive equation

$$G_{ij} = \frac{\partial g_i}{\partial x_j} + \frac{\partial g_j}{\partial x_i} + \frac{2\nu}{1-2\nu}\frac{\partial g_k}{\partial x_k}\delta_{ij}$$

4) Pore pressure: poroelasticity

$$2\mu\varepsilon_{ij} = \sigma_{ij} - \frac{\nu_u}{1+\nu_u}\sigma_{kk}\delta_{ij} + \frac{2GB}{3\rho_0}\Delta m\delta_{ij}$$

$$\Delta m = \frac{3\rho_0(\nu_u - \nu)}{2GB(1+\nu)(1+\nu_u)}\left[\sigma_{kk} + \frac{3}{B}p_f\right]$$

where,
ε_{ij}: strain
σ_{ij}: stress
p_f: fluid pore pressure
Δm: fluid mass content per unit vol.
v: Poisson's ratio

Numerical Simulation

- COMSOL poroelasticity module: Darcy's law + Poroelasticity

Fluid equation ⟷ Solid mechanics

$$\frac{\partial}{\partial t}(\rho_f \phi) + \nabla \cdot (\rho_f \boldsymbol{u}) = Q_m$$

Velocity: $\boldsymbol{u} = -\frac{\kappa}{\mu}(\nabla p_f + \rho_f g \nabla h)$

Storage: $\frac{\partial}{\partial t}(\rho_f \phi) = \rho_f S \frac{\partial p_f}{\partial t}$

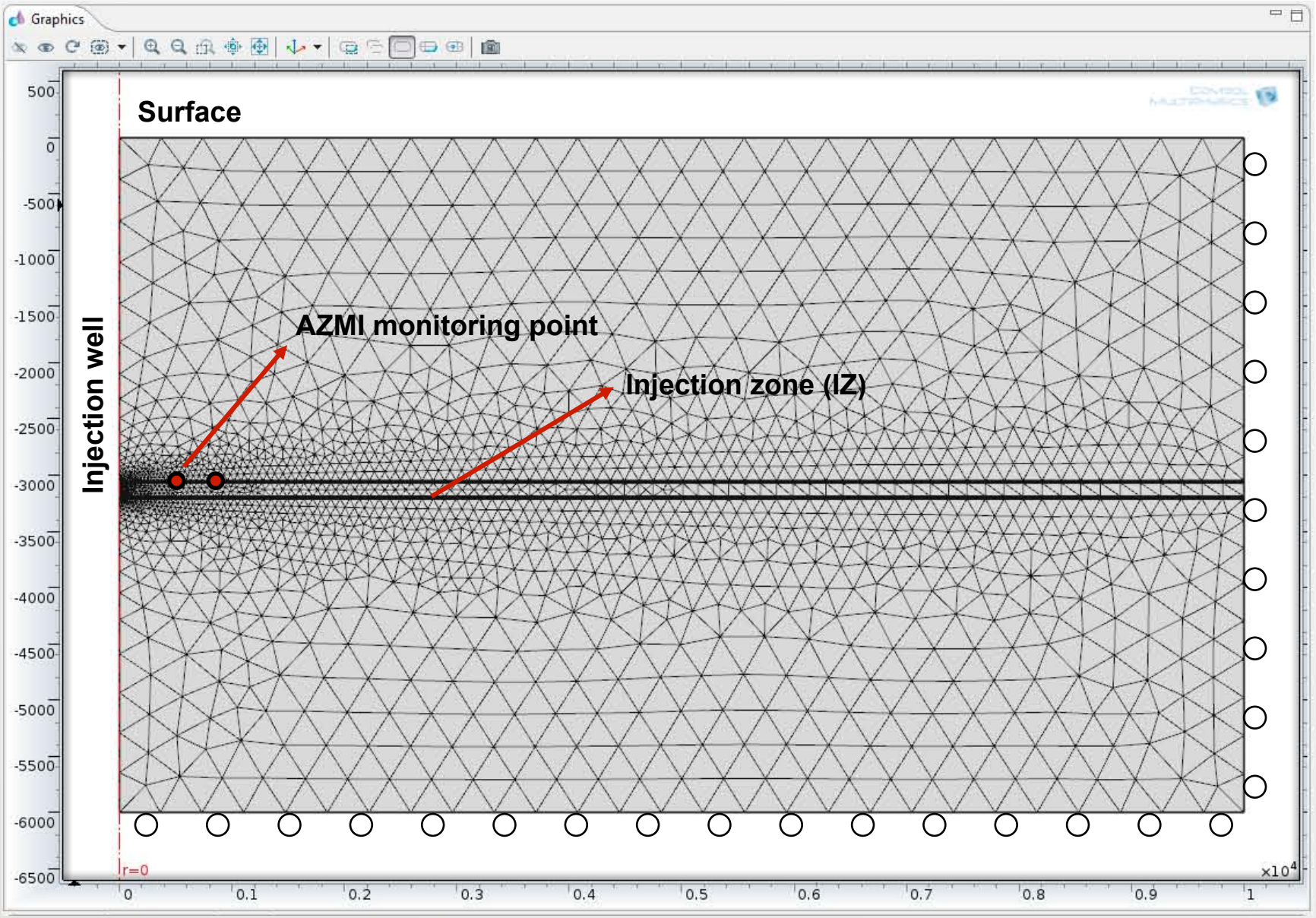
$$\sigma = \boldsymbol{C}\varepsilon - \alpha p_f \boldsymbol{I}$$

Volumetric part: $\frac{\sigma_{kk}}{3} = K_d \varepsilon_{vol} - \alpha p_f$

Pore pressure: $p_f = \frac{(\zeta - \alpha \varepsilon_{vol})}{S}$

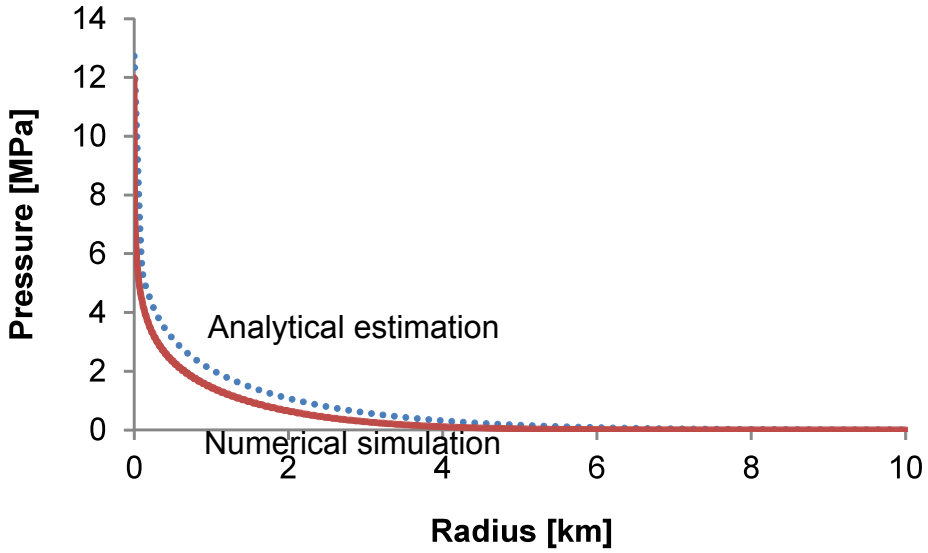
where, $S = \frac{\phi}{K_f} + (\alpha - \phi)\frac{1-\alpha}{K_d}$

- COMSOL: simulation model

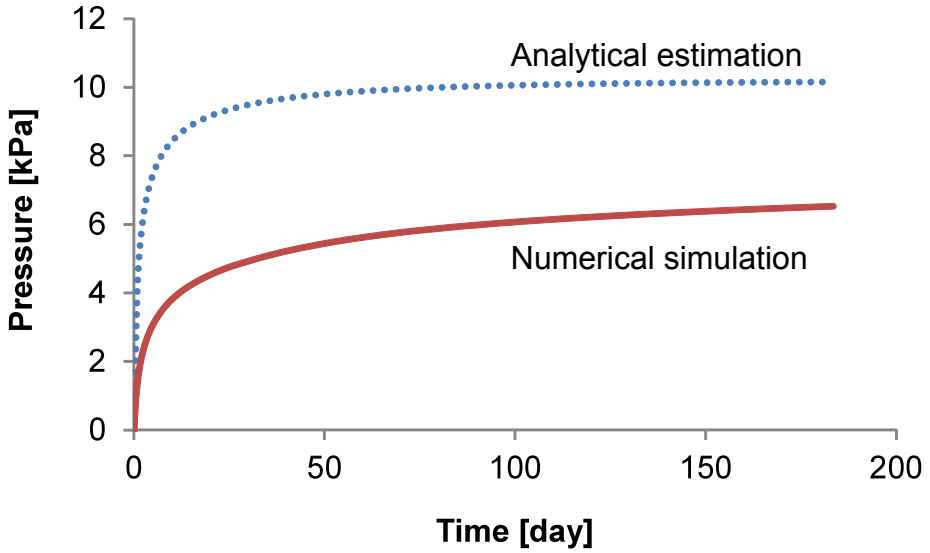


Comparison with Analytical Approach

Pore pressure distribution - IZ

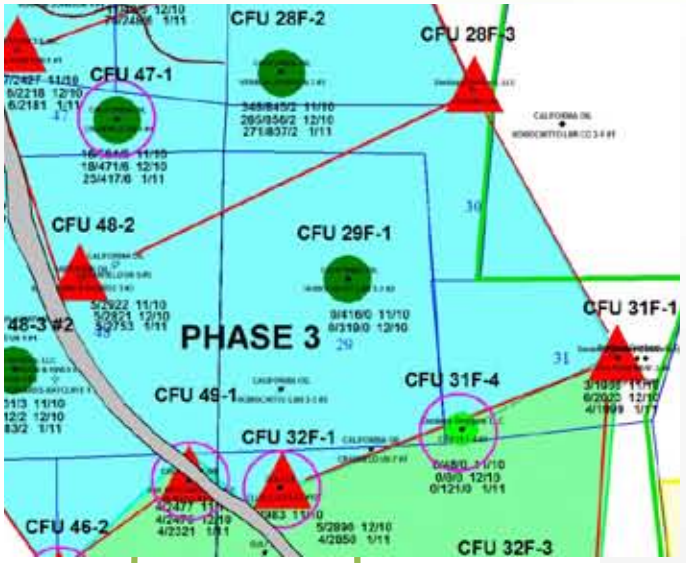


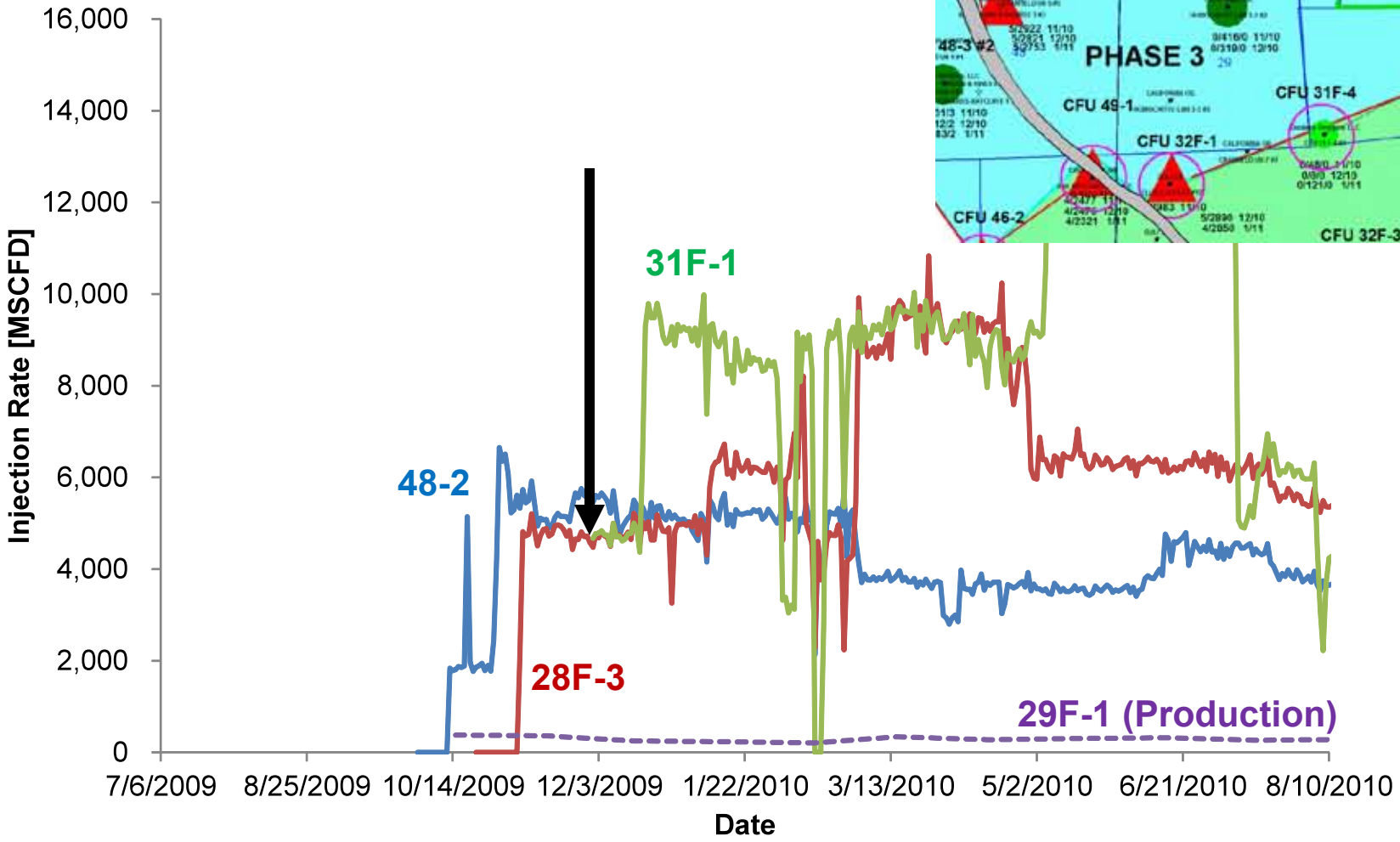
Pore pressure in AZMI



- Stress relief due to displacements (numerical simulation)

Cranfield- Operatio





Gulf Coast Carbon Center: Near-Surface Update

Jacob Anderson, Dr. Katherine Romanak, Dr. Changbing Yang
Gulf Coast Carbon Center, Bureau of Economic Geology
Jackson School of Geosciences, University of Texas at Austin

presentation for:
SECARB 9th Annual Stakeholders Briefing

Atlanta, GA
March 4-5, 2014

Content

- Groundwater
  - Sampling Updates
  - CO_2 Impacts on Groundwater
- Soil Gas
  - Process-Based Approach
  - Case Study – Cranfield P-Site
- Innovative New Methods

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Field campaign for groundwater sampling

- Two field campaigns
  - June, 2013
  - December, 2013



  - ~10 water wells
  - Groundwater pH, alkalinity, DIC, concentrations of major and trace elements
  - Dissolved gases in groundwater, especially CH_4

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Field campaign for groundwater sampling

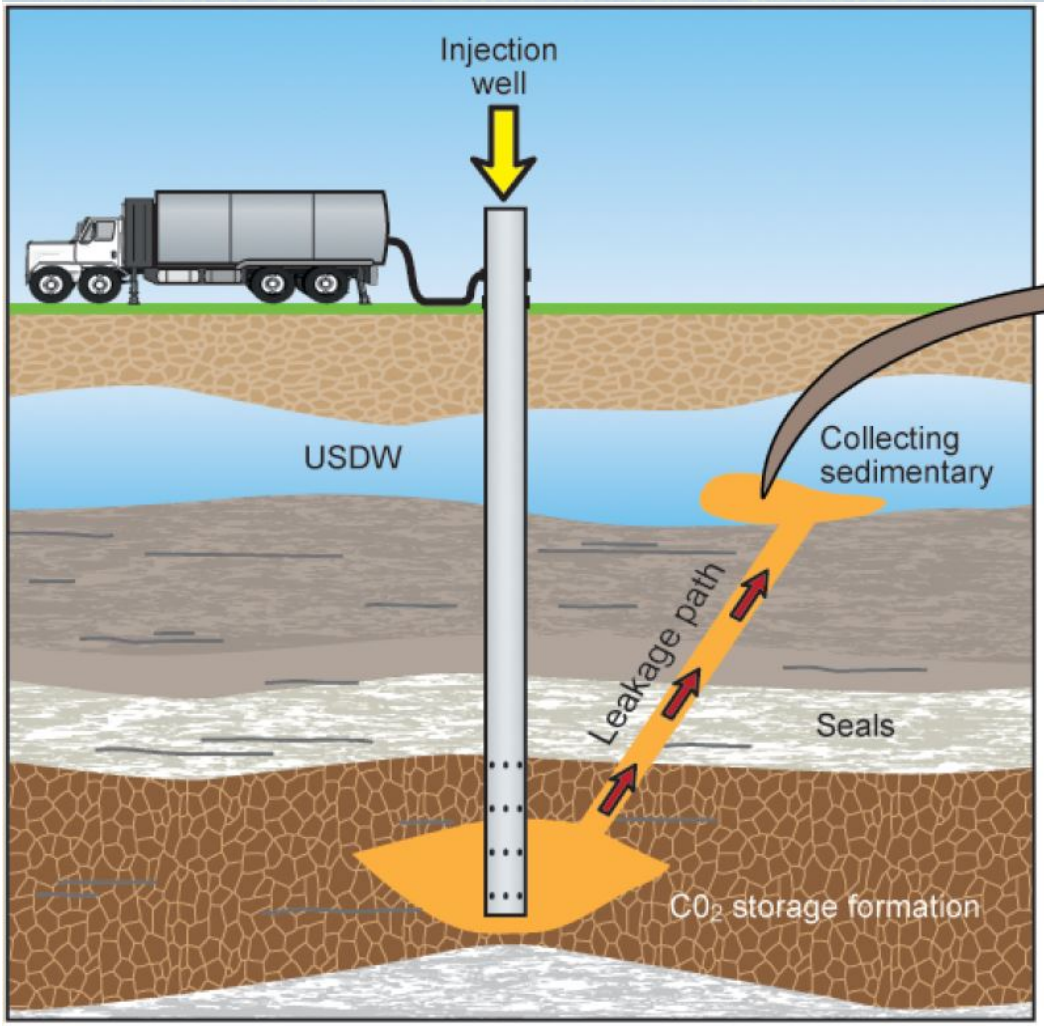
- No obvious change in groundwater chemistry in the shallow aquifer

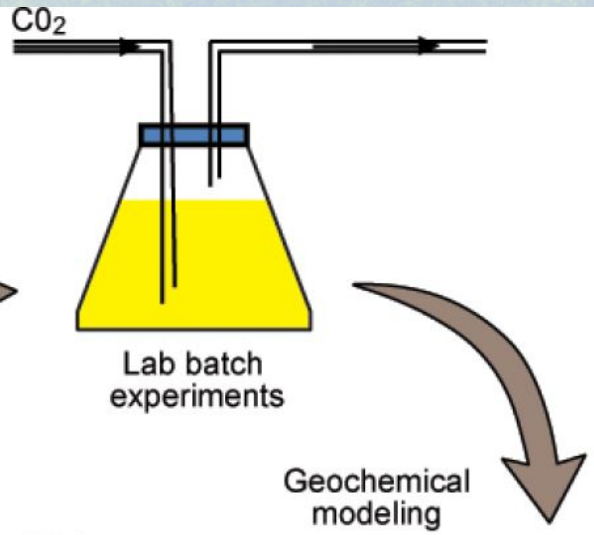
- Dissolved CH4 in groundwater are very low, some are under detection



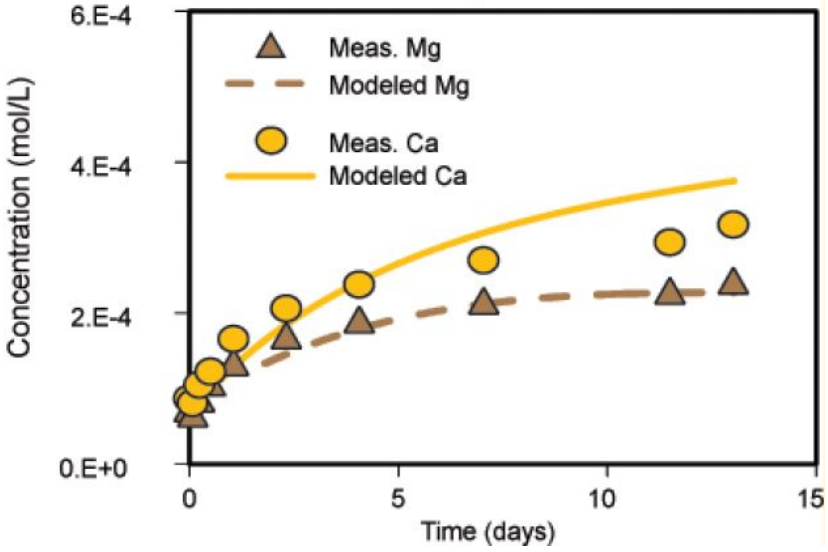


Inverse Modeling of Water-Rock-CO_2 Batch Experiments: Potential Impacts on Groundwater Resources at Carbon Sequestration Sites





Geochemical modeling



Inverse Modeling of Water-Rock-CO_2 Batch Experiments: Potential Impacts on Groundwater Resources at Carbon Sequestration Sites

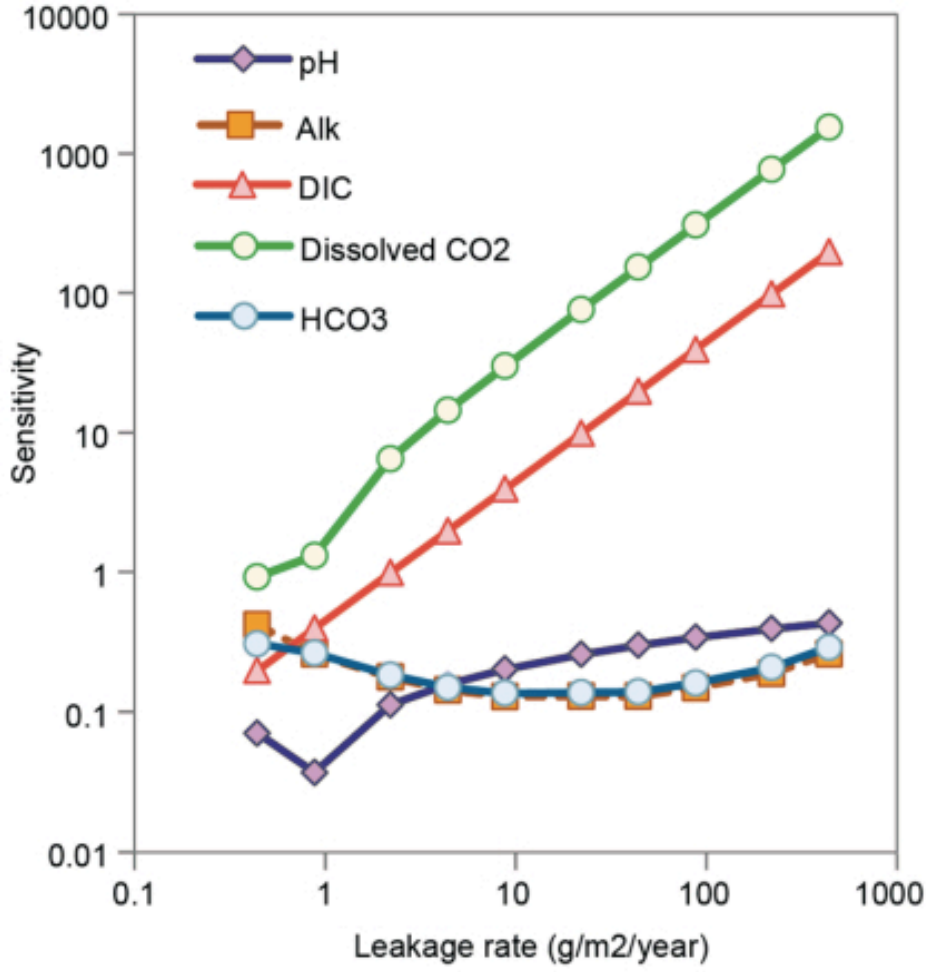
- Groundwater pH reductions were more significant in the carbonate-poor aquifers than in the carbonate-rich aquifers.

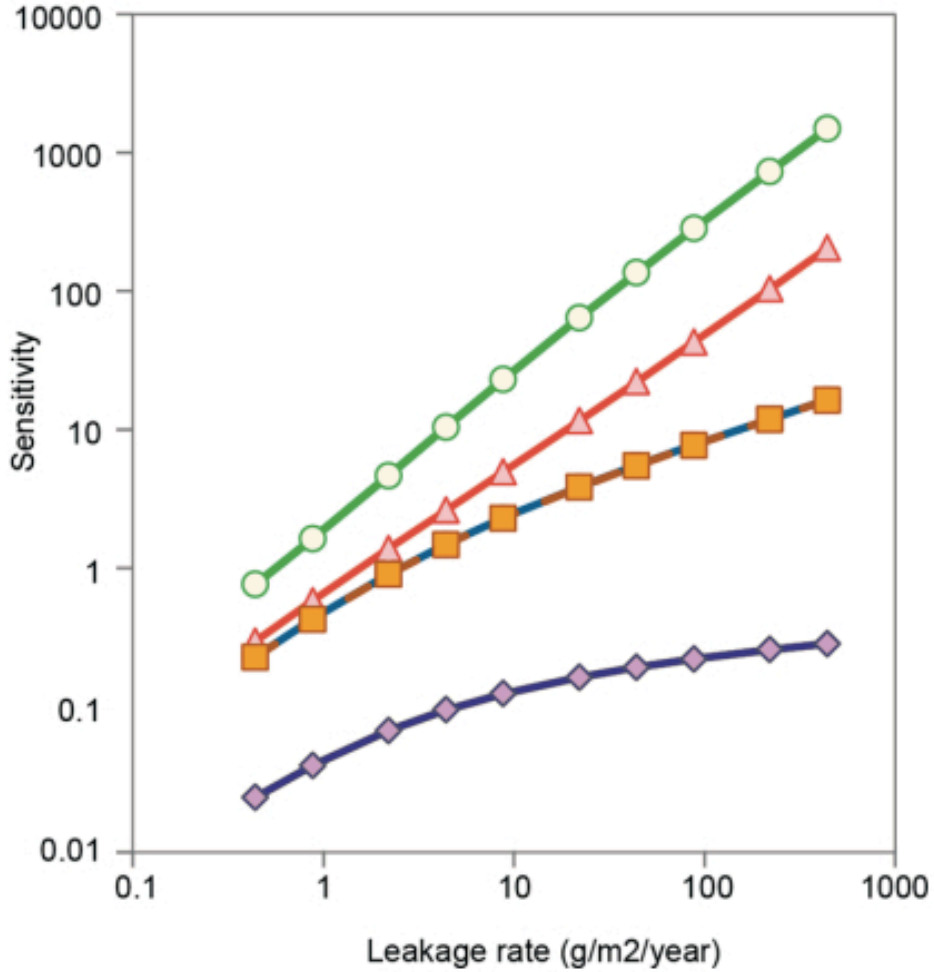
- The geochemical model confirmed that mobilization of trace metals was caused likely by mineral dissolution and desorption from clay mineral surfaces.

- A selection of geochemical parameters are needed for site-specific CO2 leakage detection.

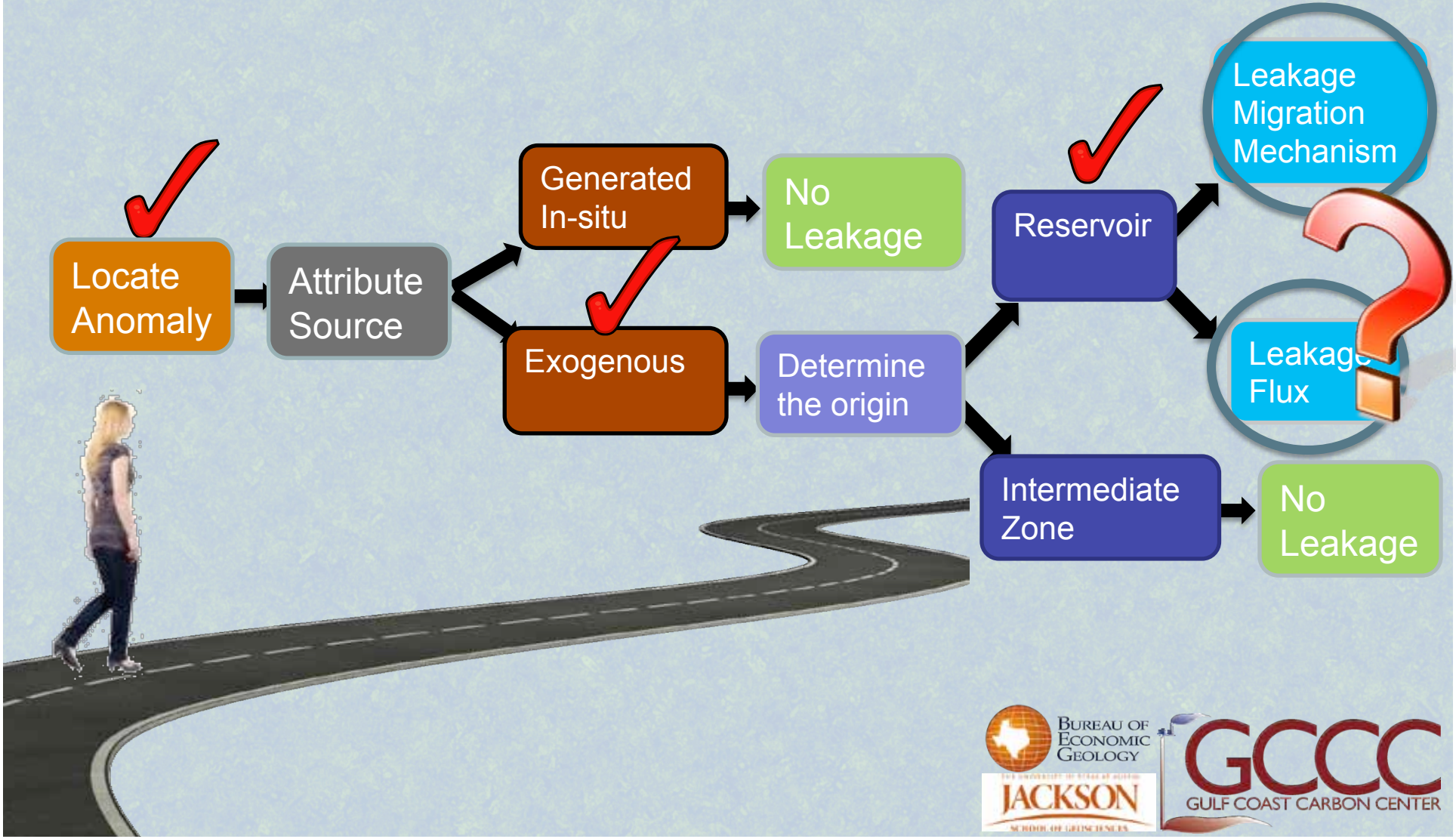
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Geochemical sensitivity to CO_2 leakage: detection in potable aquifers at carbon sequestration sites





Near-Surface Leakage Assessment



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Process-Based Soil-Gas Approach





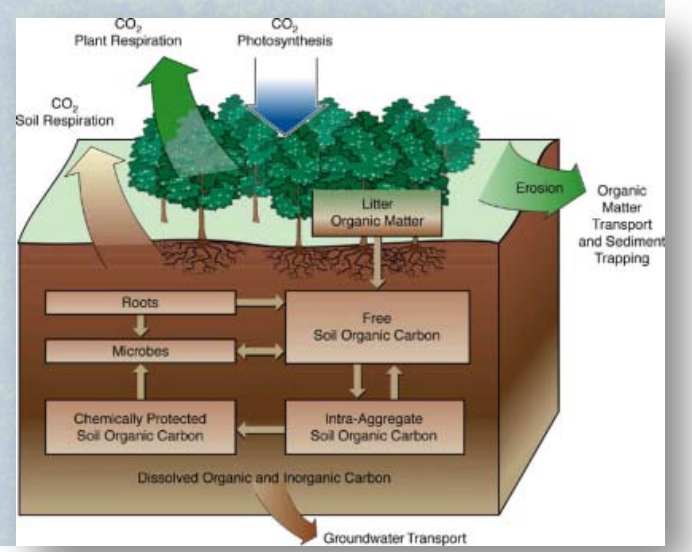


- Developed at a natural CO_2-rich perched playa wetland in West Texas (Romanak et al., 2012)
- Tested at ZERT Controlled Release Field Laboratory (Romanak et al., 2013a)
- Applied at the Kerr Farm, Weyburn-Midale Oilfield where landowners claimed leakage (Romanak et al., 2013b)

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Process-Based Approach

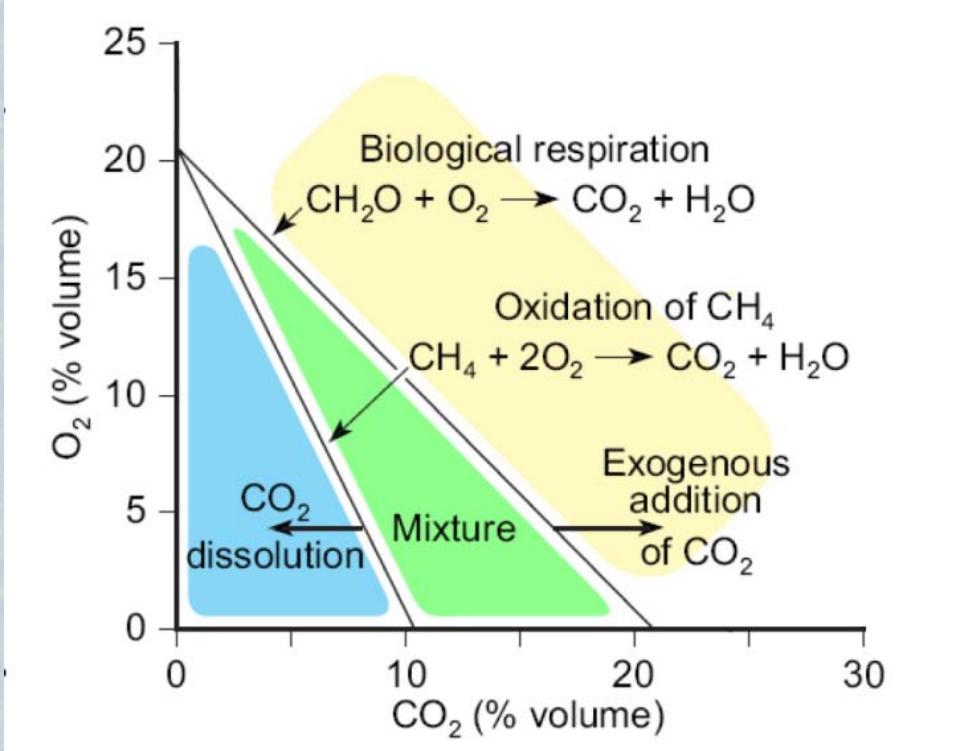
- Approach for near-surface leakage detection above CCS sites
- Different than concentration-based methods that rely on 1-3 years of background measurements and large complex data sets
- Promptly identifies a leakage signal using 3 important ratios of simple coexisting gases (CO_2, CH_4, N_2, O_2)
- Discerns among:
  - Methane oxidation
  - Biologic respiration
  - CO_2 dissolution and reaction with carbonate
  - Atmospheric mixing/dilution
  - Leakage Signal



Process-Based Gas Ratio - 1

O_2 vs. CO_2

- Indicates natural processes that affect CO_2 concentrations
- Distinguishes among respiration, CH_4 oxidation and dissolution
- Gives an initial assessment of leakage

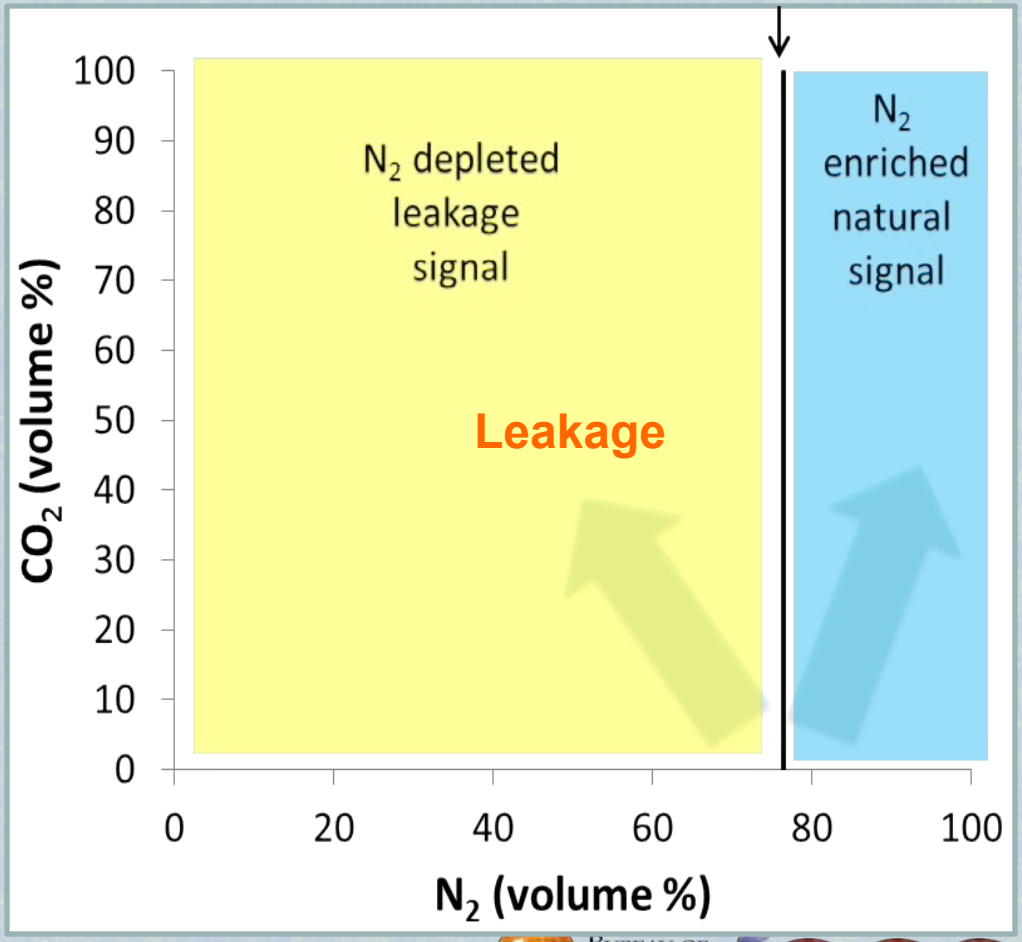


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Process-Based Gas Ratio - 2

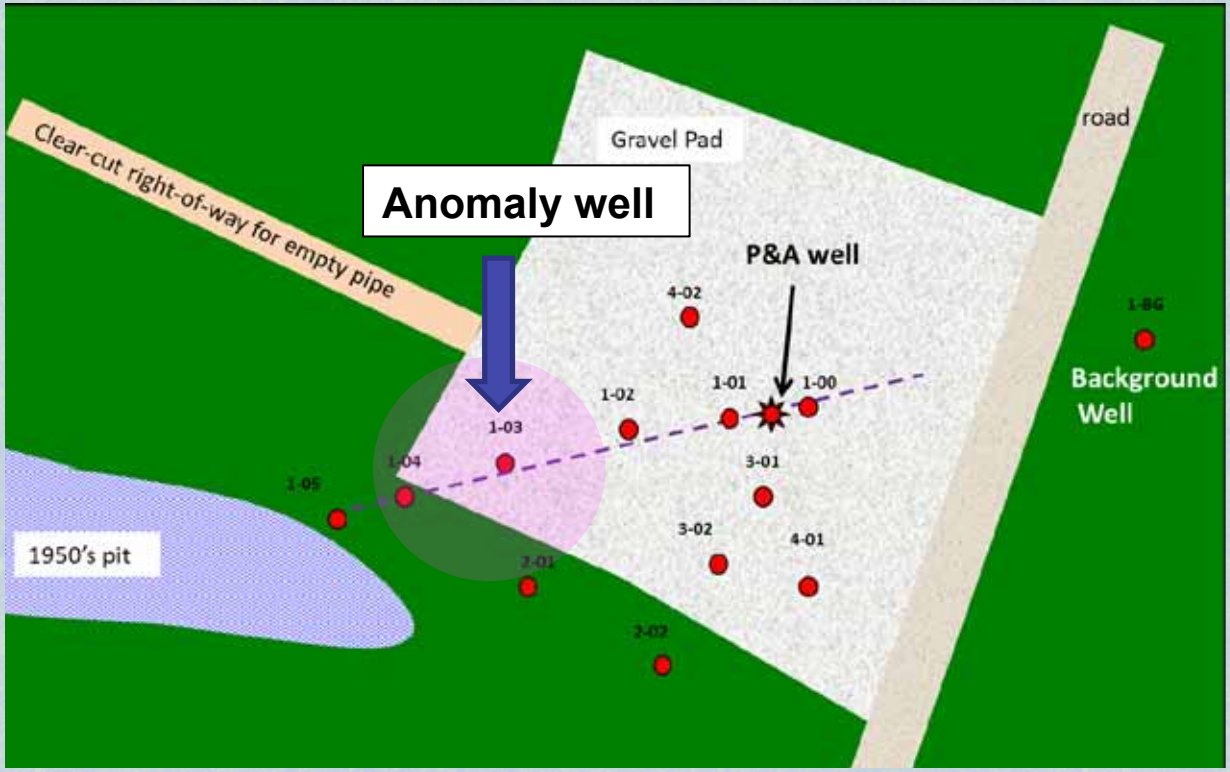
CO_2 vs. N_2

- Identifies whether gas has migrated from depth.
- Indicates whether CO_2 is being added through leakage or lost through dissolution.



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Cranfield, MS P-Site

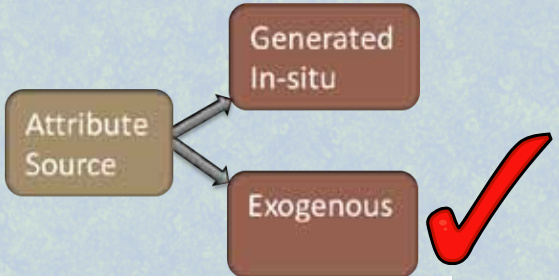


- Pad, Pit, Plants, P&A well
- Localized monitoring beginning Sept 2009
- 13 multi-depth soil gas sampling stations - 5 m depth
- Localized soil gas anomaly at 1-03
  - **$CH_4 \leq 50$ vol. %**
  - **$CO_2 \leq 45$ vol. %**

✓ Locate Anomaly

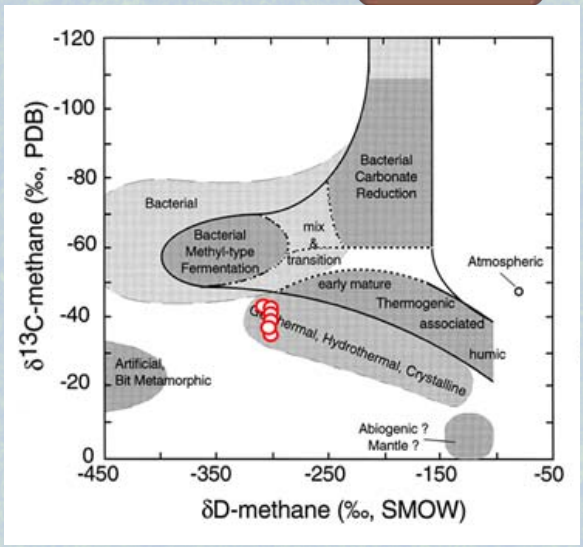
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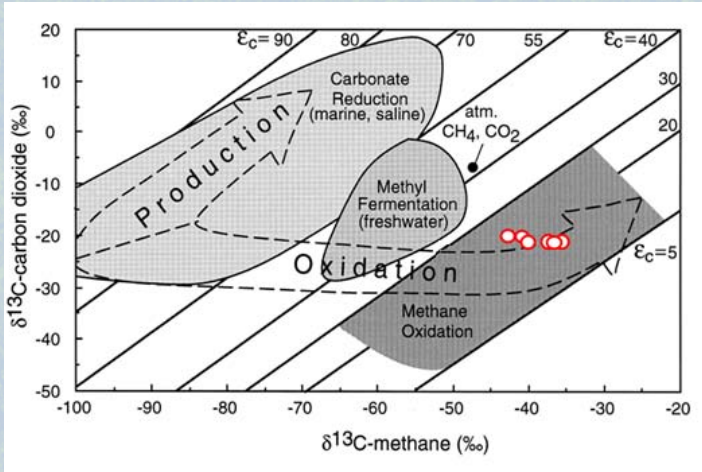
Attribute Source



Exogenous Source Confirmed by Isotopic Signature

- Anomalous CH_4 from a deep thermogenic oil and gas reservoir
- CO_2 derived from oxidation of the methane

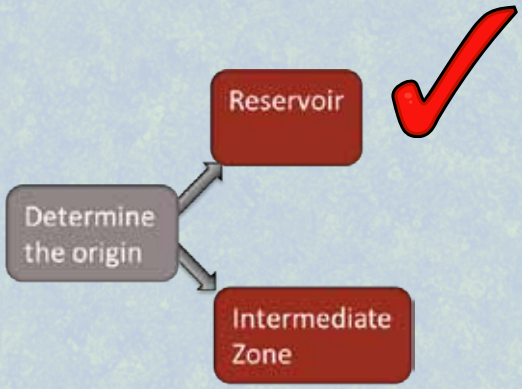


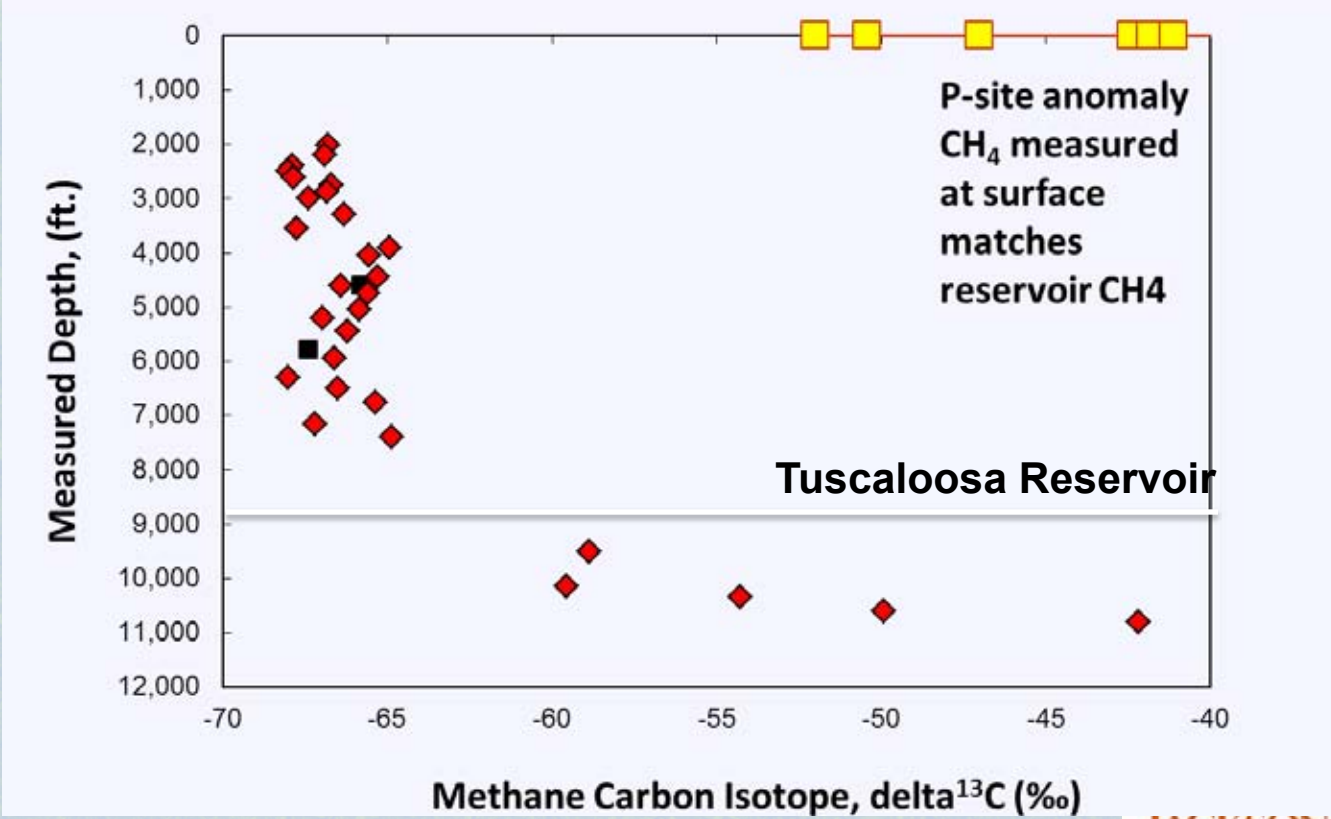


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Determining Origin

Tuscaloosa reservoir (10,000 ft, 3200 m)
or intermediate Wilcox (6,000 ft, 2000 m)





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Environmental



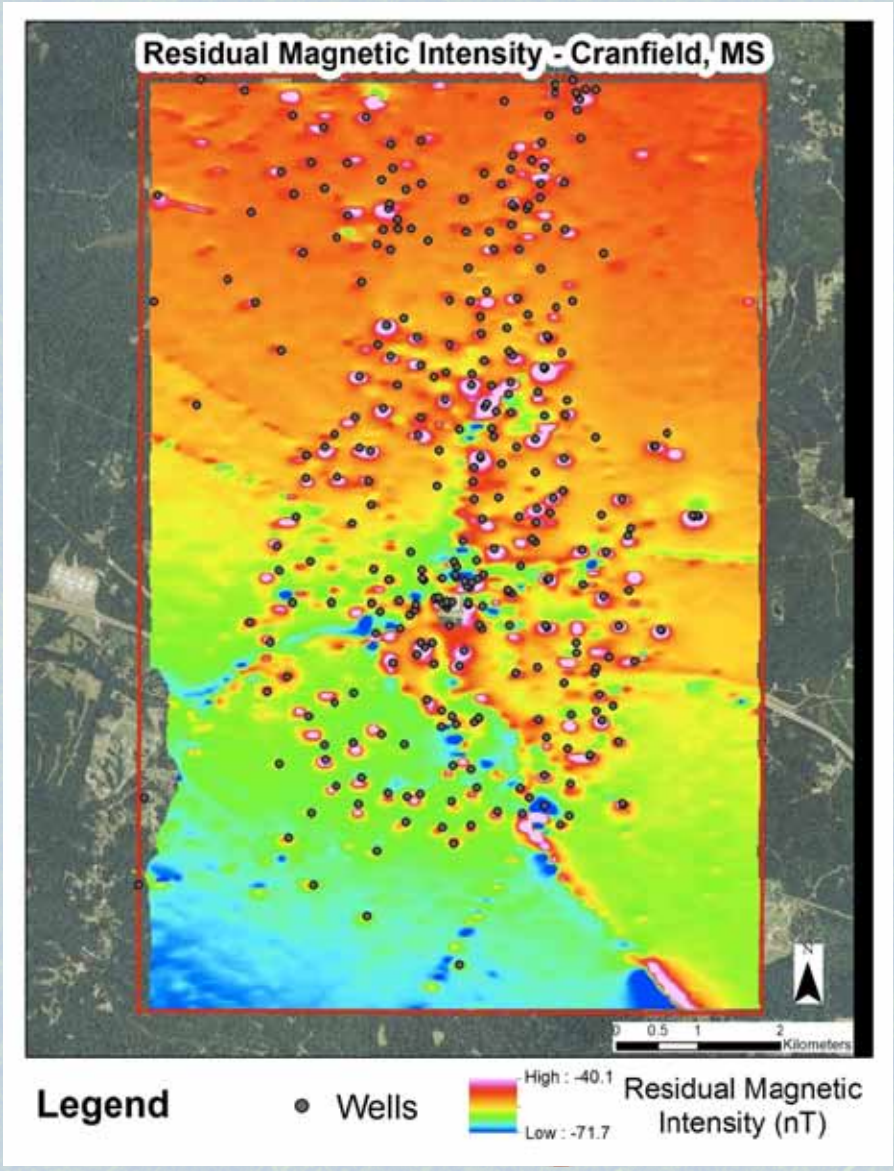
Innovative Use of Magnetics

Goal:

- Improve CCS site characterization by identifying past hydrocarbon migration.
- Hydrocarbon migration can cause deposition of magnetic minerals.

Next Steps:

- Remove cultural signals.
- Remove regional geological trend.
- Identify near-surface geological anomalies.



Conclusions

- Almost no observed changes in groundwater chemistry from injection.
- Numerical simulations show that DIC is most sensitive to leakage.
- Process-based soil gas monitoring can effectively identify leakage.
- Future work includes migration pathway identification and innovative monitoring methods.

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JACKSON SCHOOL OF GEOSCIENCES
GCCC
GULF COAST CARBON CENTER

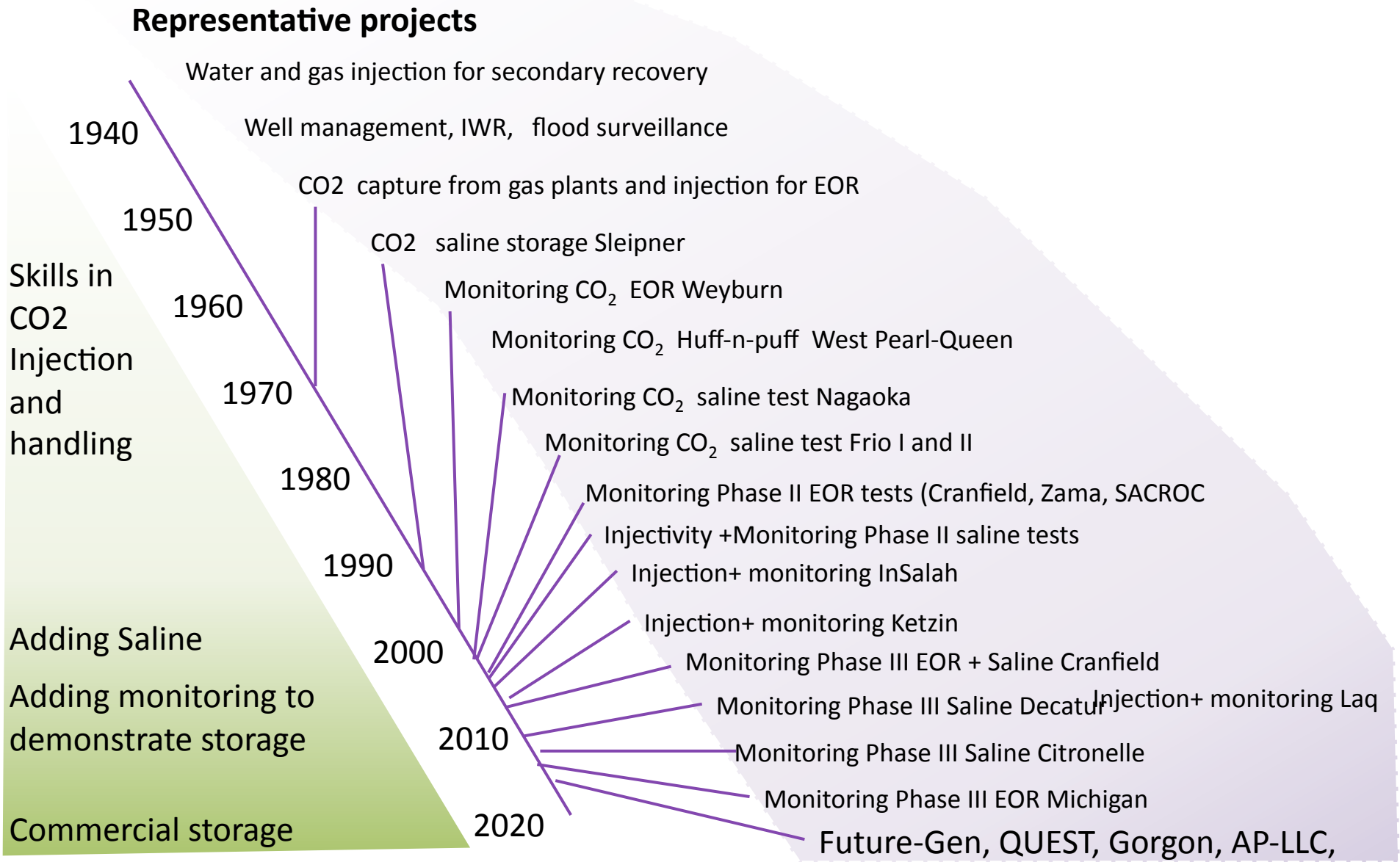
Monitoring Design Best Practices

Susan Hovorka
Gulf Coast Carbon Center
Bureau of Economic Geology
The University of Texas at Austin

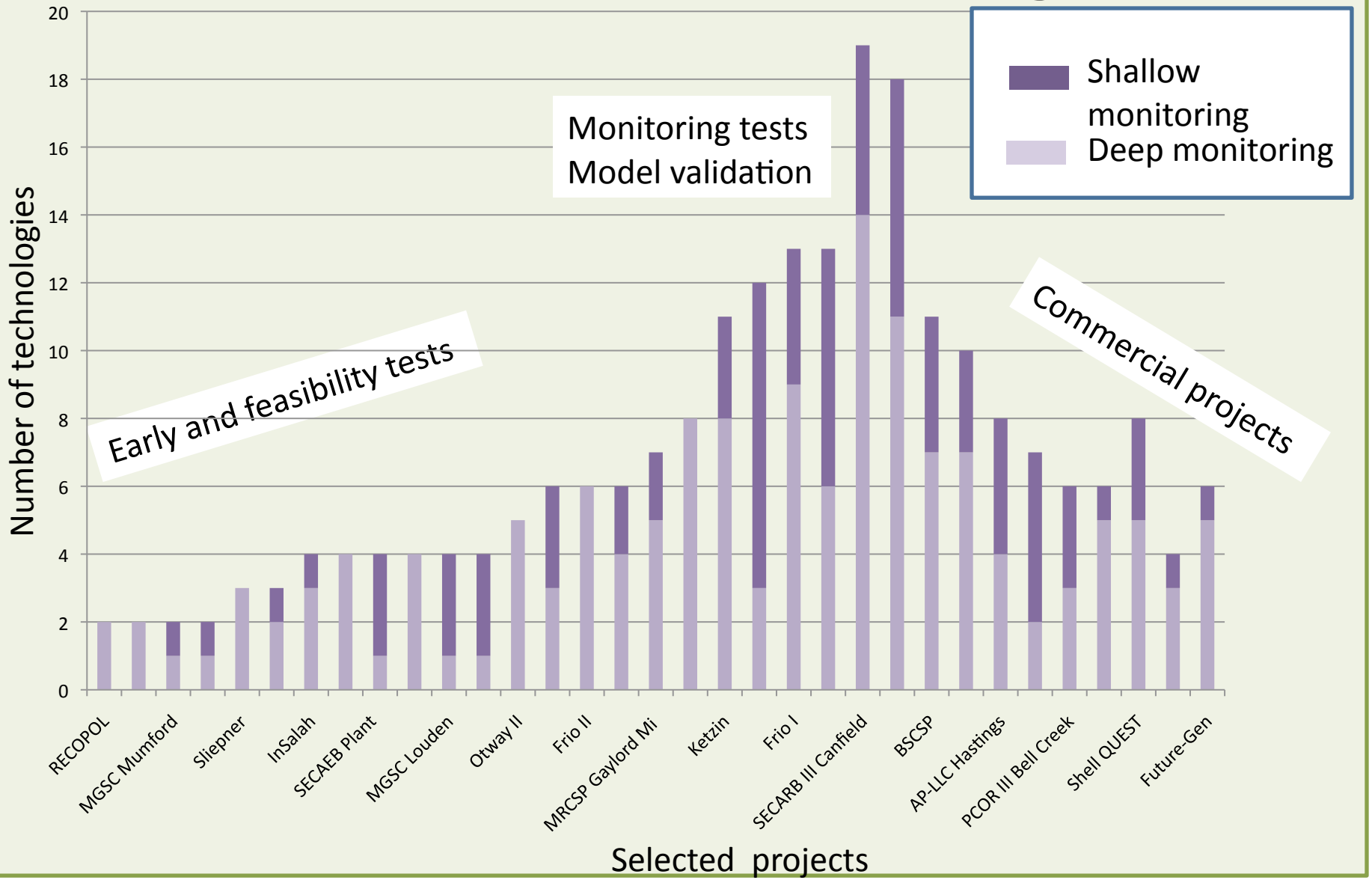
Presented at the
SECARB Stakeholders Briefing

March 5, 2014, Atlanta GA

Safe and Effective Injection > 50 years



Amount of Monitoring



Transition From… To

Research Monitoring

Tests-

- Hypotheses about the nature of the perturbation created
  - compare response modeled to the response observed via monitoring.
- Performance and sensitivity of monitoring tools
  - sensitivity to the perturbation
  - conditions under which tool is useful,
  - reliability under field conditions.

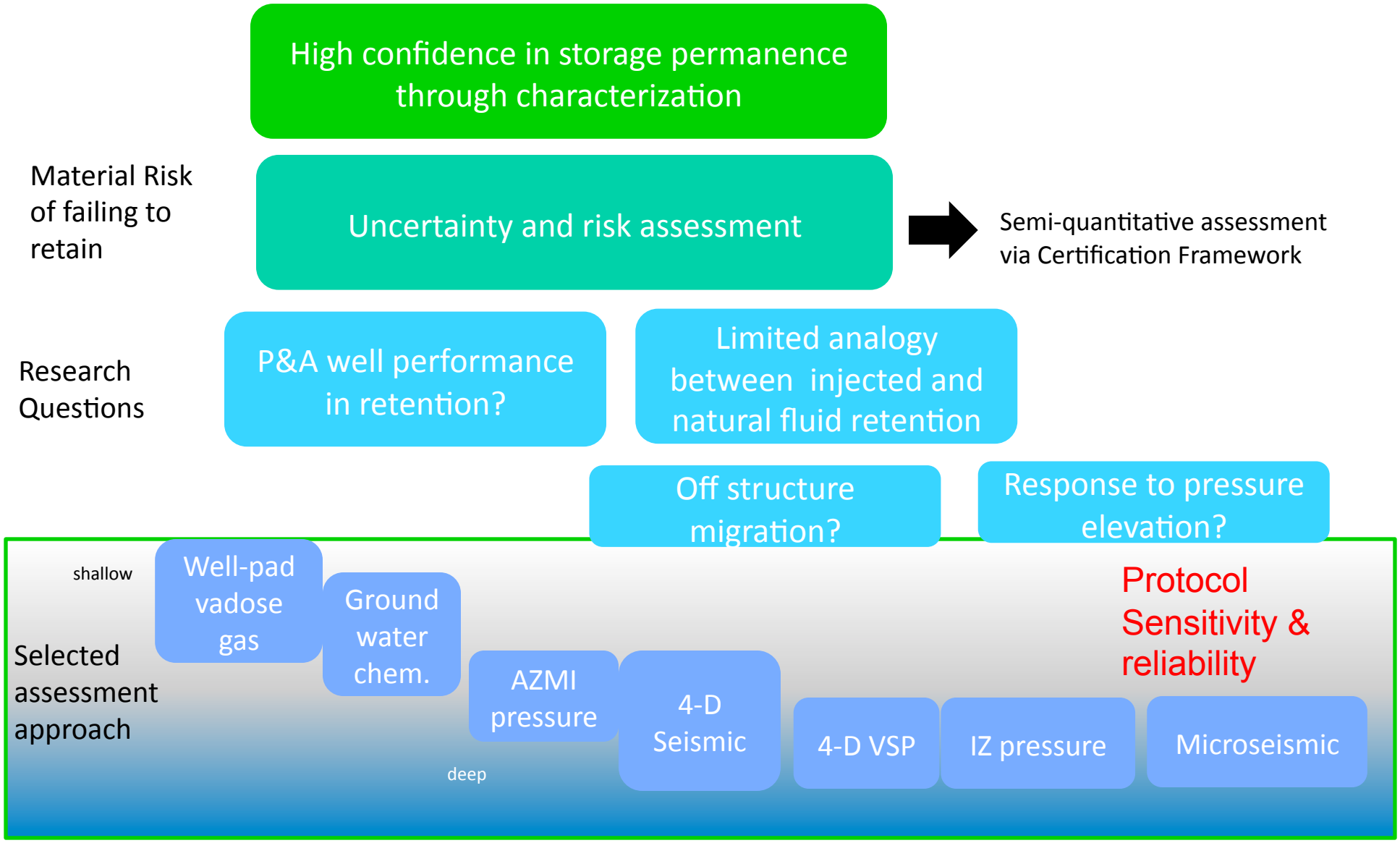
Commercial Monitoring

Driven by regulation/busisness

Confirms -

- Predictions of containment based on site characterization at the time of permitting are correct
- Confidence to continue injection is gained
- Monitoring frequency could be diminished through the life of the project
  - eventually stopped, allowing the project to be closed.

Regional Carbon Sequestration Partnership program goal: Evaluate protocols to demonstrate that CO_2 is retained



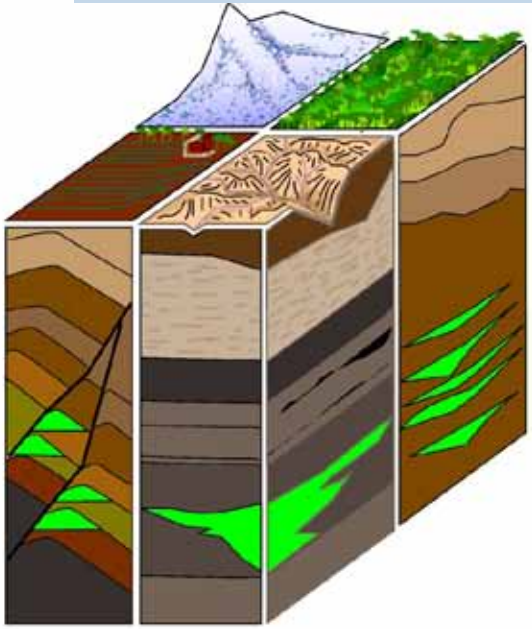
Characteristics of site change monitoring need

Typical of EOR operation		Typical of injection into unused saline formation
Well known volume because of production history	Storage Capacity	May not accept planned mass at planned rate
Area of plume and amount of pressure change well known and actively managed	AOR	Uncertain plume size and pressure response
Demonstrated trapping because of hydrocarbon history	Quality of Confinement	Need for during- and post-injection monitoring

Site specific drivers of monitoring design

Project monitoring drivers:
Regulatory prescriptions
Regulatory choices
Supplier/Operator/Stakeholder needs

Site Specific Geotechnical Risks



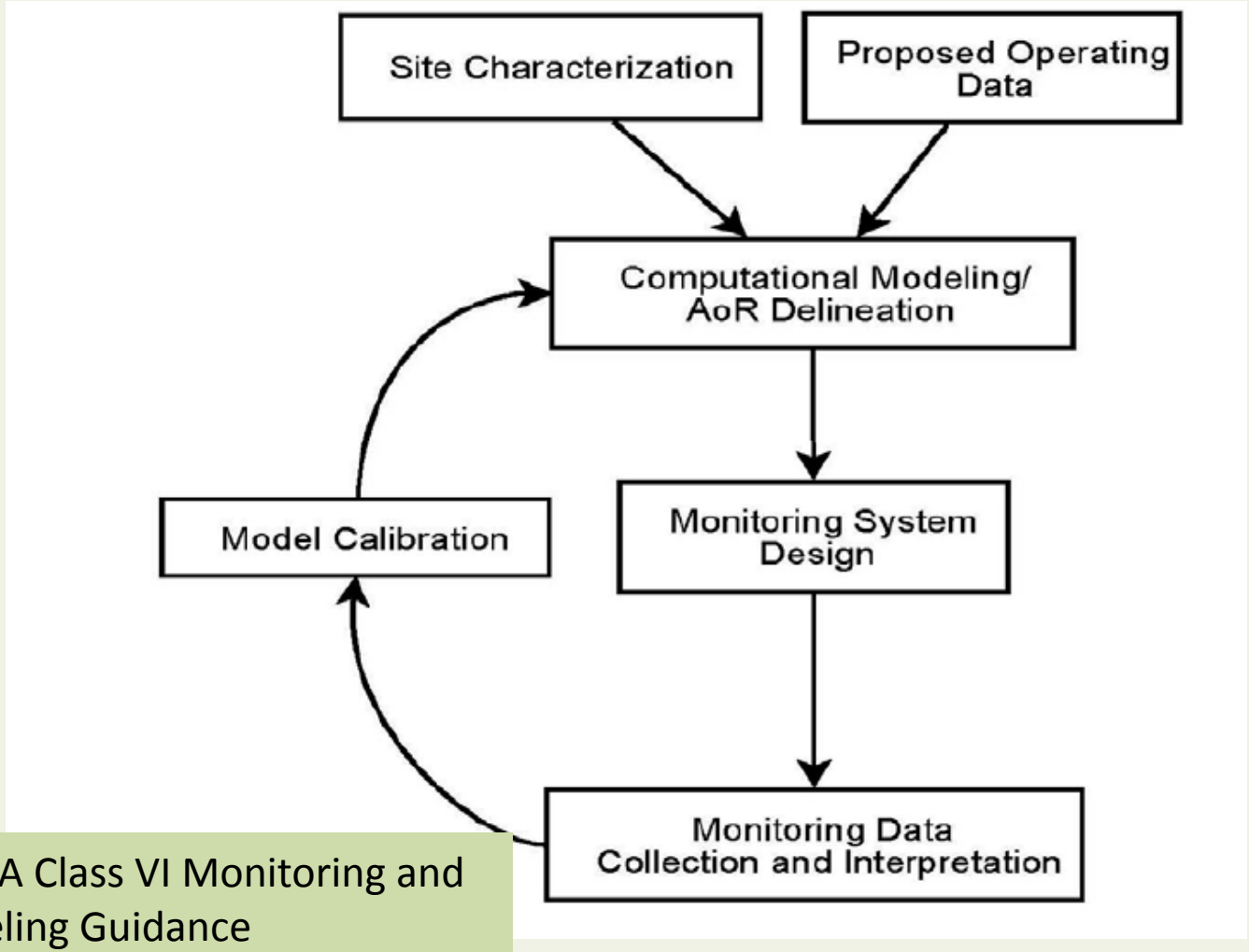
Monitoring targets

Monitoring Design

Site specific technology limitations

EPA STAR Project using SECARB data

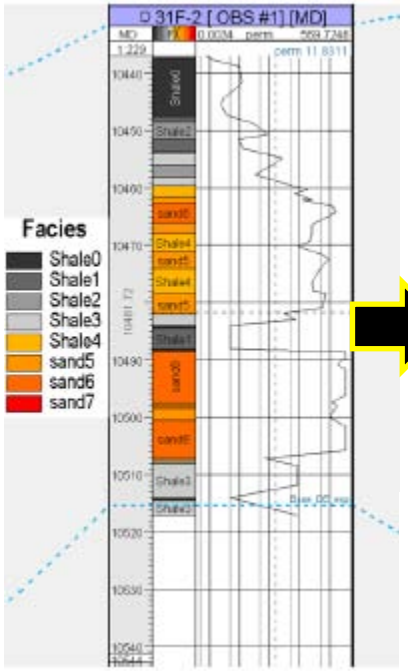
Regulator Expectation: monitor plume & match to models



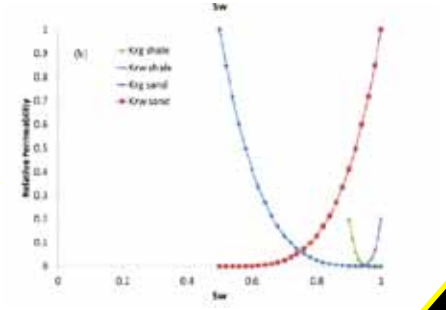
US EPA Class VI Monitoring and Modeling Guidance

Modeled expectations repeatedly adjusted to match measurements

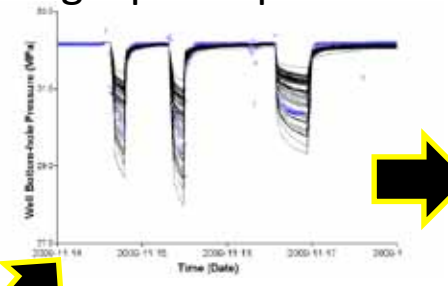
Reservoir characterization



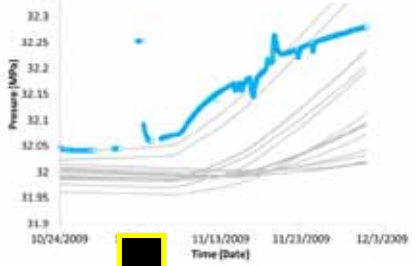
Relative permeablities



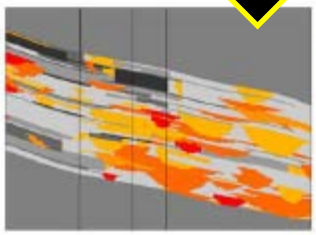
Single phase pressure

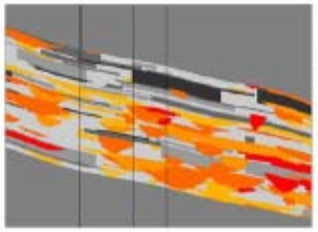


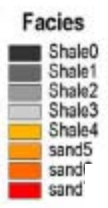
Multi phase pressure

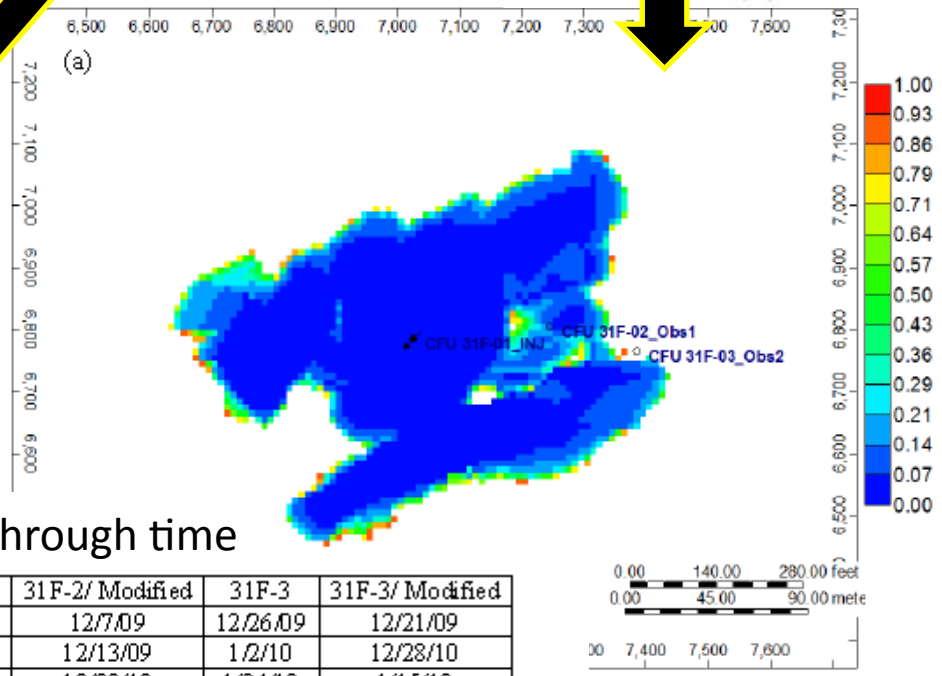


Probabilistic realizations of reservoir architecture









Breakthrough time

Realization Number	31F-2	31F-2/ Modified	31F-3	31F-3/ Modified
35	12/8/09	12/7/09	12/26/09	12/21/09
18	12/15/09	12/13/09	1/2/10	12/28/10
8	1/3/10	12/28/10	1/24/10	1/15/10
15	12/20/09	12/16/09	1/11/10	1/2/10
ACTUAL		12/12/09		12/16/09

Hosseini and others, 2013
Cranfield

Value of a history-matched model

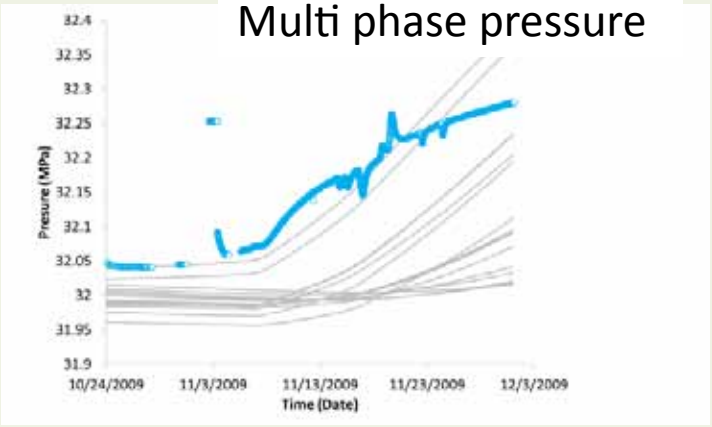
Accomplishments

- Improved understanding of reservoir and fluid properties
- Possible to make predictions
- Eliminate some scenarios

Limits

- Not " the right" answer
- Only probes calibrated conditions, not "in the white space"

Multi phase pressure



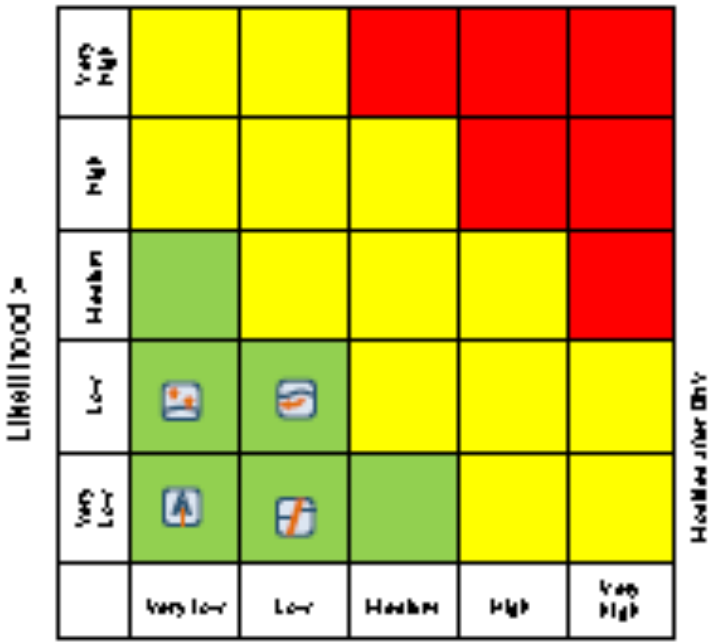
All models are wrong, but some are useful

GDP Box

Not all miss-matches are important to the project

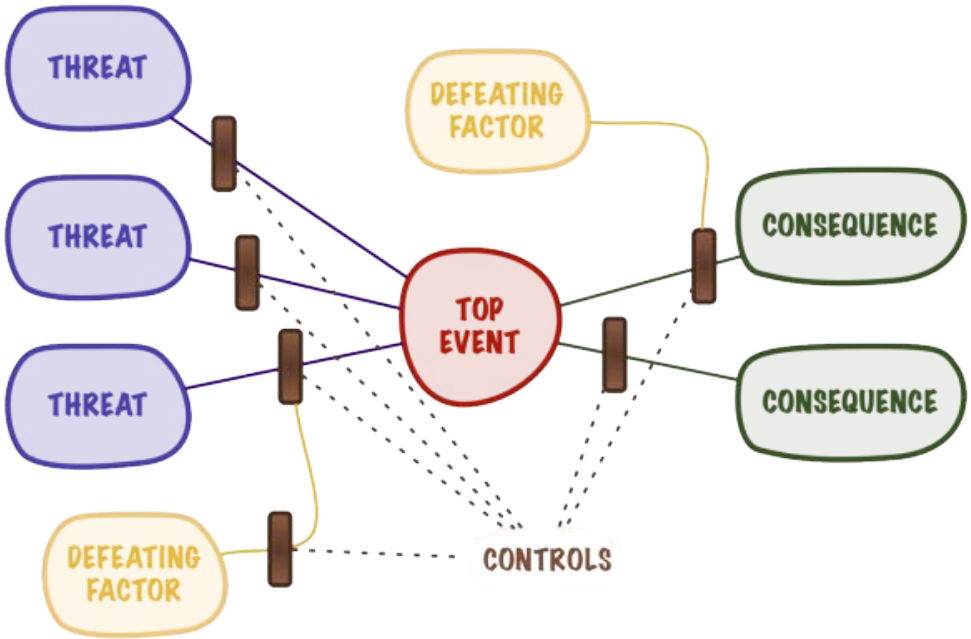
- A range of outcomes can meet most project objectives
- Need statement of what outcomes are unacceptable
  - "Failure"
  - "Leakage"
  - "Damage"
- Need a safe word: Assessment of low probability material impact ALPMI

“Risk assessment drives monitoring”



TNO -K12 B – CO2 CARE

- Seepage through the caprock
- Spilling of CO_2 (spill-point) out of reservoir
- Leakage along faults
- Leakage along the well-bores



How exactly does risk assessment drive monitoring?

- Many mismatches between models and observed geosystem response
- Modeling expected reservoir response cannot predict response to low probability unexpected outlier conditions
- Monitoring cannot assess all outcomes

Monitoring designer should play antagonist role to armor the project

- Quantitative statement of project goals
- Assessment of material impact
- For each case, monitoring asks project " how do I know this material impact is not occurring and will not occur?"
- A method of answering:
  - Models created to illustrate material impact cases
  - Characterization/monitoring designed to disprove material impact scenarios.

Solving the dilemma

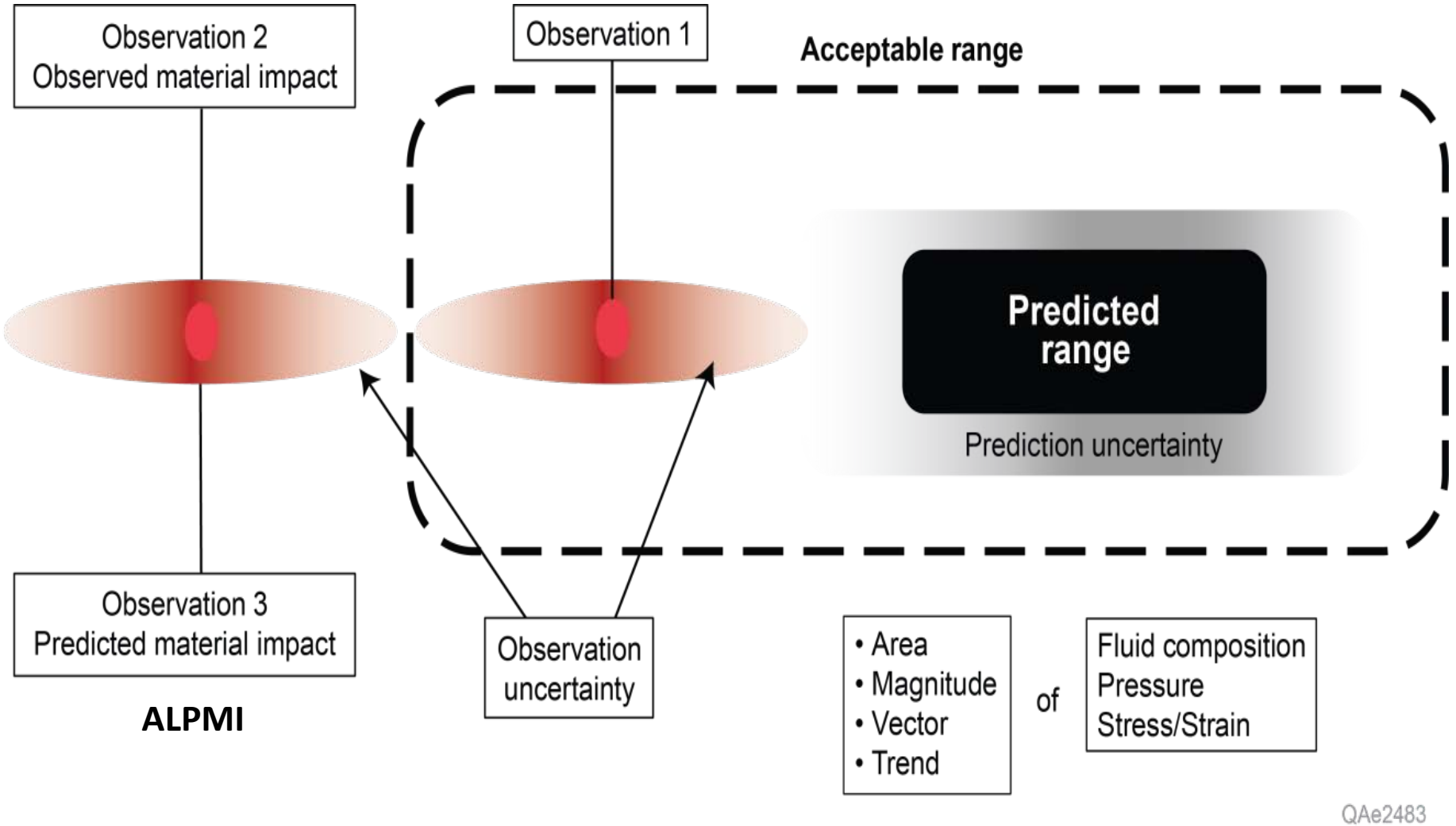
Inventory of material impact scenarios – all in

Create (physical, conceptual, numerical) models of material impact

Define conditions precedent to material impact

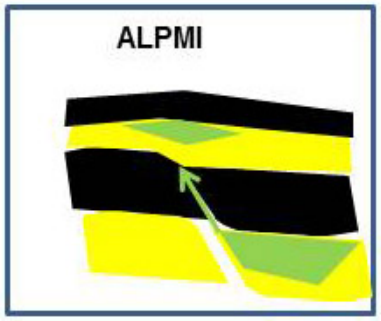
Characterize and monitor those conditions

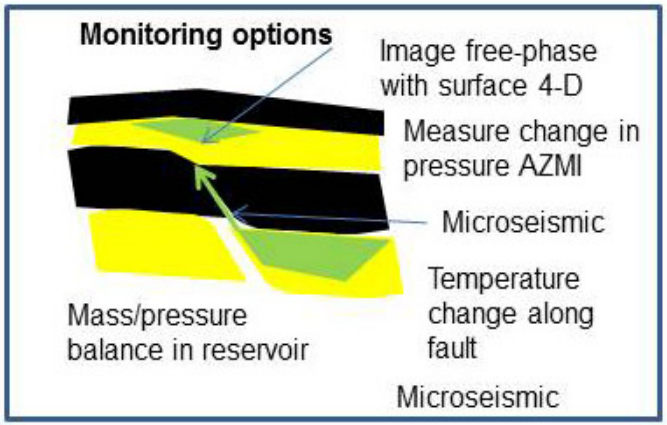
Assessing Low Probability Material Impact

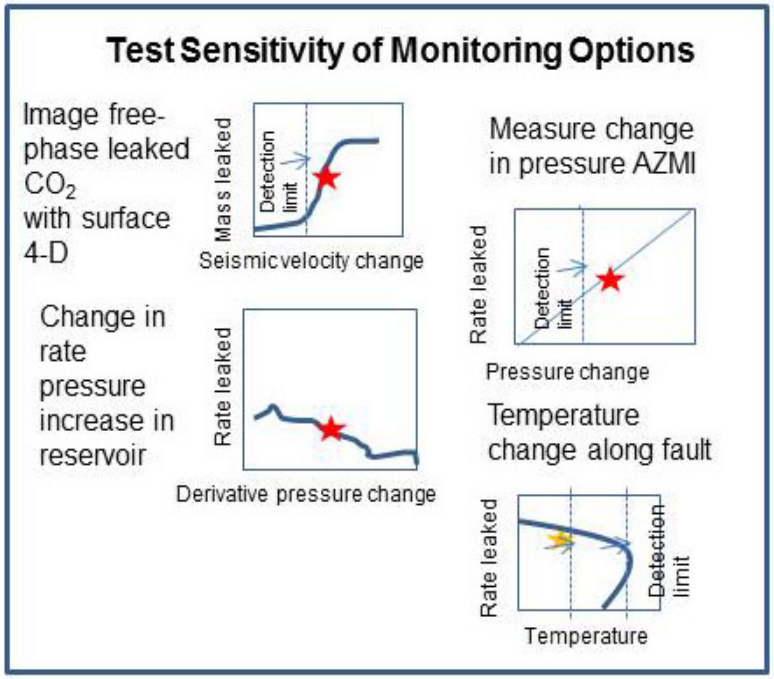


Using ALPMI to Design Monitoring





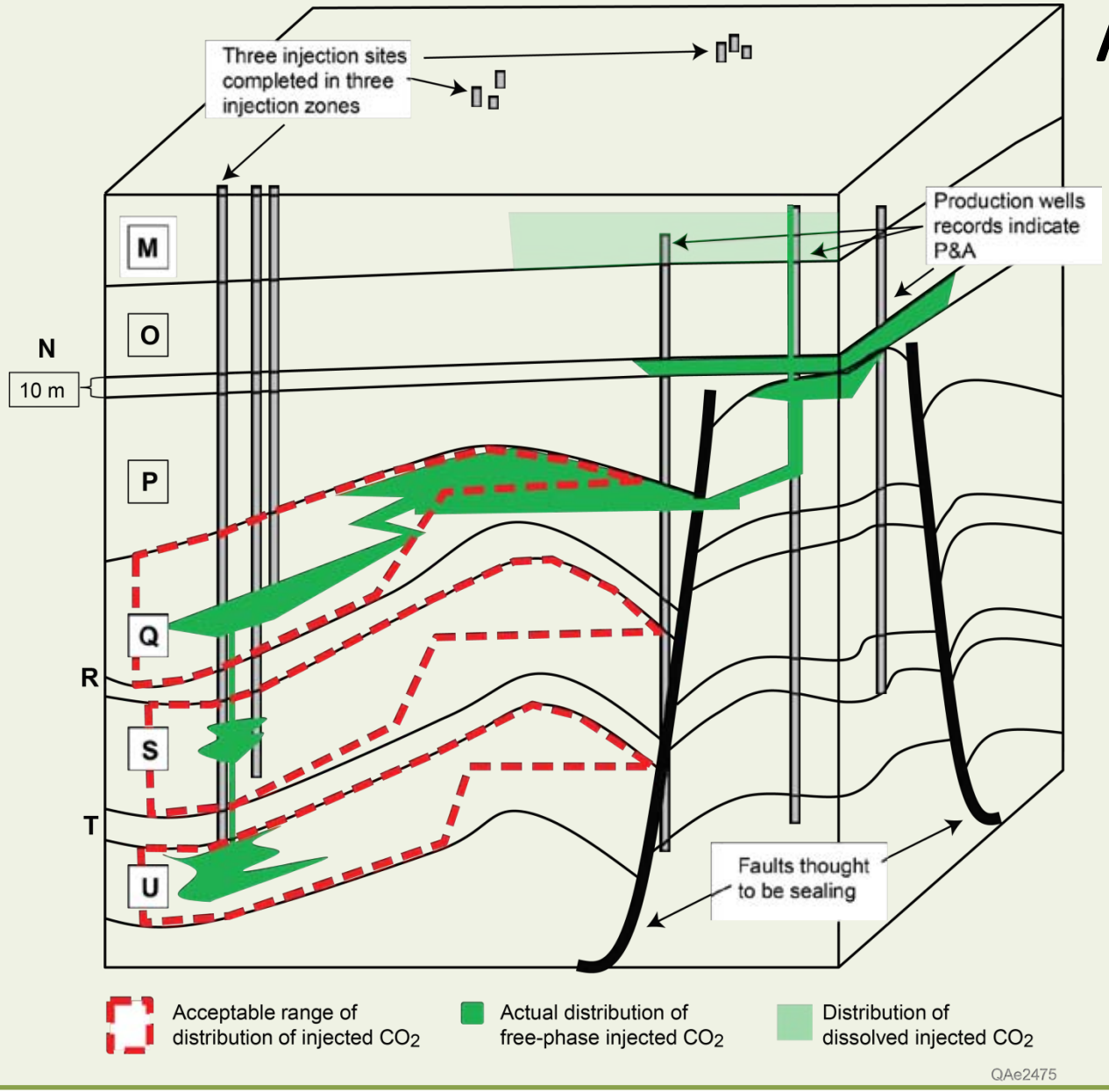




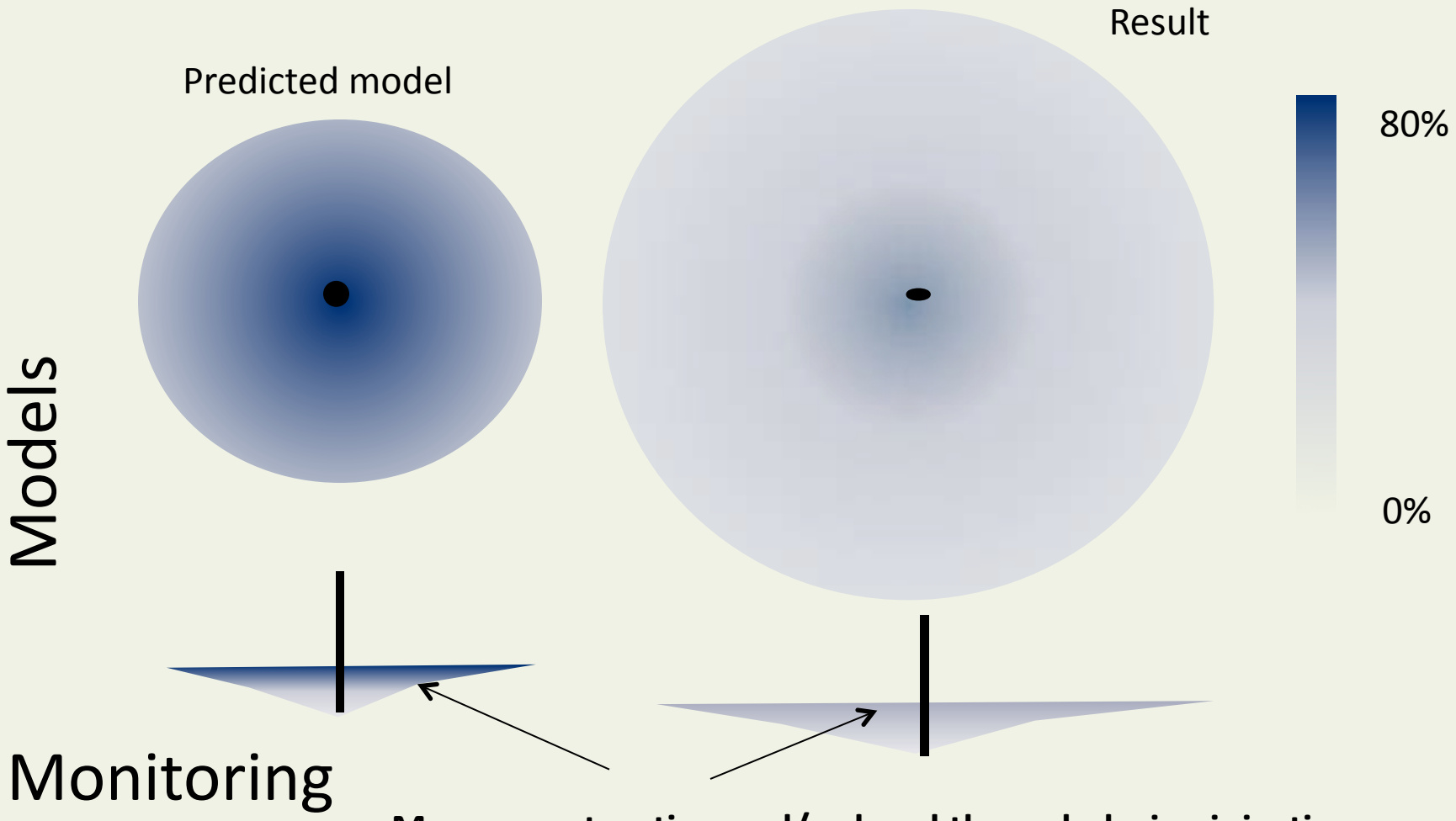
Set triggers, stage monitoring options

- 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

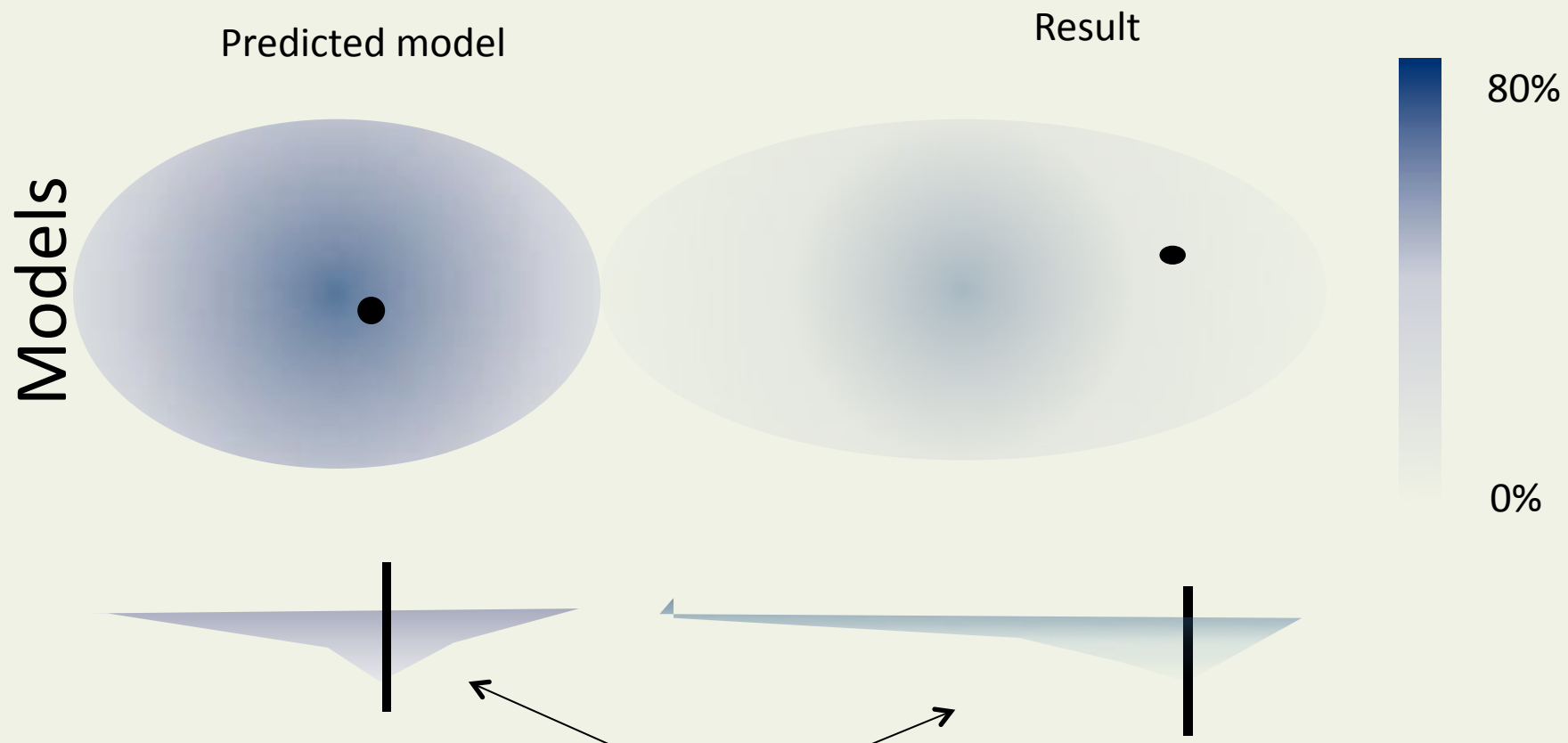
ALPMI


Three injection sites completed in three injection zones
Production wells records indicate P&A
M
O
N
10 m
P
Q
R
S
T
U
Faults thought to be sealing
Acceptable range of distribution of injected CO_2
Actual distribution of free-phase injected CO_2
Distribution of dissolved injected CO_2
QAe2475

