Monitoring Design Best Practices

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

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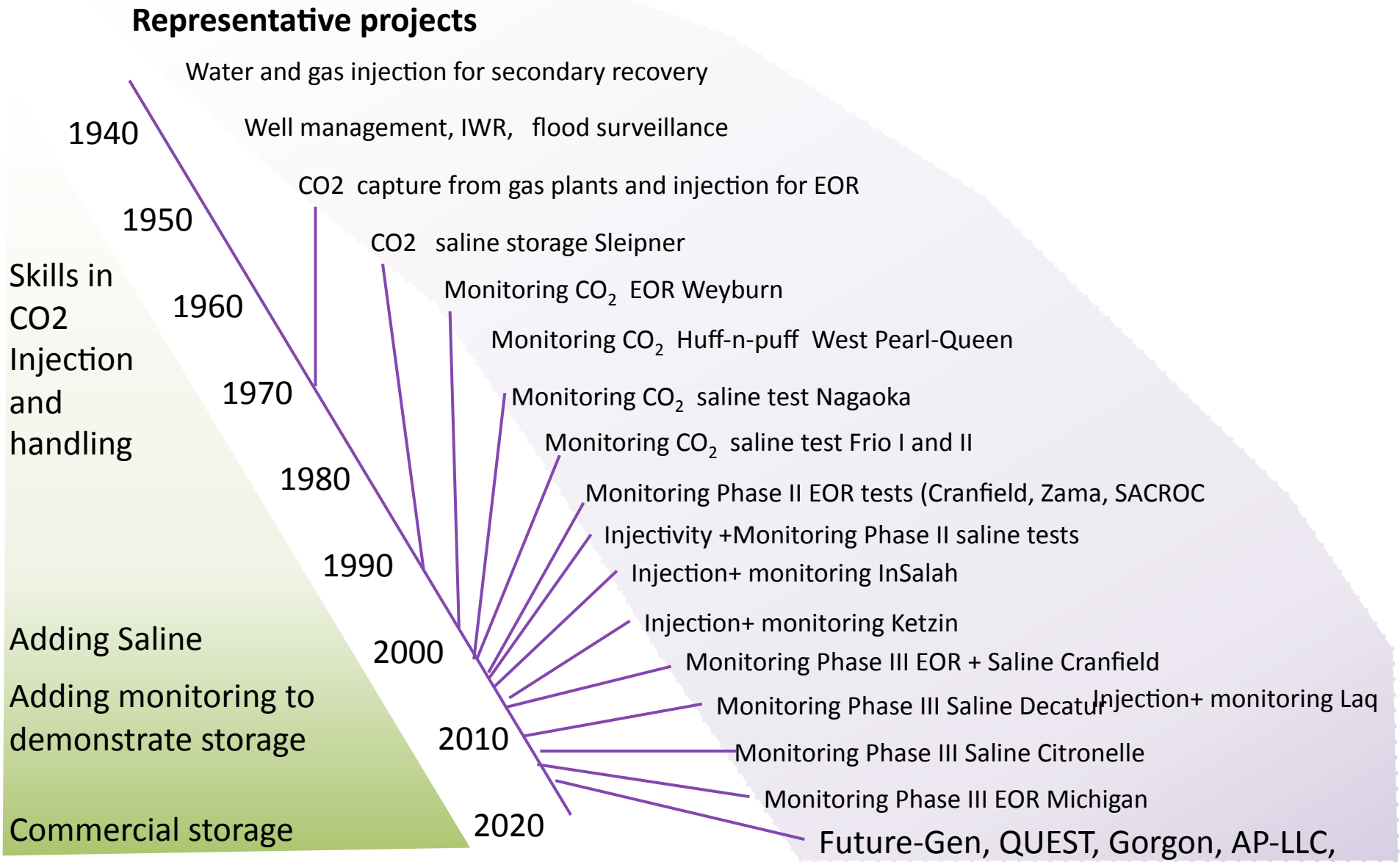
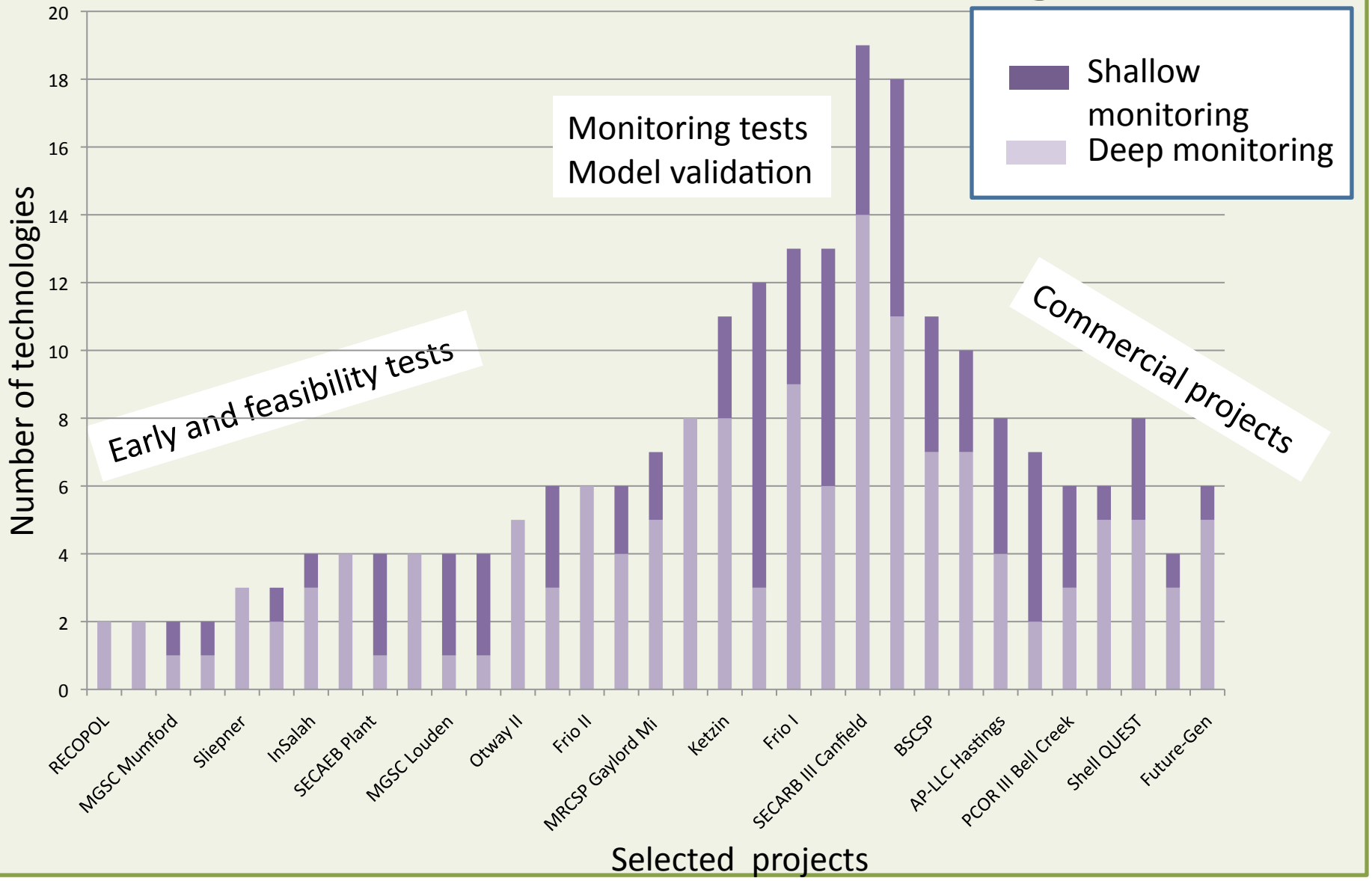
Safe and Effective Injection > 50 years



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.

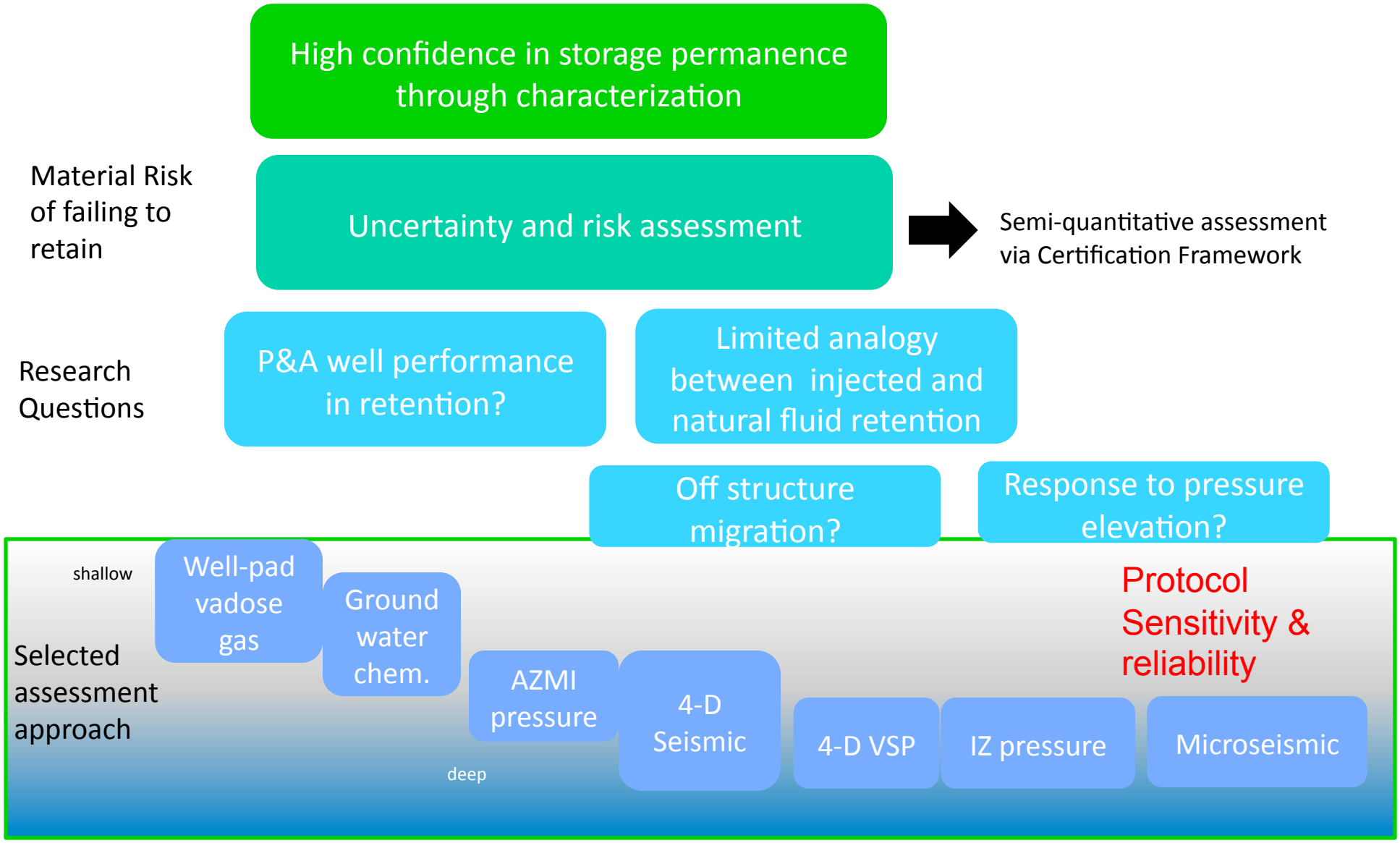
Commercial Monitoring

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



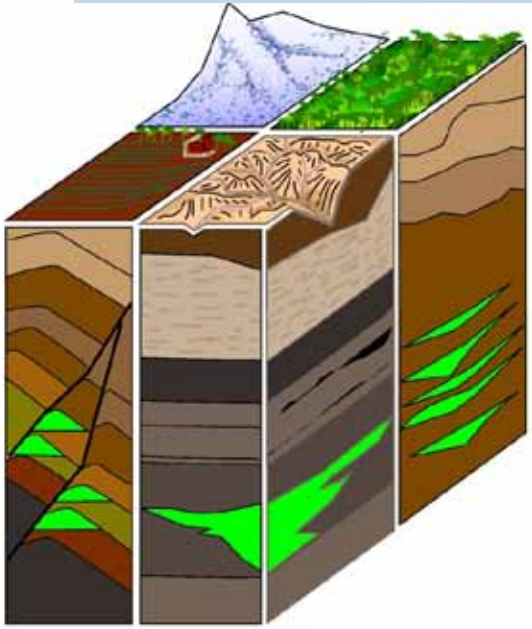
Characteristics of site change monitoring need