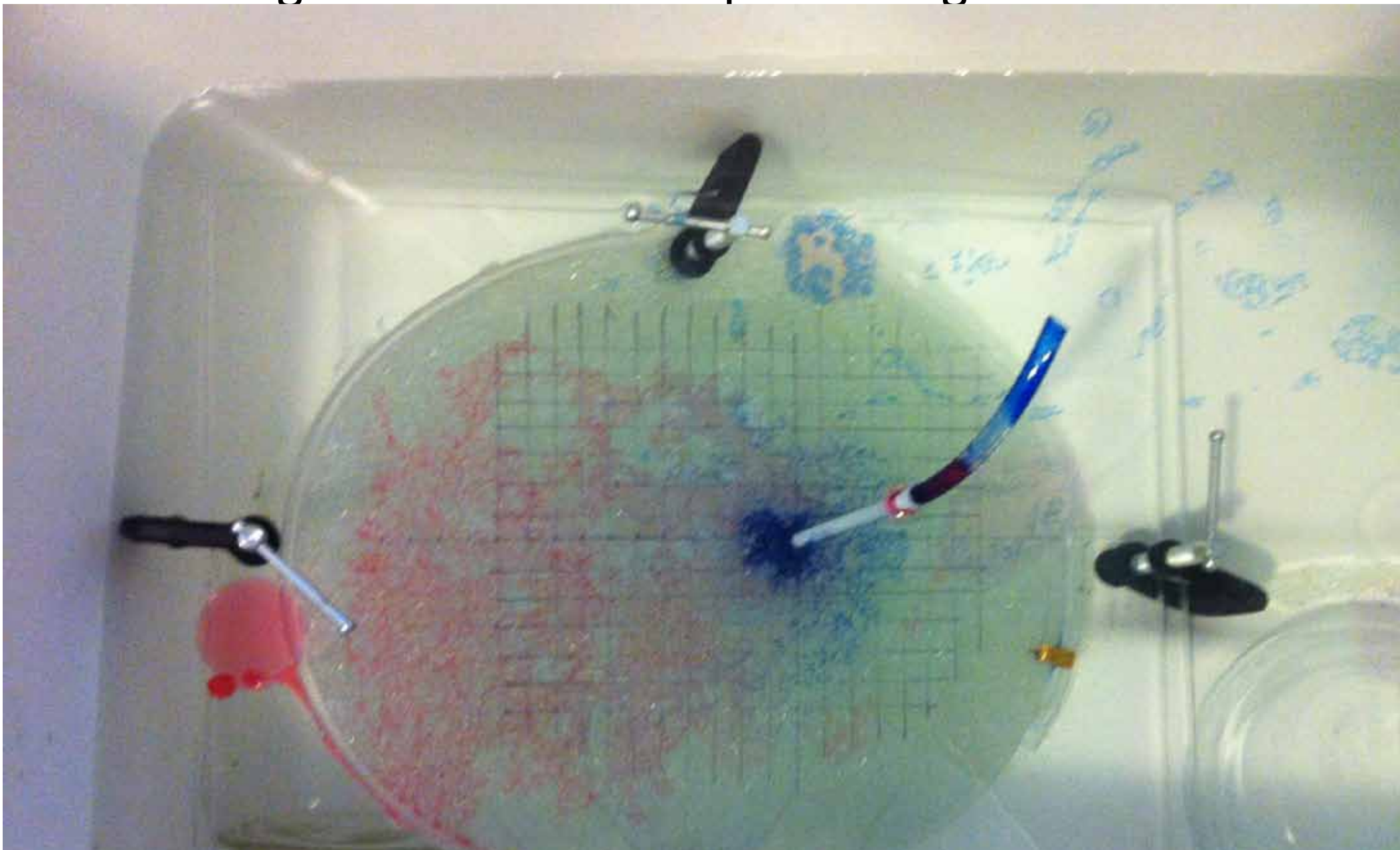
ALPMI Case 1: Water saturation higher than predicted: large plume during injection



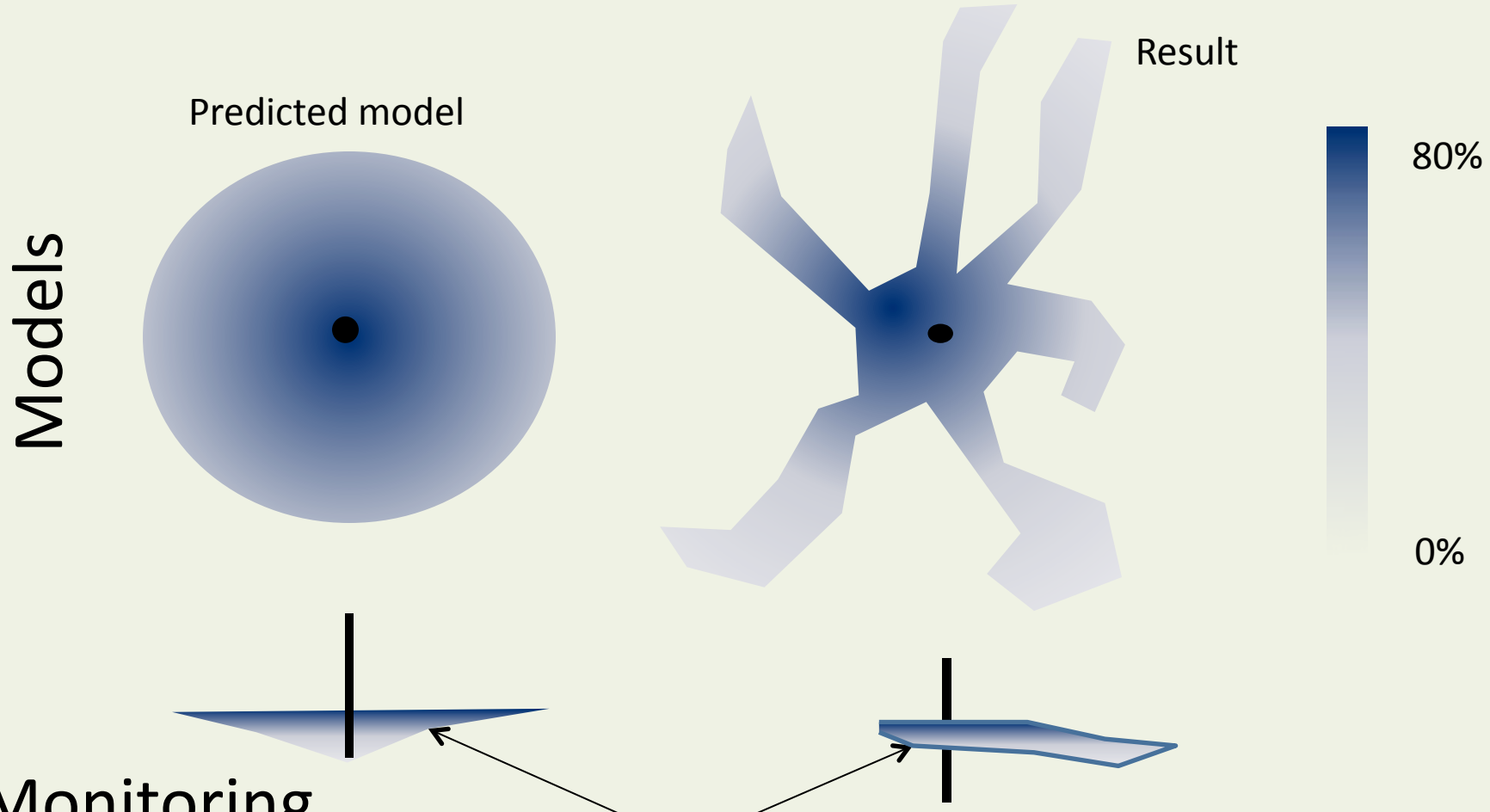
ALPMI Case 2: CO_2 residual saturation lower than predicted: large plume during migration



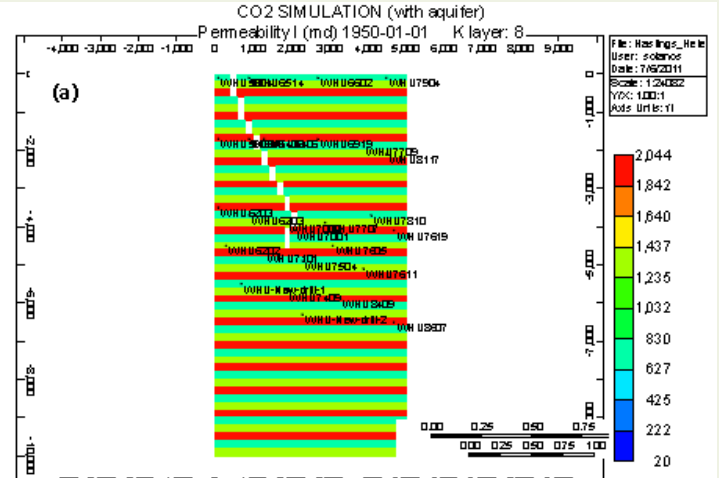
ALPMI 2 physical model
Wrong imbibition curve: plume migrates too far

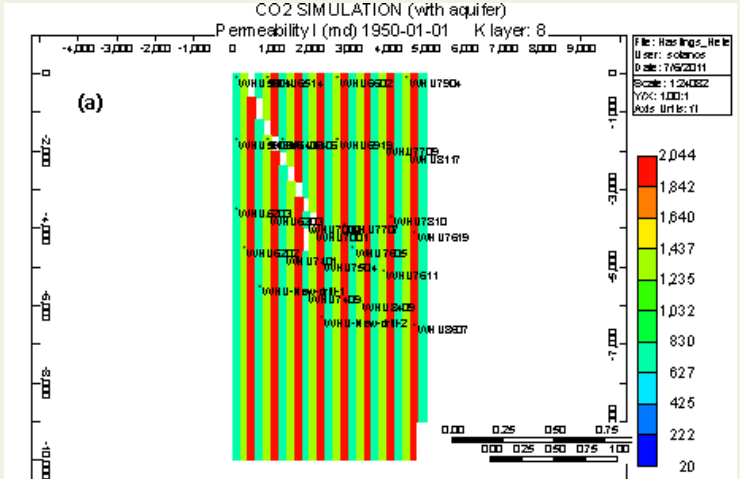


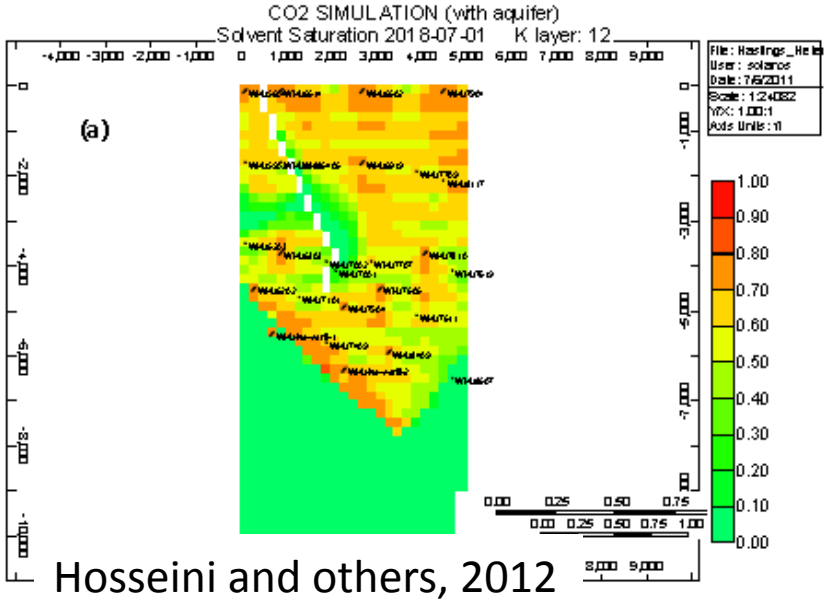
ALPMI Case 3: CO_2 plume strongly fingered horizontally and/or vertically

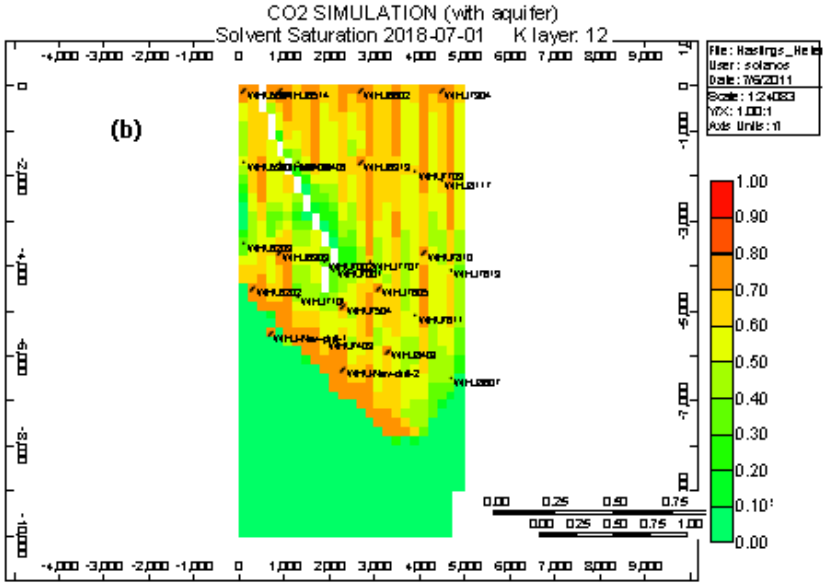


ALMPI 3
Anisotropy such that plume migrates too far





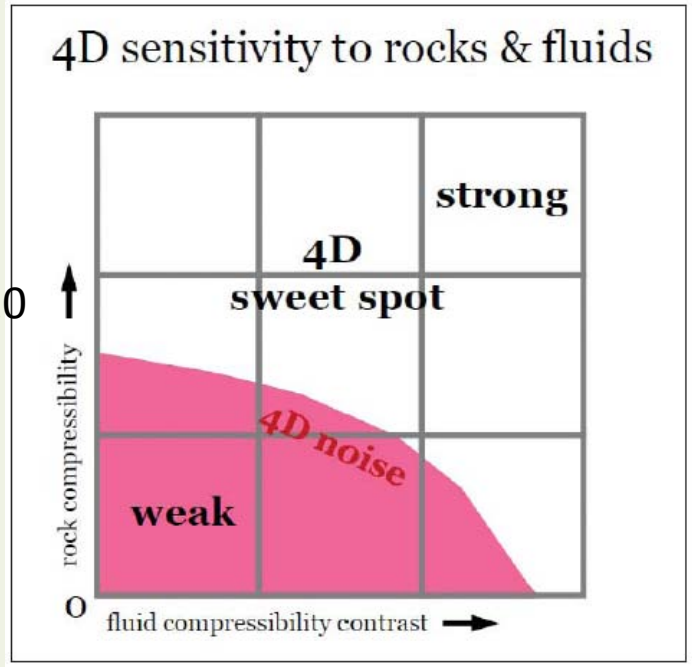




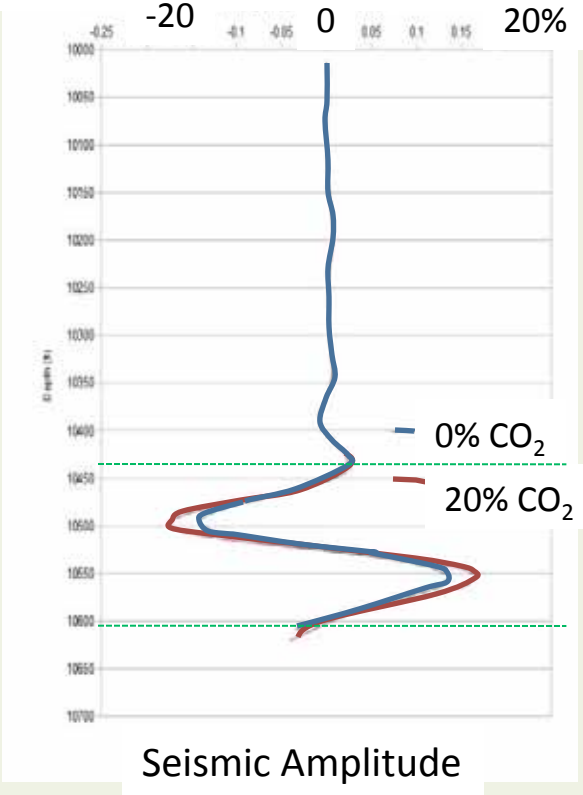
Hosseini and others, 2012

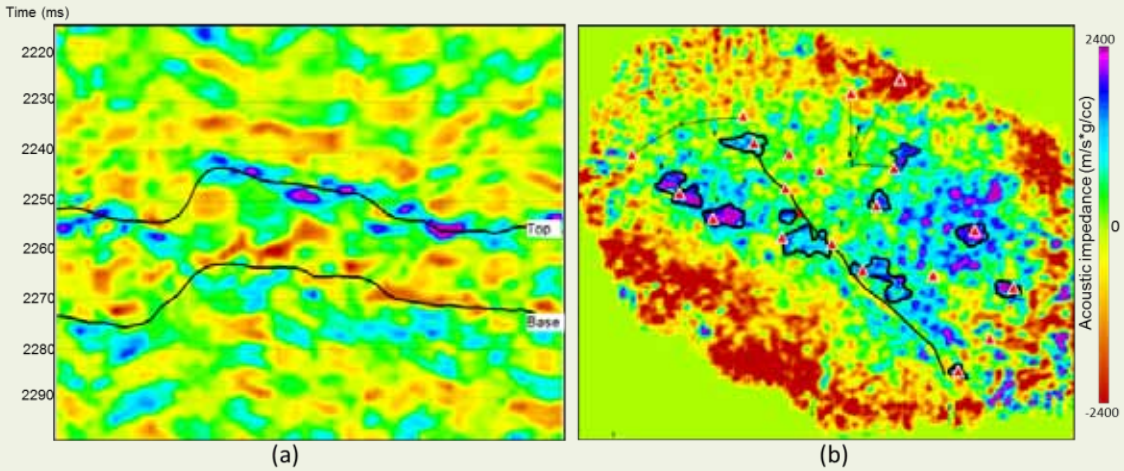
Seismic Sensitivity

Lumley, 2010



Modeled change in amplitude
Cranfield

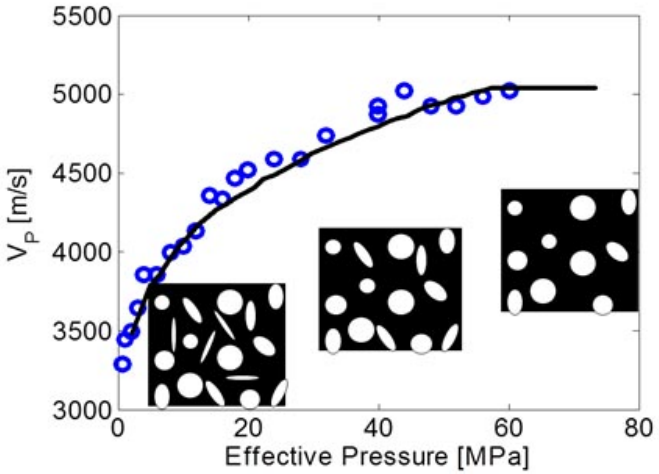




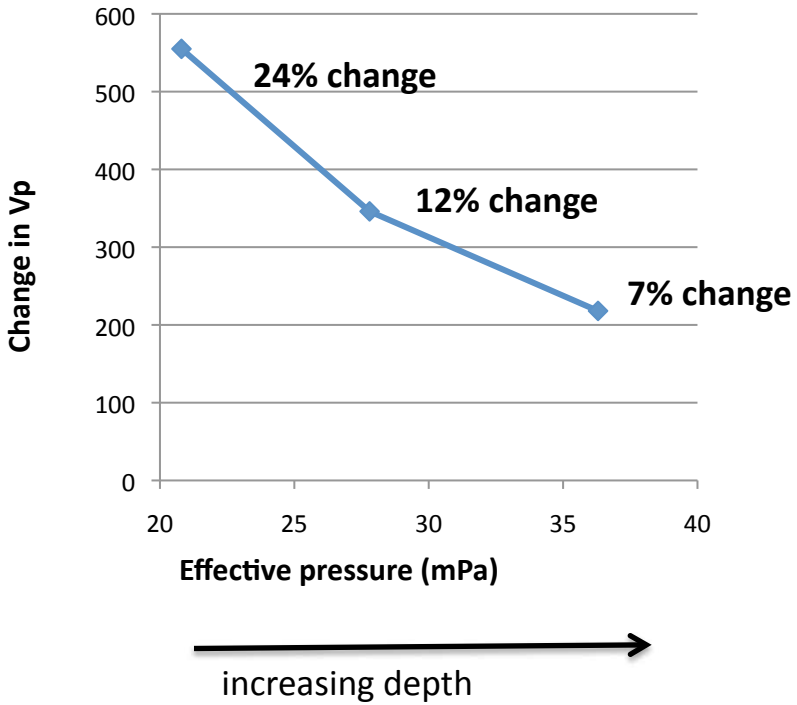
Zhang, 2012, 4-D survey
Cranfield reservoir

CO_2

Site specific seismic sensitivity: velocity change with depth

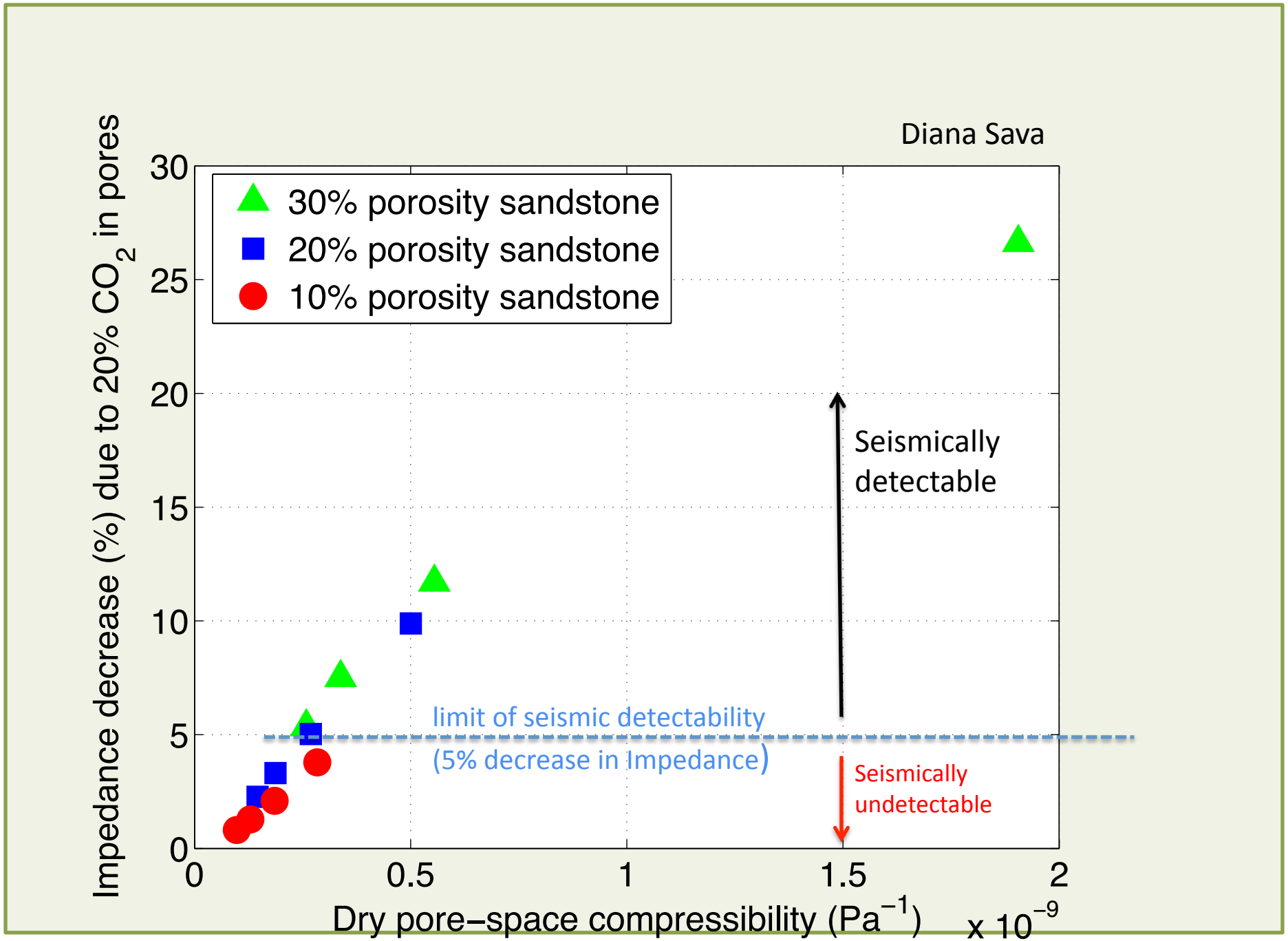


Rock physics model, self consistent approximations (Berryman 1995), data Purcell and Harbert University of Pittsburg

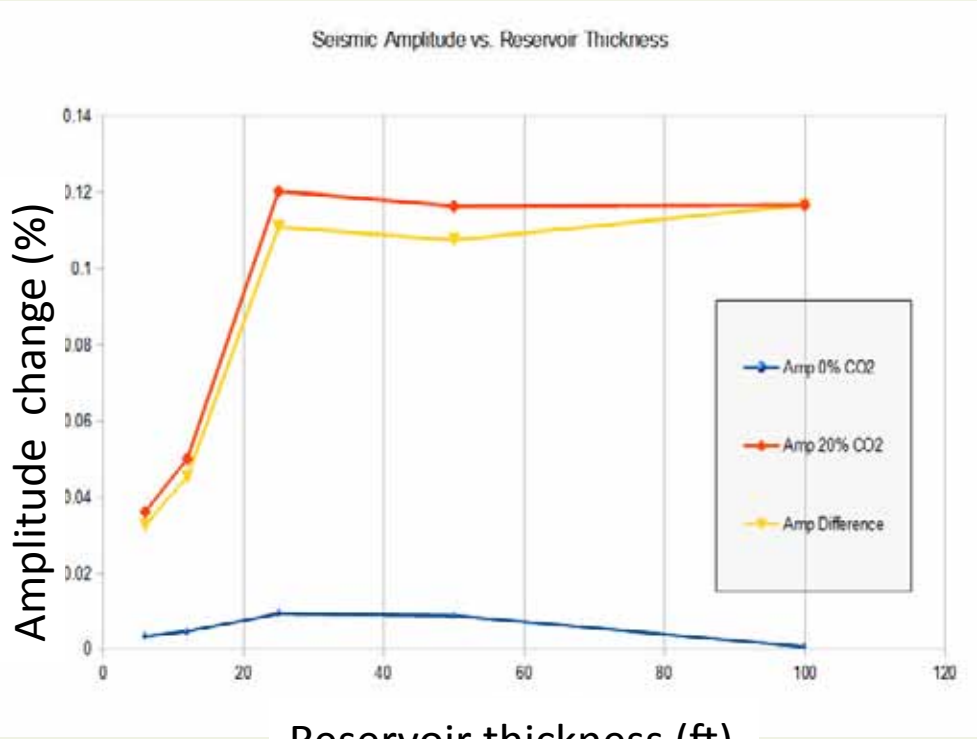


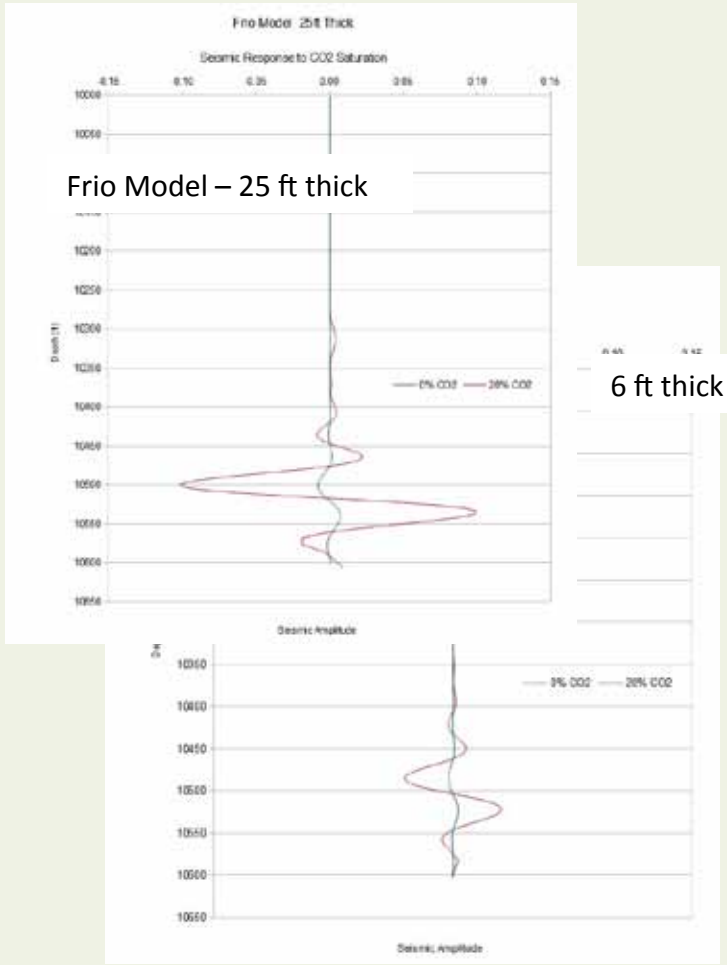
average elastic properties, Gassman (1951) theory, 30% porosity, 20% fluid substitution CO2 for brine, not changes to minerals, fluids do not support shear, Reuss (1929) model

Diana Sava


Diana Sava
30% porosity sandstone
20% porosity sandstone
10% porosity sandstone
Impedance decrease (%) due to 20% CO_2 in pores
Dry pore–space compressibility (Pa^{-1})
x 10^{-9}
0
5
10
15
20
25
30
0
0.5
1
1.5
2
Seismically detectable
limit of seismic detectability
(5% decrease in Impedance)
Seismically undetectable

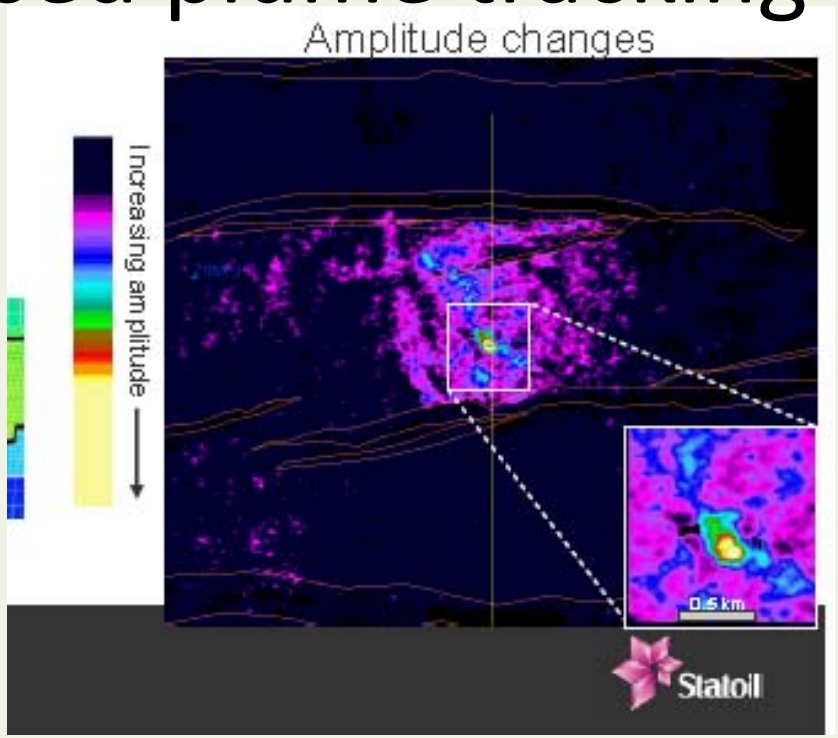
Site specific seismic sensitivity: saturated zone thickness



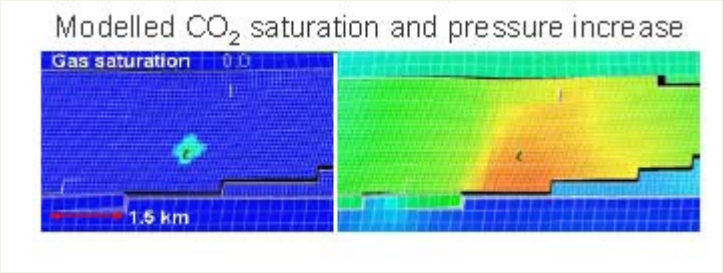


Frio Model - Randy Remington

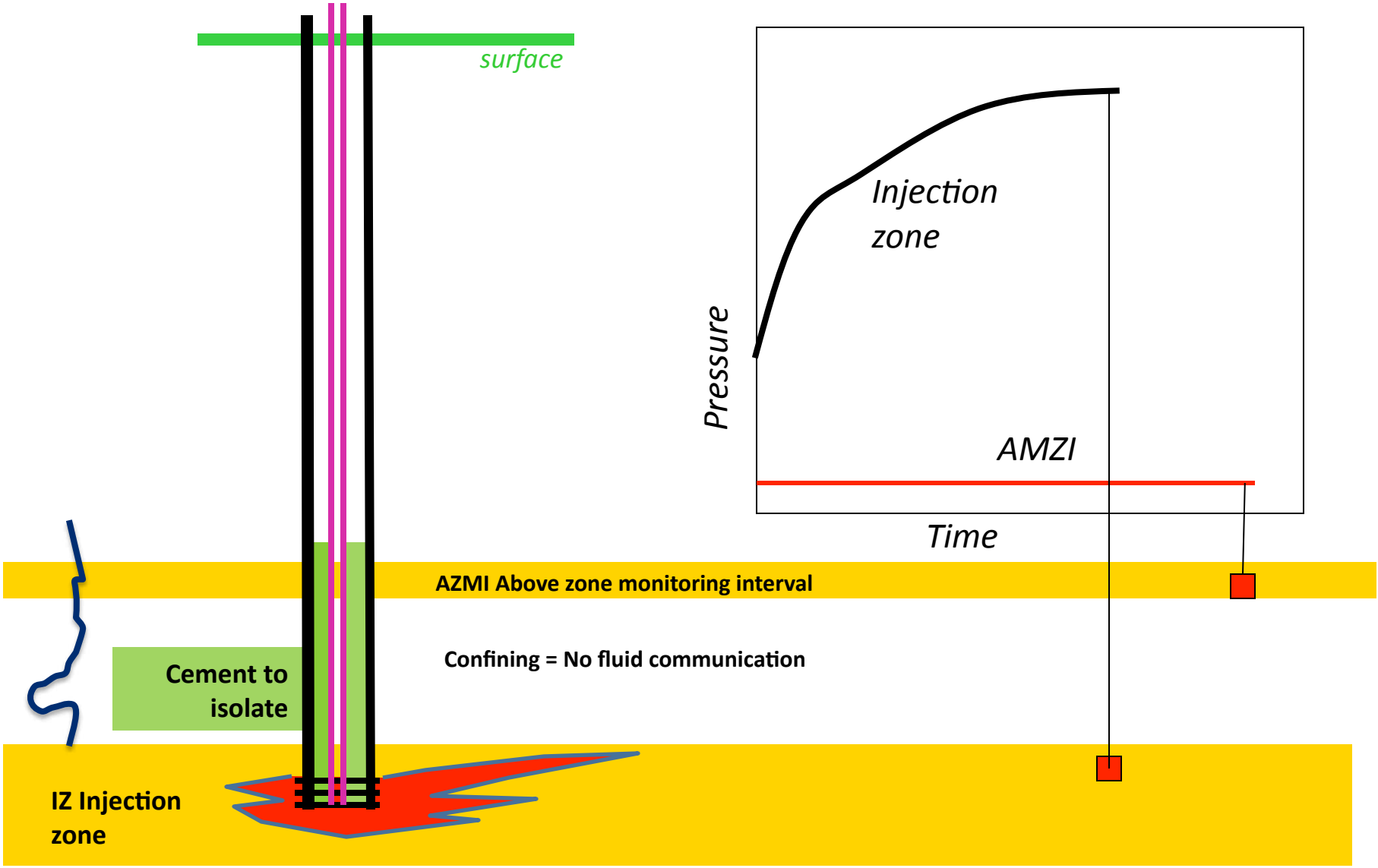
Value and limits of seismic and well-based plume tracking



Eiken et al, 2010 (GHGT10)

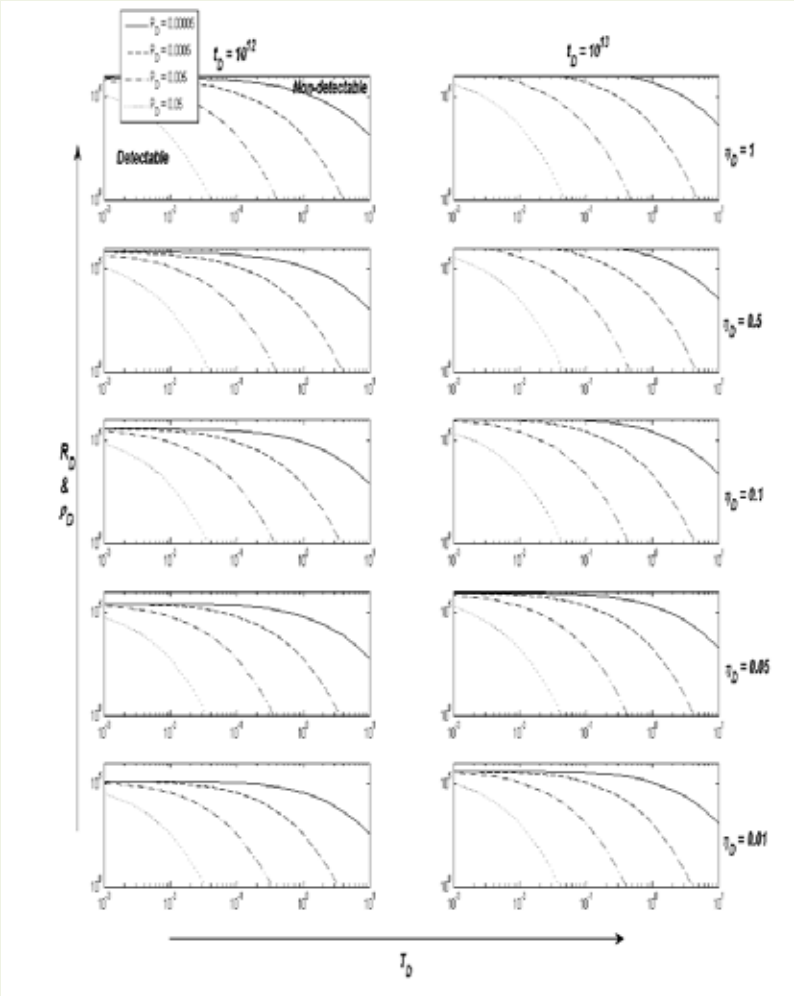


Using above AZMI pressure to assess storage permanence



AZMI Pressure sensitivity for leakage detection: non parametric tables

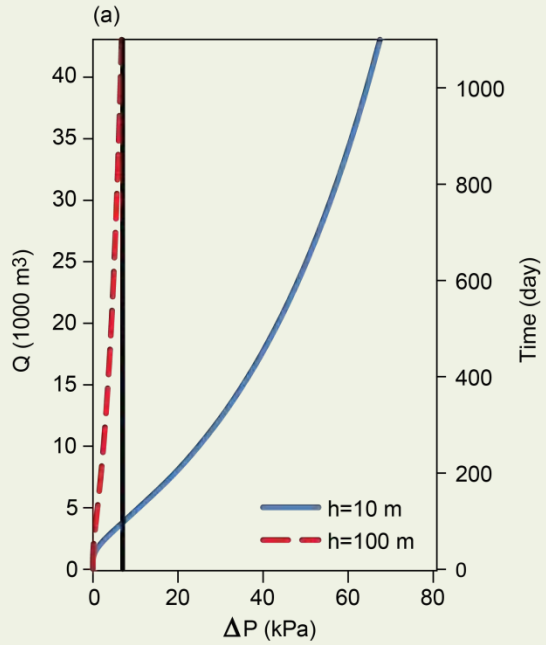
Parameter
m, brine viscosity (Pa.s)
IZ formation compressibility (1/Pa)
IZ formation porosity (fraction)
k, IZ formation permeability (m^2)
h, IZ formation thickness (m)
h, diffusivity (m^2/s)
AZMI compressibility (1/Pa)
AZMI porosity (fraction)
k_a, AZMI permeability (m^2)
h_a, AZMI thickness (m)
h_a, AZMI diffusivity (m^2/s)
q, injection rate (Mt/year)
r_w, injection well radius (m)
r_l, Leak radius (m)
h_l, leakage interval (m)
B, CO_2 formation volume factor (Rm^3/stm^3)



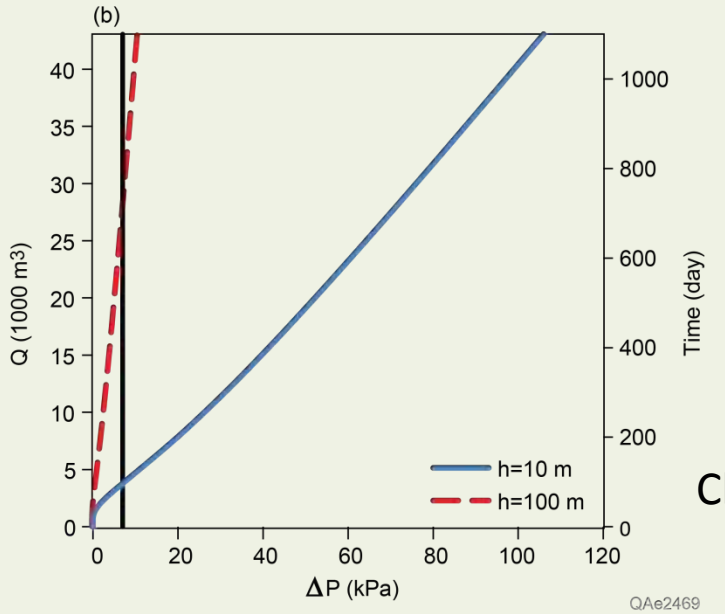
Mehdi Zeidouni

AZMI thickness vs sensitivity

Leakage rate

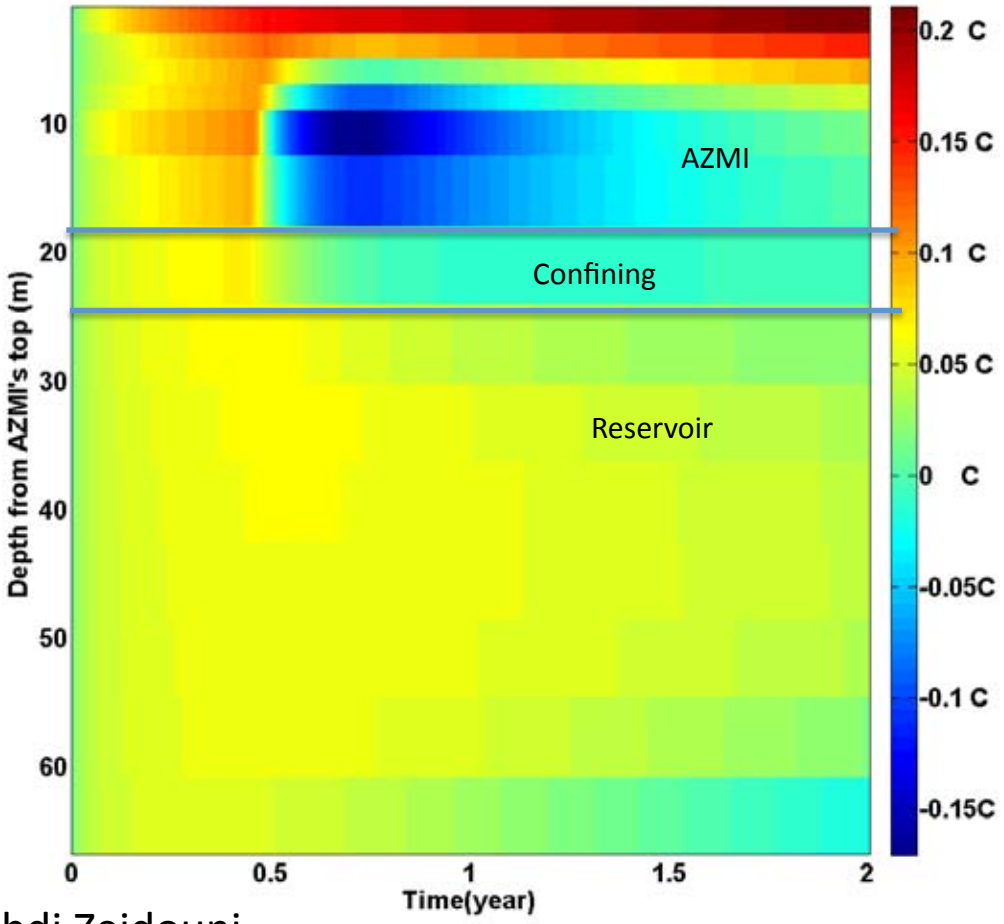


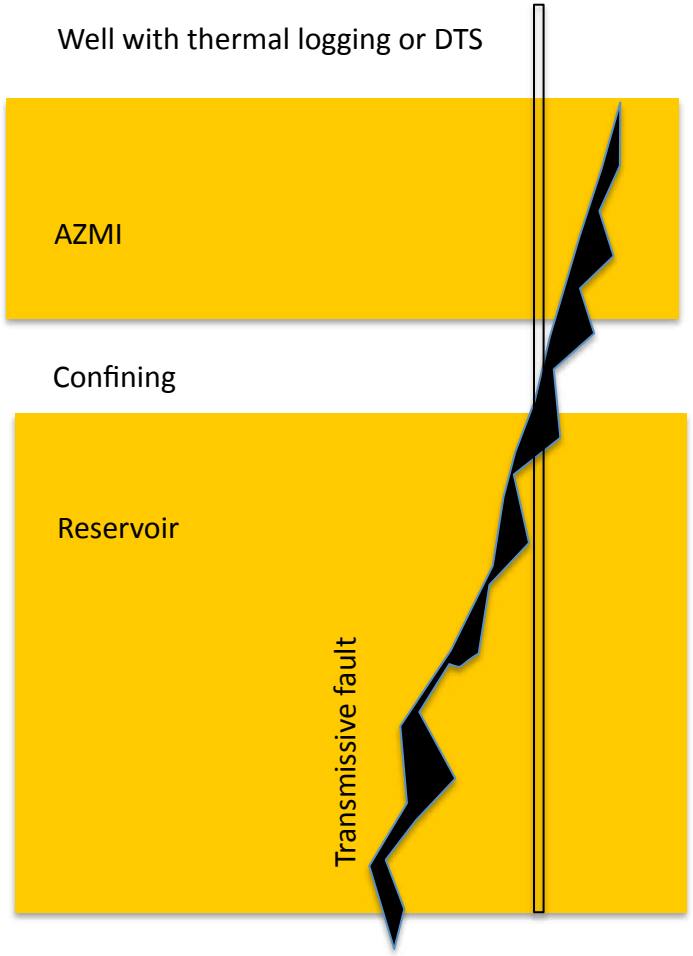
Infinite-acting boundary conditions



Closed boundary at 6 km

Thermal Sensitivity of AZMI to leakage

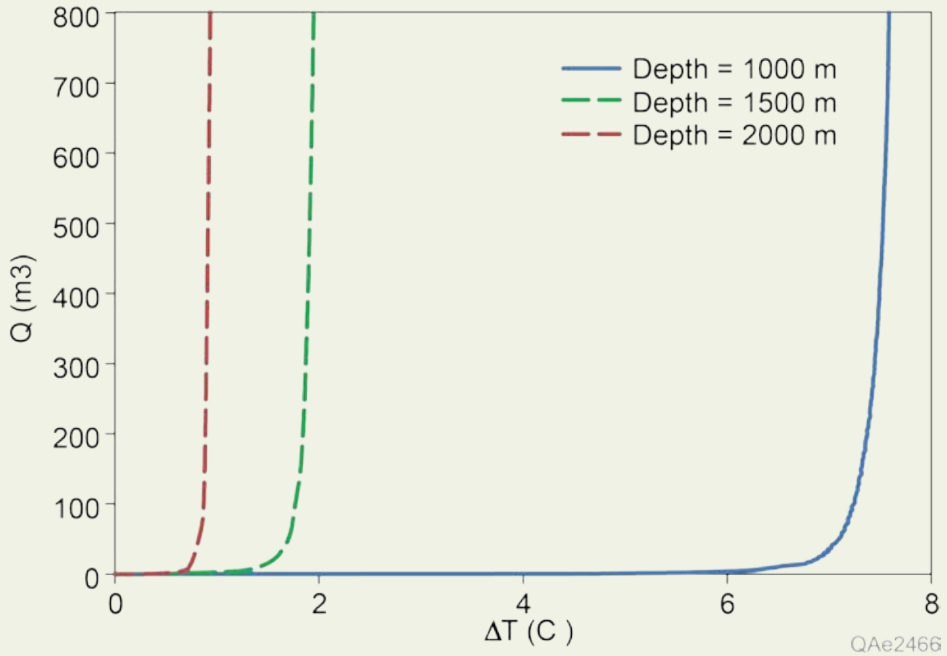




Mehdi Zeidouni

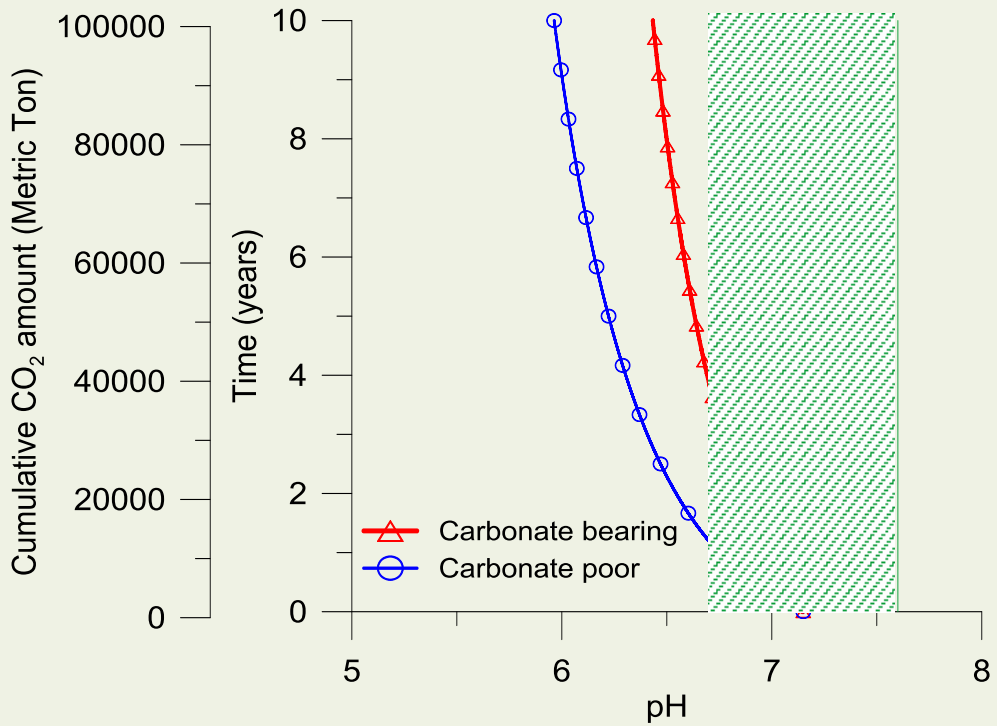
Idealized so well measured center of fault

Thermal sensitivity depth dependent



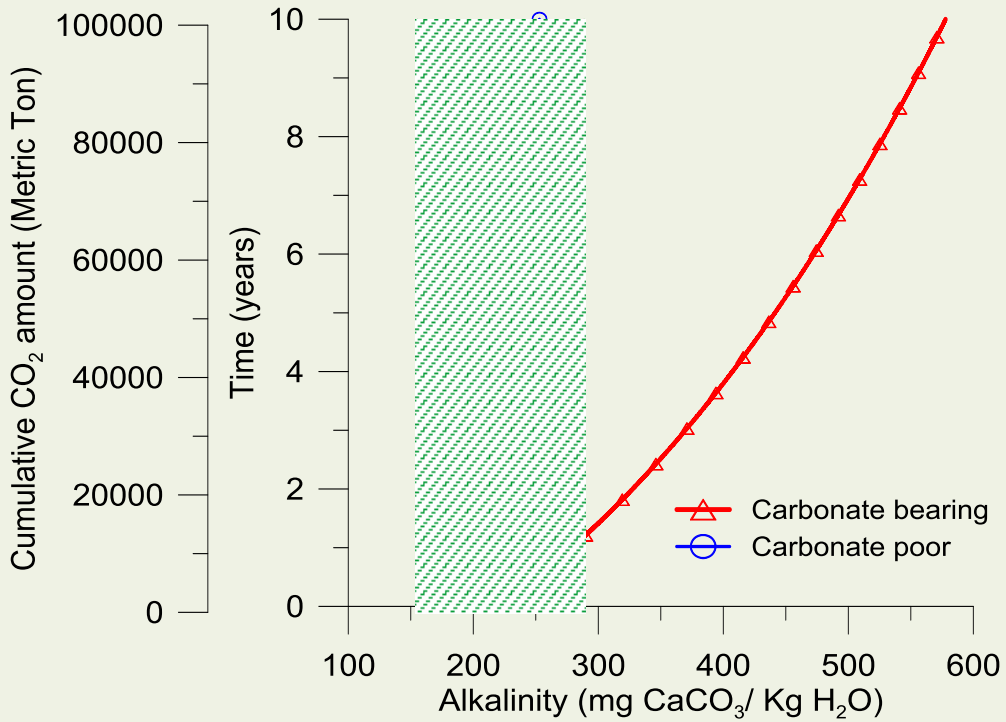
Mehdi Zeidouni

Site Specific Freshwater Geochemical Sensitivity



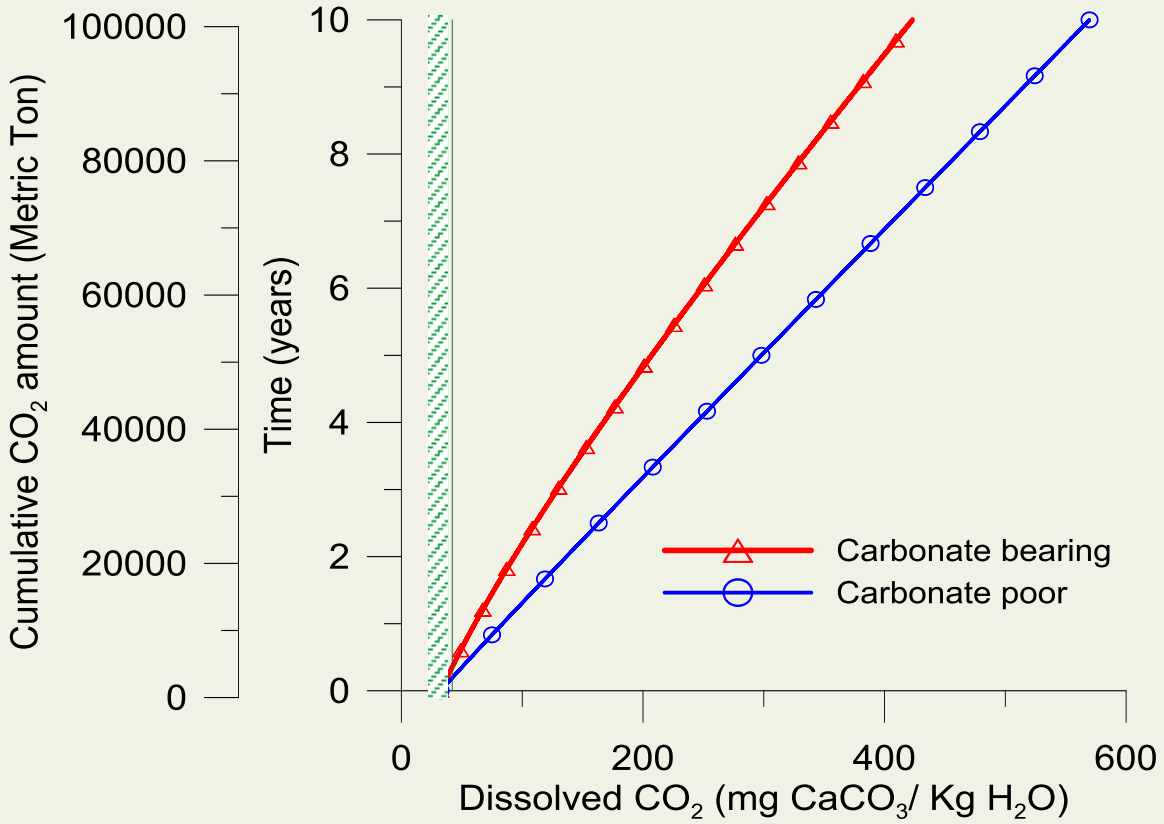
Changbing Yang

Site Specific Freshwater Geochemical Sensitivity-Alkalinity



Changbing Yang

Site Specific Freshwater Geochemical Sensitivity- Dissolved CO_2



Changbing Yang

Conclusions

- Monitoring depends on goals and ALPMI
- Monitoring not used primarily for model match but for ALPMI
- For each ALPMI, monitoring can show that even though some uncertainties remain in terms of geologic response to injection, there is no trend to defined material impact

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RITE
CO2-CRC

Assessing Impacts of CO_2 Leakage on Groundwater Quality and Monitoring Network Efficiency: Case Study at A CO_2-EOR site

Changbing Yang
Susan Hovorka
Ramon Trevino
Gulf Coast Carbon Center
Bureau of Economic Geology
The University of Texas at Austin
March 11, 2013

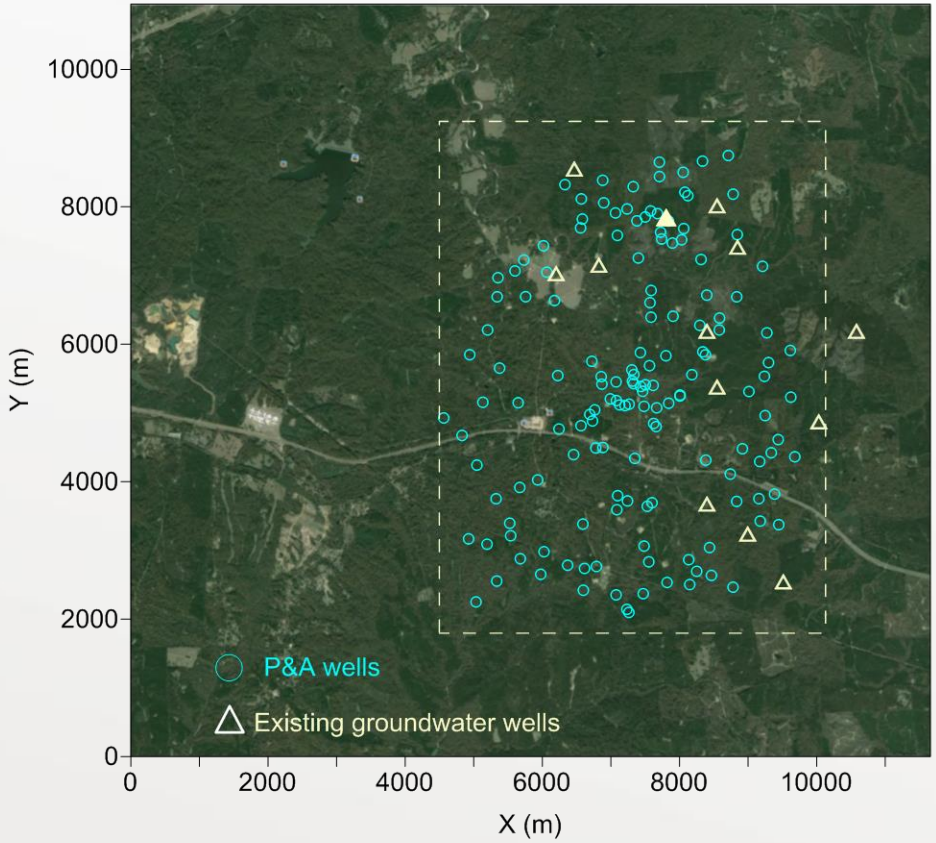
Acknowledgements

- This material is based upon work supported by the U.S. Department of Energy National Energy Technology Laboratory.
- Cost share and research support provided by SECARB/SSEB Carbon Management Partners.



Previous research

- Field campaigns for groundwater sampling
- Lab experiments of water-rock-CO_2 interactions
- Single-well push-pull test



No CO_2 leakage signals have been detected.

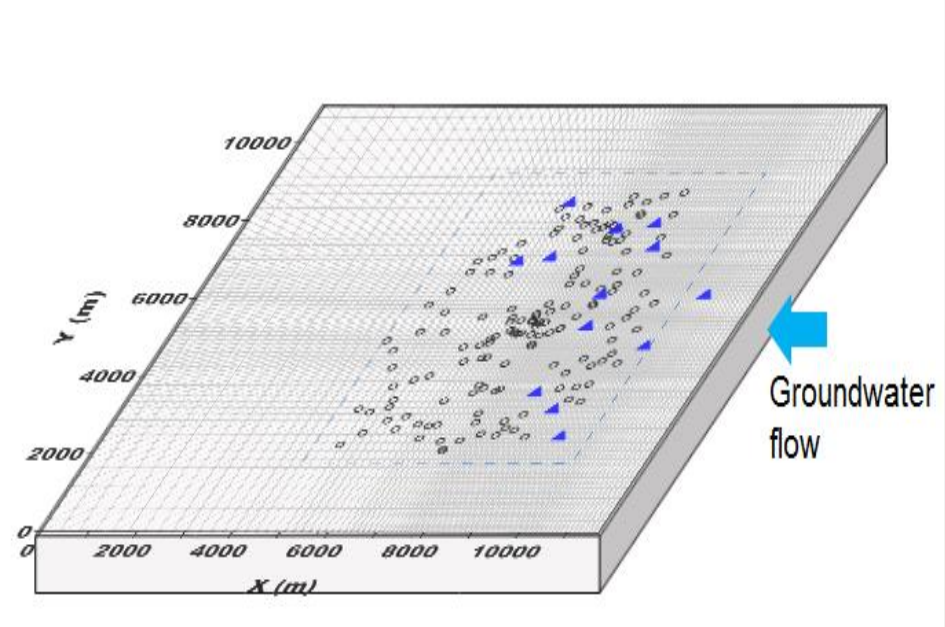
Objectives

Use reactive transport modeling

- Assess impacts of CO_2 leakage on groundwater chemistry;
- Evaluate monitoring network efficiency

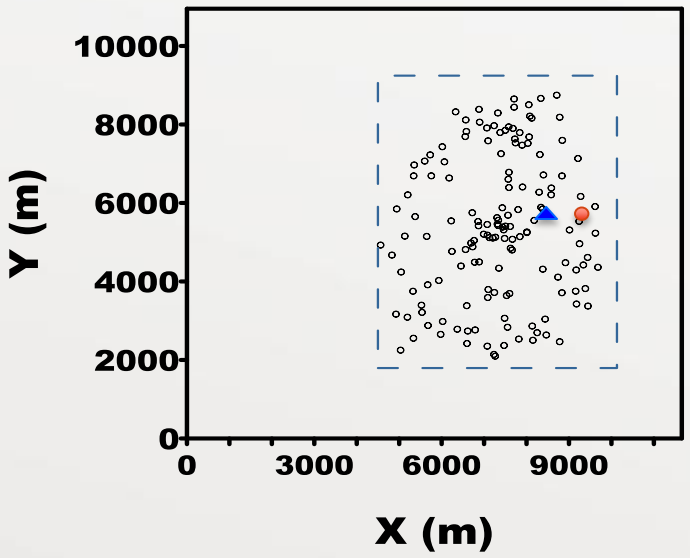
Regional-Scale Reactive Transport Modeling (RSRTM)

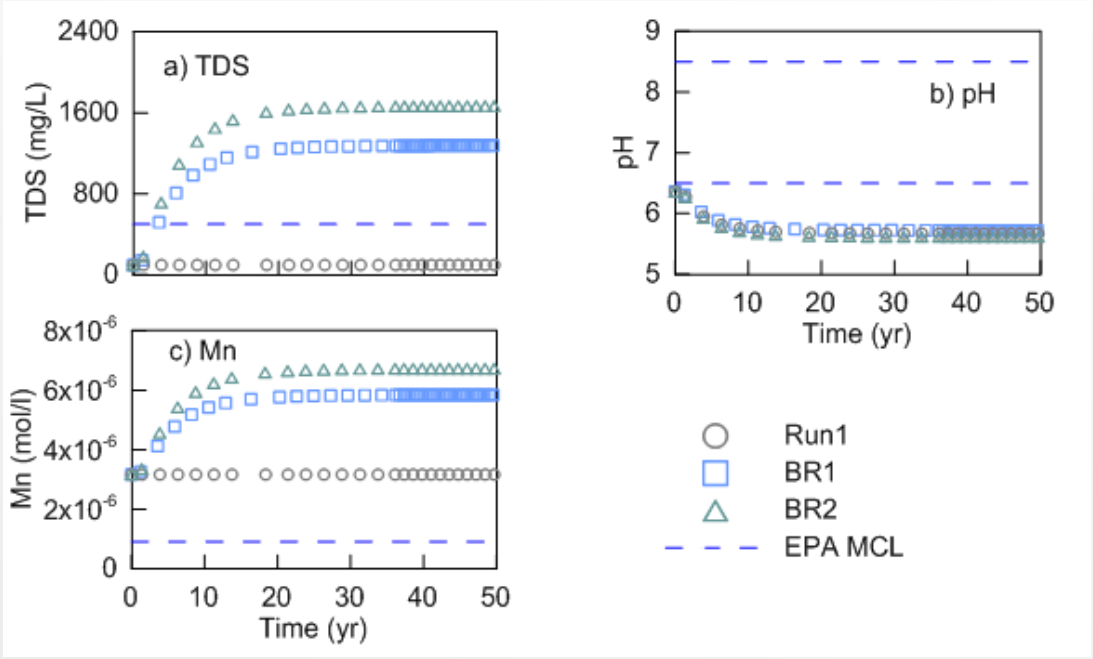
- Aquifer simplification (shallow, confined, homogeneous, groundwater flows from right to left);
- Geochemical interactions of water-rock-CO_2 tested and validated with laboratory experiments & the field test



- CO_2 as dissolved phase in either fresh groundwater or brine
- CO_2 leakage rate from 0.9 to 100 metric ton/yr

Potential impacts of CO_2 leakage on groundwater chemistry





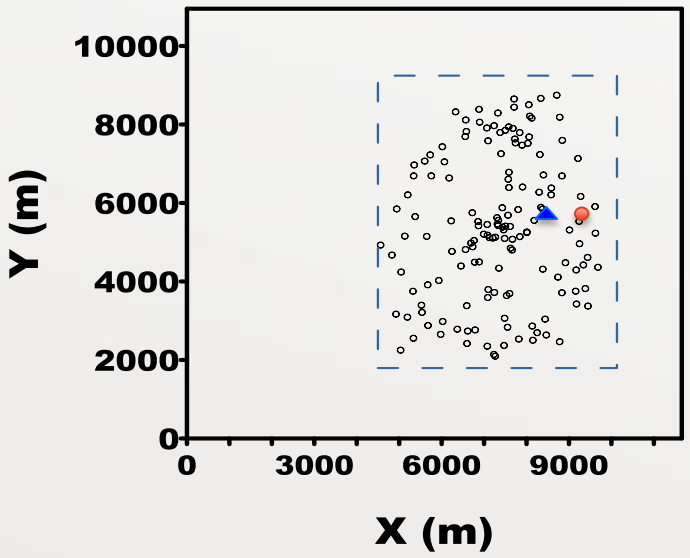
Leakage rate metric ton/yr

Run1: 50.3
BR1: 37.3
BR2: 50.3

J=0.5%

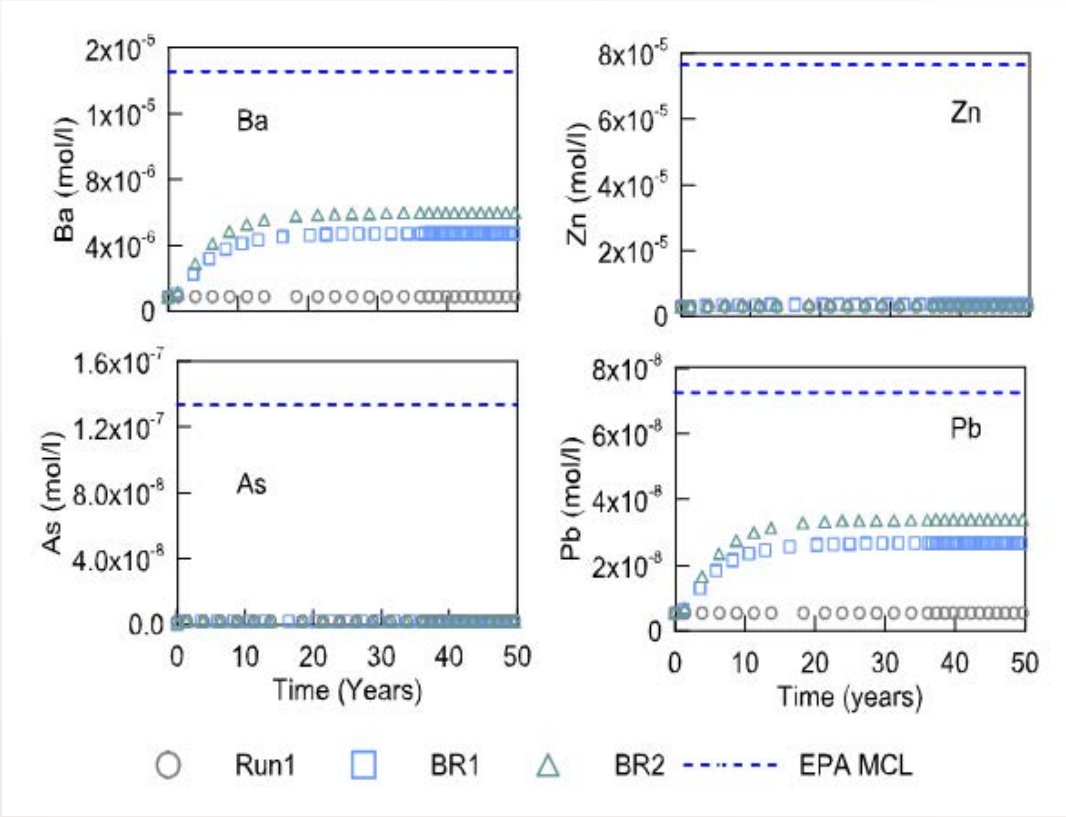
- TDS exceeds the EPA MCL if brine is leaked;
- pH degradation
- Mn is a concern

Potential impacts of CO_2 leakage on groundwater chemistry



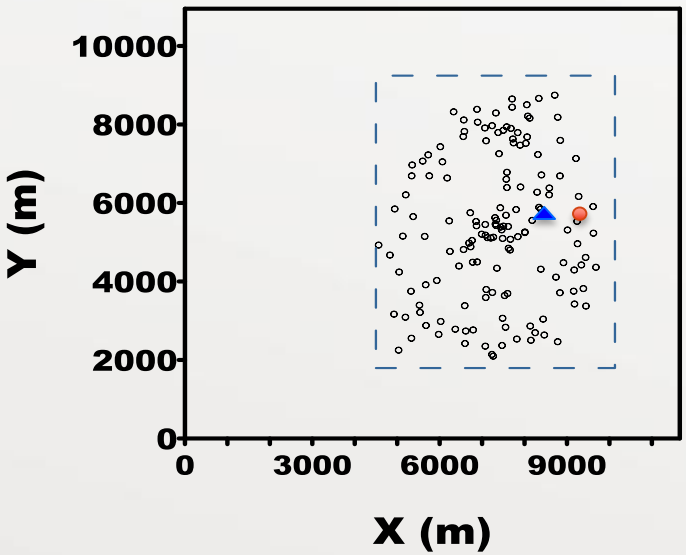
Leakage rate
metric ton/yr

Run1: 50.3
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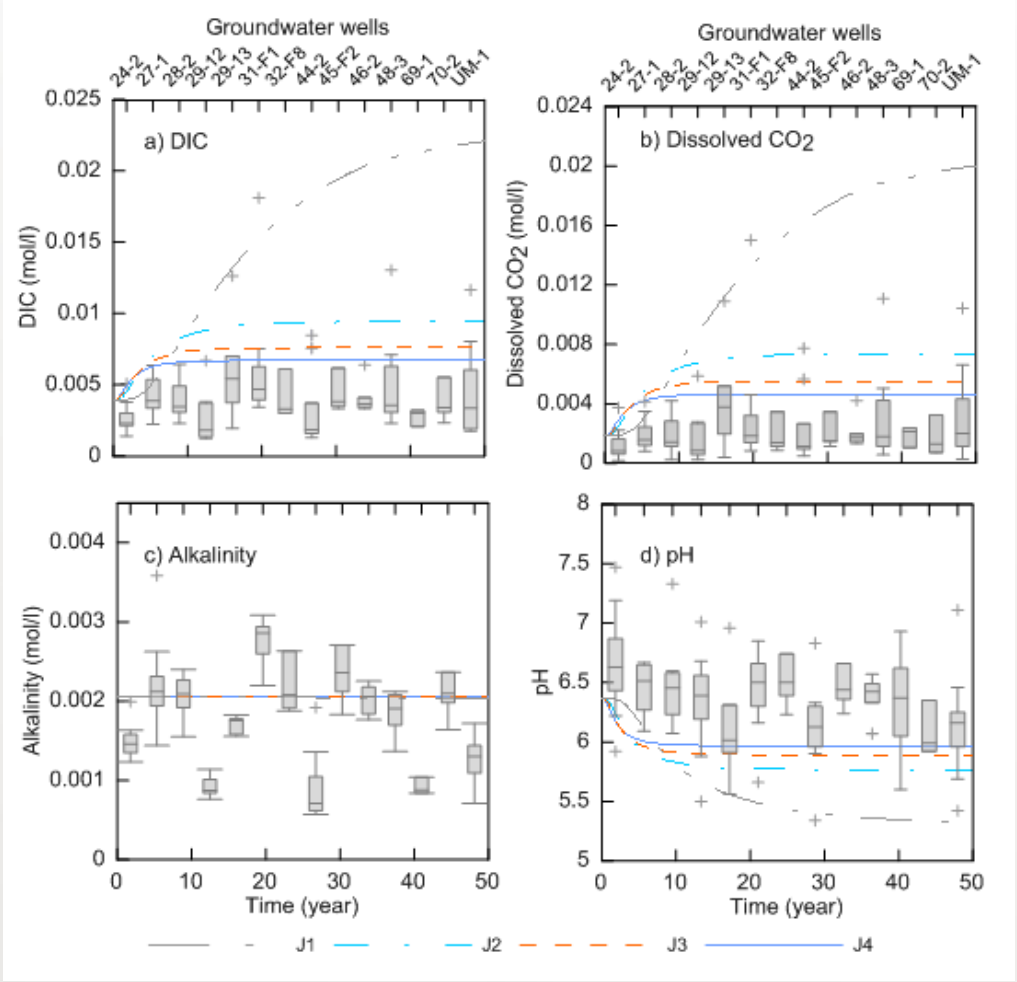
- Simulated conc. < EPA MCL
- Ba and Pb increase caused by brine leakage

Potential impacts of CO_2 leakage on groundwater chemistry



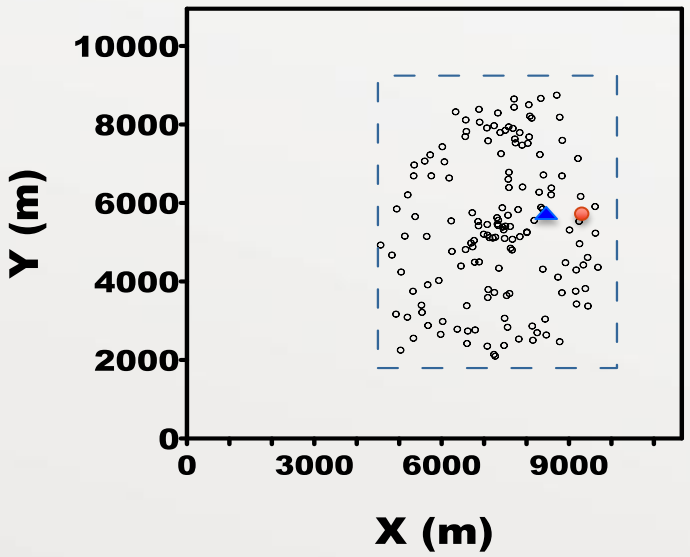
Regional hydraulic gradient

J1: 0.1%
J2: 0.5% (in the shallow aquifer)
J3: 0.8%
J4: 1.0%



Leakage rate: 37.7 metric ton/yr

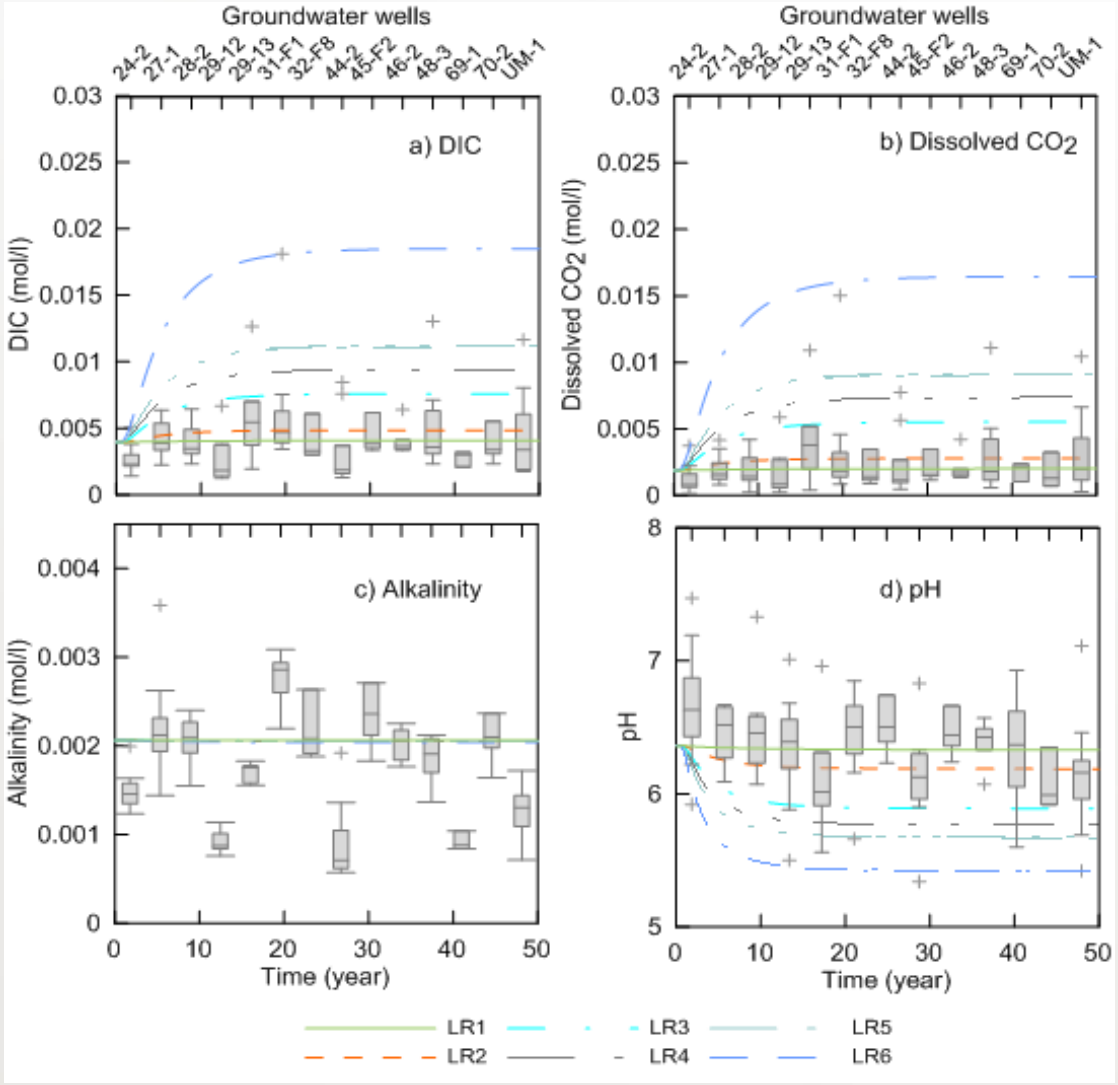
Potential impacts of CO_2 leakage on groundwater chemistry



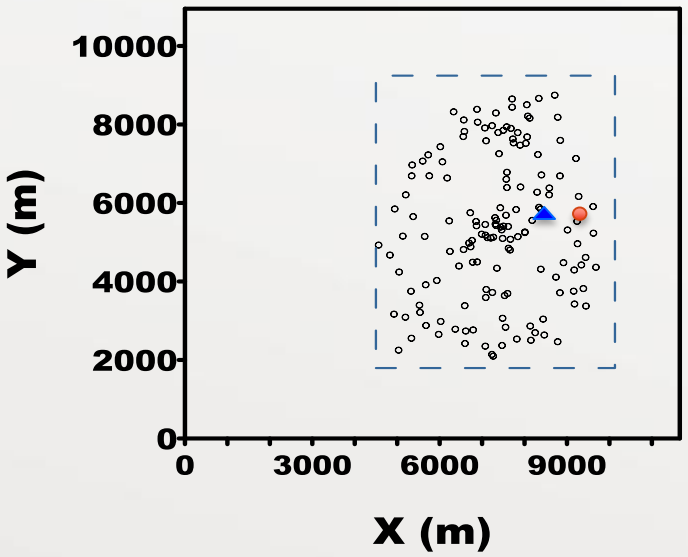
Leakage rate: metric ton/yr

LR1: 0.94
LR2: 6.28
LR3: 25.1
LR4: 37.7
LR5: 50.3
LR6: 100

J=0.5%

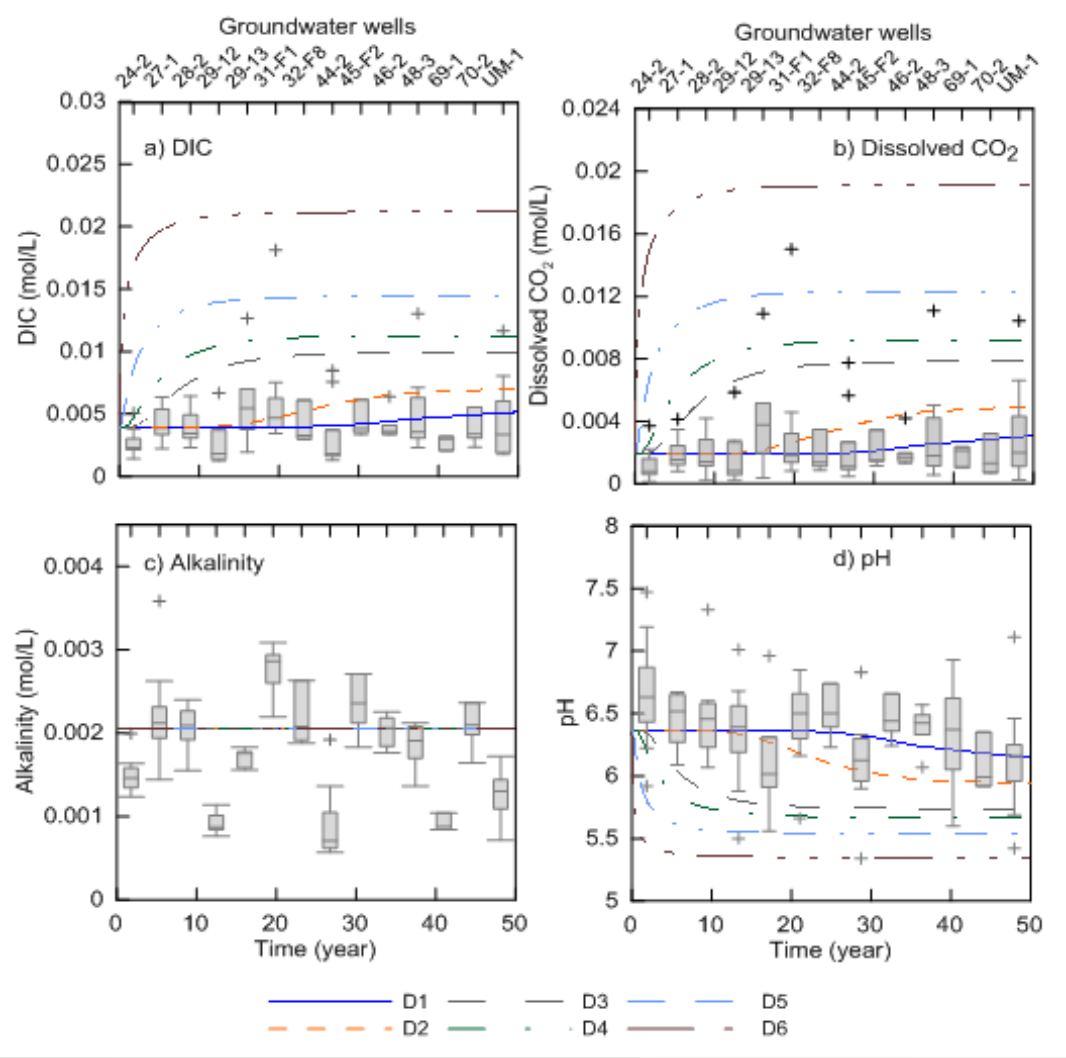


Potential impacts of CO_2 leakage on groundwater chemistry



Distance to the leakage well

D1: 6.1 km
D2: 3.6 km
D3: 1.0 km
D4: 0.67 km
D5: 0.3 km
D6: 70 m



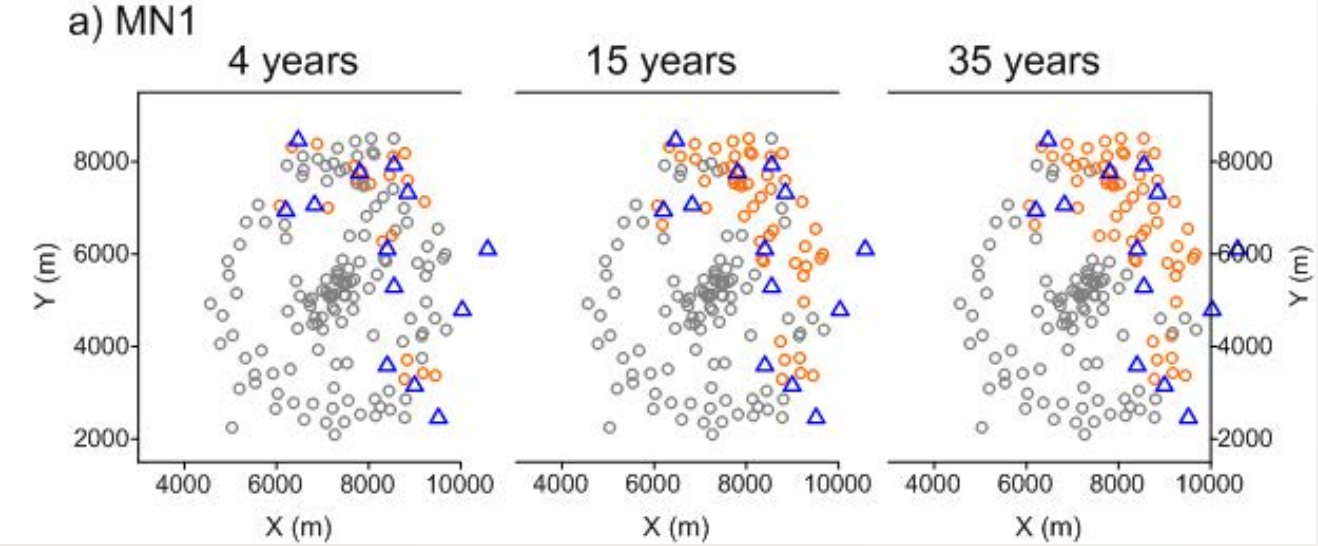
Leakage rate: 37.7 metric ton/yr

J=0.5%

Monitoring Network Efficiency

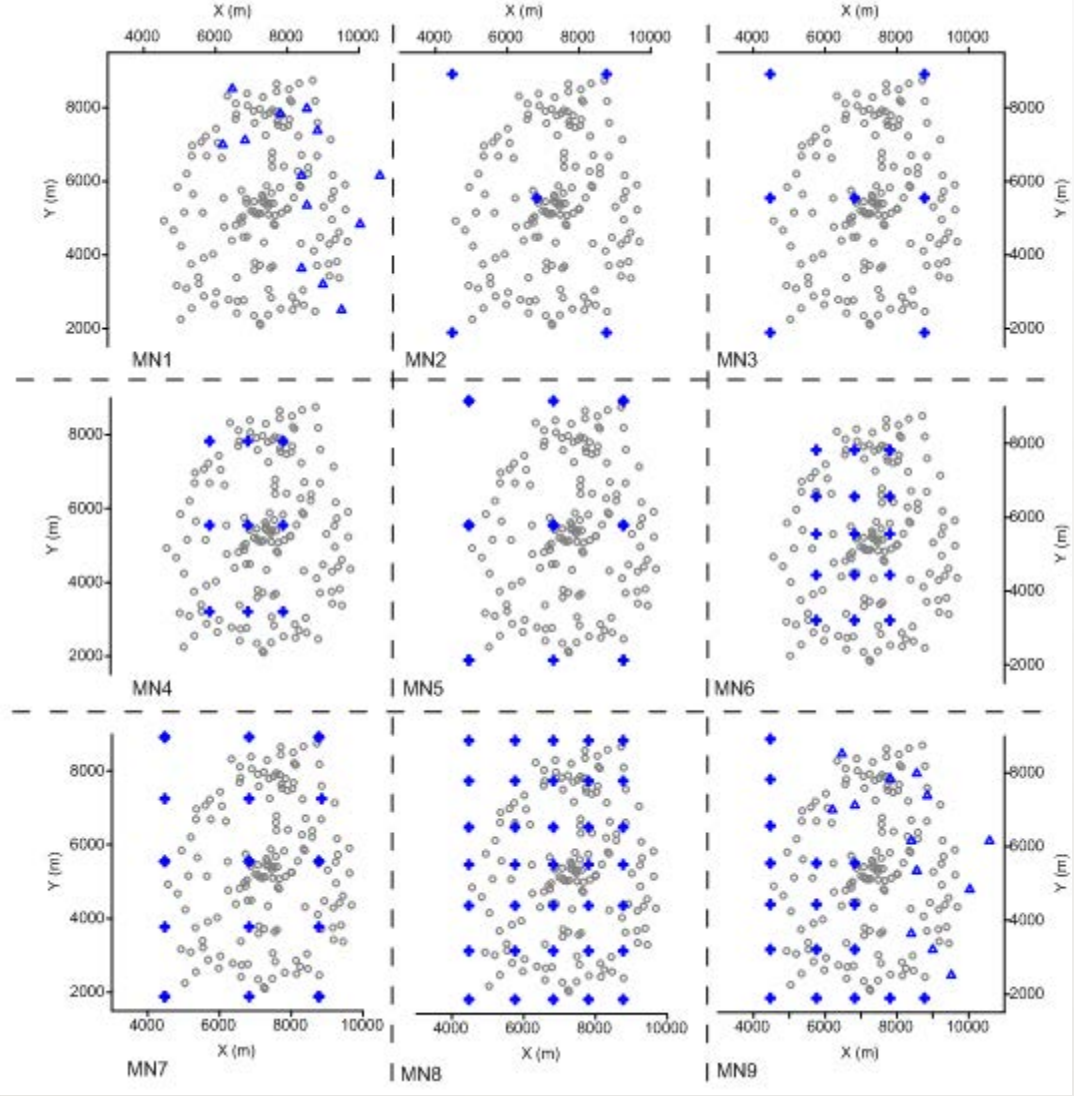
$$ME = \frac{W^d}{W^T}$$

- 20/151=0.13 by 4 years
- 50/151=0.33 by 15 years
- 58/151=0.38 by 35 years



CO_2 leakage from a P&A well is detected by a monitoring net work if change in DIC, dissolved CO_2, or pH in any one of wells of the monitoring network is higher than one standard deviation of the groundwater chemistry data collected in the shallow aquifer over the last 6 years.

Monitoring Network Efficiency

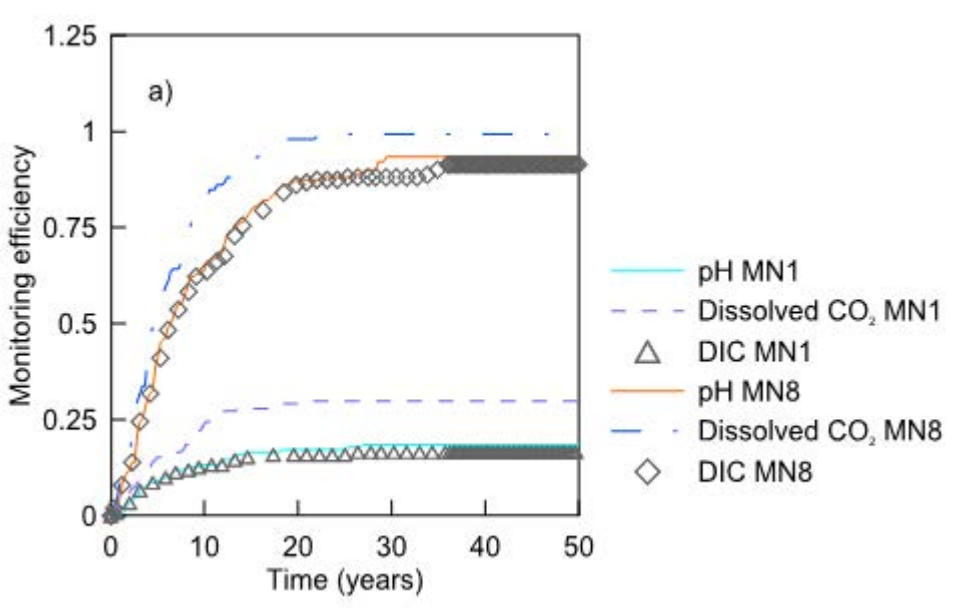


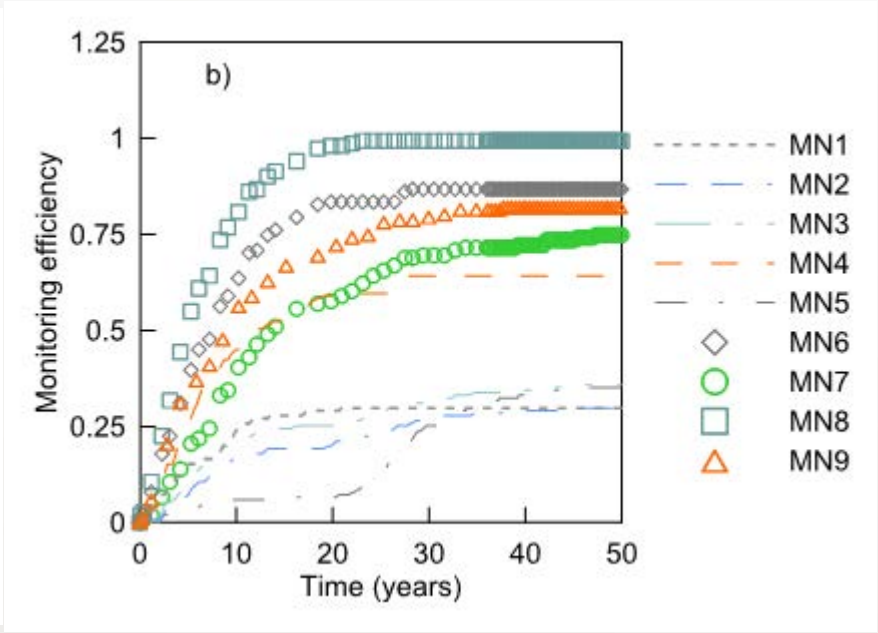
Unit: wells/km^2

MN1: 0.322
MN2: 0.124
MN3: 0.173
MN4: 0.223
MN5: 0.223
MN6: 0.371
MN7: 0.371
MN8: 0.866
MN9: 0.742

Monitoring Network Efficiency

Leakage rate=37.7 metric ton/yr; J= 0.5%



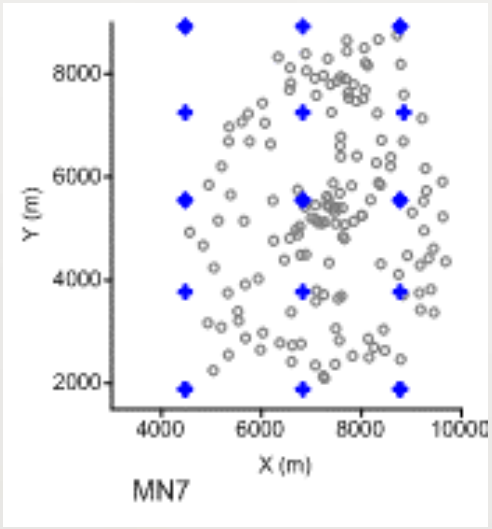


Comparison of ME for a) with pH, dissolved CO_2 and DIC as indicators for the two monitoring networks, MN1 and MN8

- Comparison of ME with dissolved CO_2 as indicator for the 9 monitoring networks
- Well densities for MN4 and MN5 are 0.223 wells/km2; ME of MN4 is ~2 times of ME of MN5, suggesting well locations are important

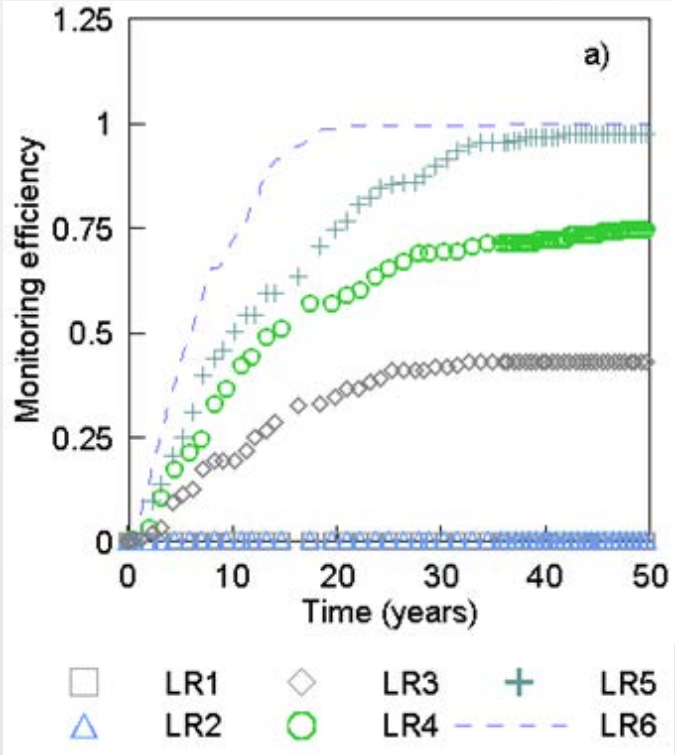
Monitoring Network Efficiency

Monitoring efficiency of MN7 with dissolved CO_2 as an indicator



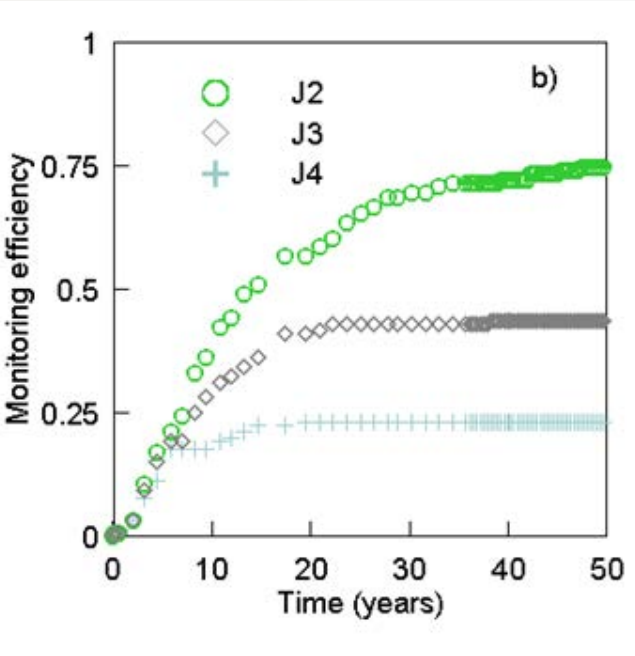
Leakage rate: metric ton/yr

LR1: 0.94, LR2: 6.28
LR3: 25.1, LR4: 37.7
LR5: 50.3, LR6: 100

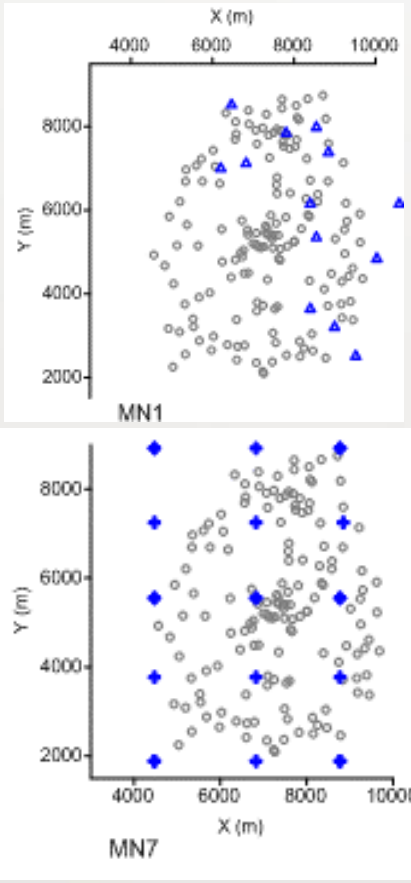


Regional hydraulic gradient

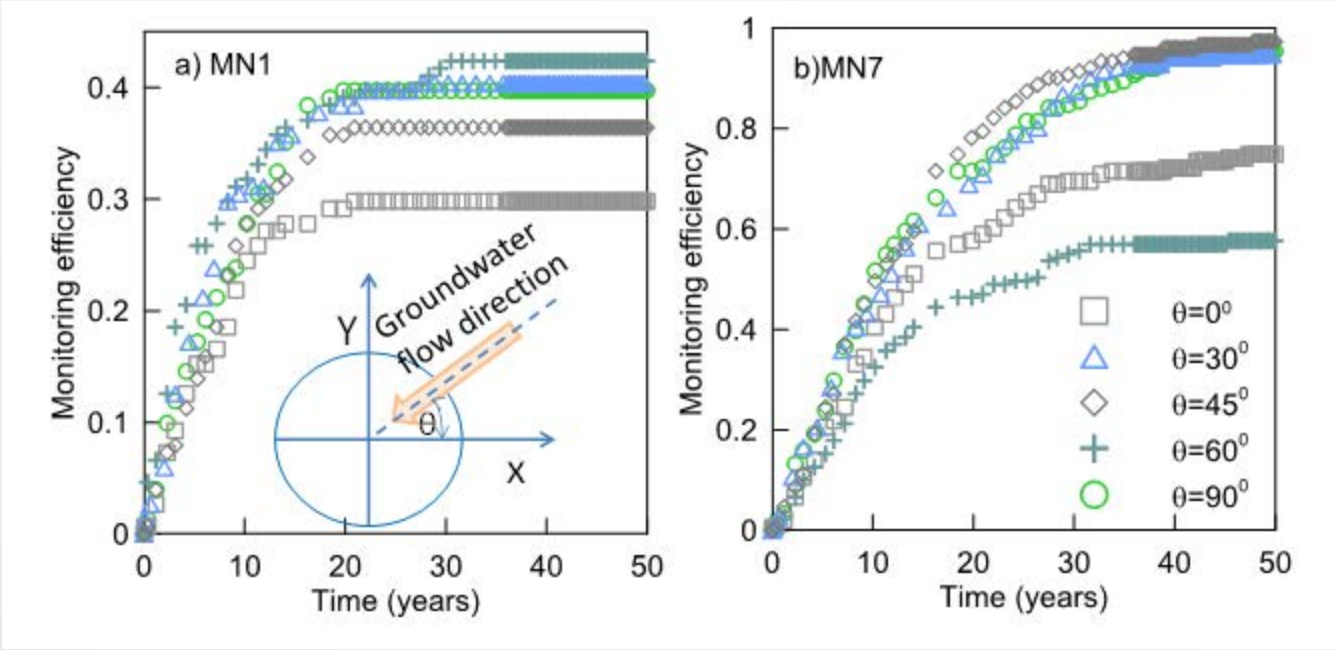
J2: 0.5% , J3: 0.8%
J4: 1.0%



Monitoring Network Efficiency



Groundwater flow direction



MN1 has the lowest ME for θ = 0°, the greatest ME for θ = 60°

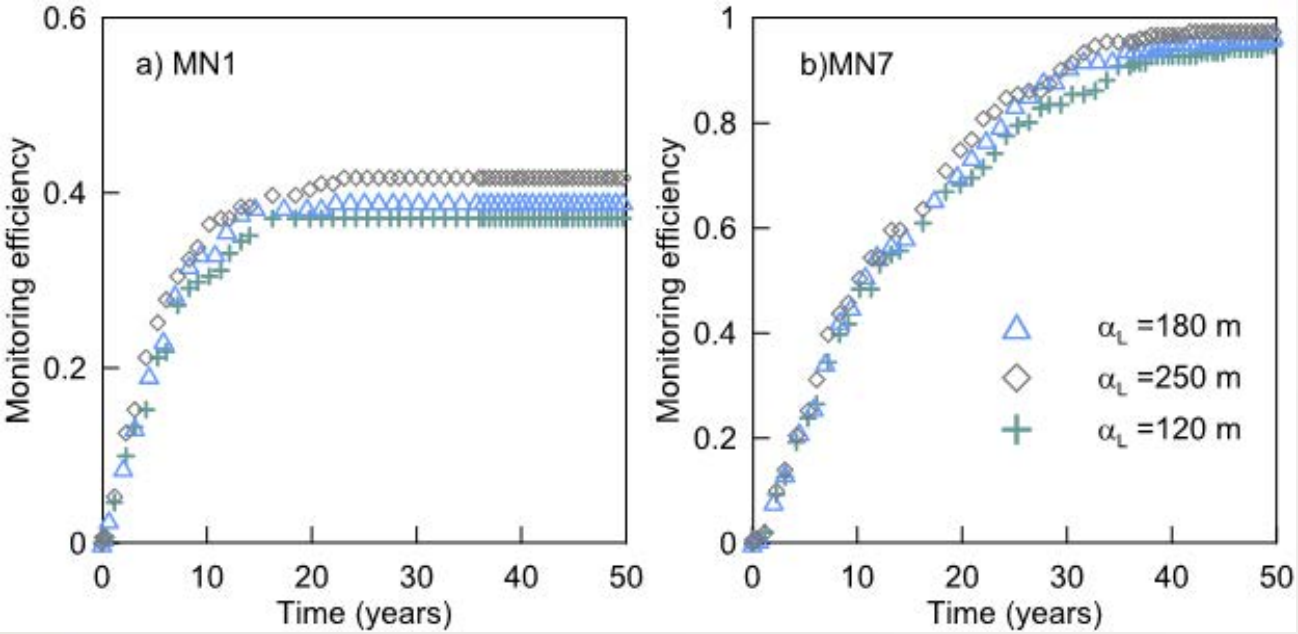
MN7 has the lowest ME for θ = 60°, the greatest ME for θ = 45°,

Groundwater flow direction is important for a monitoring network design

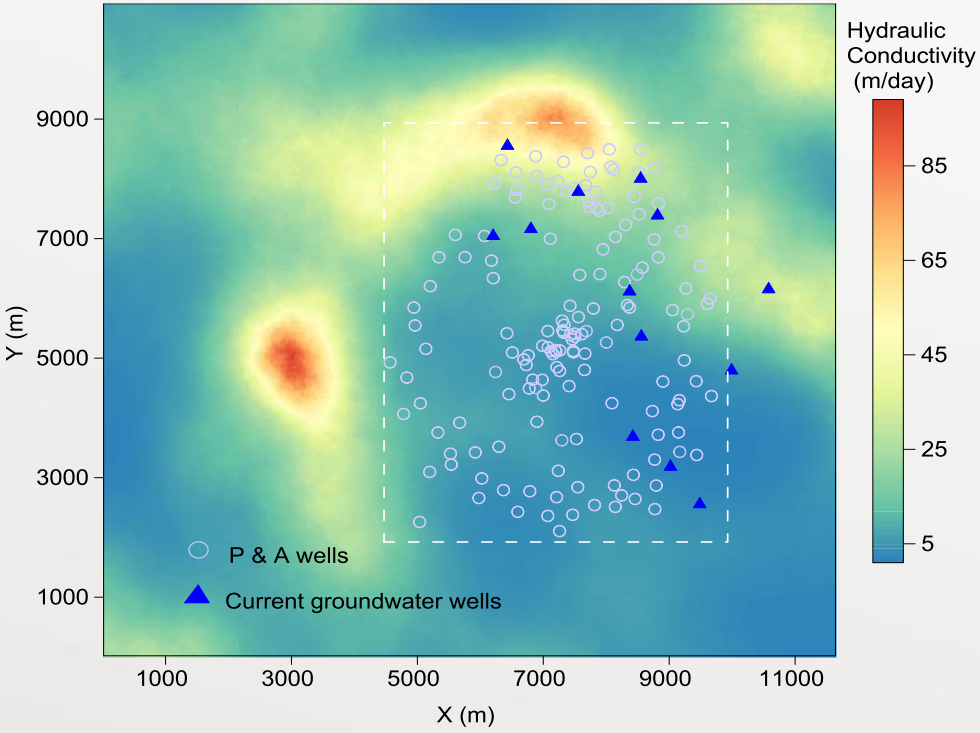
Monitoring Network Efficiency

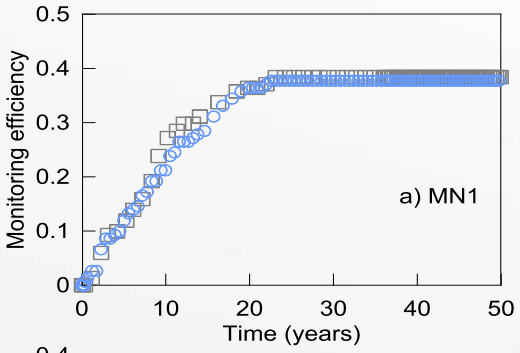
Dispersion coefficient

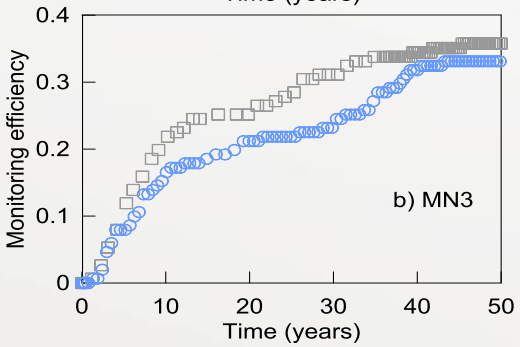
Dispersion coefficient can impact on lateral and longitudinal extension of a CO_2 plume in an aquifer

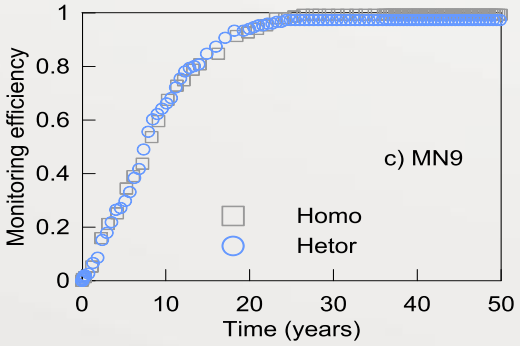


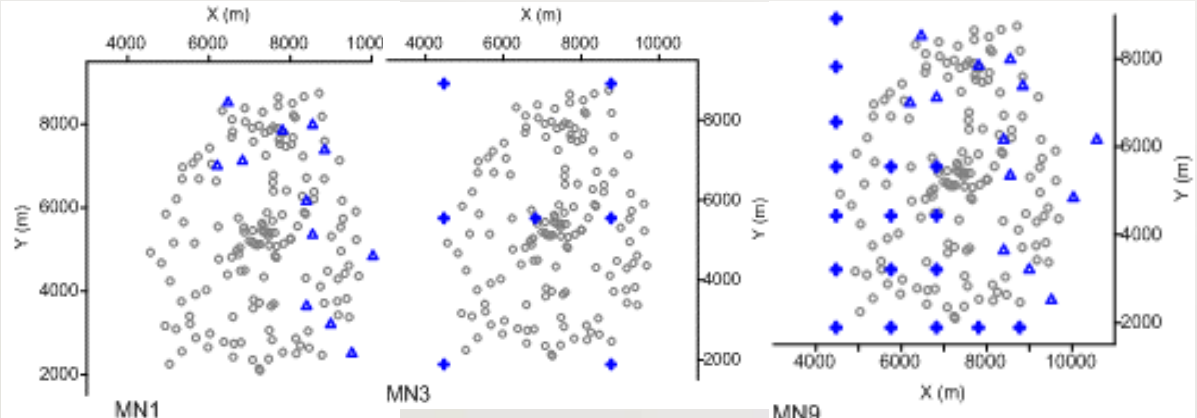
Monitoring Network Efficiency











Summary

- No obvious degradation in groundwater quality (except degradation in pH) if only CO_2 is leaked. Salinization would be problematic if brine+CO_2 are leaked.
- Dissolved CO_2 appears to be a better indicator than DIC, pH, alkalinity for CO_2 leakage detection at the CO_2-EOR site, however, dependent on regional hydraulic gradient, leakage rate.
- Monitoring network efficiency depends on regional hydraulic gradient, leakage rate, flow direction, and also aquifer heterogeneity. Impact of dispersion coefficient could be neglected.

Summary

- The existing groundwater wells can monitor CO_2 leakage from up to 60 P&A wells and MN8, the ideal monitoring network which consists of 35 water wells can detect CO_2 leakage from almost all P&A wells.
- Site characterization + lab experiments + single-well PPTs + RTM could be enough for risk assessment.
- Long-term geochemical monitoring for CO_2 leakage detection many not be very helpful because of complexity of the natural system, especially in a CO_2-EOR setting.

Thanks for your attention!

Near-surface Stratigraphy and Geophysics

L. Costard, J. Paine, S. Hovorka
Gulf Coast Carbon Center, Bureau of Economic Geology
Jackson School of Geosciences, The University of Texas at Austin

10th Annual SECARB Stakeholders' Briefing
Atlanta, March 11 2015















Survey Objectives

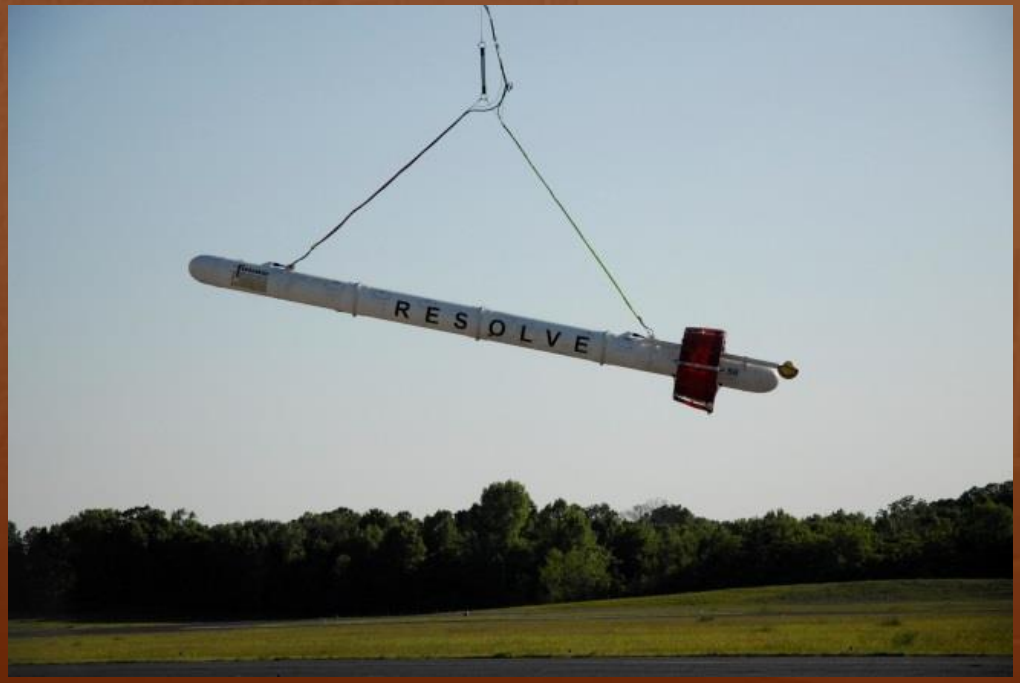
(1) Characterize the near-surface geology and hydrostratigraphy of Cranfield Field, MS

(2) Determine the initial electrical conductivity distribution to establish baseline salinity conditions

(3) Assess possible CO_2 migration paths and environmental impacts

Airborne Geophysics

Electromagnetic and Magnetic helicopter-borne geophysical survey in April 2013





Surface Geophysics

Electromagnetic surface surveys in September 2014





Borehole Geophysics

Borehole conductivity, natural gamma spectra and activity, and water level measurements at 13 water wells in March 2009 and September 2014



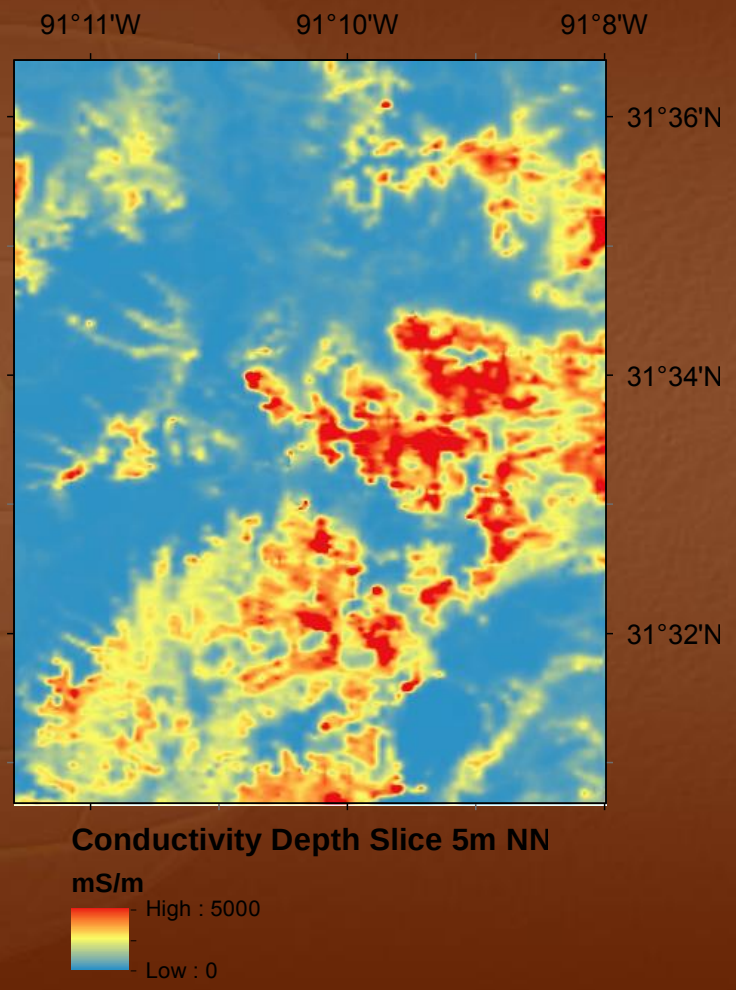


Current Results

- Initial processing of individual surveys completed

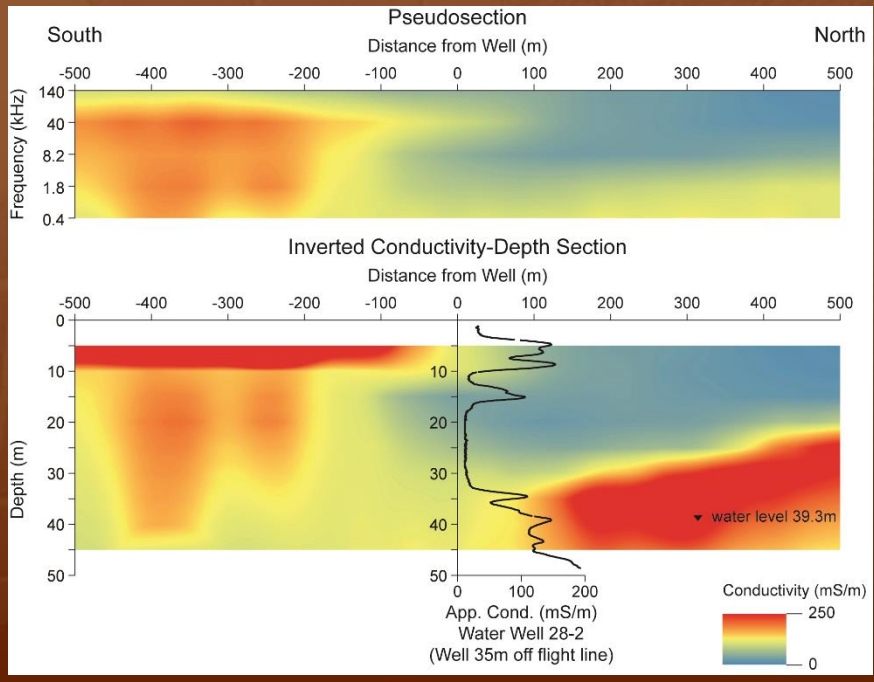
Current Results

- Initial processing of individual surveys completed
- Production of conductivity maps in depth of 5 to 45 m



Current Results

- Initial processing of individual surveys completed
- Production of conductivity maps in depth of 5 to 45 m
- Production of cross sections from borehole and airborne surveys for more detailed information



Future work

- Comprehensive assessment of geology and hydrostratigraphy of the site by combining completed surveys and drillers' log reports
- Comparison of stratigraphy and conductivities for possible initial-state salinity distribution in the near-surface environment

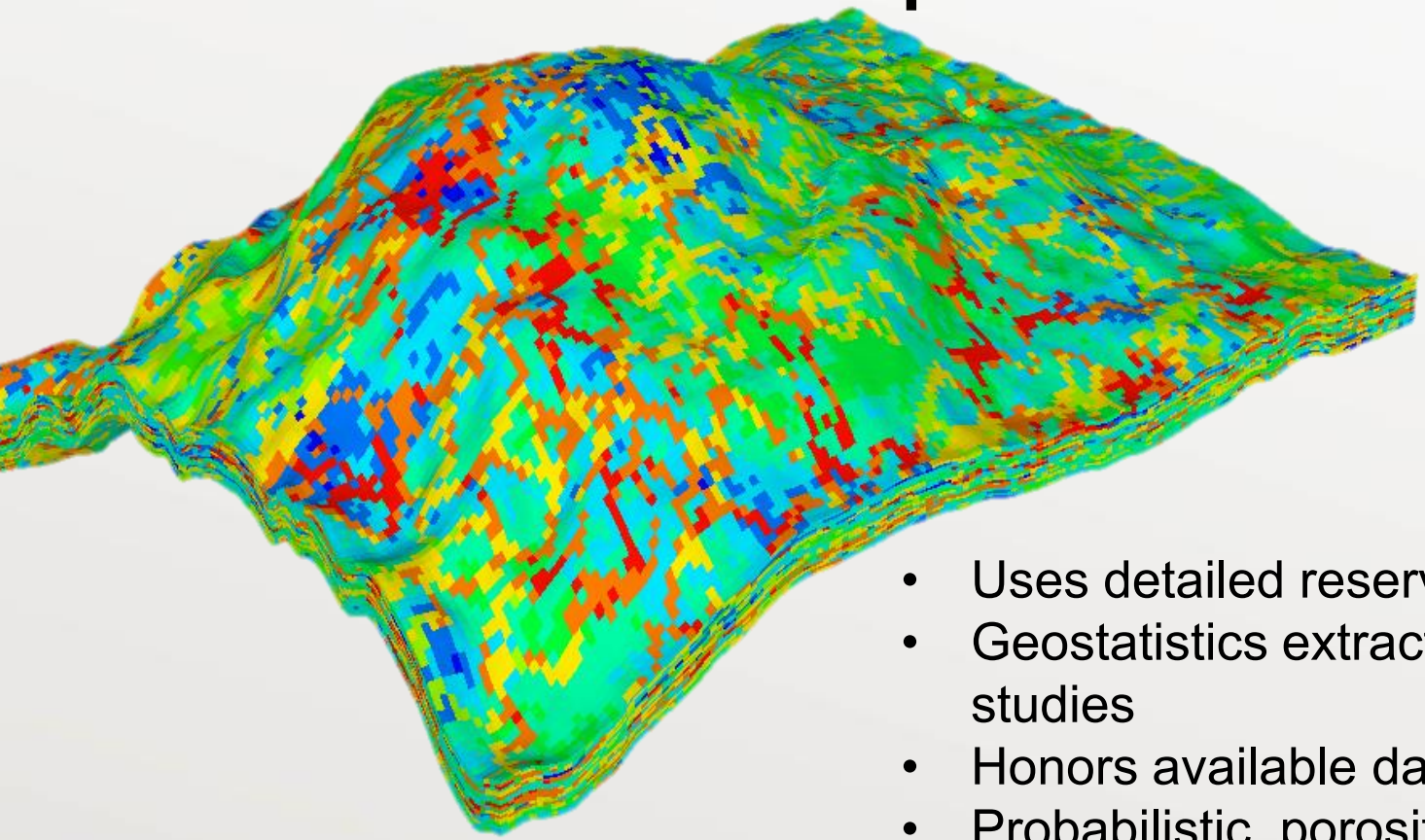
Update on Reservoir Modeling and Final Testing and P&A underway

Susan Hovorka
Seyyed Hossieni
Ramon Trevino
Gulf Coast Carbon Center
Bureau of Economic Geology
The University of Texas at Austin
March 11, 2013

Modeling Update (Hossieni)

- Significant progress since last update
  - History matching 1943-1966 production
  - Included oil using black oil simulator
    - Modeling not focused on production but CO_2 tracking
  - Expanded domain modeled to whole field
  - Expanded time frame to current project and model into future
  - Approximate match with time-lapse seismic
- Model can be now used for scenarios

Reservoir properties: Porosity input

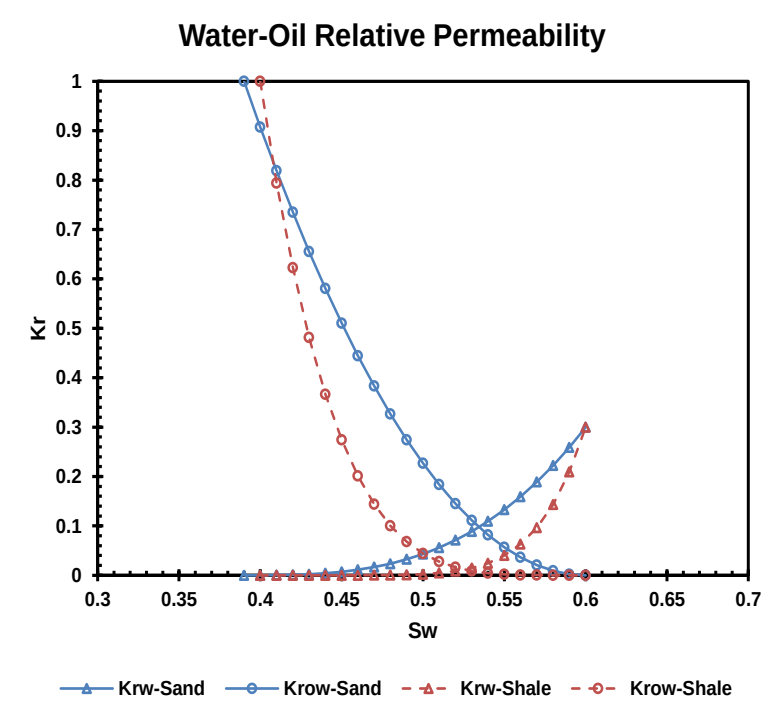


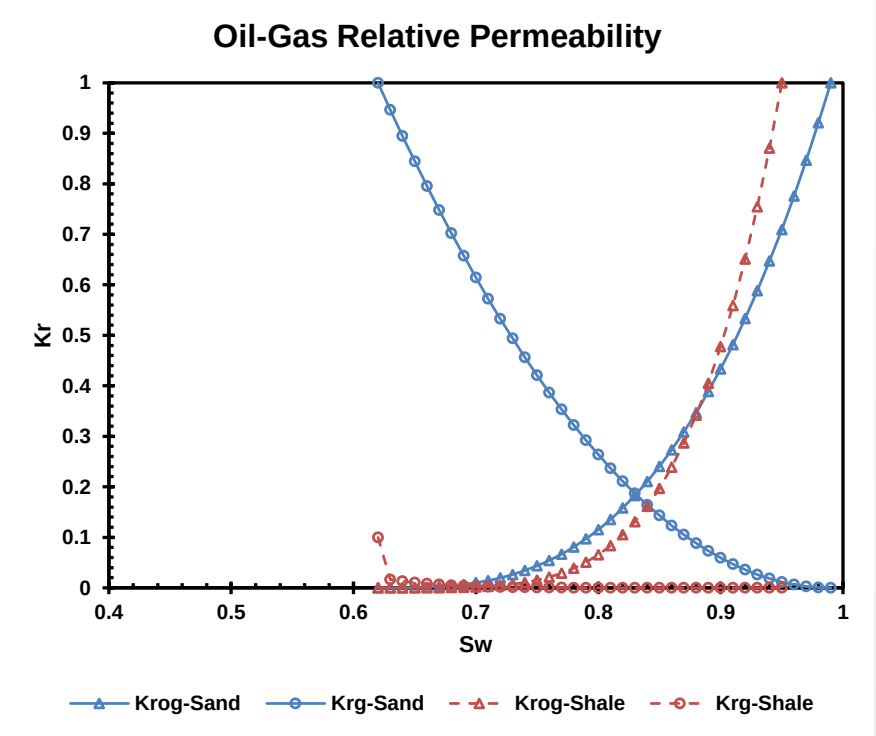
- Uses detailed reservoir geometry
- Geostatistics extracted from detailed studies
- Honors available data
- Probabilistic porosity and permeability

Reservoir related parameters used in the simulator

Parameter	Value
Stock tank oil density	873 kg/m^3
Gas density SC	0.942 kg/m^3
Water density	1108 kg/m^3
Solvent (CO_2) density	1.8 kg/m^3
Oil compressibility above pb	1.98E-9 Pa^{-1}
Initial Pb	31.06 MPa
Original water oil contact depth	3064 m
Original gas oil contact depth	3008 m
Pressure at ref depth of 3048 m	32.03 MPa

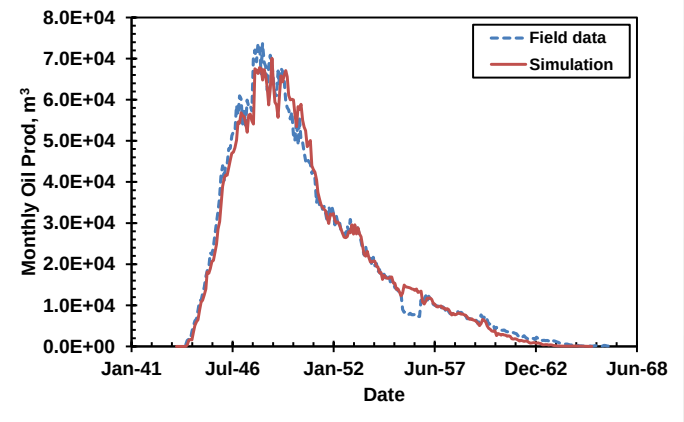
Model using black oil simulator CMG-IMEX

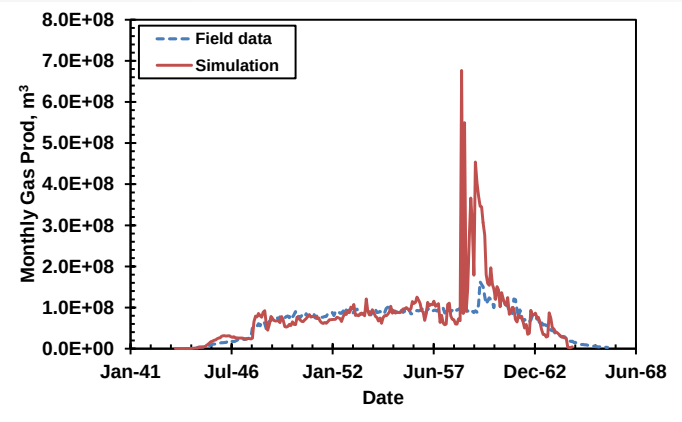


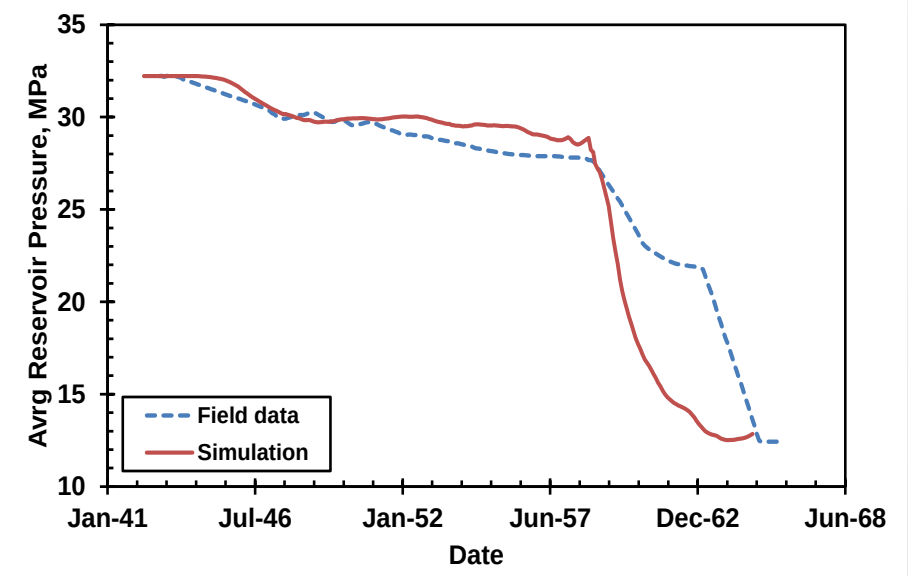


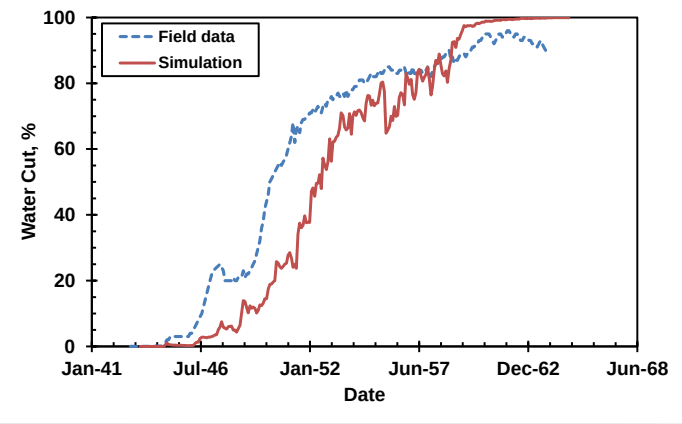
Pseudo-miscible model, Todd and Longstaff 1972

Historic data history matching

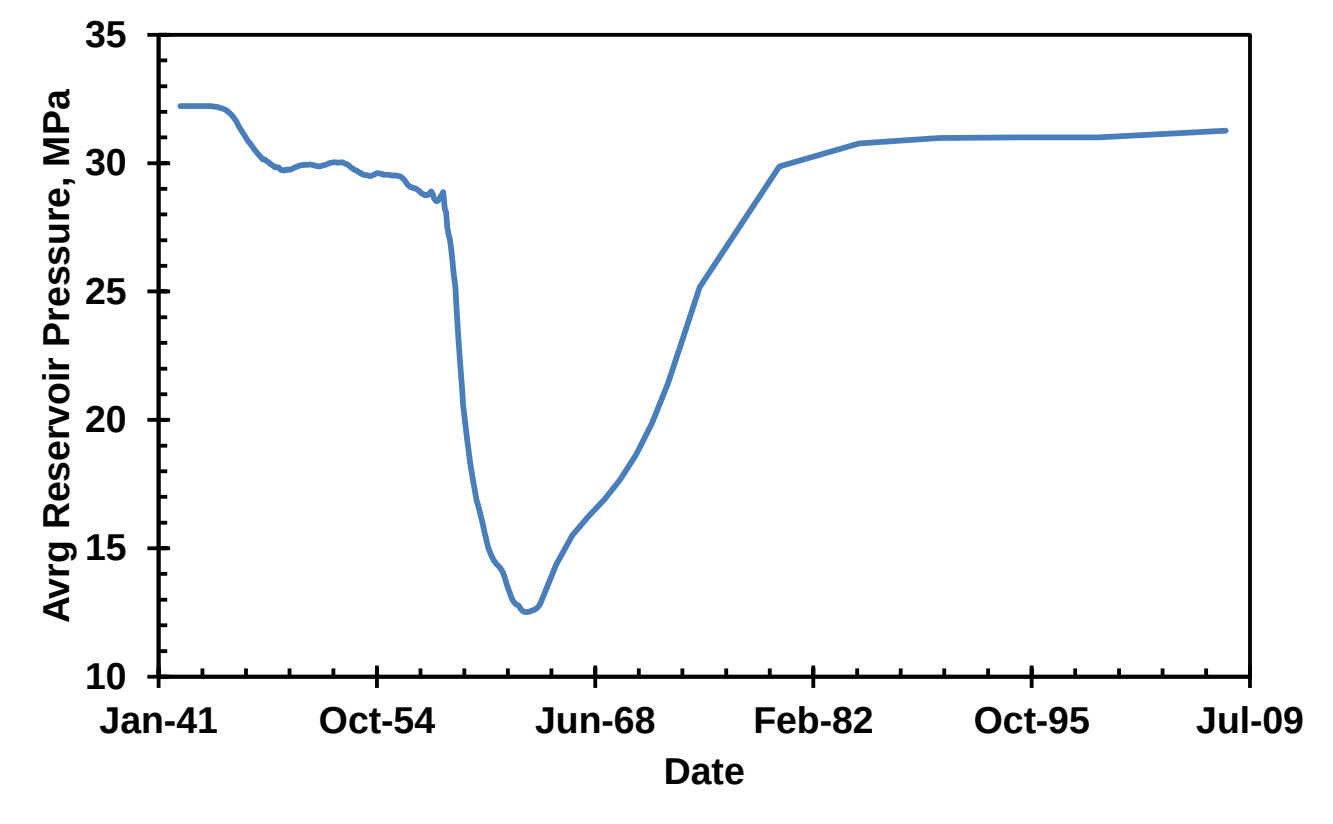






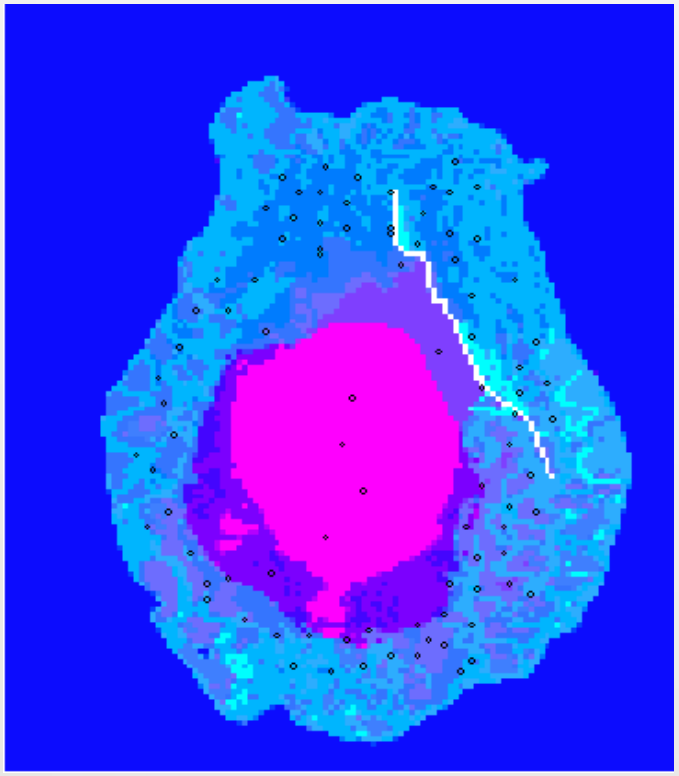


Preinjection Pressure history

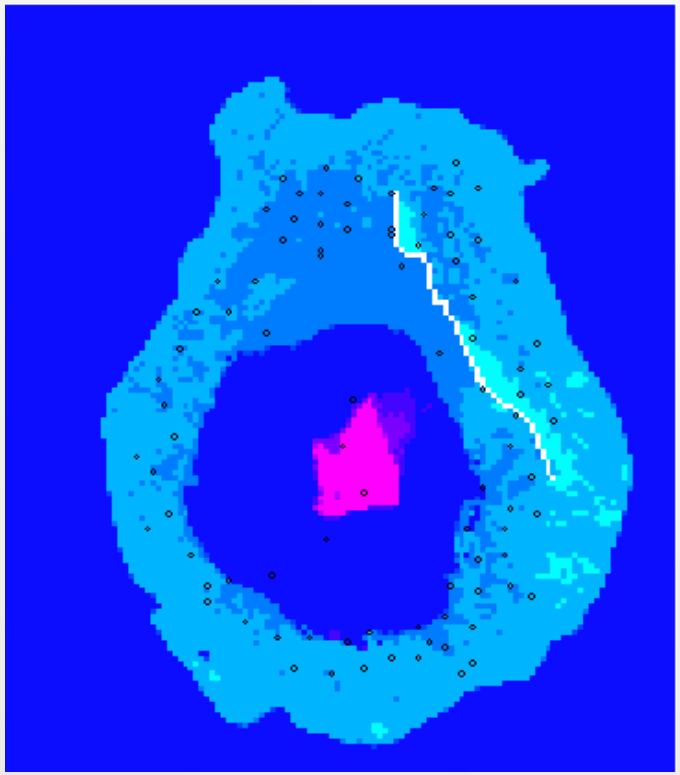


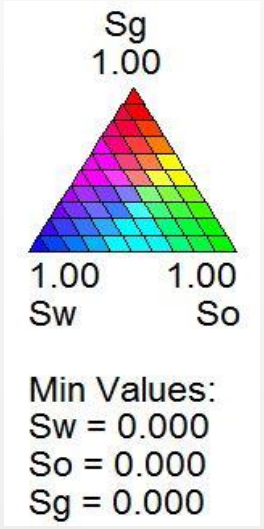
Initial Conditions to EOR

1966



2008

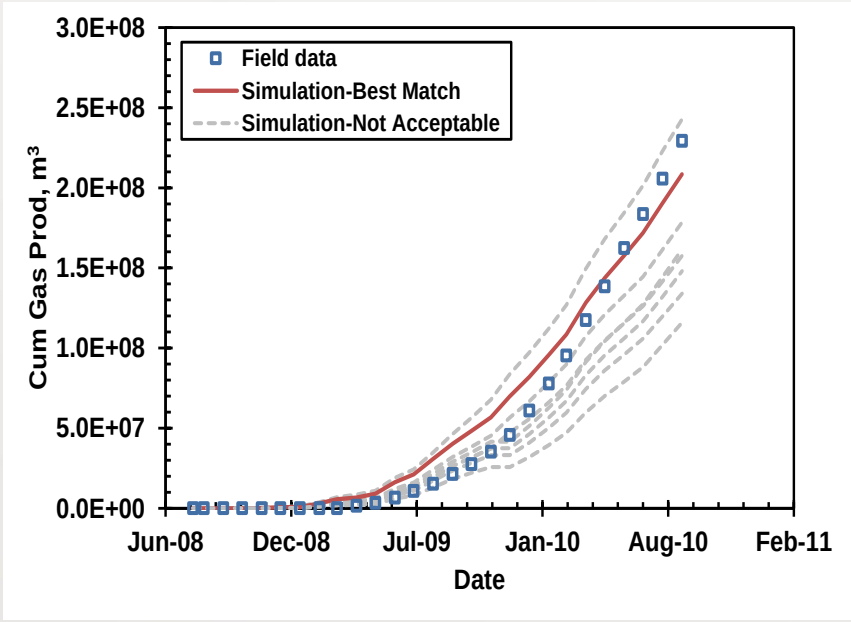




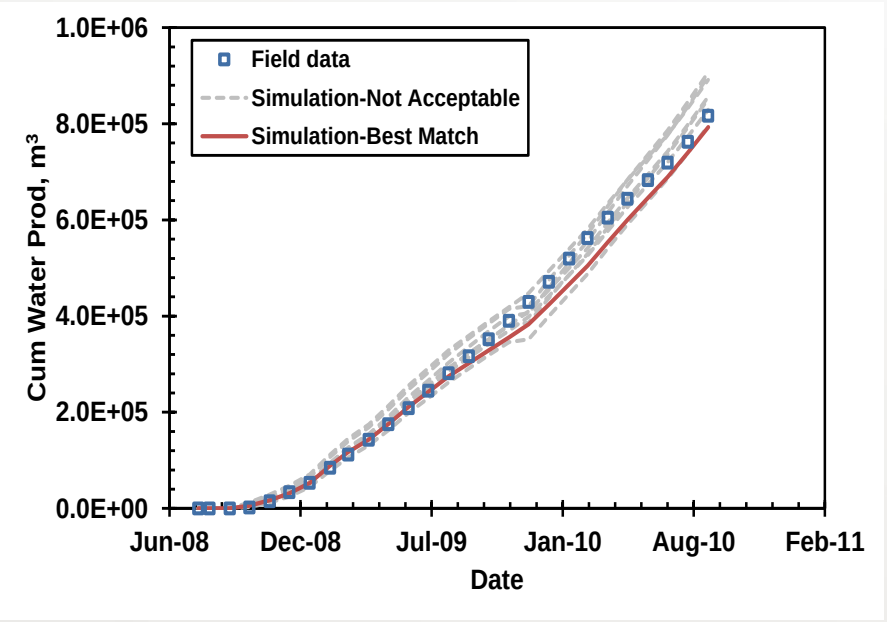


EOR flood history match

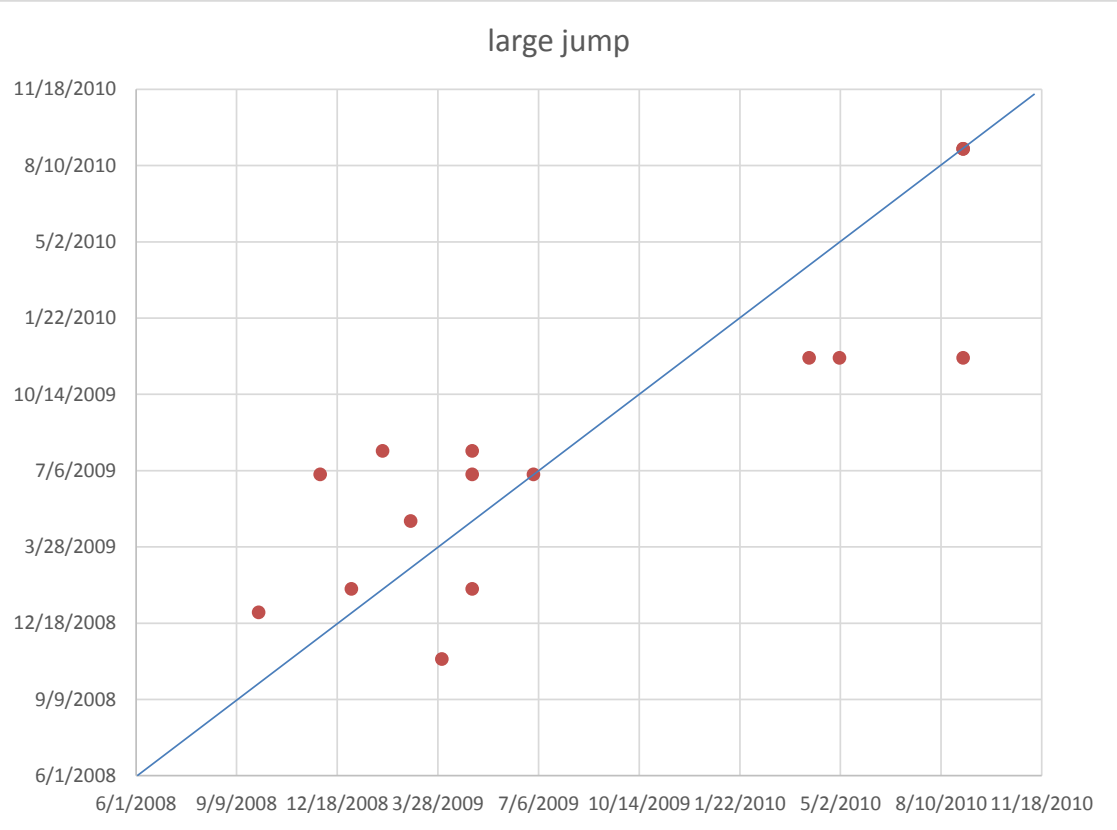
Cumulative Gas production



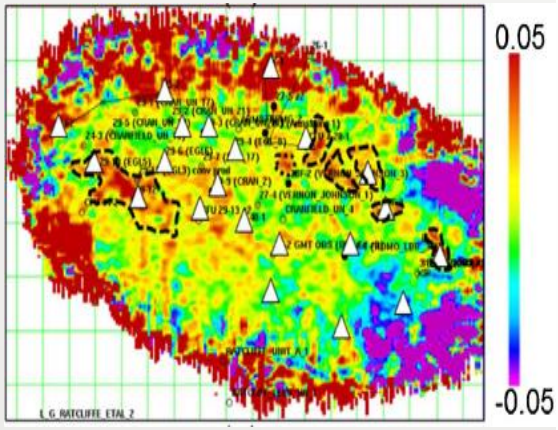
Cumulative water production



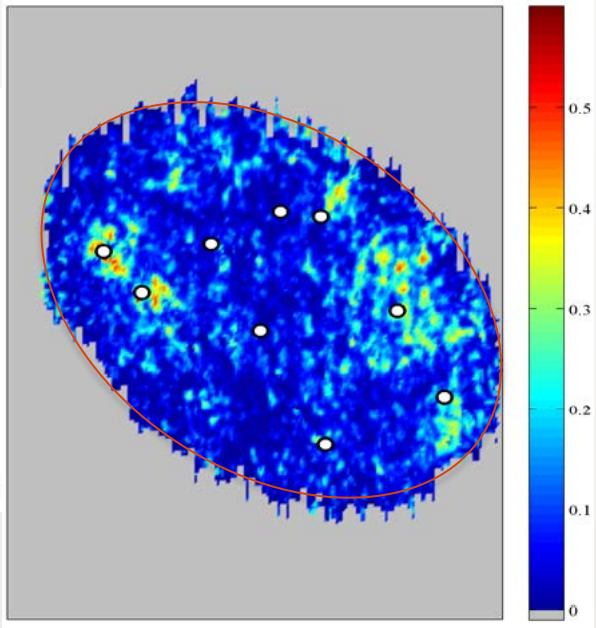
History Match Modeled and measured CO_2 breakthrough



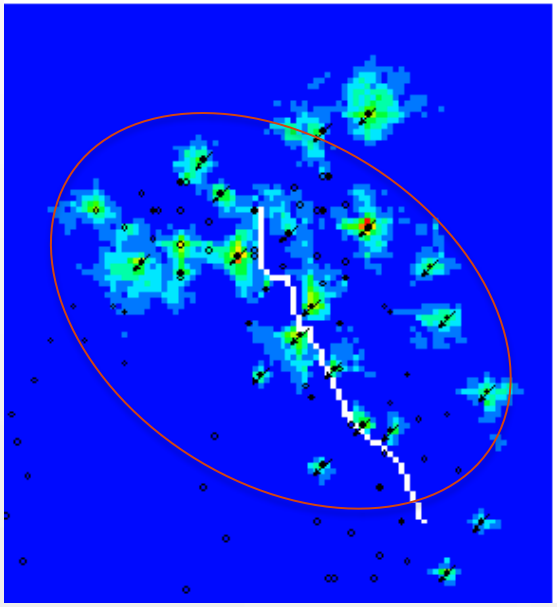
Approximate match with time-lapse seismic 2008-2010



$v_p - v_s$ ratio difference Zhang et al. (2014)

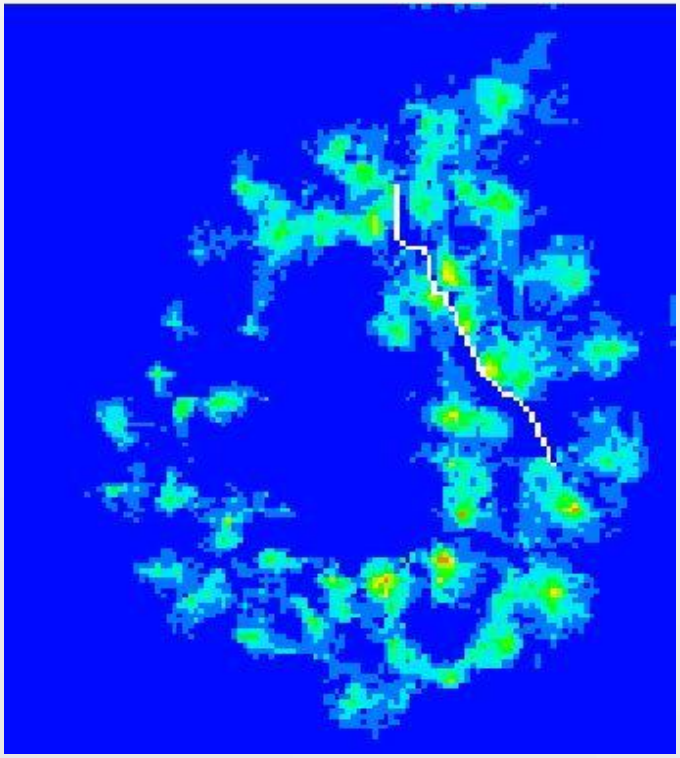


CO_2 saturation distribution estimate using rock physics 2010 from 3D seismic data (Carter 2014)

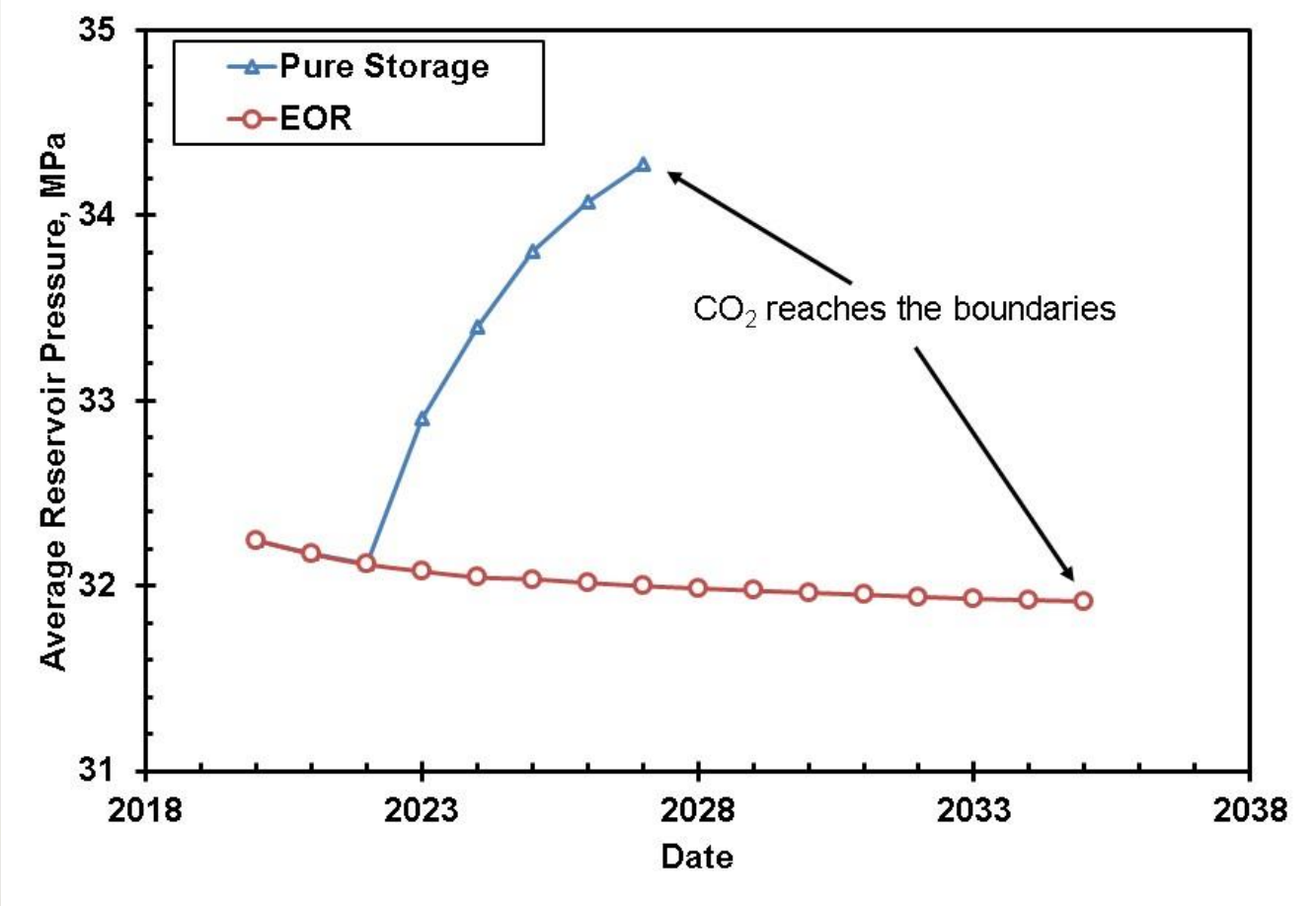


Modeled CO_2 distribution

Theoretical 2018 CO_2 distribution based on continued same build-out process



Theoretical Scenarios



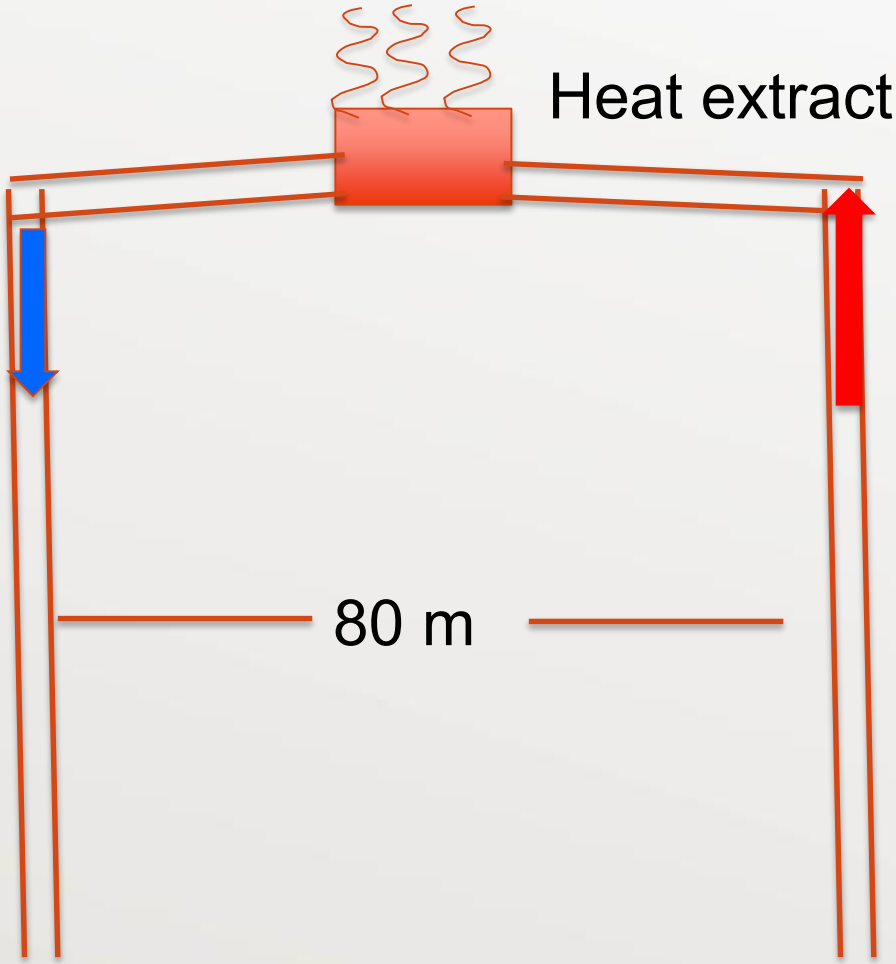
Summary

- A black-oil simulation of the whole field has been developed based on characterization and history-matched to past production
- Model was successfully history matched to EOR development using produced fluids and this matched CO_2 breakthrough times (as a population)
- Reasonable match between modeled CO_2 saturation and that estimated from time lapse seismic, limitations noted
- Limitations also observed to pressure match
- Can use calibrated model for scenarios

Final Testing and P&A

- Last two stages of project:
  - Pulse testing and thermosyphon completed in January 2015
  - P&A and final data collection to be completed in April, 2015
- This will conclude field phase of Early Test
  - Denbury commercial EOR will continue
  - DOE program work will extract lessons learned and conduct technologies transfer

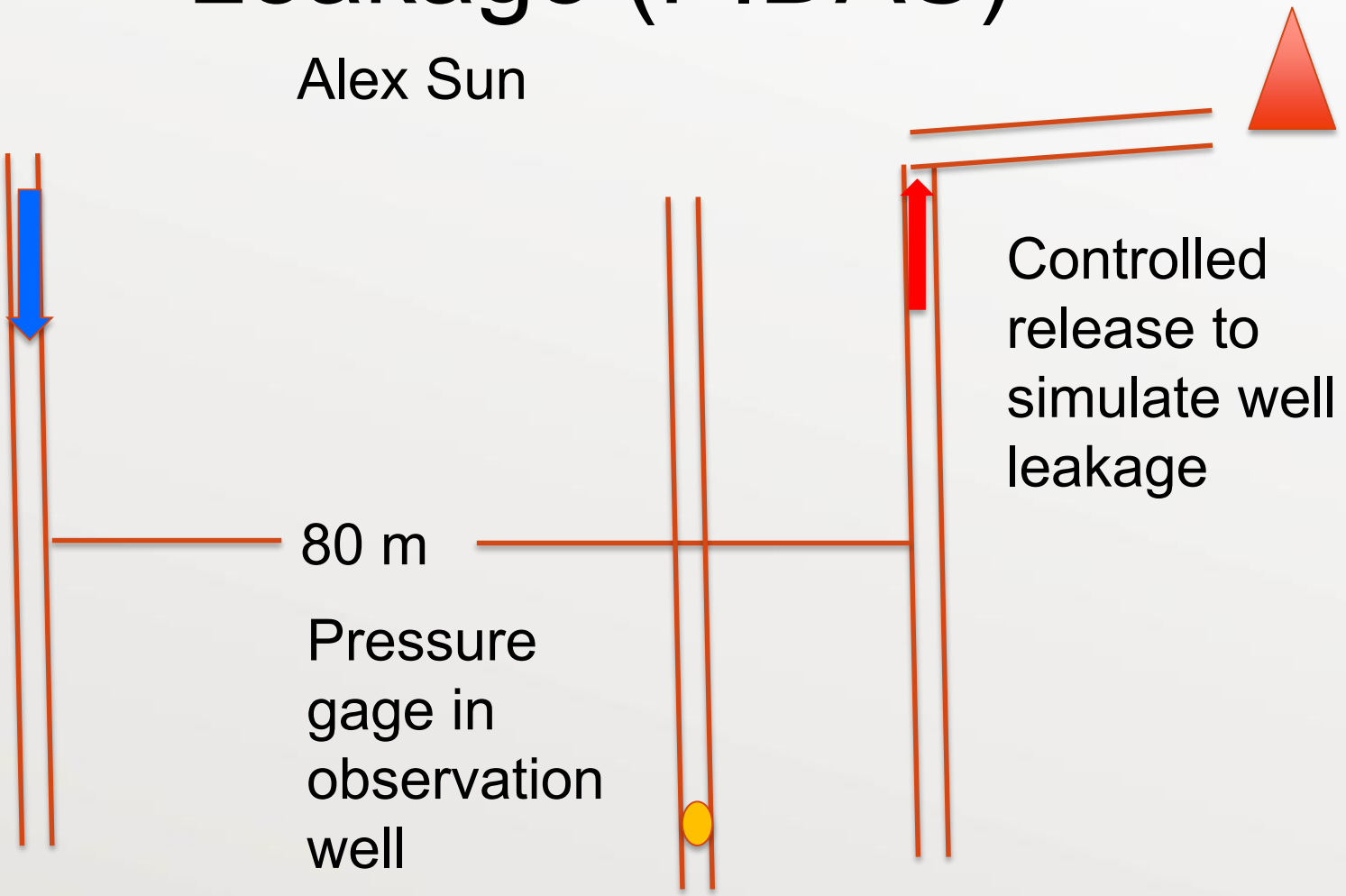
Thermosyphon (Barry Freifeld)



DOE program combining CCUS and geothermal; LBNL lead

Harmonic Pulse testing for Leakage (PIDAS)

Alex Sun





Heat exchanger



Vent system

Photos by Lu

Plugging Procedure Overview

- Final Repeat RST
- “Kill” F2 and F3 wells
- Remove packers
- Squeeze Tuscaloosa perforations, test
- Logging, Sonic, USIT, Cross-well, sidewall cores, gyro
- Fluid sampling and hydro tests in AZMI
- Squeeze perforations
- Cement and abandon according to MO&G Board rules

Next steps

- Analysis of data collected – value and best practices to commercial CCUS monitoring
  - Publications
- Technology transfer
  - Current commercial projects
  - International collaborators

Summary

- Monitored >5 million metric tons CO_2 stored in EOR + saline setting 2008-2014
  - Monitoring tool performance
  - History matching
  - “learn by doing” best practices development
- Technology transfer
  - Projects
  - Protocols
  - publications

Thanks for your attention!

SECARB Early Test Retrospective

Susan Hovorka, *Ramón Treviño*, Tip Meckel,
Jacob Anderson, Seyyed Hosseini, Jiemin Lu, JP Nicot,
Katherine Romanak, Changbing Yang

Early Test Research team

NETL

SECARB
Southeast Regional Carbon Sequestration Partnership

Southern States Energy Board

SECARB Anthropogenic Test At Plant Barry/ Citronelle

Bureau of Economic Geology

Gulf Coast Carbon Center

Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

Core Lab
UT DoG
Anchor QEA

Environmental Information Volumes
Walden Consulting

Federal collaborators Via FWP

Denbury Resources
Field owner and injection system design, management, 4-D survey, HS&E

Sandia Technologies
Monitoring Systems
Design, Installation, HS&E

LBNL
Well-based geophysics, U-tube and lab design and fabrication

LLNL
ERT

USGS
Geochemistry

Vendors
e.g. equipment

Separately funded

ORNL
PFT, Stable isotopes

NRAP
VSP& analysis

NETL
Rock-water interaction

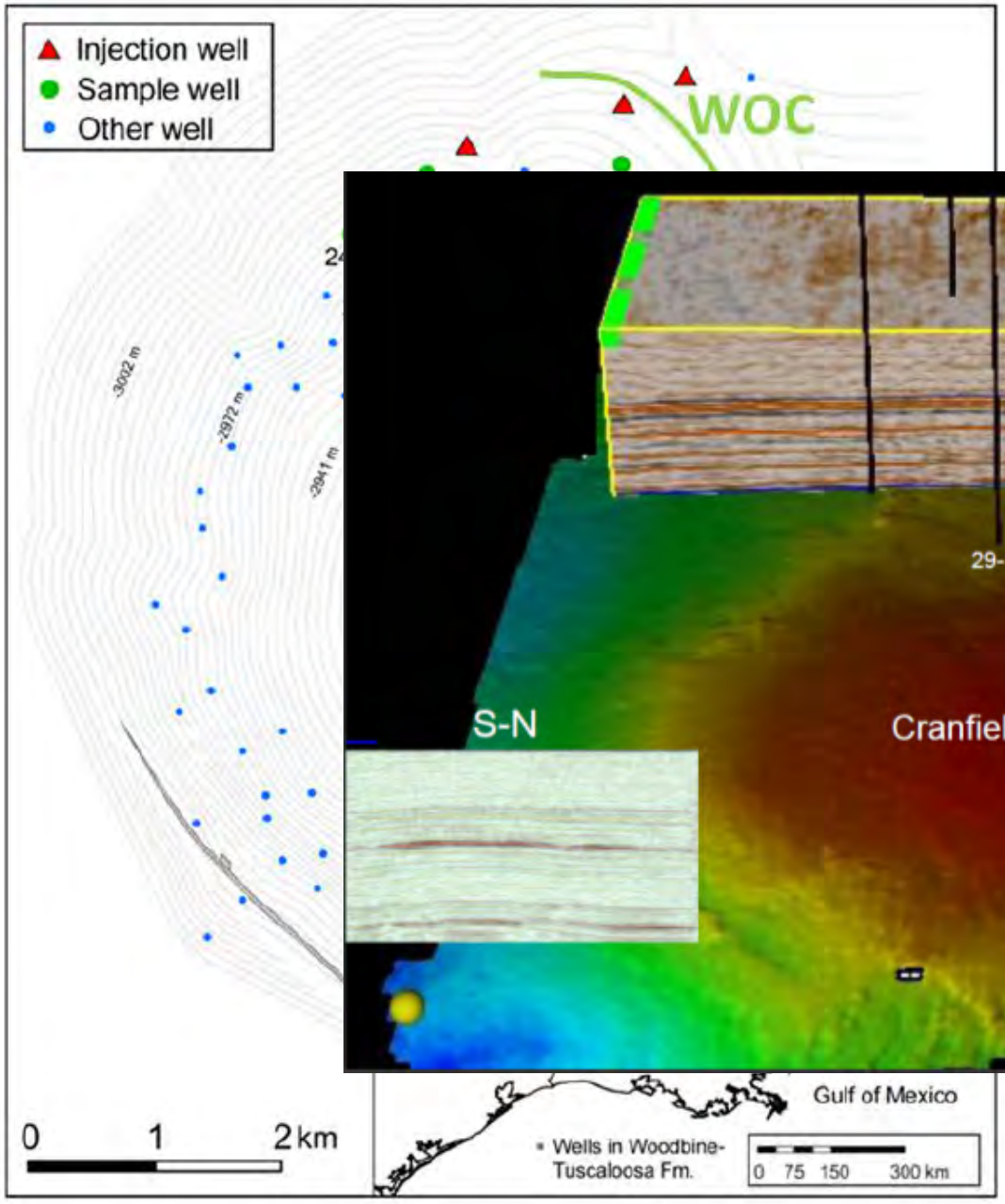
Stanford, Princeton, U Edinburgh, UT PGE & ICES (CFSES), U. Tennessee, USGS RITE, BP, CCP, Durham, AWWA

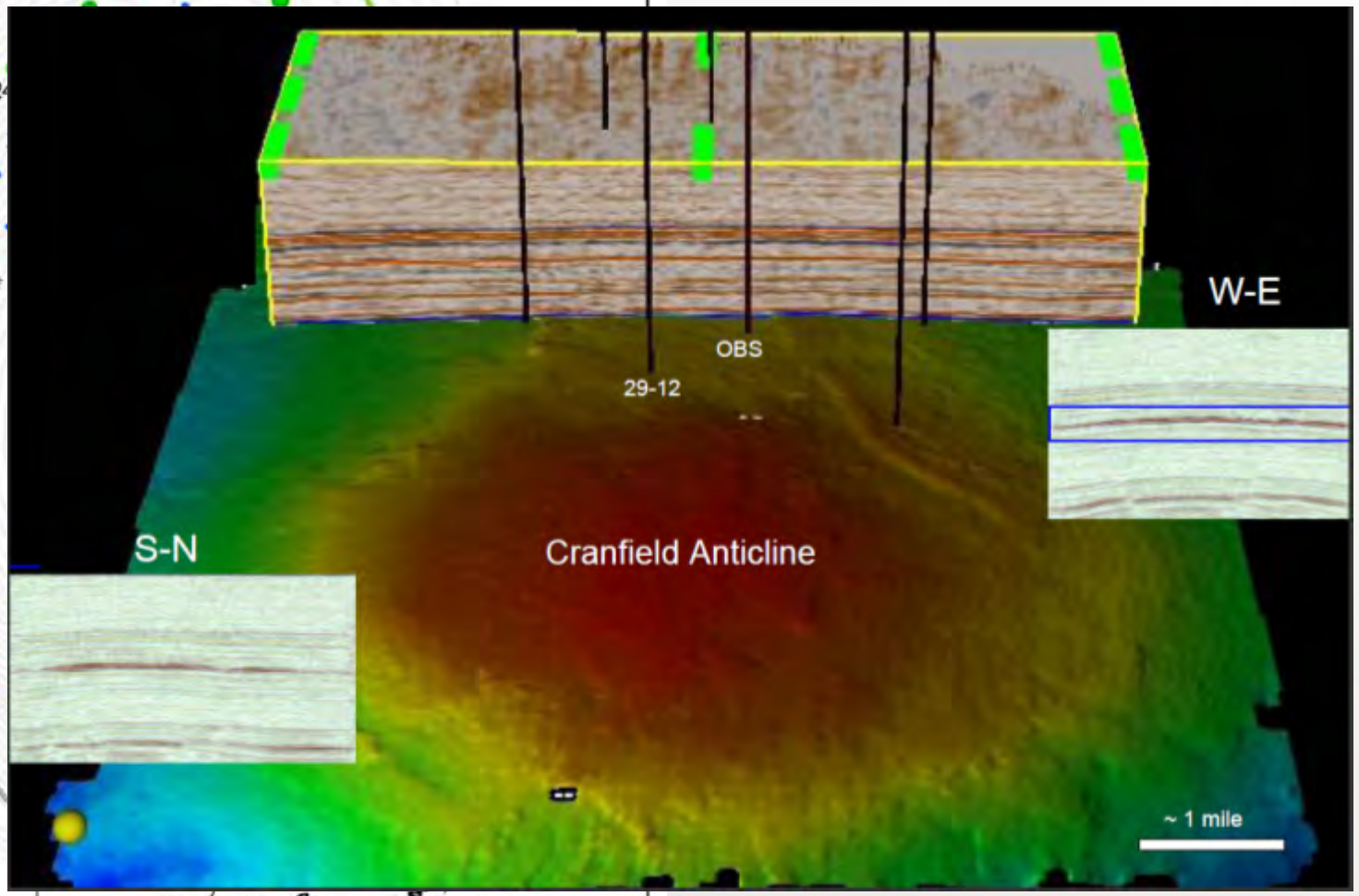
Vendors
e.g. local landman

50 Vendors
e.g. Schlumberger

MSU UMiss
Hydro & hydrochem

Curtin University, Perth


Injection well
Sample well
Other well
WOC
-3002 m
-2972 m
-2941 m
0 1 2 km
Gulf of Mexico
Wells in Woodbine-Tuscaloosa Fm.
0 75 150 300 km

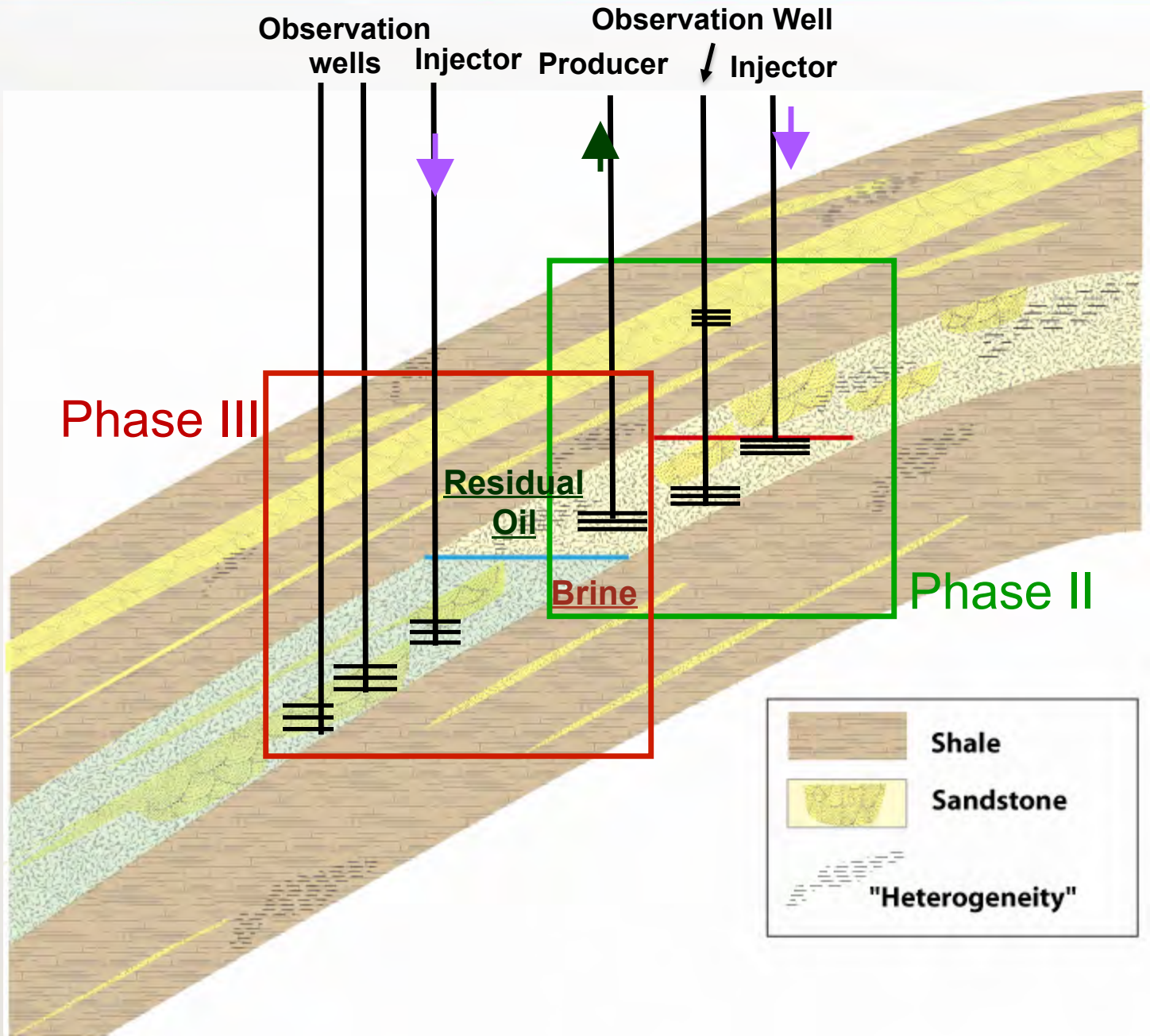

W-E
OBS
29-12
S-N
Cranfield Anticline
~ 1 mile

Overview

- > 1 Million metric tonne / yr injection
- Quick start up = “Early test” (bridge between pilot scale and SECARB’s Plant Barry/Citronelle anthropogenic test)
- Of possible sites, Denbury’s Cranfield field scheduled for 2008 CO_2 injection start was favorable:
  - Time to collect pre-injection data before injection
  - Build quickly to >1 MMT per year CO_2 injection rate (sufficient to assure project metrics met & *exceeded*)
  - Experienced operator in CO_2 EOR – low risk of permitting delay: ***early results for RCSP program***
  - Field abandoned (40 years); pressure recovered and equilibrated

Favorable Characteristics of Cranfield for SECARB Early test

- Follow-on between Phase II and Phase III
  - Phase II lower budget experiment, single monitoring well in EOR zone
  - Used Phase II as far-field and comparison point to Phase III
- Phase III planned in water leg downdip of oil zone
- Provided RCSP experience with CO2 EOR, (grew in importance)


Observation wells
Injector
Observation Well
Producer
Injector
Phase III
Residual Oil
Brine
Phase II
Shale
Sandstone
"Heterogeneity"

Less than-ideal characteristics

- CO_2 from Jackson Dome (not anthropogenic)
- Field commercial EOR
  - operational aspects not under project's control
  - some data proprietary
- Research purpose only
  - Designed prior to EPA or international regulations
- Relatively complex geology both deep & near surface
- Modeling reservoir's injection response complicated
  - by oil presence
  - injection and withdrawal complexities – ***managed…***

Simplified by:

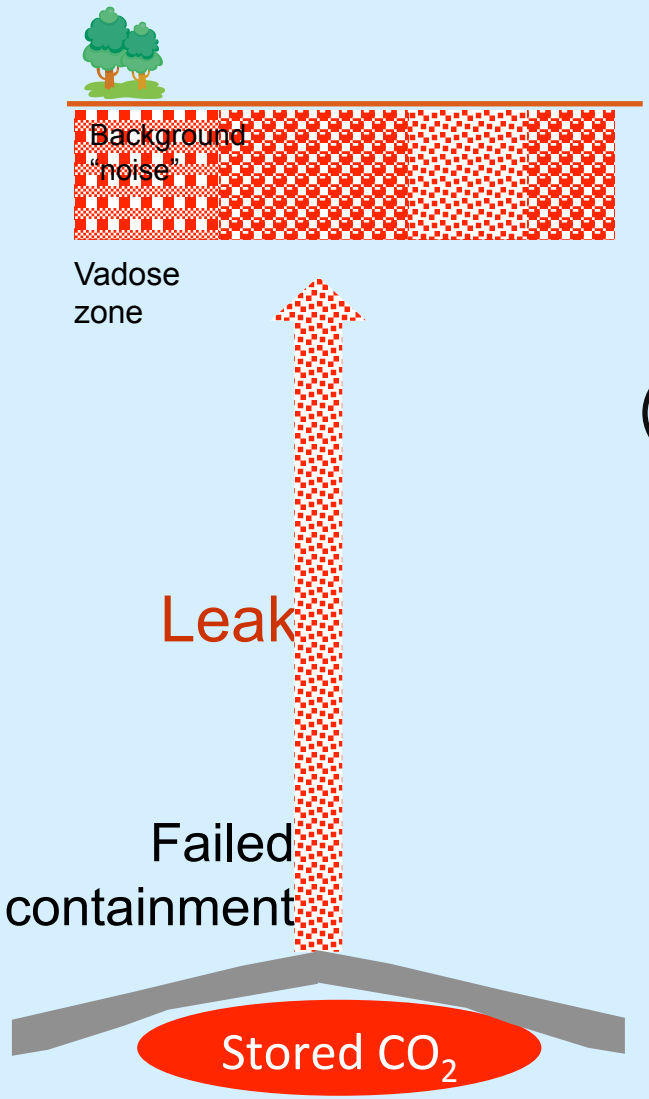
Focus on the DAS - ***brine only***

Early timing - ***production & recycle was minimal***

Developing the Experiment

- Year-long series of meetings (2007-2008)
  - designed plan
- Aligned general research objectives
  - well locations
  - selected team members
  - budget
- Designed detailed plans - major components
- Adapted to fast EOR field development
  - NEPA permitting (slow)
  - other timeline issues
    - equipment rental
    - procurement
    - cash flow (2009 “cash call”)

Project objectives



Produce CO_2
Concentrate CO_2 → Mask signal

False positives

Consume CO_2
Disperse CO_2 → Dampen signal

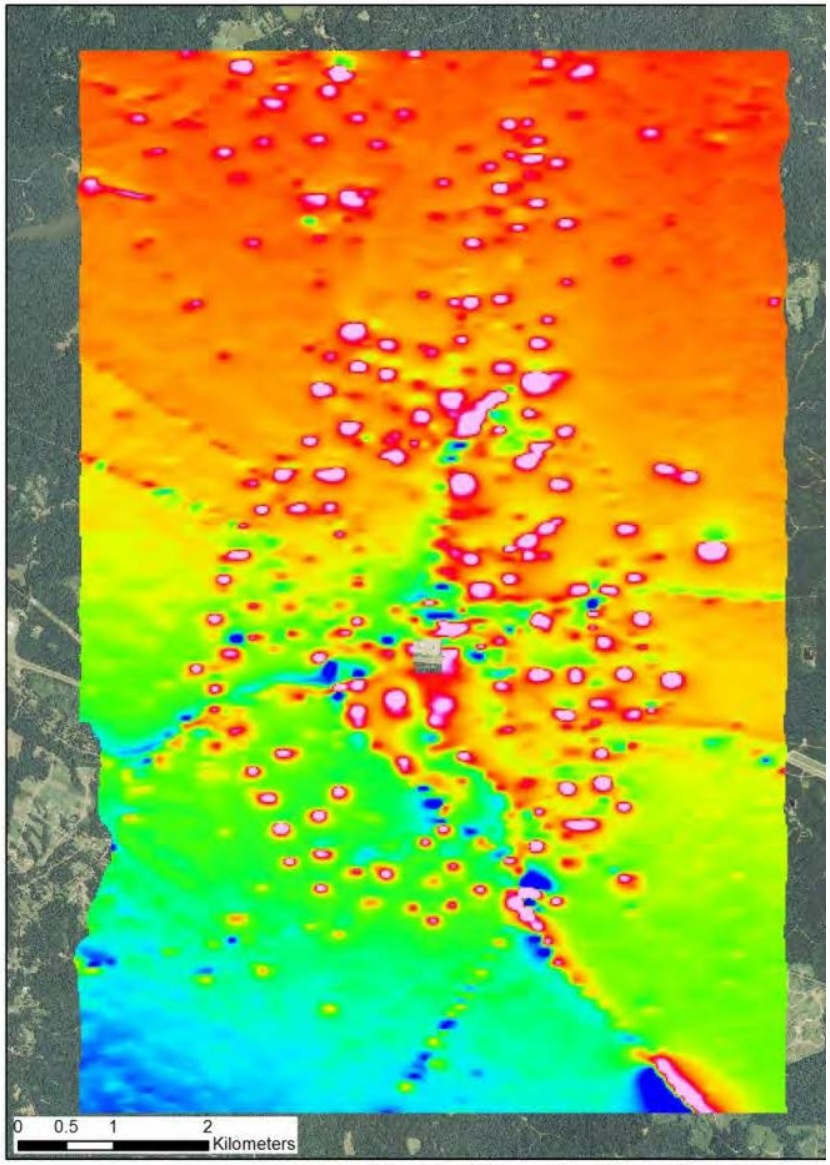
False negatives

Plant activity
Organics → CO_2
Soil carbonate
Soil moisture
Weather fronts

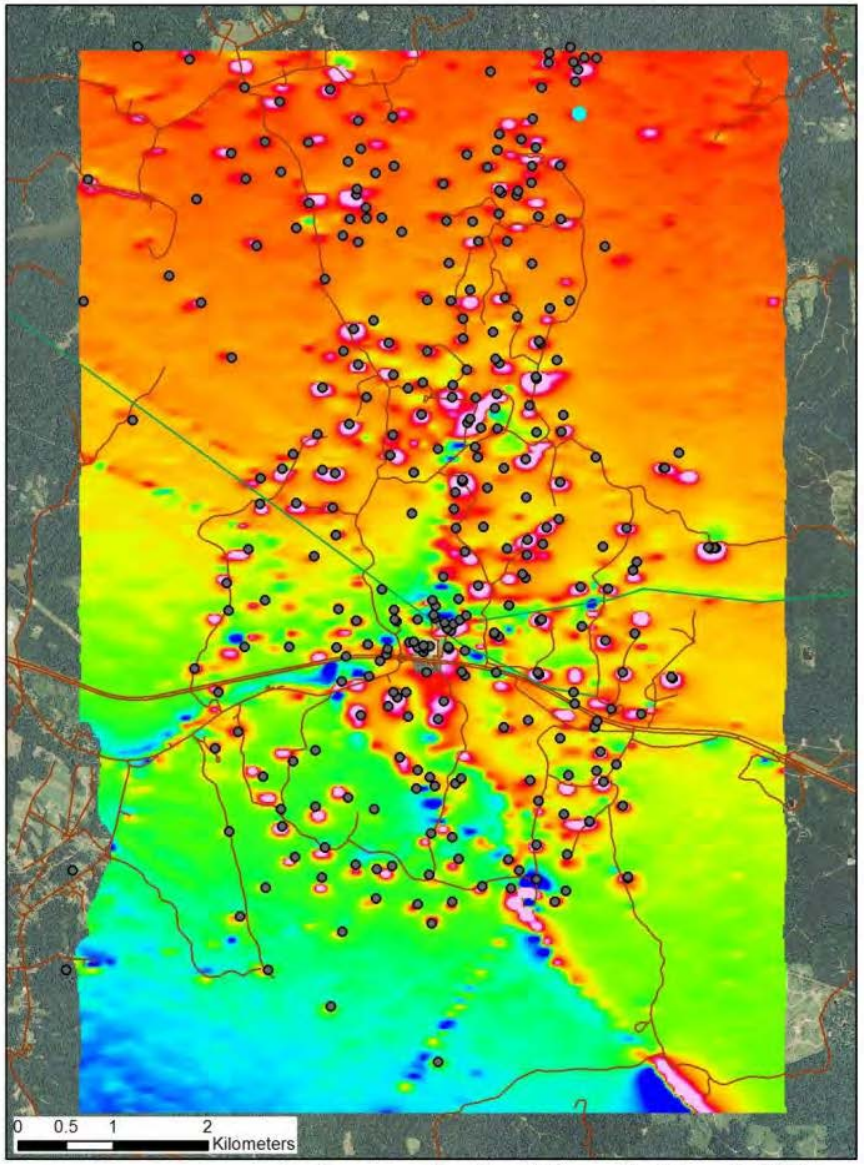
} Produce, consume, redistribute CO_2

Katherine Romanak BEG

Residual Magnetic Intensity - Cranfield, MS



Residual Magnetic Intensity - Cranfield, MS

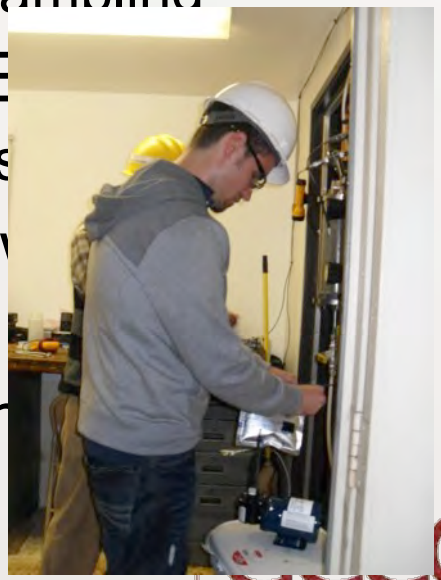


Tasks/Contributions (2)

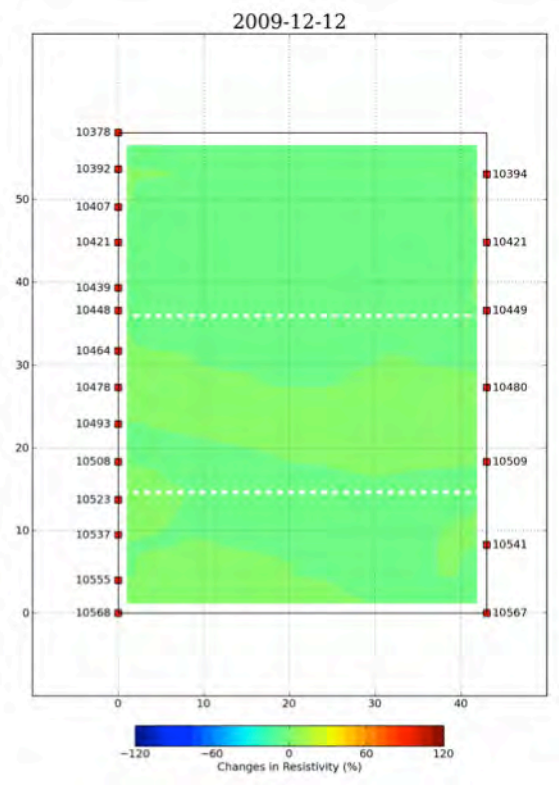


- Schlumberger Carbon Services
  - well logging
  - Cross well Seismic
  - AZMI fluid collection

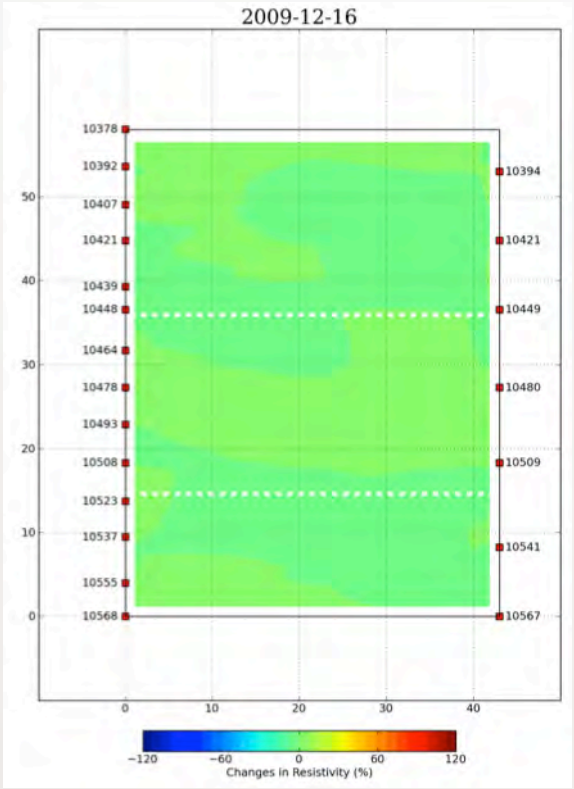
- LBNL / NRAP
  - U-tube,
  - 3-D VSP
  - downhole fiber optic CASSM
- Oak Ridge NL
  - PFT and sampling
- University E
  - Noble gass
- Local landow
  - access
- Walden Cor
  - NEPA