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



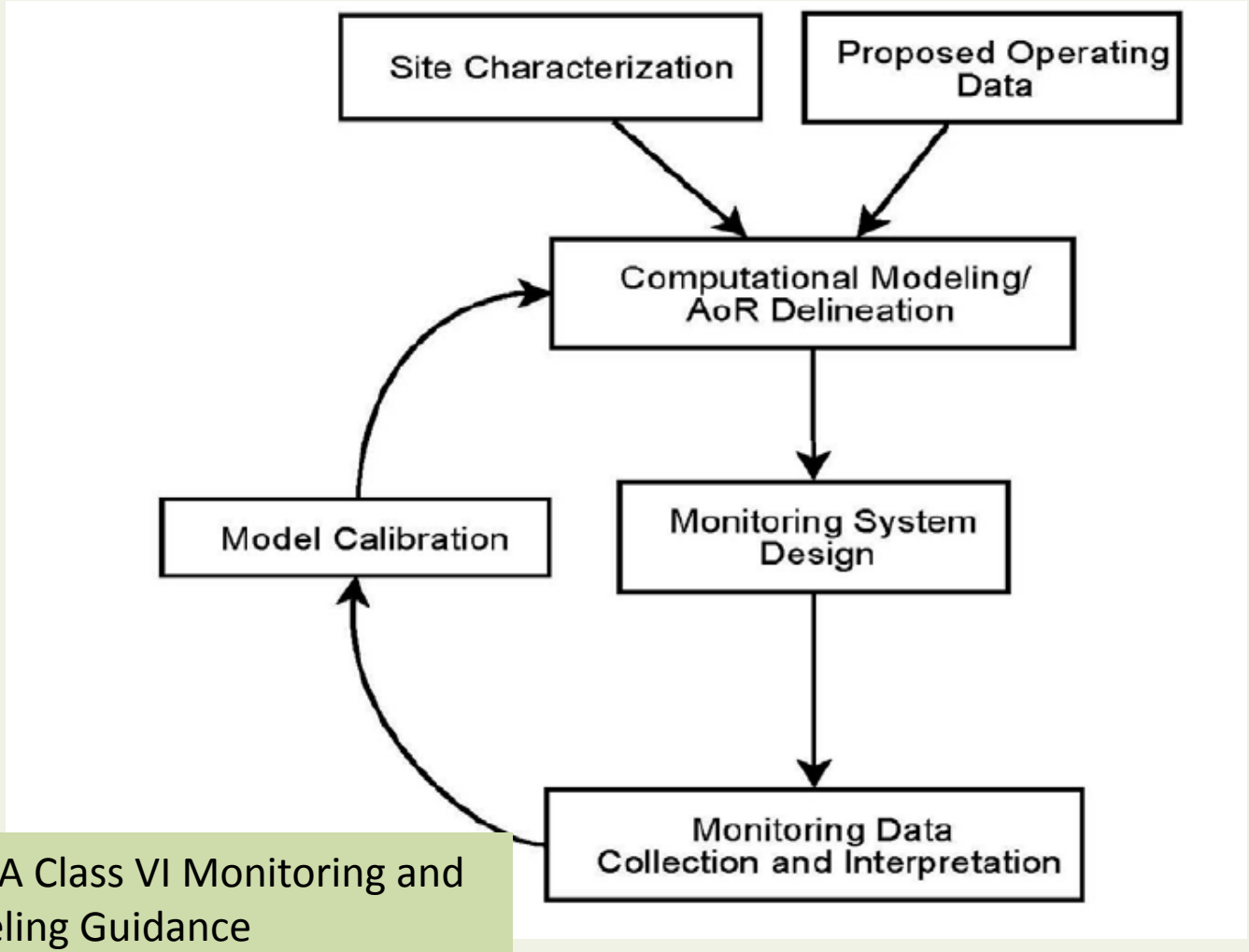
Monitoring targets

Monitoring Design

Site specific technology limitations

EPA STAR Project using SECARB data

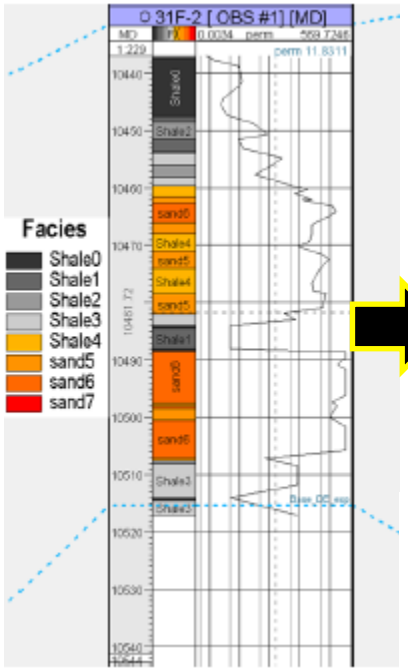
Regulator Expectation: monitor plume & match to models



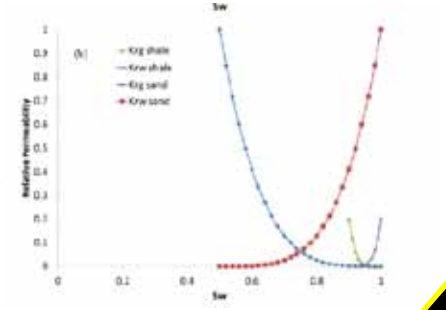
US EPA Class VI Monitoring and Modeling Guidance

Modeled expectations repeatedly adjusted to match measurements

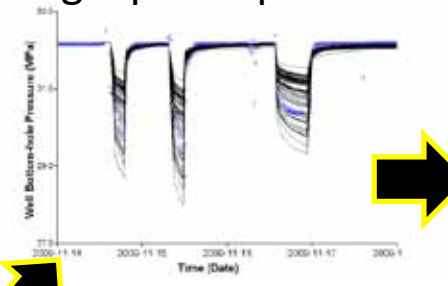
Reservoir characterization



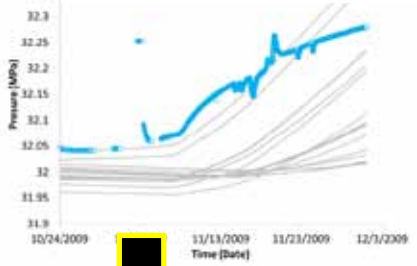
Relative permeablities



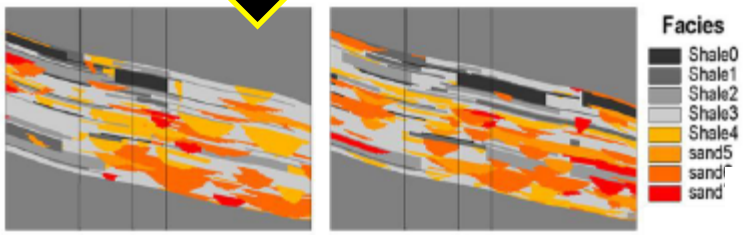
Single phase pressure

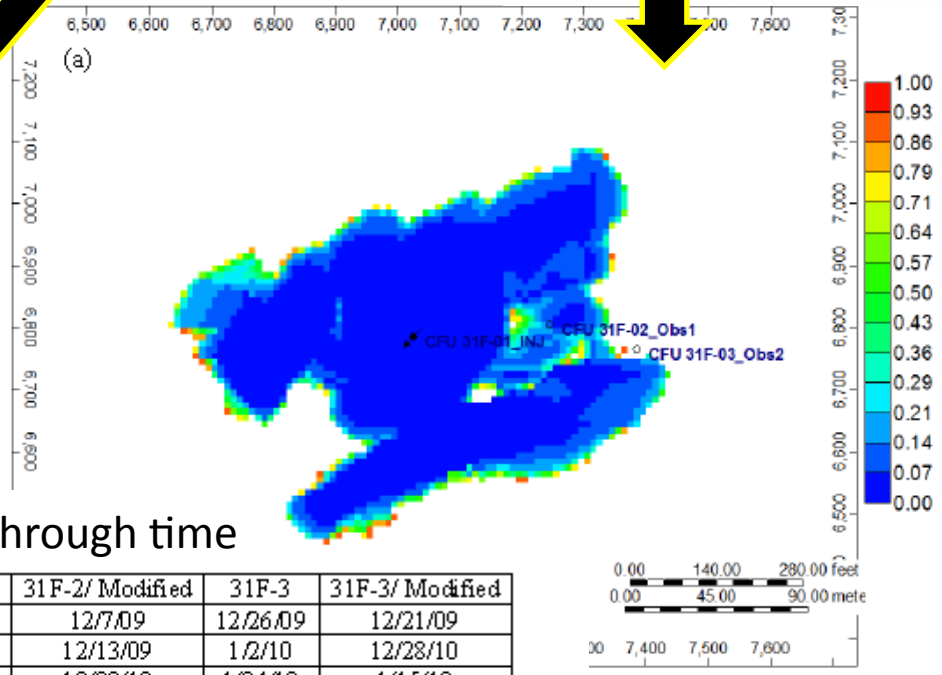


Multi phase pressure



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

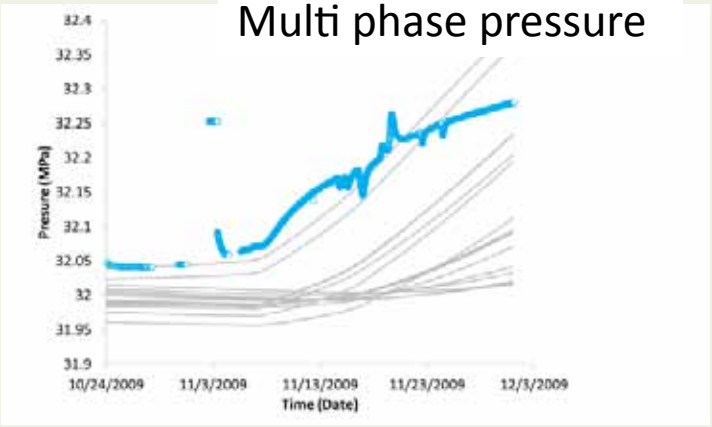
Accomplishments

- 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



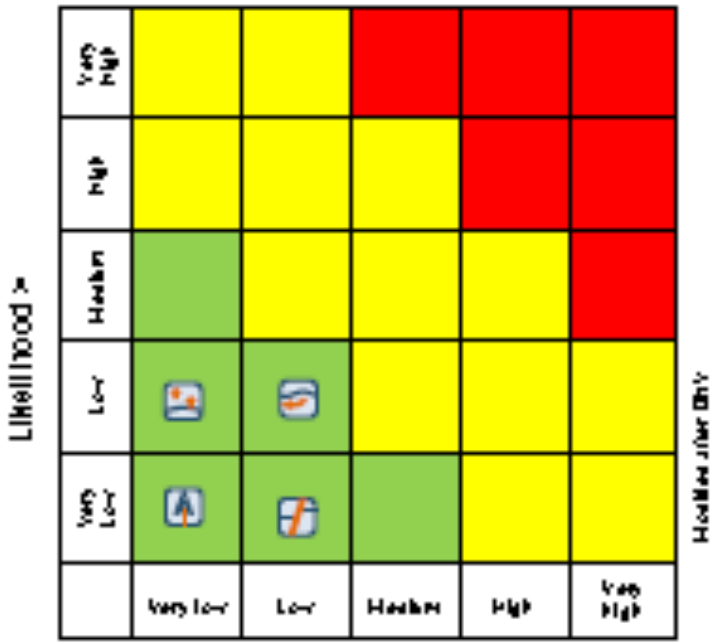
All models are wrong, but some are useful

GDP Box

Not all miss-matches are important to the project

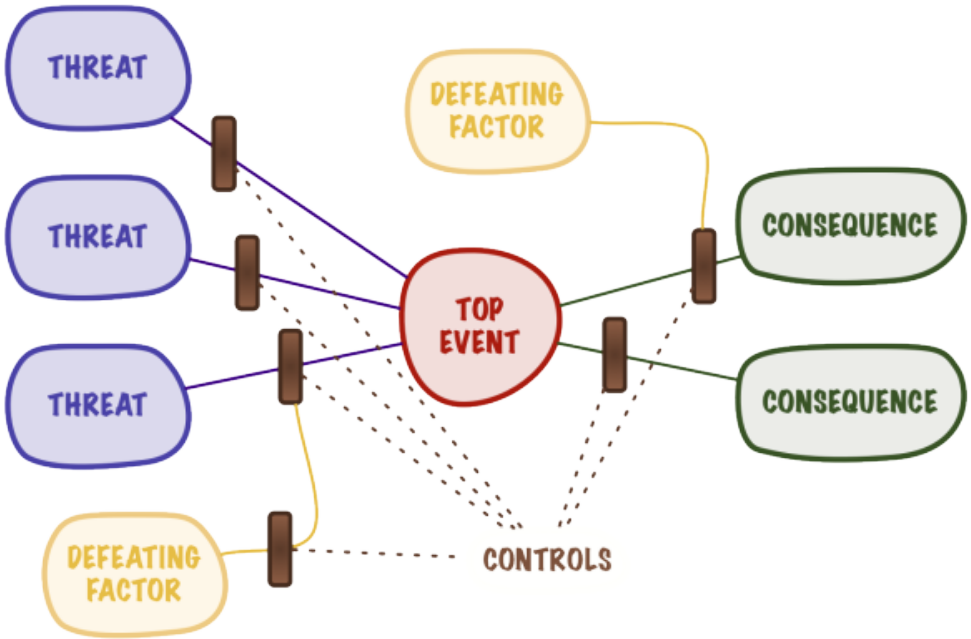
- A range of outcomes can meet most project objectives
- Need statement of what outcomes are unacceptable
  - "Failure"
  - "Leakage"
  - "Damage"
- Need a safe word: Assessment of low probability material impact ALPMI

“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

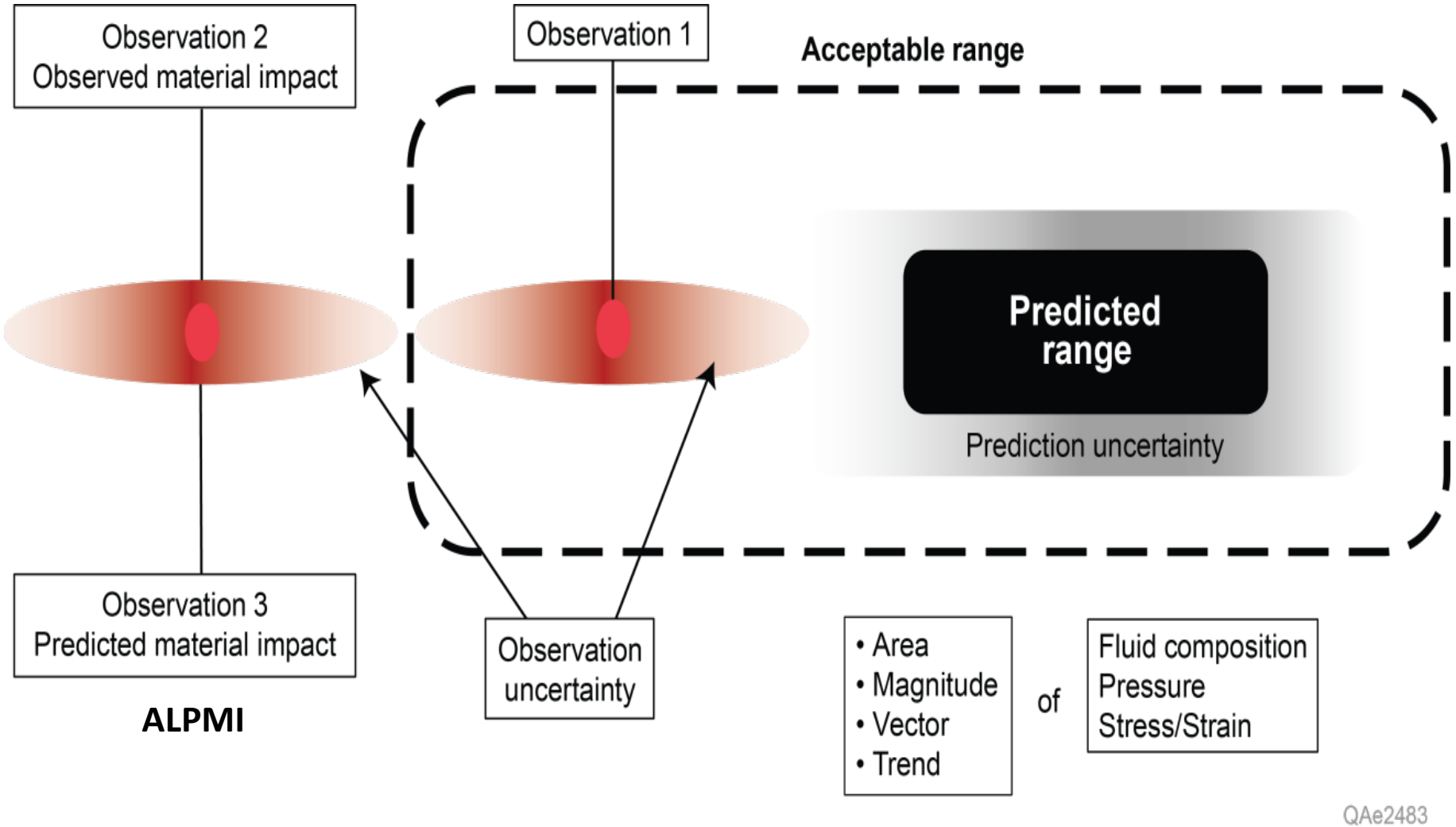
Inventory of material impact scenarios – all in

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

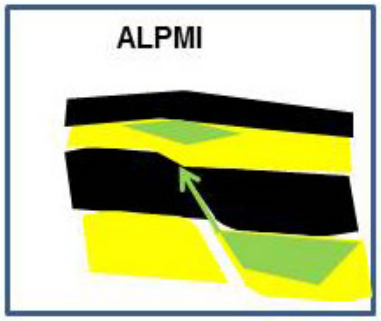
Define conditions precedent to material impact

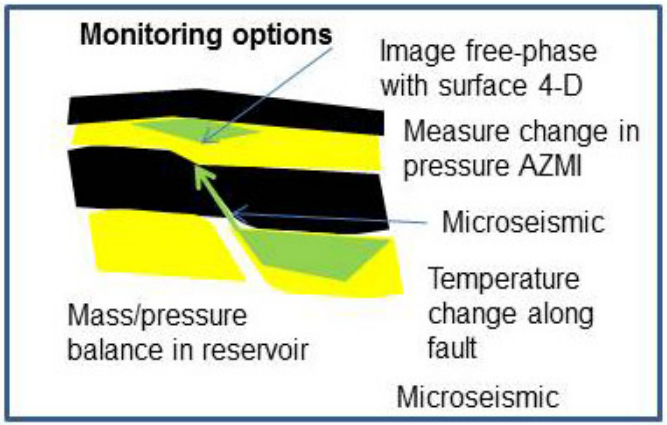
Characterize and monitor those conditions

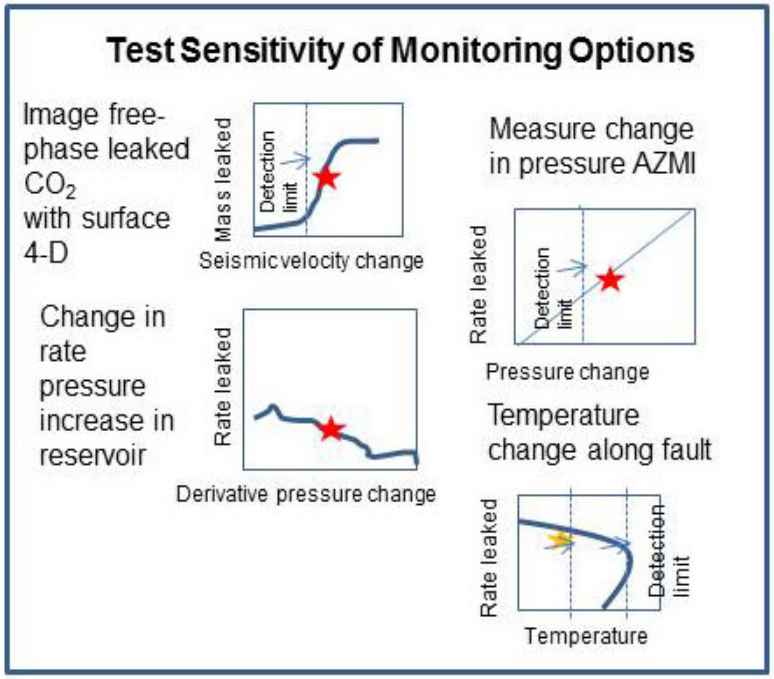
Assessing Low Probability Material Impact