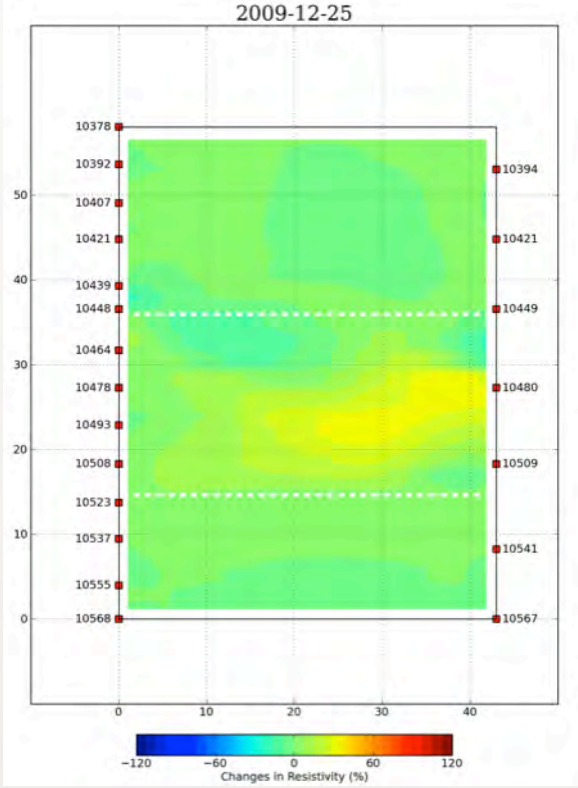
Time Lapse Resistivity Changes



Initial CO_2 Breakthrough in F2

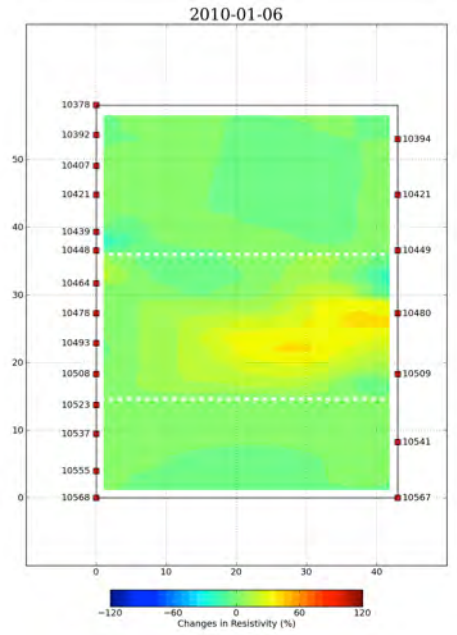


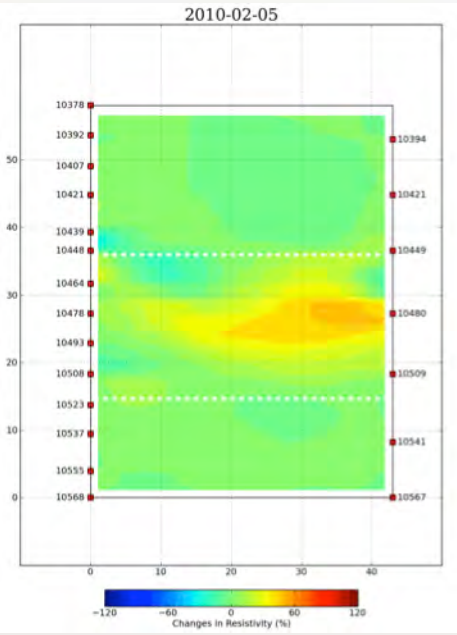
Initial CO_2 Breakthrough in F3

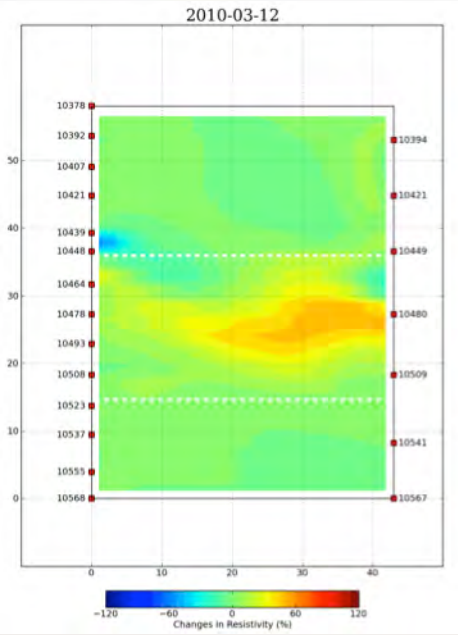


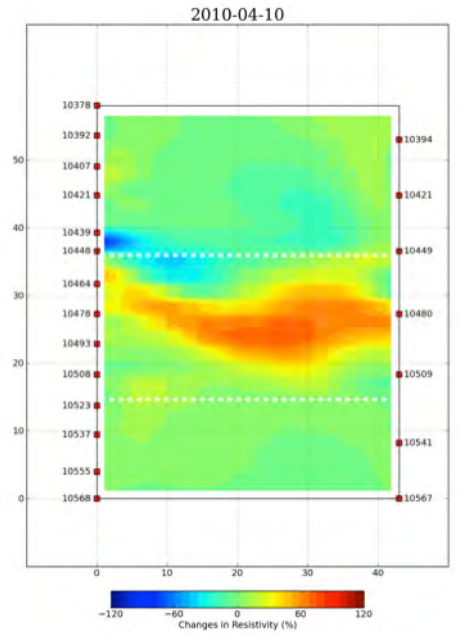
GCCC
GULF COAST CARBON CENTER

Time Lapse Resistivity Changes

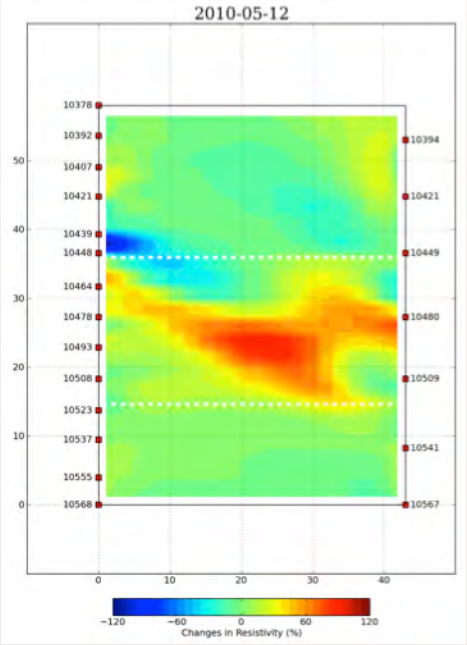


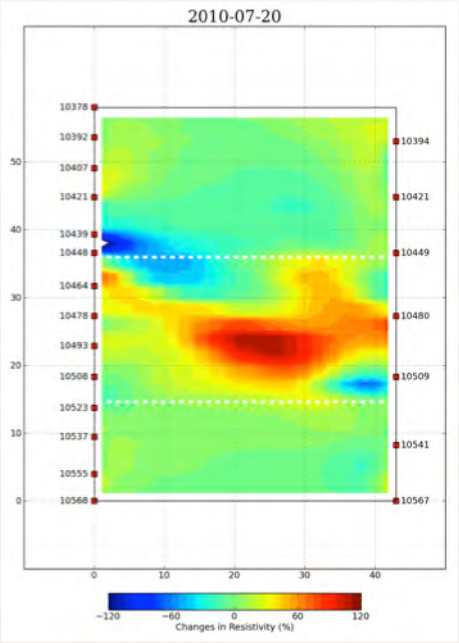


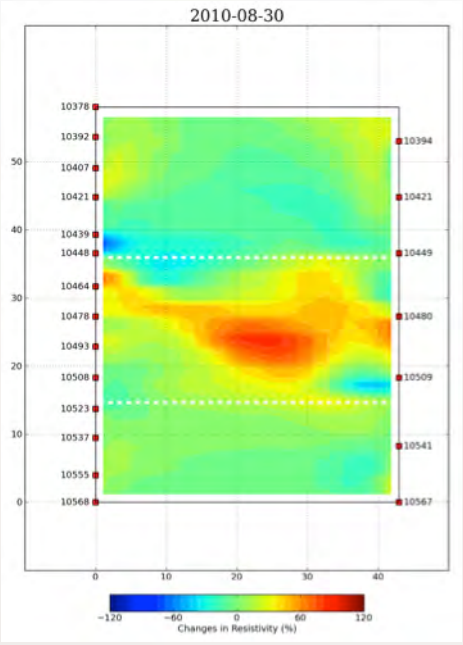


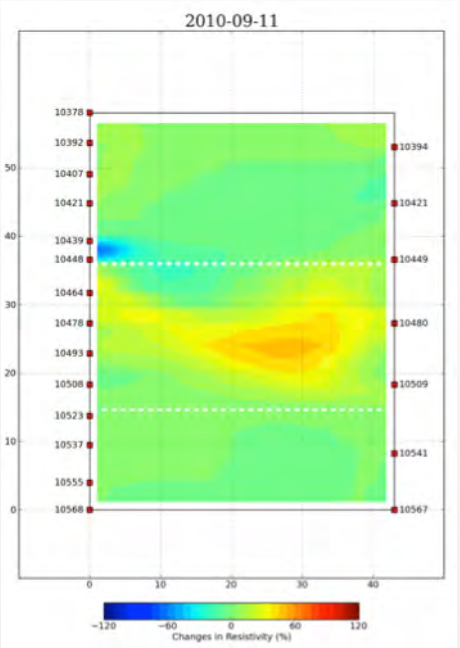


Time Lapse Resistivity Changes









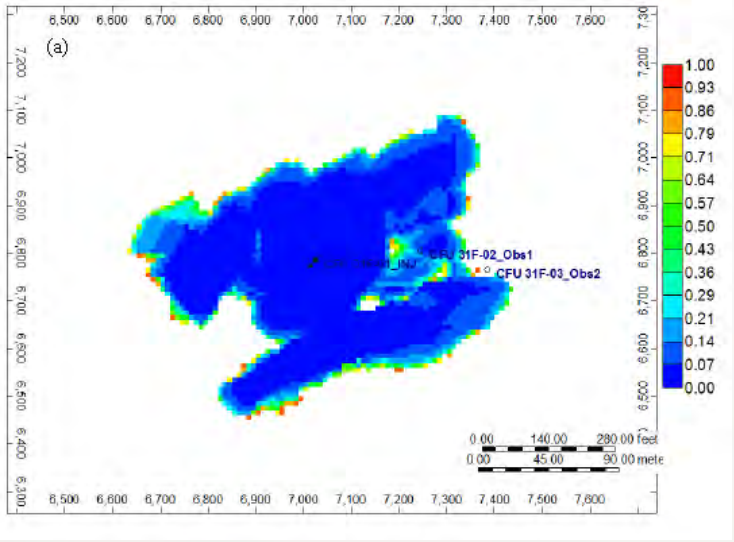
After Work-over in 9/2010

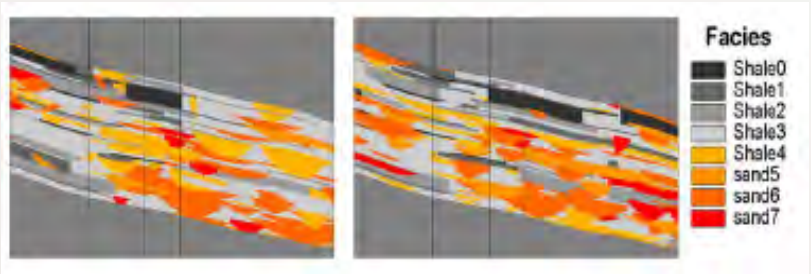
Contributions: Support Collaborators

- CFSES
  - rock samples for geomechanics
- NRAP
  - field site for 3D-VSP
- SIM SEQ
  - comparative modeling data set
- NETL
  - CO_2 EOR model data

Accomplishments

- Monitored CO_2 injection 2008 – 2015
- Injection through 23 wells, cumulative volume over 8 million metric tons
- First US test of ERT for GS (deepest)
- Time lapse plume imaging with cross well seismic, VSP, RST, & surface 3-D seismic
- RITE microseismic – none detected
- Groundwater sensitivity assessment (push-pull)
- Recognized by Carbon Sequestration Leadership Forum (CSLF) in 2010 for research contributions
- SIM-Seq inter-partnership model development test
- Knowledge sharing to Anthropogenic Test and other U.S./International CCS projects





"Early Test's" Major Contributions

- Large volume injection bridged RCSP to current & future anthropogenic sources
- Value of AZMI pressure monitoring in demonstrating reservoir fluid retention
- Probabilistic monitoring helps history-match fluid response to injection in a complex reservoir
- Process-based soil gas method developed and demonstrated for the first time
- Demonstrated utility and site-specific limitations of groundwater monitoring

Future (1)

- Model additional scenarios incorporating uncertainties
- Forward-model seismic response
- Compare Cranfield ERT to Ketzin
- Evaluate ERT for long-term viability (distinguish noise from signal)
- Determine time-dependent capacity through modeling
- Participate in ISO 265
- Further optimize process-based soil-gas method
- Further optimize groundwater uncertainties

Future (2)

- Technology transfer
  - Deployment of monitoring strategies developed at SECARB “Early” test as well as other RCSP and international CCUS sites
  - Support for maturation of monitoring for EOR as well as saline sites through international standards, best practices, critical reviews

SECARB Southeast Regional Carbon Sequestration Partnership

SOUTHERN STATES ENERGY BOARD

NETL

Monitoring a CO_2 EOR Project to Document Storage

Susan D. Hovorka
Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of Geoscience
University of Texas at Austin

Current Status Of Monitoring CO_2 EOR for Storage – in evolution

- Recommendations based on SECARB experience to optimize in future MRV plans.
- Transfer to other CO_2 EOR projects in DOE's program
- Provide to ISO 265 Standard for geologic storage Working group 6 on EOR with associated storage
- First EPA CO_2 EOR project MRV plan under CAA subpart RR approved for OXY's Denver unit of Wasson field
  - San Andres reservoir
  - Long history – under CO_2 flood since 1980's
  - Many unique aspects of the field
  - Multiple units in field
- Breakdown the elements and make them generic

Denver unit MRV plan 2015

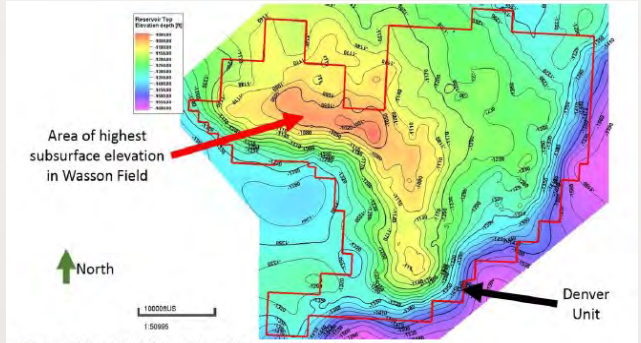
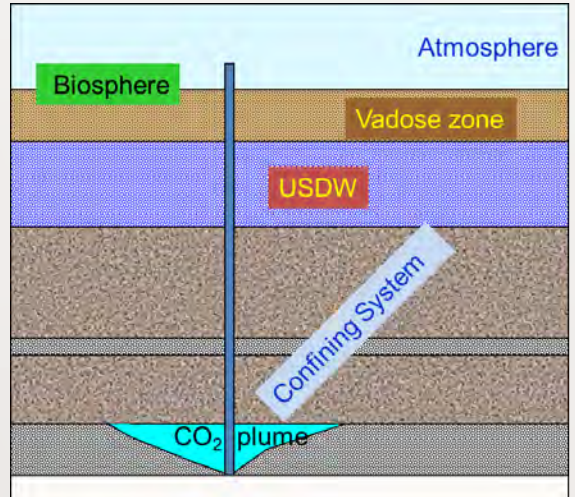


Figure 8 Structure Map on Top of San Andres Pay (F1)

Cranfield Early Test – Testing monitoring for CO_2 EOR

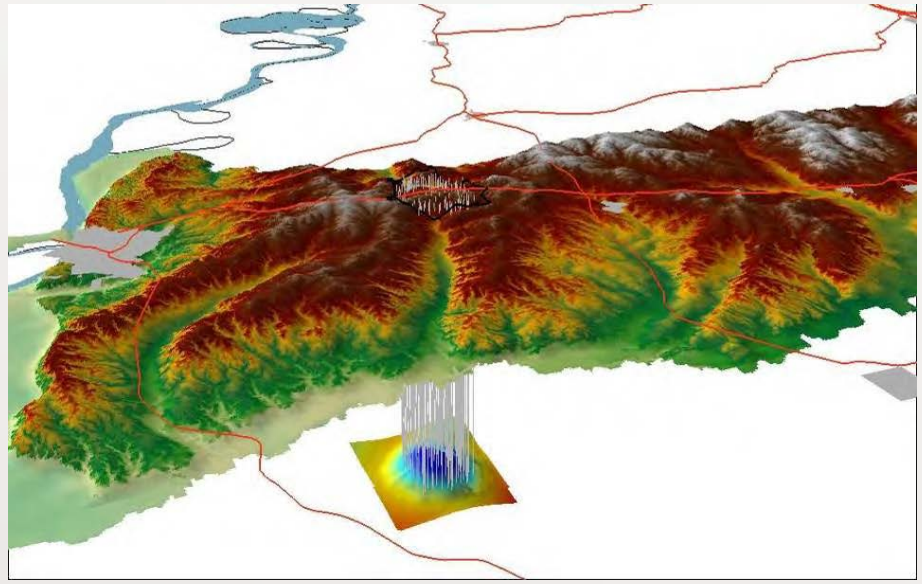
- Saline DAS + Adjacent EOR
- Above zone monitoring interval pressure surveillance to assess multiple well integrity
- Limits of seismic imaging in hydrocarbon area.
- Soil gas and groundwater – complexity in hydrocarbon areas
- Modeling of over-fill and out-of-structure migration

Early test design



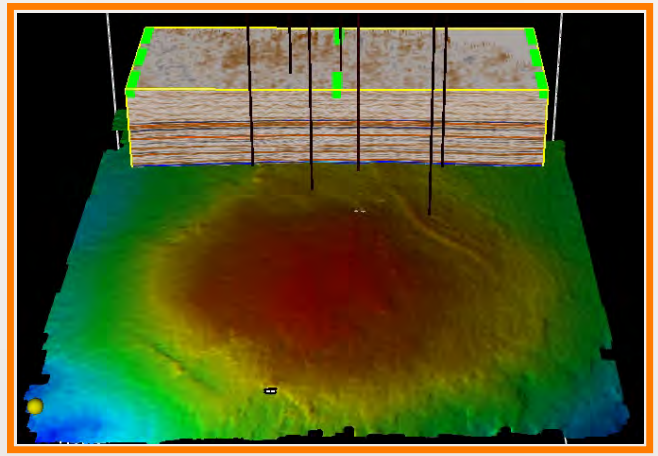
Parts of the CO_2-EOR+ Storage Monitoring Plan

- Definition of the project
- Characterization of the reservoir, structure and EOR project system boundaries
- Past operation review
- Planned operation
- Fluid, CO_2 and pressure accounting
- Documentation and reporting
- Project cessation and close out



Definition of the project

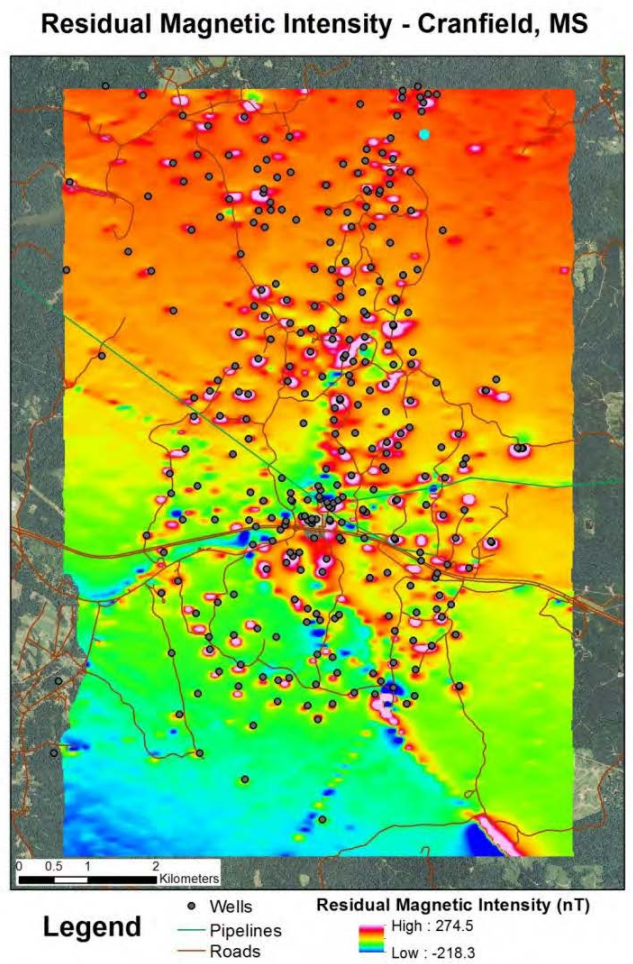
- Project components
  - CO_2 "purchase" meter, surface infrastructure, subsurface units
- Physical project boundaries (surface maps, subsurface maps and cross sections)
- Temporal boundaries (history, storage accounting start and end)
- Permitting boundaries – topics including and outside MRV plan
- CO_2 inventory
  - Accounting goals
  - Specify boundaries inside accounting



Reservoir characterization at Cranfield, Meckel

Characterization of the reservoir, structure and EOR project system boundaries

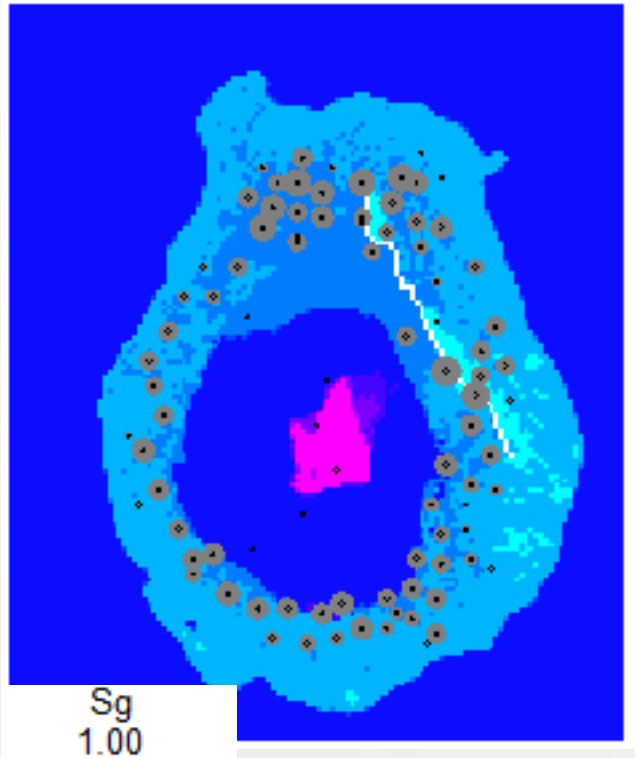
- Maps and cross sections of injection reservoir
- Define the hydrocarbon trap, including spill points should the reservoir be overfilled
- Lease and operational unit boundaries, define the zone in which CO_2 will be retained
- Locate adjacent extraction and injection operations and nature or interactions with the project
- Condition of wells



Locating wells with aeromagnetics at Cranfield

Past operation review

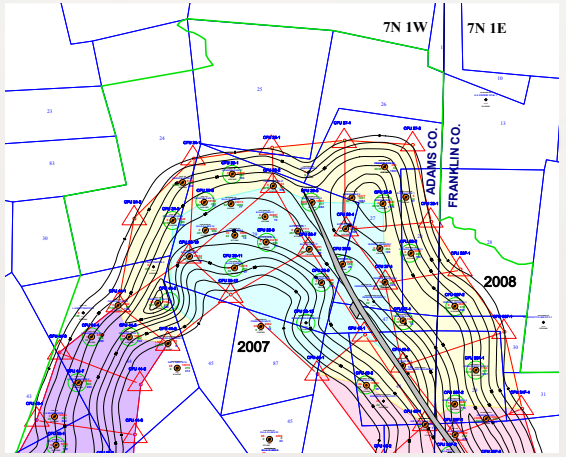
- Overview original reservoir fluid distribution, composition, and pressures
- Review stages in past operations including well drilling, infill drilling and other modifications, fluid extraction history, pressure response, injection history, pressure response
- Current pressure and fluid distribution



Modeled reservoir fluids 2007 Cranfield Hossieni

Planned operation

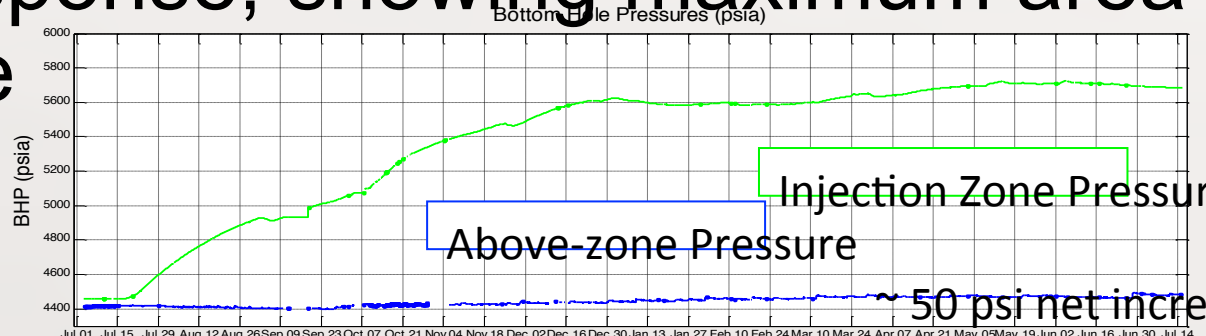
- Planned patters to be flooded, showing injection and withdrawal (this should be generalized to allow during flood modifications, such as stages of build out.
- Water curtains or other operational controls



Pattern flood build-out plan, Denbury Onshore LLC

Fluid, CO_2 and pressure accounting

- Meters, test facilities and other measurements points
- Fluid compositional accounting
- Meter validation, calibration and reporting procedures
- Planned and actual injection rates separating new CO_2 and recycle
- Planned and actual extraction rates
- Planned and actual pressure response, showing maximum area of significantly elevated pressure

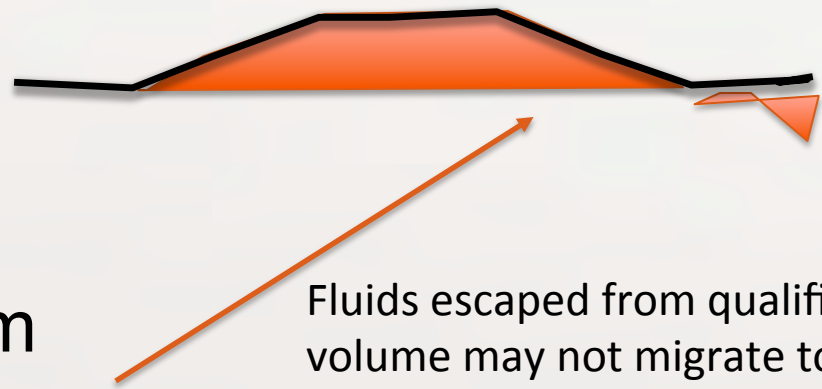


Project cessation and close out

- Difficulties include:
  - For atmospheric benefit, need to have long term assurance
  - However conflict with mineral issues
    - Ownership
    - Period of lease
    - Value of remaining hydrocarbons
    - Need for operational flexibility
    - Legacy issues
- Separate geologic and infrastructure adequacy from future deliberate action

Documentation and Reporting

- Interface with existing reporting to oil and gas regulator
- Transparent and possible to validate
- Report amount of CO_2 stored in reservoir
  - Annually
  - However only that for which long term storage is assured can be counted.



Fluids escaped from qualified volume may not migrate to atmosphere, but storage is not assured

Conclusions: Next actions

- Monitoring for CO_2 EOR+ storage is different from saline
- Prepare white paper
- Deploy at other DOE projects
- Input into ISO 265 Standards



Thank you!

NETL

SECARB
Southeast Regional Carbon Sequestration Partnership

SOUTHERN STATES ENERGY BOARD

Fluid Source Attribution at CCS and CO_2-EOR Sites

Jacob Anderson

SECARB Meeting

March 8, 2016

CCS Project Workflow

Leakage Risk Assessment

Pre-injection

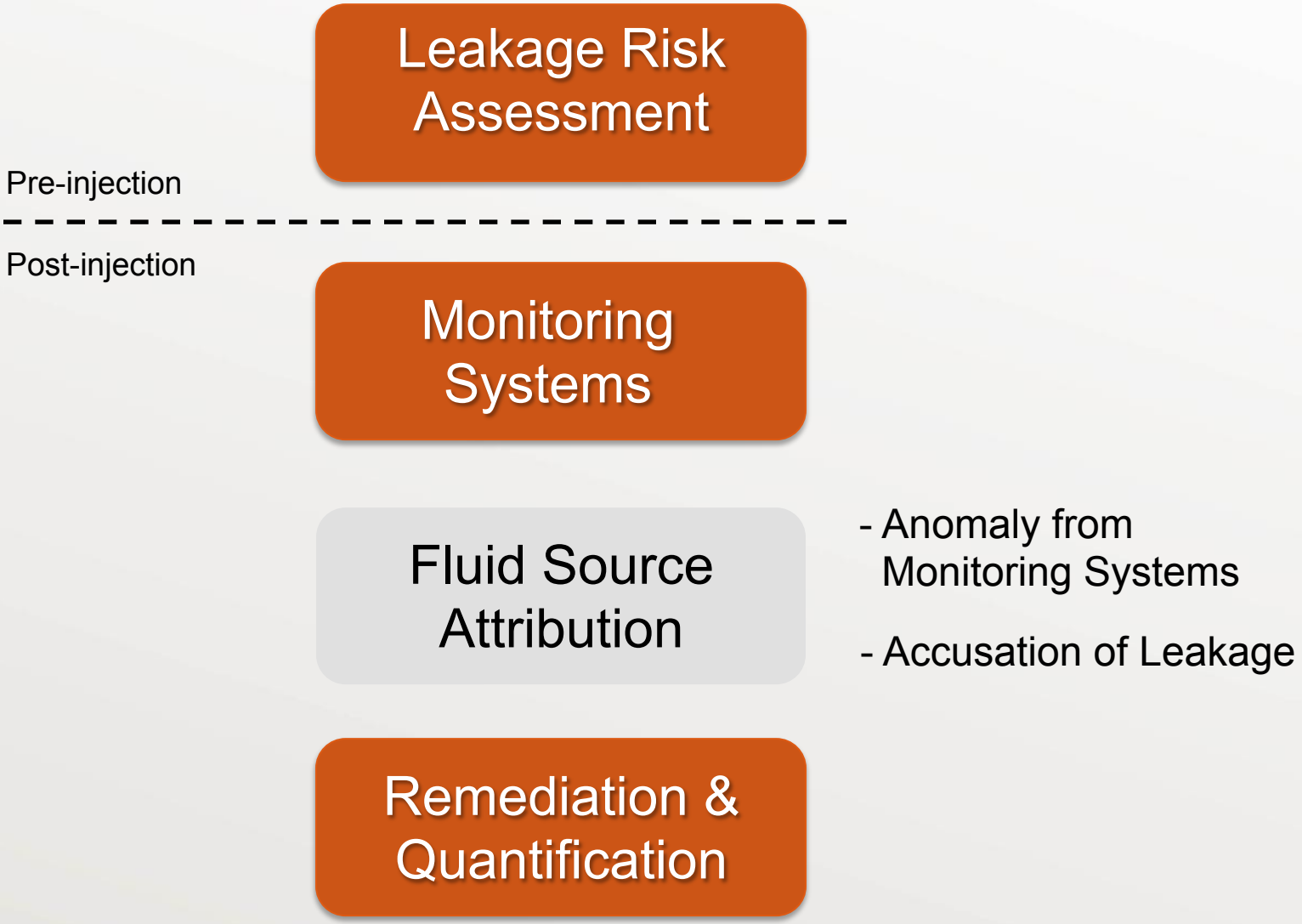
Post-injection

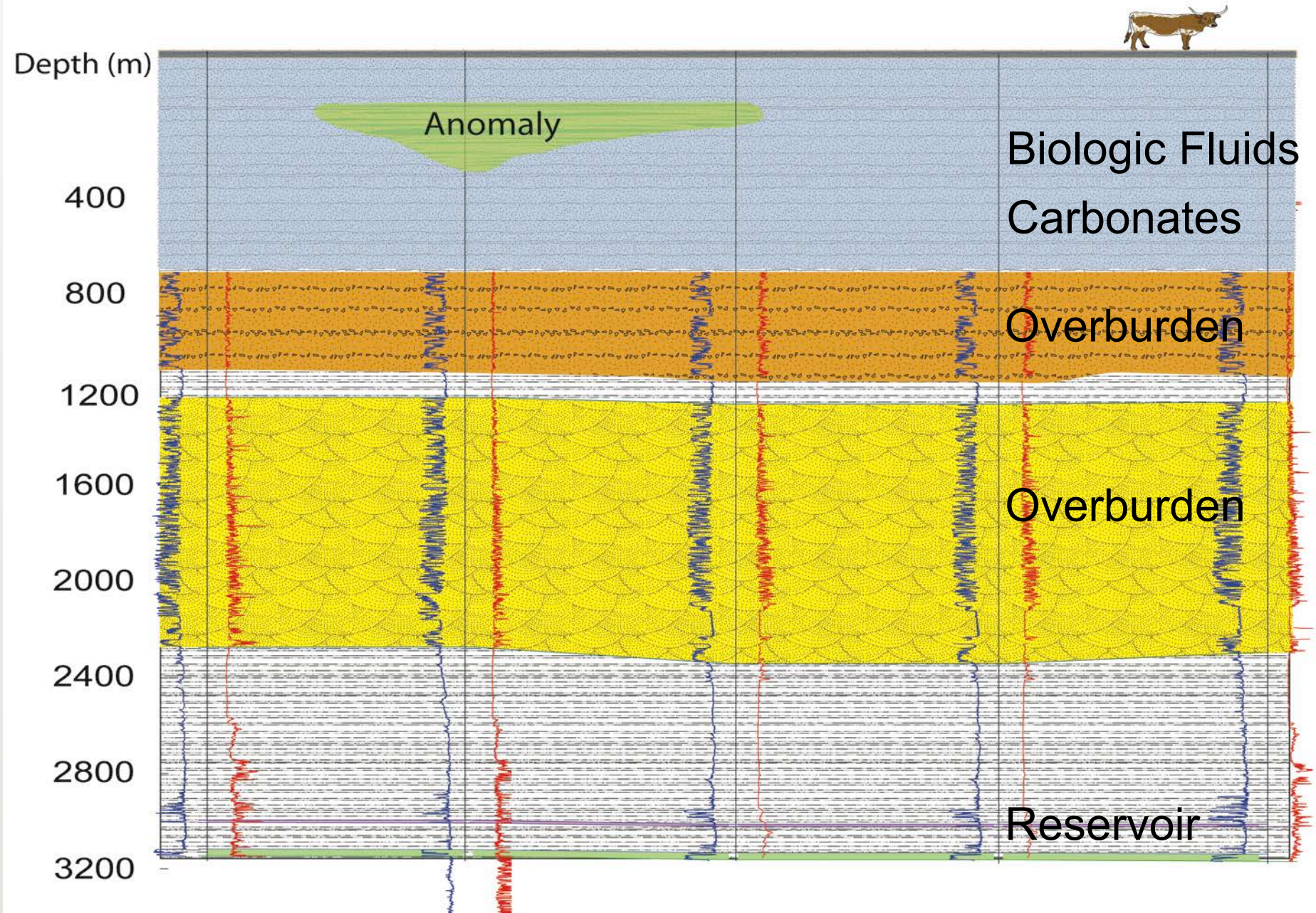
Monitoring Systems

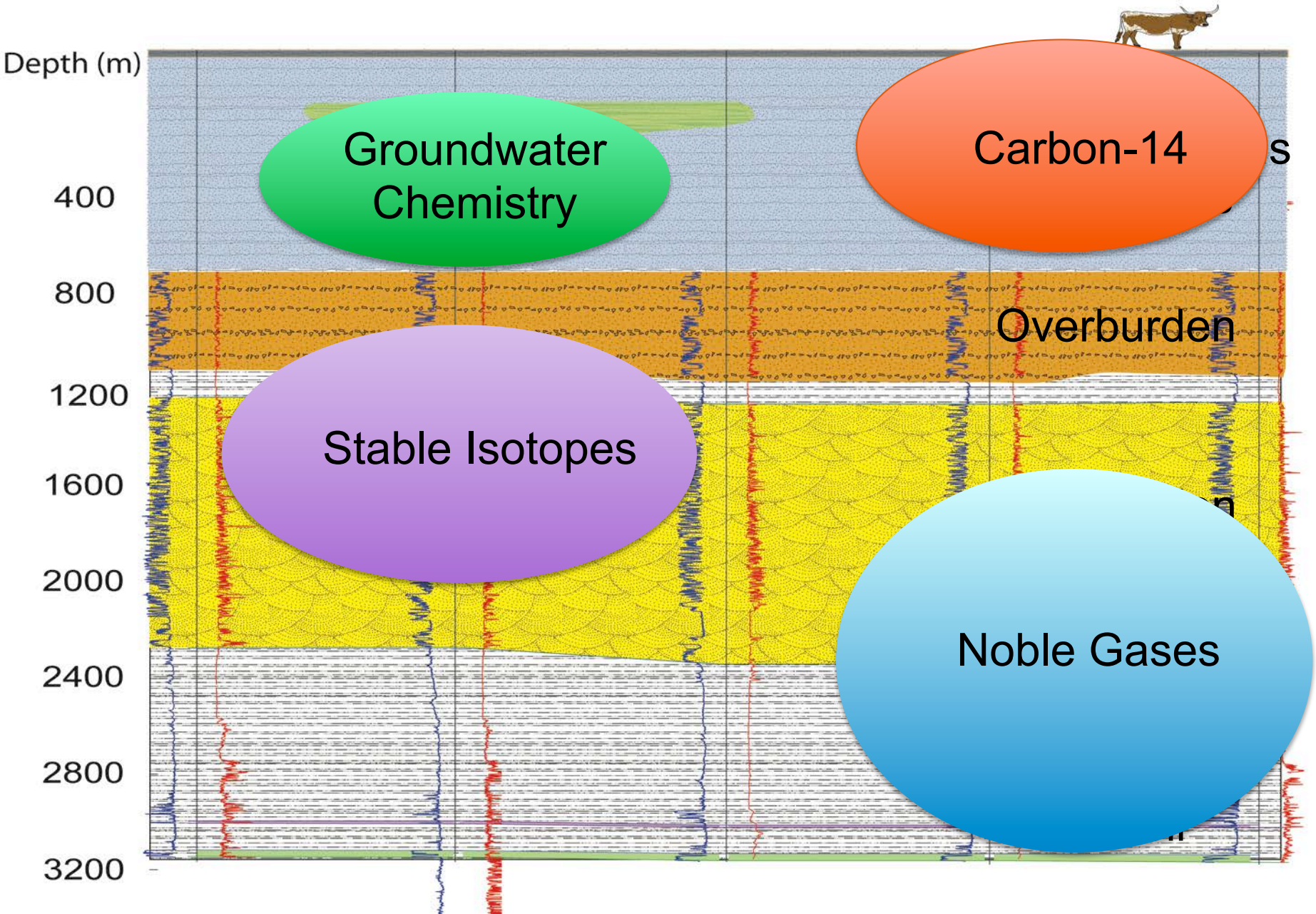
Fluid Source Attribution

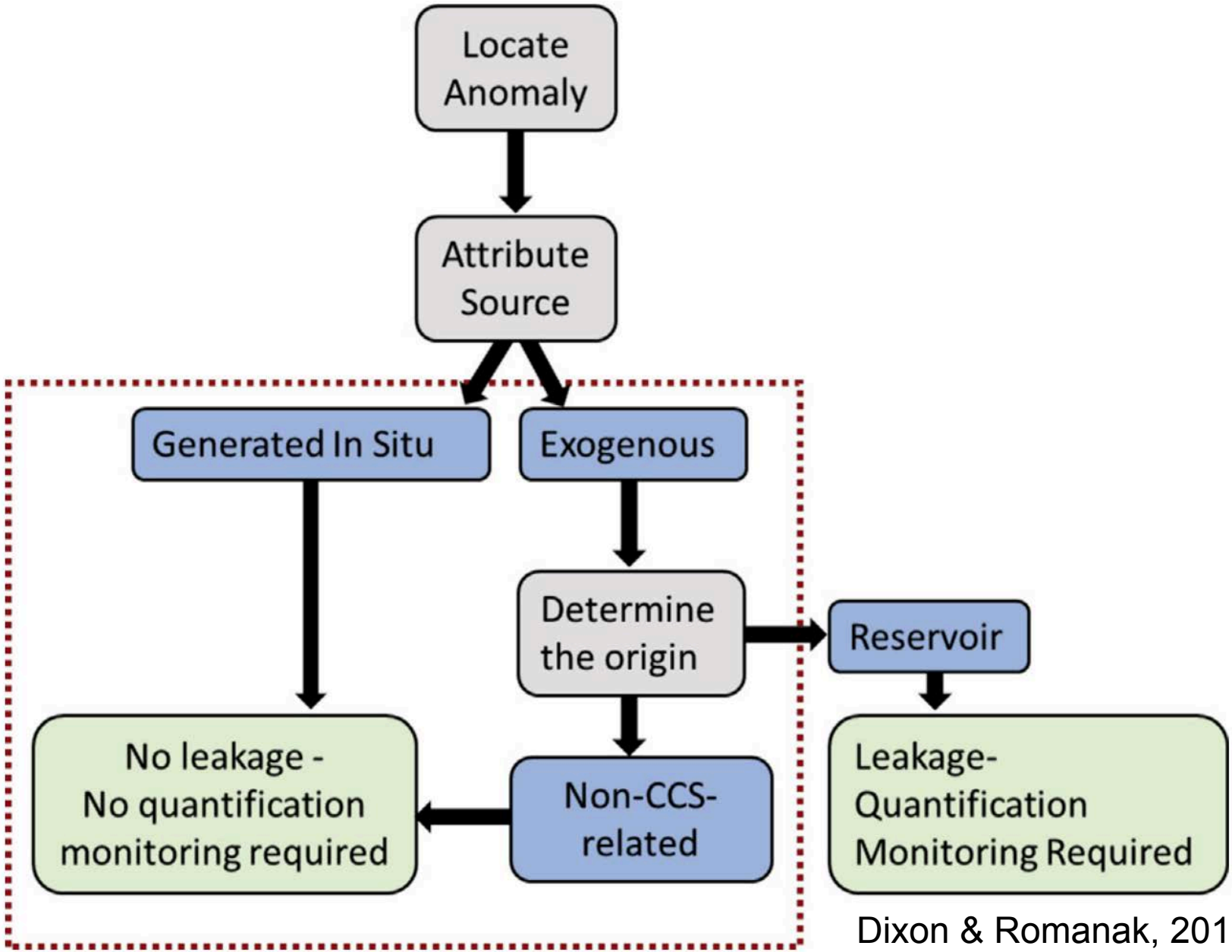
Remediation & Quantification

CCS Project Workflow

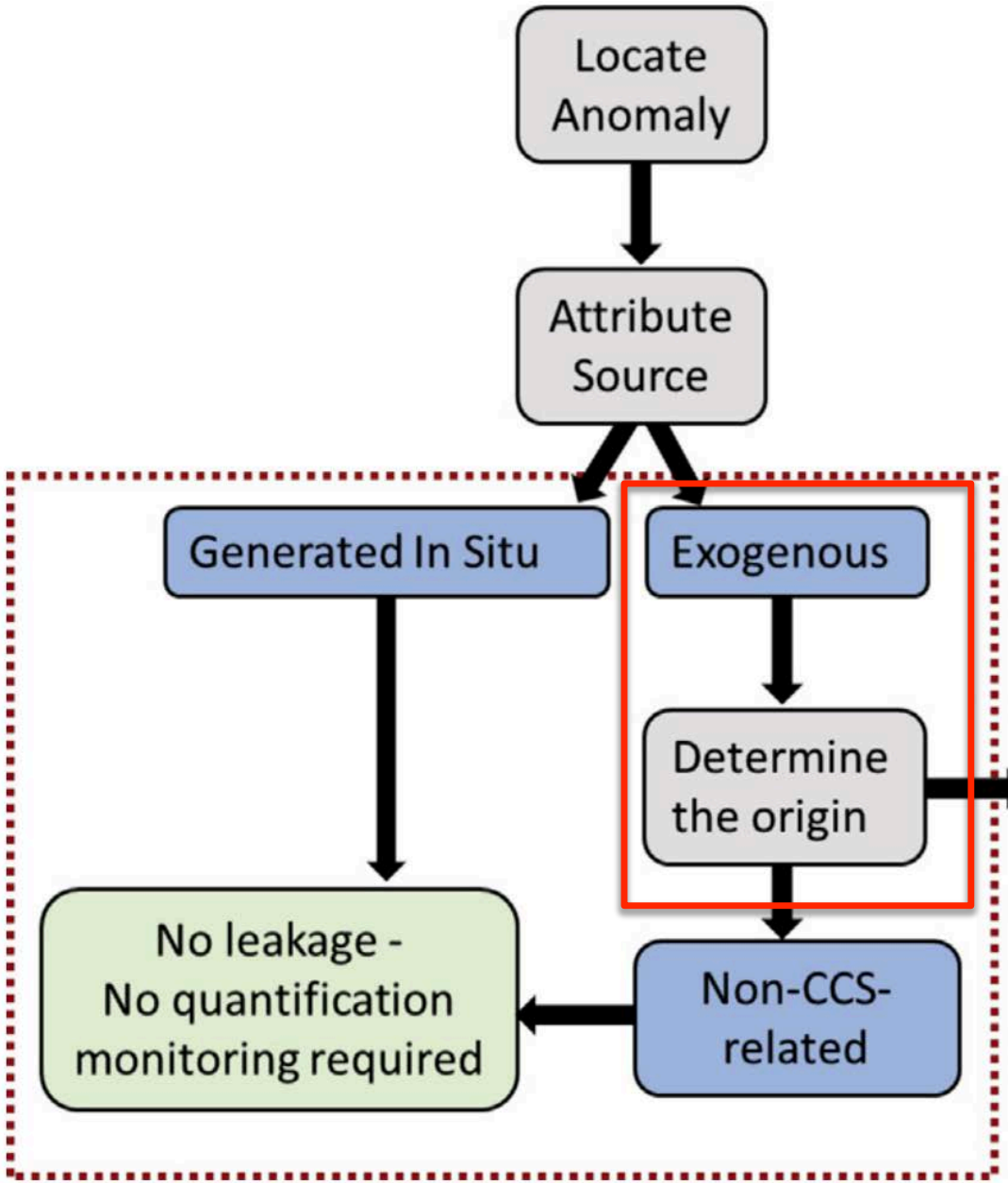



Depth (m)
400
800
1200
1600
2000
2400
2800
3200
Anomaly
Biologic Fluids
Carbonates
Overburden
Overburden
Reservoir


Depth (m)
400
800
1200
1600
2000
2400
2800
3200
Groundwater Chemistry
Carbon-14
Overburden
Stable Isotopes
Noble Gases

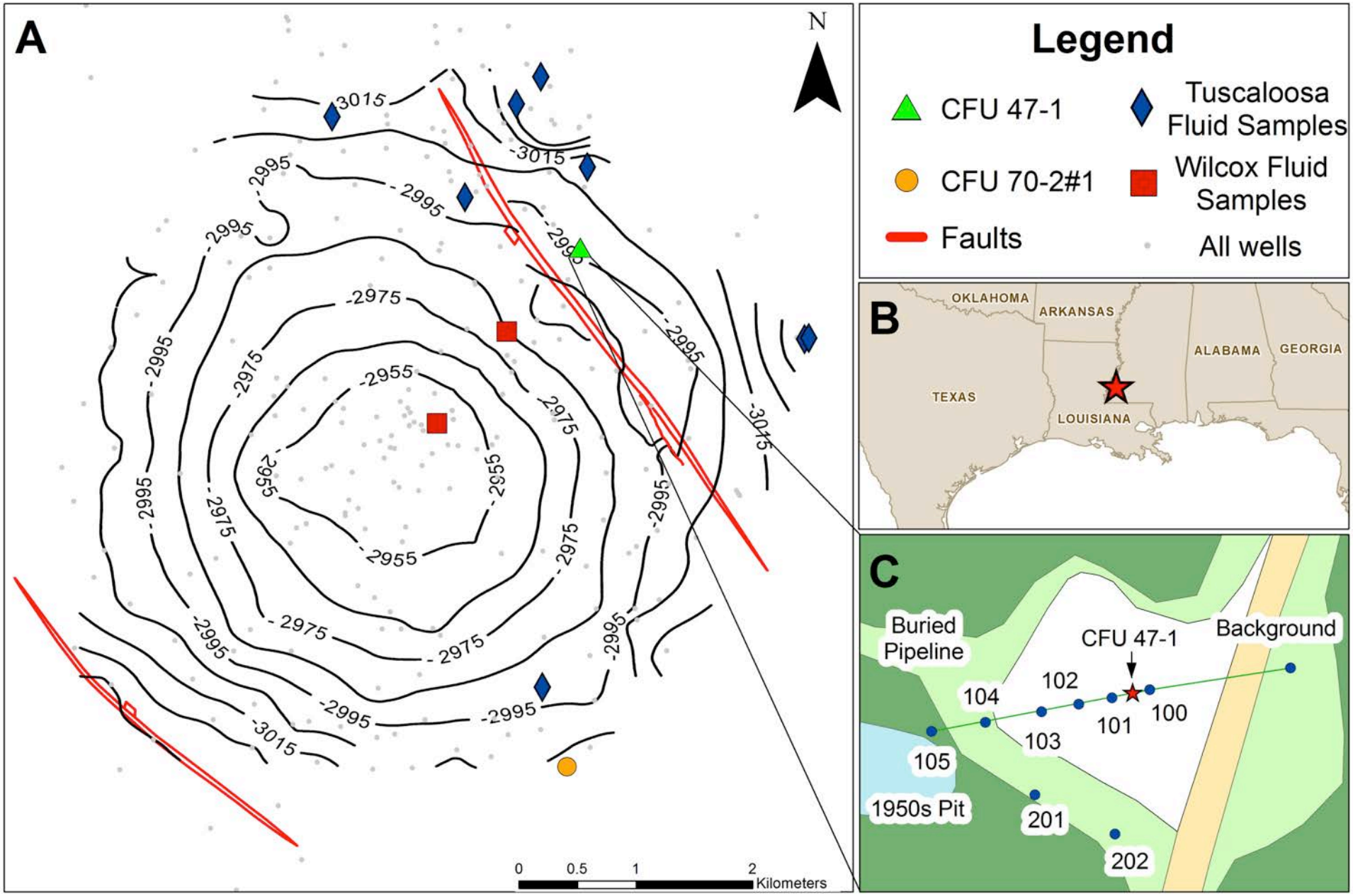


Dixon & Romanak, 2015



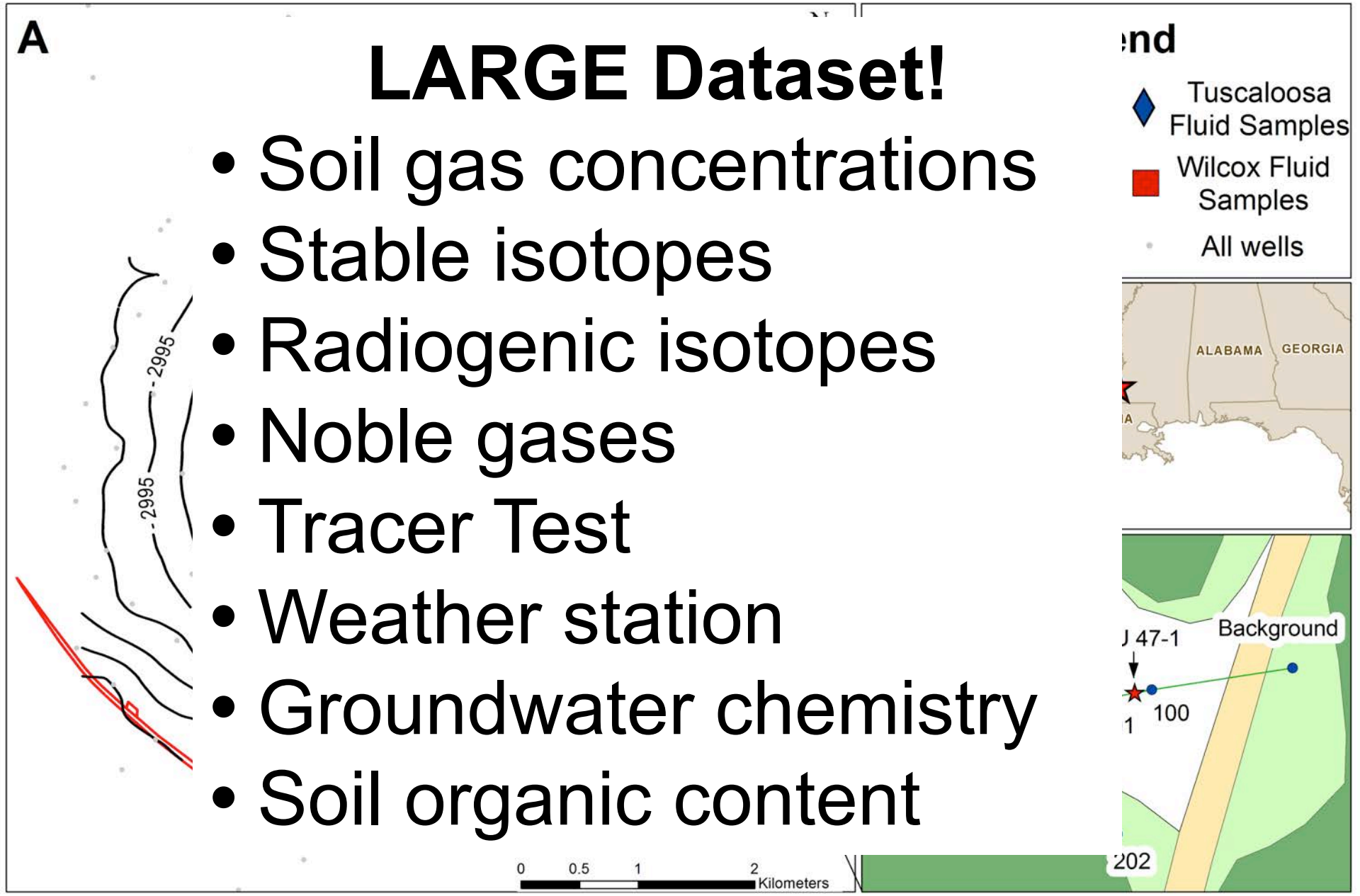
Near-surface CO_2 & CH_4 at Cranfield

Dixon & Romanak, 2015


A
N
-3015
-2995
-2975
-2955
0
0.5
1
2
Kilometers
Legend
CFU 47-1
CFU 70-2#1
Faults
Tuscaloosa Fluid Samples
Wilcox Fluid Samples
All wells
B
OKLAHOMA
ARKANSAS
TEXAS
LOUISIANA
ALABAMA
GEORGIA
C
Buried Pipeline
CFU 47-1
Background
102
104
100
101
103
105
1950s Pit
201
202

LARGE Dataset!

- Soil gas concentrations
- Stable isotopes
- Radiogenic isotopes
- Noble gases
- Tracer Test
- Weather station
- Groundwater chemistry
- Soil organic content



Measurement	Cranfield Result
Radiocarbon of soil gas CO_2 and CH_4	Nonleakage
Methane-stable isotopes of soil gas	Ambiguous
Light hydrocarbon concentrations	Likely Nonleakage
CO_2 stable isotopes	Likely Nonleakage
Methane-stable isotopes of groundwater	Nonleakage
Sulfate concentrations	Potentially biogenic
Radiocarbon of DIC, DOC, and $CH_{4(aq)}$	Nonleakage
Noble gases	Nonleakage

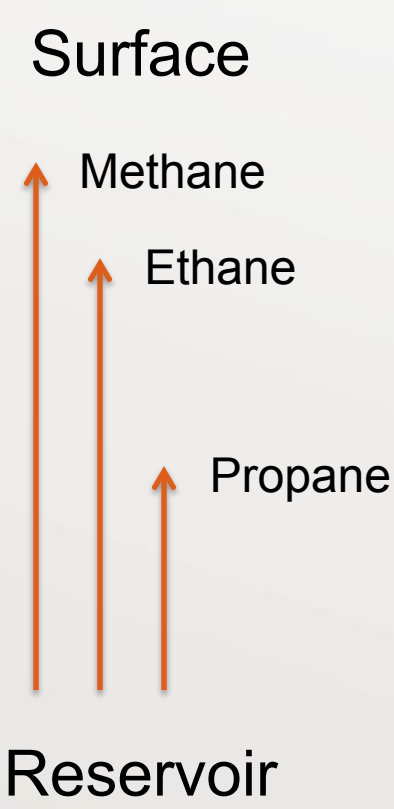
Measurement	Cranfield Result	Interpretation Criteria for Nonleakage Source	Step
Radiocarbon of soil gas CO_2 and CH_4	Nonleakage	>100 pMC	Step 1
Methane-stable isotopes of soil gas	Ambiguous	Biogenic formation pathway following Schoell (1983)	Step 2.1
		--- and ---	
Light hydrocarbon concentrations	Likely Nonleakage	<1% C_{2+} alkanes	Step 2.2
		--- and ---	
CO_2 stable isotopes	Likely Nonleakage	$\delta^{13}C$-CO_2 = -30 to -8‰	Step 2.3
Methane-stable isotopes of groundwater	Nonleakage	Biogenic formation pathway following Schoell (1983)	Step 3.1
		--- and ---	
Sulfate concentrations	Potentially biogenic	<200 µmole/L	Step 3.2
		--- and ---	
Radiocarbon of DIC, DOC, and $CH_{4(aq)}$	Nonleakage	^{14}C of $CH_{4(aq)}$ > DIC & DOC	Step 3.3
Noble gases	Nonleakage	Mixing model of air-saturated water, crustal signatures, and injectate/produced fluids	Step 4

Measurement	Cranfield Result	Interpretation Criteria for Nonleakage Source	Step
Radioca… CO…	…eakage	>100 pMC	Step 1
Methane… of soil gas	…Ambiguous	Biogenic formation pathway following Schoell (1983)	Step 2.1
Light hydrocarbon concentrations	…kage	--- and --- <1% C_{2+} alkanes --- and ---	Step 2.2
CO_2 stable isotopes	…N…	$\delta^{13}C\text{-}CO_2$ = -30 to -8‰	Step 2.3
Methane-stable isotopes of groundwater	Nonleakage	Biogenic formation pathway …hoell (1983)	Step 3.1
Sulfate concentrations	Potentially biogenic	…d --- …200 µmole/L	Step 3.2
Radiocarbon of DIC, DOC, and $CH_{4(aq)}$	Nonleakage	--- an… ^{14}C of $CH_{4(aq)}$ …	Step 3.3
Noble gases	Nonleakage	Mixing model of air-saturated water, crustal signatures, and injectate/produced fluids	Step 4

How would CO_2 change during upward migration?

- ✔ Dissolves into Water
- ✔ Trapped in Capillaries
- Other Processes?

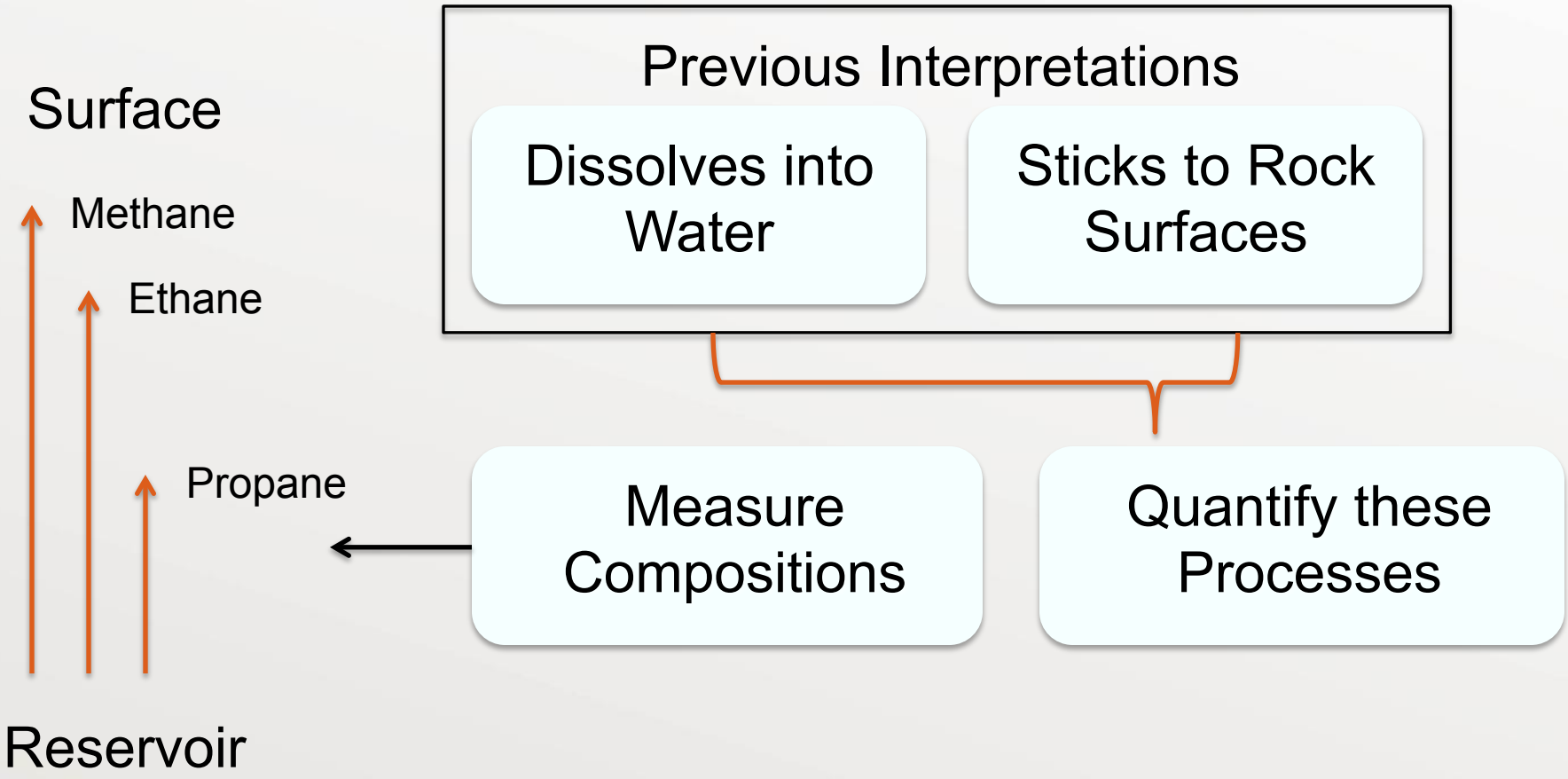
Light Hydrocarbons as an Analog for CO_2



Previous Interpretations

- Dissolves into Water
- Sticks to Rock Surfaces

Light Hydrocarbons as an Analog for CO_2



Light Hydrocarbons as an Analog for CO_2

Surface

Methane

Ethane

Propane

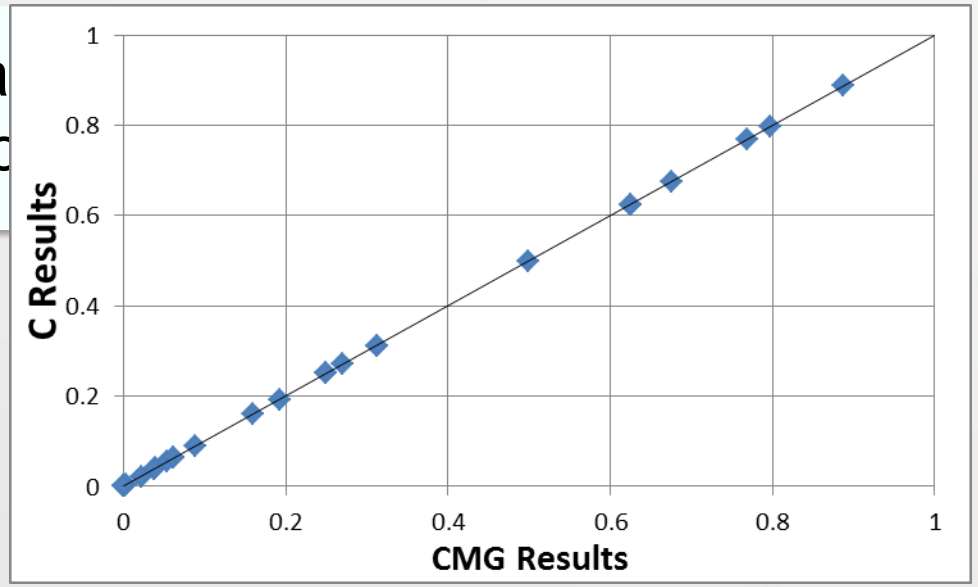
Reservoir

Previous Interpretations

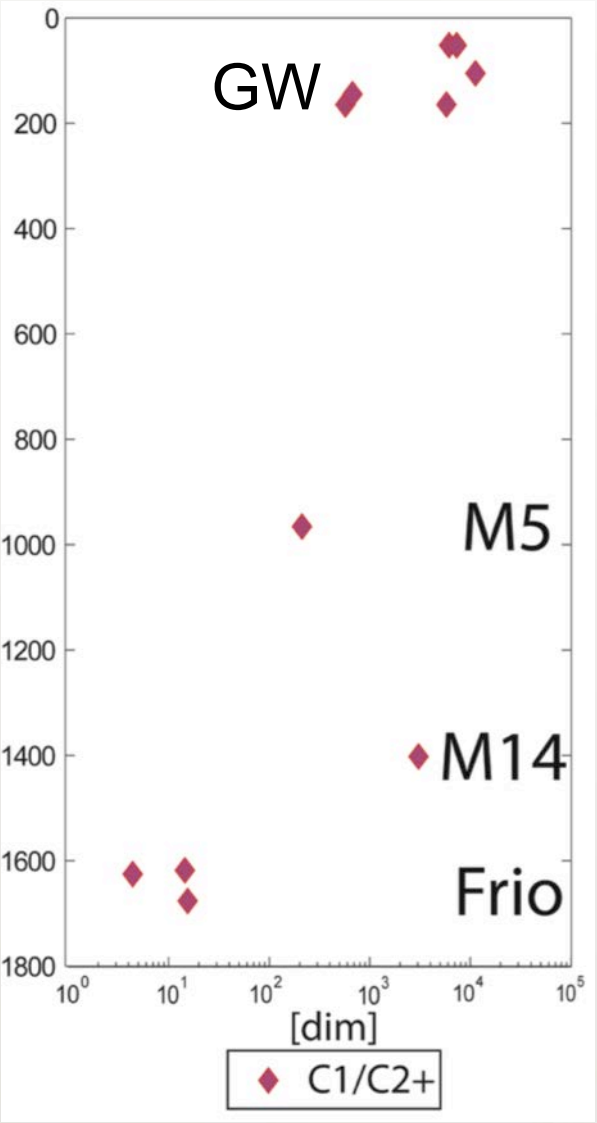
Dissolves into Water

Sticks to Rock Surfaces

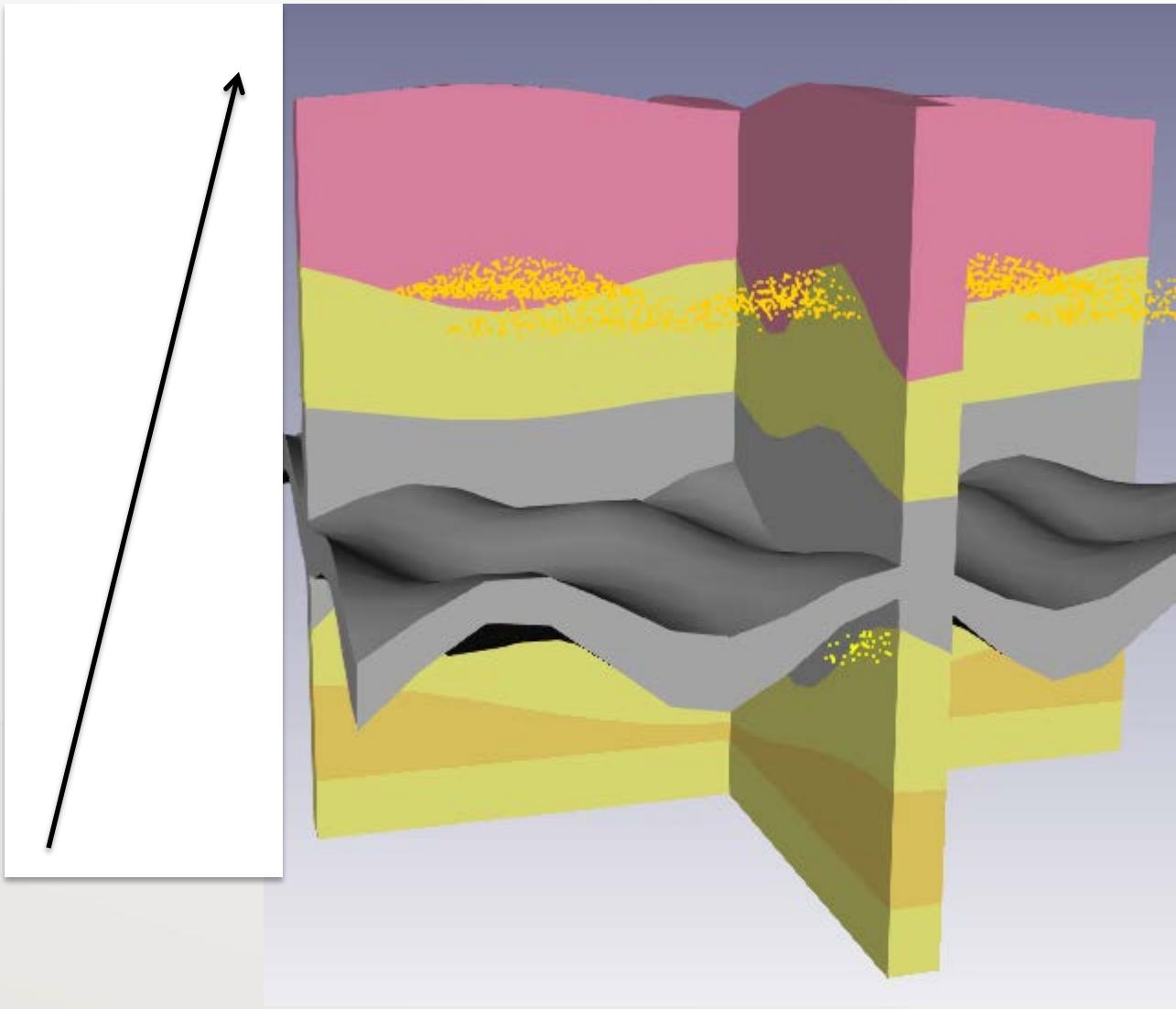
Mea
Compo



Field Data



PERMEDIA™ Simulation Results



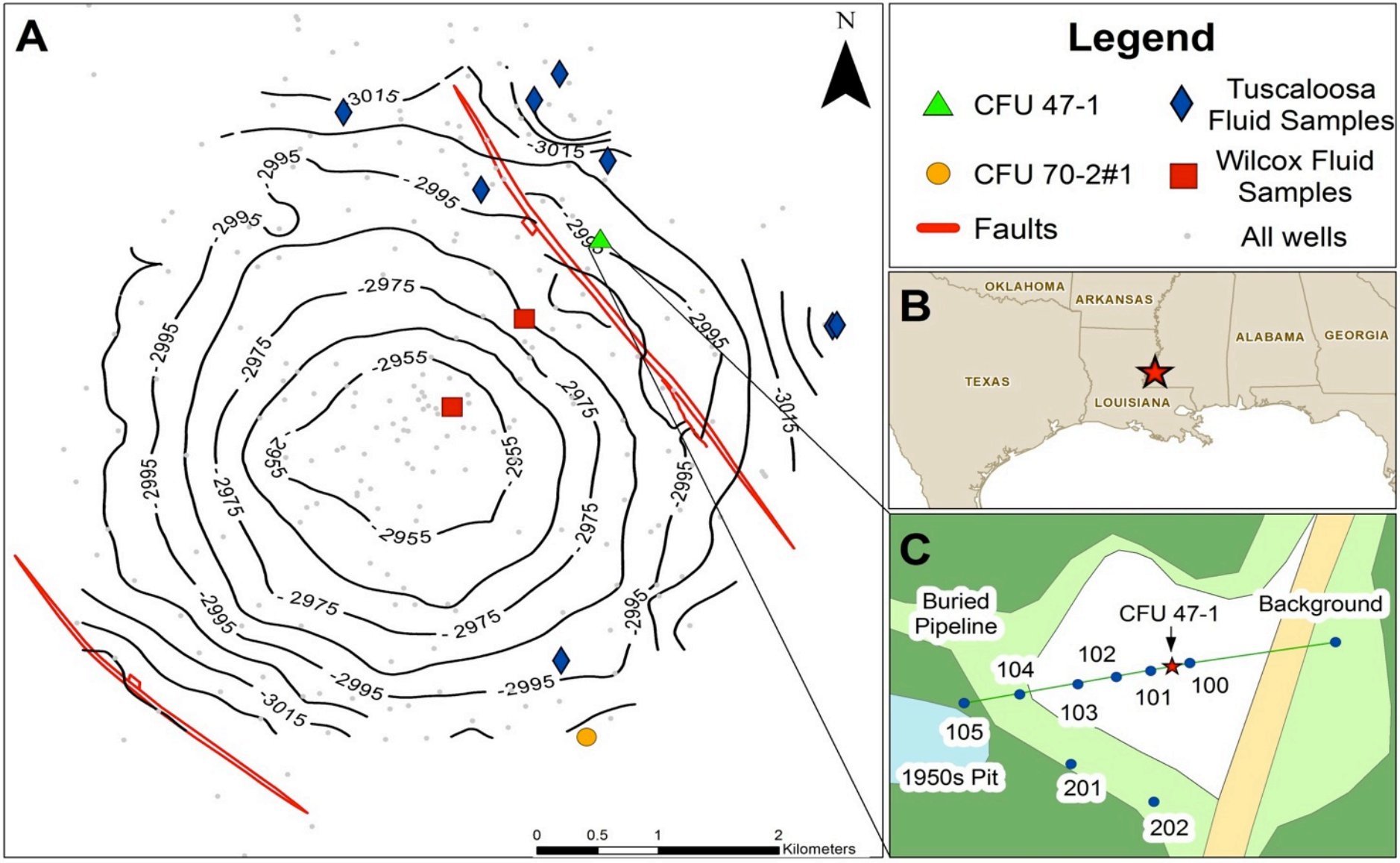
Value of Outcome

- Forward model CO_2 compositional changes.
- Improve fluid source attribution.
- Constrain detectability from potential variation.

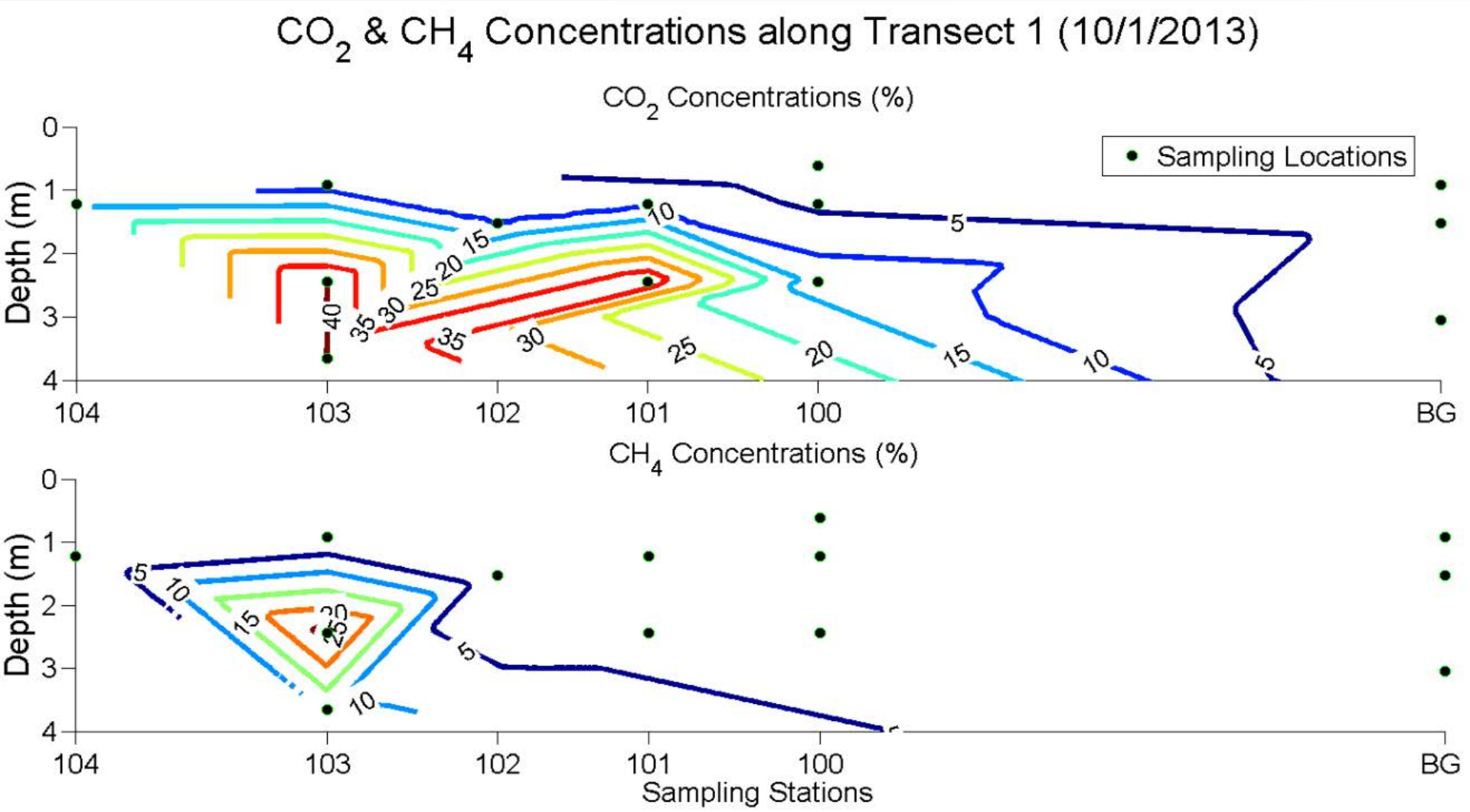
Helium Isotopes

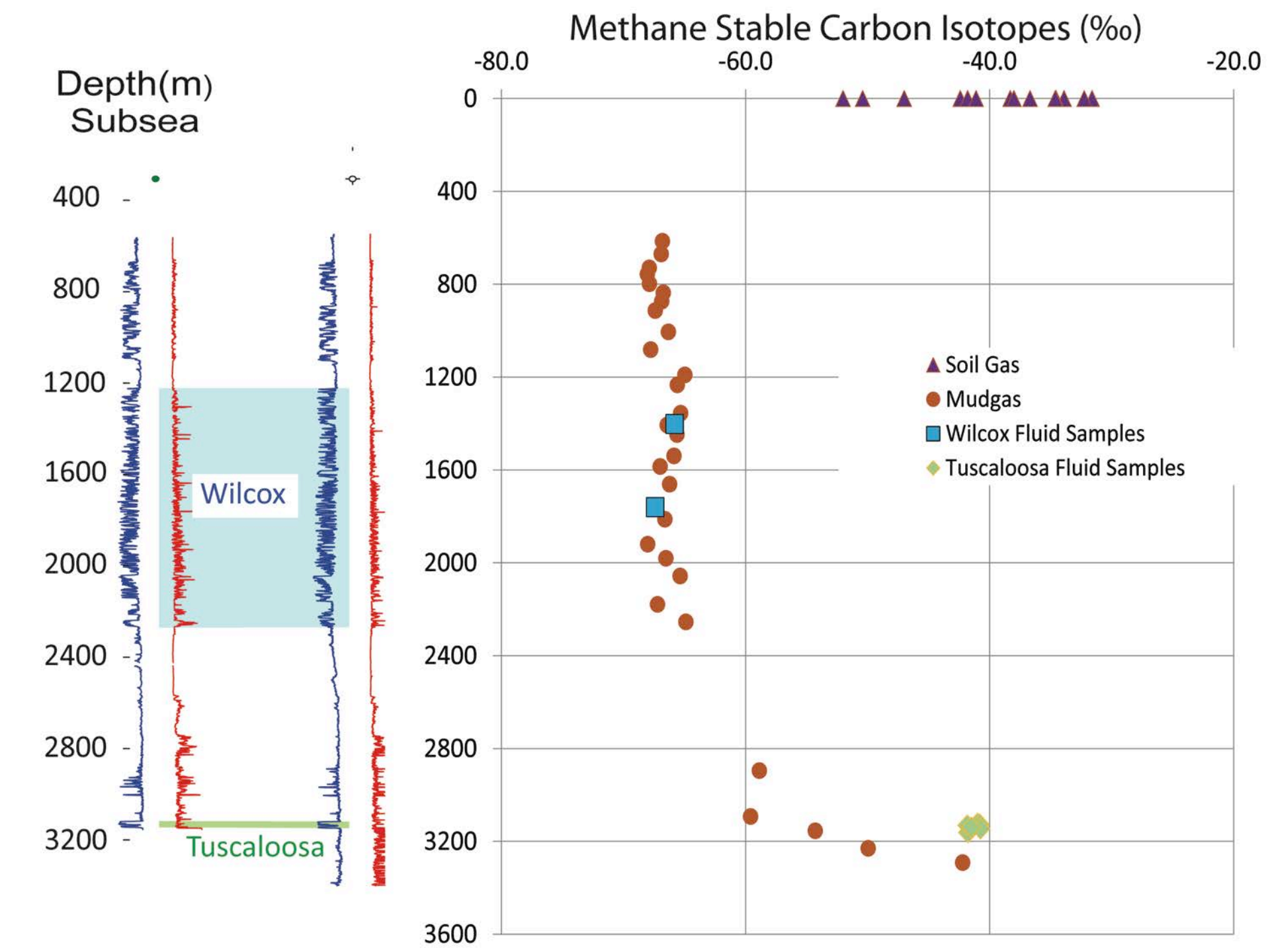
- Soil Gas R/Ra: 0.857 to 1.236
- Air R/Ra = 1;
- Reservoir ranges from 0.21 to 5.32 due to mixing of natural gas (low R/Ra) and injectate CO_2 (high R/Ra) (Gyore et al., 2015).

Cranfield Field

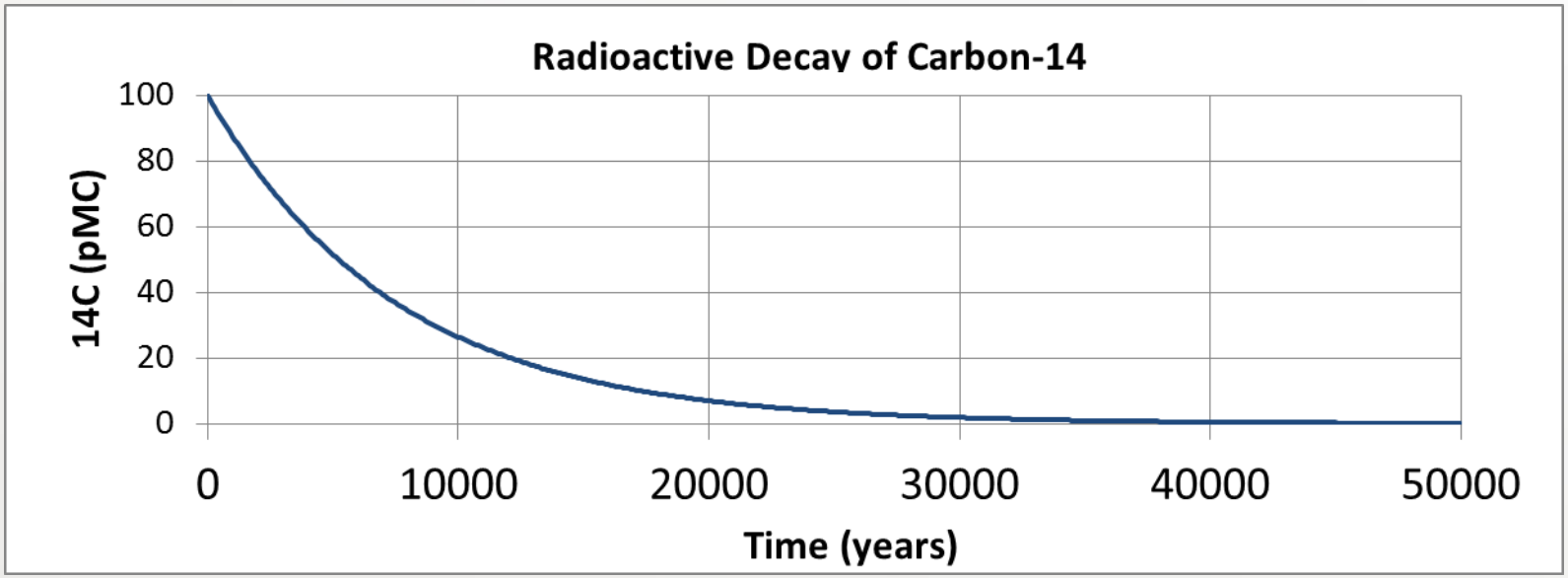


Wellbore Leakage?