Using ALPMI to Design Monitoring



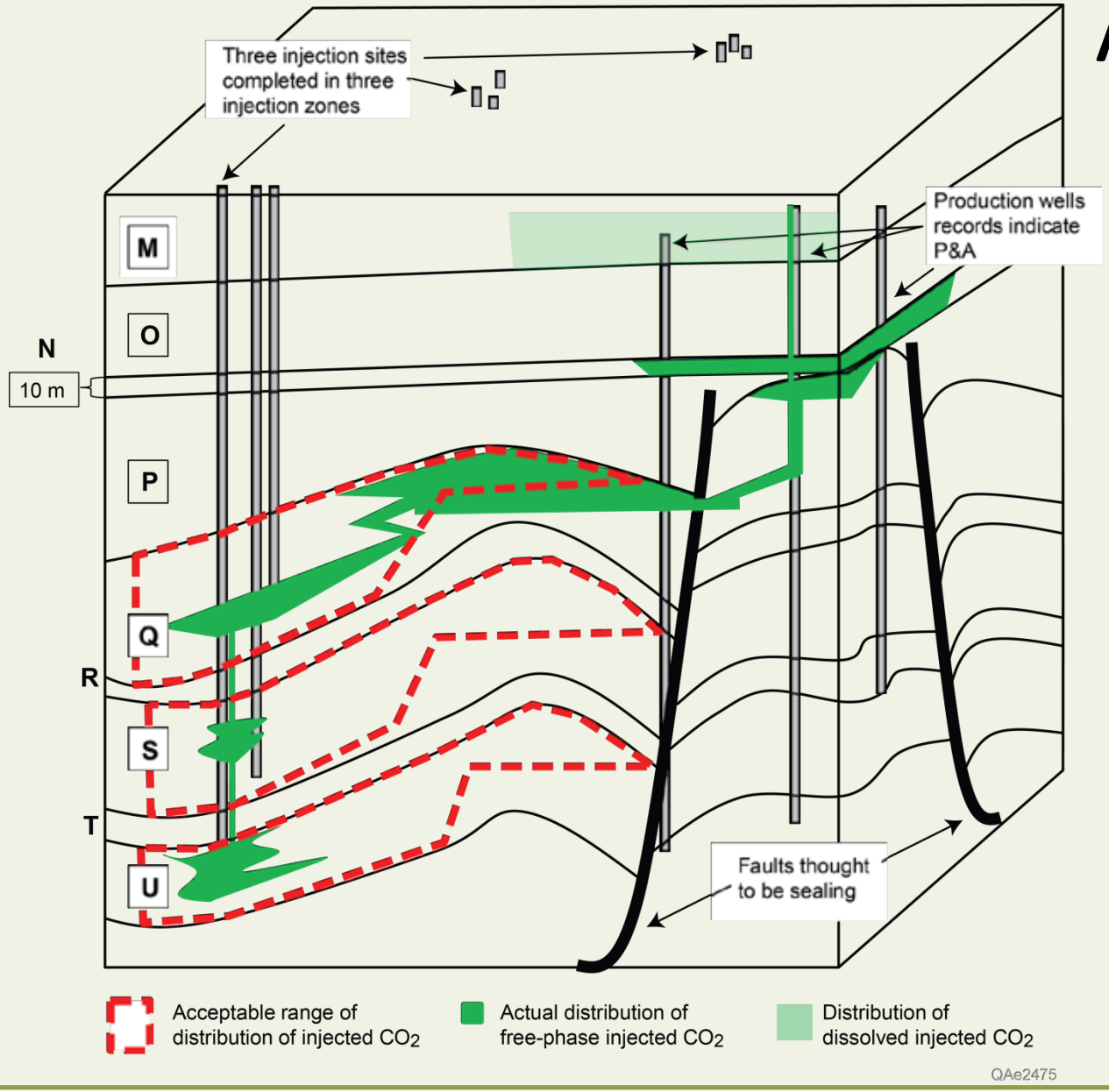




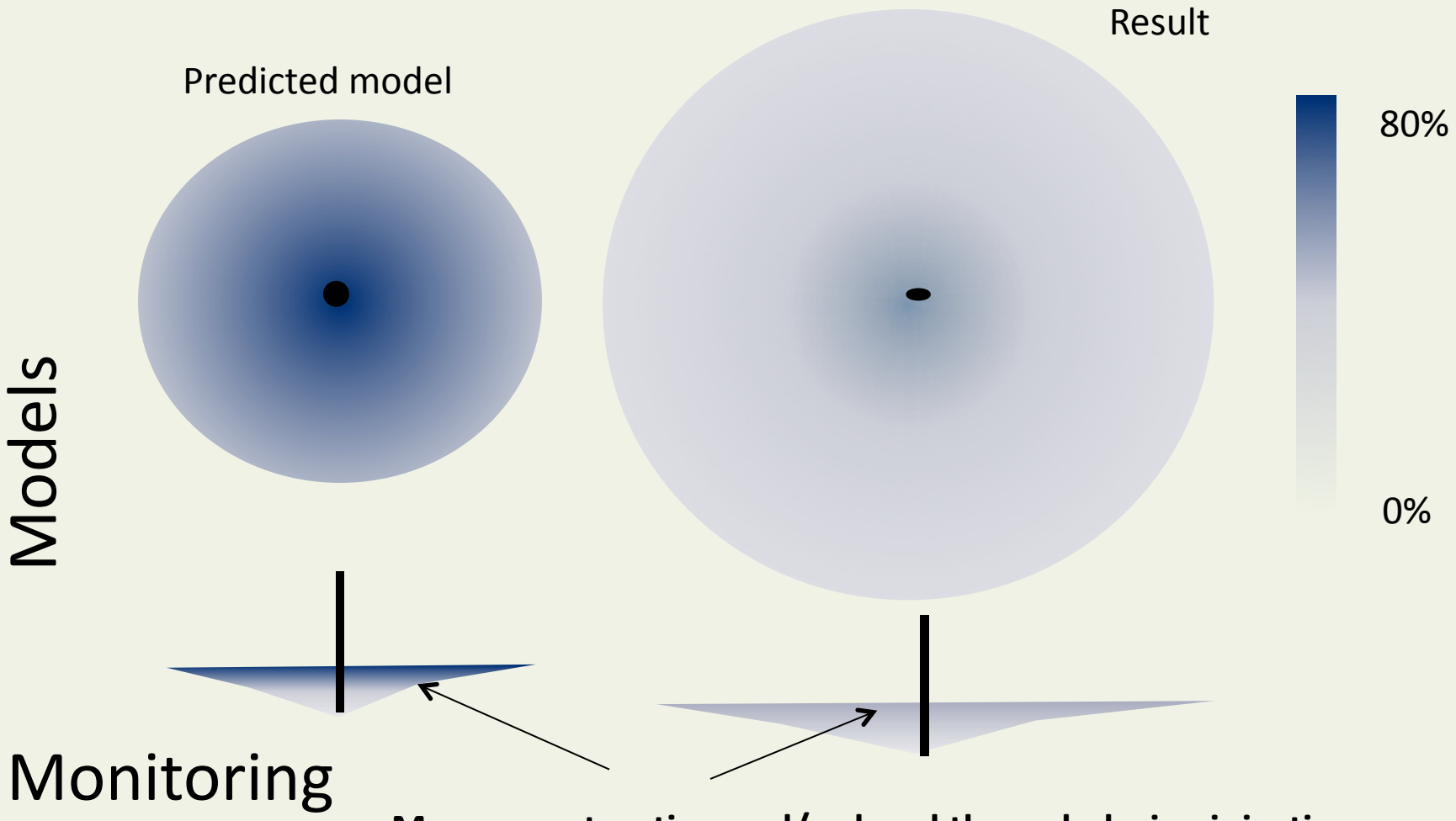
Set triggers, stage monitoring options

- 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

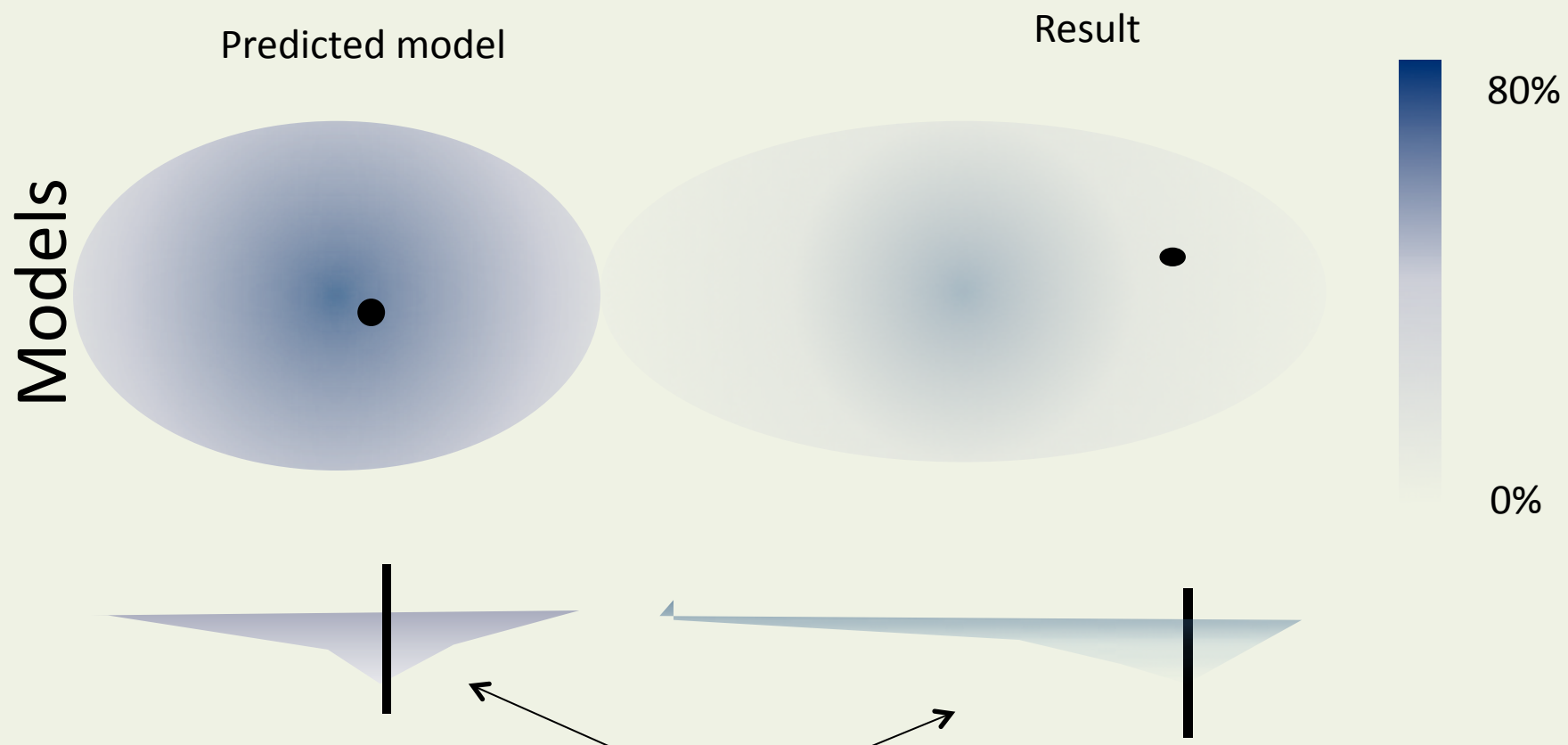
ALPMI


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

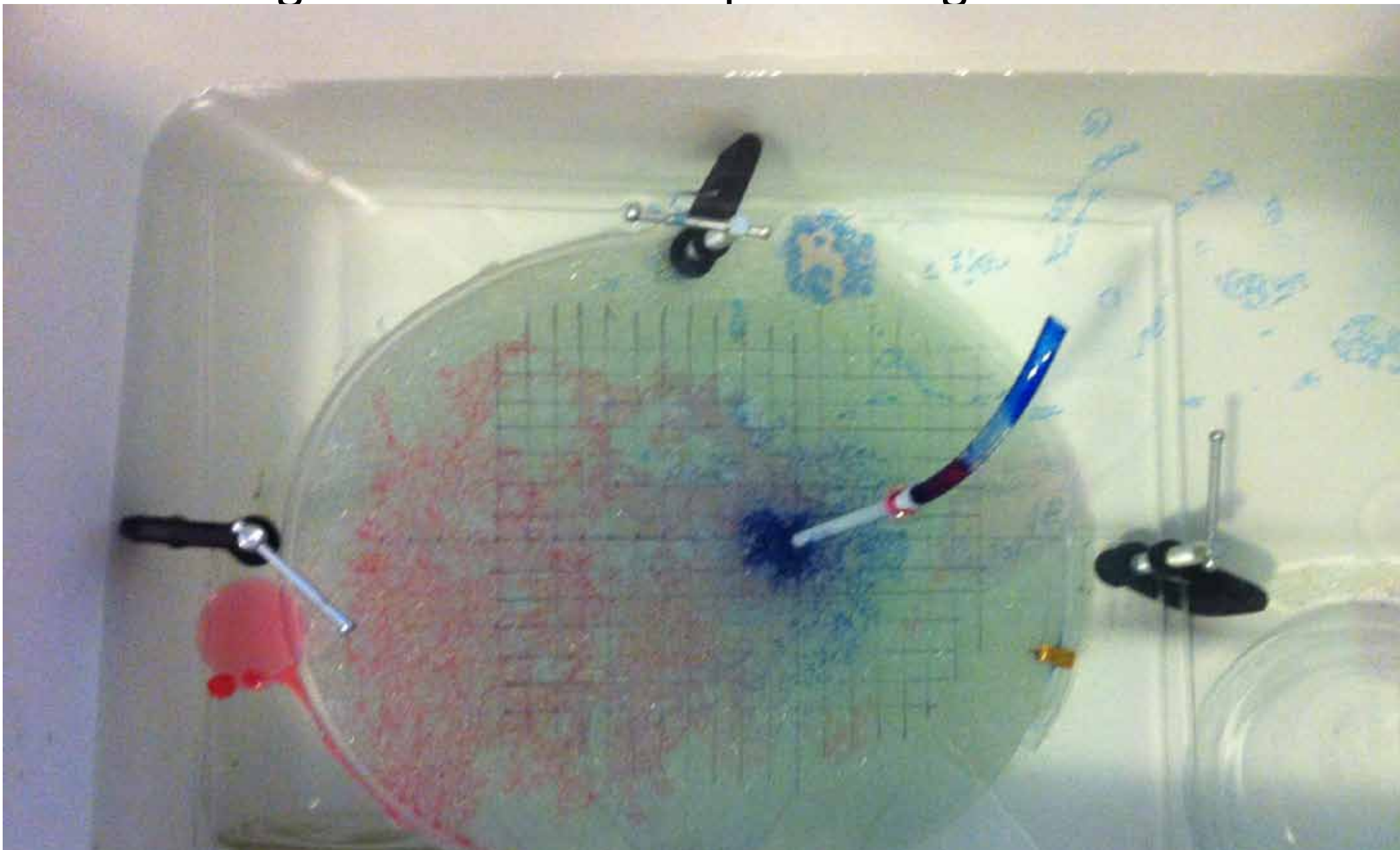
ALPMI Case 1: Water saturation higher than predicted: large plume during injection



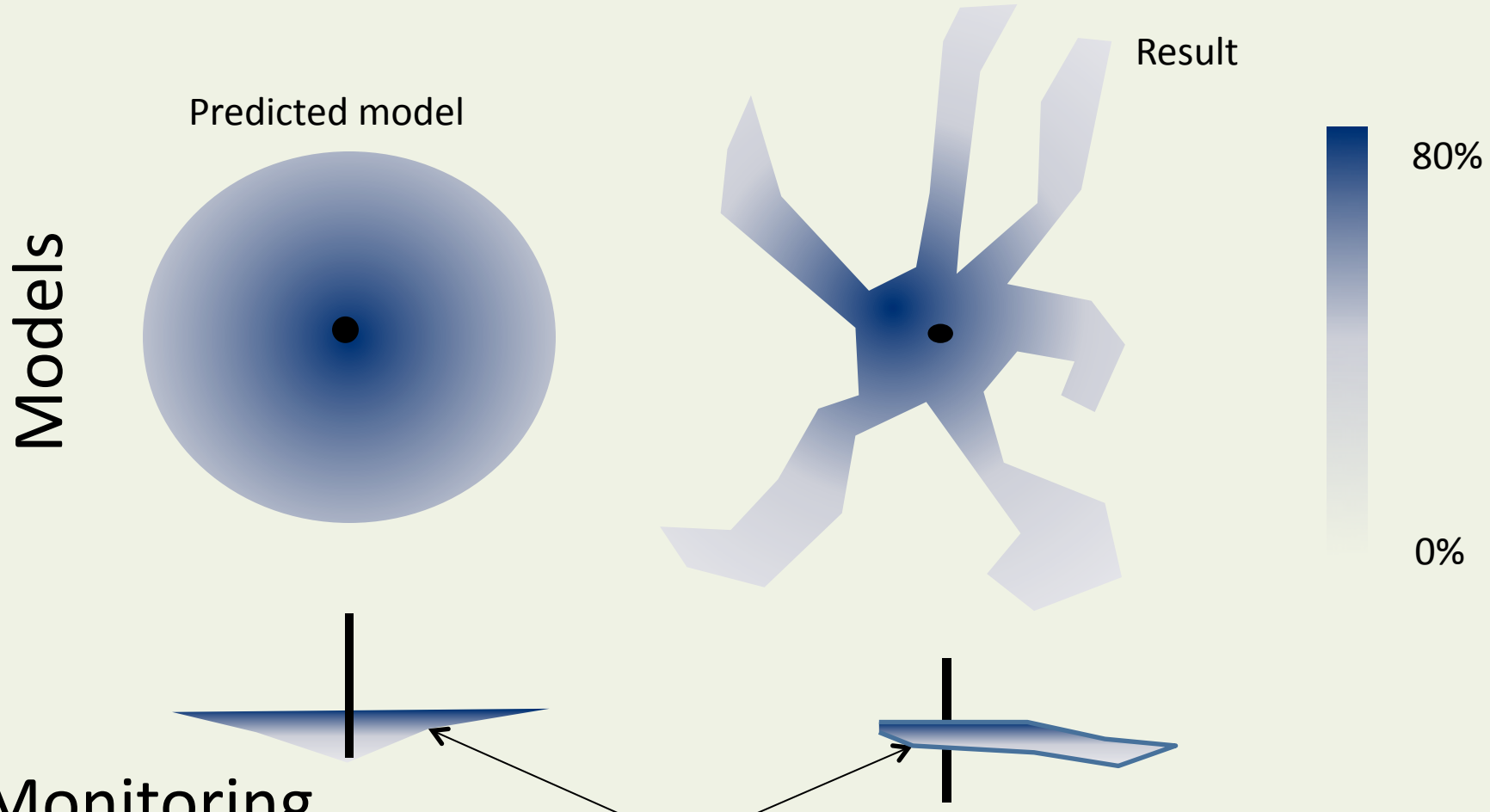
ALPMI Case 2: CO_2 residual saturation lower than predicted: large plume during migration



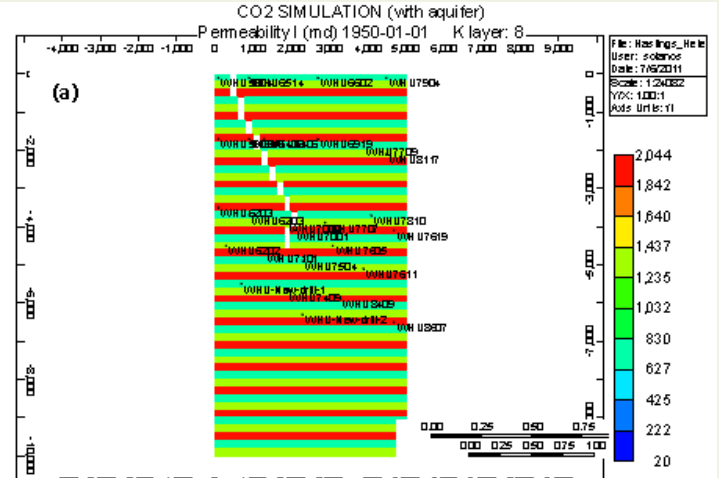
ALPMI 2 physical model
Wrong imbibition curve: plume migrates too far

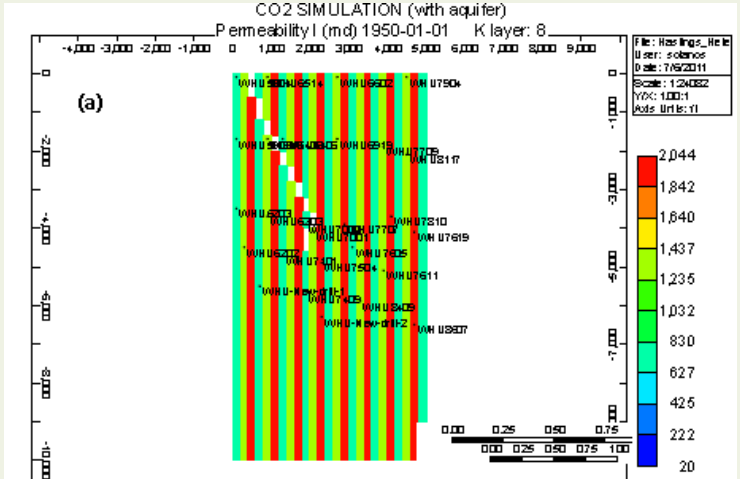


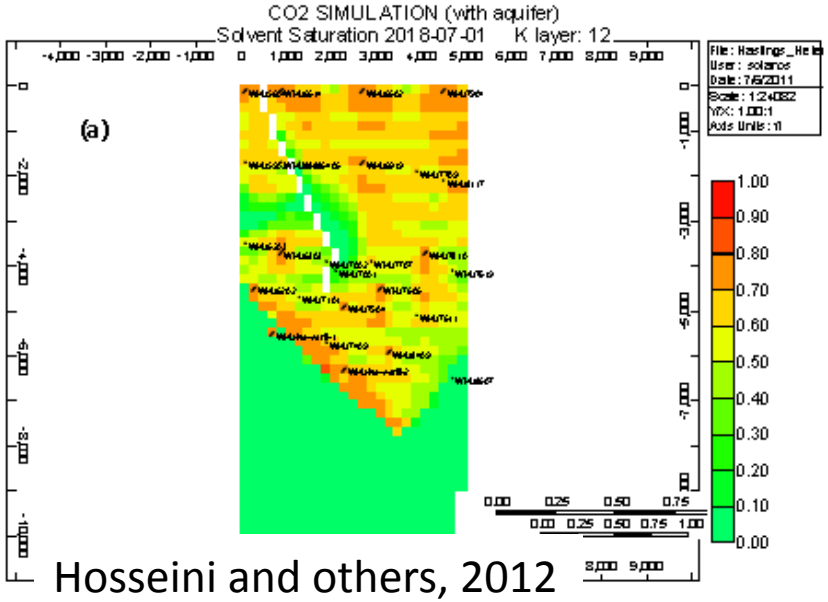
ALPMI Case 3: CO_2 plume strongly fingered horizontally and/or vertically