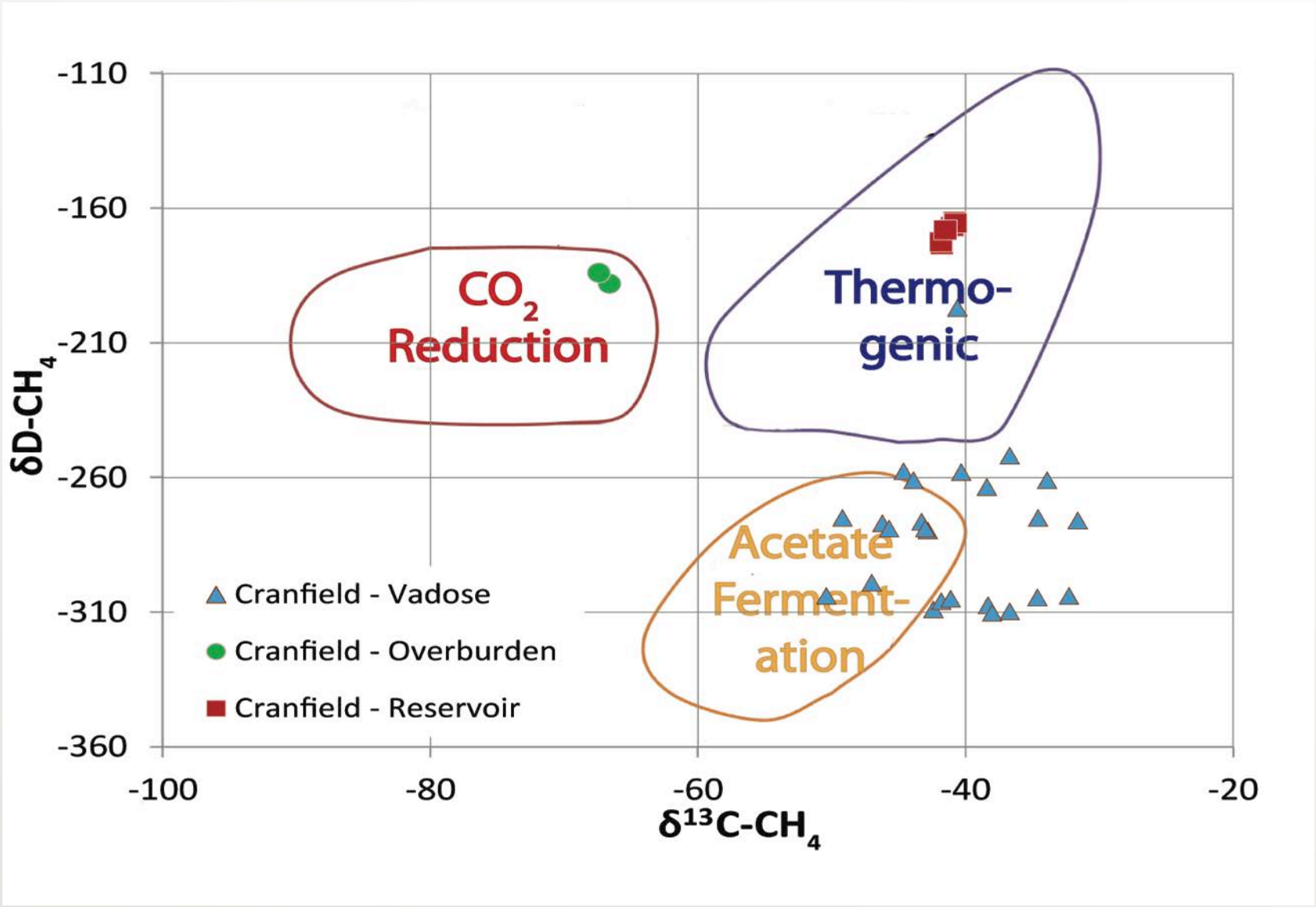

Depth(m)
Subsea
400
800
1200
1600
2000
2400
2800
3200
Wilcox
Tuscaloosa
Methane Stable Carbon Isotopes (‰)
-80.0
-60.0
-40.0
-20.0
0
400
800
1200
1600
2000
2400
2800
3200
3600
Soil Gas
Mudgas
Wilcox Fluid Samples
Tuscaloosa Fluid Samples

Not leakage … Gas is biogenic



Sampling Station (Date / Depth m)	$^{14}CO_2$ (pMC)	$^{14}C_1$ (pMC)
Station 103 – (Mar 2011 / 2.4 m)	105.7	109.9
Station 103 – (Oct 2014 / 2.4 m)	106.7	109.7
Background – (Mar 2011 / 3.6 m)	102.8	

Not leakage … Gas is biogenic



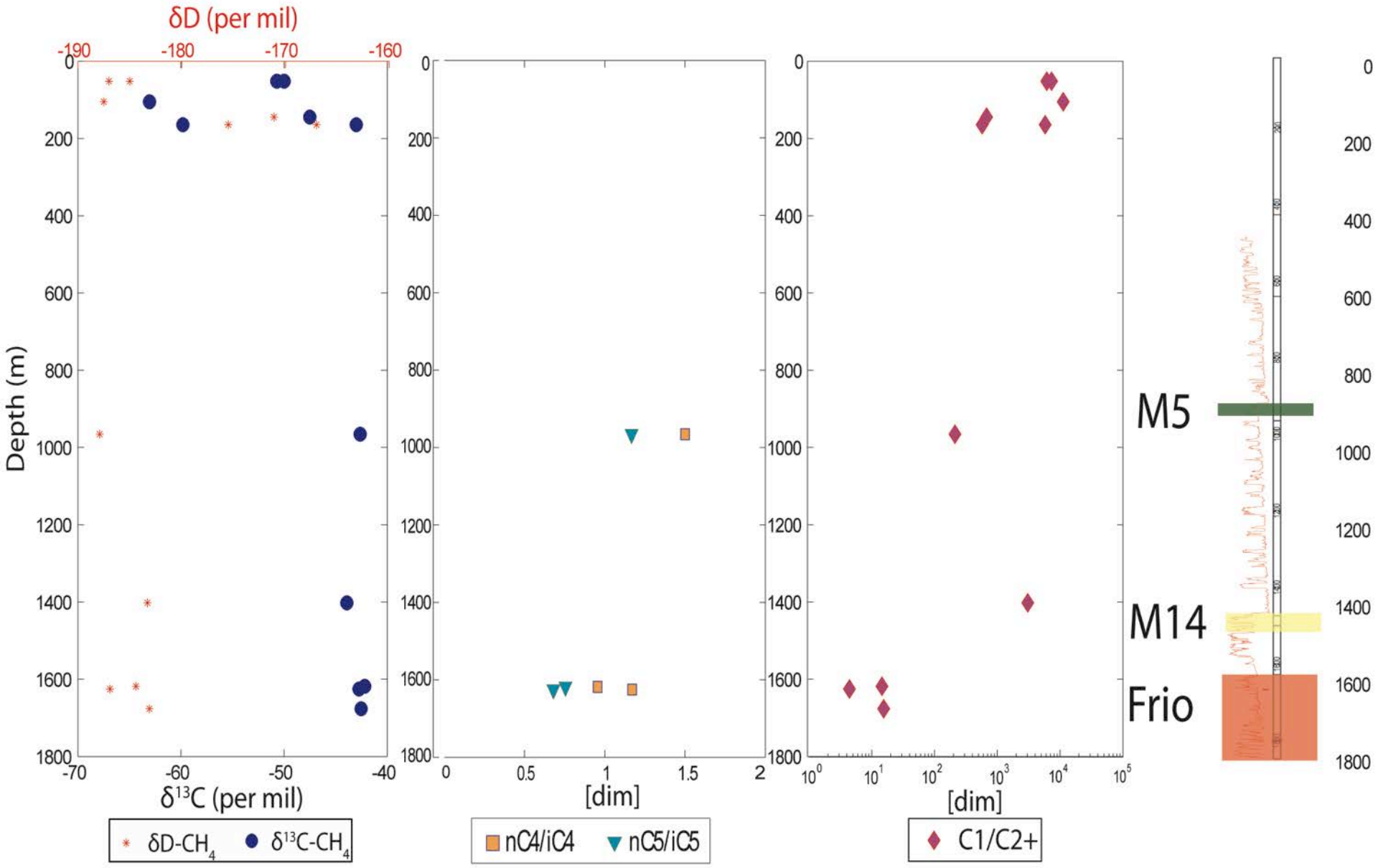
Not leakage … Gas is biogenic

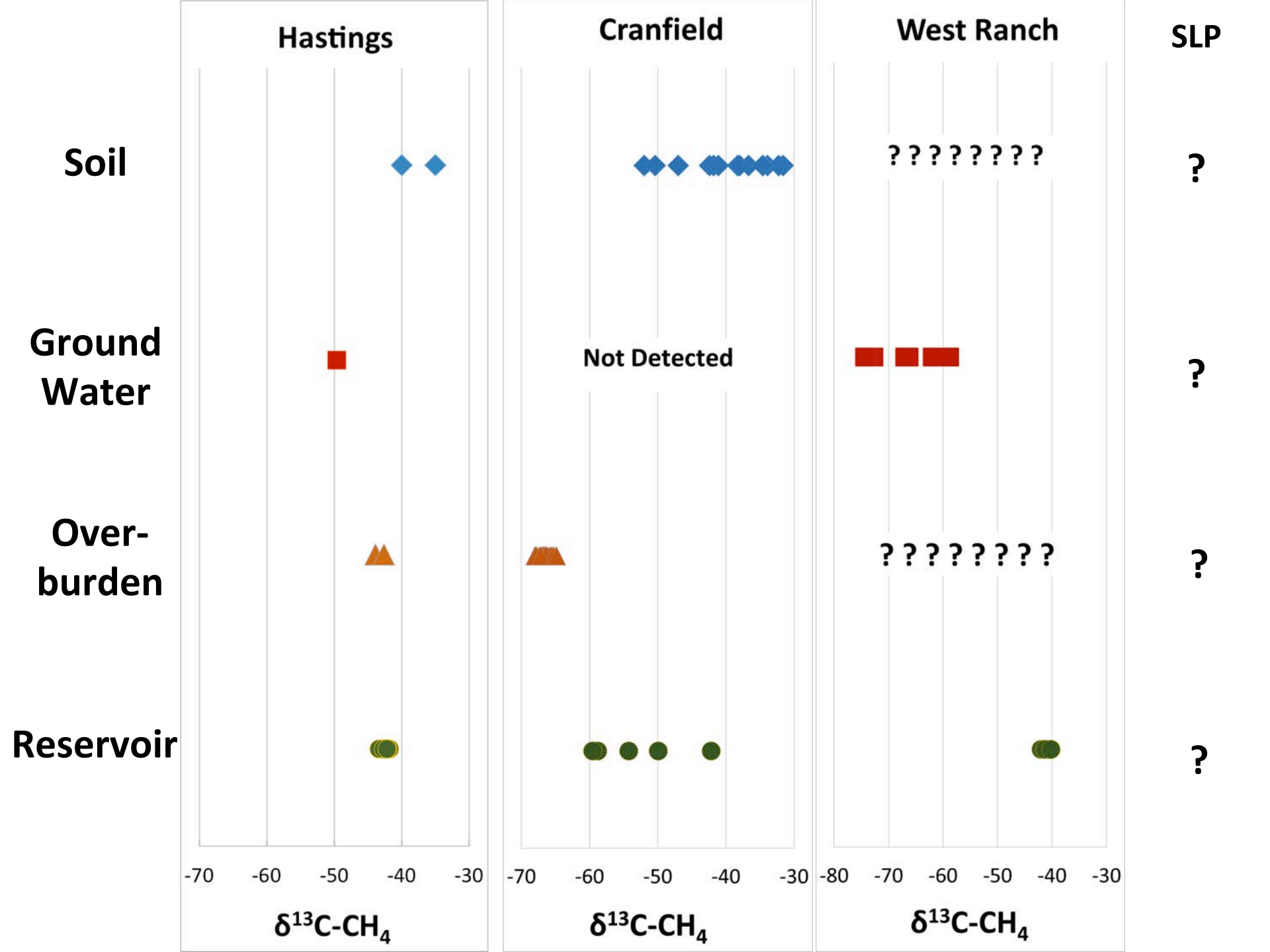
	Methane	Ethane	Ethene	Propane	Propene	iso-Butane	n-Butane	iso-Pentane	n-Pentane	C_6+	% of C2+ Alkanes
Sample Location (Depth) - Date	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	%
Station 103 (2.4 m) - Oct 2013	268800	nd	34	2	nd	1	nd	nd	nd	nd	<0.01
Tuscaloosa - Oct 2013 (Lu et al., 2012)	133900	10000	nd	3000	nd	695	1230	833	643	3490	12.9
Wilcox - Apr 2012	919400	2780	38	803	nd	1120	932	2020	1530	4120	1.4
Background Station (3.6 m) - Oct 2011	53	nd	nd	nd	nd	nd	nd	nd	nd	nd	0

Fluid Source Attribution Workflow

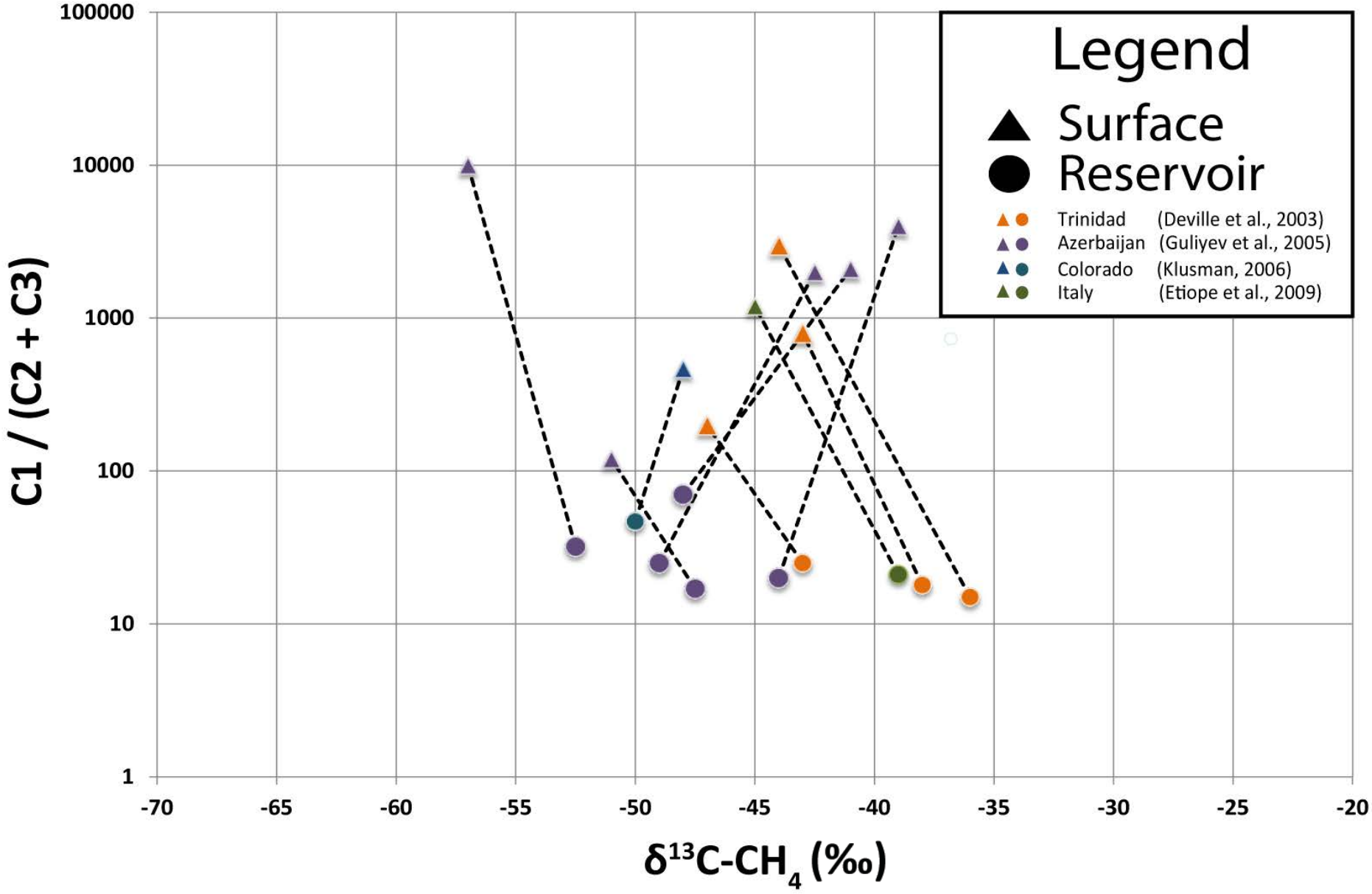
Step	Measurement	Interpretation Criteria for Non-leakage Source	Cranfield Result
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Step 2.1	Methane Stable Isotopes of soil gas	Biogenic formation pathway following Schoell, 1983	Ambiguous
		--- and ---	
Step 2.2	Light hydrocarbon concentrations	<1% C2+ alkanes	Non-leakage
		--- and ---	
Step 2.3	CO_2 stable isotopes	$\delta^{13}C$-CO_2 = -30 to -8 ‰	Non-leakage
Step 3.1	Methane Stable Isotopes of groundwater	Biogenic formation pathway following Schoell, 1983	Non-leakage
		--- and ---	
Step 3.2	Sulfate concentrations	< 200 µmole/L	Potentially Biogenic
		--- and ---	
Step 3.3	Radiocarbon of DIC, DOC, and $CH_{4(aq)}$	^{14}C of $CH_{4(aq)}$ < DIC & DOC	Non-leakage
Step 4	Noble gases	Mixing model of air-saturated water, crustal signatures and injectate/produced fluids	Not measured

Quantify changes during transport

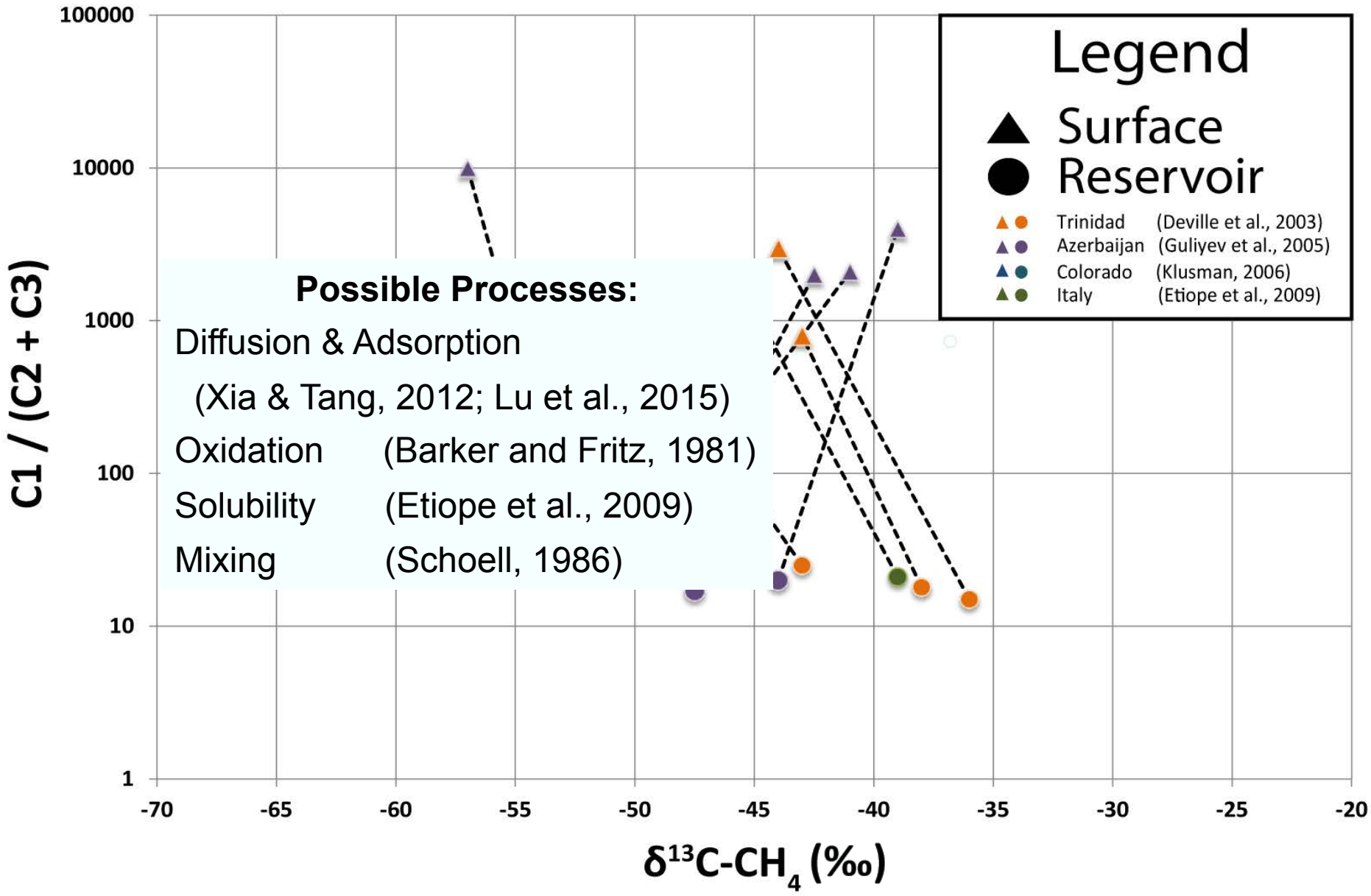



Hastings
Cranfield
West Ranch
SLP
Soil
Ground Water
Over-burden
Reservoir
? ? ? ? ? ? ? ?
Not Detected
? ? ? ? ? ? ? ?
?
?
?
?
-70 -60 -50 -40 -30
-70 -60 -50 -40 -30
-80 -70 -60 -50 -40 -30
δ13C-CH4
δ13C-CH4
δ13C-CH4

Fluid compositions evolve during transport



Fluid compositions evolve during transport



SECARB "Early Test" at Cranfield

DE-FC26-05NT42590

Susan D. Hovorka
Gulf Coast Carbon Center
Bureau of Economic geology
Jackson School of Geoscience
The University of Texas at Austin



SECARB

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

12th Annual Stakeholders' Briefing

Hyatt Regency Atlanta
Atlanta, Georgia
March 8-9, 2017

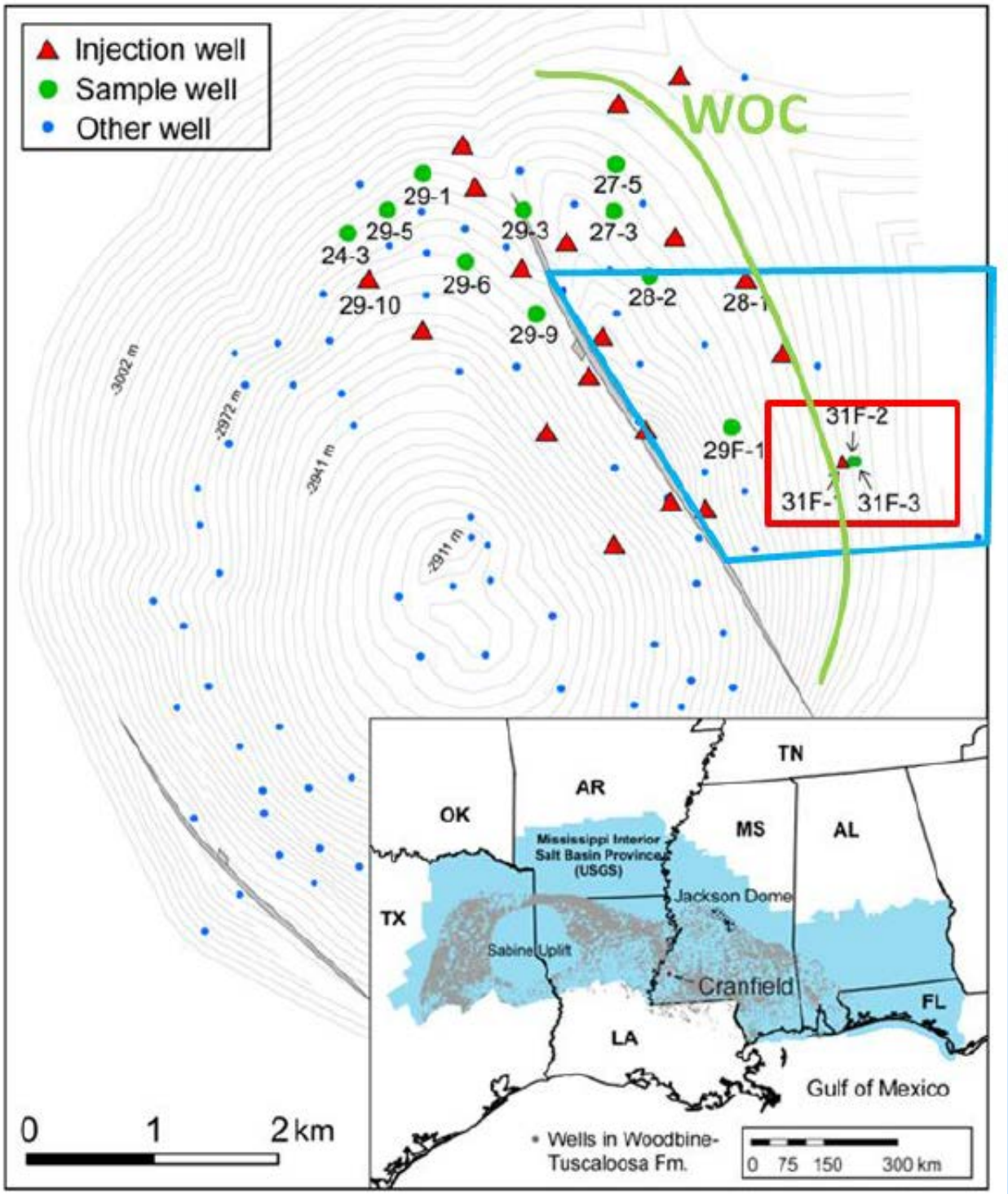
Introduction – Early Test Motivation

- MIT report “Future of Coal” 2007
  - Set 1 MMT injection goal “proceed .. as soon as possible. Several integrated large-scale demonstrations with appropriate measurement, monitoring and verification are needed. ... establish public confidence for future.”
- In 2007 scale and timing of large-scale capture in region still uncertain
  - SECARB anthropogenic test (2011)
  - >1 MMT Commercial Capture in region (2014, 2017)
- Early Test design to progress in the gap
  - Piggy-back on soon-to-start EOR project
  - Permits, source and infrastructure in place
  - Direct injection – relevant to large scale saline CCS

Introduction – Early Test design

- Large-scale storage demonstration
  - 1 MMT/year over >1.5 years
    - Periods of high injection rates
    - Result >5 years with >5 MMT CO_2 stored
- Measurement, monitoring and verification
  - Tool testing and optimization approach
  - Deploy as many tools, analysis methods, and models as possible
- Stacked EOR and saline storage

Location


Injection well
Sample well
Other well
WOC
29-1
29-5
24-3
29-10
29-6
29-3
27-5
27-3
28-2
29-9
29F-1
31F-2
31F-3
-3002 m
-2972 m
-2941 m
-2911 m
0 1 2 km
TN
AR
OK
MS
AL
TX
LA
FL
Mississippi Interior Salt Basin Province (USGS)
Jackson Dome
Sabine Uplift
Cranfield
Gulf of Mexico
Wells in Woodbine-Tuscaloosa Fm.
0 75 150 300 km

Introduction – Major Conclusions

- Early Test Developed monitoring approaches for later commercial projects
  - Process-based soil gas method
  - Effectiveness of groundwater surveillance
  - Pressure and fluid chemistry monitoring in Above-Zone Monitoring Interval (AZMI)
  - ERT for deep CO_2 plume
  - Limitations of 4-D seismic
- Published and propagated techniques for widespread application

Scope of Work from Statement of Project Objectives

SOPO Goals

1,000,000 metric tons of CO_2 will be injected per year for up to one and a half years into the Lower Tuscaloosa saline reservoir of the flanks of the Cranfield oil field

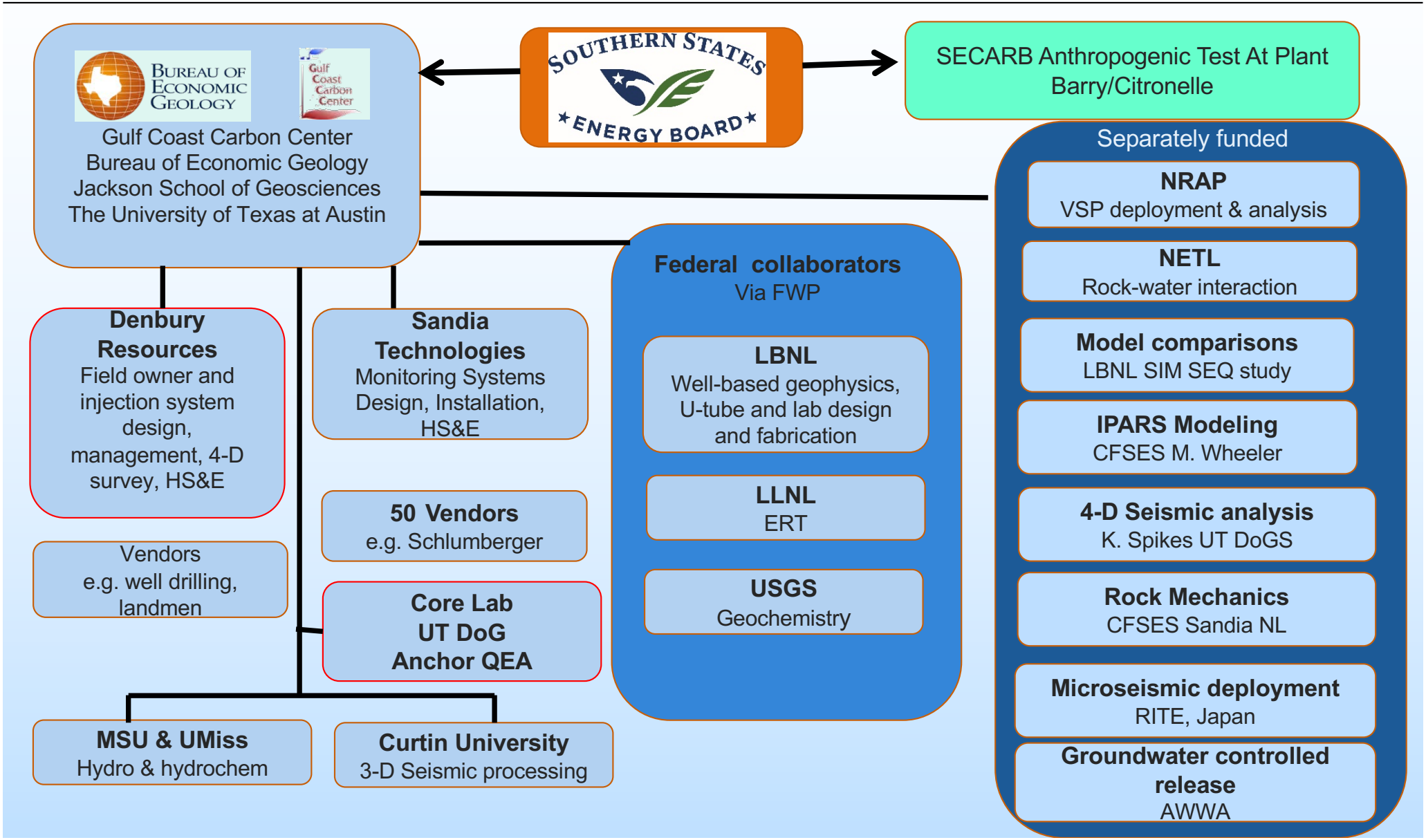
Develop the technical scope of work, local education, permitting, outreach, MMV, and maintain the demonstration tests' schedules and budgets

Success metrics

- Site Characterization, Modeling and Monitoring Plan
- Revise location, design, and planned number of injection wells and location, design, and tool selection for observation wells.
- Subsurface Monitoring Plan Integration of assessments, tool selection, preparation of well instrument string design
- Implementation of Discontinuation Plan
- Finalize, Distribute and Archive Subsurface Data Compilation.
- Final History Match: Subsurface Plume Development, Early Test
- Finalize, Distribute and Archive Data Compilation Surface Monitoring

Note: All metrics and field activites completed April 2015

Team Structure



Facilities and materials

Provided at site

Historic data (logs, production history)

Baseline 3-D seismic survey

2 new cores and 20 new open hole logs

Slim tube analyses

Roads pipelines, operations

Health and safely

15 fresh water wells

Access to roads and well pads and public acceptance (lease agreement and landmen).

CO_2 supply (5,326,750 MT)

Data from EOR operation e.g.

Mass flow at meters, BHP

Purchased by project

Three new wells with OH logs, 2 cores *

Instrumentation (ERT, CASSM) detailed area study

Additional RST logs

Repeat 3-D seismic for active part of field

224,781 tons additional CO_2 to assure meeting project metrics

Soil gas array, P-site

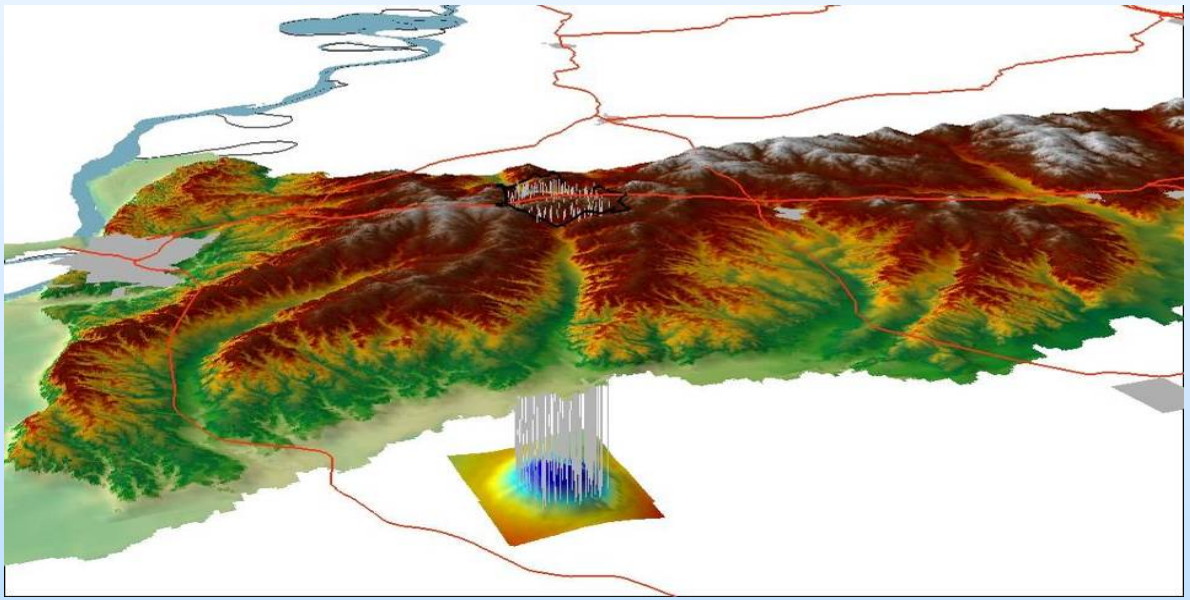
*Leveraged access to 3 additional injectors. “cash call” during recession

Technical Approach

- Early test was conceptualized as earliest part of the RCSP portfolio to support future integrated projects
  - SECARB Anthropogenic test
  - Other RCSP tests
  - Also future tests e.g.
    - Air Products commercial 1MMT/capture at Port Arthur
    - Petra Nova commercial 1MMT/capture near Houston
- Resulting limitations
  - Not captured CO_2 (natural source at Jackson Dome)
  - Project started with large volume direct (no WAG) CO2 injection – very analogous to saline
  - Evolved by year 3 to be dominated by recycle.
  - Complexities of hydrocarbons in part of the study area
  - No post injection period possible – injection for EOR continues commercially

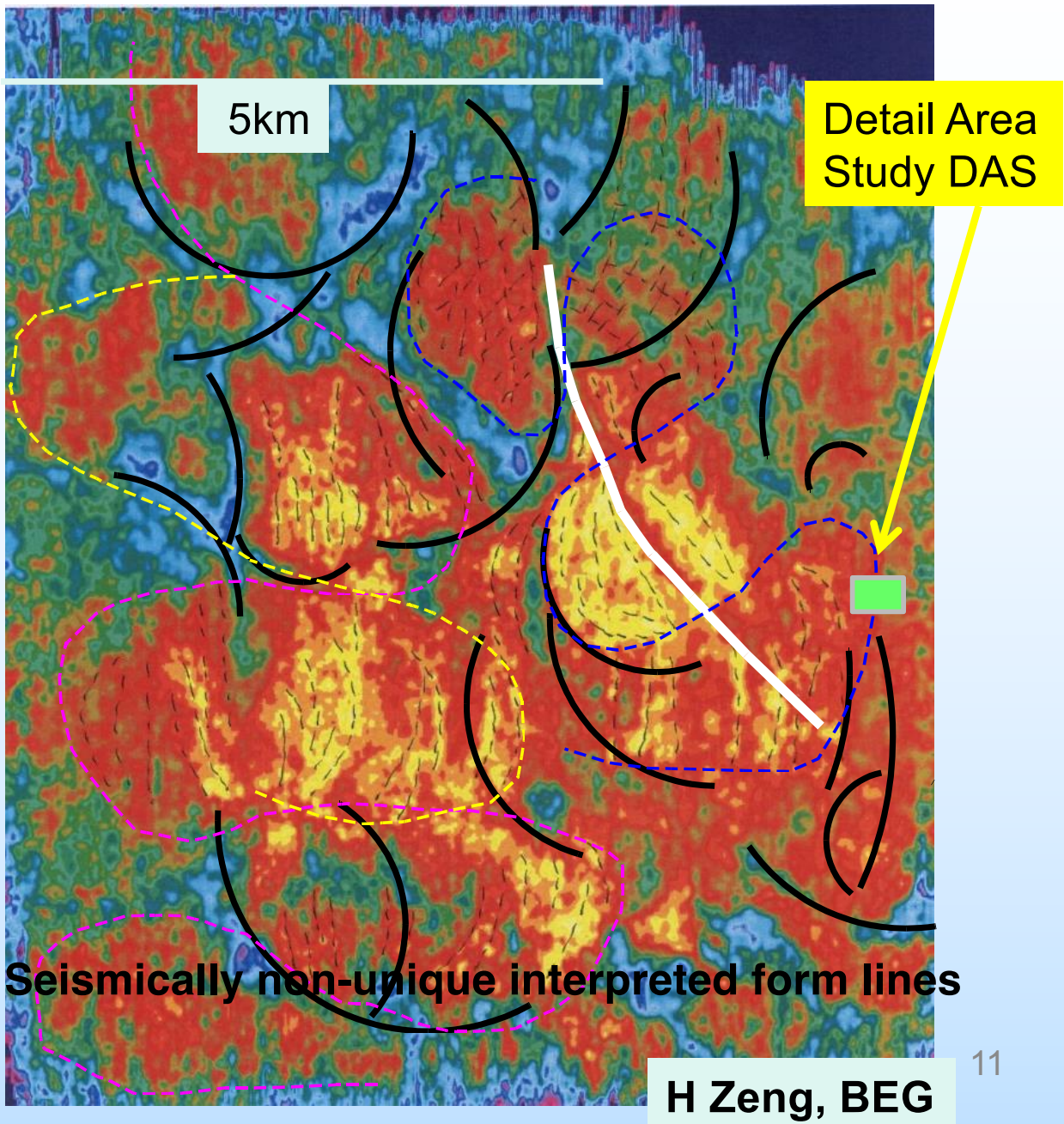
Site Characterization Approach

- Historical data – maps and cross sections, production history
- New 3-D seismic
- Re-evaluation of new and existing logs, new cores
  - Core analysis
  - Capillary entry pressure
  - thin sections petrography
  - XRD
  - Diverse laboratory tests



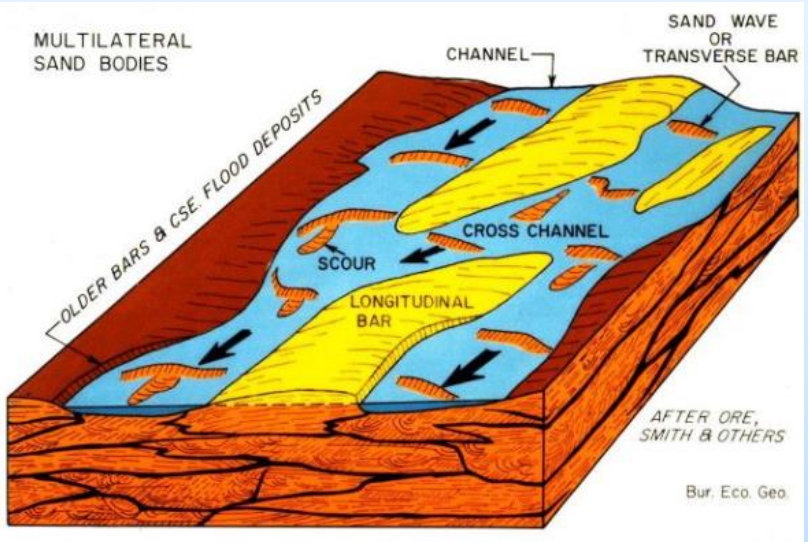
Site Characterization Approach

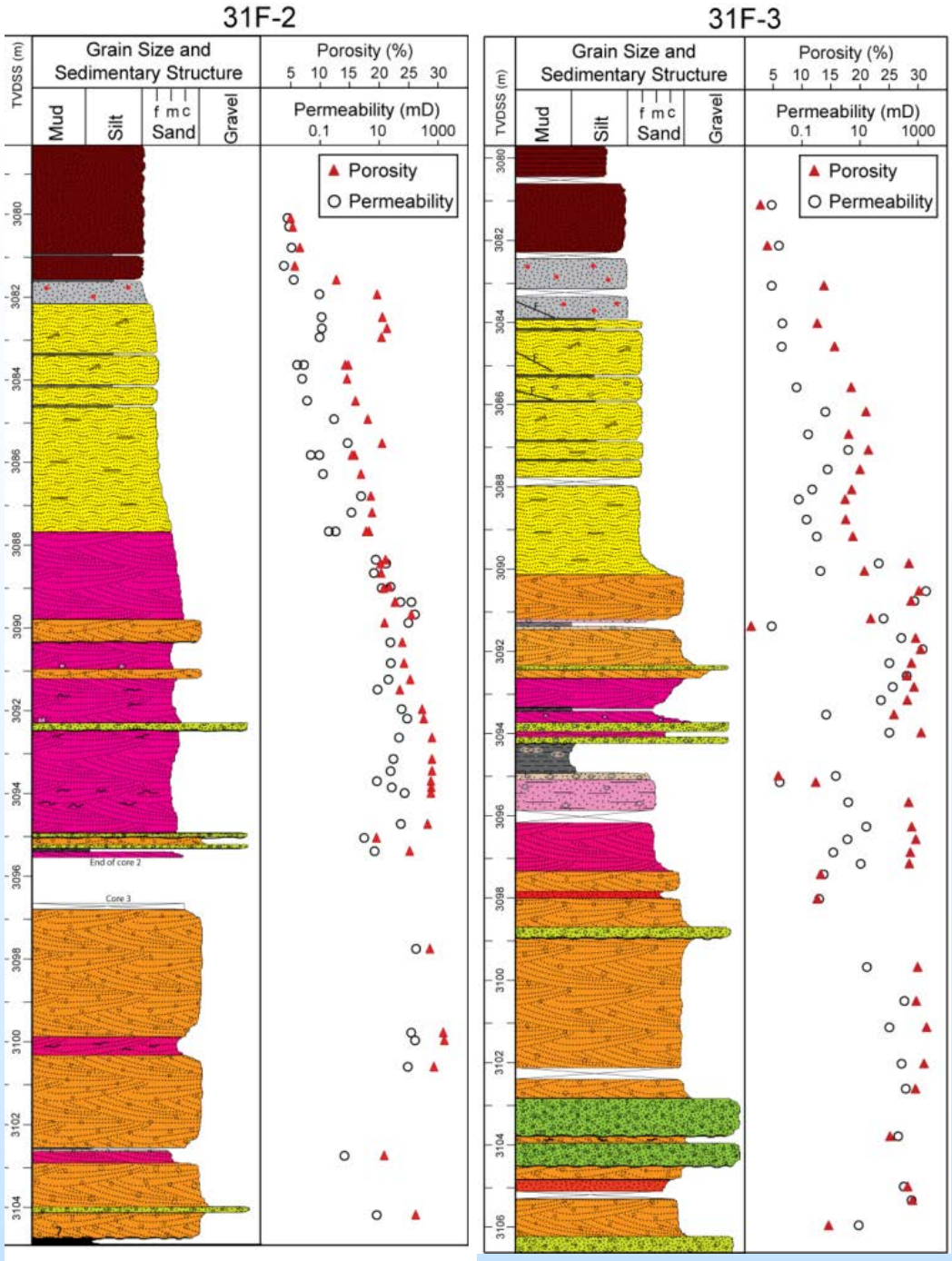




Amalgamated Fluvial Channels - Heterogeneity







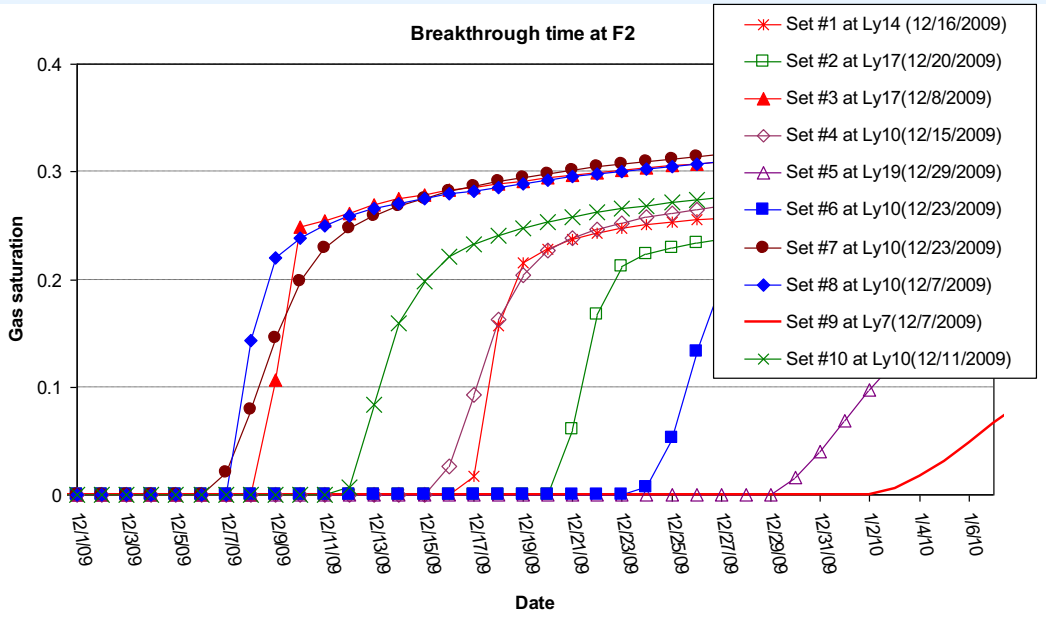
30-m apart

M. Kordi , BEG

Modeling Approach

Evaluation Criterion 2

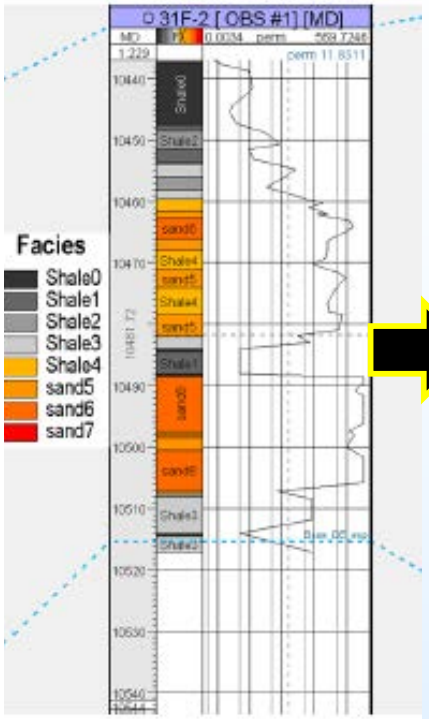
- Multiple models
  - I-PARS
  - SIM-SEQ model approach comparison
- CGM GEM
  - Probabilistic approaches
  - Match 100 realizations to subset of modeled data
  - Forward model scenarios



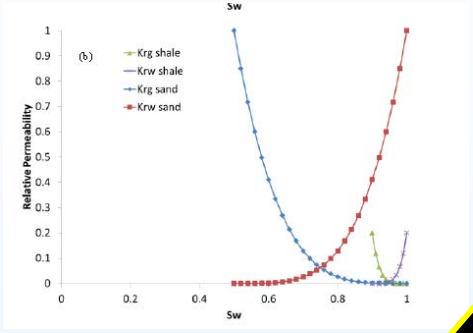
Pre-injection forward model breakthrough times to design geochemical sampling

Modeling Approach

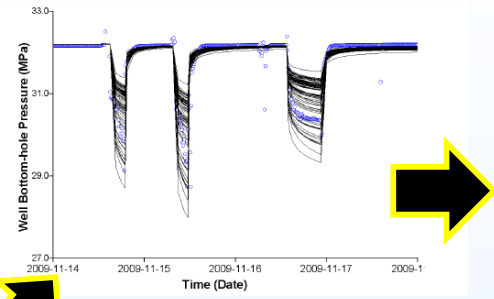
Reservoir characterization



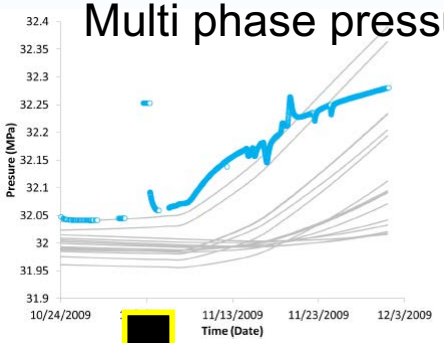
Relative permeablities



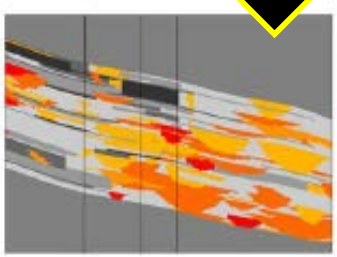
Single phase pressure

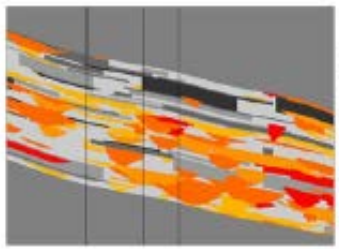


Multi phase pressure



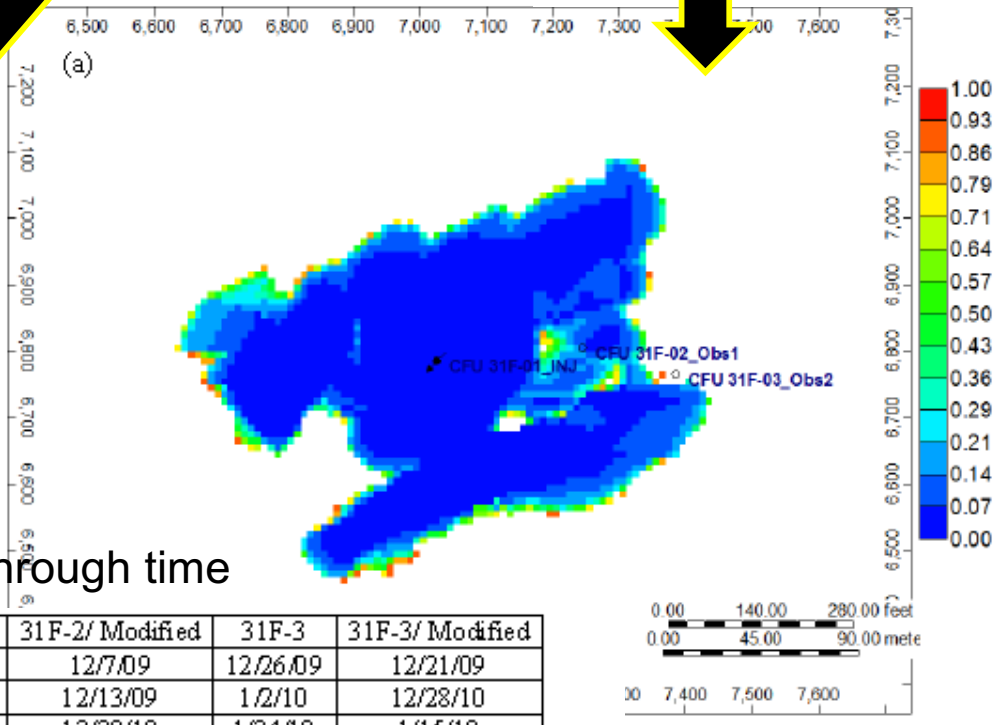
Probabilistic realizations of reservoir architecture







Breakthrough time

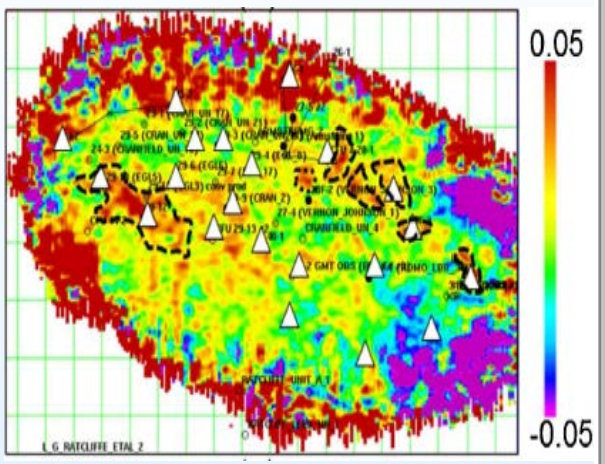


Realization Number	31F-2	31F-2/ Modified	31F-3	31F-3/ Modified
35	12/8/09	12/7/09	12/26/09	12/21/09
18	12/15/09	12/13/09	1/2/10	12/28/10
8	1/3/10	12/28/10	1/24/10	1/15/10
15	12/20/09	12/16/09	1/11/10	1/2/10
ACTUAL		12/12/09		12/16/09

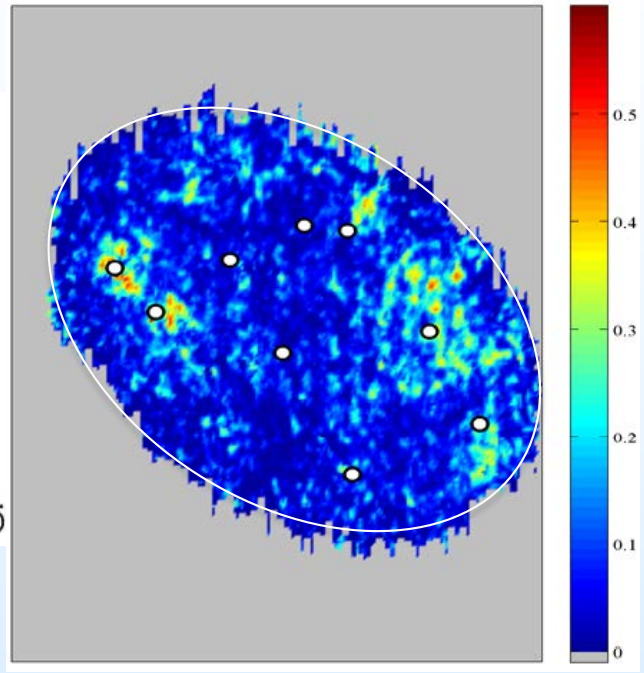
Hosseini and others, 2013
Cranfield

Modeling Approach

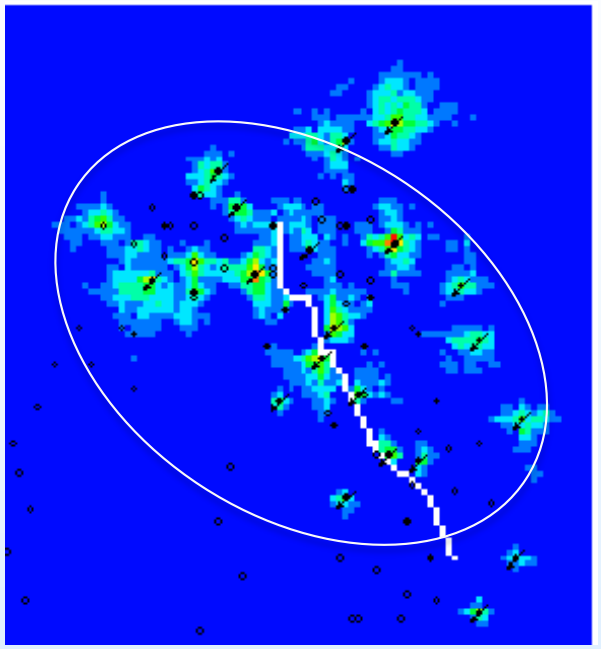
Comparing measurement to modeling



$v_p - v_s$ ratio difference
Zhang et al. (2014)

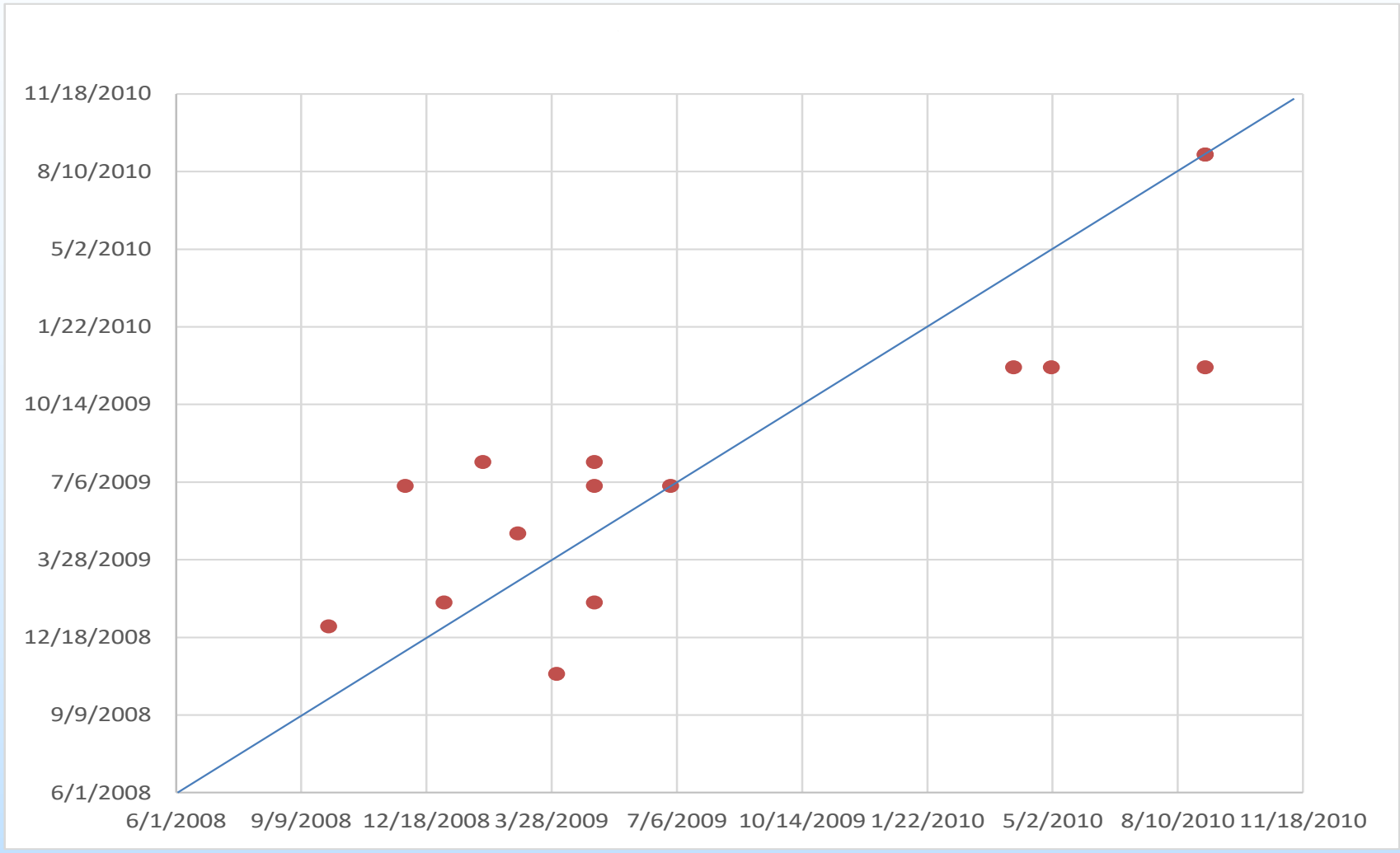


CO_2 saturation distribution estimate using rock physics 2010 from 3D seismic data (Carter 2014)



Modeled CO_2 distribution

History Match Modeled and measured CO_2 breakthrough





EARTH & ENVIRONMENTAL SCIENCES

BERKELEY LAB
Lawrence Berkeley National Laboratory

Analysis of Seismic Time-Lapse Observations at Cranfield

D. W. Vasco, Tom Daley, Jonathan Ajo-Franklin,
LBL

Accomplishments:

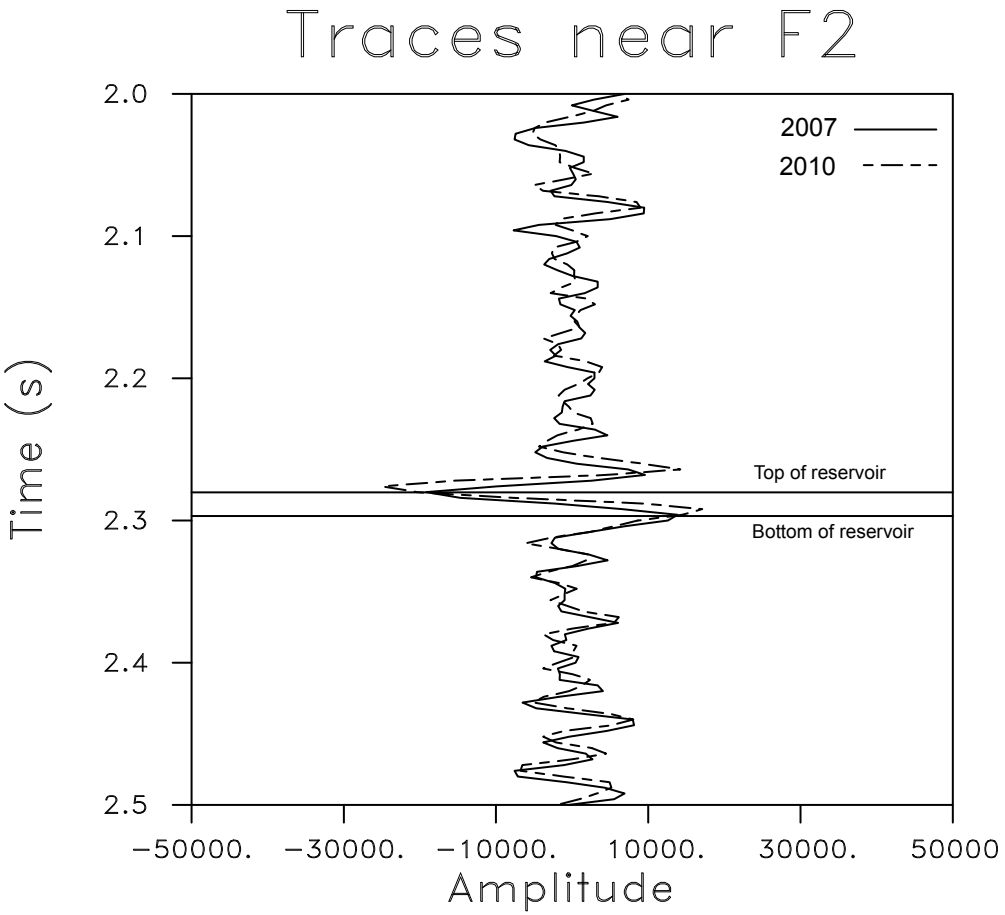
- Estimated seismic time-shifts from 4D data

- Calculated seismic velocity variations due to changes in fluid phases from compositional modeling.

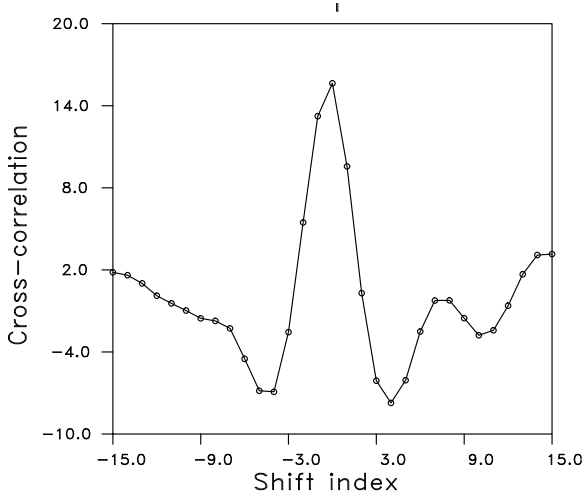
- Compared velocity changes to observed time-shifts and seismic amplitude changes

Estimating Seismic Time-Shifts

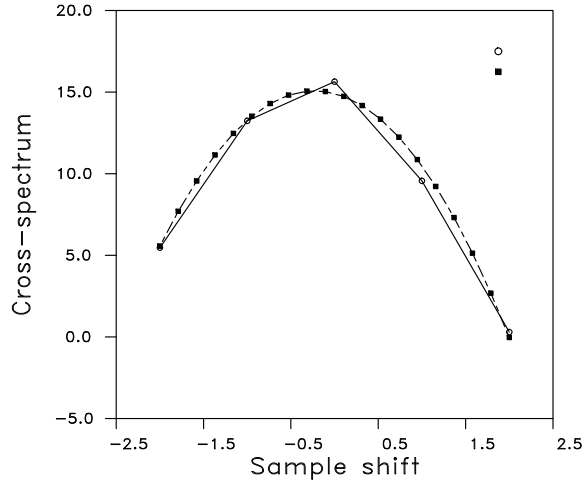
- Line up traces using reflections from horizons just above the reservoir



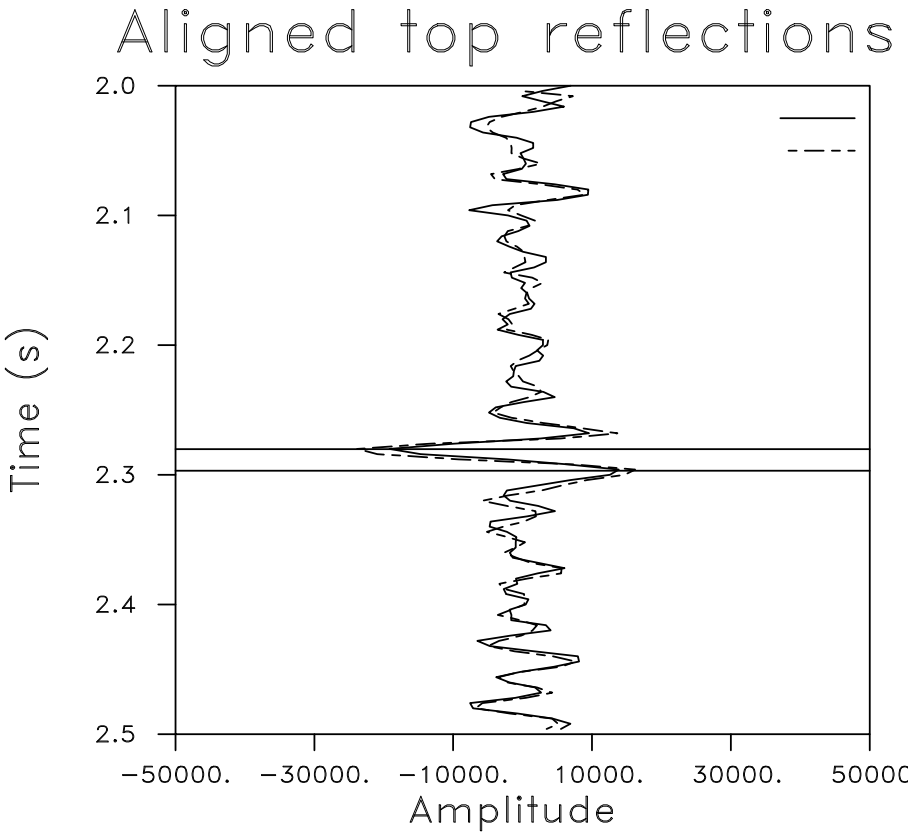
Cross-correlate

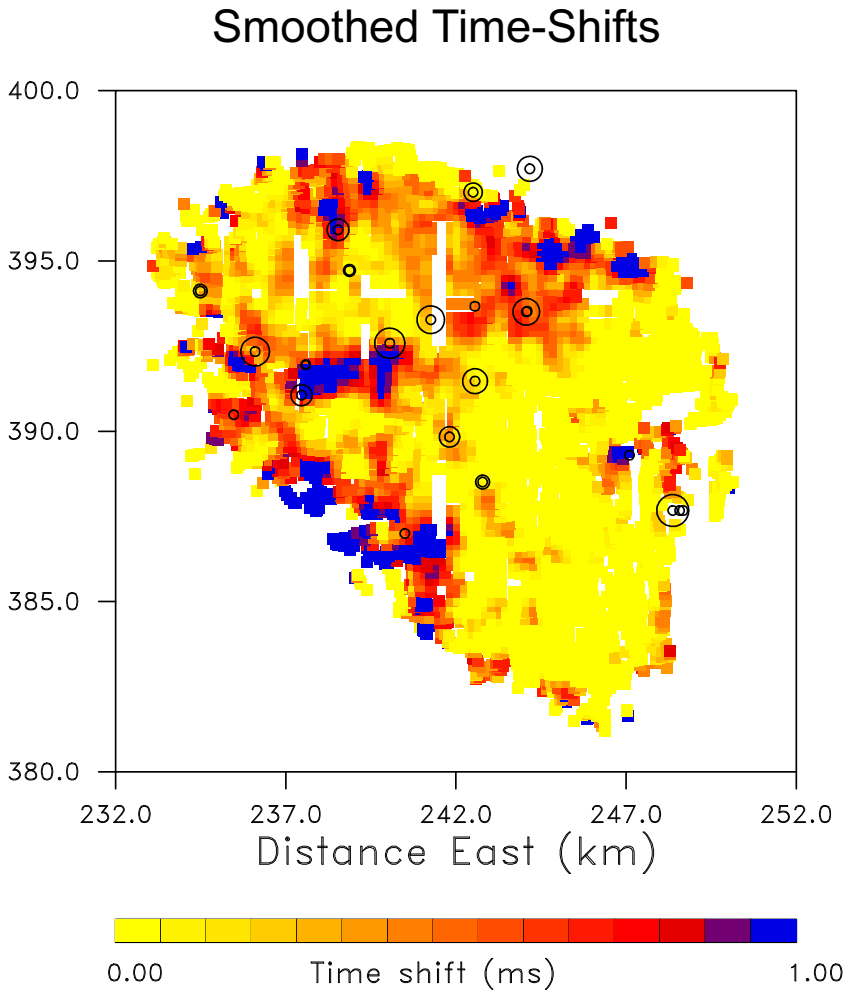


Quadratic fit for sub-sample precision

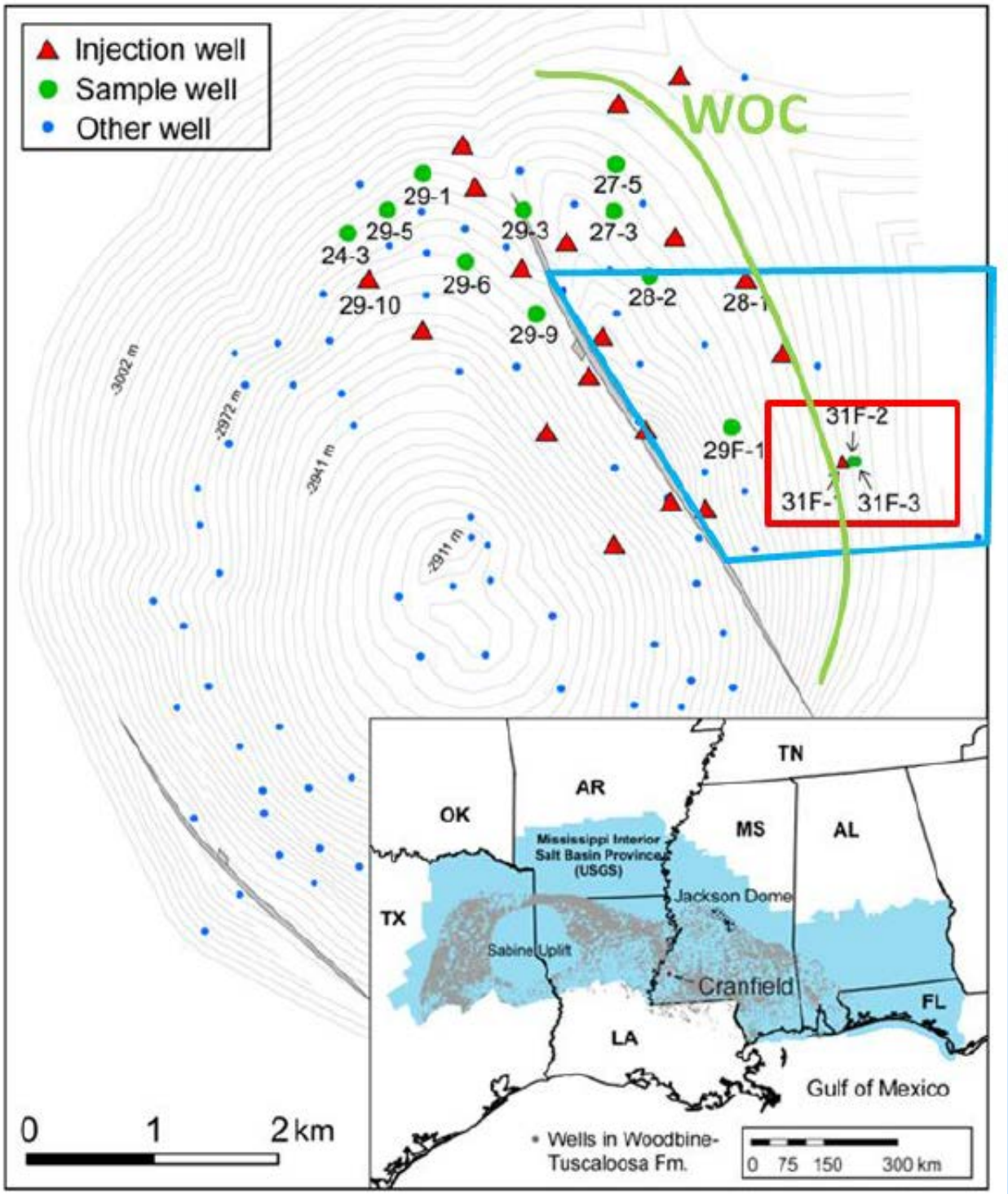


- Calculate resulting time shifts for reflections just below the reservoir.

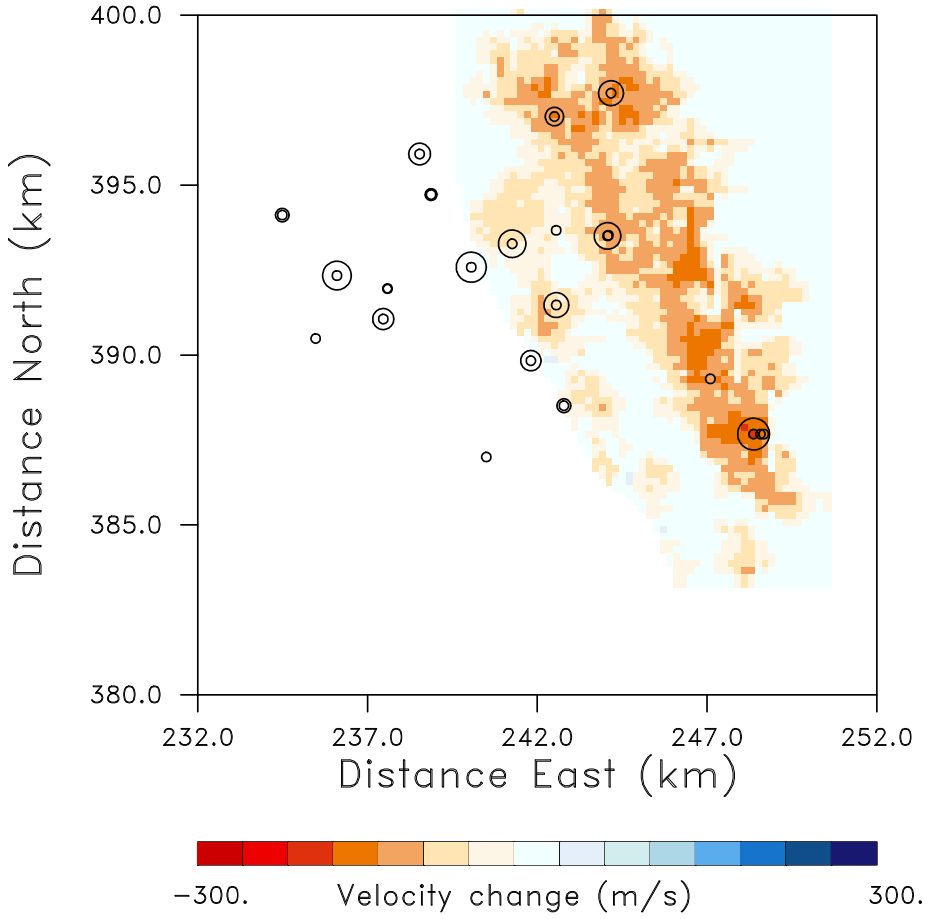


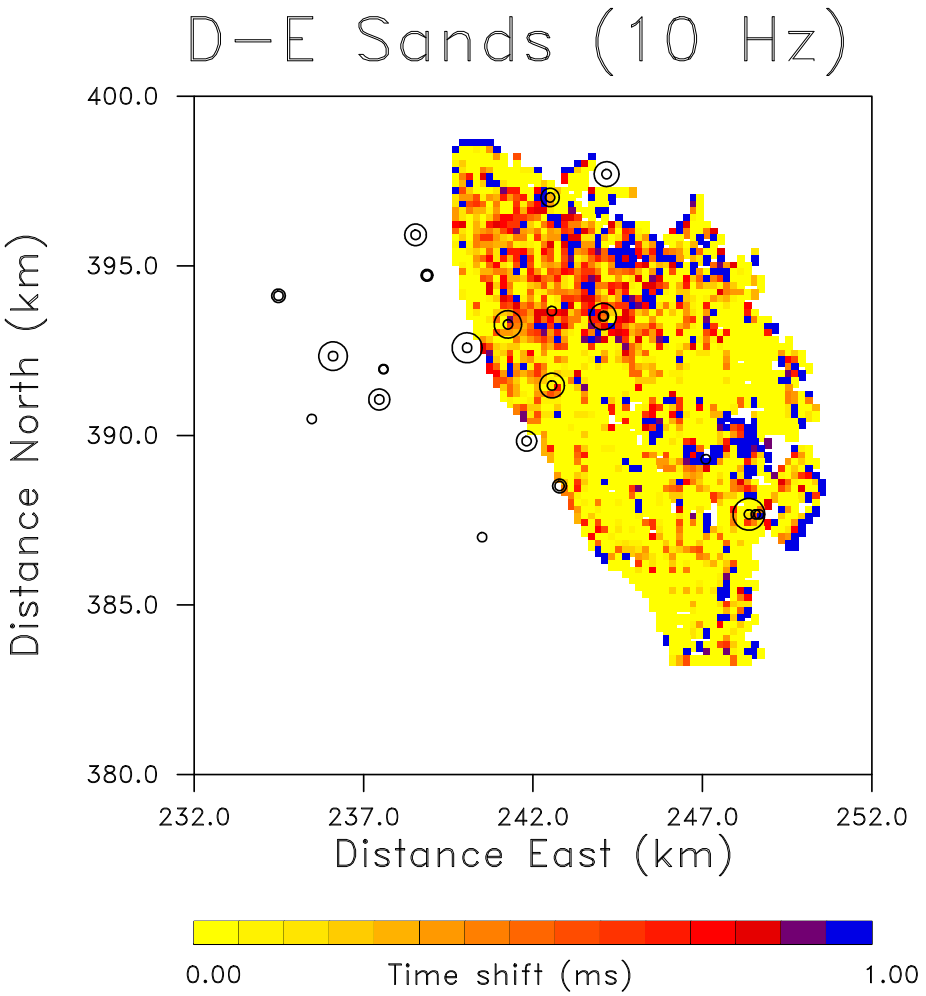


Location

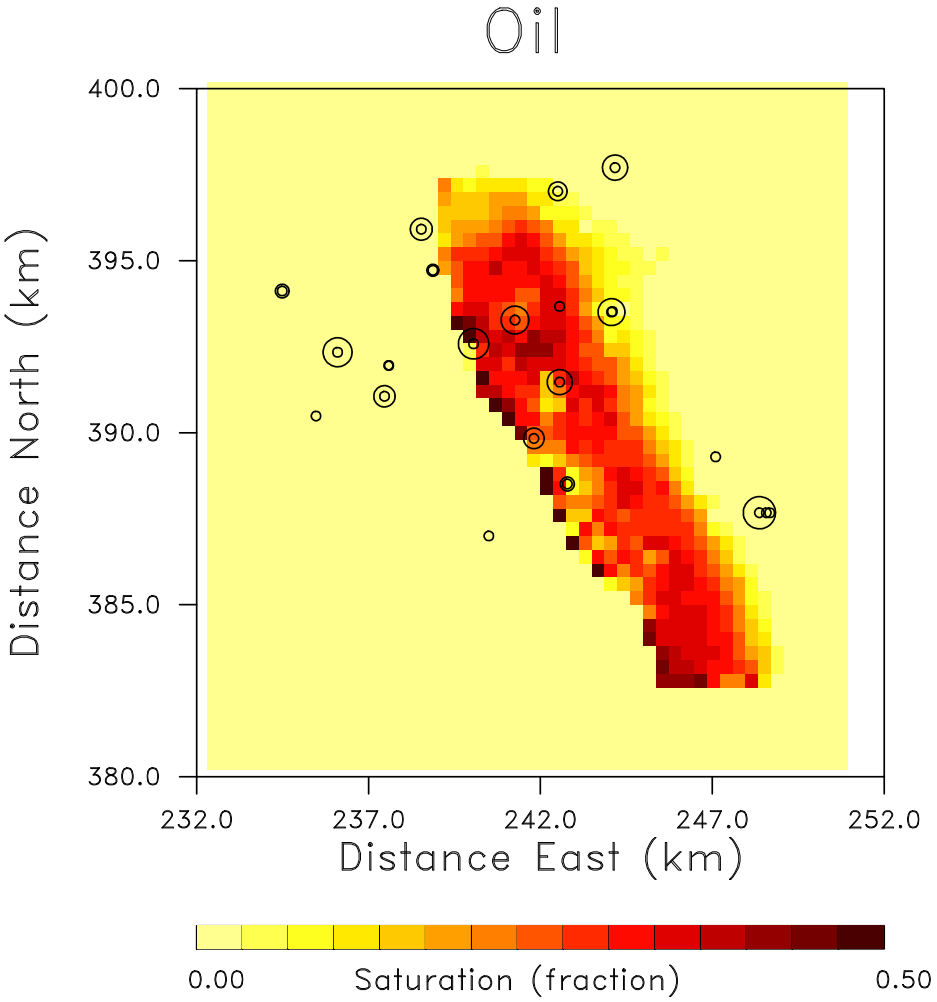

Injection well
Sample well
Other well
WOC
29-1
29-5
24-3
29-10
29-6
29-3
27-5
27-3
28-2
29-9
29F-1
31F-2
31F-3
-3002 m
-2972 m
-2941 m
-2911 m
0 1 2 km
TN
AR
OK
MS
AL
TX
LA
FL
Mississippi Interior Salt Basin Province (USGS)
Jackson Dome
Sabine Uplift
Cranfield
Gulf of Mexico
Wells in Woodbine-Tuscaloosa Fm.
0 75 150 300 km

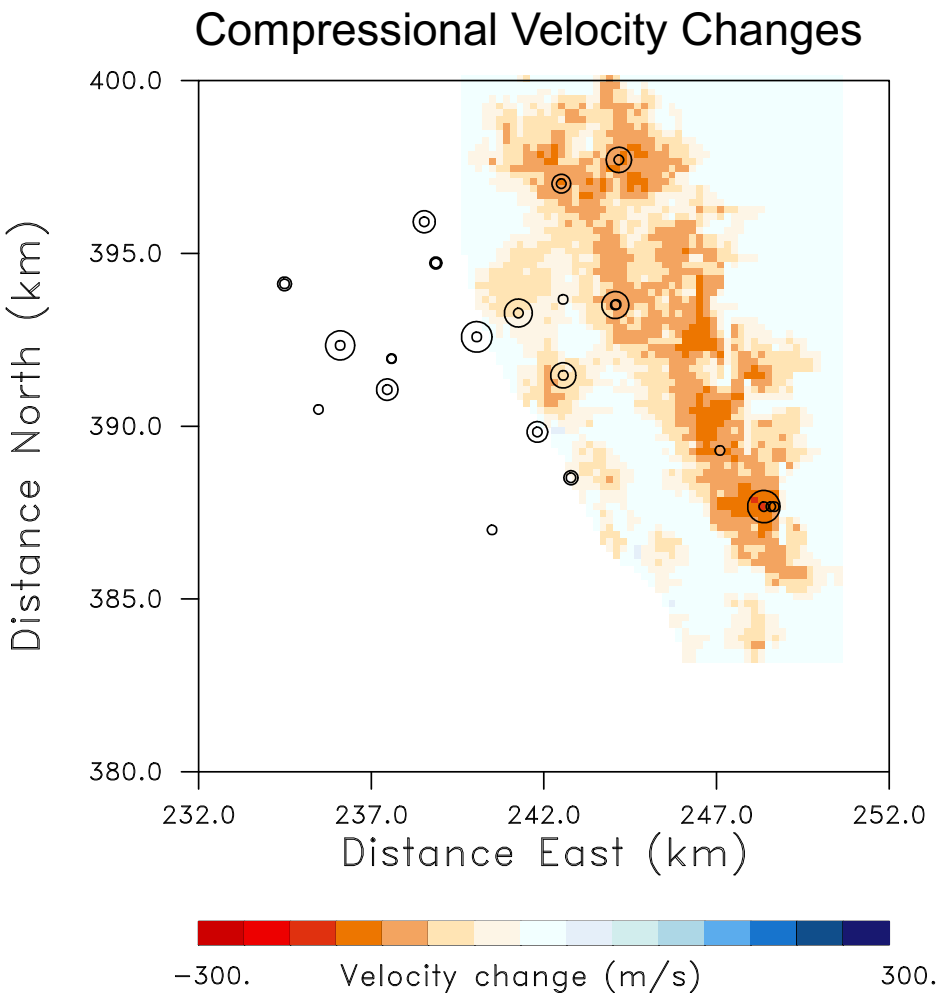
- Largest seismic time shifts in area with greatest velocity changes



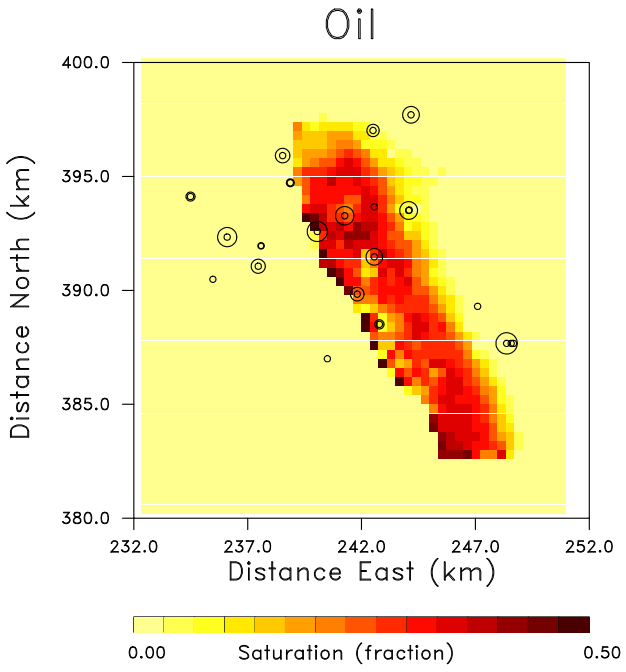


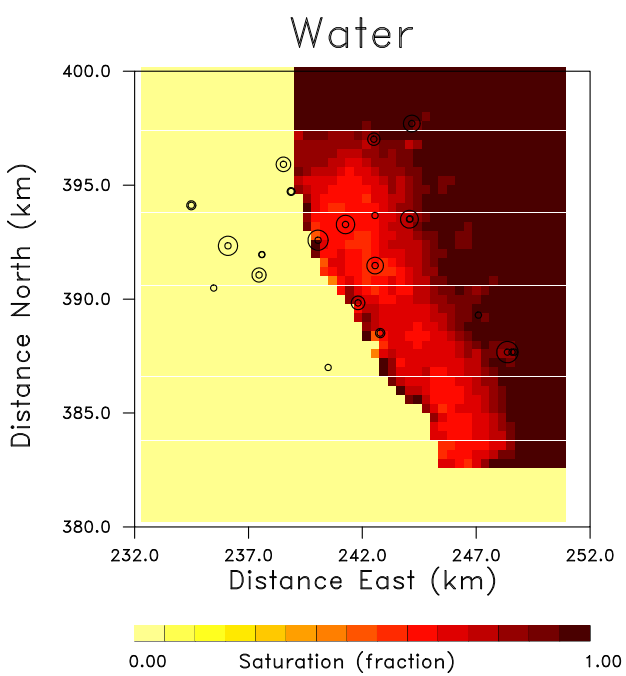
- Biggest velocity changes due to the injection of carbon dioxide are in the water leg

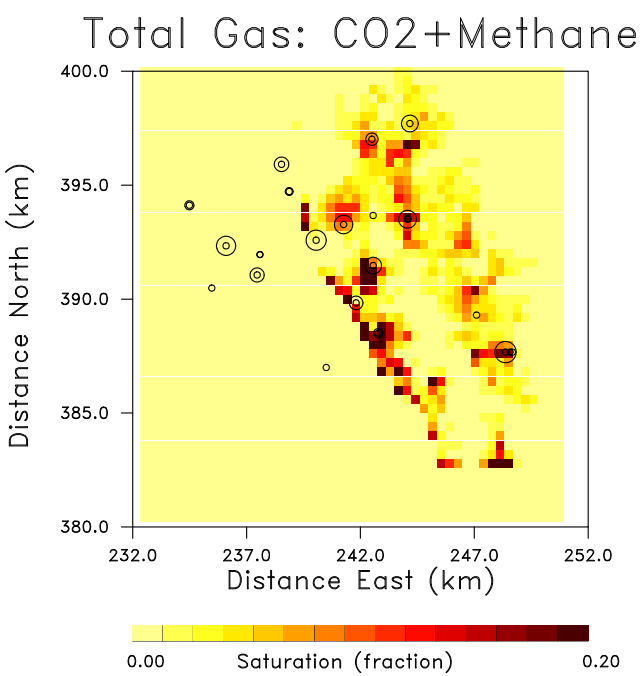




2010

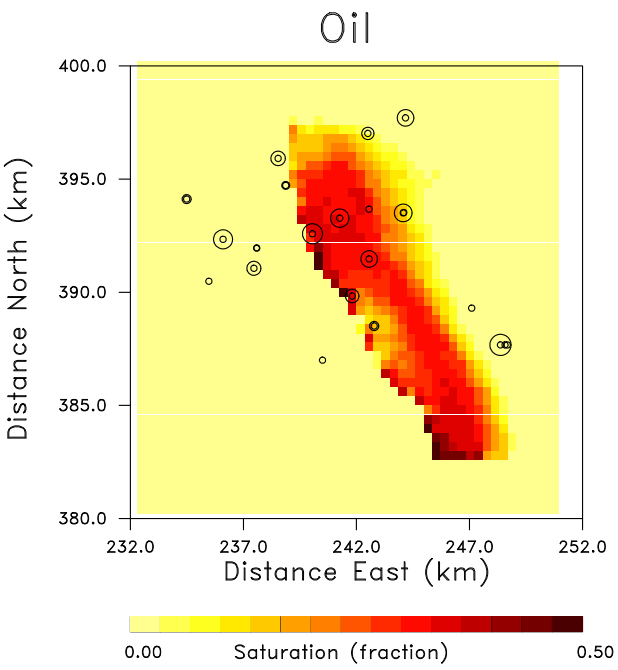

Oil
Distance North (km)
400.0
395.0
390.0
385.0
380.0
232.0
237.0
242.0
247.0
252.0
Distance East (km)
0.00
Saturation (fraction)
0.50

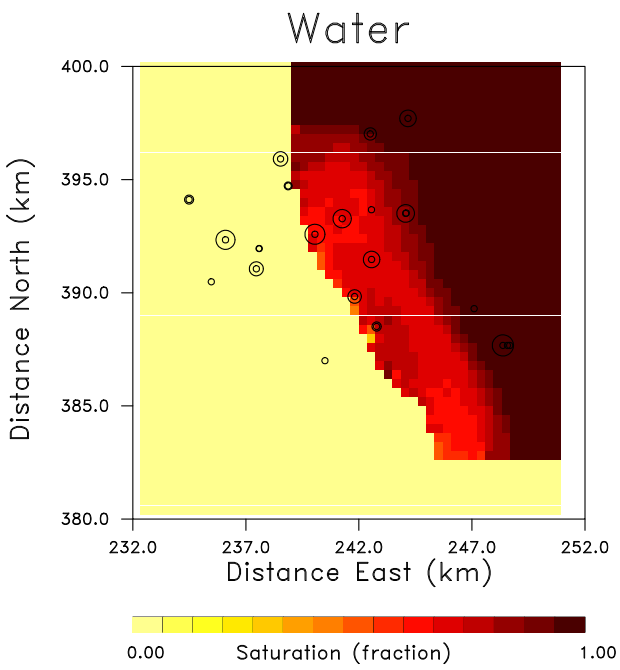

Water
Distance North (km)
400.0
395.0
390.0
385.0
380.0
232.0
237.0
242.0
247.0
252.0
Distance East (km)
0.00
Saturation (fraction)
1.00

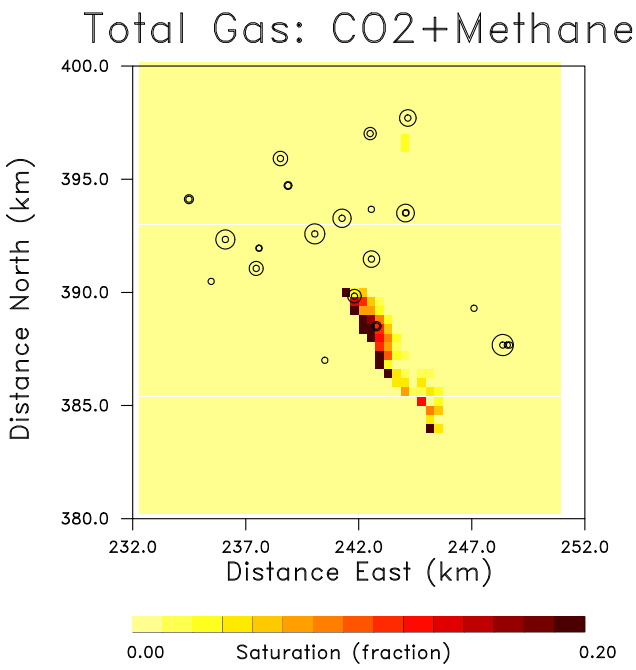

Total Gas: CO2+Methane
Distance North (km)
400.0
395.0
390.0
385.0
380.0
232.0
237.0
242.0
247.0
252.0
Distance East (km)
0.00
Saturation (fraction)
0.20

- Fluid saturations from simulations by Seyyed Hosseini of Texas Bureau of Economic Geology

2008







Accomplishments to date

- Estimated seismic time-shifts from 4D data

- Calculated seismic velocity variations due to changes in fluid phases from compositional modeling.

- Compared velocity changes to observed time-shifts and seismic amplitude changes

Conclusions: status

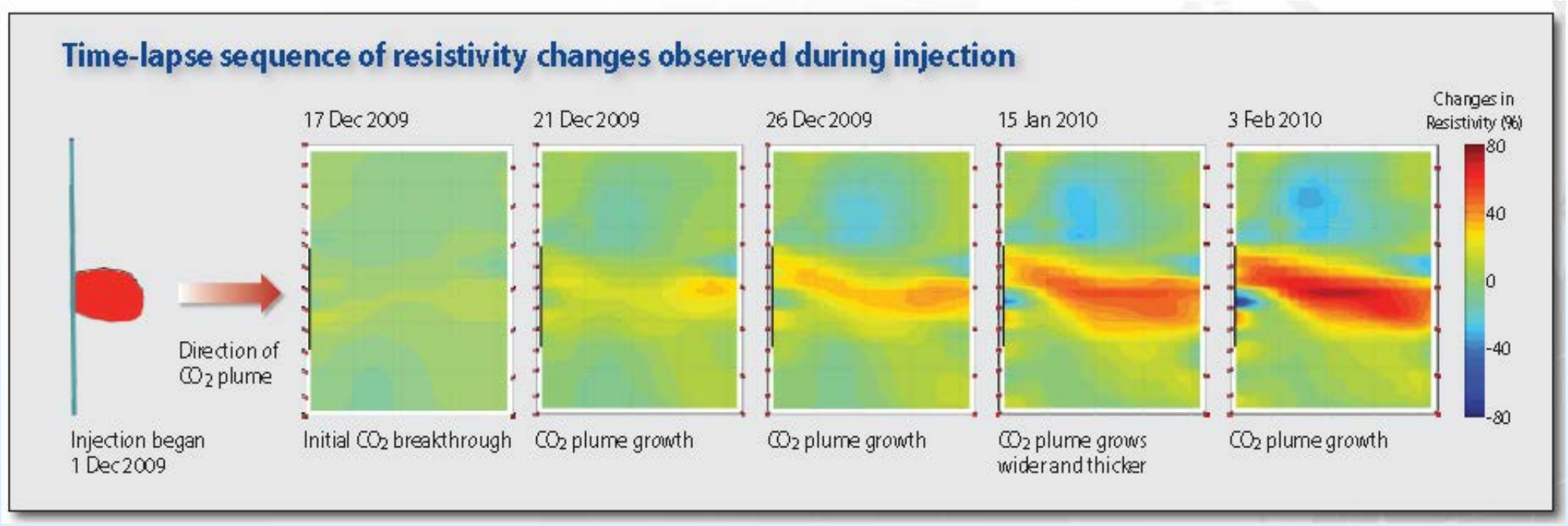
- Seismic velocity changes depend upon all fluid saturations.

- Oil saturation has a significant influence on the velocity changes due to injected carbon dioxide.

- Reservoir simulation results are compatible with observed seismic reflection data and time shifts.

LLNL Electrical Resistance Tomography- changes in response with saturation

F1 **F2** **F3**

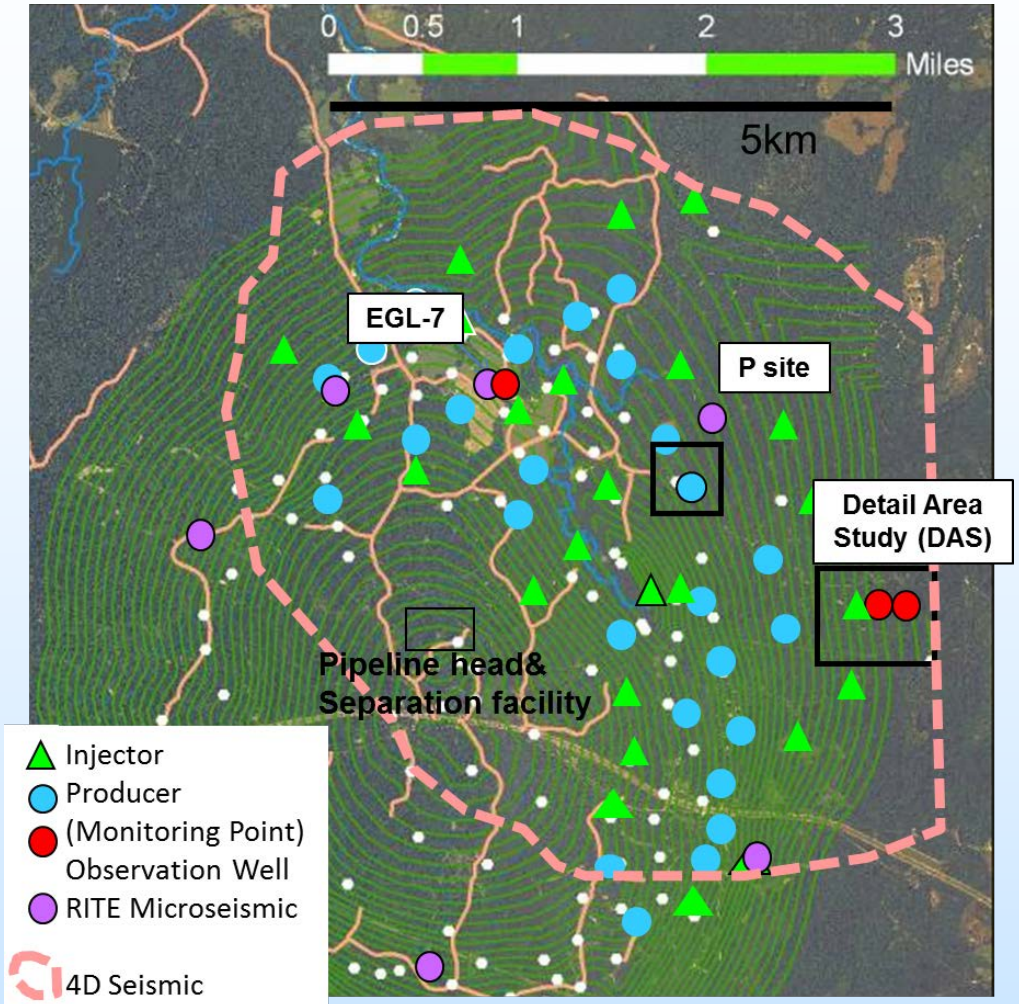


Additional work planned to extend imaging to 2015

Lawrence Livermore National Laboratory

C. Carrigan, X Yang, LLNL
D. LaBrecque Multi-Phase Technologies

MVA Approach



MVA Approach

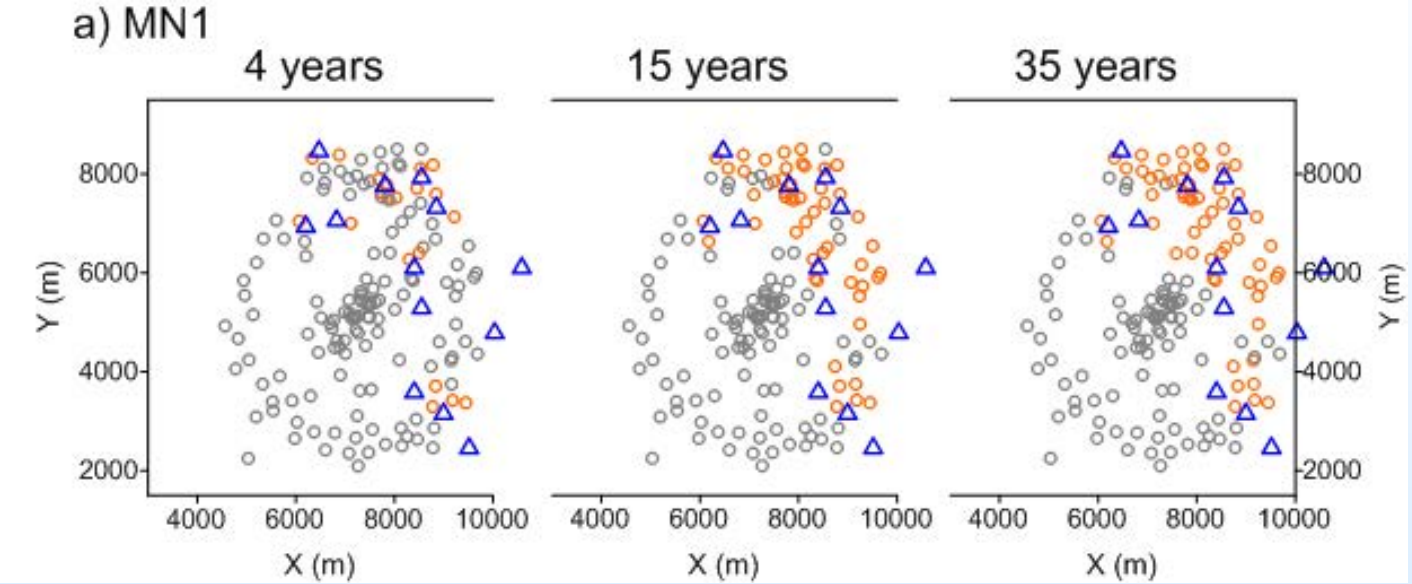
.

Area tested	Whole plume	Focus study
Atmosphere	Not tested	Not tested
Soil gas	Active and P&A well pads	“P site” methodology assessment
Groundwater	Monitoring well at each injector	EGL-7 UM test well, Push-pull test
Shallow production	Not tested	Not tested
AZMI	Not tested	DAS pressure EGL 7 press + fluids
Geomechanics	RITE micro seismic study	GMT (failed)
Injection zone	Geochemistry breakthrough	DAS multi-well multi-tool array

Groundwater Monitoring Network Efficiency

$$ME = \frac{W^d}{W^T}$$

- 20/151=0.13 by 4 years
- 50/151=0.33 by 15 years
- 58/151=0.38 by 35 years



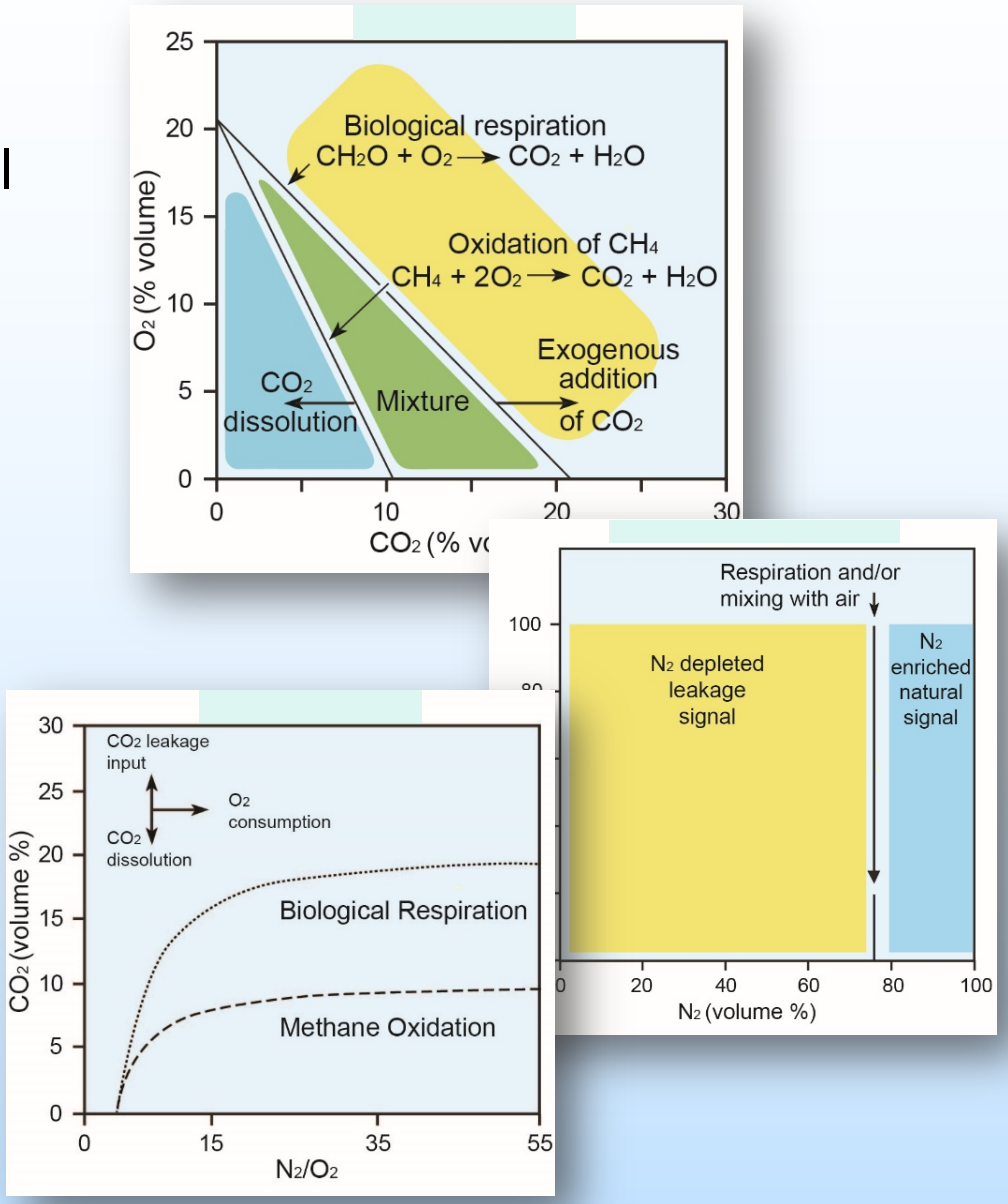
CO_2 leakage from a P&A well is detected by a monitoring net work if change in DIC, dissolved CO_2, or pH in any one of wells of the monitoring network is higher than one standard deviation of the groundwater chemistry data collected in the shallow aquifer over the last 6 years.