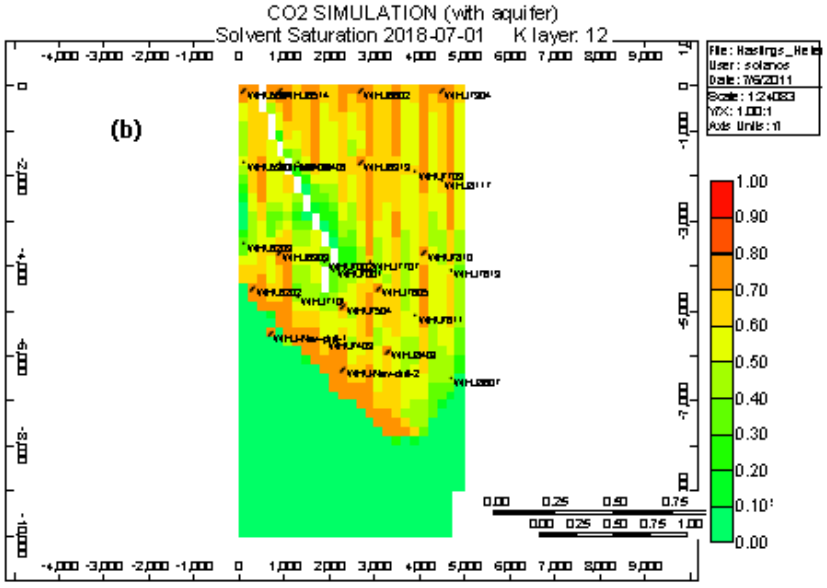


ALMPI 3
Anisotropy such that plume migrates too far





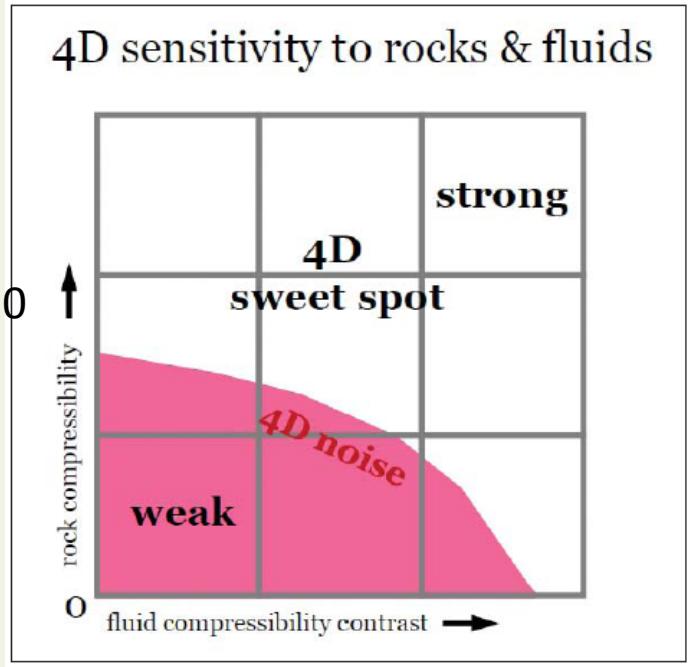




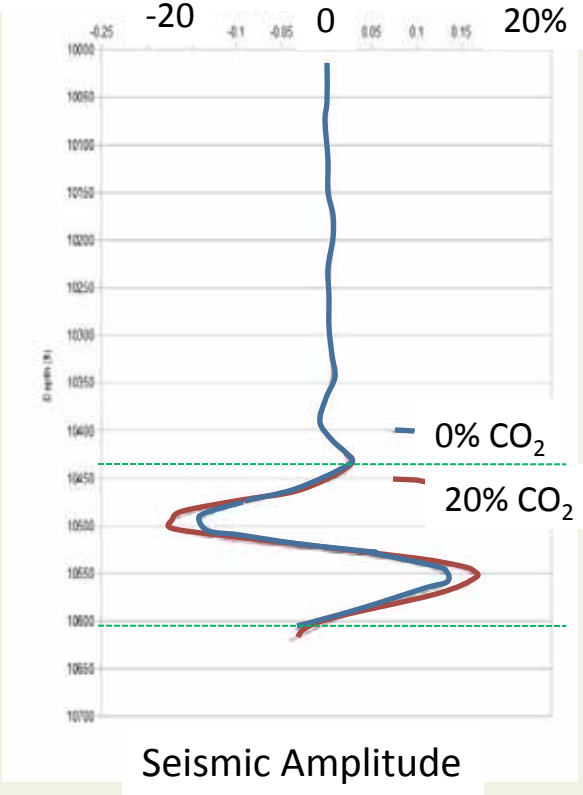
Hosseini and others, 2012

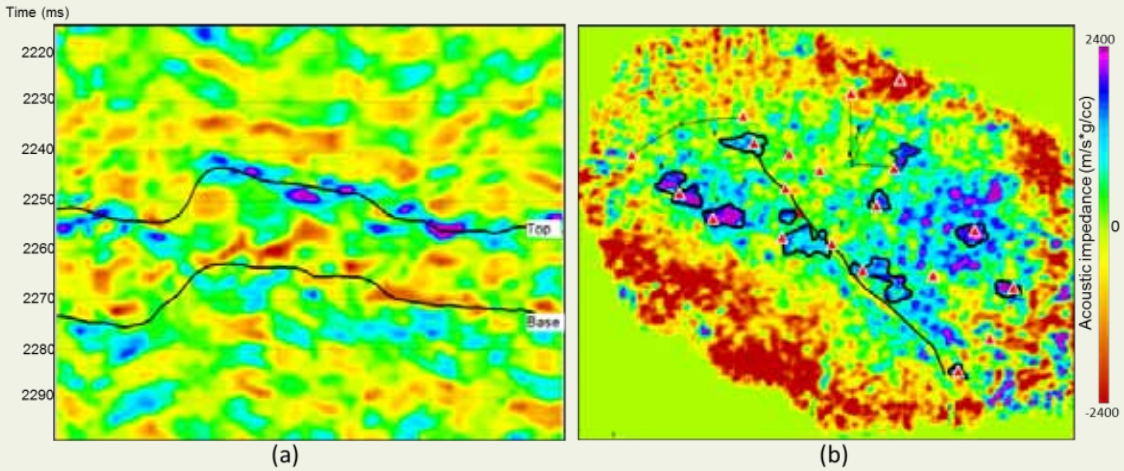
Seismic Sensitivity

Lumley, 2010



Modeled change in amplitude
Cranfield

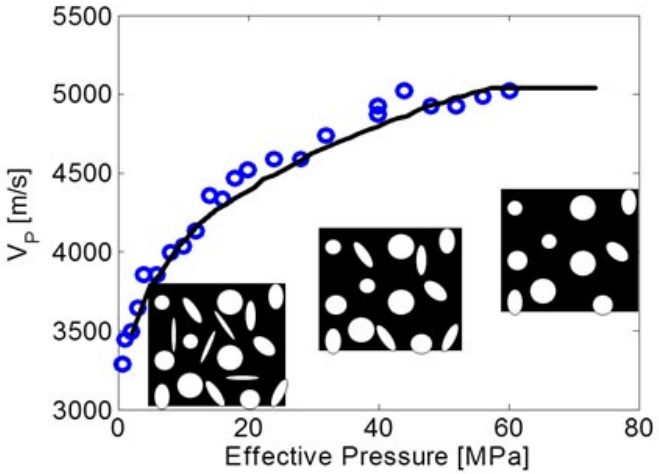




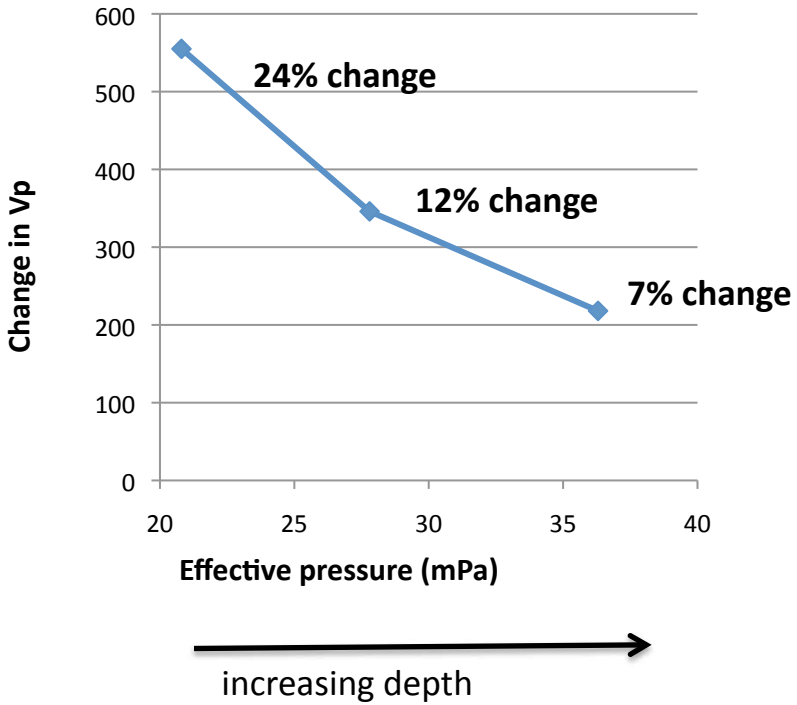
Zhang, 2012, 4-D survey
Cranfield reservoir

CO_2

Site specific seismic sensitivity: velocity change with depth

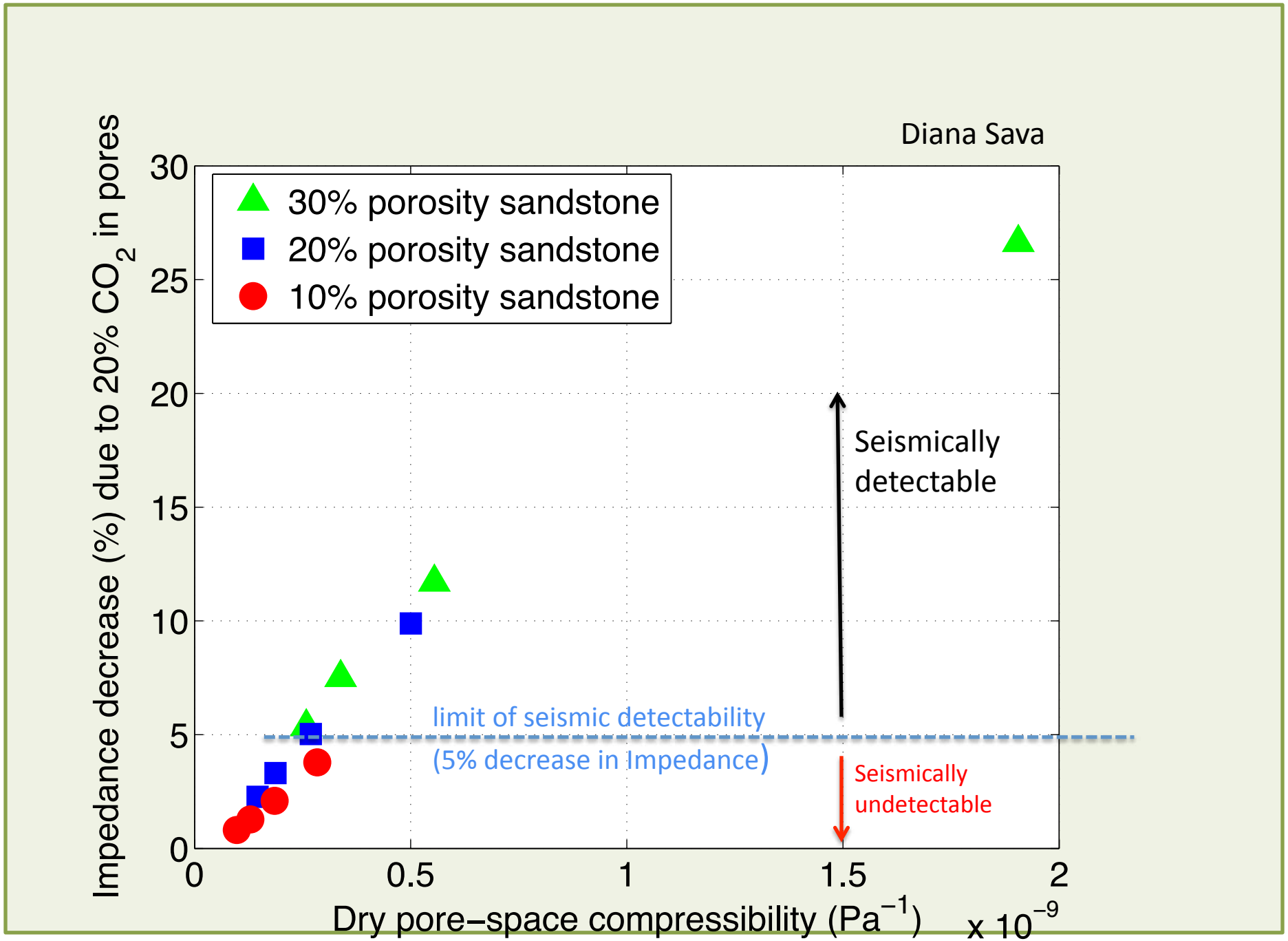


Rock physics model, self consistent approximations (Berryman 1995), data Purcell and Harbert University of Pittsburg

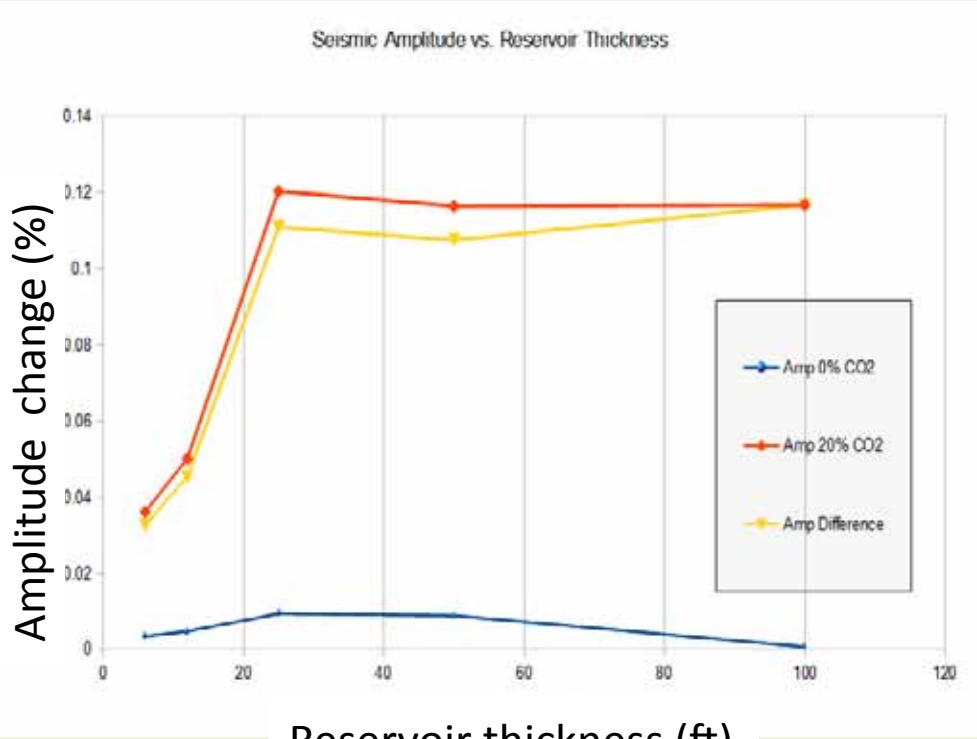


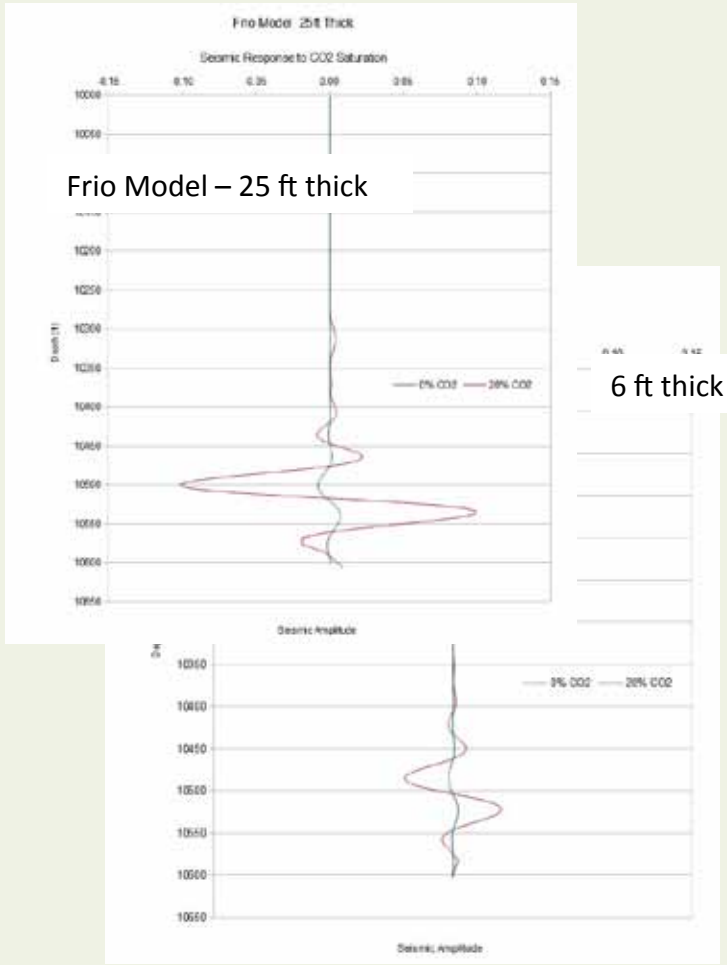
average elastic properties, Gassman (1951) theory, 30% porosity, 20% fluid substitution CO2 for brine, not changes to minerals, fluids do not support shear, Reuss (1929) model

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

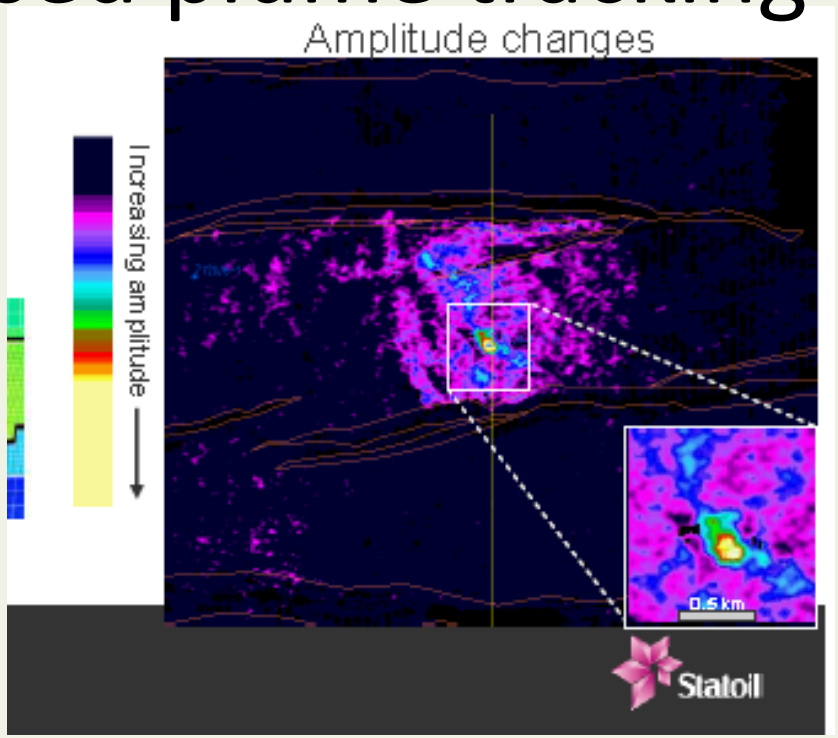
Site specific seismic sensitivity: saturated zone thickness



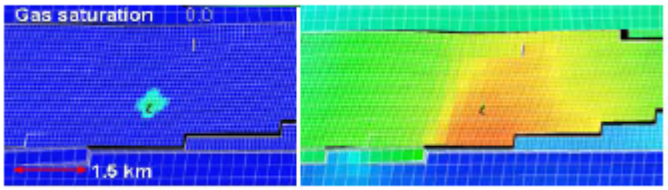


Frio Model - Randy Remington

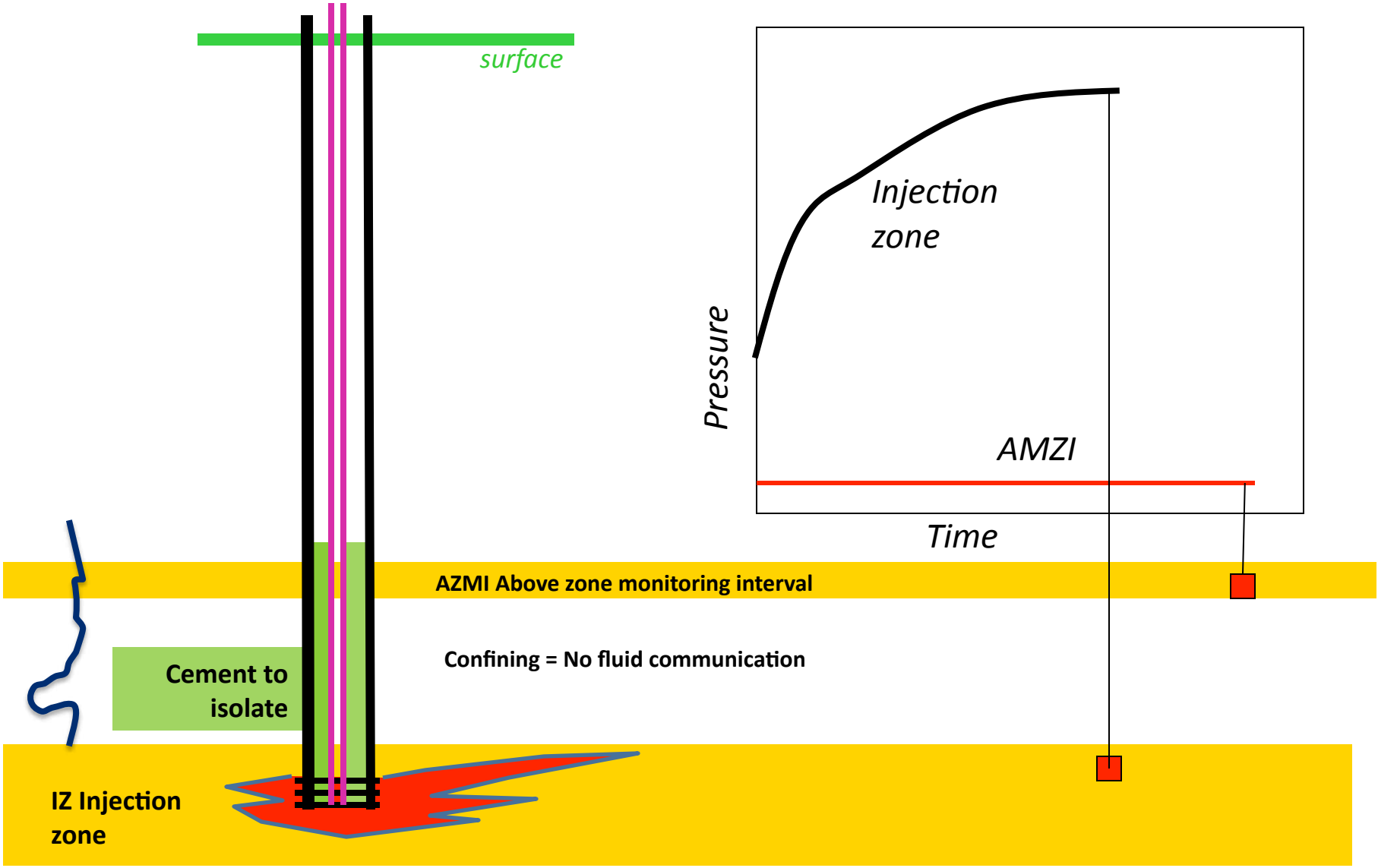
Value and limits of seismic and well-based plume tracking



Eiken et al, 2010 (GHGT10)

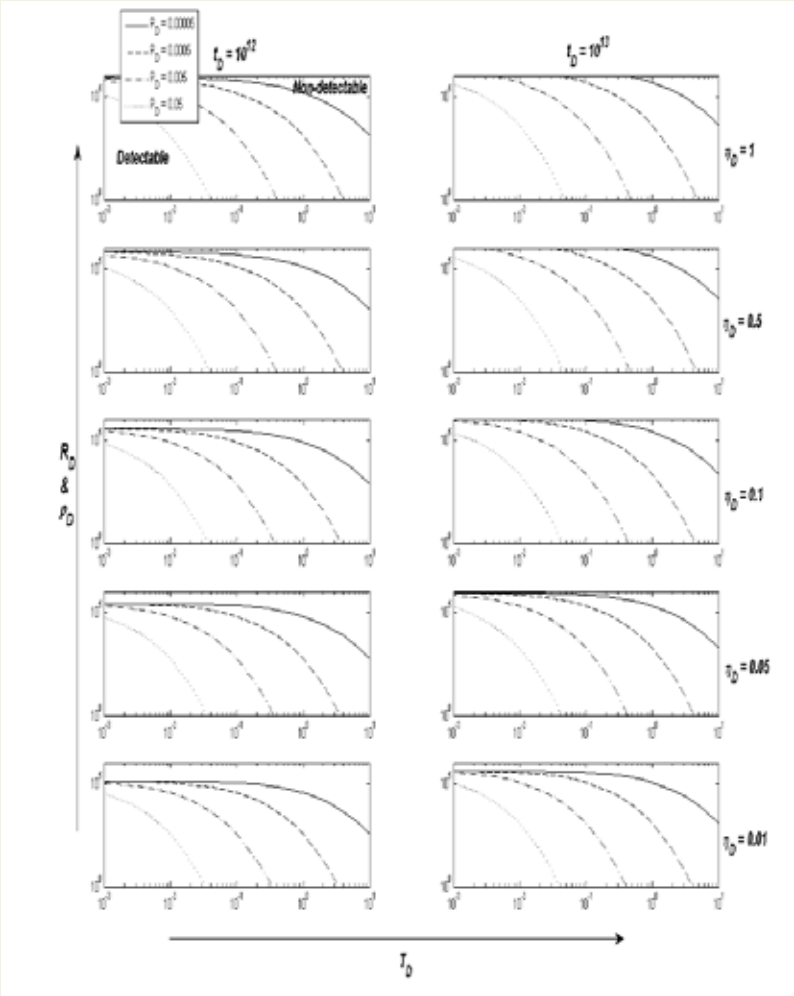


Using above AZMI pressure to assess storage permanence



AZMI Pressure sensitivity for leakage detection: non parametric tables

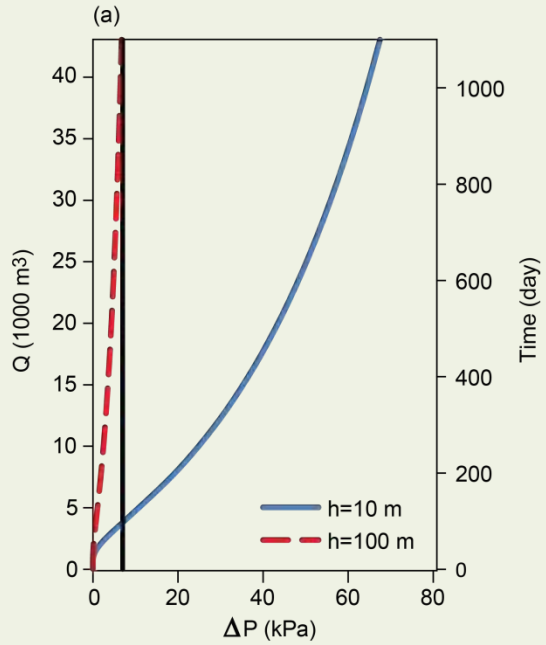
Parameter
m, brine viscosity (Pa.s)
IZ formation compressibility (1/Pa)
IZ formation porosity (fraction)
k, IZ formation permeability (m^2)
h, IZ formation thickness (m)
h, diffusivity (m^2/s)
AZMI compressibility (1/Pa)
AZMI porosity (fraction)
k_a, AZMI permeability (m^2)
h_a, AZMI thickness (m)
h_a, 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)