Changbing Yang

Process-Based Soil Gas Monitoring

- No need for years of background measurements.
- Promptly identifies leakage signal over background noise.
- Uses simple gas ratios

  (CO_2, CH_4, N_2, O_2)
- Can discern many CO_2 sources and sinks
  - Biologic respiration
  - CO_2 dissolution
  - Oxidation of CH_4 into CO_2 (Important at CCUS sites)
  - Influx air into sediments
  - CO_2 leakage



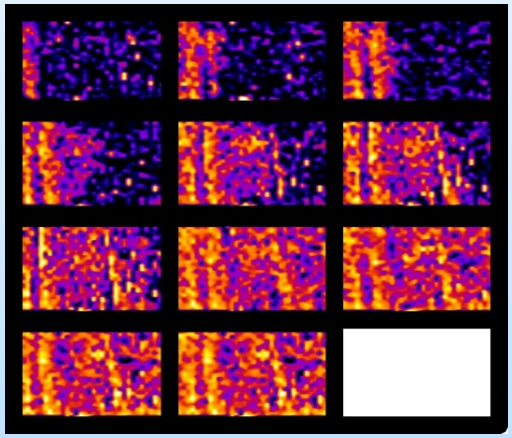
Katherine Romanak BEG

Major Technical Accomplishments

- Multiphysics CO_2 plume detection
  - Surface 4-D; Azimuthal VSP, cross well, ERT, Pulsed neutron, fiber-optic thermal, sonic logs, PNC logs
  - Limits evaluated (depth, gas)
- In-zone and Above-zone pressure method validation
  - Casing deployed BHP with real-time readout
- Minimal geochemical change in-zone, geomechanical softening
- Non-detect of microseismicity by RITE at >1000 psi pressure increase
- Reservoir response to heterogeneity – non-linear breakthrough
- Groundwater sensitivity assessment
  - Value of DIC, sensitivity to carbonate in rock matrix
  - Value for incident or allegation
- Process-based soil gas
  - Reduced sensitivity to environmental fluctuation, not dependent on baseline. Value of attribution

Rate of Progress

- All elements have been completed on plan
  - (three years injection + three “post closure”)
- Under budget
  - Major saving was not needing to purchase CO_2 to meet the project goal; commercial injection was high during early project stages
- Emphasis on publication and technical outreach
  - 91 technical papers published 2009-2017
- Leveraged by data-sharing



Coreflood micro CT J Ajo-Franklin LBNL

Potential Leakage Risks Considered

- Formal leakage/seepage risk assessment under Certification Framework (LBNL)
  - Identified wells as highest risk leakage points
    - Most wells are P&A
- Responses
  - Groundwater and soil gas measured at all injectors
    - Detailed measurements at P-site methane and CO_2 anomaly
  - AZMI pressure
    - Detection and separation of fluid flow from geomechanical response
    - Improved deployment at commercial sites

Potential Business/Project Risks Considered

- Quality of collaboration with operator
  - Details specified in contract
  - Offset by reduced risk in CO_2 supply, permitting, public acceptance
- Co-ordination with commercial activities
  - Upfront modeling of impacts
    - Impact of gas cap
    - Impact of production
  - Strong initial push toward data collection pre-production phase
  - Focus on data collection in dedicated site in water leg
  - Strong co-ordination with operations team
  - No closure phase planned

Plan to Complete

- No post- injection period possible
- Used three years after end of CO_2 purchase for multiple tasks:
  - Support increased DOE interest in EOR, e.g. supplied data to NETL economic model; NCNO projects
  - Geothermal CO_2 feasibility test (Freifeld, LBNL)
  - Harmonic pulse testing (Sun, BEG)
  - RITE microseismic
- Extensive publication and analysis
- Wide collaboration

Overall accomplishments-Key findings

- Early large volume storage project to lead of RCSP effort
- Advancement of multiple monitoring tools
  - AZMI
  - Process-based soil gas method
  - Deep ERT
- Novel scientific findings
  - AZMI geomechanical response
  - Non-linear pressure response
  - Advanced groundwater geochemical surveillance
  - No detectable microseismicity to >1000 psi pressure increase
  - Limitations of 4-D seismic 3 Km depth and in presence of methane

Lessons Learned (where is improvement needed?)

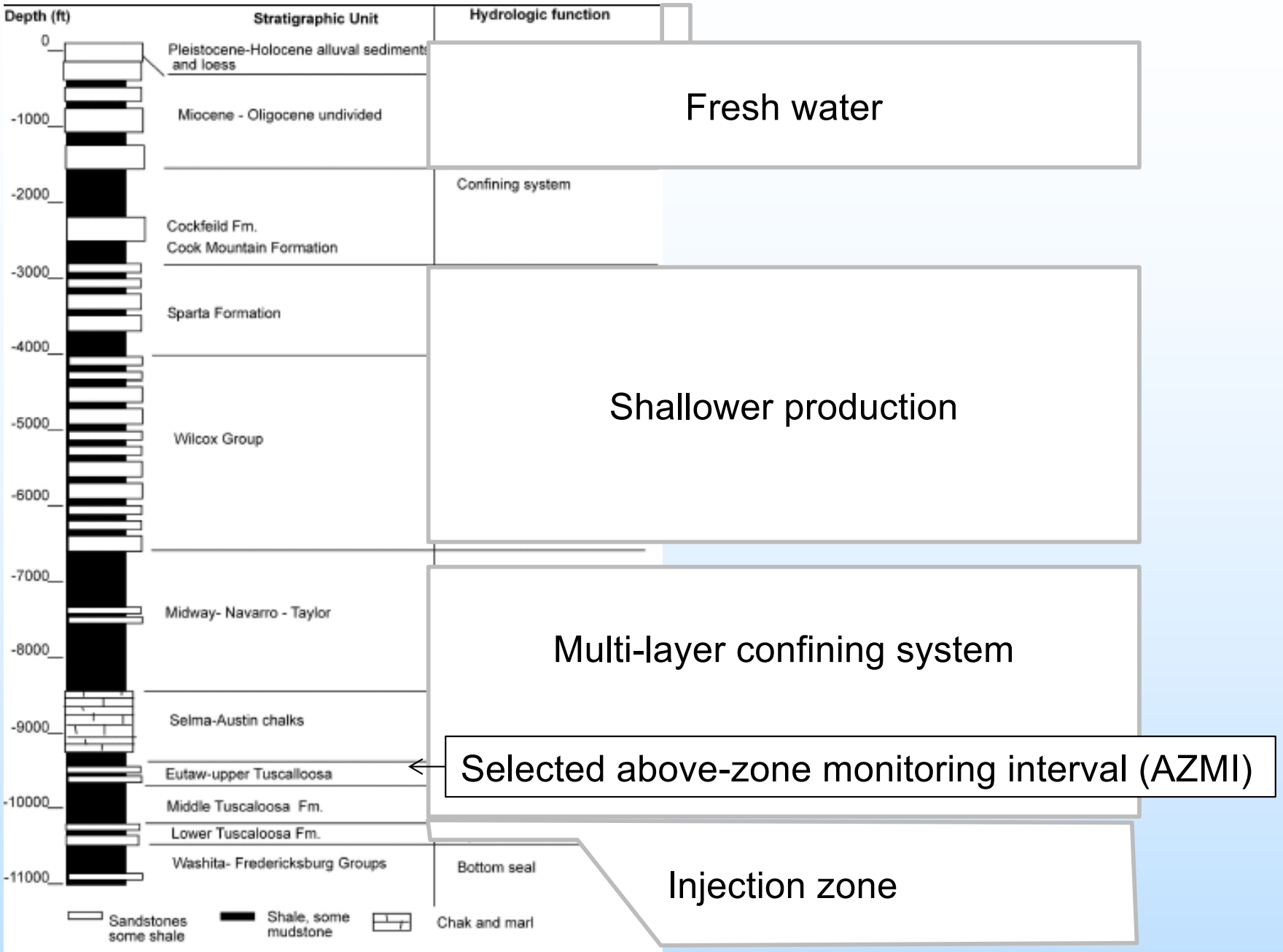
- Simplified AZMI completions
- Improved high temperature and pressure equipment
- Simplified ERT deep installation
- Remote tools for water and soil gas surveillance
- Maturation of monitoring design planning
  - Interaction with international community

Future Plans

- Widespread application of results via publications and applications
- Fluid flow modeling
- Forward modeling of seismic response
- Improved ERT methods
- Public release of technology transfers to PetraNova and Air Products commercial projects
- International Standard for accounting for CO_2 stored in associated with EOR
- Technology transfer and implementation vis Gulf Coast Carbon SAFE

- Questions?

Characterization of Overburden



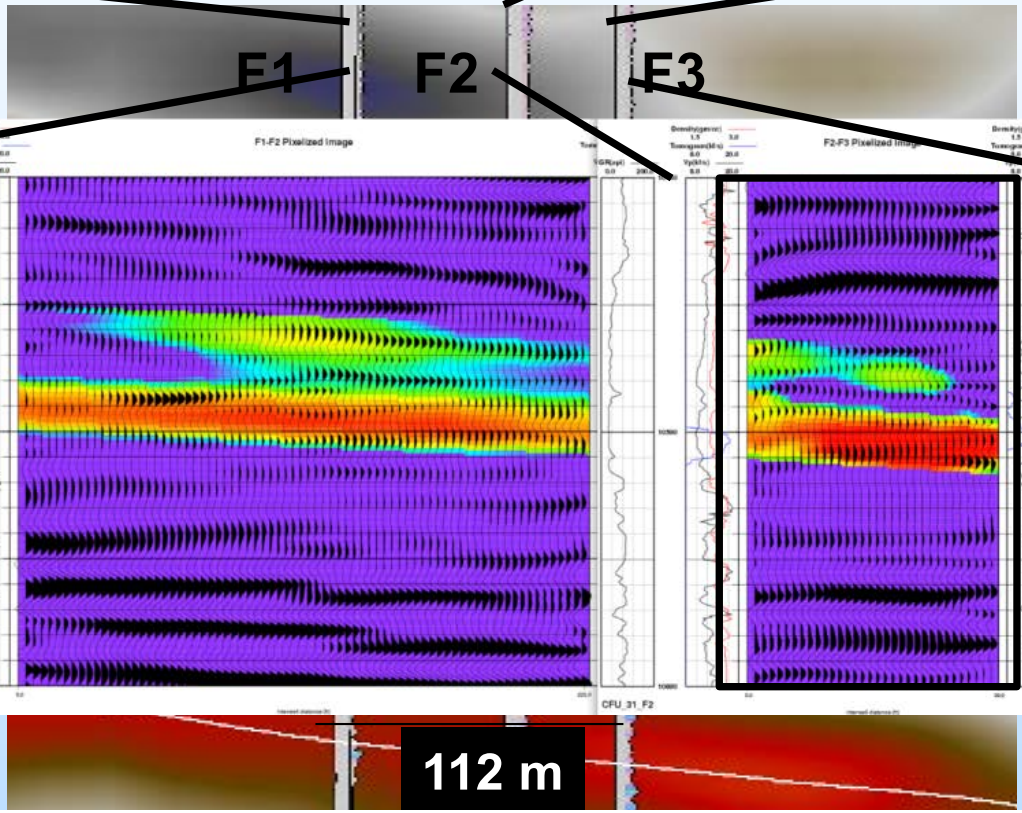
Detailed Area Study (DAS)



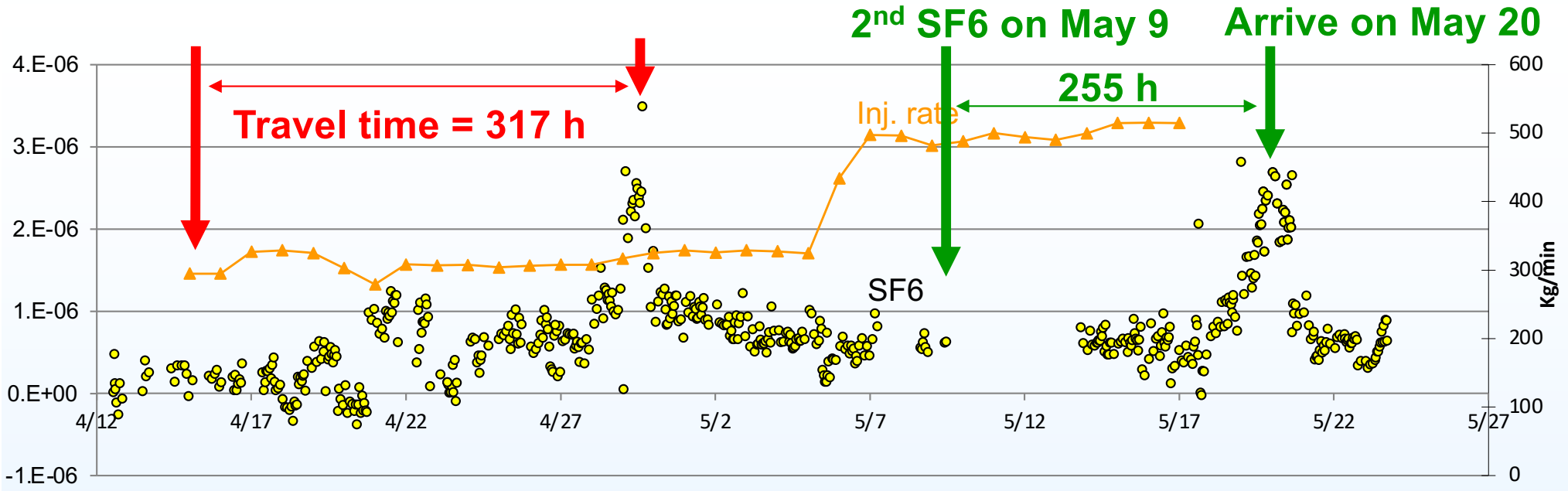
Closely spaced well array to examine flow in complex reservoir

Tuscaloosa D-E reservoir

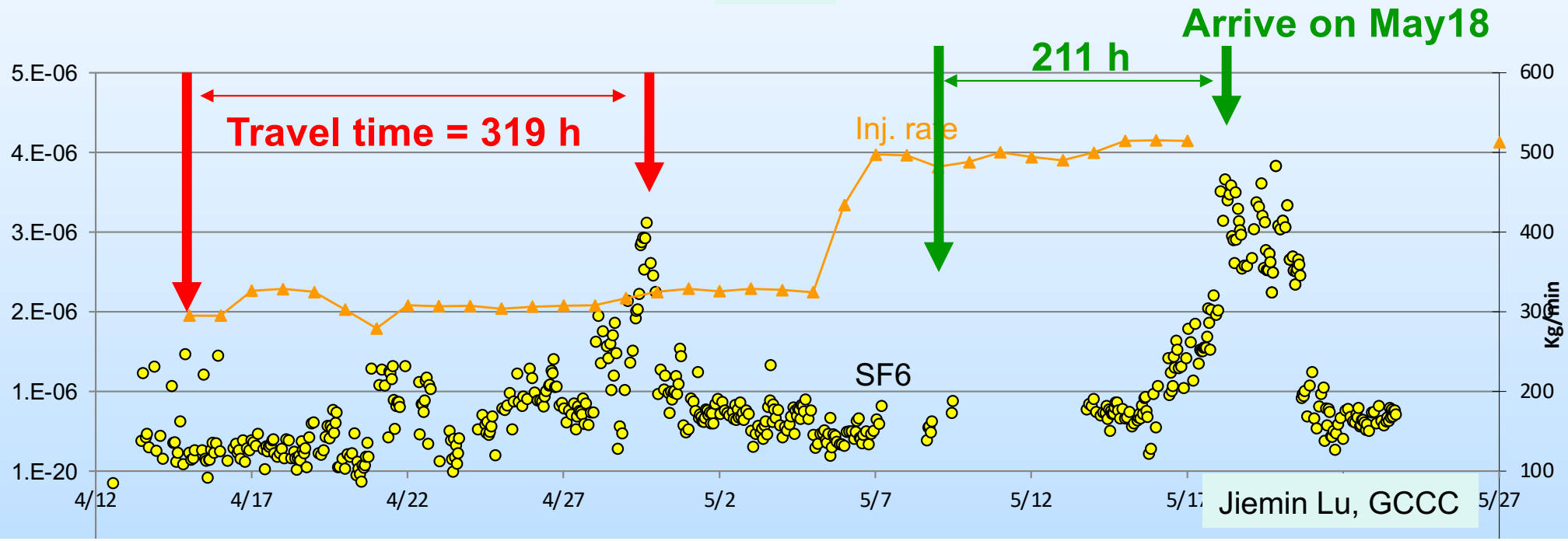
Petrel model Tip Meckel
Time-lapse cross well
Schlumberger



CFU31F-2, 68 m away from injector SF6



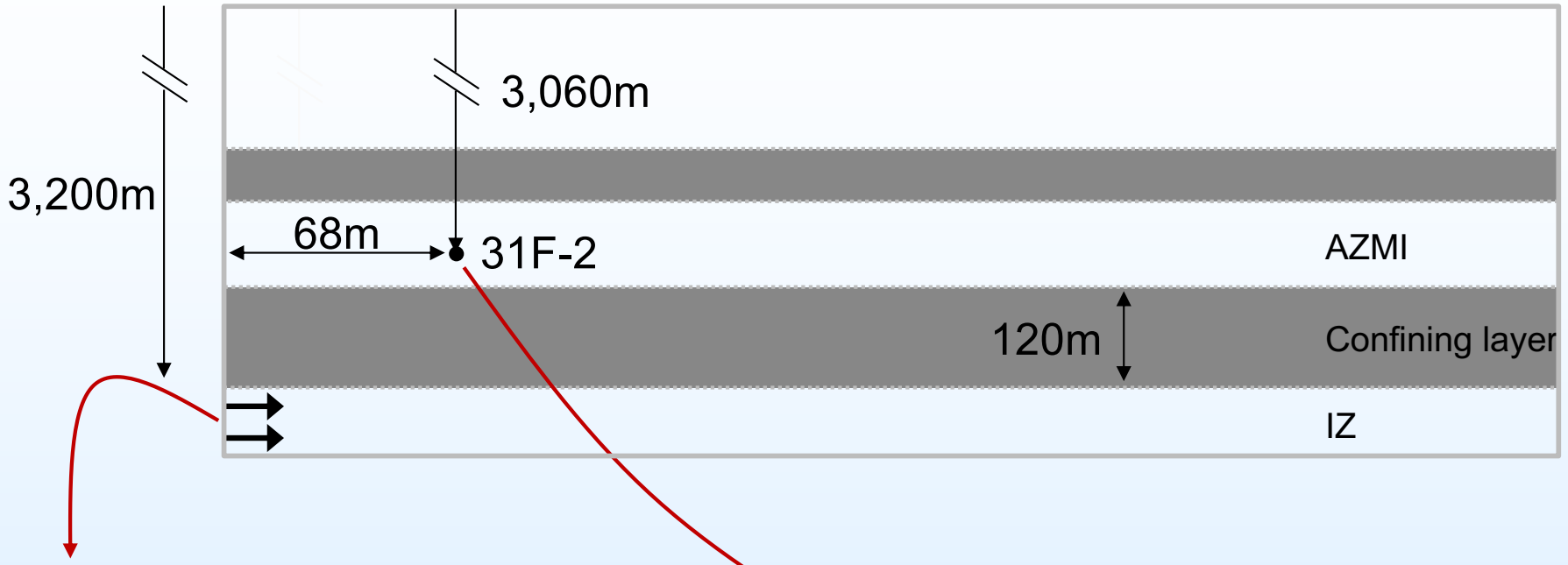
CFU31F-3, 112 m away from injector SF6

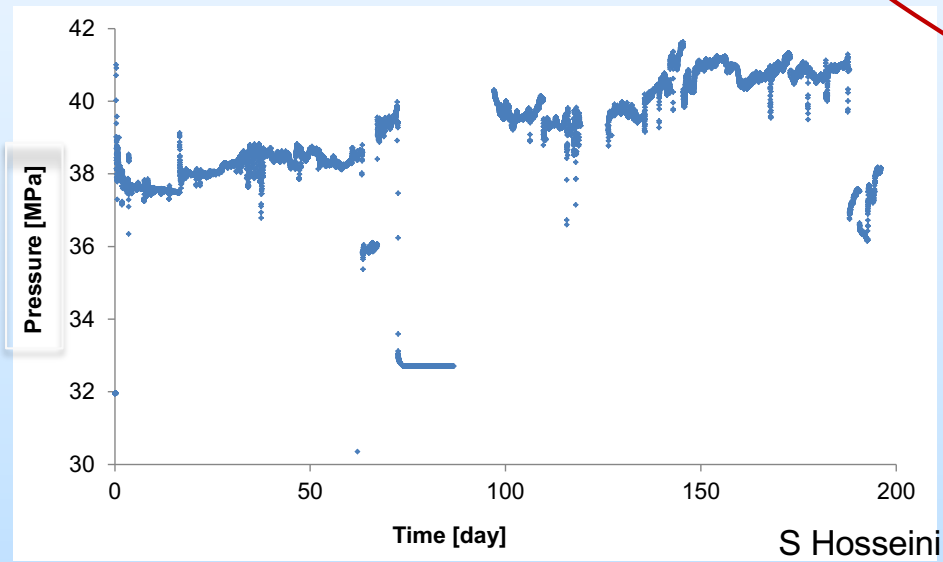


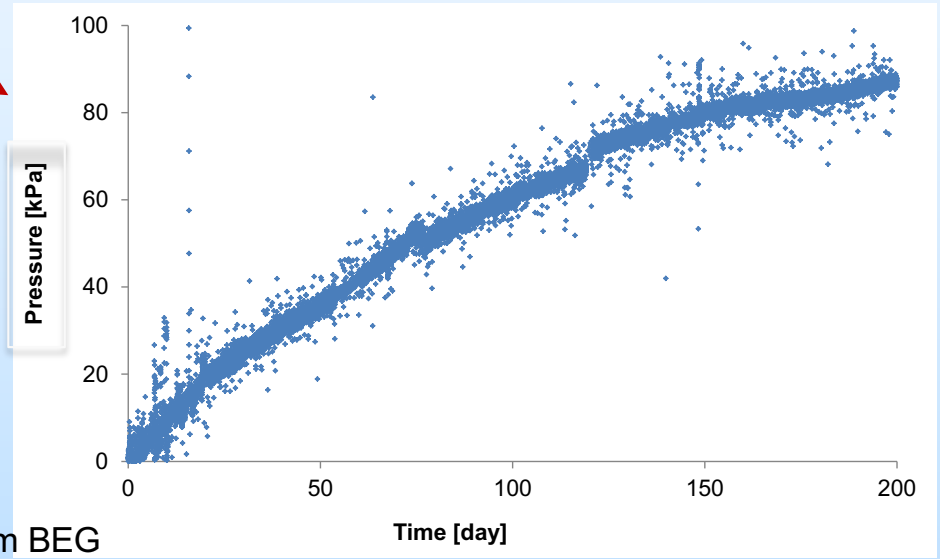
Jiemin Lu, GCCC

Field Observation

(not scaled)



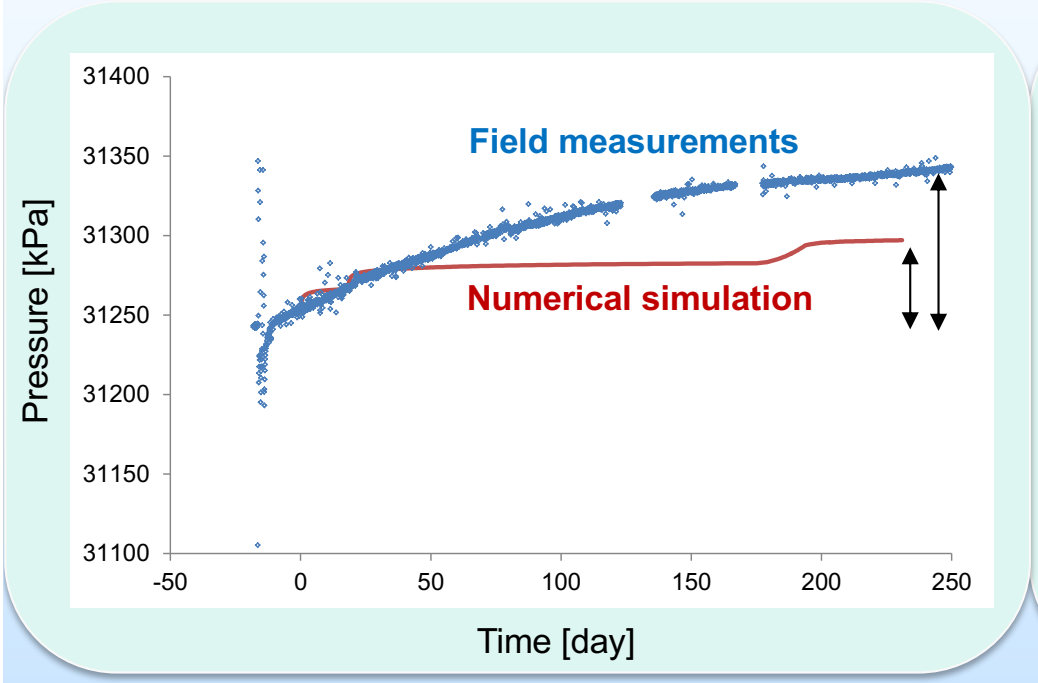




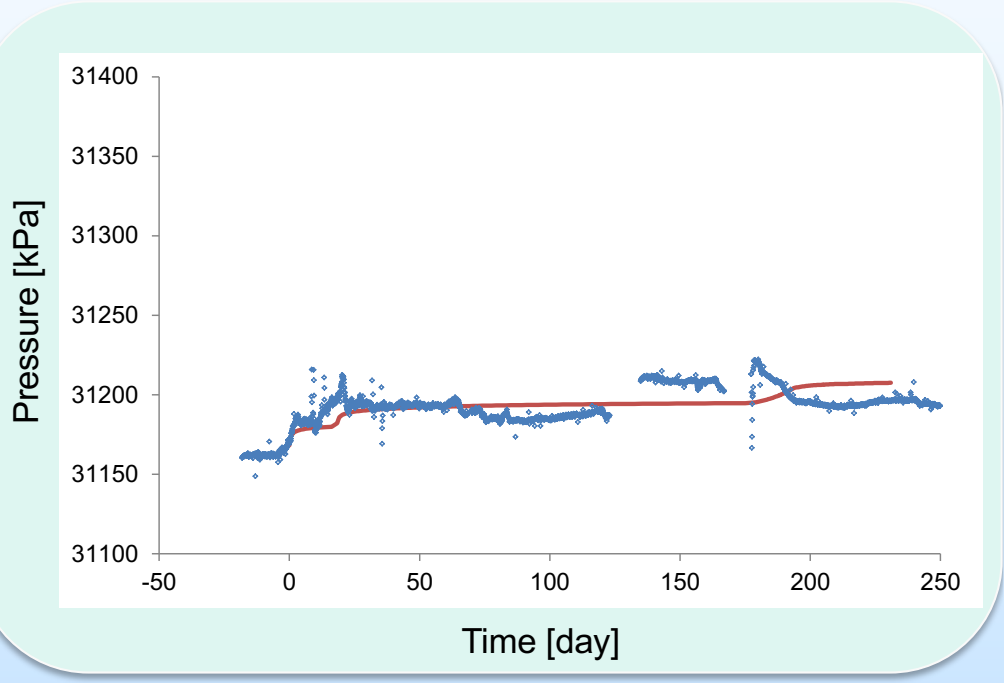
S Hosseini, S. Kim BEG

Matching pressure in AZMI

- 31 F2 Mon. Well: Pressure



- 31 F3 Mon. Well: Pressure

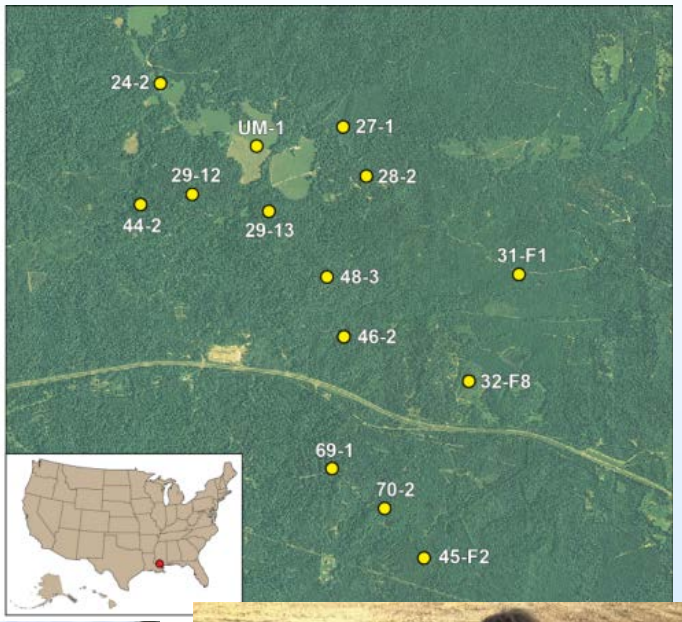


Groundwater at the Cranfield Site: Sampling

- More than 12 field campaigns since 2008
- ~ 130 groundwater samples collected for chemical analysis of

  Cations: Ag, Al, As, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Pb, Se, Zn
  Anions: F^-, Cl^-, SO_4^{2-}, Br^-, NO_3^-, PO_4^{3-}
  TOC, TIC, pH, Alkalinity, VOC, $\delta C13$

  On-site: pH, temperature, alkalinity, water level



- ~10 samples for noble gases
- ~20 groundwater samples for dissolved CH_4

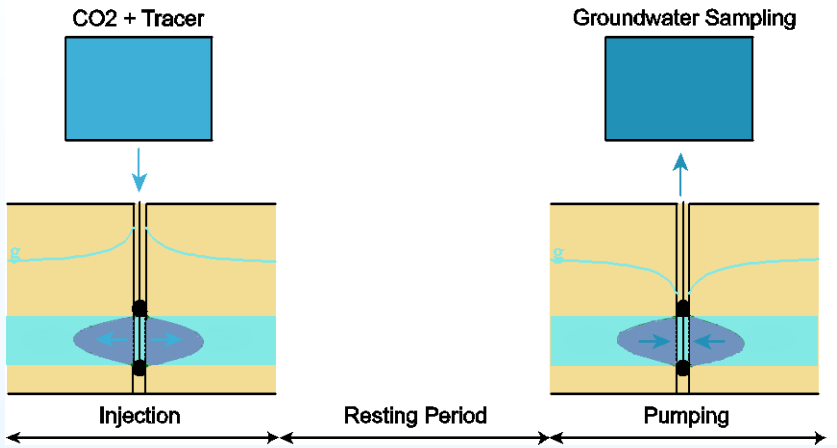




C. Yang, BEG

Groundwater at the Cranfield Site Single-Well Push-Pull Test

- Maximum concentrations of trace metals observed, such as As and Pb, are much less than the EPA contamination levels;
- Single well push-pull test appears to be a convenient field controlled-release test for assessing potential impacts of CO_2 leakage on drinking groundwater resources;



Results were summarized in the following paper

International Journal of Greenhouse Gas Control 18 (2013) 375–387

Contents lists available at ScienceDirect

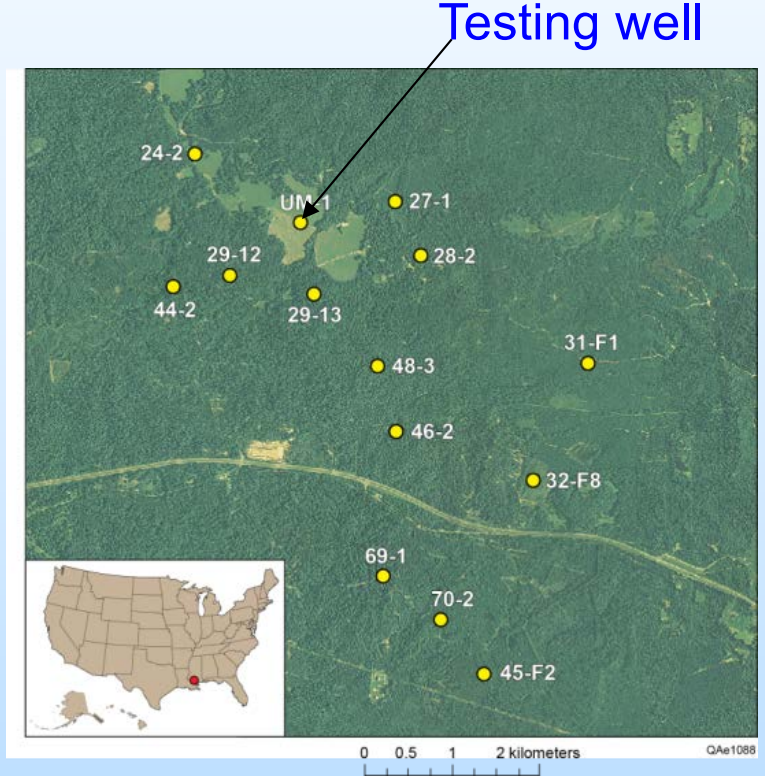
International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Single-well push–pull test for assessing potential impacts of CO_2 leakage on groundwater quality in a shallow Gulf Coast aquifer in Cranfield, Mississippi

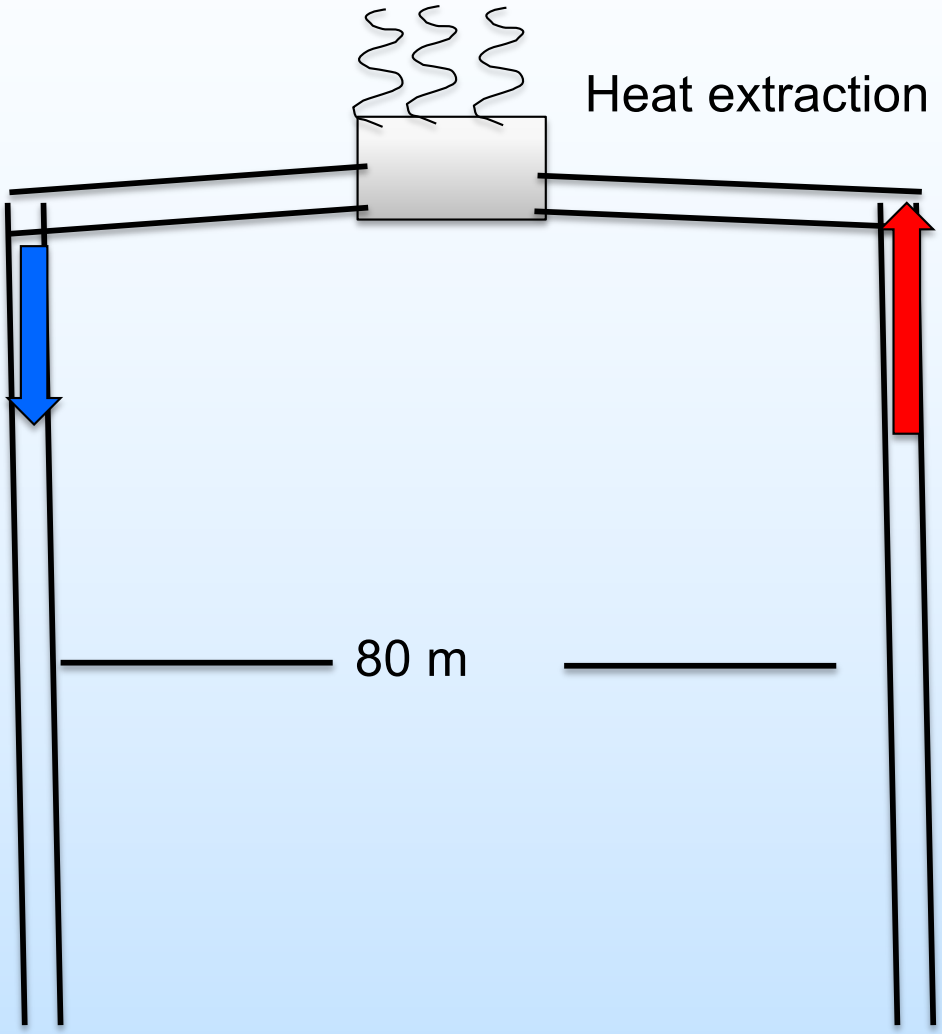
Changbing Yang[a,*], Patrick J. Mickler[a], Robert Reedy[a], Bridget R. Scanlon[a], Katherine D. Romanak[a], Jean-Philippe Nicot[a], Susan D. Hovorka[a], Ramon H. Trevino[a], Toti Larson[b]

[a] Bureau of Economic Geology, The University of Texas at Austin, 10100 Burnet Road, Bldg 130, Austin, TX 78758, United States
[b] Department of Geological Sciences, The University of Texas at Austin, 2275 Speedway Stop C9000, Austin, TX 78712-1722, United States



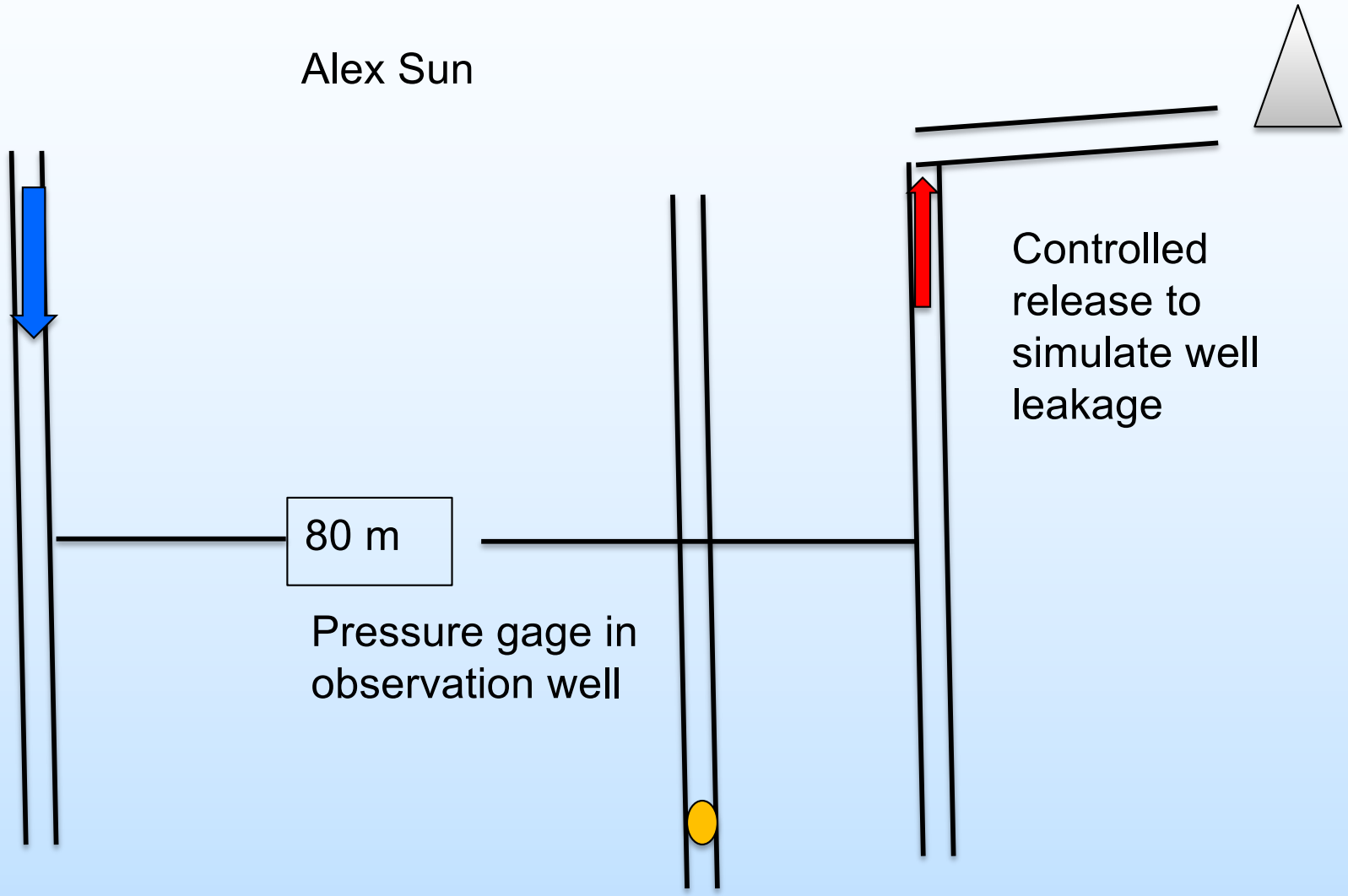
C. Yang, BEG

Thermosyphon (Barry Freifeld)

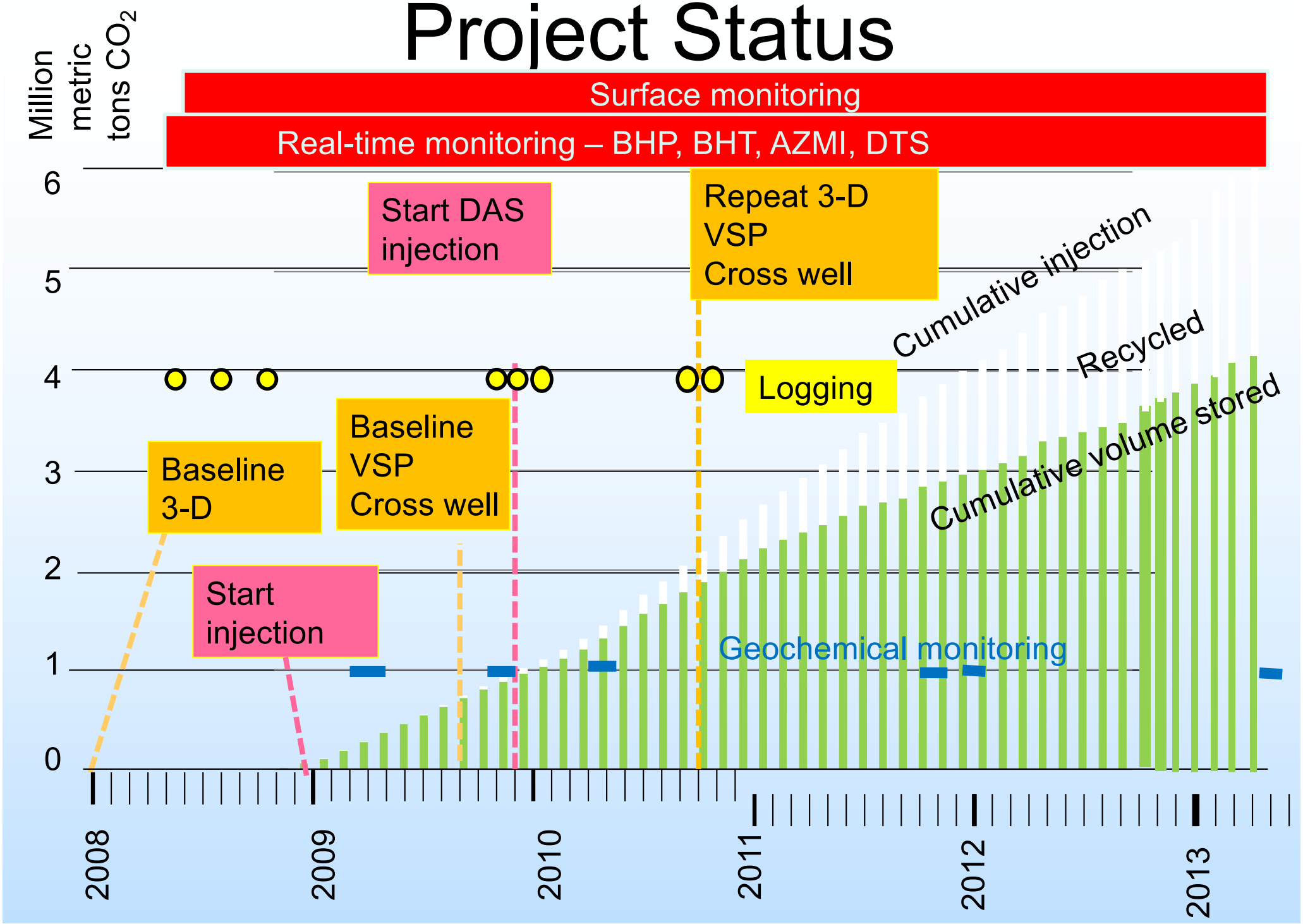


DOE program combining CCSU and geothermal; LBNL lead

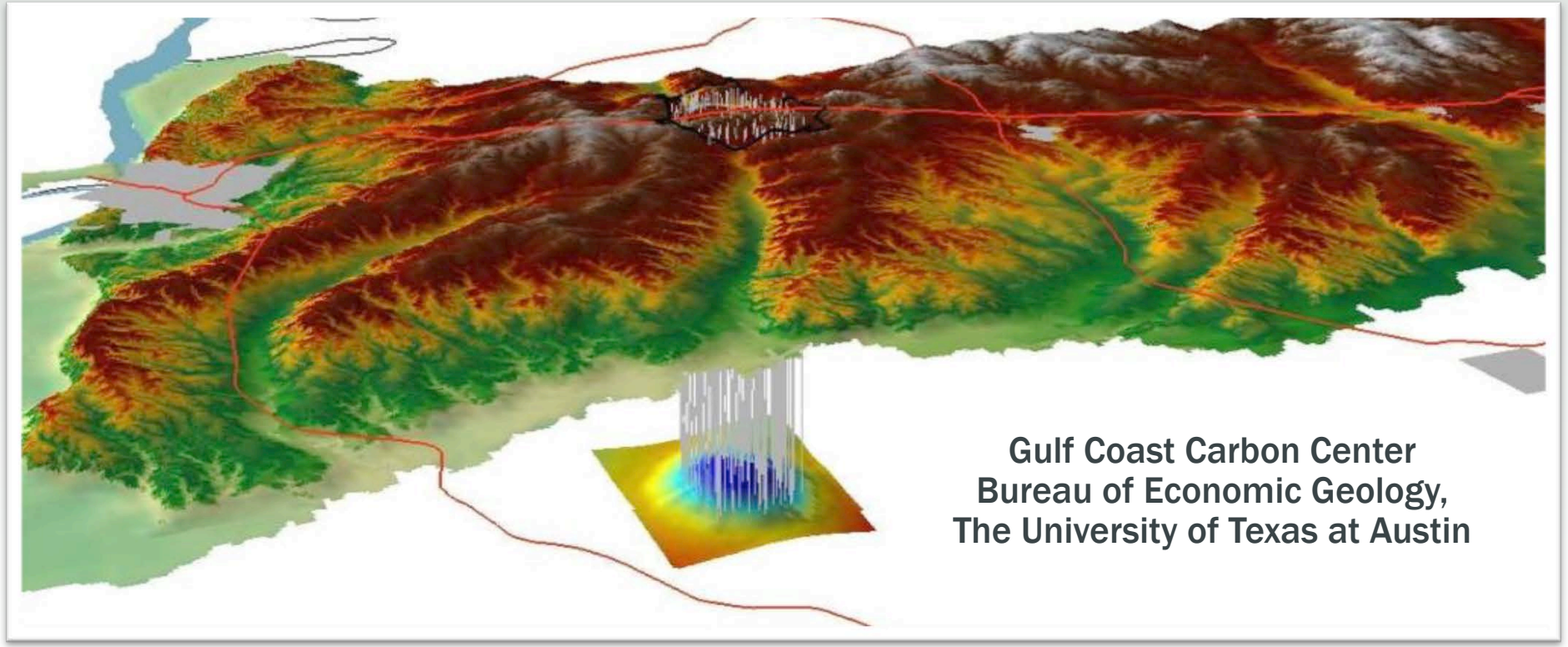
Harmonic Pulse testing for Leakage (PIDAS)



Project Status



SECARB Phase III
Cranfield Project (Early Test)



Presented by Katherine Romanak
March 8, 2018
Atlanta Georgia

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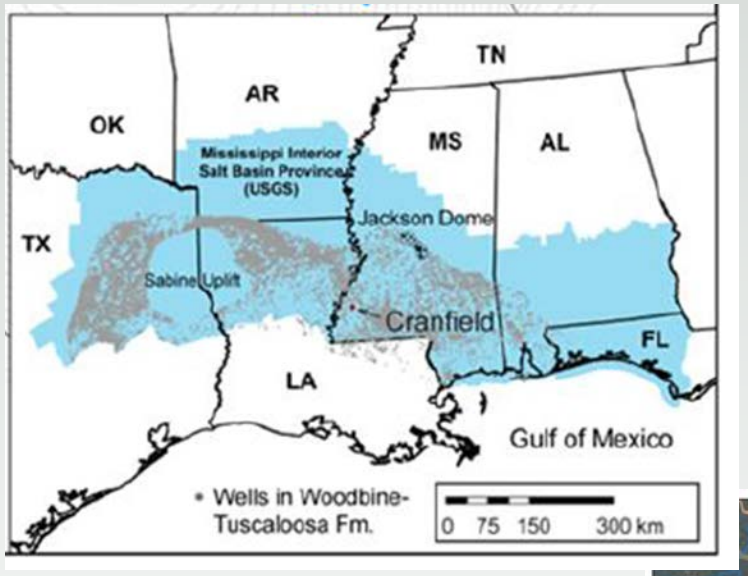
Bureau of Economic Geology

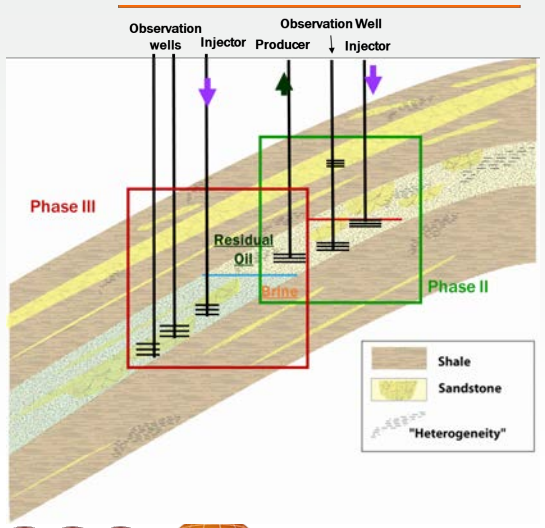
Susan Hovorka,
Principle Investigator

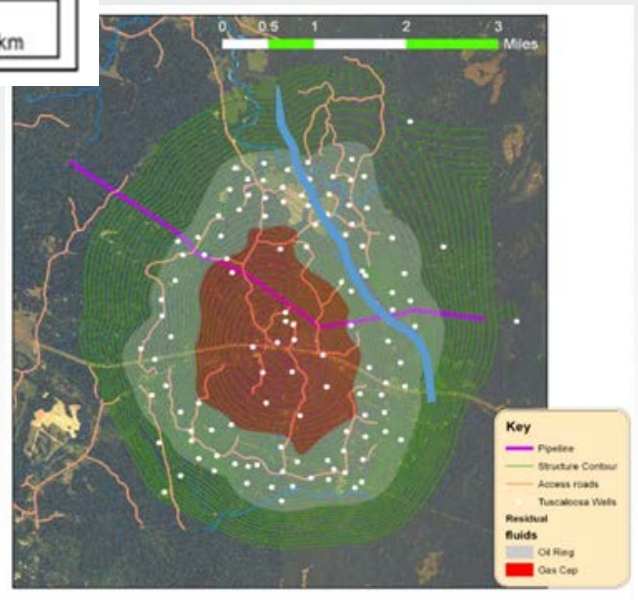
Early Test at Cranfield

- One of the earlier storage projects to lead off RCSP effort
- Data collection and characterization began in 2008
- 25 institutions collaborating
- As of April 2015, project metrics and field activities completed
- Current focus making Cranfield project knowledge…
  - **Commercial** via engagement in other projects.
  - **Impactful** through developing major conceptual advances
  - **Practical** through knowledge sharing

Cranfield Setting







- Near Natchez Mississippi
- Clastic, fluvial Tuscaloosa Fm
- Reservoir 10,000 ft deep
- Apex of 4-way closed anticline
- Gas cap and oil ring
- Productive during 1940s and 50s
- Stacked storage focus (EOR and Brine)

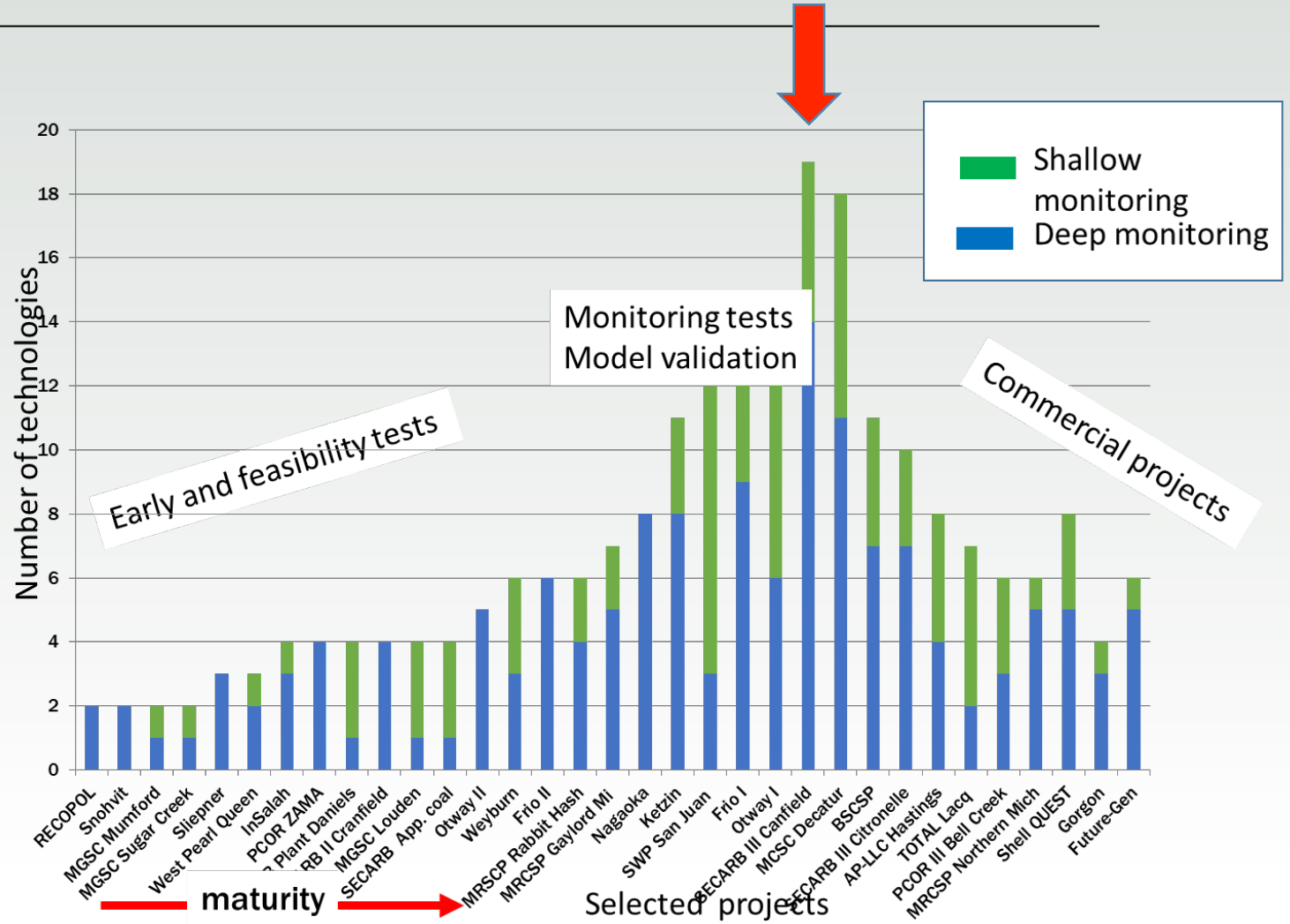
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Hosseini et al., 2013

Commercialization of Monitoring

- Measurement, monitoring and verification
  - Deploy as many tools, analysis methods, and models as possible
  - Tool testing and optimization

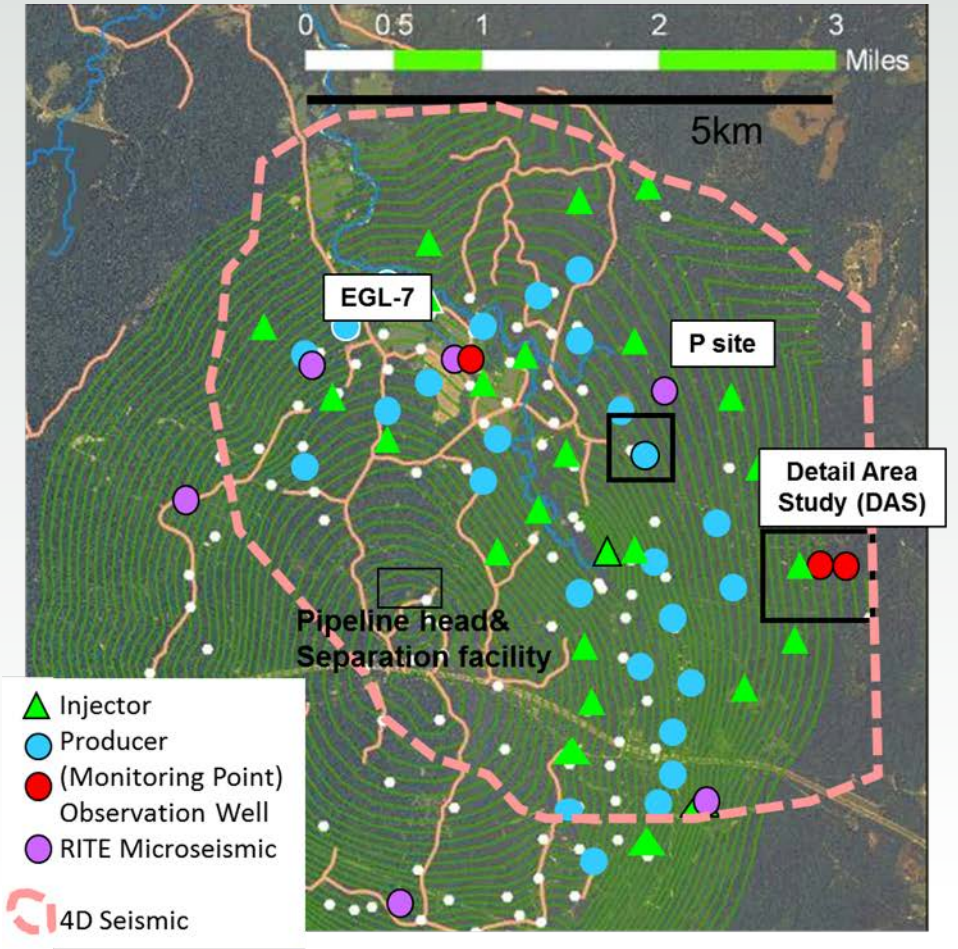


Monitoring Overview



Monitoring in every subsurface zone

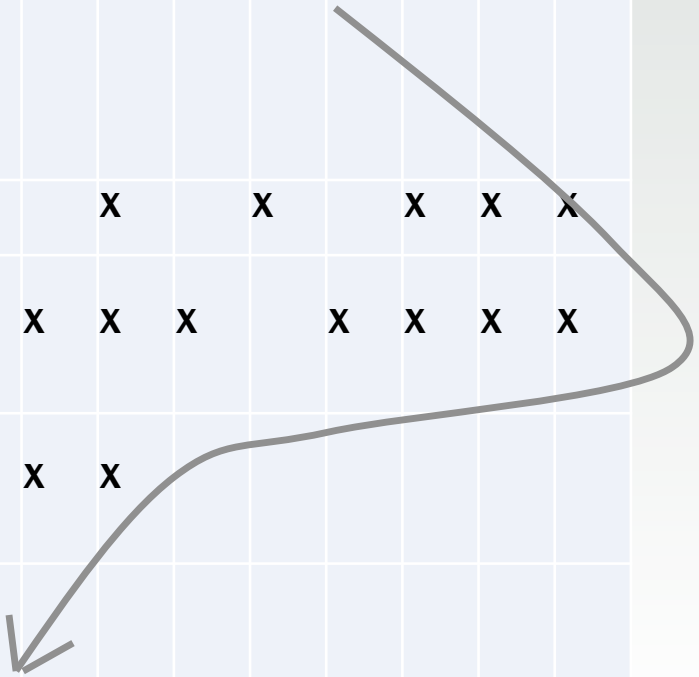
- EGL7 observation well (IZ and AZMI)
- DAS -
  - 1 injector and two closely spaced observation wells
  - below the oil–water interface
  - assess fluid flow at the inter-well scale.
- Fresh-water system – domestic wells and water supply wells
- Vadose zone – P-site



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Commercialization of Monitoring

	Mass balance	soil gas	groundwater chem	AZMI chem	AZMI pressure	3D seismic	VSP	ERT	EM	gravity	u-tube	IZ chem	tracers
Frio	x	x	x	x			x		x		x	x	x
SECARB Early test at Cranfield	x	x	x	x	x	x	x	x		x	x	x	x
Industrial capture Air Products -Hastings	x	x	x		x	x	x						
Clean Coal Power initiative Petra Nova/ West Ranch	x	x	x	x	x								



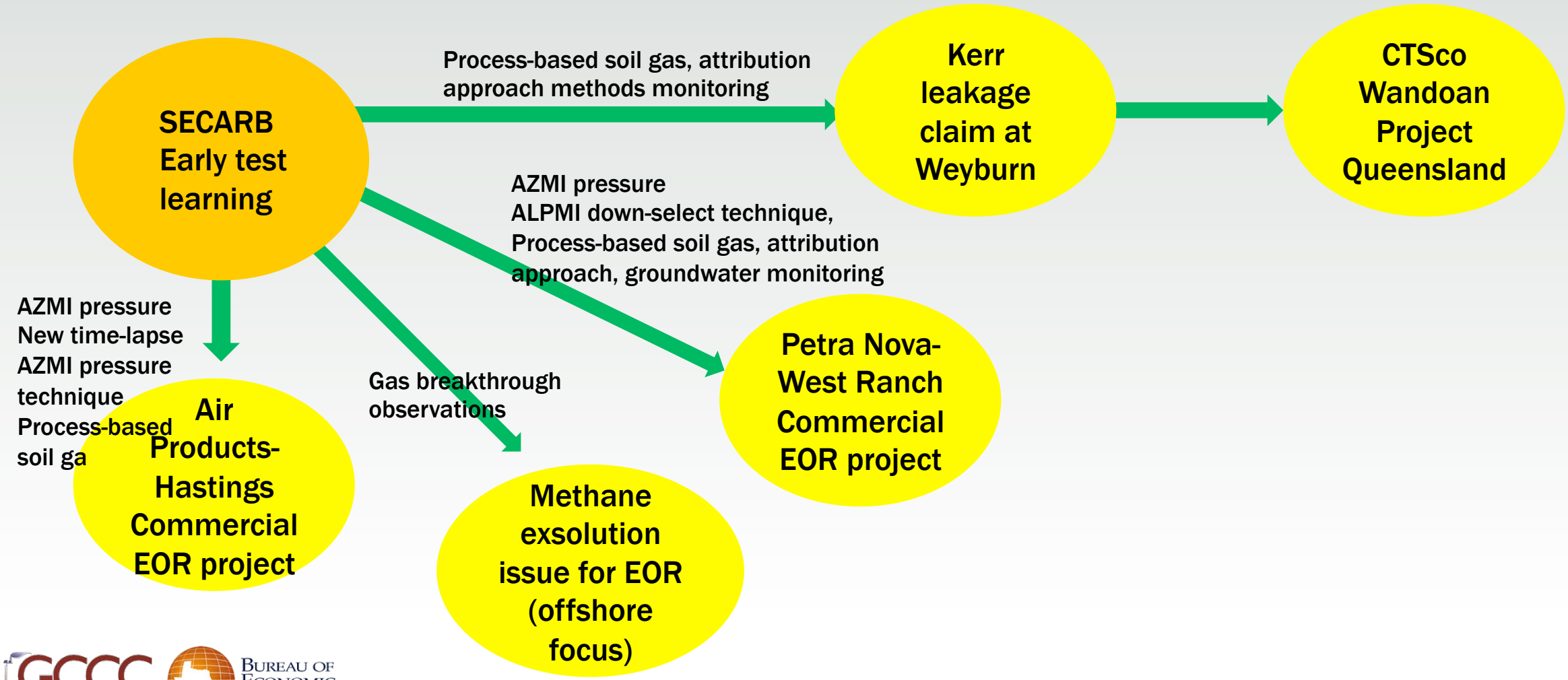
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Notable developments-applications

- Early Test developed monitoring approaches for later commercial projects
  - Assessment of Low Probability Material Impacts (ALPMI)
  - Above-Zone Monitoring Interval (AZMI)
  - Attribution and Process-based soil gas method –
  - CH_4 limiting CO_2-EOR
  - Effectiveness limiting of groundwater surveillance
  - Easi-tool for capacity assessment
  - Net Carbon Negative Oil
- Published and propagated techniques for widespread application

Technology transfer from SECARB early test to other projects



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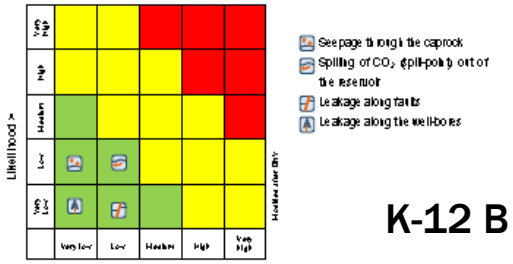
ALPMI - Assessment of Low-Probability Material Impacts

Susan Hovorka

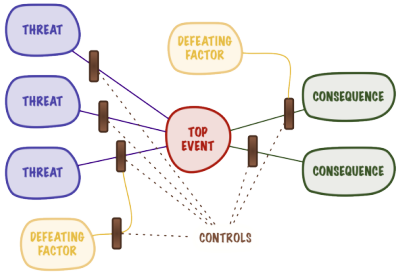
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Linking risk assessment with monitoring

Risk Assessment method

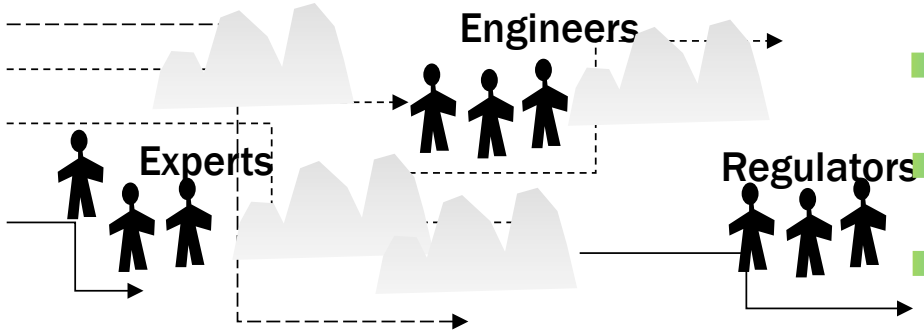


K-12 B (CO2CARE)



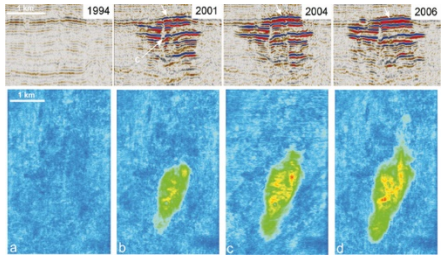
Bow Tie

Process is cloudy or obscured

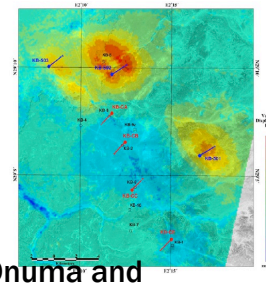


Process of designing and selecting monitoring can be complex, conducted without documented process, non-linear and therefore difficult to duplicate or justify

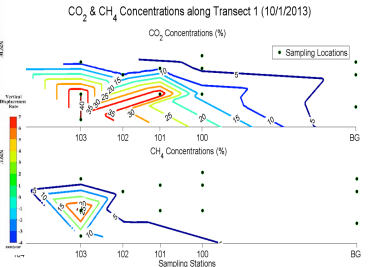
Select monitoring systems



Chadwick BGS



Onuma and Ohkawa, 2009



Romanak

ALPMI method

Assessment of Low Probability Material Impact (ALPMI)

- Part 1: Describing *material impact** quantitatively
- Part 2: Sensitivity of monitoring strategy to *material impact**

- Monitoring tool selection that is reproducible and transparent.
- Makes explicit why different monitoring is selected for different sites and for different business and stakeholder settings

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* Examples next slides

ALPMI Workflow

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

Model material impact scenarios

Explicitly model unacceptable outcomes showing leakage cases.

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.

Select monitoring tools that can detect these signals at required sensitivity

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

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.”

Deploy tools, collect and analyze data

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

Report if material impact did/did not occur

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

Part 1: Describing material impact quantitatively - examples (random)

- Loss of CO_2 at a rate greater than 10,000 tones per year for a period of more than 10 years @ 80% confidence
- >5% probability of earthquake > magnitude 4 within 100 years
- Pressure trend that will exceed calculation mechanical stability prior to project completion
- Plume migration such that location of saturation of >5% pore volume CO_2 at stabilization is within a footprint (shown on a map)

ALPMI part 2: Assess sensitivity of monitoring strategy to material impact

Essential to forward model impact

1. **Create material impact scenarios**

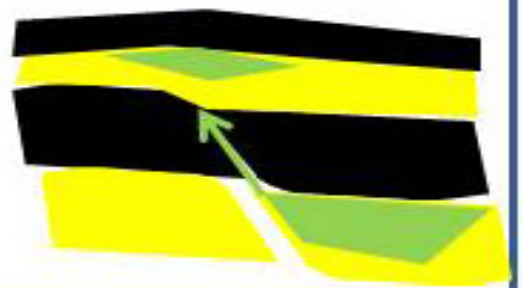
   e.g. for CO_2 leakage or change in pore pressure that would increase seismic risk

2. **Evaluate sensitivity of instruments, spacing, frequency of data collection, other statistical measures against scenarios.**

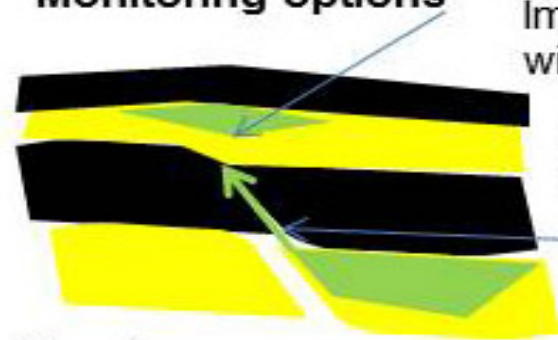
Characterization Uncertainty: Fault-seal?



ALPMI

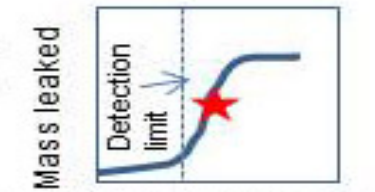


Monitoring options

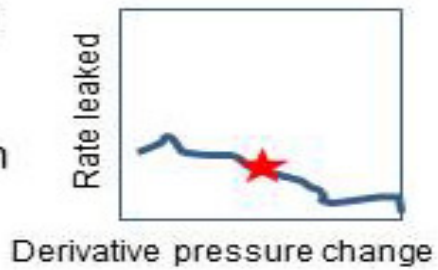


Test Sensitivity of Monitoring Options

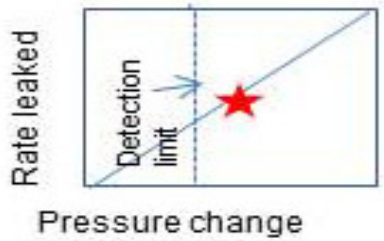
Image free-phase leaked CO_2 with surface 4-D



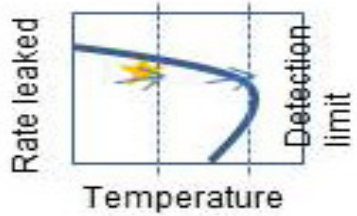
Change in rate pressure increase in reservoir



Measure change in pressure AZMI



Temperature change along fault



Set triggers, stage monitoring options

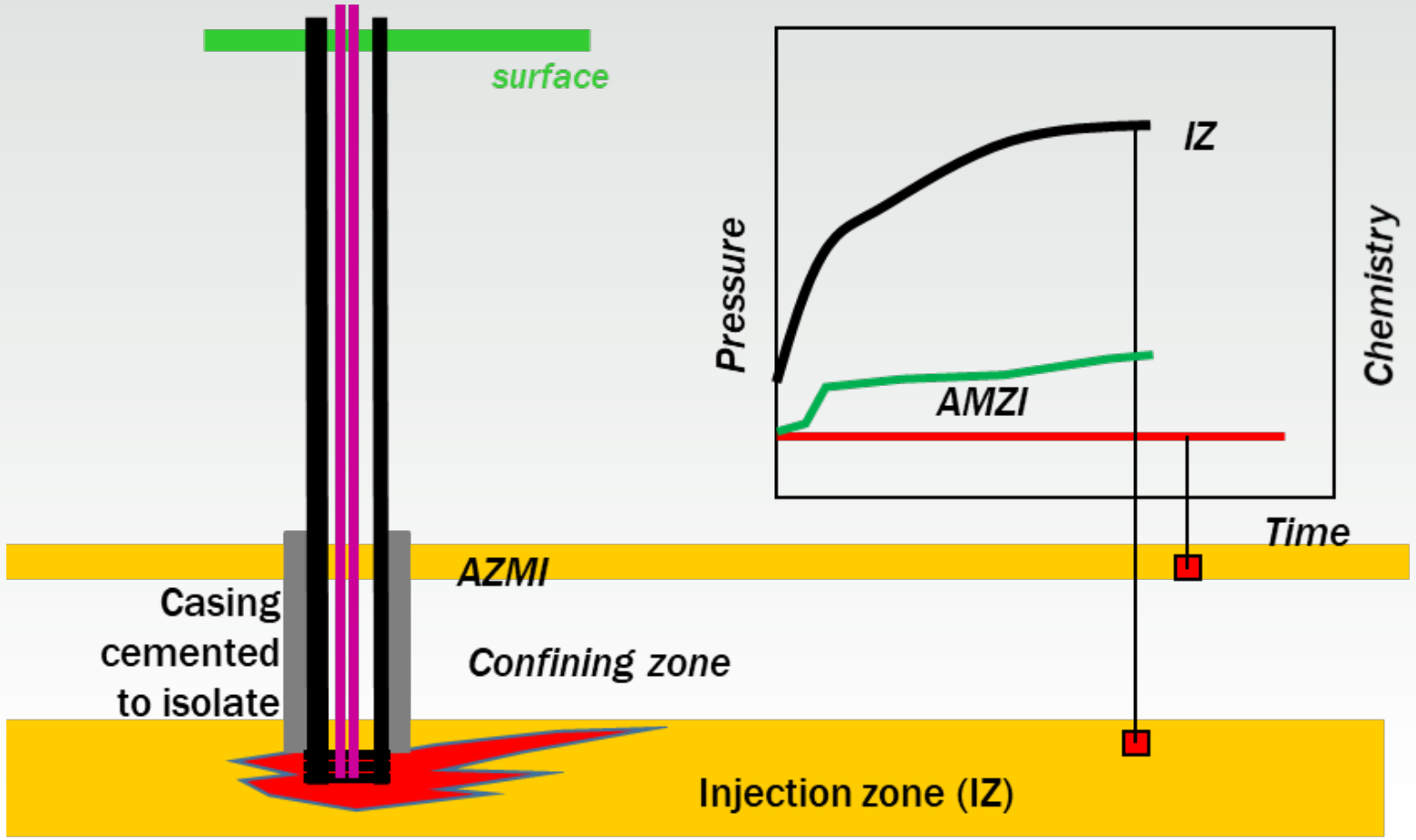
- Select microseismic as pre-failure trigger
- AZMI pressure as most sensitive trigger
- Select Image with surface 4- D and change in rate of pressure change in reservoir as post-trigger follow up.
- Decrease analysis of microseismic after pressure peaks and plateaus

Above-Zone Monitoring Interval (AZMI)

Susan Hovorka, Tip Meckel, Behni Bllhassani, Seyyed Hosseini

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Example of optimizing leakage detection: AZMI Pressure or chemistry?



Simple model of leakage response: Input parameters - CMG

User defined parameters

Pressure-based Model Parameter	Value	Unit
Permeability	9.87e-13	(m^2)
Porosity of monitoring reservoir	0.25	-
Leakage rate at reservoir condition	0.0001	(m^3/s)
Total compressibility	1E-9	(Pa^{-1})
Temperature	47.78	°C
Pressure	9,652,660	(Pa)
Thickness of monitoring reservoir	25	(m)
Monitoring detection time	365	(day)
Radius of leaky well	0.05	(m)
Viscosity	0.000578	(Pa.s)
CO_2 viscosity	0.0000302	(Pa.s)
CO_2 density	401	(kg/m^3)
Pressure gauge detection threshold	10000	(Pa)

Geochemical-based Model Parameter	Value	Unit
Dispersion coefficient	400	dm
Hydraulic gradient	0.05	-
Cpi1 (CO_2 initial concentration)	0.71552e-3	mol/day
Cpi2 (H^+ initial concentration)	0.61843e-7	mol/day
Cpi3 ($HCOE^-$ initial concentration)	0.47522e-2	mol/day
Cpi4 ($CO3^{-2}$ initial concentration)	0.30728e-5	mol/day
Cpi5 (OH^- initial concentration)	0.15091e-6	mol/day
Cpi6 (Ca^{+2} initial concentration)	0.77923e-3	mol/day
Leakage detection limit	10*cpi	mol/day

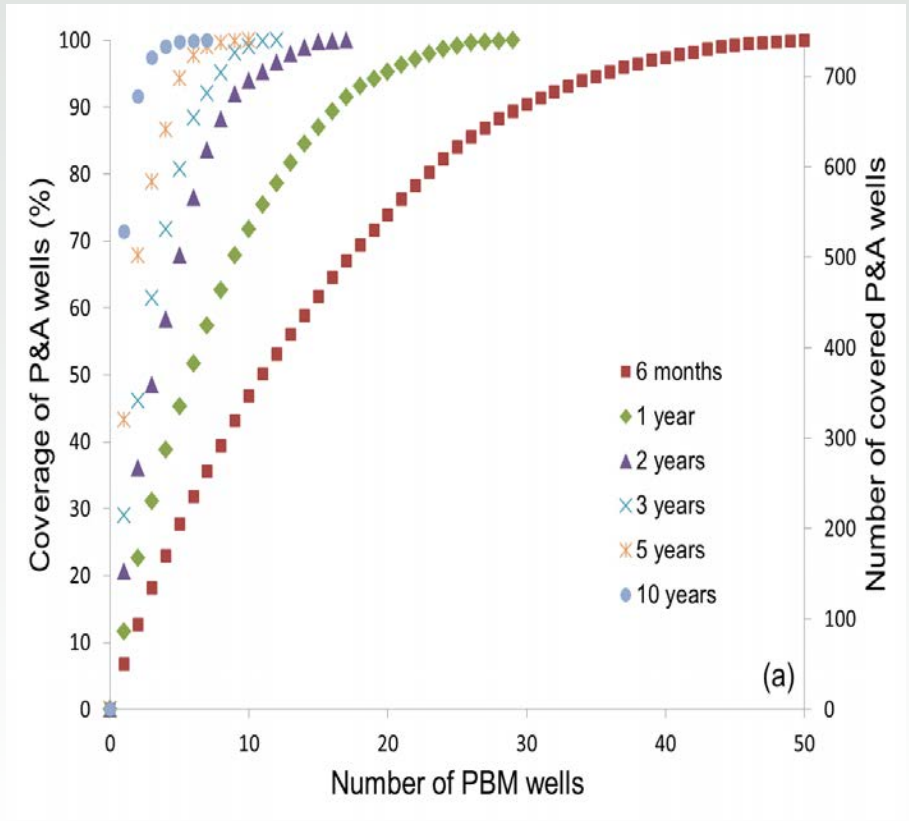
Behni Bollhassani, UT MS thesis

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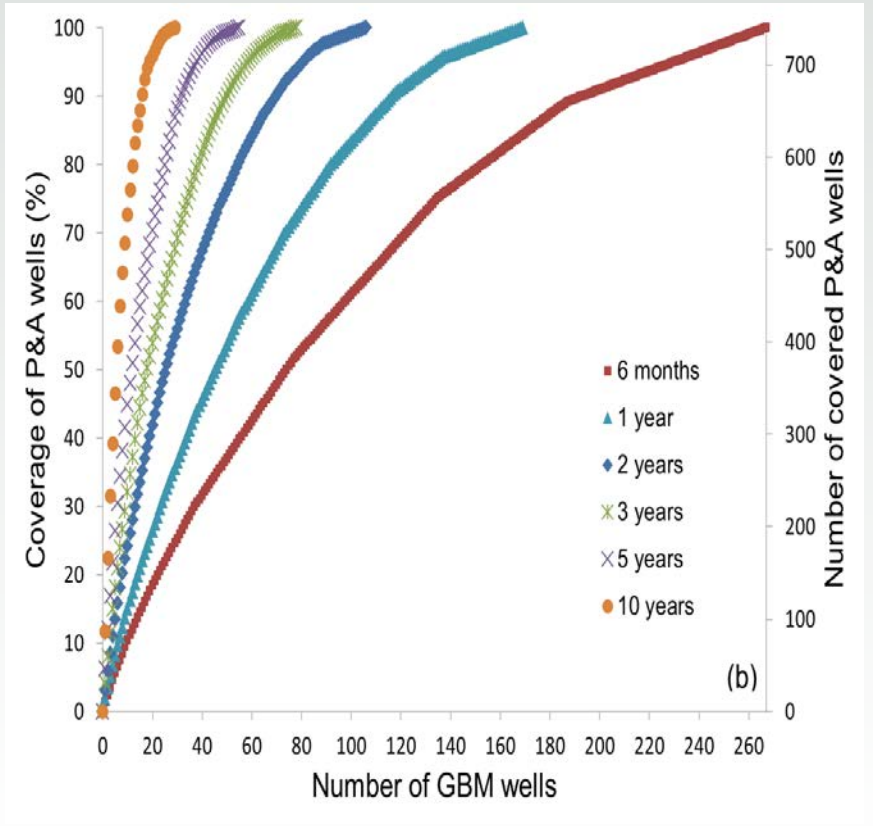
ECONOMIC GEOLOGY

Sensitivity analysis for leakage detection time

Detecting pressure signal



Detecting geochemical signal



Behni Bollhassani, UT MS thesis

2. Process-based soil gas method and the importance of attribution

Katherine Romanak, Changbing Yang, Jacob Anderson

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False Allegation of a “Leak” at the Kerr Farm

January 11, 2011



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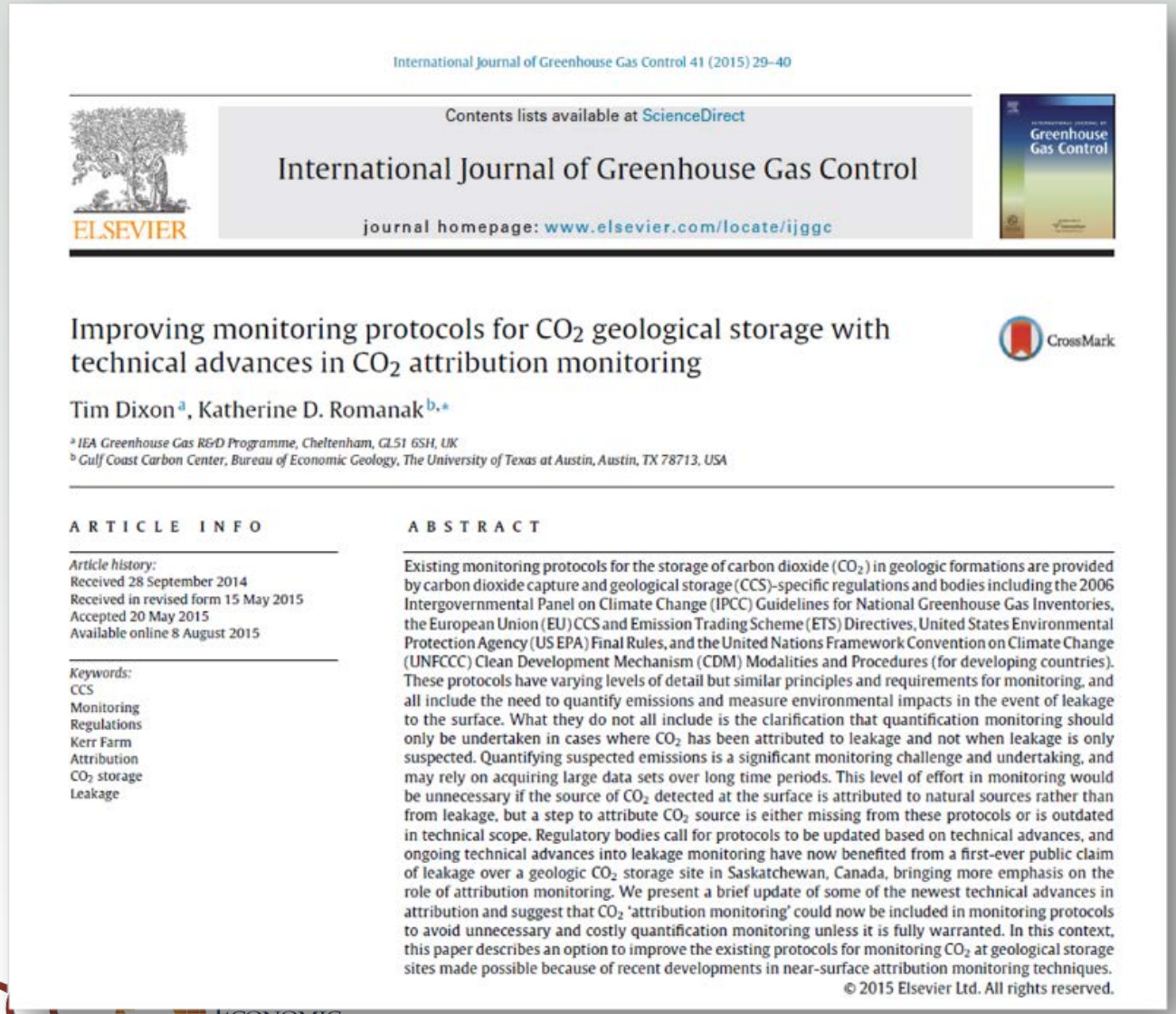
BUR ECO GEO

Attribution of Near-surface Anomalies

Attribution is:

- **Response to an incident or an allegation (and how to tell the difference)**
- **Essential to plan in advance to avoid damage to project reputation**
- **Should be accurate AND stakeholder-friendly**
- **Is required BEFORE corrective action, mitigation, remediation, and quantification (if needed)**
- **Difficult (as shown by experience)**

Source Attribution is Critical



International Journal of Greenhouse Gas Control 41 (2015) 29–40

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Improving monitoring protocols for CO_2 geological storage with technical advances in CO_2 attribution monitoring

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ARTICLE INFO

Article history:
Received 28 September 2014
Received in revised form 15 May 2015
Accepted 20 May 2015
Available online 8 August 2015

Keywords:
CCS
Monitoring
Regulations
Kerr Farm
Attribution
CO_2 storage
Leakage

ABSTRACT

Existing monitoring protocols for the storage of carbon dioxide (CO_2) in geologic formations are provided by carbon dioxide capture and geological storage (CCS)-specific regulations and bodies including the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, the European Union (EU) CCS and Emission Trading Scheme (ETS) Directives, United States Environmental Protection Agency (US EPA) Final Rules, and the United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM) Modalities and Procedures (for developing countries). These protocols have varying levels of detail but similar principles and requirements for monitoring, and all include the need to quantify emissions and measure environmental impacts in the event of leakage to the surface. What they do not all include is the clarification that quantification monitoring should only be undertaken in cases where CO_2 has been attributed to leakage and not when leakage is only suspected. Quantifying suspected emissions is a significant monitoring challenge and undertaking, and may rely on acquiring large data sets over long time periods. This level of effort in monitoring would be unnecessary if the source of CO_2 detected at the surface is attributed to natural sources rather than from leakage, but a step to attribute CO_2 source is either missing from these protocols or is outdated in technical scope. Regulatory bodies call for protocols to be updated based on technical advances, and ongoing technical advances into leakage monitoring have now benefited from a first-ever public claim of leakage over a geologic CO_2 storage site in Saskatchewan, Canada, bringing more emphasis on the role of attribution monitoring. We present a brief update of some of the newest technical advances in attribution and suggest that CO_2 'attribution monitoring' could now be included in monitoring protocols to avoid unnecessary and costly quantification monitoring unless it is fully warranted. In this context, this paper describes an option to improve the existing protocols for monitoring CO_2 at geological storage sites made possible because of recent developments in near-surface attribution monitoring techniques.

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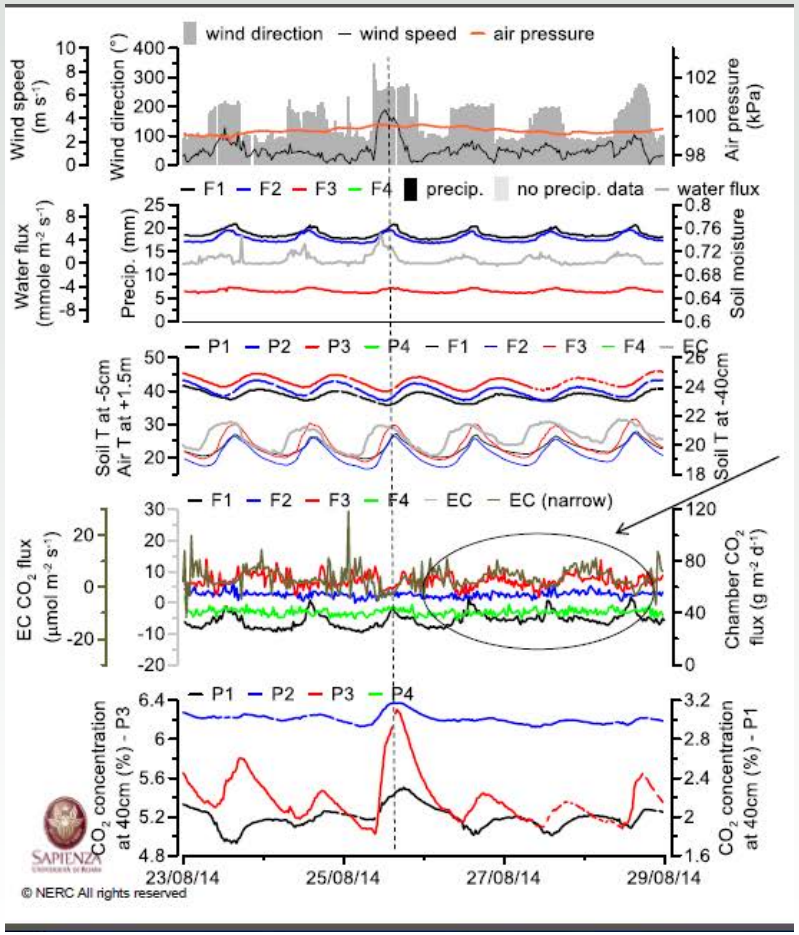
Dixon and Romanak, 2015, Improving monitoring protocols for CO_2 geological storage with technical advances in CO_2 attribution monitoring, IJGGC vol 41

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ECONOMIC GEOLOGY

Former approach to attribution

Complexity of CO_2 Concentration Variations



Dave Jones, British Geological Survey

Former approach:

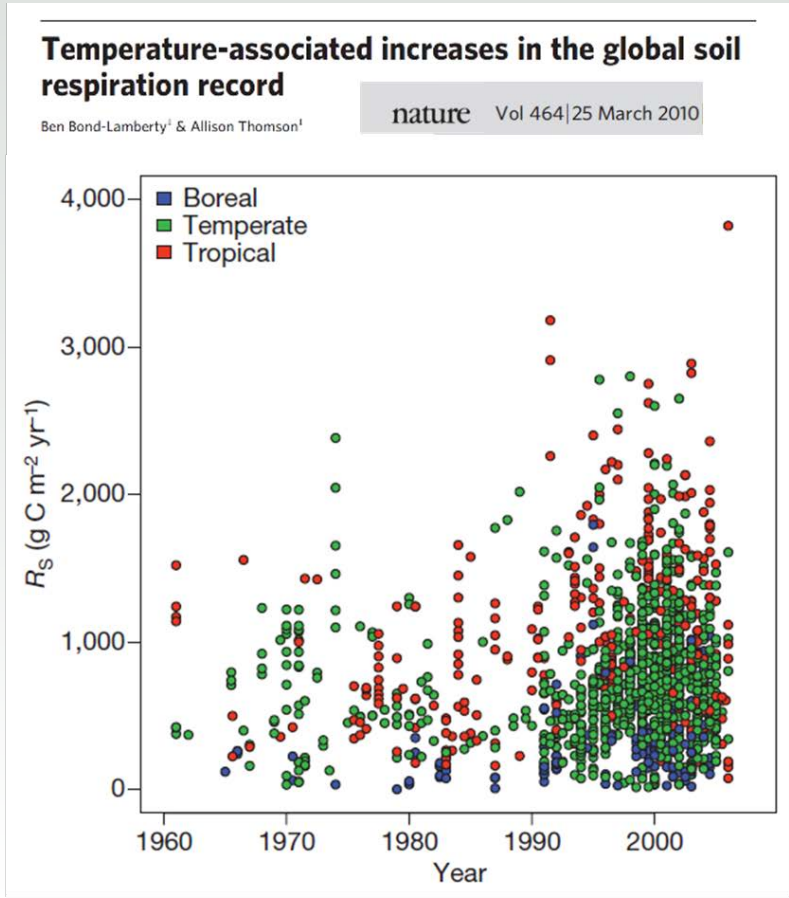
- Collect baseline of all relevant parameters
- Systematically watch all parameters for change with weather and seasons
- No change above baseline, no leakage, and project can be closed

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Many troubles with change from baseline approach

- Ambient temporal and spatial variably is high
  - False positives
- Parameters are naturally dynamic
  - Land use, climate, environmental improvement
- High cost to explain all the changes that occur
- Too complex for stakeholder engagement
- Difficult to pre-define trigger points
- Risk to project financially and in terms of public acceptance of expecting no change

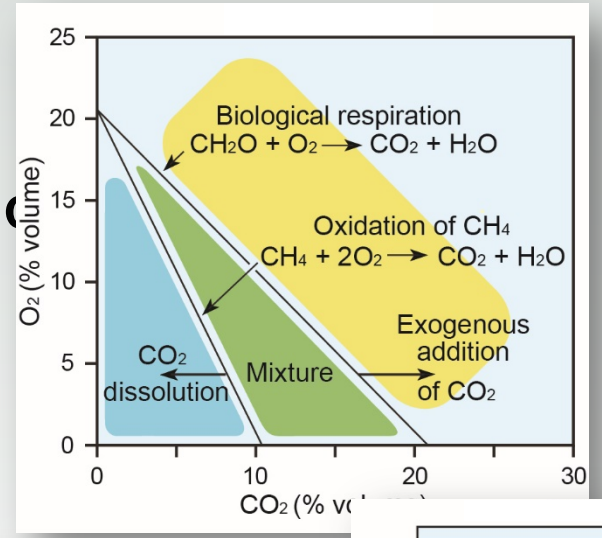


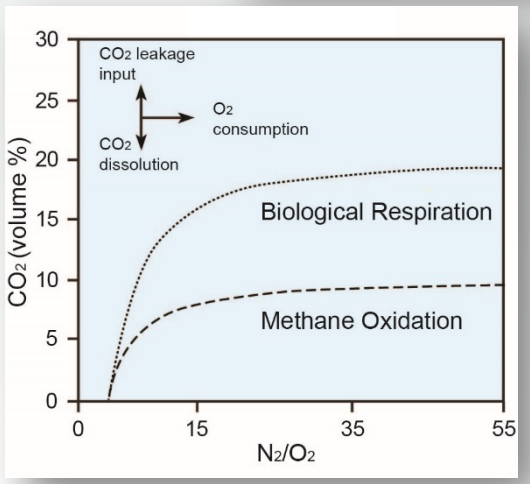
RS = flux of microbial and plant-respired CO_2 from the soil surface to the atmosphe

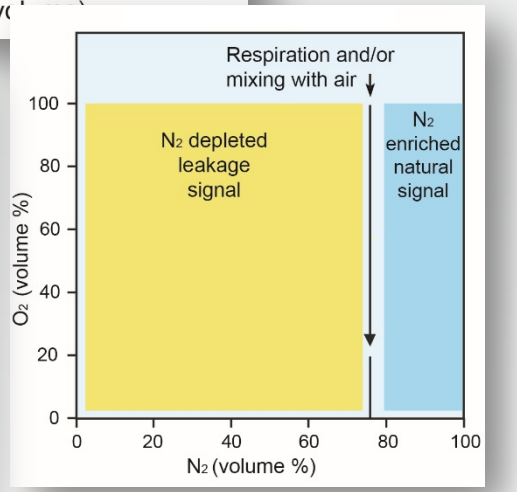
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Process-Based Soil Gas Monitoring

- No need for years of background measurements.
- Promptly identifies leakage signal over background n
- Uses simple gas ratios (CO_2, CH_4, N_2, O_2)
- Can discern many CO_2 sources and sinks
  - Biologic respiration
  - CO_2 dissolution
  - Oxidation of CH_4 into CO_2 (Important at CCUS sites)
  - Influx air into sediments
  - CO_2 leakage
- Being taken up as best practice internationally
  - Aquistore, Lac Rouse, Otway, CTSCo,





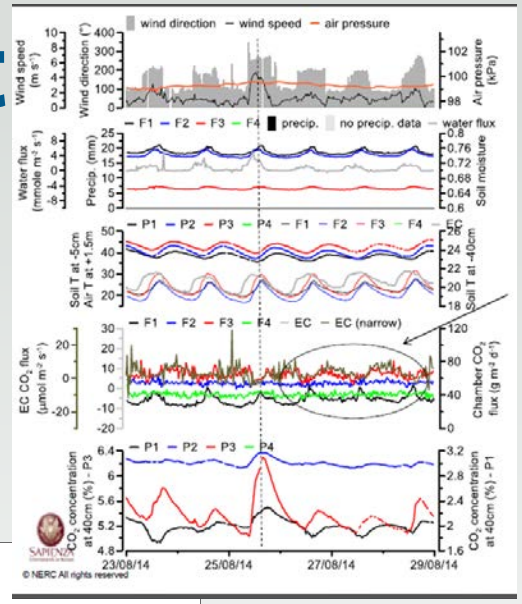


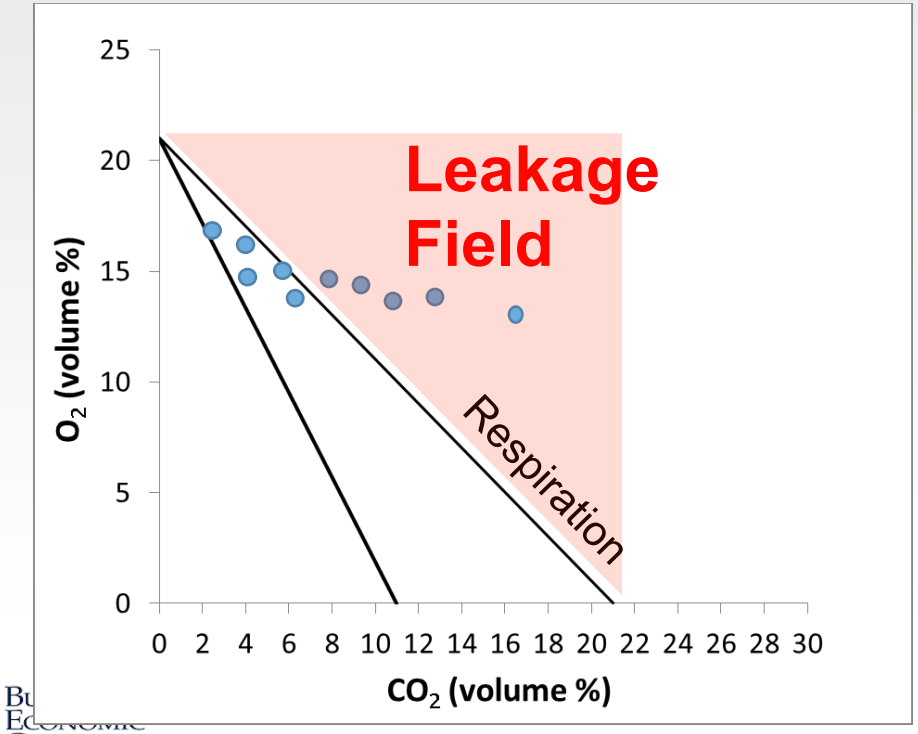
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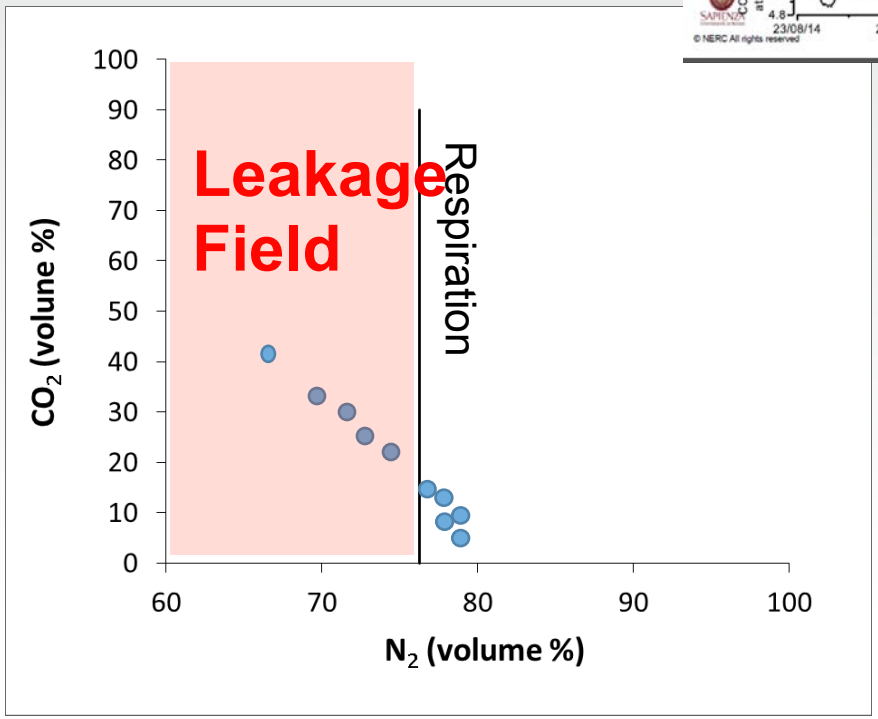
Katherine Romanak BEG

“User-Friendly” for Public Engagement

- Instant data reduction
- Reduces risk of false positives.
- Graphical analysis
- Continuous monitoring capability will give instant real-time leakage detection information.