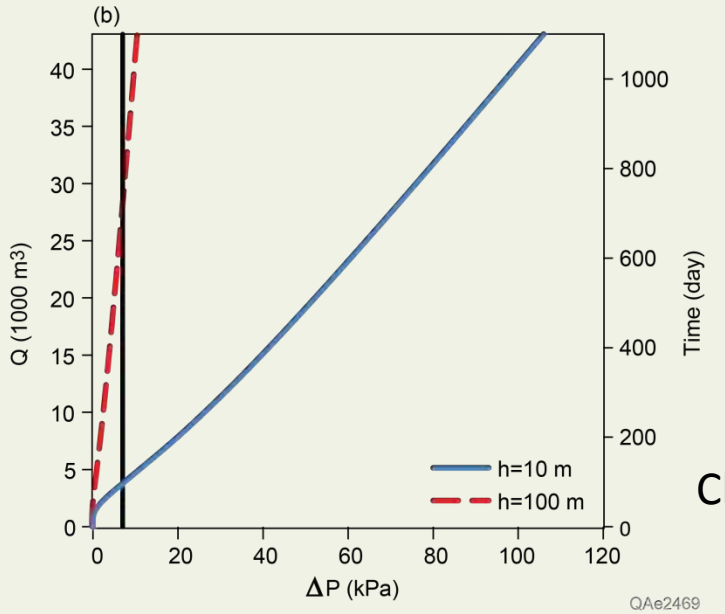
Mehdi Zeidouni

AZMI thickness vs sensitivity

Leakage rate

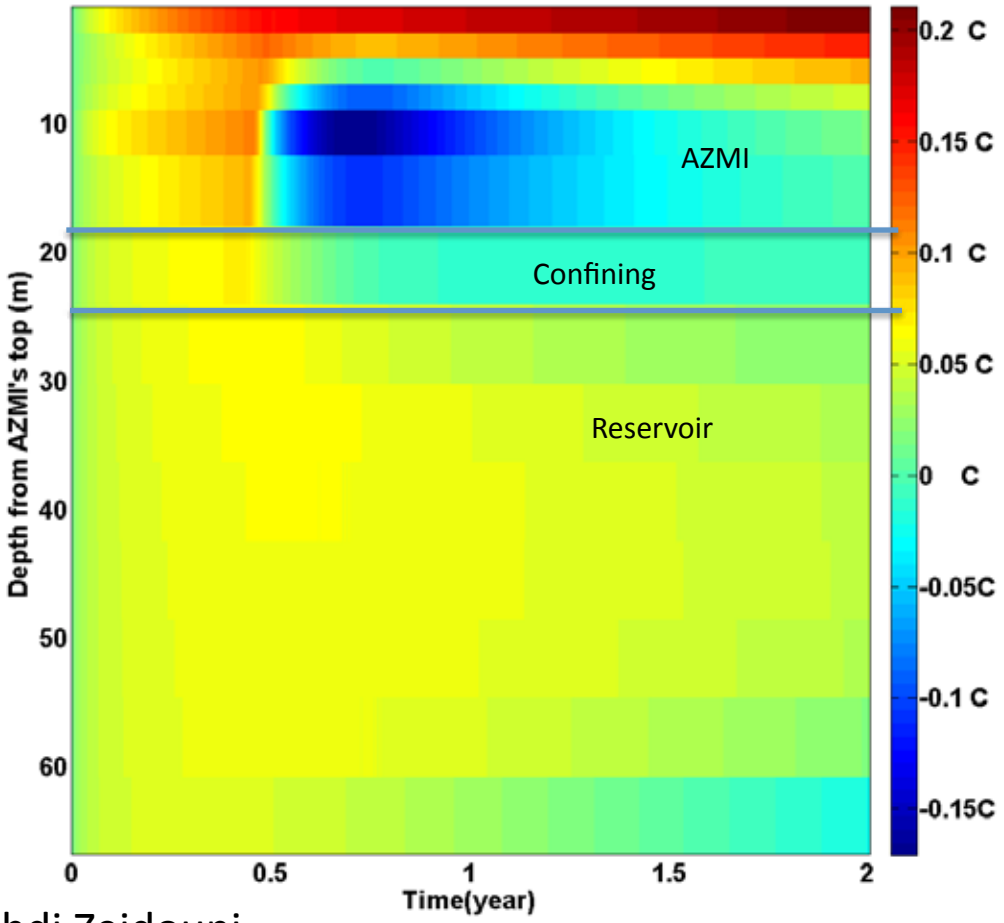


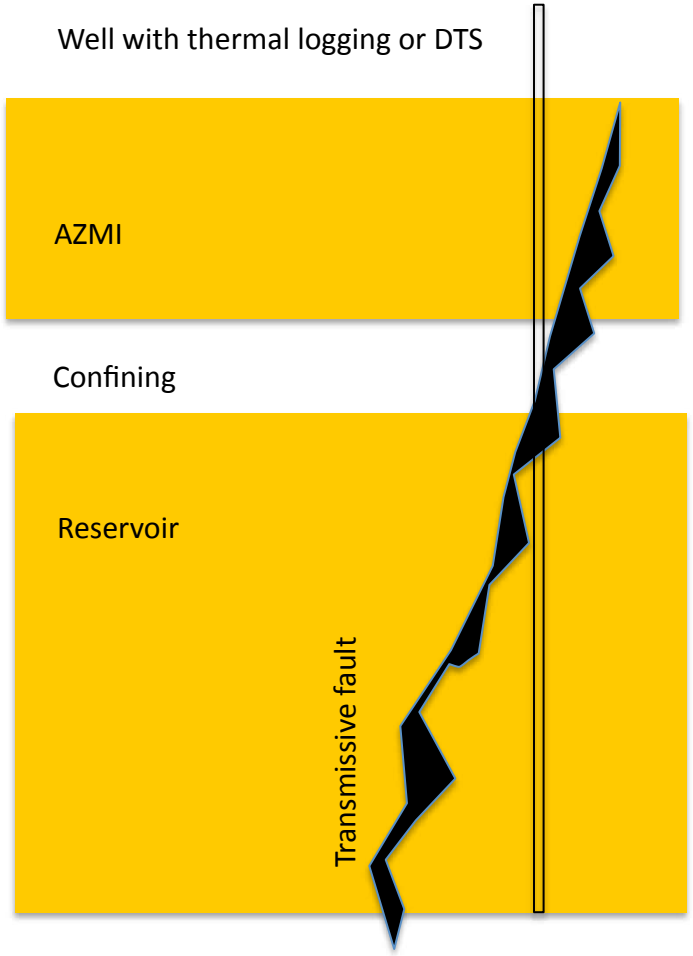
Infinite-acting boundary conditions



Closed boundary at 6 km

Thermal Sensitivity of AZMI to leakage

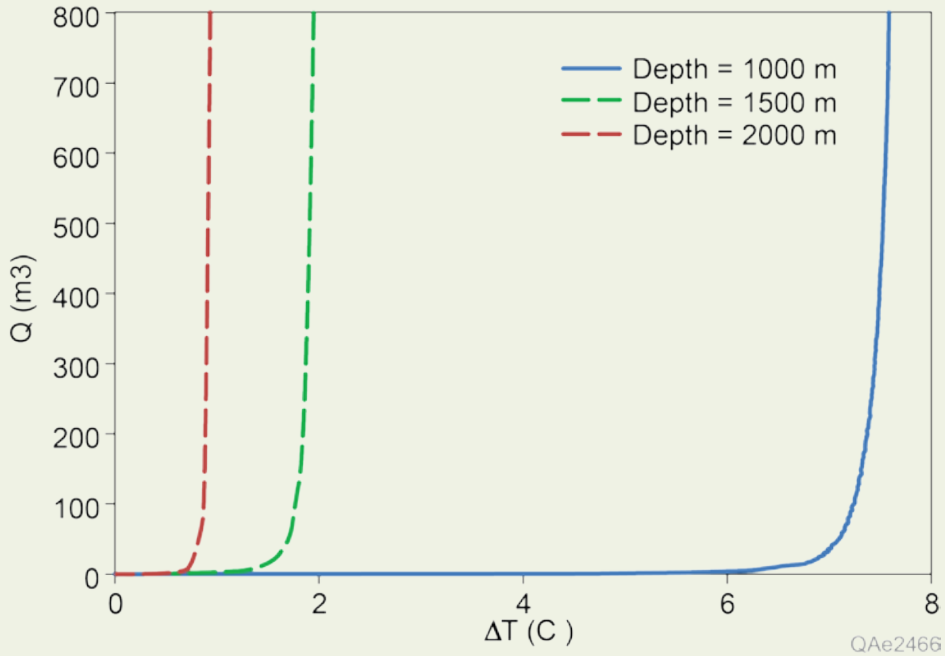




Mehdi Zeidouni

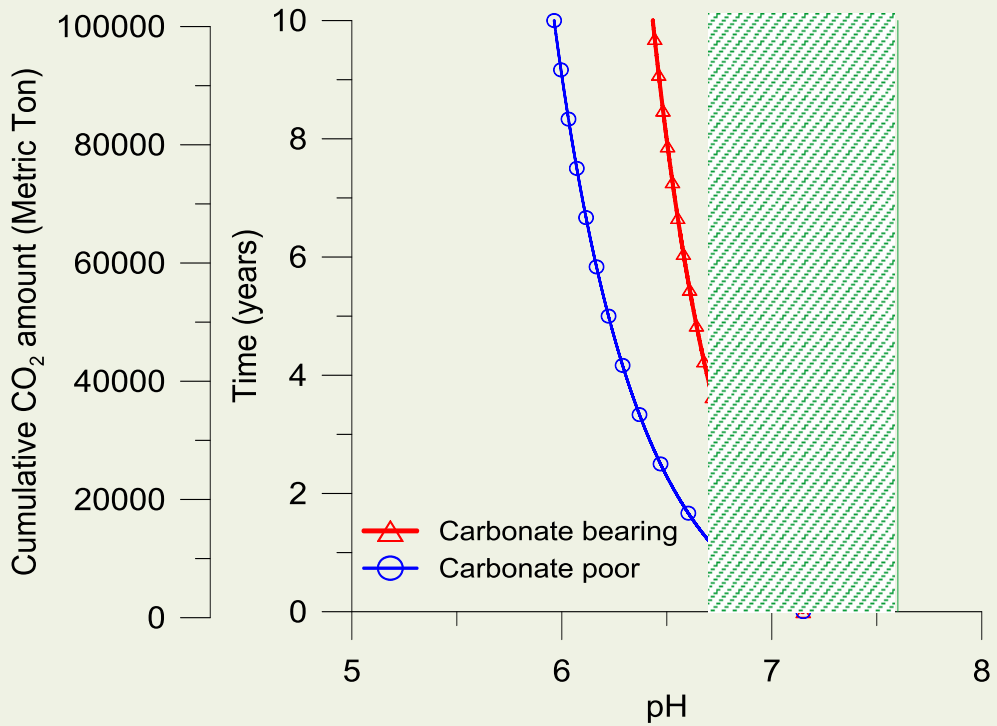
Idealized so well measured center of fault

Thermal sensitivity depth dependent



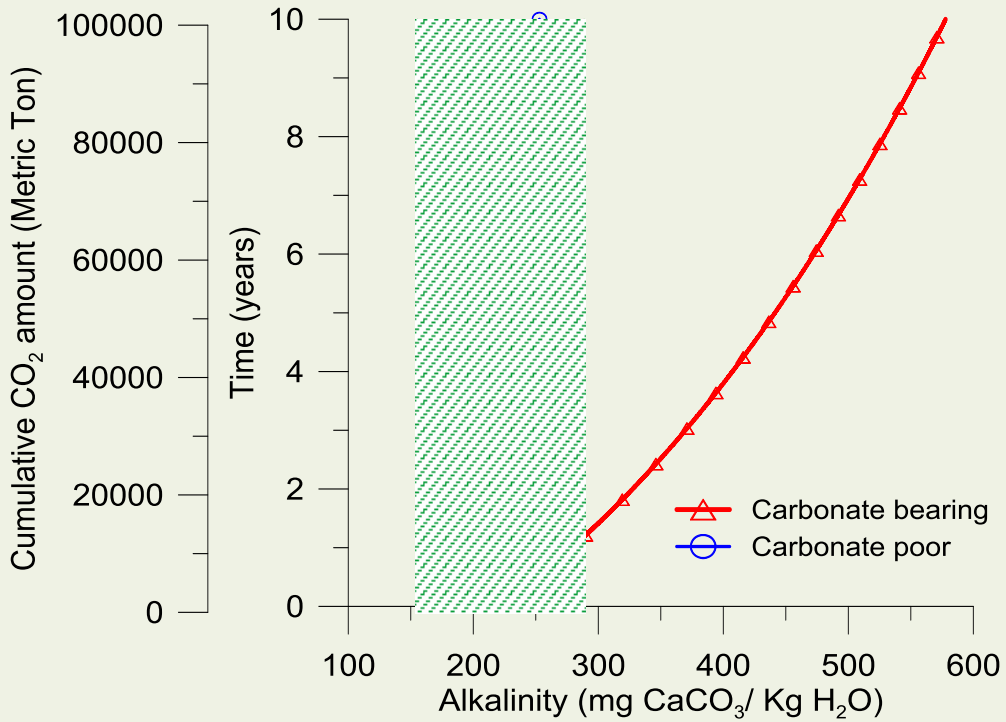
Mehdi Zeidouni

Site Specific Freshwater Geochemical Sensitivity



Changbing Yang

Site Specific Freshwater Geochemical Sensitivity-Alkalinity



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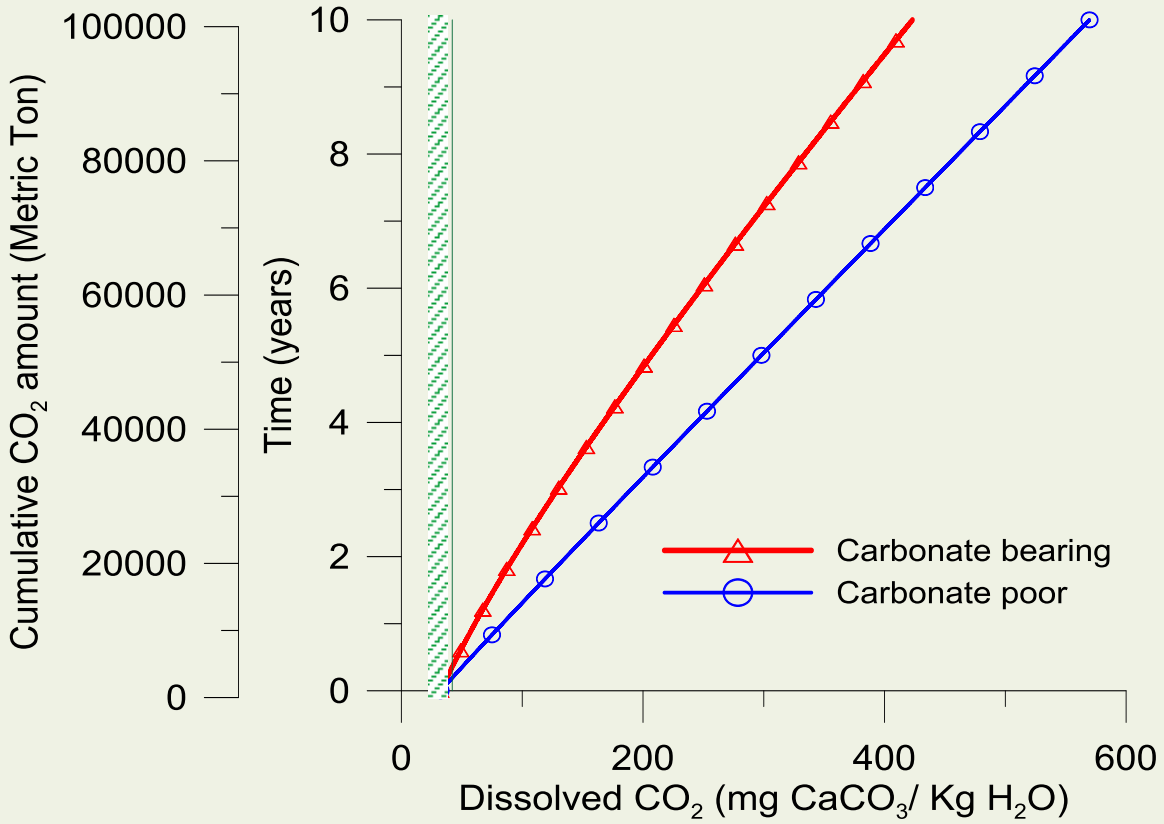
Site Specific Freshwater Geochemical Sensitivity- Dissolved CO_2



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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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