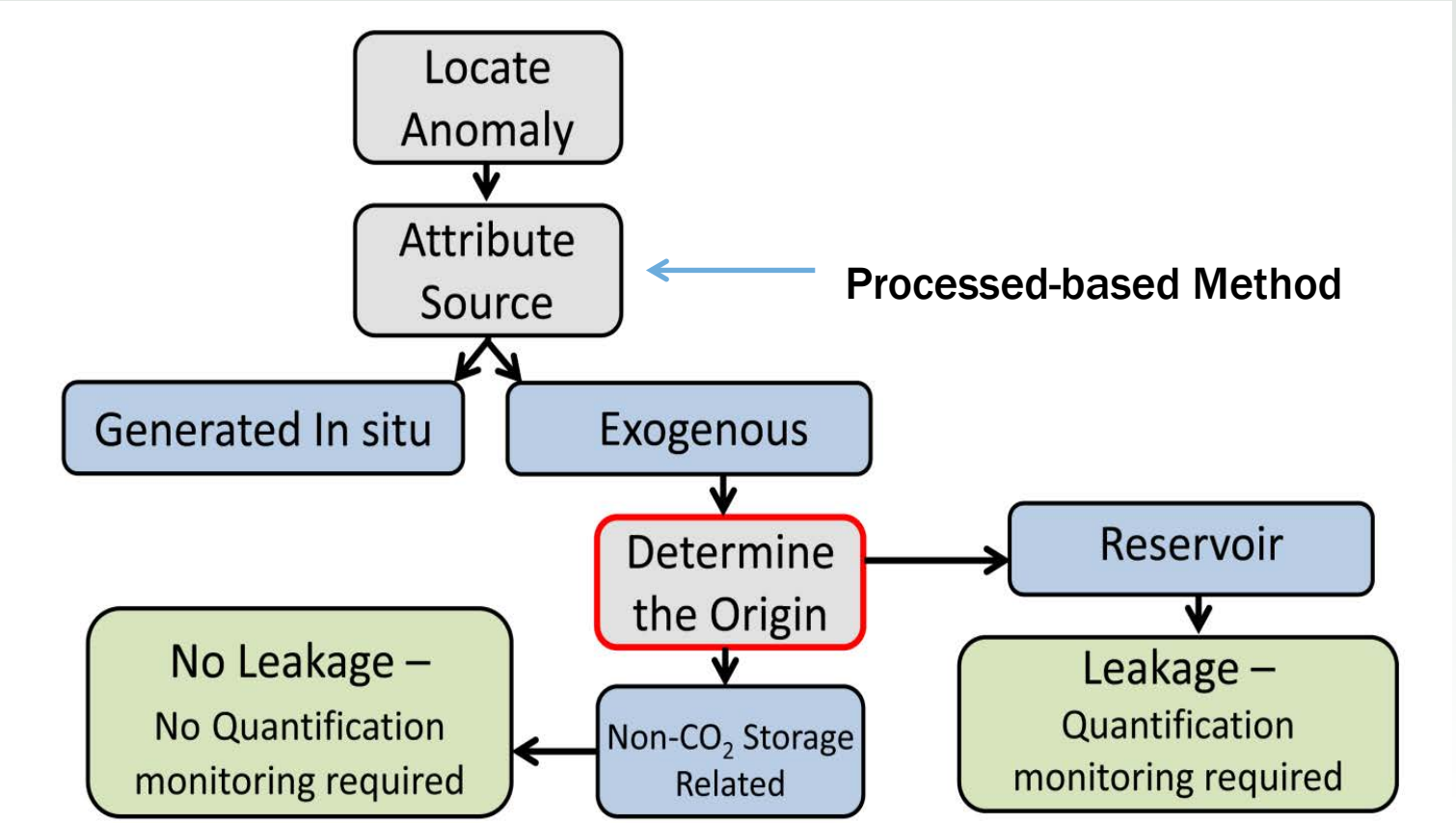


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Katherine Romanak BEG

What is the current status?
Anomaly Attribution



Romanak et al., 2012

Increasing skills in PB soil gas interpretation

Gaining as much experience as possible in different settings

- Field
- Lab
- Analogs



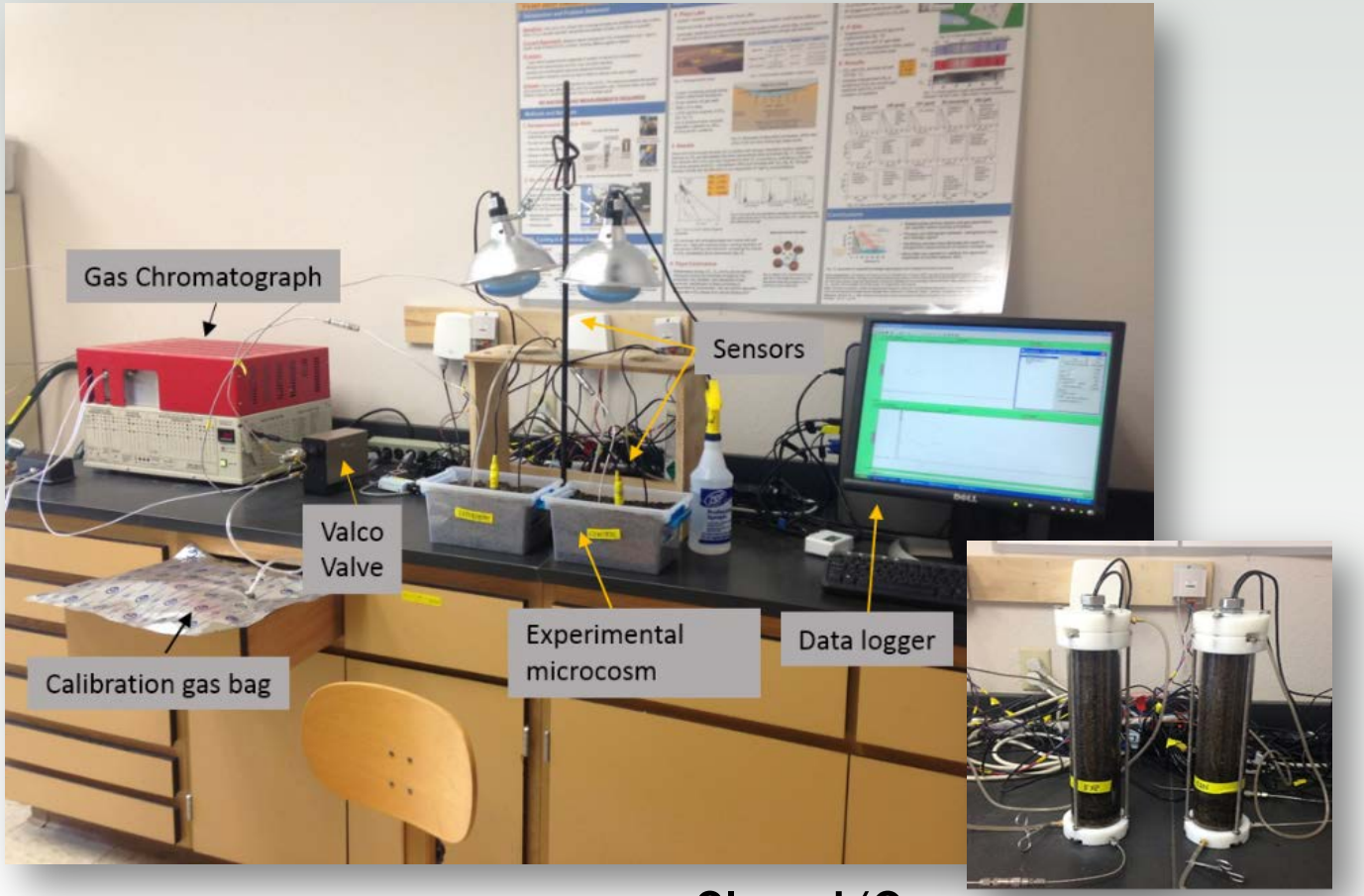
Paul Jensen (ALS Laboratory group), Nick Hudson (CTSCo) and Katherine Romanak (BEG) stand beside one of the soil gas stations being used for real-time environmental monitoring at the Surat Basin CCS demonstration site

Carbon Transport and Storage Corporation Pty Ltd (CTSCo) Surat CCS demonstration project
Australian National Low Emissions Coal Research and Development Ltd (ANLEC R&D)

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Lab work on recognizing CO_2 leaked from depth in near surface settings

- To define and quantify changes to soil gas ratios under varying conditions
- Expand the process-based matrix to additional processes
- Develop best practice for anomaly attribution

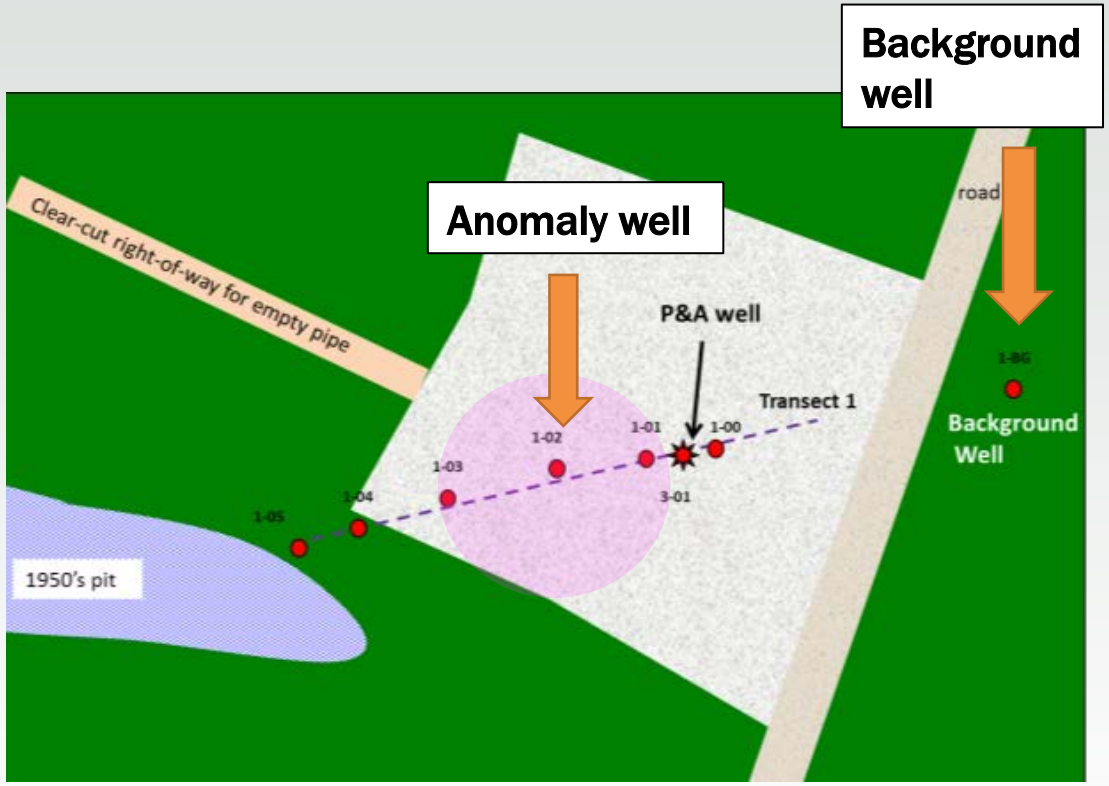


Closed/Open
Anaerobic/Aerobic

Katherine Romanak and students

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Soil Gas Anomaly “P-Site”

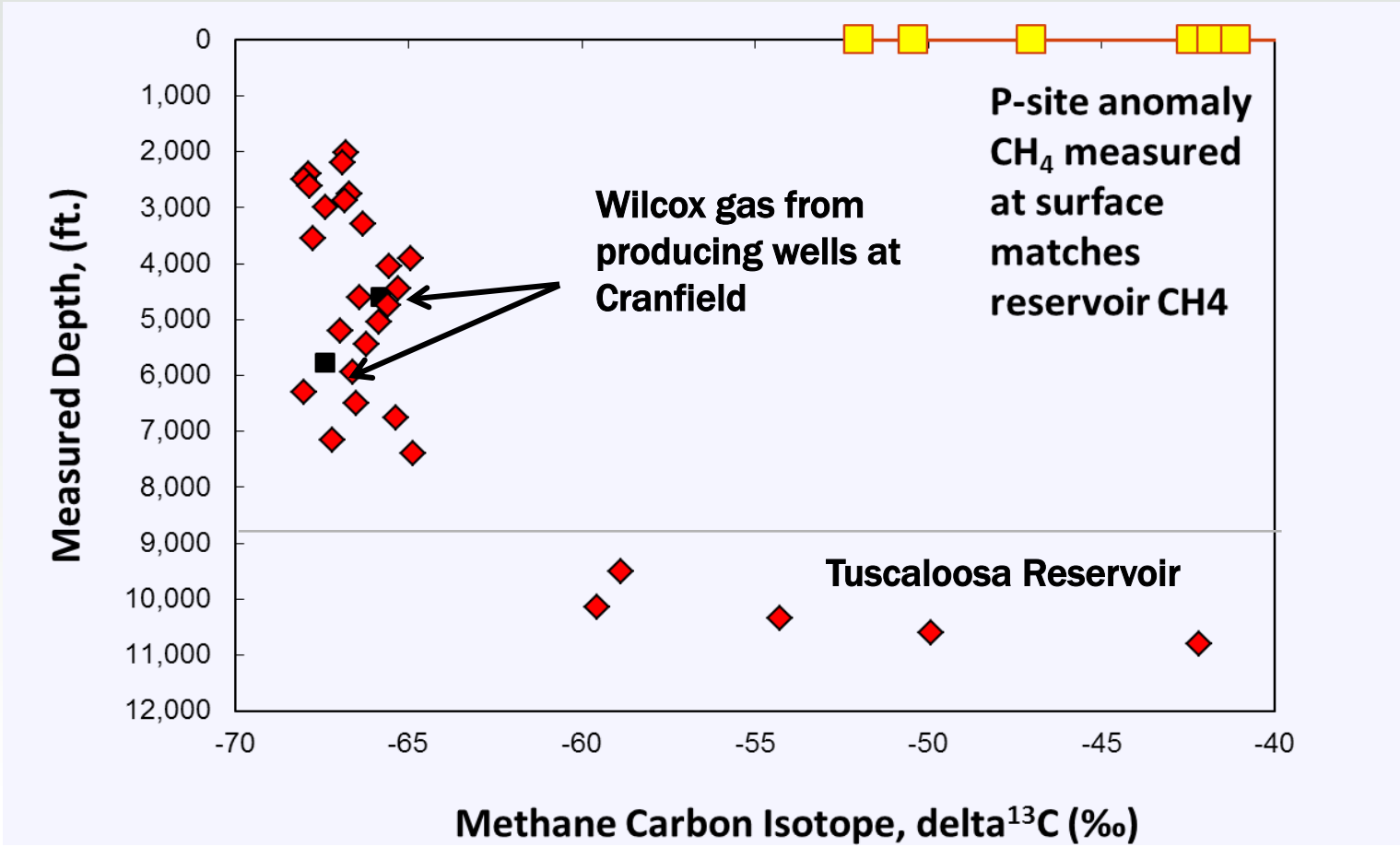


- Focused study at historic well
- 13 multi-depth soil gas sampling stations - 5 m depth
- Localized soil gas anomaly
  - $CH_4 \leq 48$ vol. %
  - $CO_2 \leq 45$ vol. %

Tricky Attribution

- Initially believed to indicate well-failure.
- Potential origin from reservoir or intermediate units
- Based on ^{14}C was found not to be from the reservoir.
- Expanding PB soil gas method

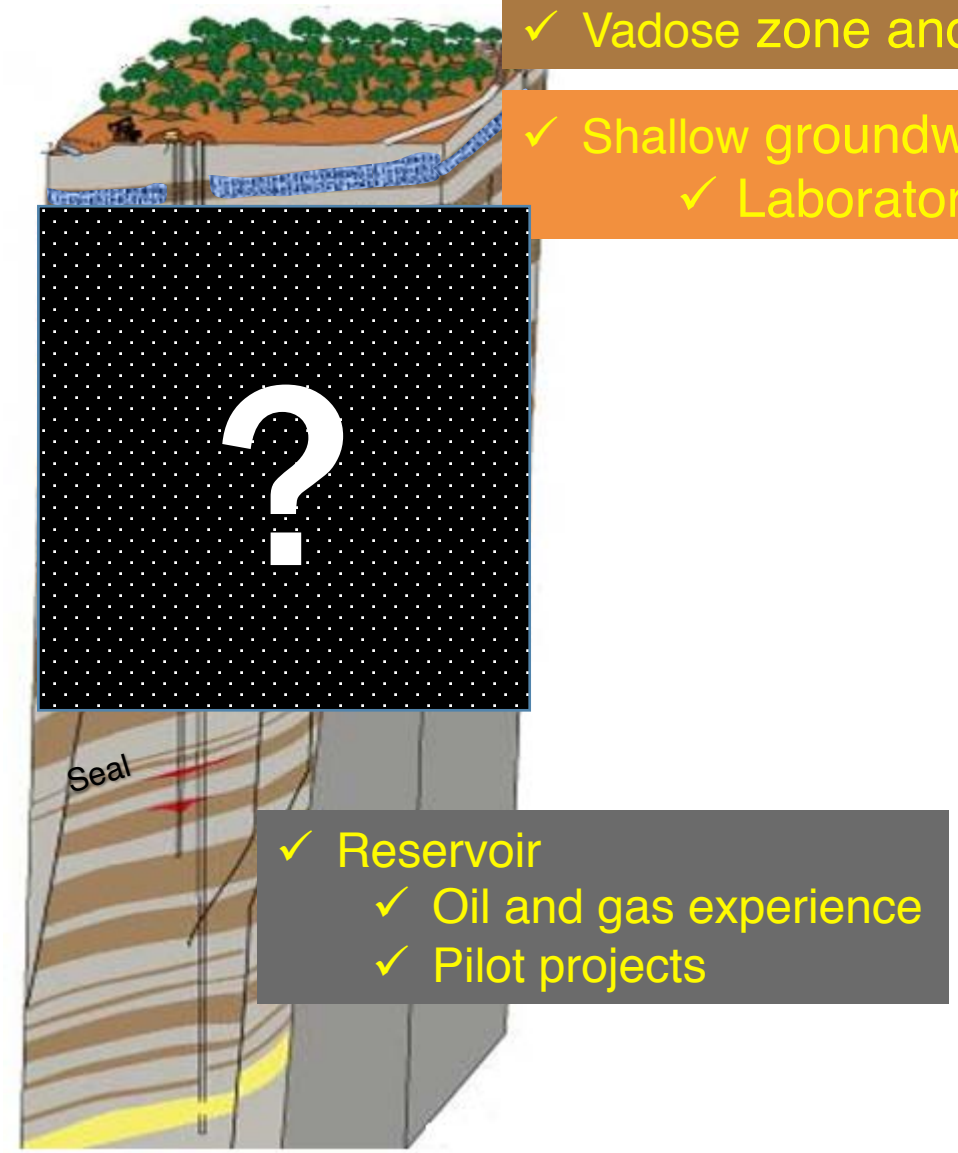
Mudgas Analysis



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Attribution and the Black Box



✓ Vadose zone and atmosphere – Controlled releases

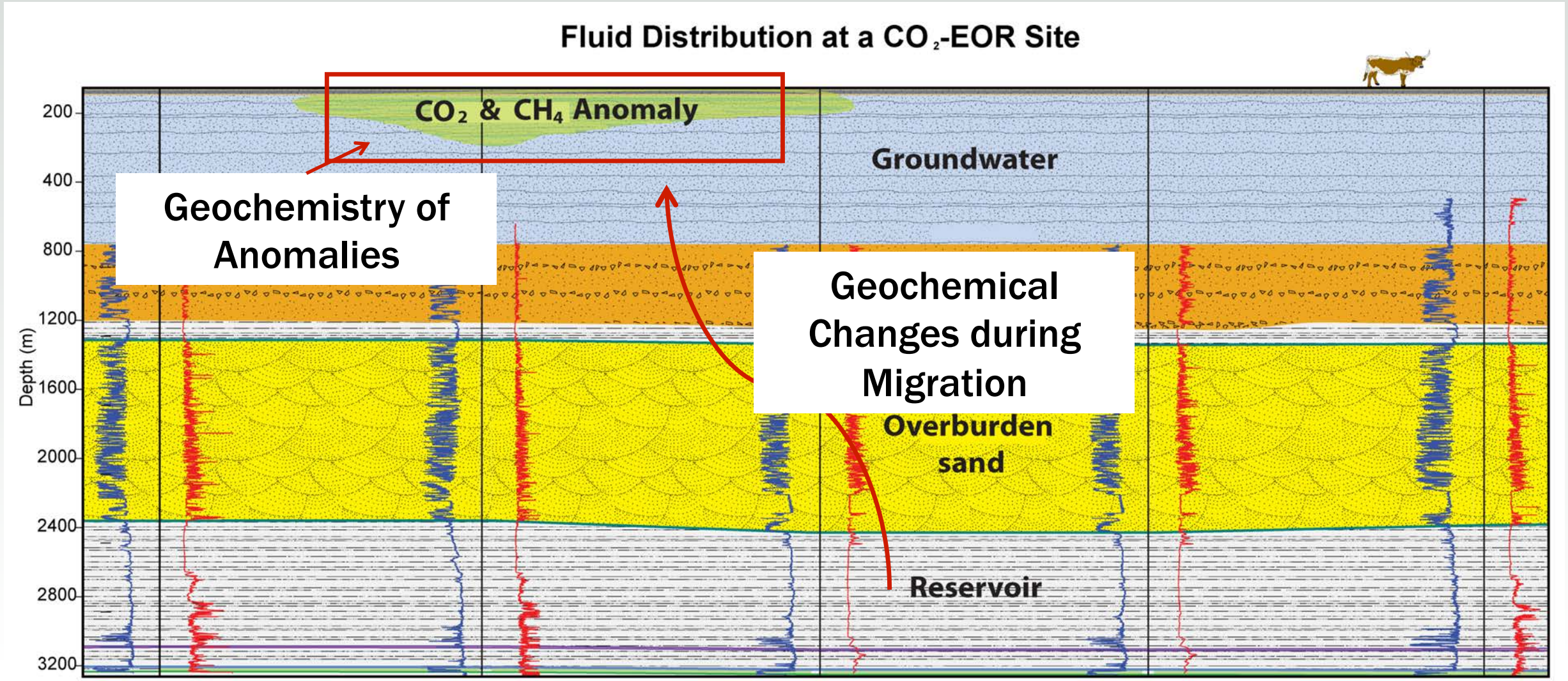
✓ Shallow groundwater
  ✓ Laboratory and push pull field testing

✓ Reservoir
  ✓ Oil and gas experience
  ✓ Pilot projects

- The overburden is a “black box” with a lack of information
- Link between shallow and deep gases - Attribution
- Understand and predict vertical migration mechanisms and processes
- Understand degree of isolation of various depths
- Understand natural and introduced tracer behavior and transport
- CO_2 transport and reactivity
- Site characterization and risk assessment – geologic structures e.g. offshore chimneys

Figure courtesy of Sue Hovorka

What's the Problem?

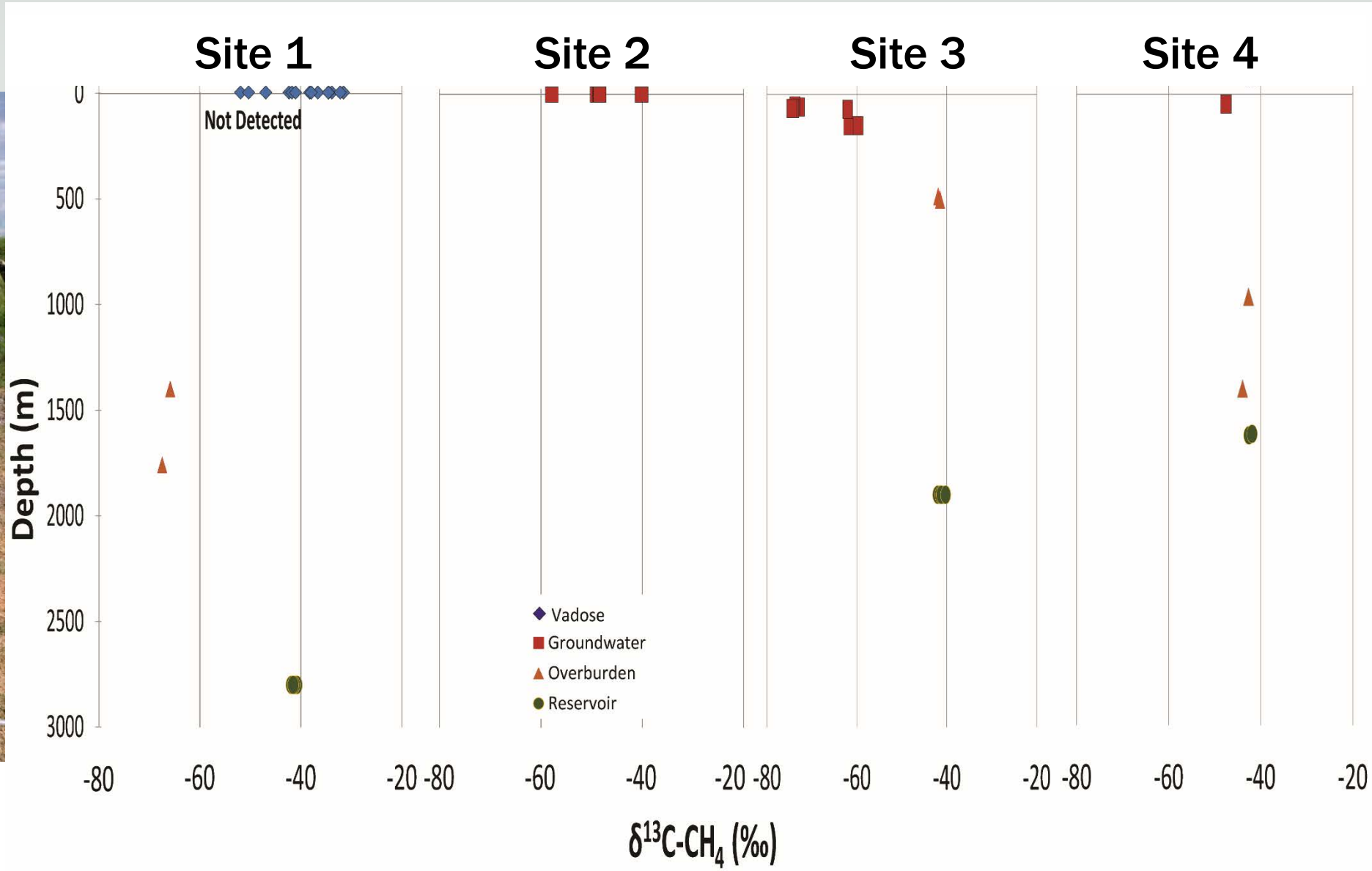


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Hydrocarbon Systems as an Analog

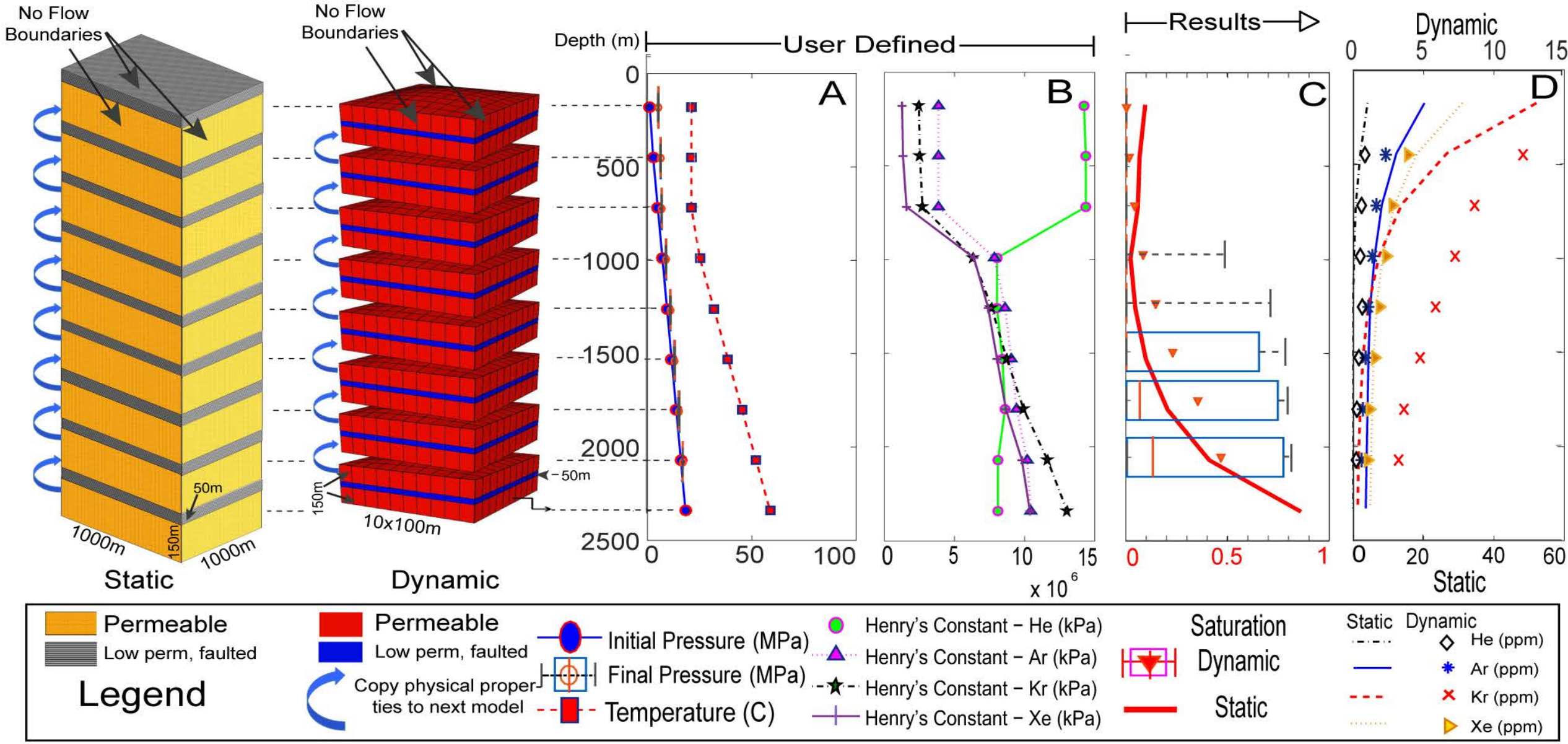




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Forward Model CO_2



Effectiveness of groundwater surveillance

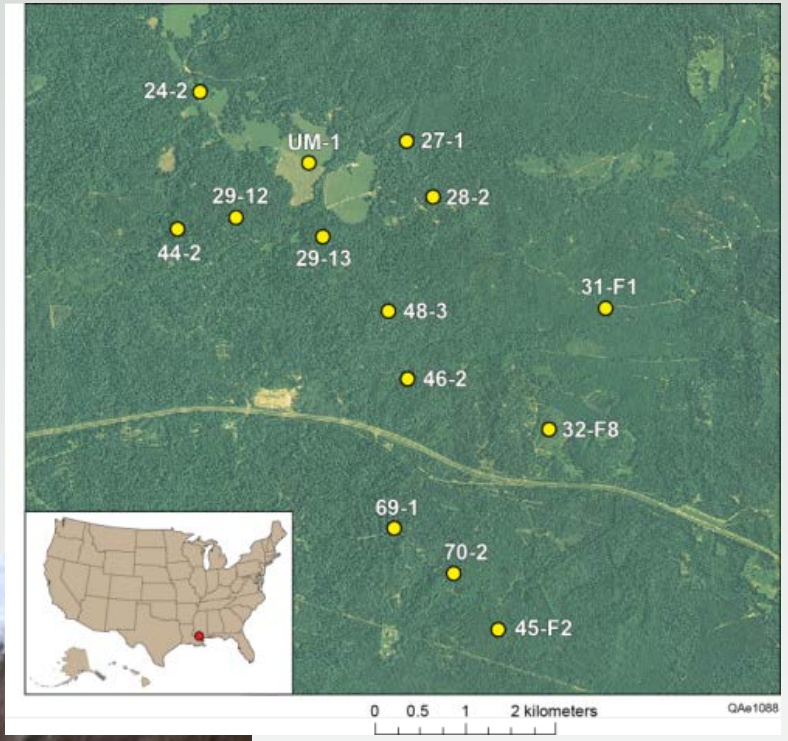
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Groundwater Sampling at the Cranfield Site

- More than 12 field campaigns
- 130 groundwater samples collected for chemical analysis

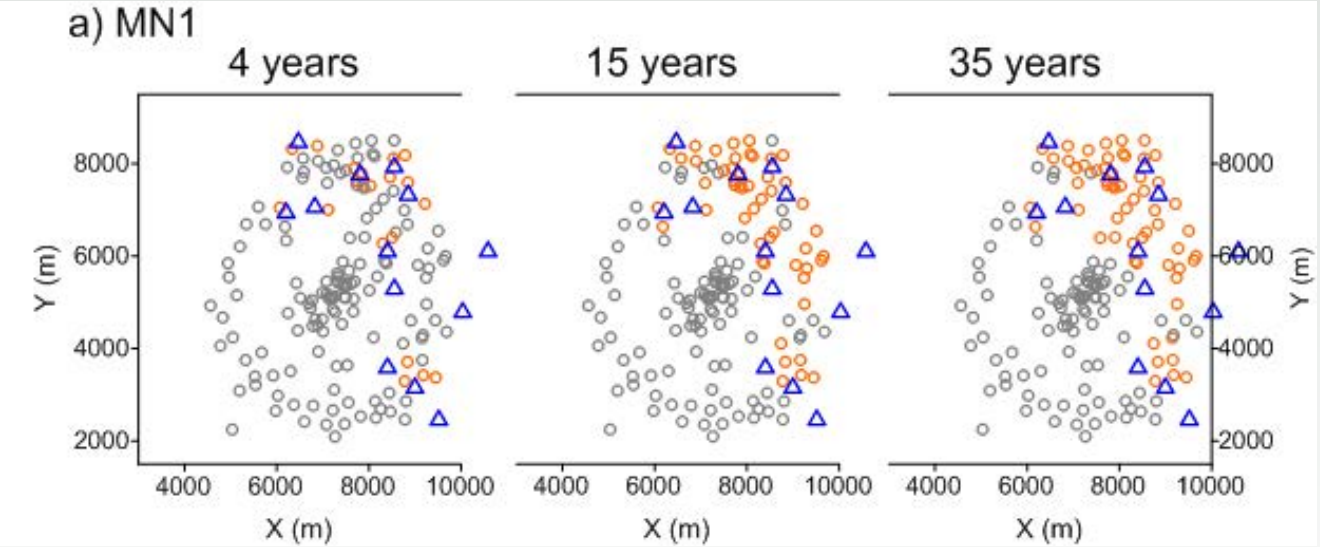




C. Yang, BEG

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Groundwater monitoring network efficiency is low



20/151=0.13 by 4 years
50/151=0.33 by 15 years
58/151=0.38 by 35 years

$$ME = W\uparrow d / W\uparrow T$$

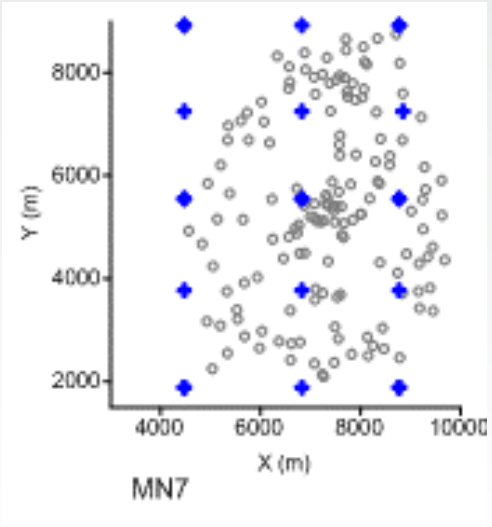
CO_2 leakage from a failed well is detected by a monitoring net work if change in DIC, dissolved CO_2, or pH in any one of wells of the monitoring network is higher than one standard deviation of the groundwater chemistry data collected in the shallow aquifer over the last 6 years.

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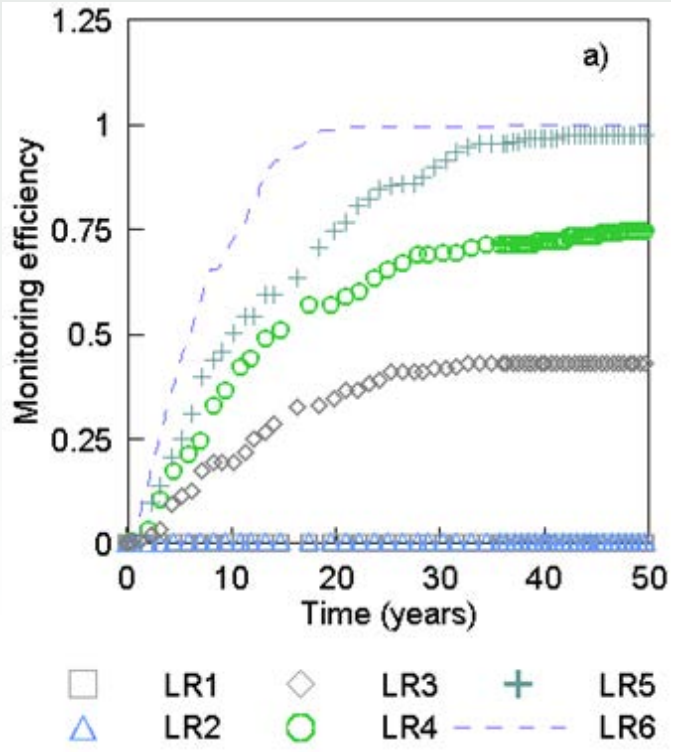
Groundwater monitoring network efficiency is low

Monitoring efficiency of MN7 with dissolved CO_2 as an indicator



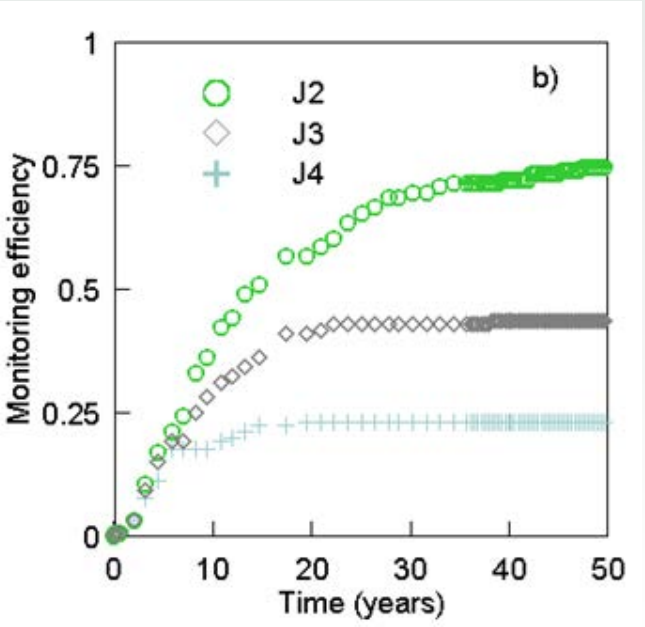
Leakage rate: metric ton/yr

LR1: 0.94, LR2: 6.28
LR3: 25.1, LR4: 37.7
LR5: 50.3, LR6: 100



Regional hydraulic gradient

J2: 0.5% , J3: 0.8%
J4: 1.0%



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Enhanced Analytical Simulation Tool (EASiTool) Dynamic Capacity Estimation

Seyyed A. Hosseini, Reza Ganjdanesh, Seunghee Kim, Ali Goudarzi

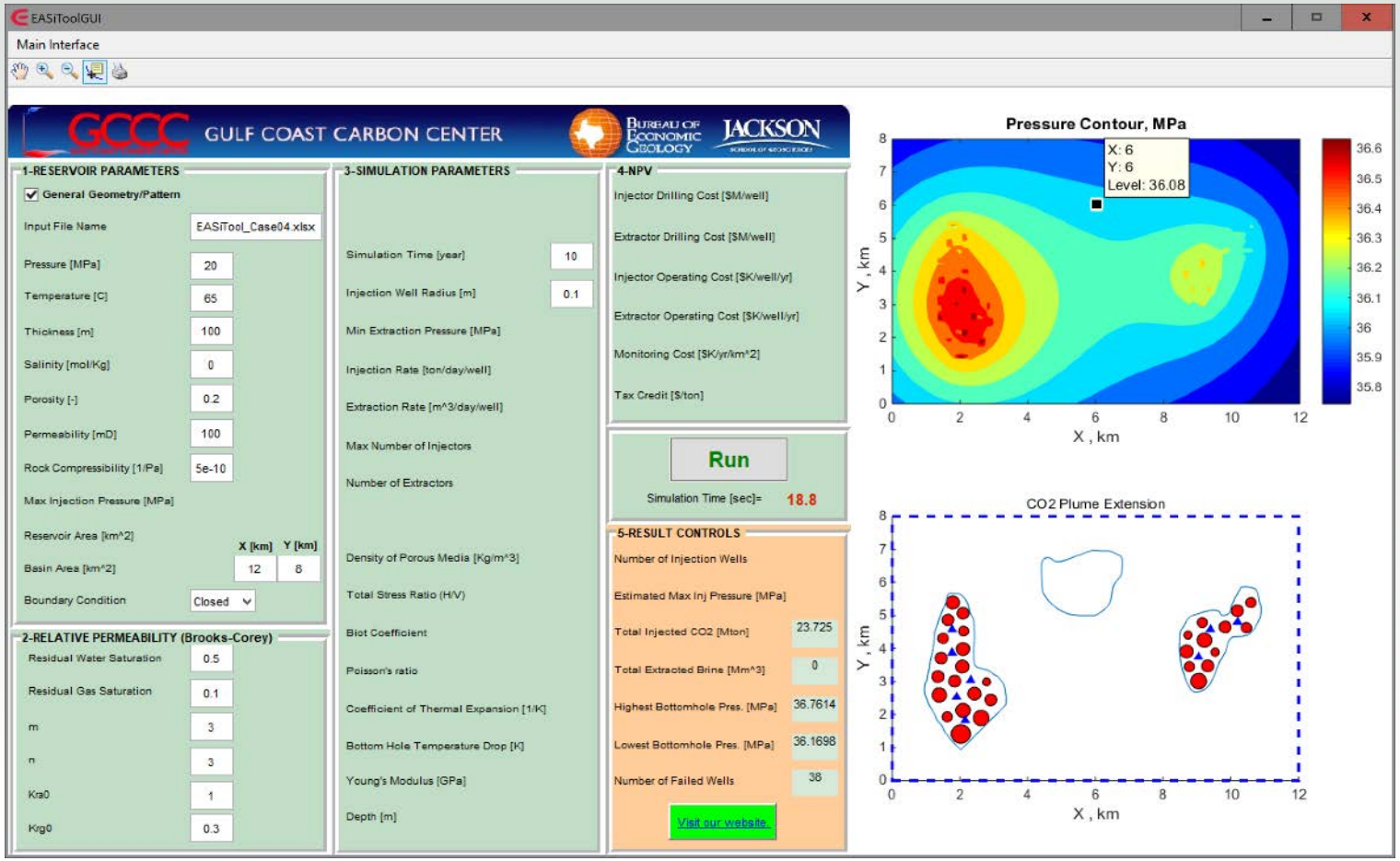
Tip Meckel, Luca Trevisan, Prasanna Krishnamurthy, Emily Beckham

Alex Sun, Akand Islam, Hoonyoung Jeong

EASiTool version 4.0

Enhanced Analytical Simulation Tool (EASiTool)

- A new scientific and user-friendly CO_2 storage capacity estimation tool
- Estimate CO2 storage capacity in saline aquifers limited by pressure buildup.
- Estimate maximum injection pressure for a given formation.
- Incorporate brine extraction into storage capacity estimation.
- Provide sensitivity analysis for input parameters.

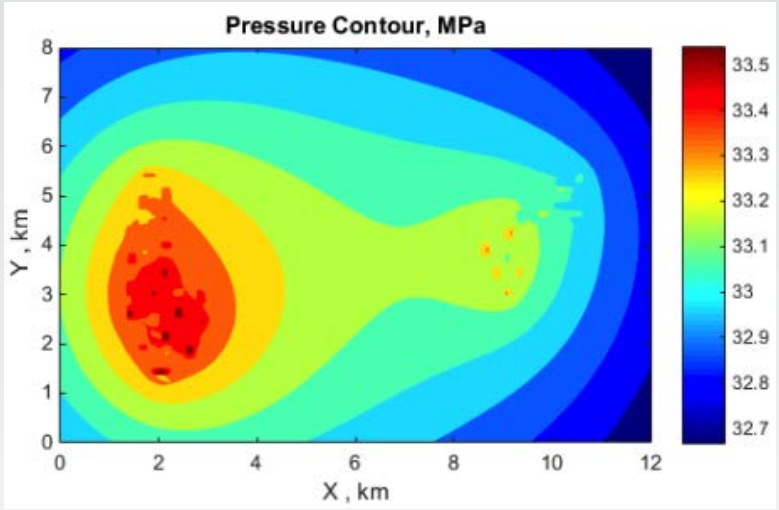


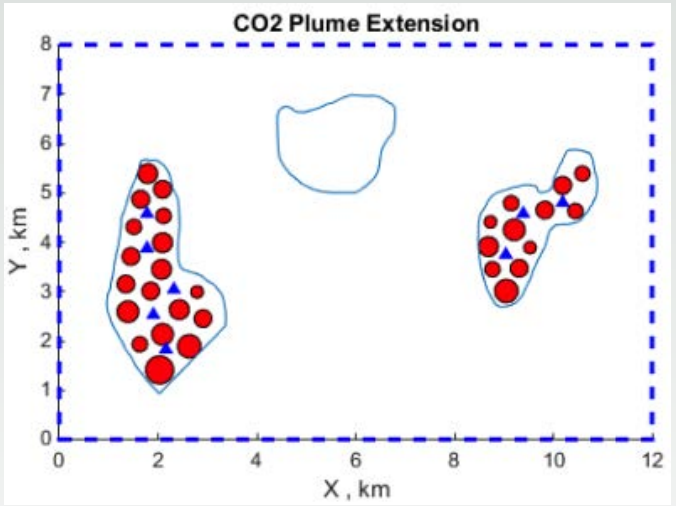
Pressure buildup constrained capacity EASiTool (DOE)

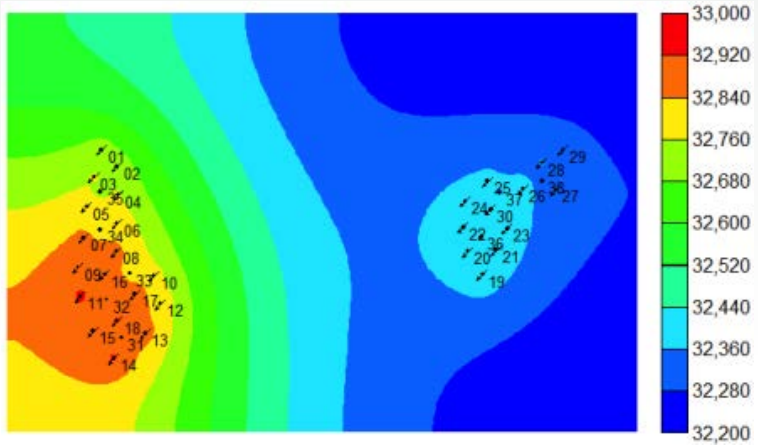
Tool/Approach Name	DOE/NETL	EERC	CSLF	USGS	EASiTool	Simulators
Accuracy	Low	Low	Low	Low	Medium (±30%)	High
Boundary conditions	No	No	No	No	Yes	Yes
Rock geomechanics	No	No	No	No	Yes	Yes
Brine management	No	No	No	No	Yes	Yes
Required expertise	Low	Low	Low	Low	Low	High
Cost of use	Low	Low	Low	Low	Low	High
Speed	High	High	High	High	High	Low
Dynamic	No	No	No	No	Yes	Yes
Uncertainty quantification	Simple	Simple	Simple	Simple	Yes	Yes

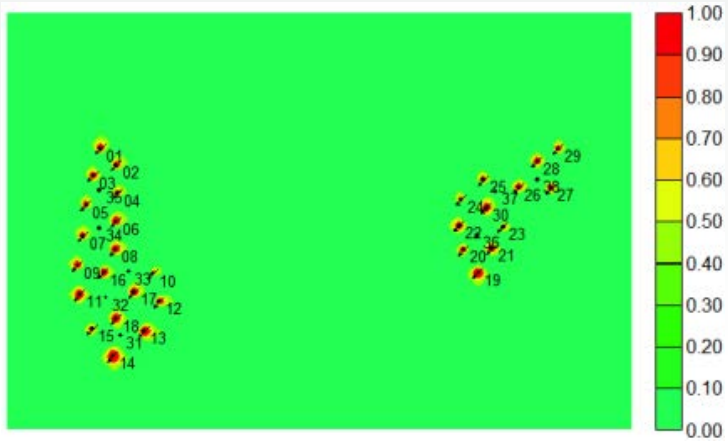
EASiTool version 4.0

- User defined well locations
- Multiple reservoirs within the same basin
- Full-field pressure maps









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EASiTool – Training with Cranfield Data

2017 Saline Aquifers CCS Workshop - Mexico city





2014 IEAGHG Summer School - Austin

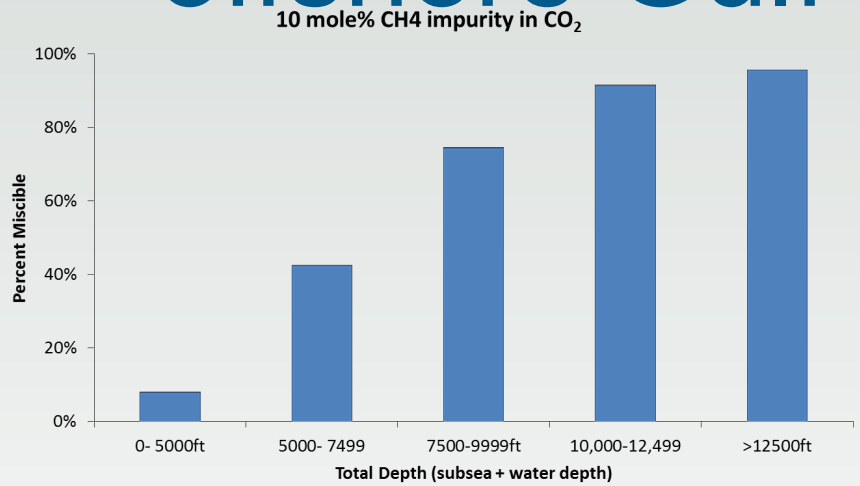


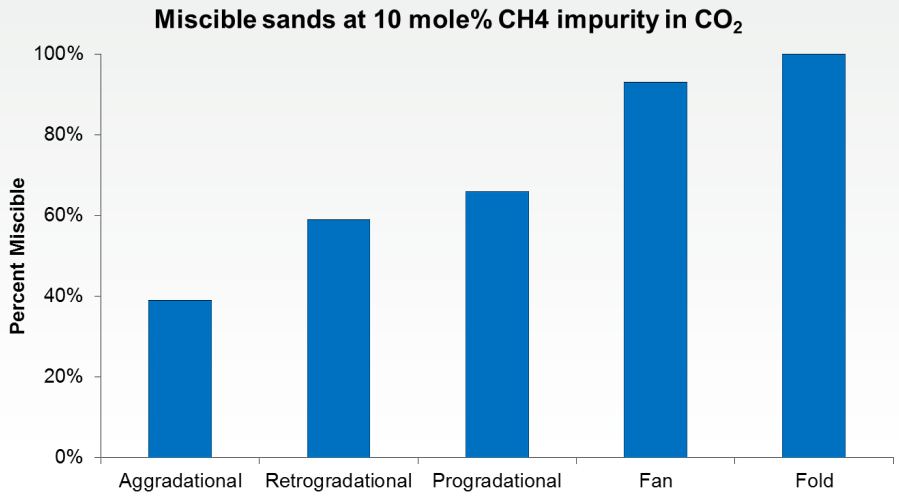
Methane Exsolution

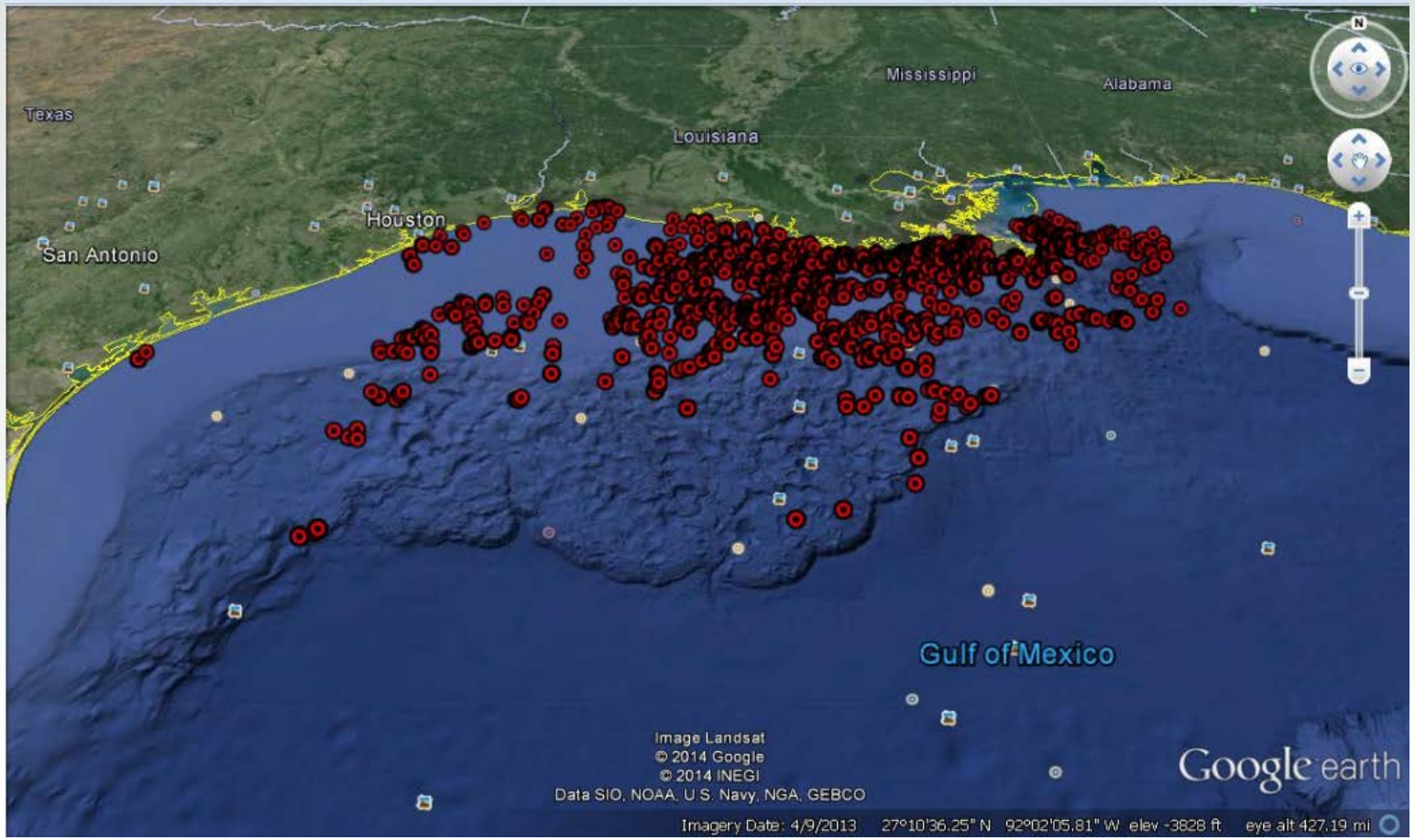
Tip Meckel

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The role of methane in limiting CO_2 EOR: offshore Gulf of Mexico oil sands







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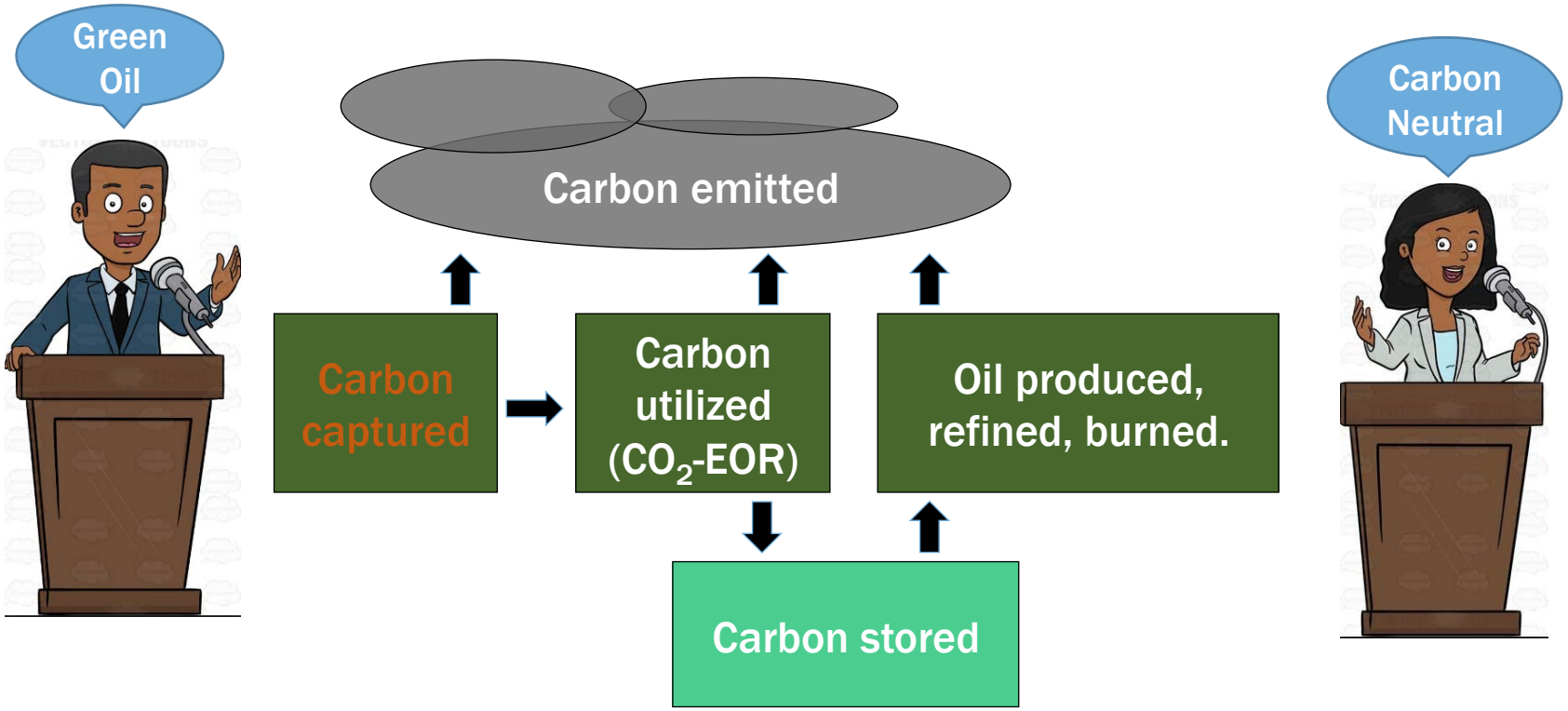
Net Carbon Negative Oil Mass accounting

Cranfield case Study

Vanessa Nuñez López, Seyyed Hosseini, Ramón Gil-Egui, Pooneh Hosseininosheri

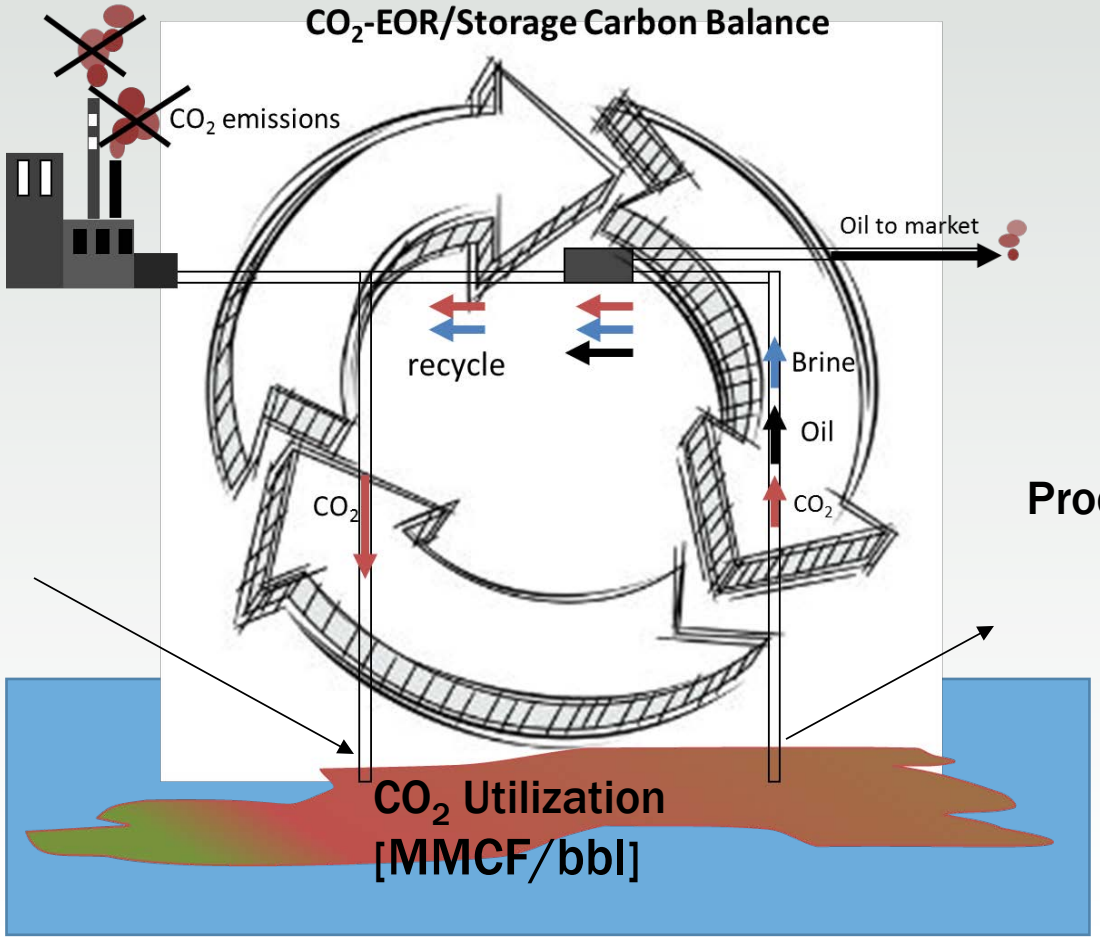
Bureau of Economic Geology

Can CO_2-EOR produce Net Carbon Negative Oil?



DOE-NETL Sponsored Project: “Carbon Life Cycle Analysis of CO_2-EOR for Net Carbon Negative Oil (NCNO) Classification”

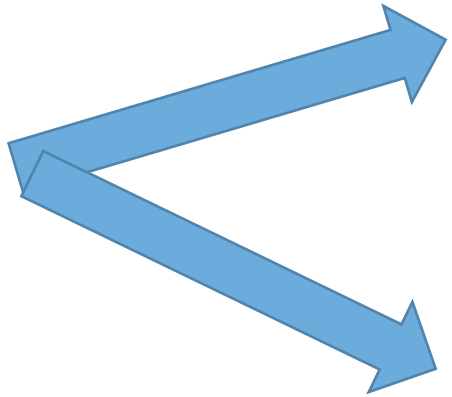
Study focus: CO_2 utilization ratios



Cranfield CO_2-EOR operations scenarios:

Injection Scenarios:

- Continuous CO_2 injection (CGI)
- Water Alternating GAS (WAG)
- Water Curtain Injection (WCI)
- WAG+WCI



IMPACT ON CARBON BALANCE

Gate-to-Gate System

Indirect Emissions:

- Artificial Lift
- Gas Injection Compression
- Pumping for injection and fluid handling
- Gas Separation Process

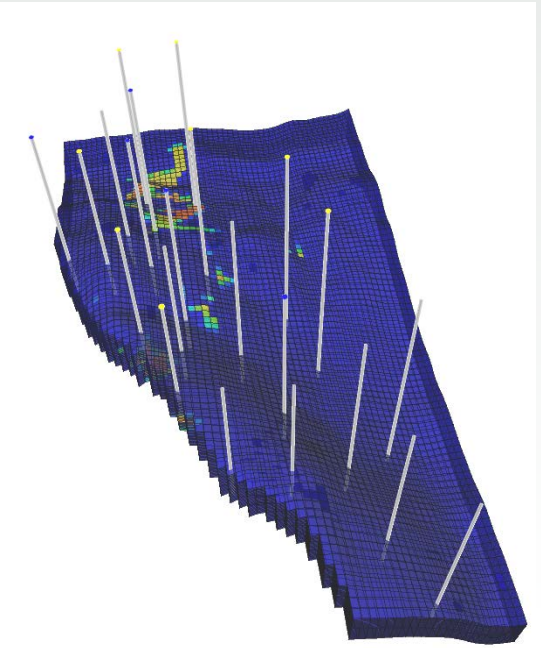
Gate-to-Grave System

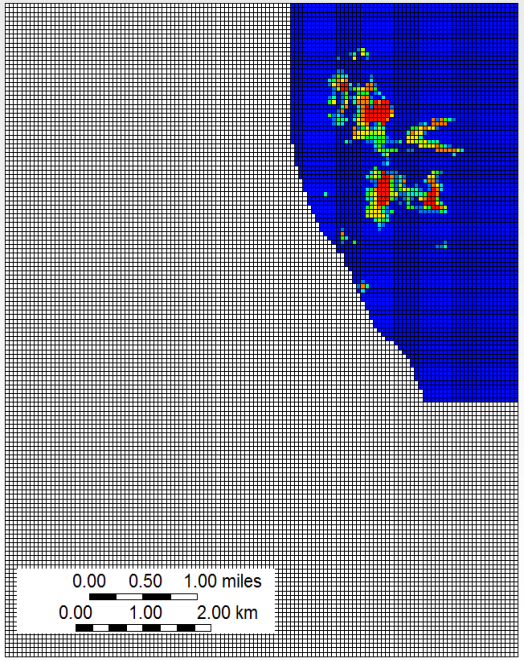
- Refinery
- Product combustion

Numerical Simulation Using Cranfield Static model

Compositional model simulates CO_2 injection

- **Compositional simulation**
- **Total number of block = 82,500**
- **25 yrs injection +75 yrs of post injection**



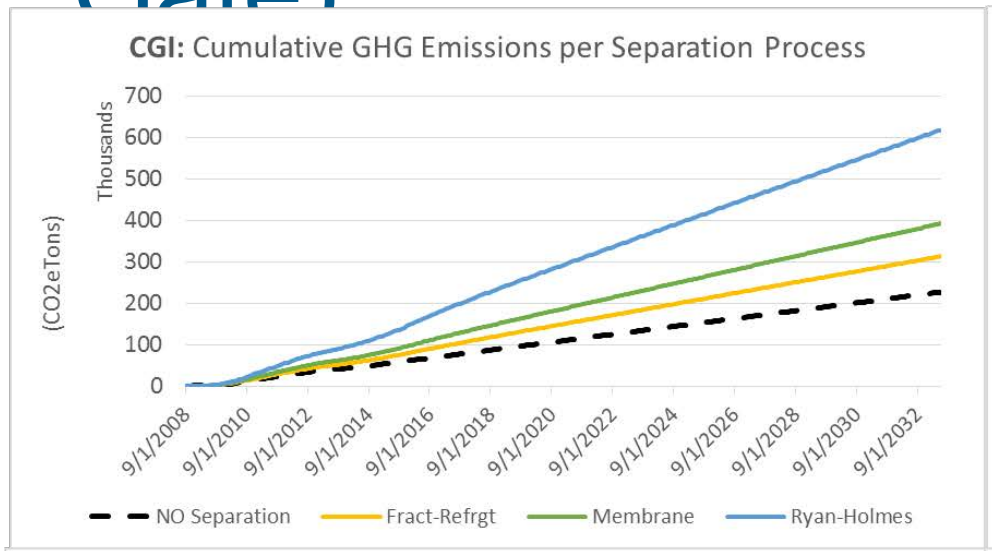


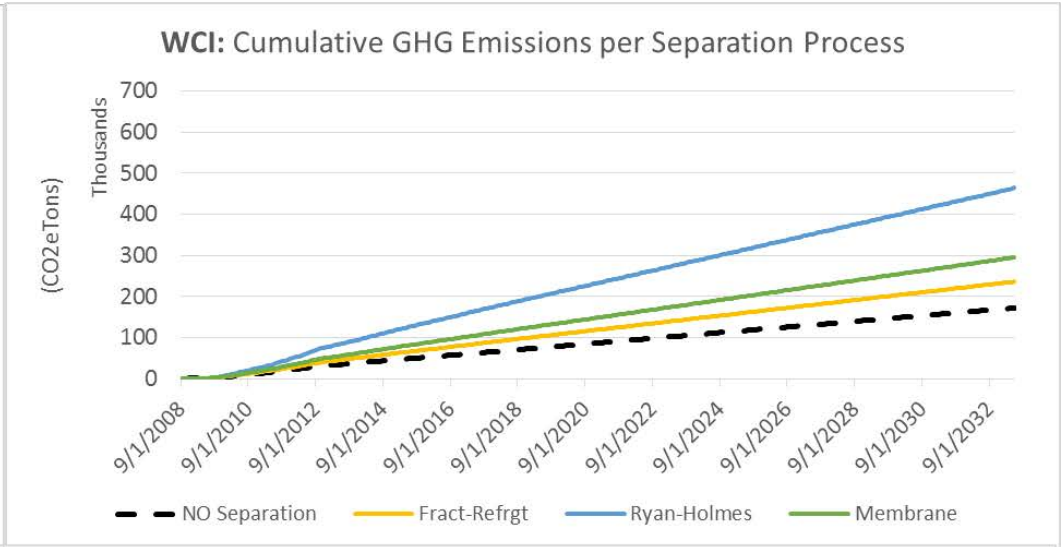
- CMG-GEM compositional package
- Solubility modeled with Henry's law
- Oil and gas PVT tuned
- History matching of historic production data (1944-1964)
- Oil, water, gas production data is available
- Shut-in period (1964-2008)

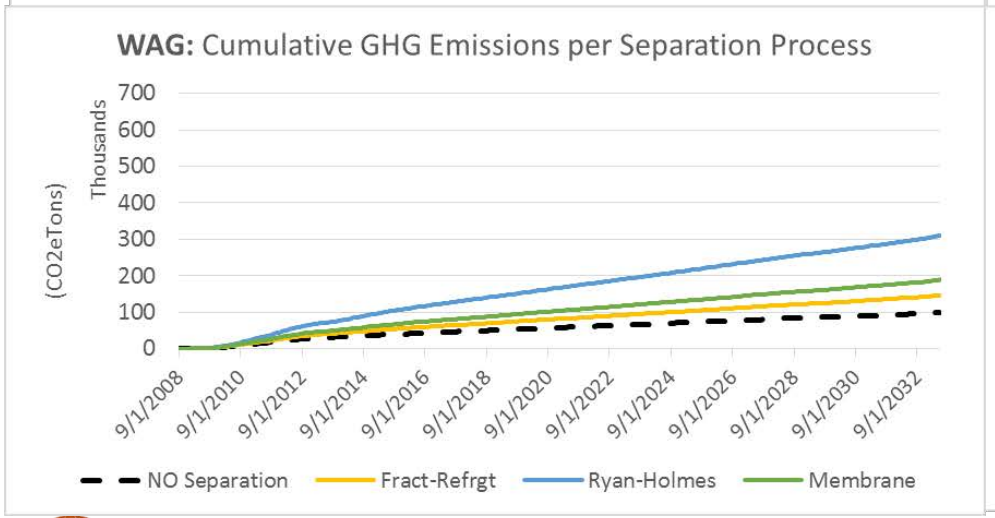
GCCC GULF COAST CARBON CENTER

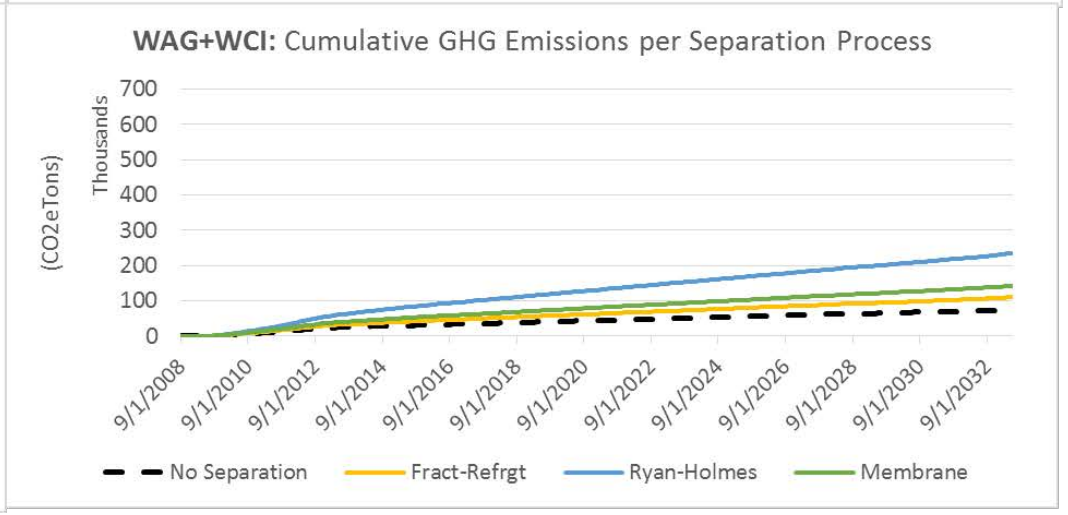
BUREAU OF ECONOMIC GEOLOGY

Emissions Evolution : EOR Site (Gate to Gate)





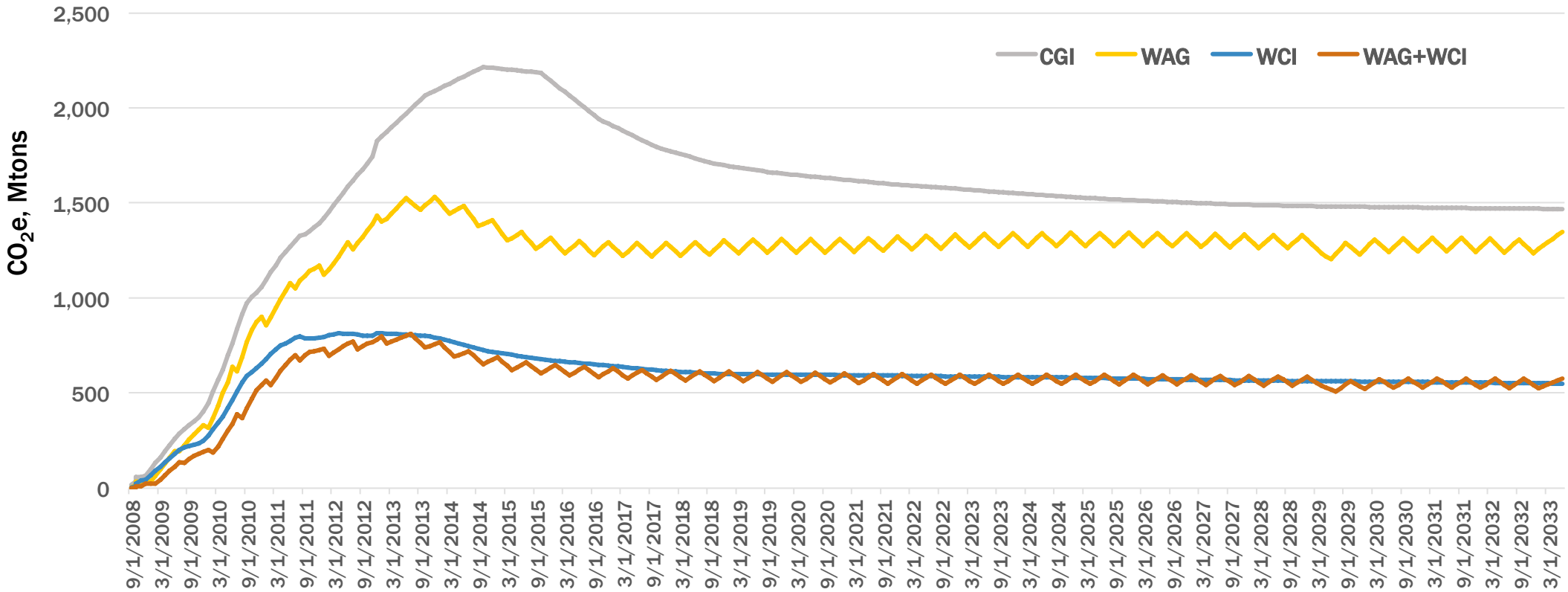




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Storage Evolution: EOR Site (Gate to Gate)

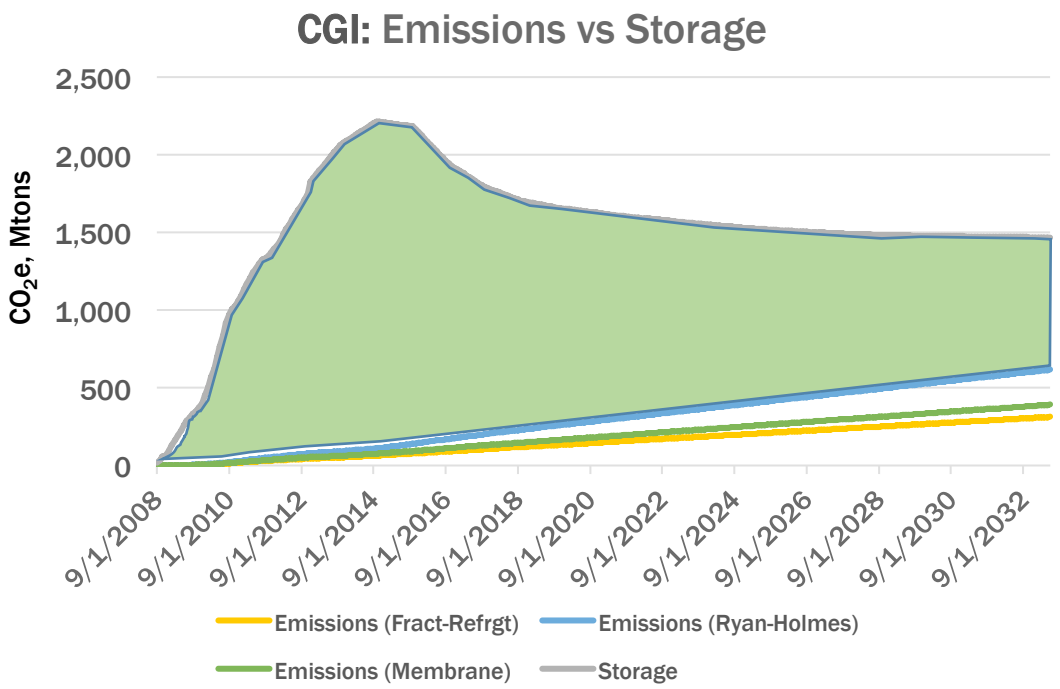


GCCC GULF COAST CARBON CENTER

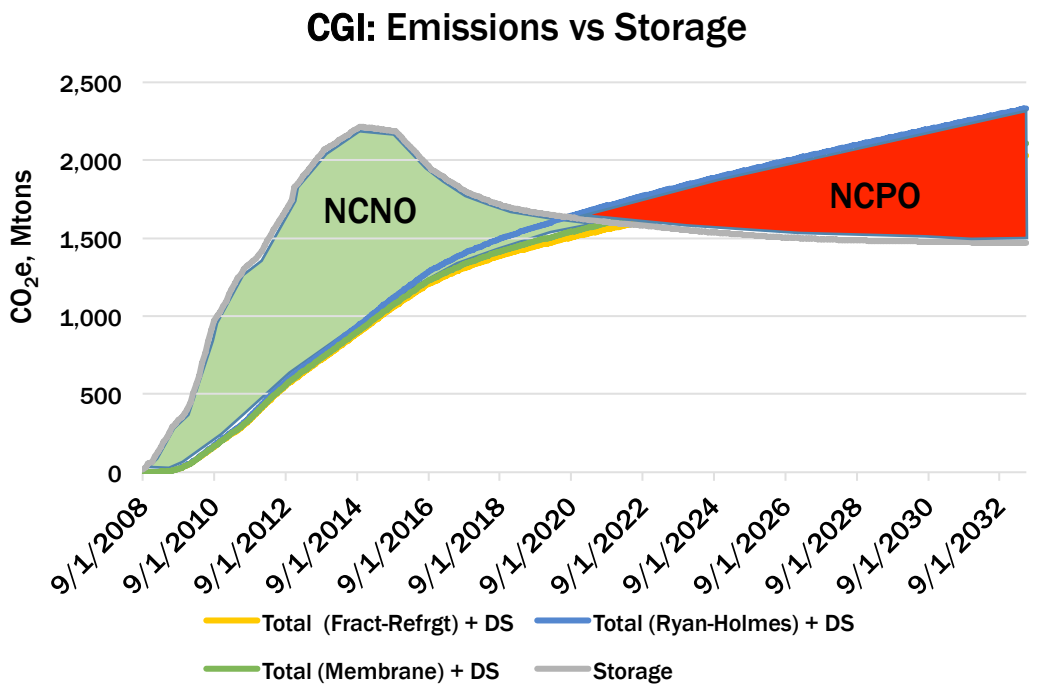
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Impact of Downstream Emissions (Gate to Grave)
(CGI Scenario)

Gate to Gate

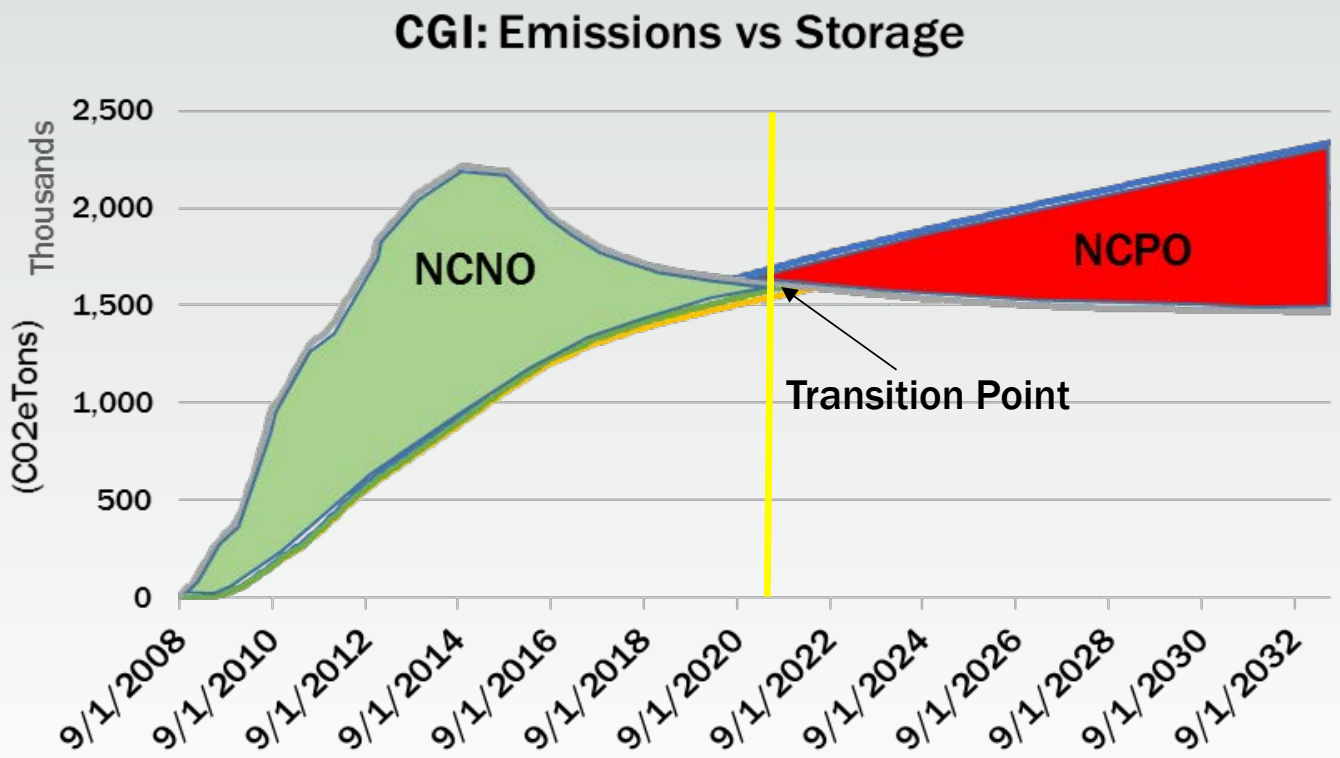


Gate to Grave



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Carbon Balance Evolution: Gate to Grave (CGI Scenario)



Values at Transition Point:

CO_2 Storage: 1.6 MMtons CO_2e

Oil Production: 3.1 MM bbls

% of Ultimate Recovery : 81%

NCNO Period: 52% (11.5 – 14 yrs)

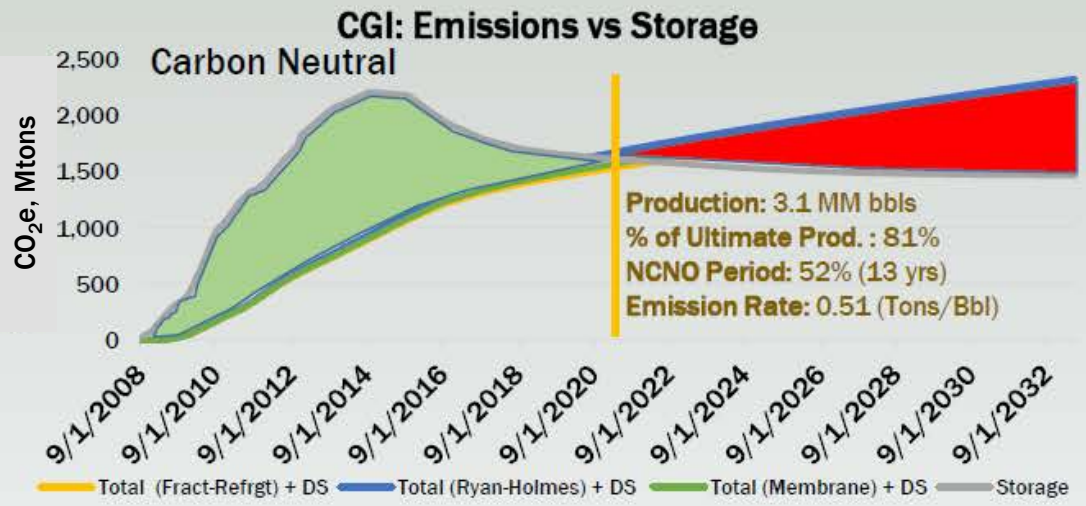
Emission Rate: 0.51 (Tons/Bbl)

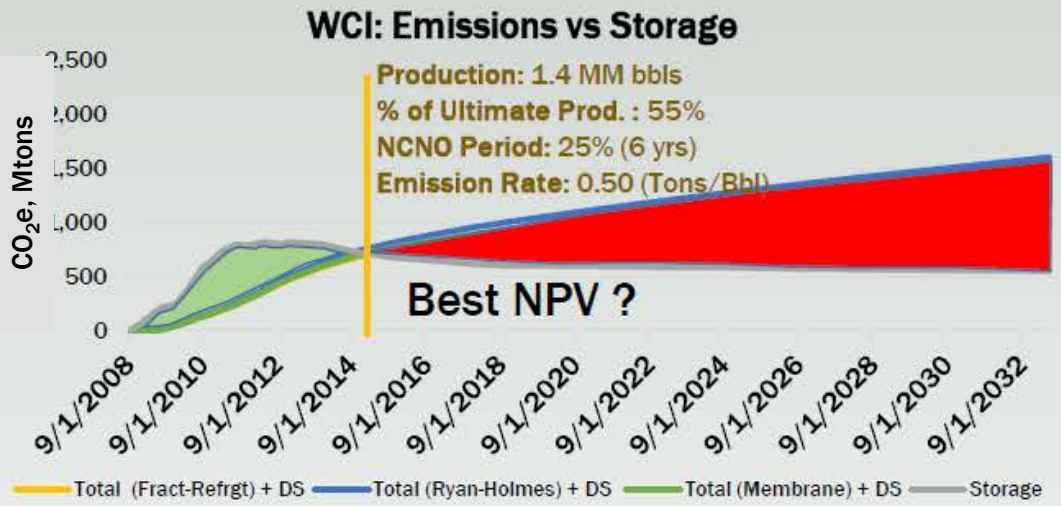
Net Injection Rate: 5.25 (Tons/Bbl)

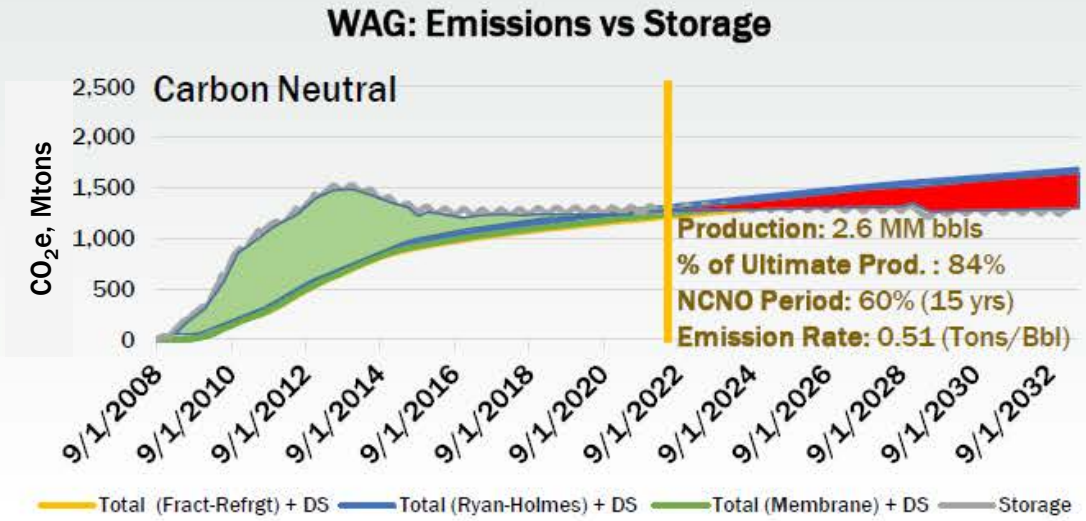
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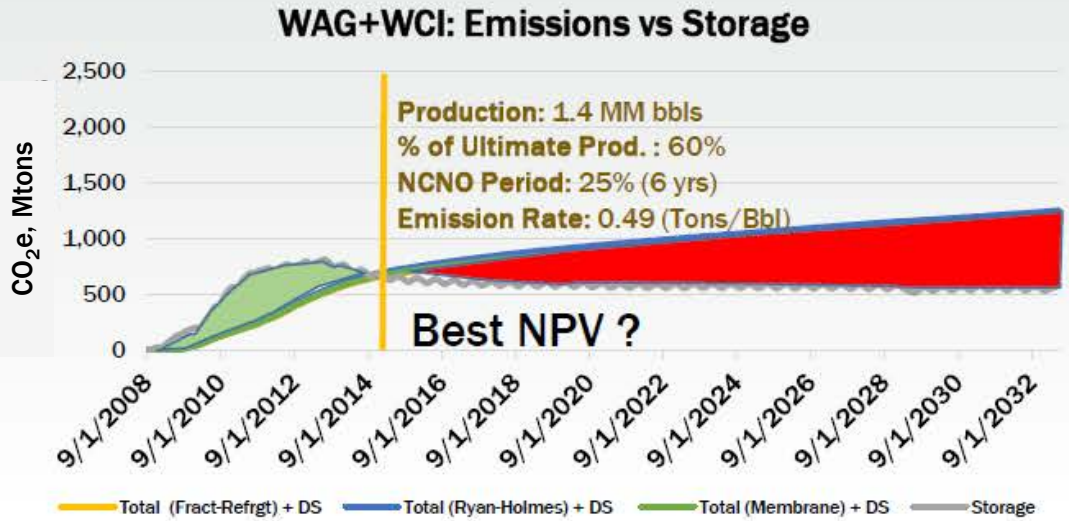
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Carbon Balance Evolution: Gate to Grave









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Impacts and Key Findings

- ✓ **Validated CO_2-EOR as a greenhouse gas emission reduction technology.**
- ✓ Obtained results that show how in our case study (Cranfield) all CO_2-EOR injection strategies start producing NCNO and at some point transition into producing net carbon positive oil (NCPO).
- ✓ The NCNO period can be engineered to last longer, as it is highly dependent on the CO_2 injection strategy.

Knowledge Sharing

Gulf Coast Carbon Center

GCCC GULF COAST CARBON CENTER

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Knowledge Sharing

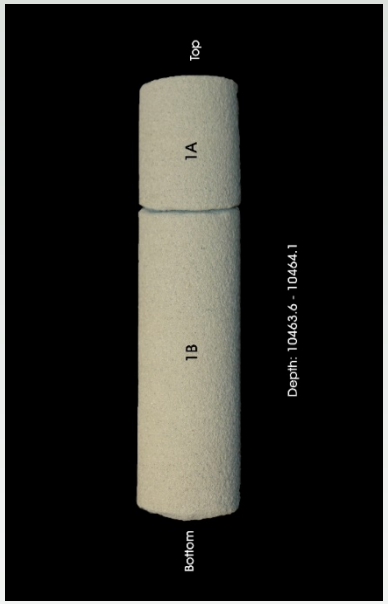
- Transmit SECARB research results to stakeholder groups though diverse, effective communication strategies.
- Engage key stakeholders, decision-makers, informal and formal education professionals and students, relevant industry and regulatory participants, or new programs.
- Provide peer review.
- Bring information developed elsewhere back for US application.

Collaboration Synergies

Field data collection
Microseismic –RITE
CO_2 Geothermal– LBNL
PIDAS – Sun
CCP-BP gravity
Microbes – U KY
3-D VSP - NRAP
Borehole seismic –Groundmetrics
Nobles - U. Edinburgh
Fluid Chem–Ohio State
Well integrity -Schlum/Battelle

Modeling efforts
SIMSEQ –LBNL
15 teams
CFSES – UT/ SNL
IPARS –Wheeler
NRAP
NCNO
LBNL
CCP3
UT- LBNL Zhang
LLNL

119 history match efforts



Additional Analysis
EOR accounting - NETL- Mei/Dilmore
Rock-water reaction - NETL-
Basic Energy Science - LLNL

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Status of EDX uploads

- 44 data sets uploaded
- 10 data sets are pending completion of QC and upload

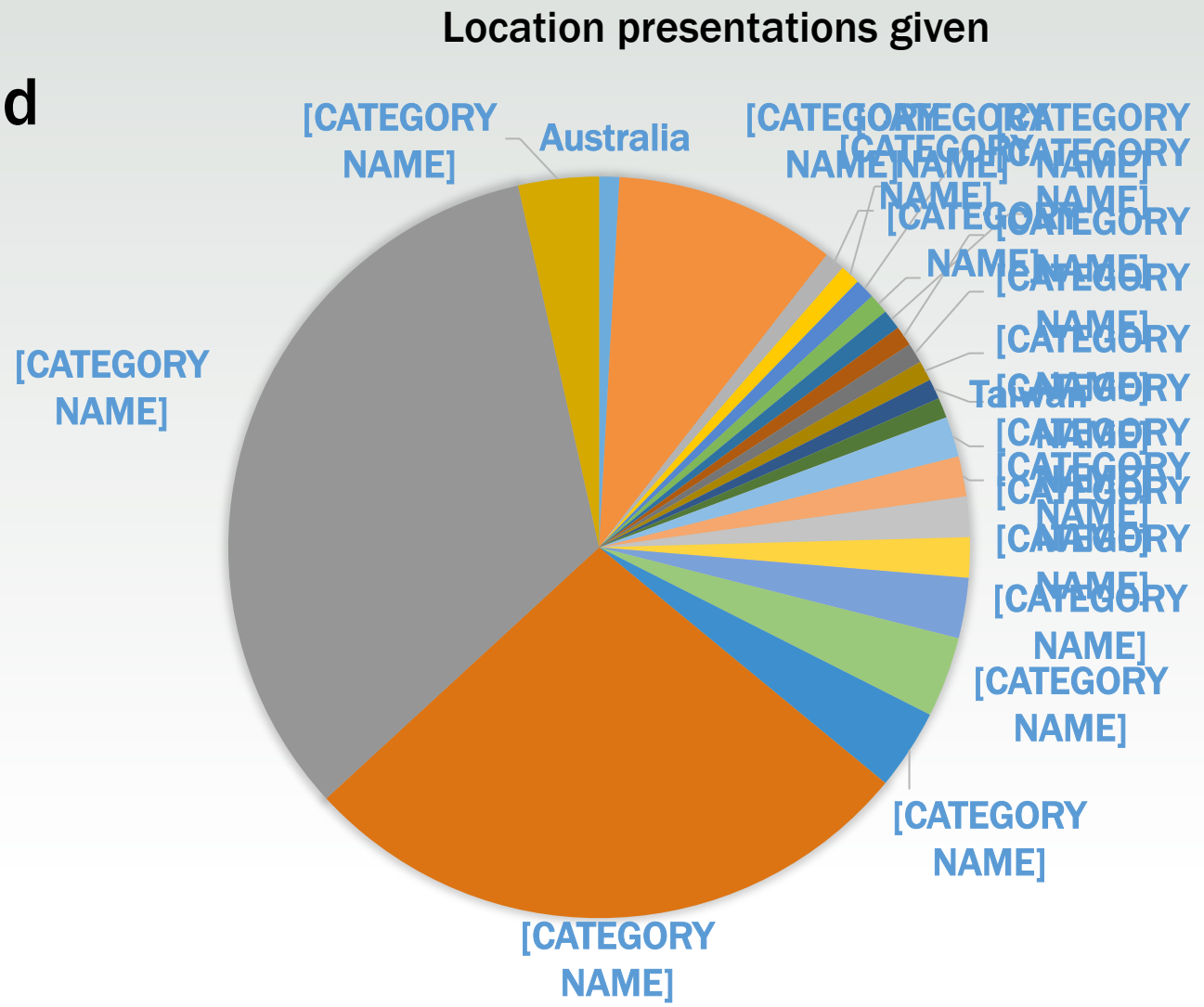
Data Type	Pending	Completed
Borehole logs	2	3
Core logs (photos and sidewall core analysis)	1	3
Rock-based data (thin section descriptions)		2
Rock-based data (thin section descriptions)		2
Rock-based data - sedimentary graphic logs		2
Rock based data - stratigraphic intervals		2
Capillary entry pressure		1
Geochemical data USGS data		1
Geochemical data - U-tube sampling operation logs		1
Cross-well seismic - baseline	1	
Cross-well seismic - repeat	1	
VSP - baseline		1
VSP - repeat		1
ERT		1
Soil gas data		1
Soil gas data - Hingst work		1
Bottom Hole pressure		4
Bottom Hole pressure AZMI		4
Tubing Pressure		4
Groundwater level		1
Groundwater chemistry	1	
Bottom Hole gravity		1
F1, F2, F3 Gyroscope survey		3
Airborne magnetic and conductivity survey	1	
DTS well design		2
DAS F2 DTS		2
Monthlies	1	
Quarterlies	1	
Topical reports and milestones	1	
Cementing data		1
TOTALS	10	44

Knowledge Transfer

- 96 publications including a special issue on Cranfield
- Technical input into International Standards Organization (ISO) standard 265 on CCS, in particular working group 6 on storage associated with EOR
- Presentations and review California Air Resource Board Draft CCS Protocol
- Draft Regulatory Amendments to the Low Carbon Fuel Standard as these pertain to CCS technology

Presentations in the past four years

- 203 presentations included SECARB results
  - Most were technical
  - 14 to students and public
  - 11 targeted to press


Location presentations given
[CATEGORY NAME]
Australia
[CATEGORY NAME]
[CATEGORY NAME]
[CATEGORY NAME]

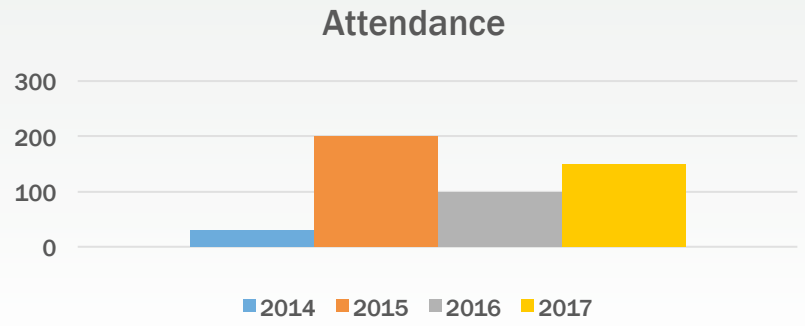
UNFCCC Climate Change Conference











Leadership and participation of this highly consequential collaborative event

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SECARB Experience

500 T

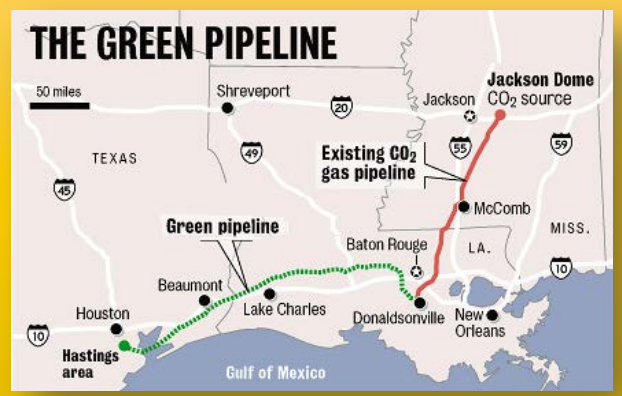


Frio Brine Storage Pilot 2004



SECARB Early Test- Cranfield Mississippi

Hastings Project



NRG Petranova Project



1.6 MMT/ year

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Participation in document preparation

- Presentations and comments to California Air Board on accounting for CCS
- International Standards Organization draft standards 265 about EOR as part of CCS
- Society of Petroleum Engineers
  Storage Resources Management System (SRMS)
- Letter to Executive Secretary of the United Nations Framework Convention on Climate Change with assurances that CCS is secure and safe

Progress in application of SECARB Learnings

- Progress on optimization of monitoring approach: ALPMI method
- Recognition of need for attribution to prepare for incident or allegation
- Understanding limitations of groundwater surveillenve
- Tool and methodology development and demonstrations
  - Soil gas
  - Groundwater
  - Pressure-based methods
- Methane limits to CO2-EOR offshore
- Project development to maximize NCNO
- Taking approaches to the field in commercial projects
- Monitoring network design
- Integrated system development
- Outreach to technical and non-technical stakeholders

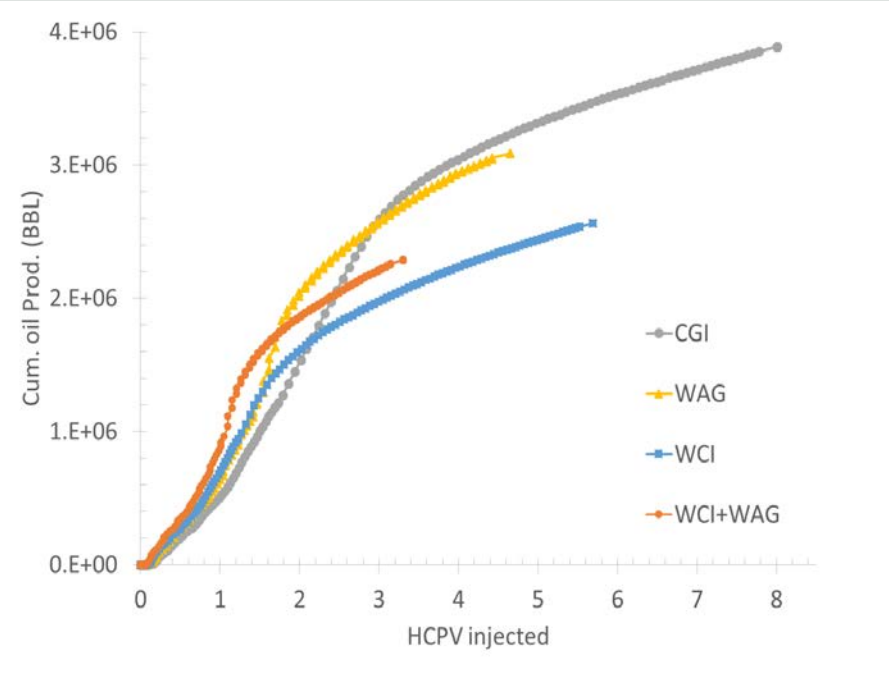
Thank you

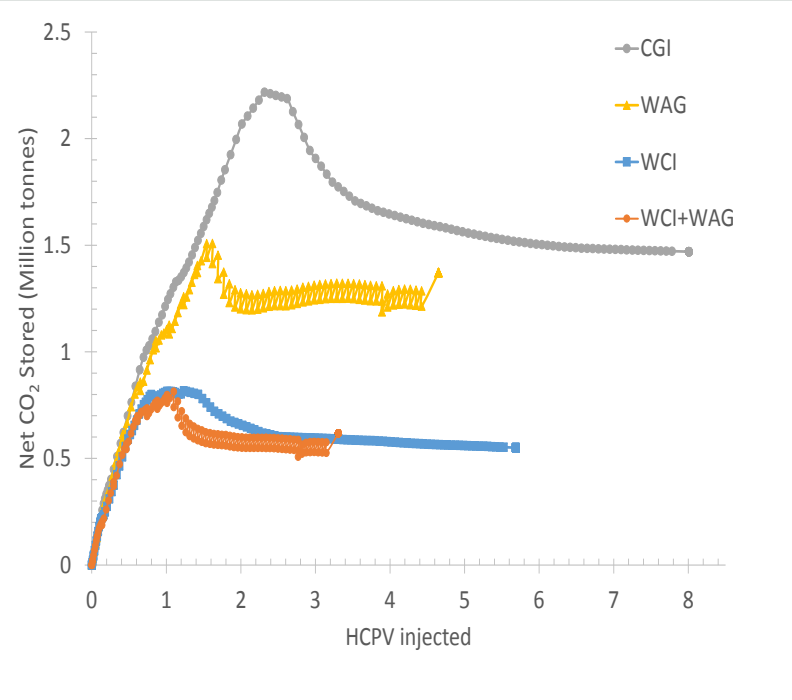
Katherine Romanak
Gulf Coast Carbon Center
Bureau of Economic Geology
The University of Texas at Austin

katherine.romanak@beg.utexas.edu

http://www.beg.utexas.edu/gccc/

Subsurface Results (Cranfield)





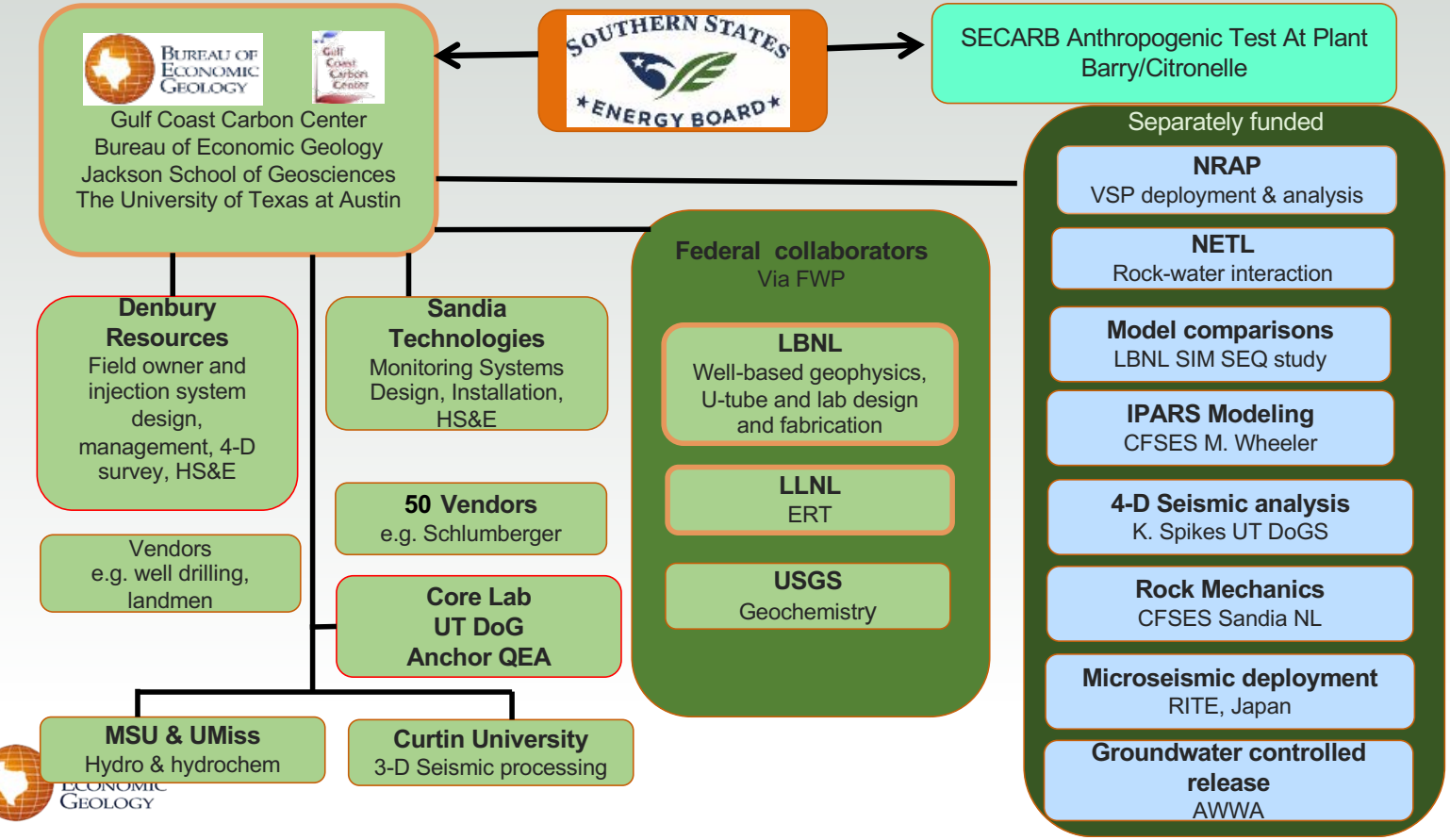
- **WAG shows a good balance between maximizing oil production and CO_2 storage with a lower gross utilization ratio compared to other scenarios.**

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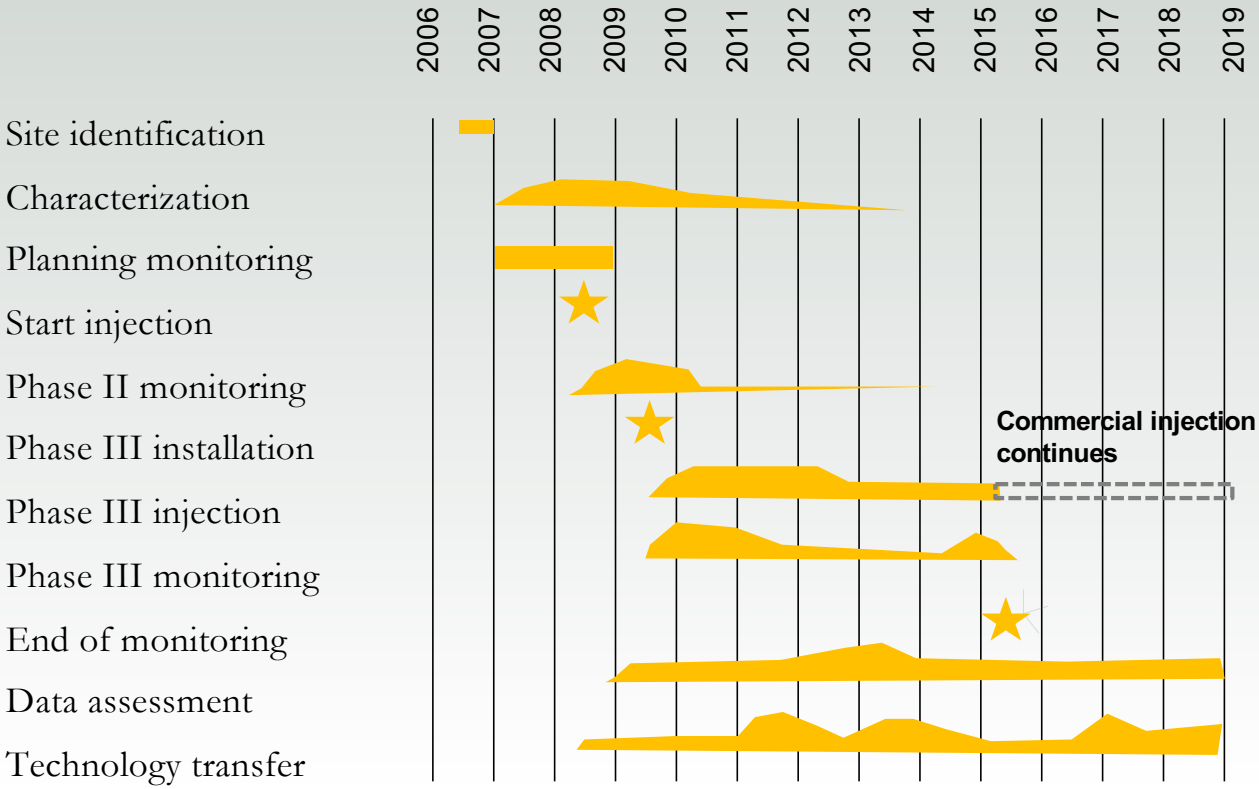
Advancing Toward Commercialization
Final Stages of the Early Test

Susan Hovorka
Gulf Coast Carbon Center
Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin

Team Structure



Early Test Evolution



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Early Test Goals

- Large-scale storage demonstration
  - 1 MMT/year over >1.5 years
  - Periods of high injection rates
    - Result >5 years monitoring with >5 MMT CO_2 stored
- Measurement, monitoring and verification
  - Tool testing and optimization approach
  - Deploy as many tools, analysis methods, and models as possible
- Stacked EOR and saline storage
- Commercial technology transfer
  - Uploaded data to EDX



Current major effort

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Contributions of Early Test

- Early Test Developed monitoring approaches for later commercial projects
  - Process-based soil gas method
  - Effectiveness of groundwater surveillance
  - Pressure and fluid chemistry monitoring in Above-Zone Monitoring Interval (AZMI)
  - ERT for deep CO_2 plume
  - Limitations of 4-D seismic

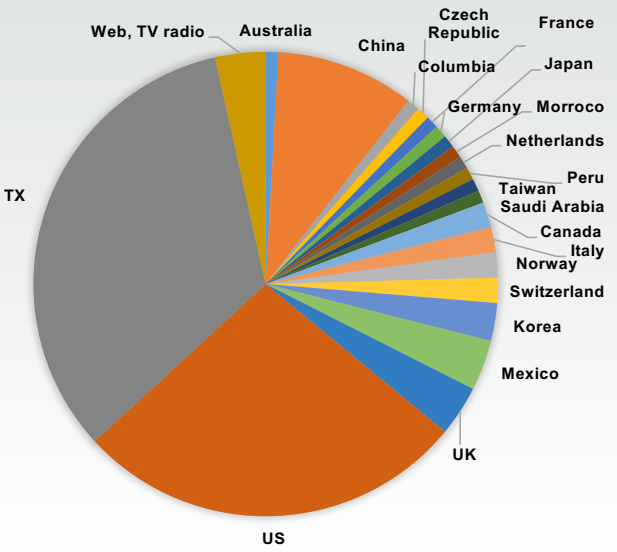
Publications, Workshops, Presentations

- 108 Early test-derived publications
- Presentations
  - http://www.beg.utexas.edu/gccc/news/2019



Katherine Romanak was a panelist and co-organizer of the only CCS-dedicated side event at the 24th Conference of the Parties to the UNFCCC (COP24) in Katowice Poland. Photo by Malgosia Rybak





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Down-selection of monitoring tools

You can't have everything! Example limitations:

- Tool interference

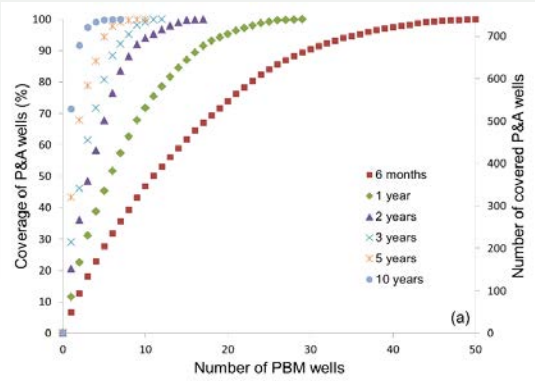
  e.g. "jewelry" on casing interferes with log response

  Perforated well – geochemical and geophysical tool deployment interference

- Tool limitations – cost, cost of analysis

  Paper on cost/value

Sensitivity of time until detection of leakage on number of wells installed, Bolhassani (*2017.)*

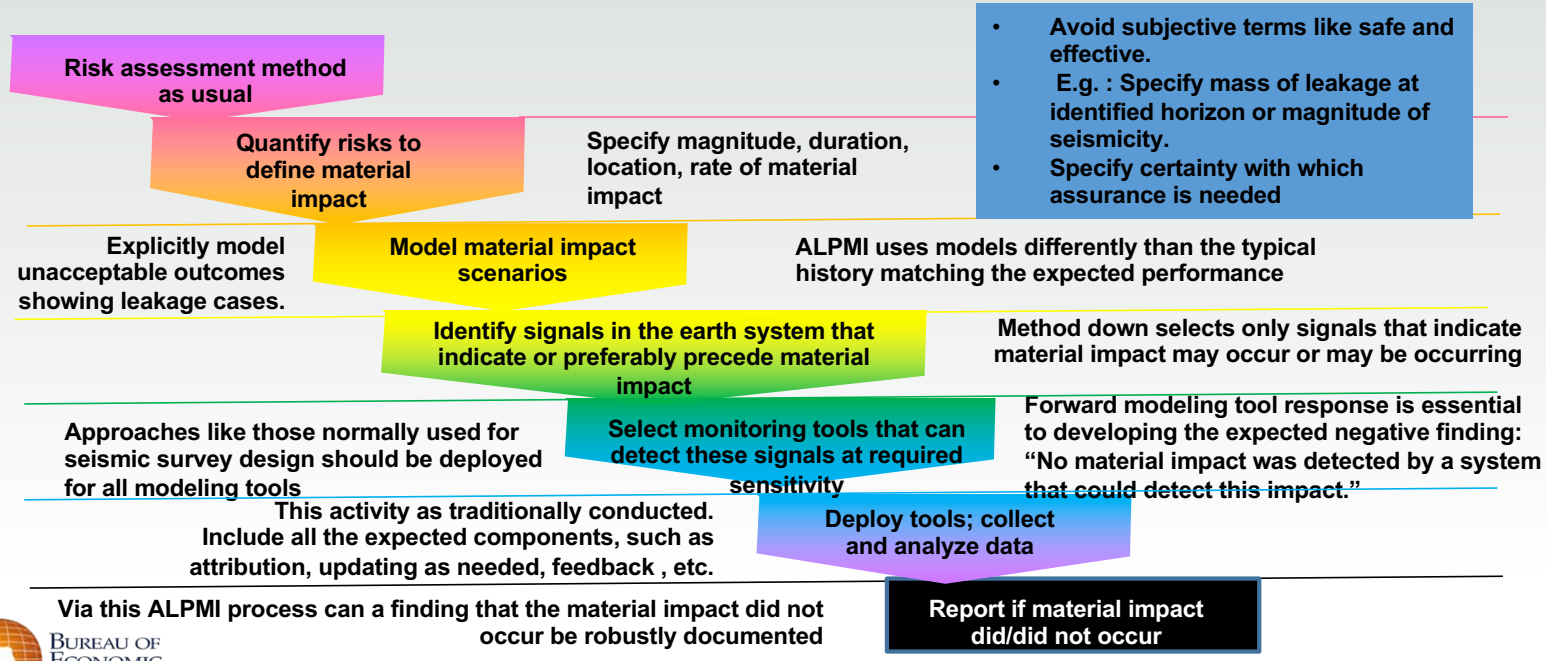


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Methods for down-selection of monitoring tools

- Optimized tool selection (Assessment of low probability material impact: ALPMI)



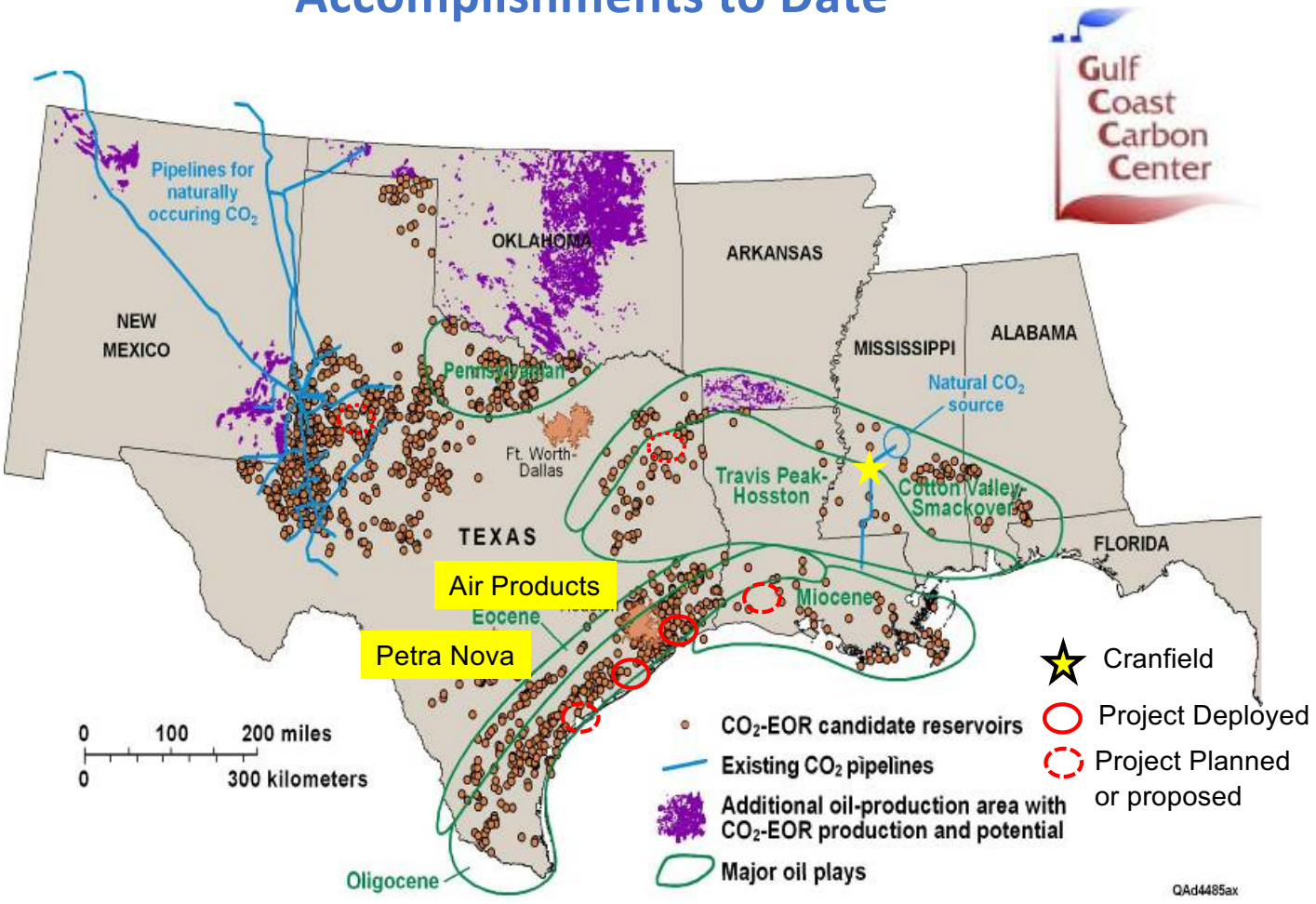
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Moving CCS toward Commercialization – technical data to inform policy

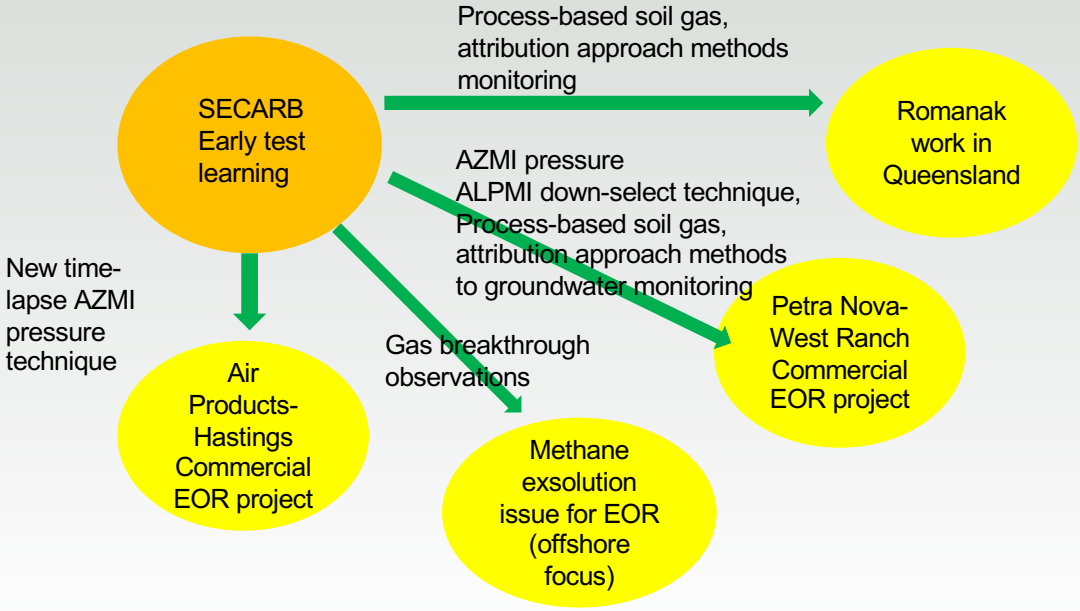
- SECARB-based work on:
- Review and comment on Draft CCS Protocol of the California Air Board Low Carbon Fuel Standards
- Assist with preparation of Society of Petroleum Engineers CO_2 Storage Resources System Management document and guidance
- Completed serving on International Standards Organization working group on accounting for storage associated with CO_2 EOR

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Commercialization of learnings at SECARB Early Test Accomplishments to Date



Technology transfer from SECARB early test to other projects



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Next Steps after RCSP

- Beyond Carbon SAFE project locations
- Monitoring linked to policy e.g. 45Q, CA LCSF and evolving
- Life cycle for EOR options
- Education of stakeholders, business, finance and local and national public, students
  - Realistic risk/benefit/feasibility
- Lower risk lower cost site closure technical input

CO_2 EOR Feasibility in SECARB Region Limited by CH_4

Sarah Prentice

Susan Hovorka, William Fisher, Tip Meckel

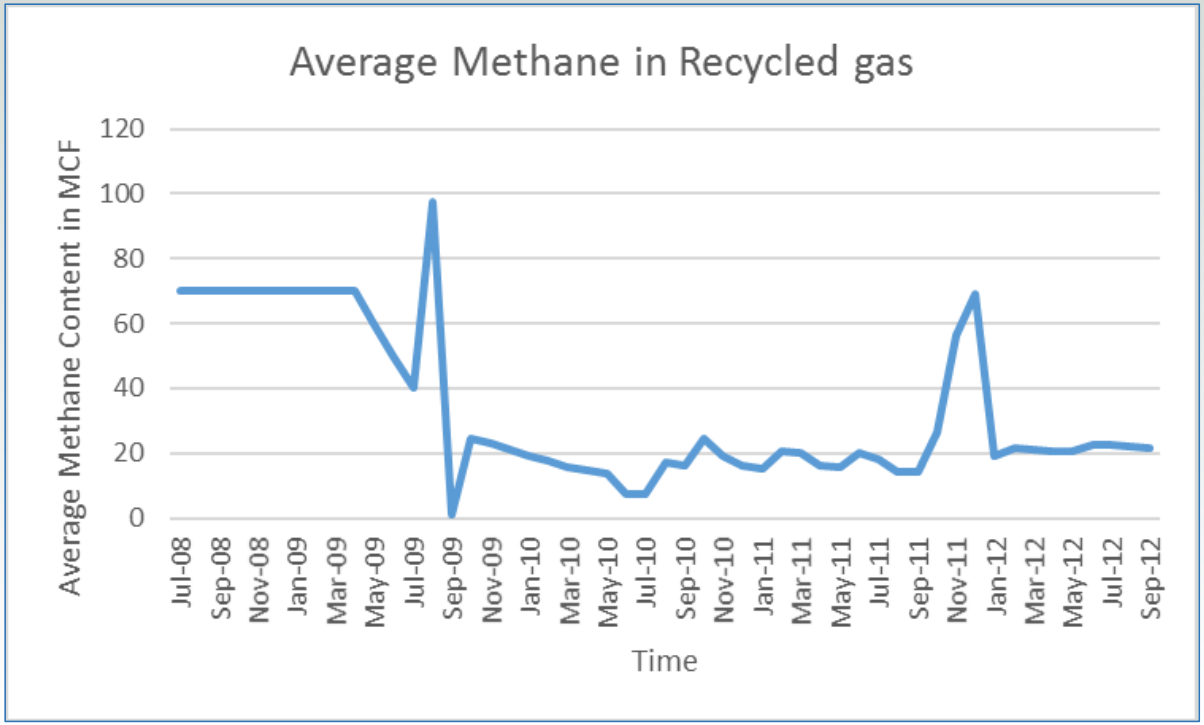
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Methane and Cranfield

Cranfield

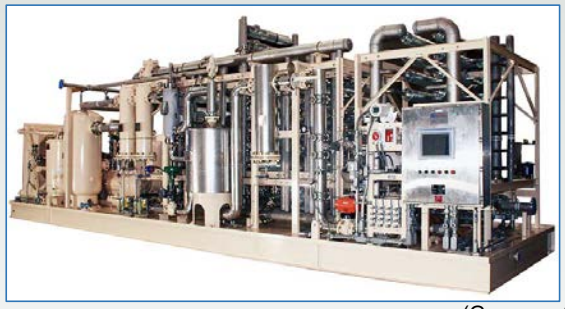
- 672,472,000 Mstd ft^3 Historic Gas Production
- 2 to <10% Methane Fraction



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(Choi et al., 2013)

Problem of Methane Removal



(Generon, 2018)

Separate CO_2 and methane

OR



Modified from (ICIQ, 2018)

Don't use recycled CO_2

OR



(Science Photo Library, 2016)

Immiscible Flooding

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Economic Impact

- Snøhvit reinjects CO_2 emissions from three fields Gas gets pumped onshore to separate CO_2 and CH_4
- Increases capex and opex costs



Potential Affects On SECARB Area: The Gulf Coast

$$28.7\ billion\ bbls\ OOIP\ - 11.6\ billion\ bbls\ recovered$$
$$= \mathbf{17.1\ billion\ bbls\ unrecovered}$$

- Recent interest in shallow water reservoirs for CO_2 EOR
- Change in miscibility could mean changes in economics of CO_2 EOR

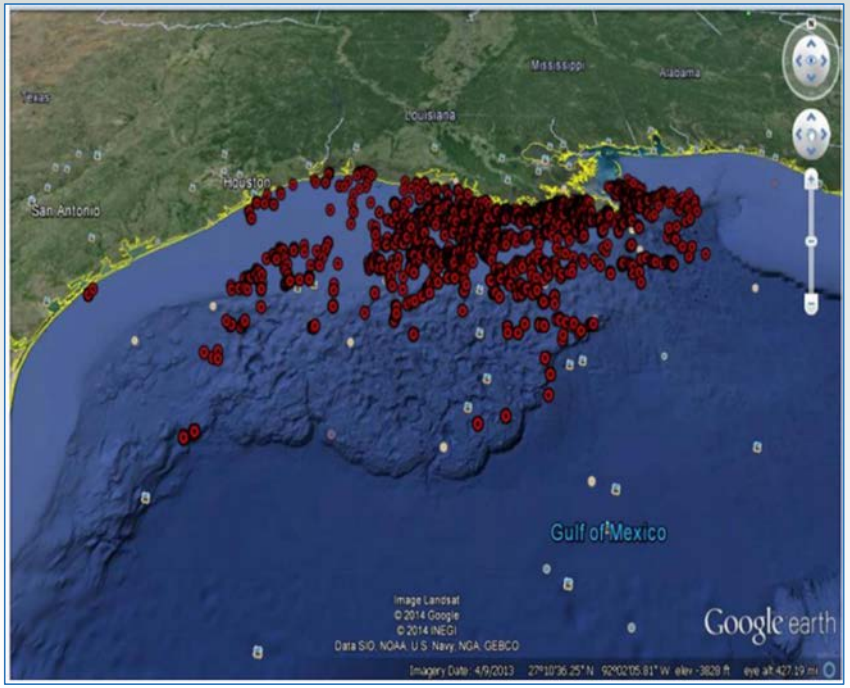


Malone et al, 2014

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Methane as a Limiting Factor in CO_2 EOR

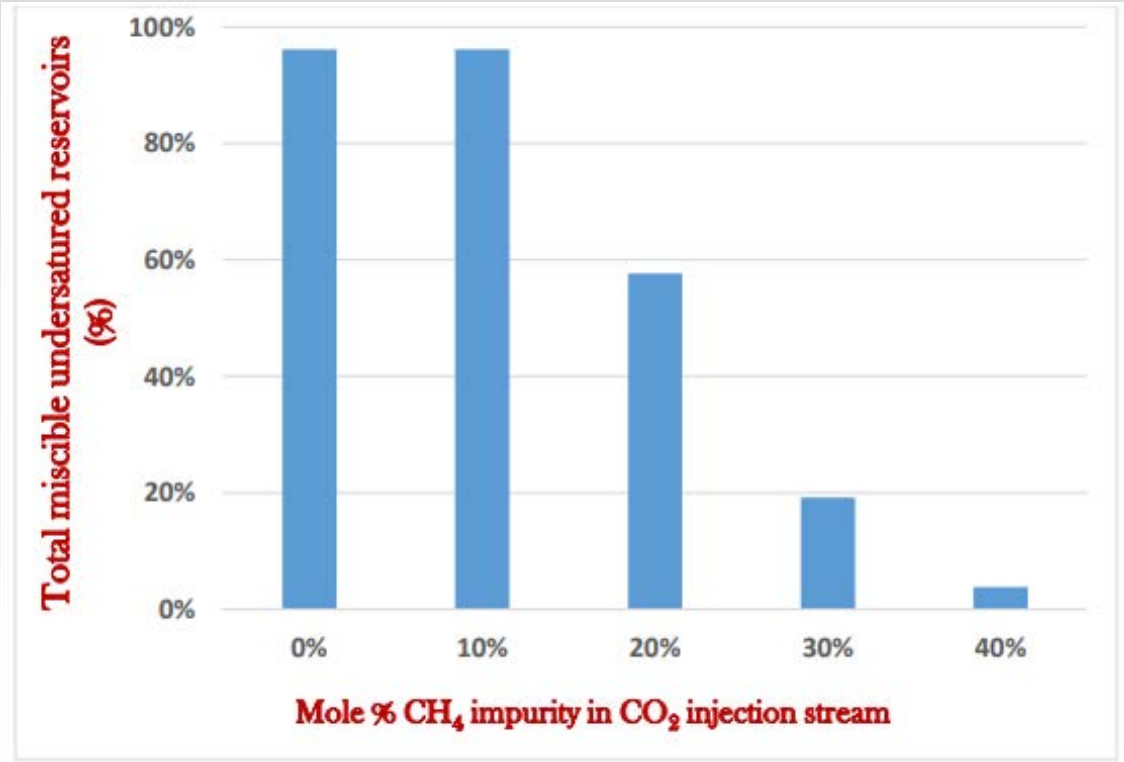
- Model tolerance of CH_4 impurity in comingled production for CO_2 EOR of 3,598 BOEM reservoirs.
- 18 mole percent CH_4 impurity in recycled CO_2 needed to sustain miscibility >70% reservoirs



Map of Offshore Gulf of Mexico Study Areas (Ogbuabuo, 2015)

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Rapid Loss of Miscible Fields At Higher Gas

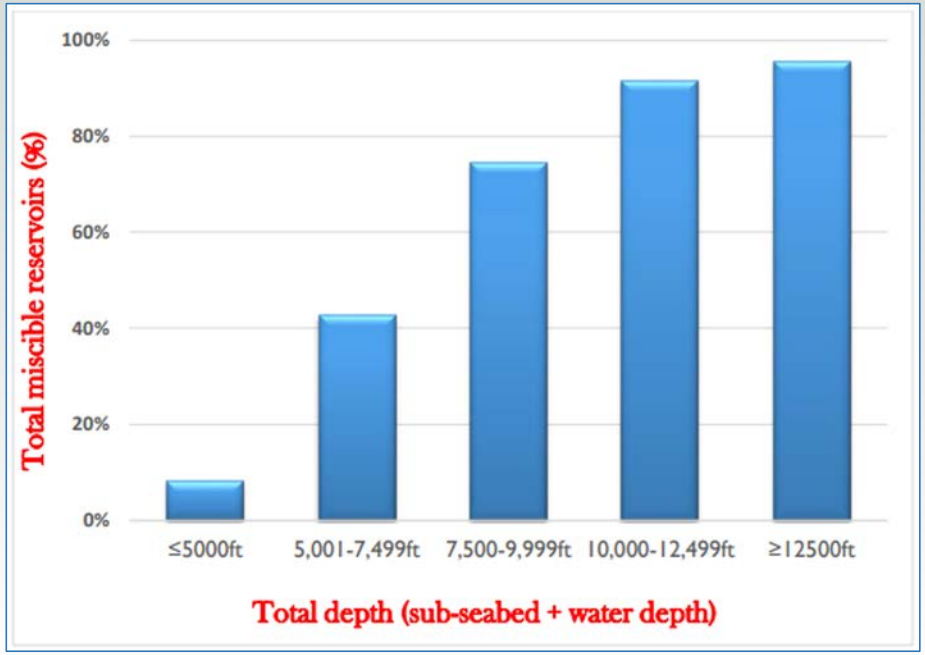


(Ogbuabuo, 2015)

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Methane as a Limiting Factor in Shallow Water CO_2 EOR

- Tolerance was affected by water depth and sub-seabed depth.
- 67% of shallow water reservoirs miscible at 18 mole percent.



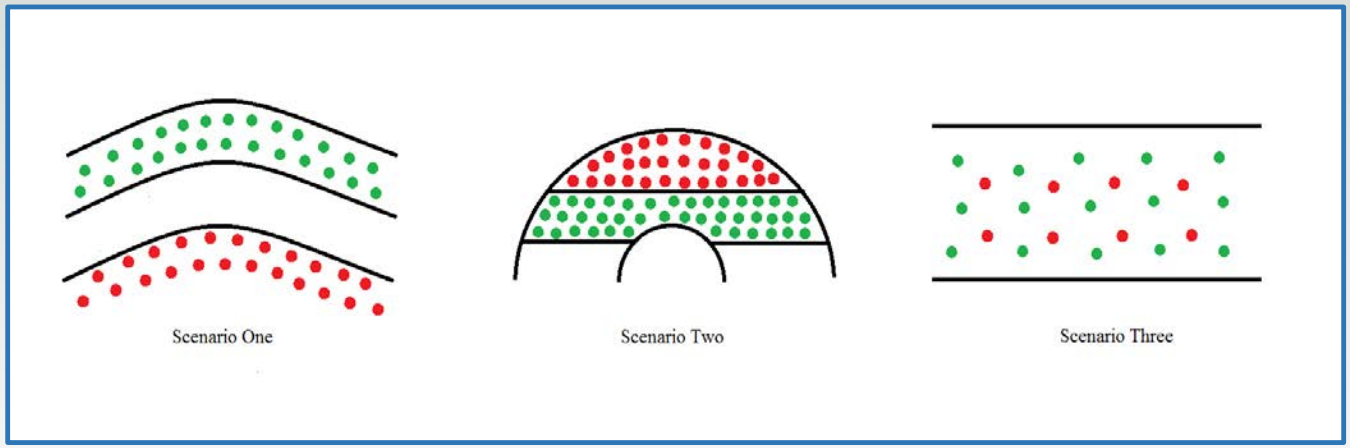
Analysis of total depth and miscibility for 18 mole percent CH_4 impurity

(Ogbuabuo, 2015)

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Applicability of Methane as a Limiting Factor



Scenario 1: Oil and gas are geologically separated by an impermeable layer

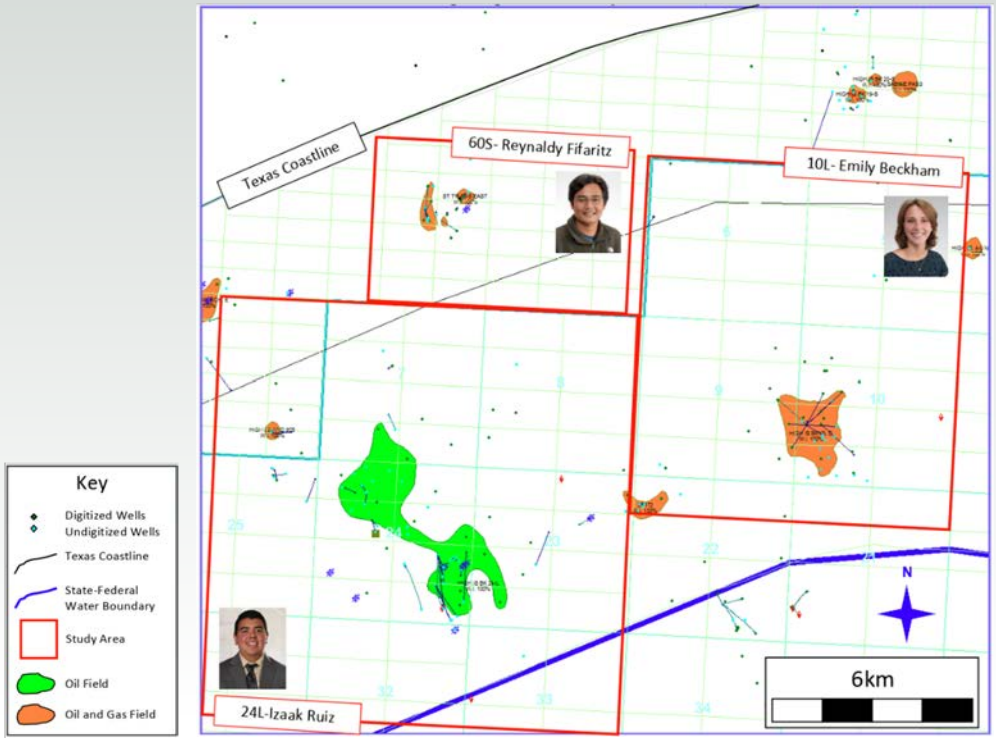
Scenario 2: Oil and gas are separated by gravity

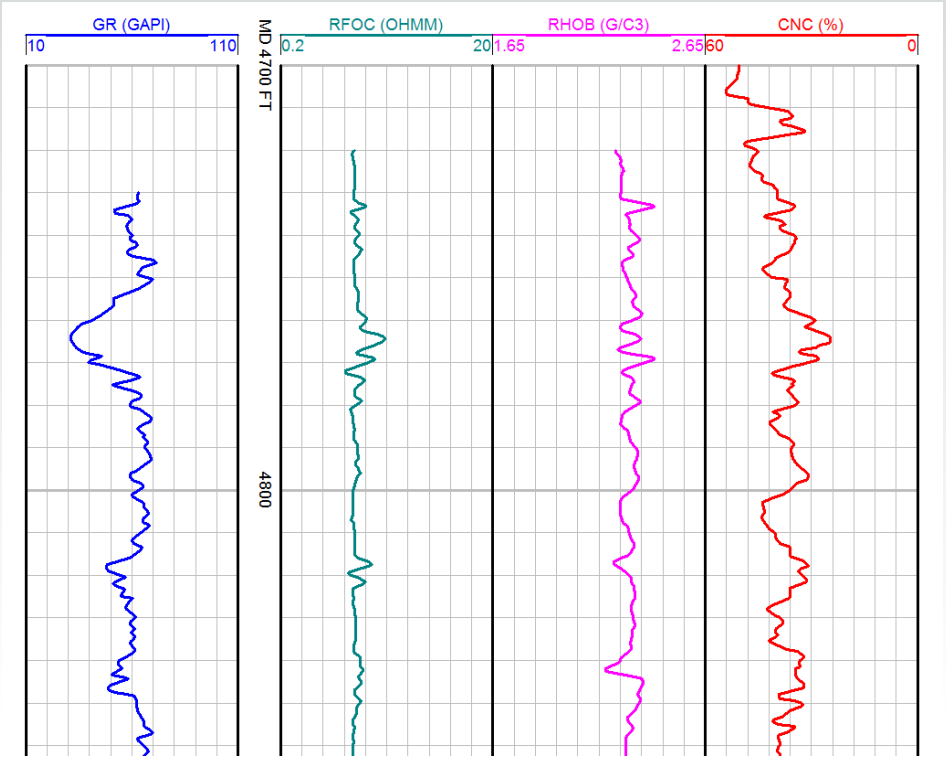
Scenario 3: Gas is dissolved in oil

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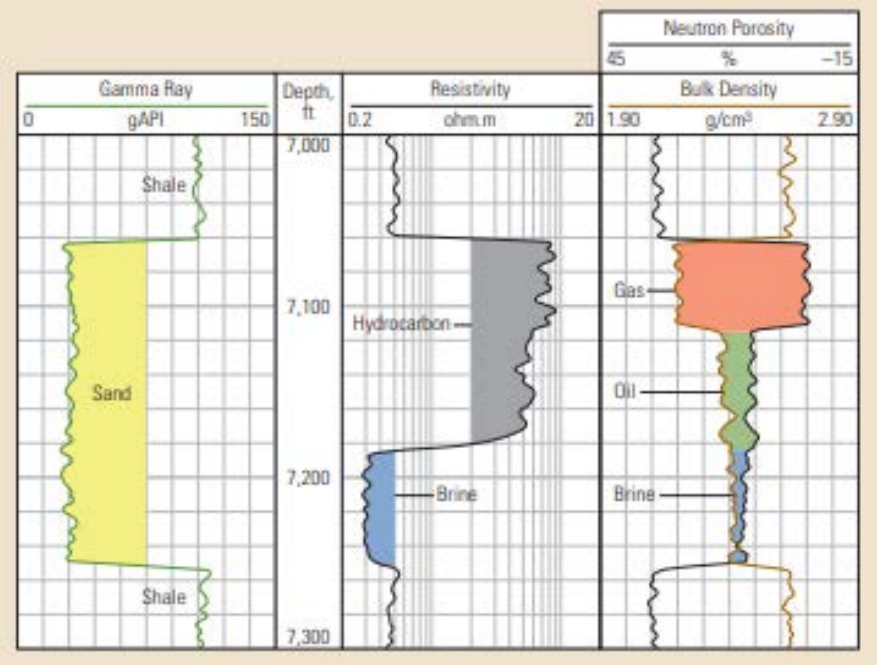
High Island Case Study Area





Gamma Ray, Resistivity, Neutron Porosity and Bulk Density from API 4260630170000

Basic Log Interpretation



Schlumberger

Gamma Ray
- Left: Sandstone
- Right: Shale

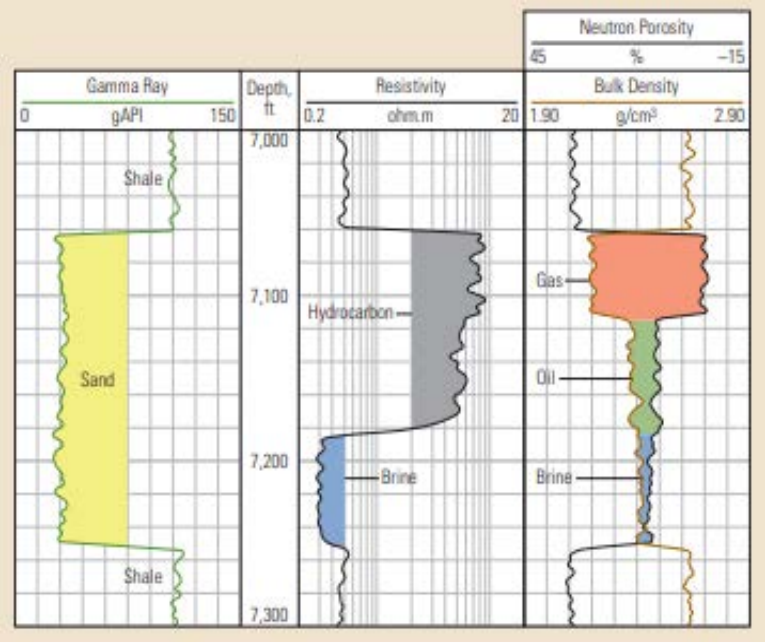
Resistivity
- Right: Hydrocarbon
- Left: Brine

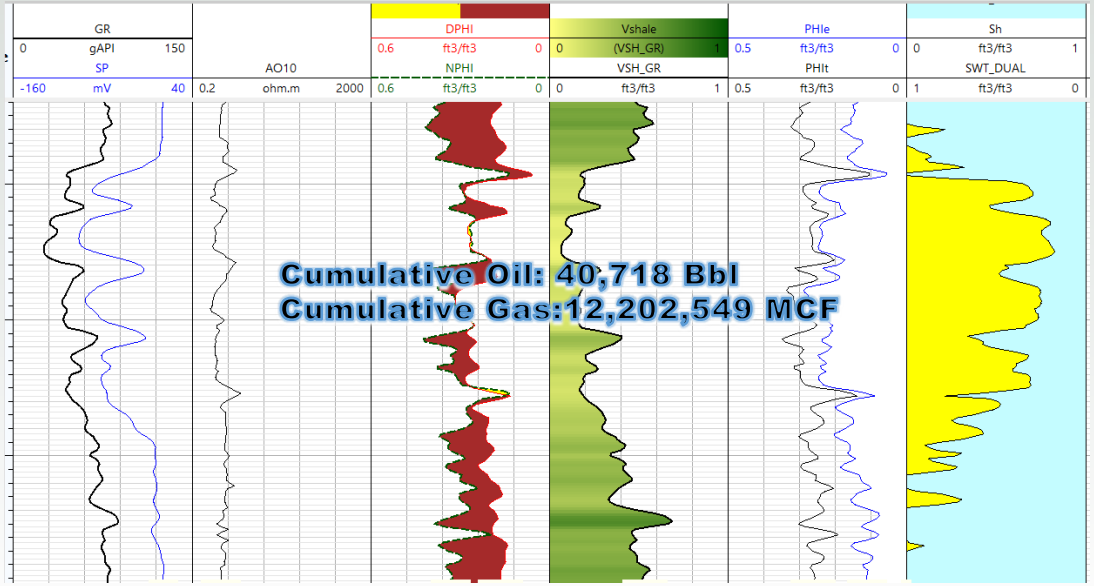
Gamma Ray Left, Resistivity to the Right, Big Cross Over: **Gas**

Gamma Ray Left, Resistivity to the Right, Small Cross Over: **Oil**

Gamma Ray Left, Resistivity to the Left, Small Cross Over: **Brine**

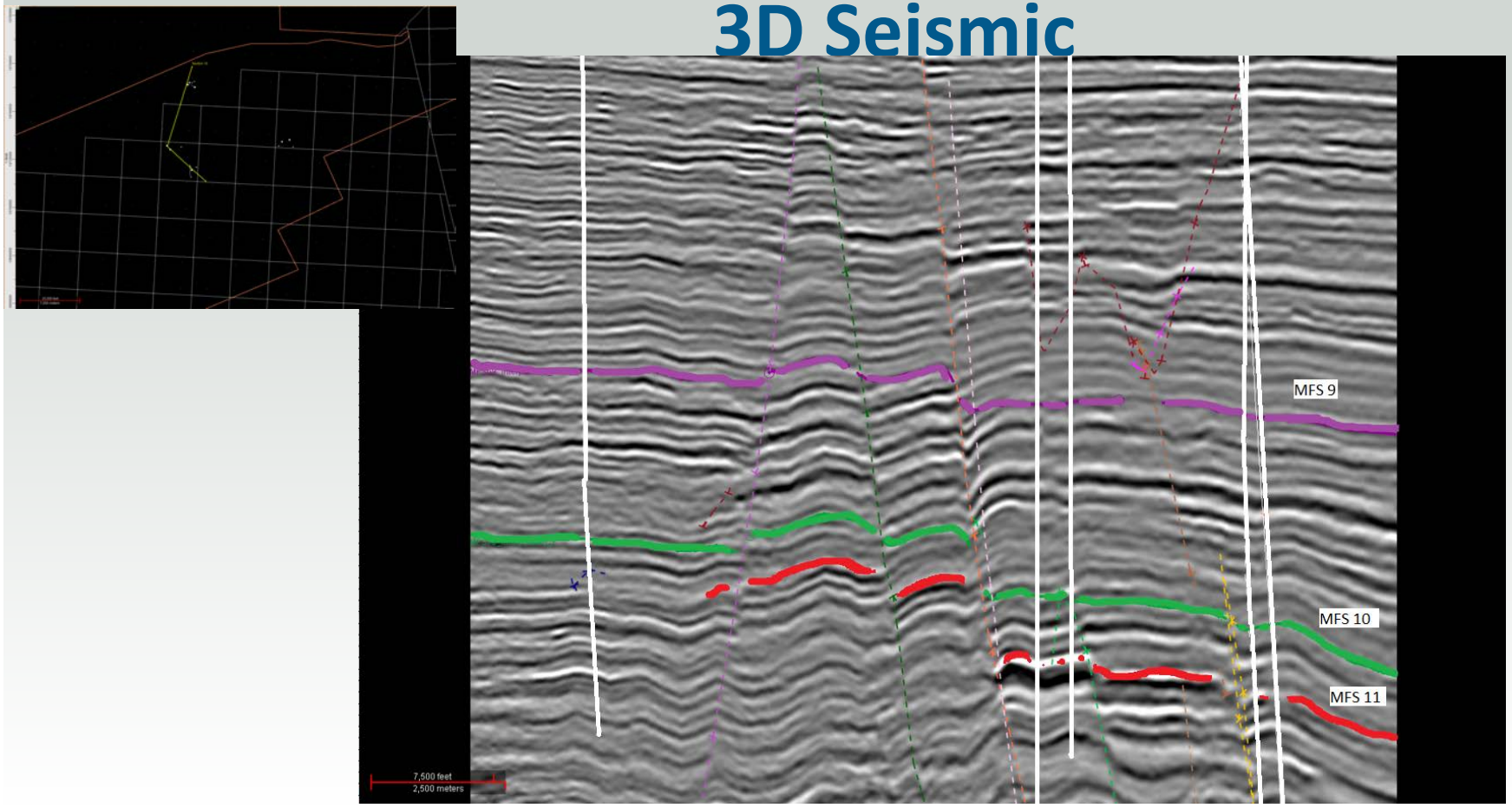
Log Interpretation





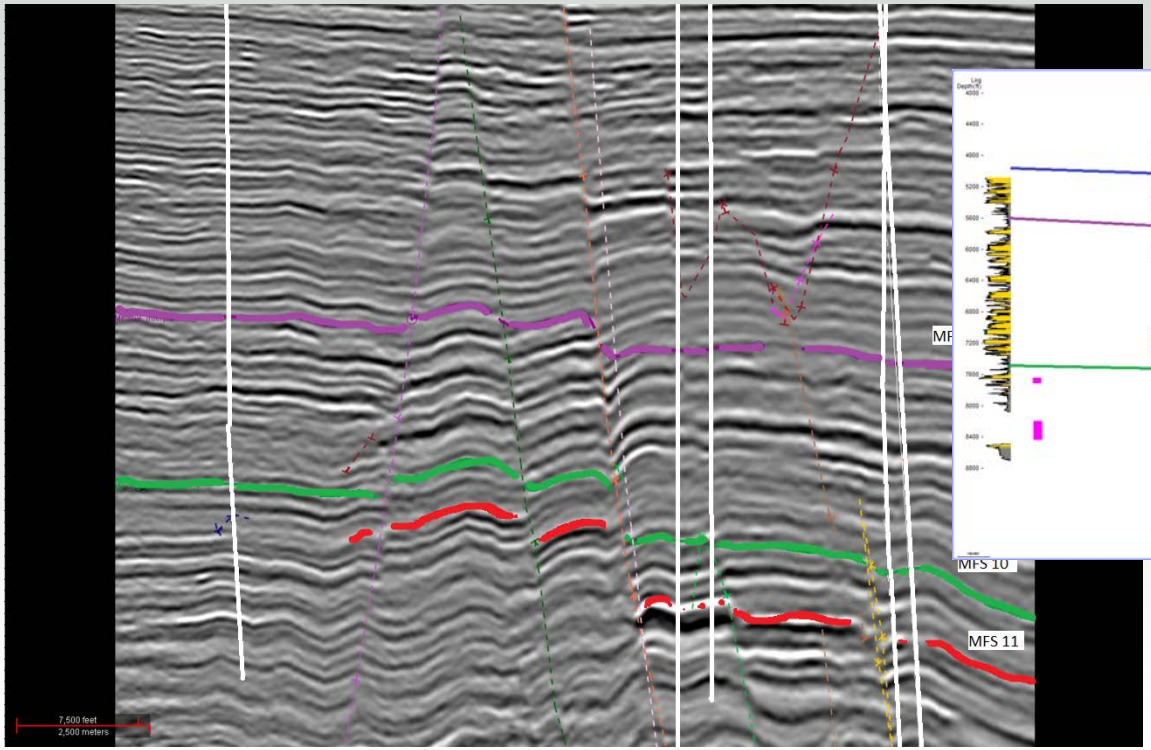
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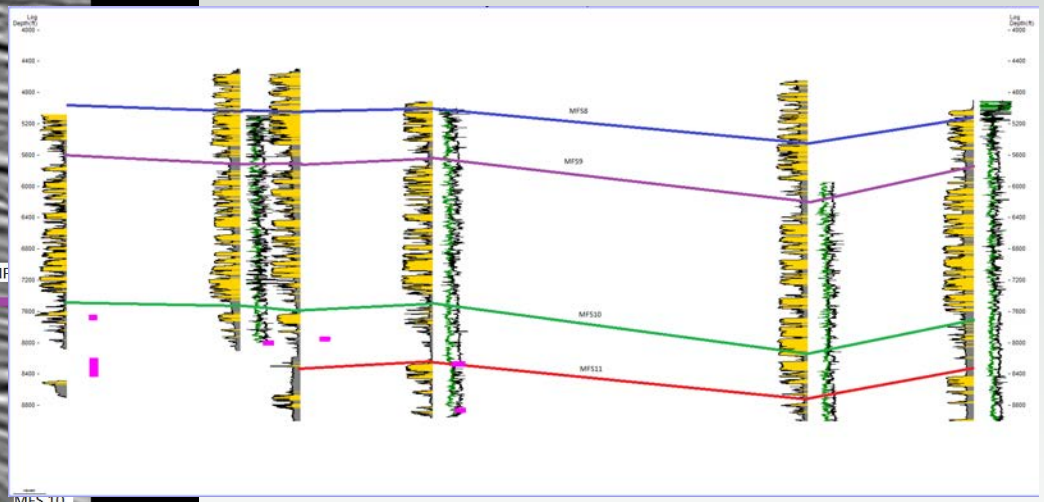
3D Seismic



Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of the Bureau of Economic Geology.

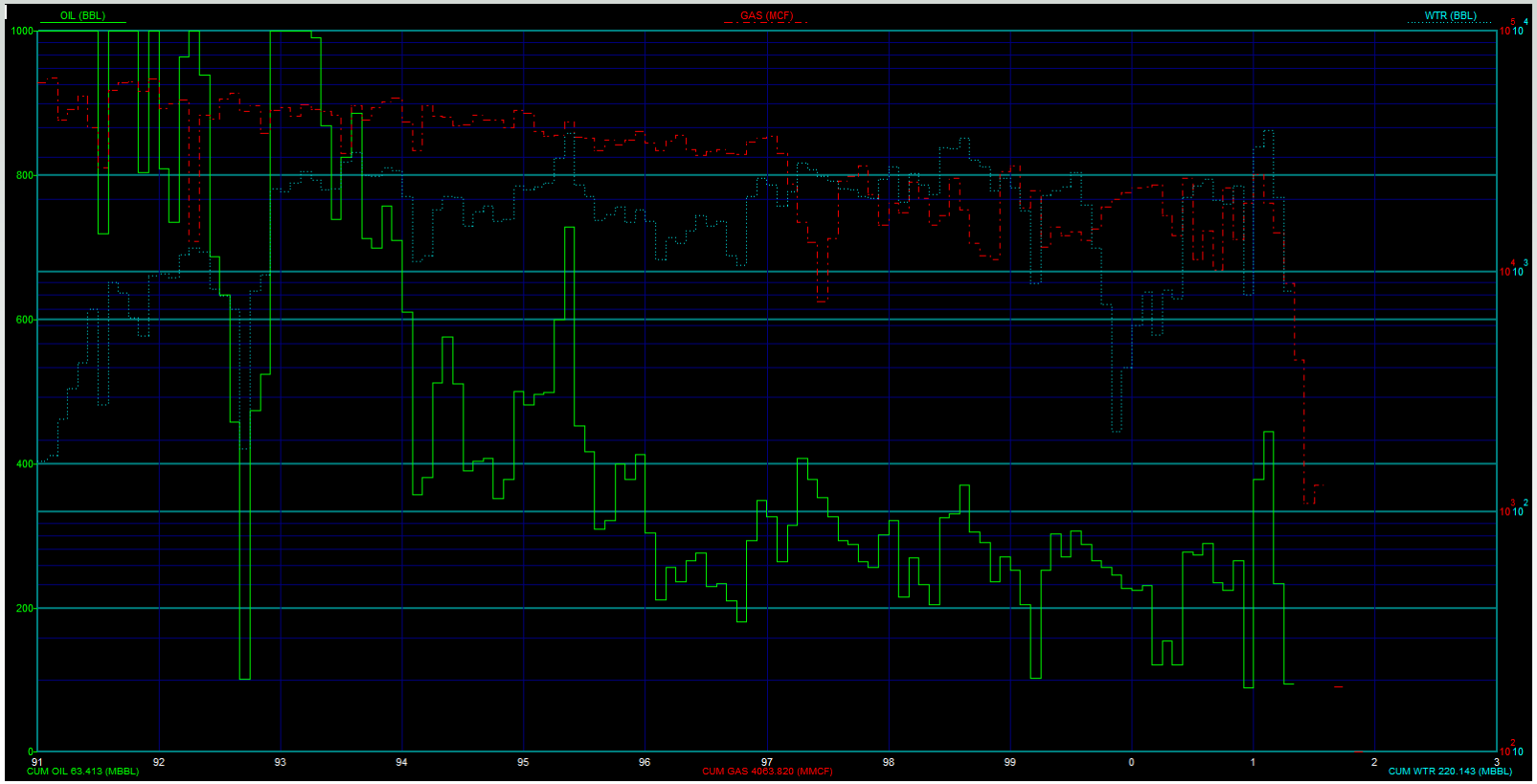
3D Seismic





Seismic data owned or controlled by Seismic Exchange, Inc.; interpretation is that of the Bureau of Economic Geology.

Production Data



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Conclusions

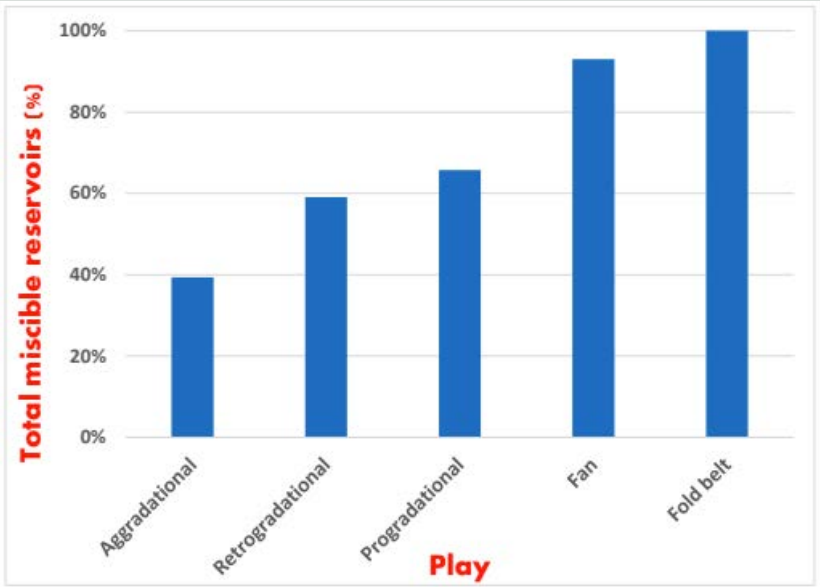
- Well design cannot be completed to avoid CH_4 coproduction in Case Study
- More areas may be affected by problem and should be studied

Choi, J., Nicot, J., Hosseini, S.A., Clift, S.J., Hovorka, S. D., 2013, CO_2 recycling accounting and EOR operation scheduling to assist in storage capacity assessment at a U.S. gulf coast depleted reservoir: International Journal of Greenhouse Gas Control, v. 18, p. 474–484.
Generon, 2019, Carbon Dioxide Separation from Natural Gas Retrieved March 5, 2019, from https://www.generon.com/product/carbon-dioxide-co2-separation/
ICIQ, (n.d.), CO2 Recycling. Retrieved from http://www.iciq.org/research/mitigating-climate-change/
Ogbuabuo, P.C., 2015, The role of methane in limiting CO_2 EOR : case study of offshore Gulf of Mexico oil reservoirs" master's thesis: The University of Texas 930029306
Malone, T., Kuuskraa, V., & DiPietro, P, 2014, *CO2-EOR Offshore Resource Assessment* (Rep. No. 2014/1631). Retrieved March 29, 2018, from U.S. Department of Energy National Energy Technology Laboratory website: https://www.netl.doe.gov/energy-analyses/temp/FY14_CO2-EOROffshoreResourceAssessment_060114.pdf

Special Thanks to: Susan Hovorka, Tip Meckle, Ramon Trevino, Mike Deangelo, Seyyed Hosseini, Dallas Dunlap, Reynaldy Fifariz, Emily Beckham, Izaak Ruiz, and Omar Ramirez Garcia.

Additional Slides

Play Type Effect on Tolerance [82CO2 + 18CH4]

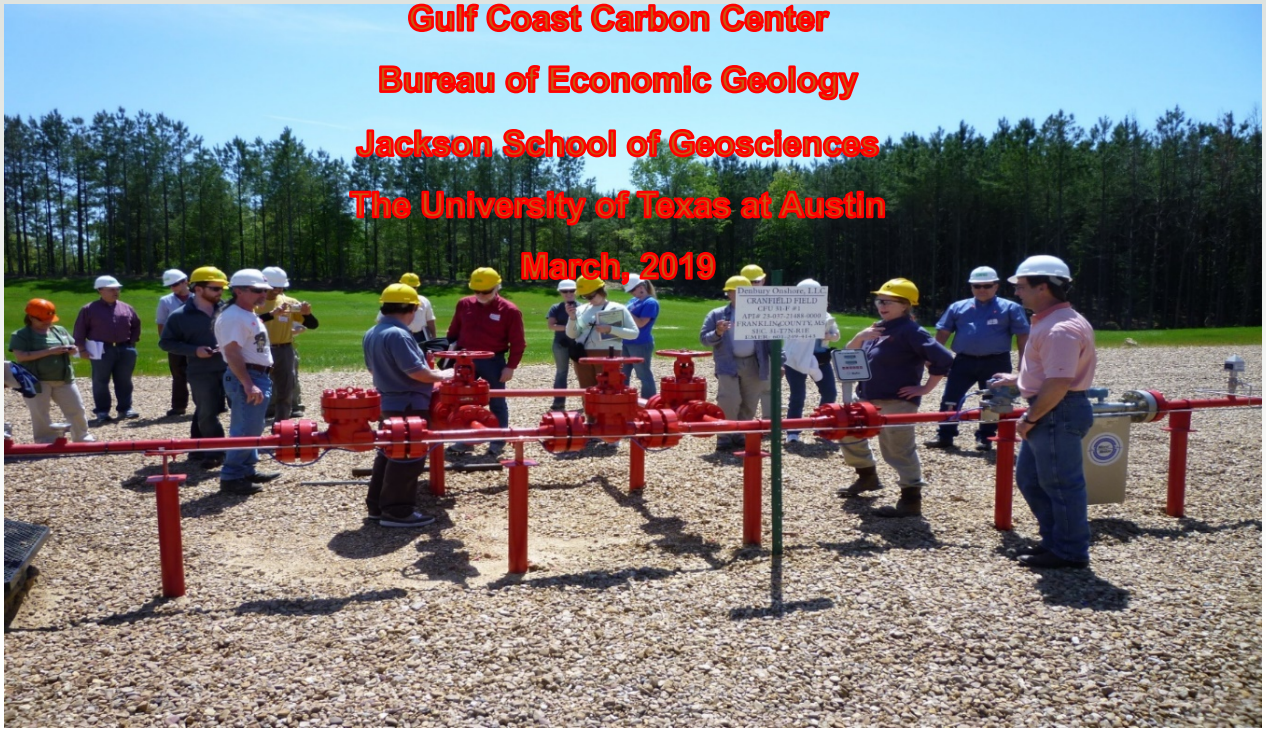


(Ogbuabuo, 2015)

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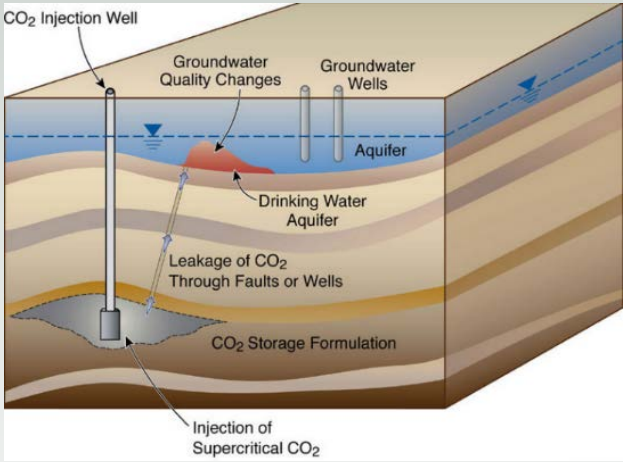
Understanding of CO_2 migration and entrapment- Cranfield site

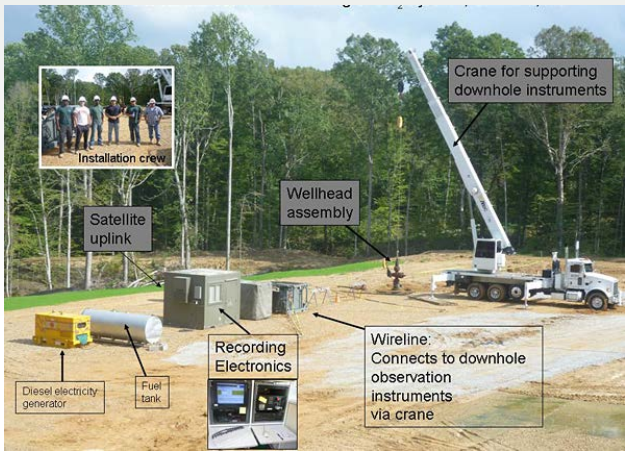
Sahar Bakhshian, Prasanna Krishnamurthy, Baole Wen, Pooneh Hosseini



Assessment of CO_2 migration

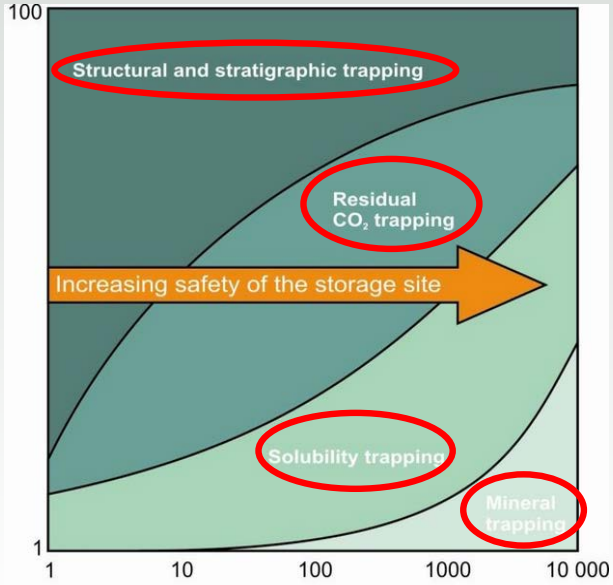
- Having a Safe and reliable long-term storage of injected CO_2
- Ultimate goal: Storage over geologic time
- Our primary concerns:
  - How far will the CO_2 plume travel (CO_2 footprint)
  - How long does the CO_2 plume remain mobile
- Assessment framework → **Migration mechanisms of CO_2**
- Prediction of CO_2 plume migration path → **Numerical simulation and experiments**





How is CO_2 stored in a saline aquifer?

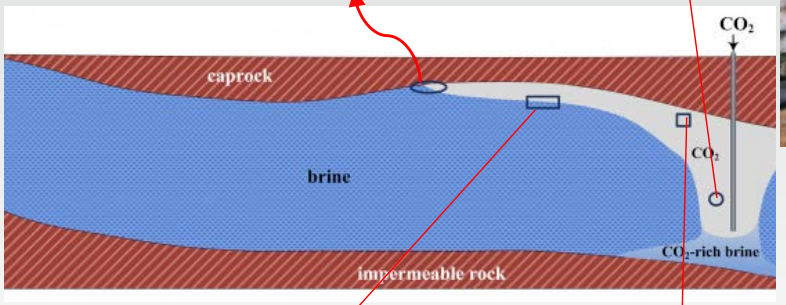
✓ CO_2 immobilization in the formation through trapping mechanisms during the **injection** and **post-injection period**





Structural Trapping: CO_2 gets physically trapped beneath the sealing cap-rock and low permeability layers

Residual (capillary) Trapping: CO_2 gets trapped as immobile isolated residual 'blobs' in the pore space





Solubility (dissolution) Trapping:CO_2 dissolves into brine

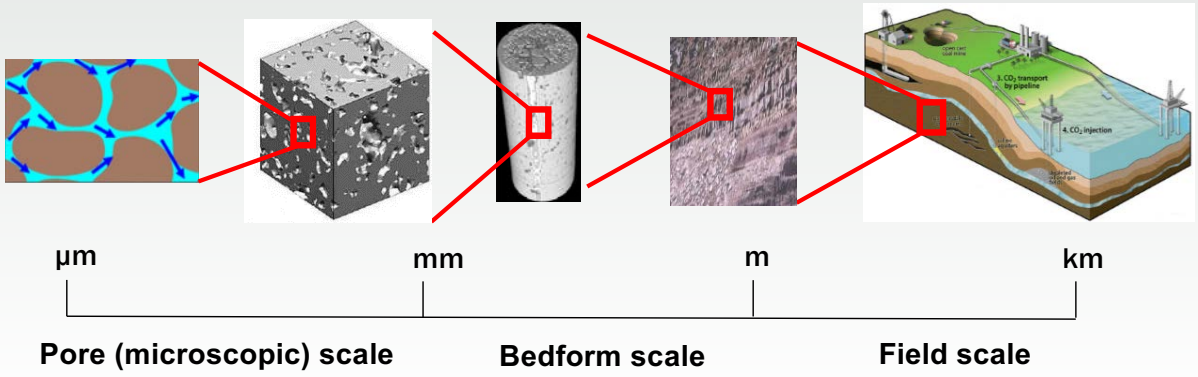


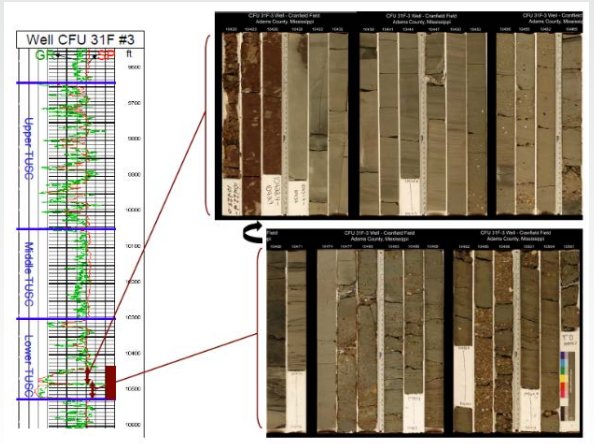
Mineral Trapping:CO_2 get mineralised (formation of carbonate minerals)



Reservoir Heterogeneity

- Geological heterogeneity of subsurface reservoirs
- Scales ranging from the pore scale (microns) up to a regional CCS network (hundreds of kilometers).
- Fluvial depositional setting ⟶ heterogeneity in lower Tuscaloosa formation

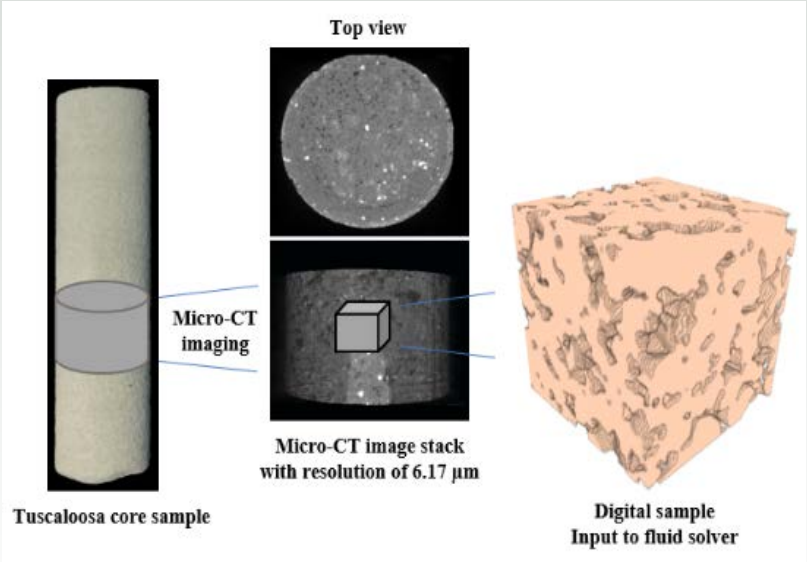




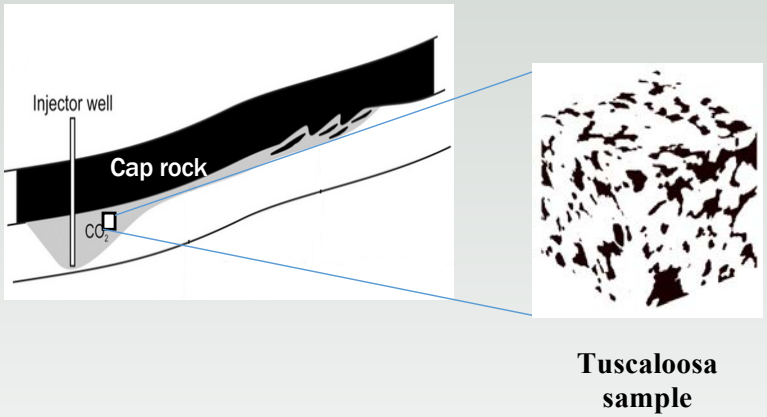
Core samples taken from different wells in the Cranfield site (lower Tuscaloosa)

Pore-scale simulation on Tuscaloosa rock samples

- Developed a **pore-scale multiphase flow simulator**
- Tuscaloosa core samples: depth of ~ 10465 ft.
- Using high resolution CT imaging of Tuscaloosa sample
- Study the cases which are unpredictable using experimental approach
- Computationally fast, using **high performance computing** system (parallel computing) at the Texas Advanced Computing Center at the University of Texas at Austin.

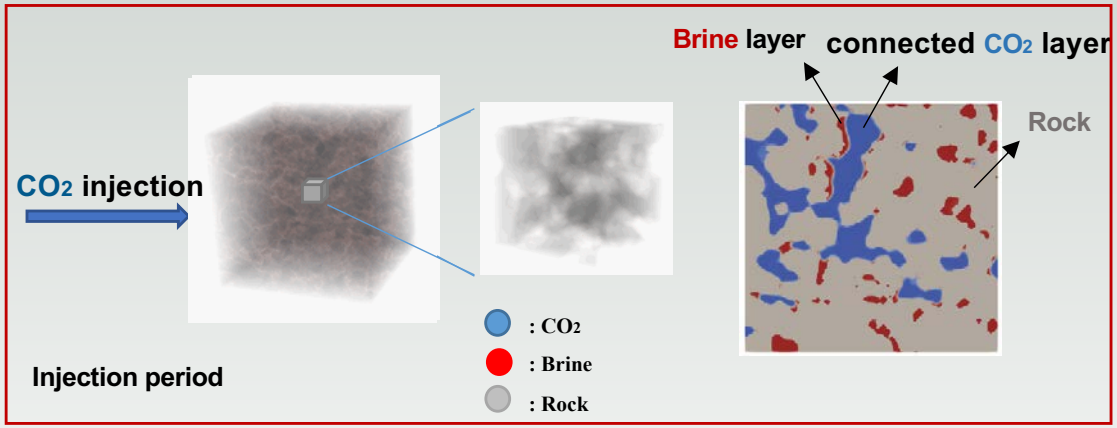


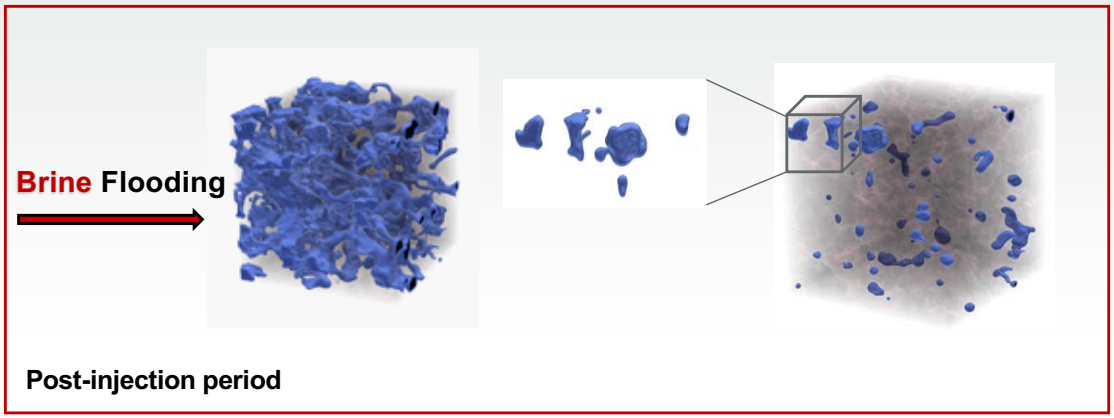
CO_2 residual trapping- Pore-scale simulations



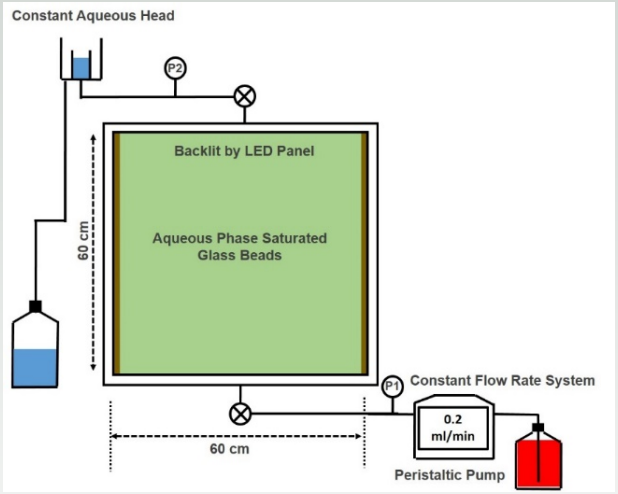
Tuscaloosa sample

- Simulation of CO_2 migration pathway during **injection period**
- Long-term stabilization of CO_2 plume during the early-stage of **post-injection period**
- Effect of **injection rate** and rock mineralogy (**wettability**) on CO_2 migration pattern and its residual trapping



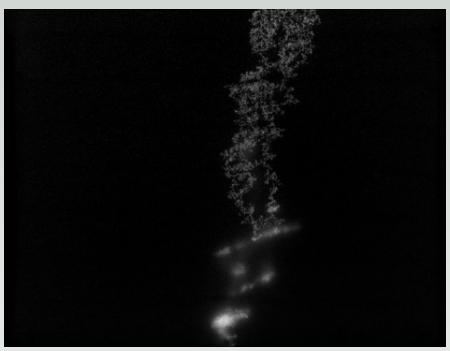


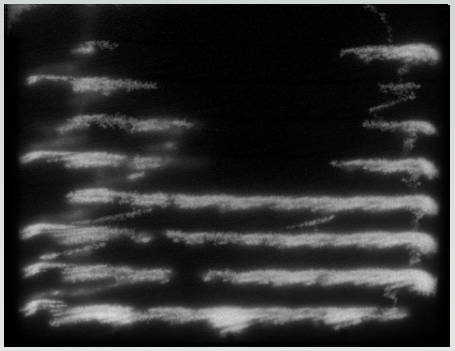
How Subtle Heterogeneity Helps Increase Trapped Saturations

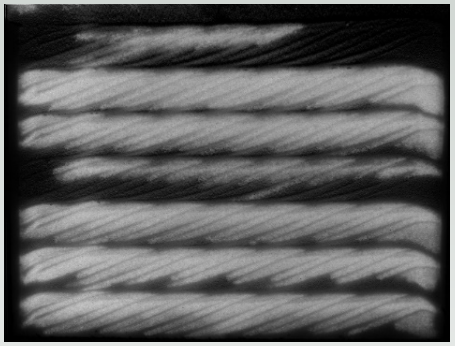


Experimental Setup

Background subtracted: Bright regions Indicate Fluids







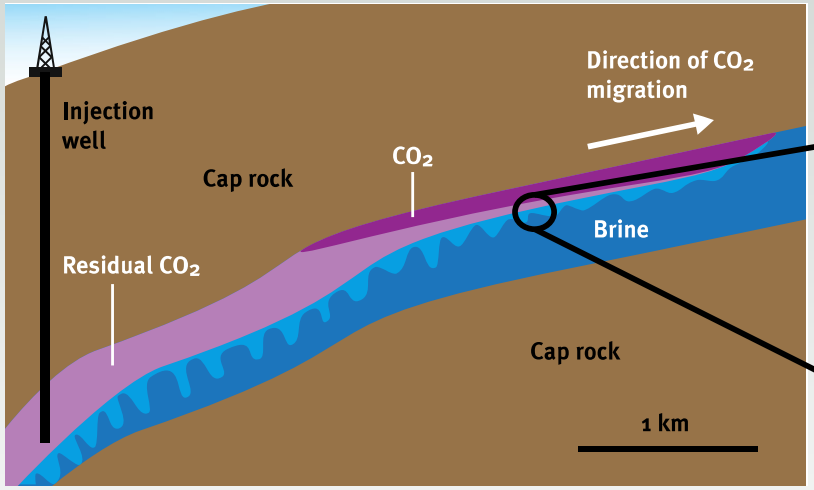
Crossbeds with Increasing Capillary Heterogeneity

Capillary Pressure Contrast: 107 pa	**Capillary Pressure Contrast:** 360 pa	**Capillary Pressure Contrast:** 760 pa
Saturation: 0.45%	**Saturation:** 6.33%	**Saturation:** 24.8%
Trapped Saturation: 0.33%	**Trapped Saturation:** 5.9%	**Trapped Saturation:** 23.5%

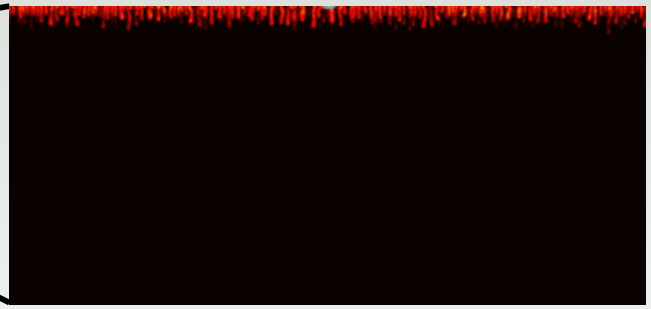
Subtle changes in grain sizes and capillary entry pressures (<1 kpa) lead to drastic changes in trapped saturations

- Prasanna Krishnamurthy

Solubility trapping- Simulation



Schematic of geologic CO_2 storage (Blunt 2010)



Convective CO_2 dissolution
(Darcy scale, Wen *et al*. 2018)

1) Solubility trapping can account for 30–40% of the total capacity in long-term storage
2) Convective mass transfer greatly increases the CO_2 dissolution rate and significantly reduces the risk of leakage

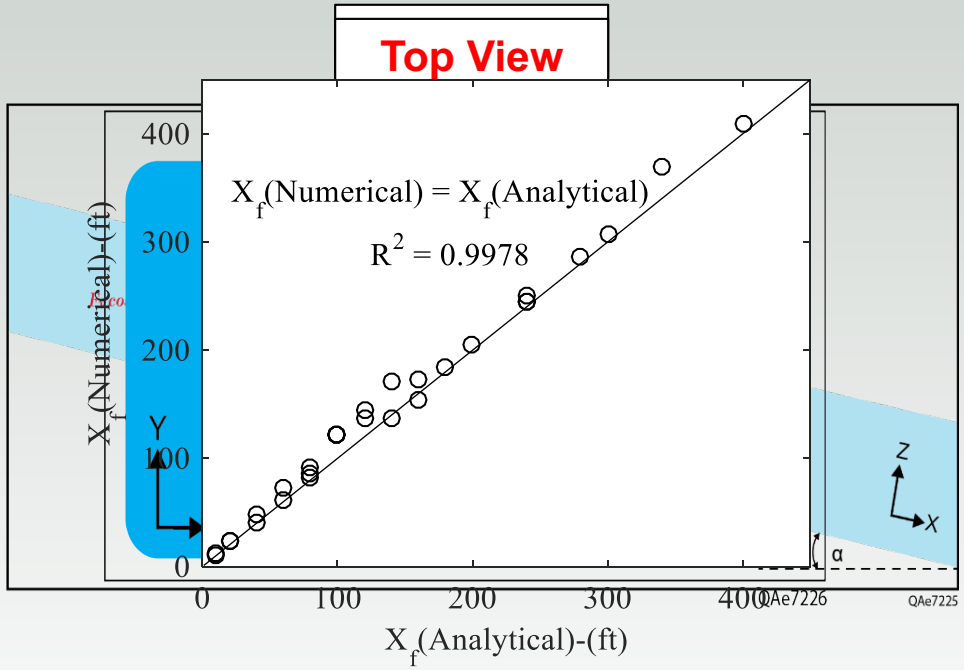
CO_2 Plume Migration in Dipping Aquifers- A field-scale study

Objectives:

- Drive a **mathematical formulation** to predict CO_2 plume extension
- finding a quicker and easier alternative to numerical simulation

Result:

- Very good agreement between mathematical model and numerical simulation (CMG-GEM) results.



Conclusion:

- The CO_2 plume extension depends on the injection rate, CO_2 viscosity, permeability, relative permeability, fluid densities, thickness, and dip angle.

We found a correlation for effective relative permeability.

- Hosseininoosheri et al., 2019 (submitted to Scientific Report)
- Corresponding author : poonehhosseini@utexas.edu

Conclusion

- Integrated experimental and numerical simulation approaches can be applied to access long-term fate of CO_2 plume during the post-injection period.

- Having knowledge about the trapping mechanisms in subsurface reservoirs can provide insight into the efficiency of CCS operations.

Thank you

