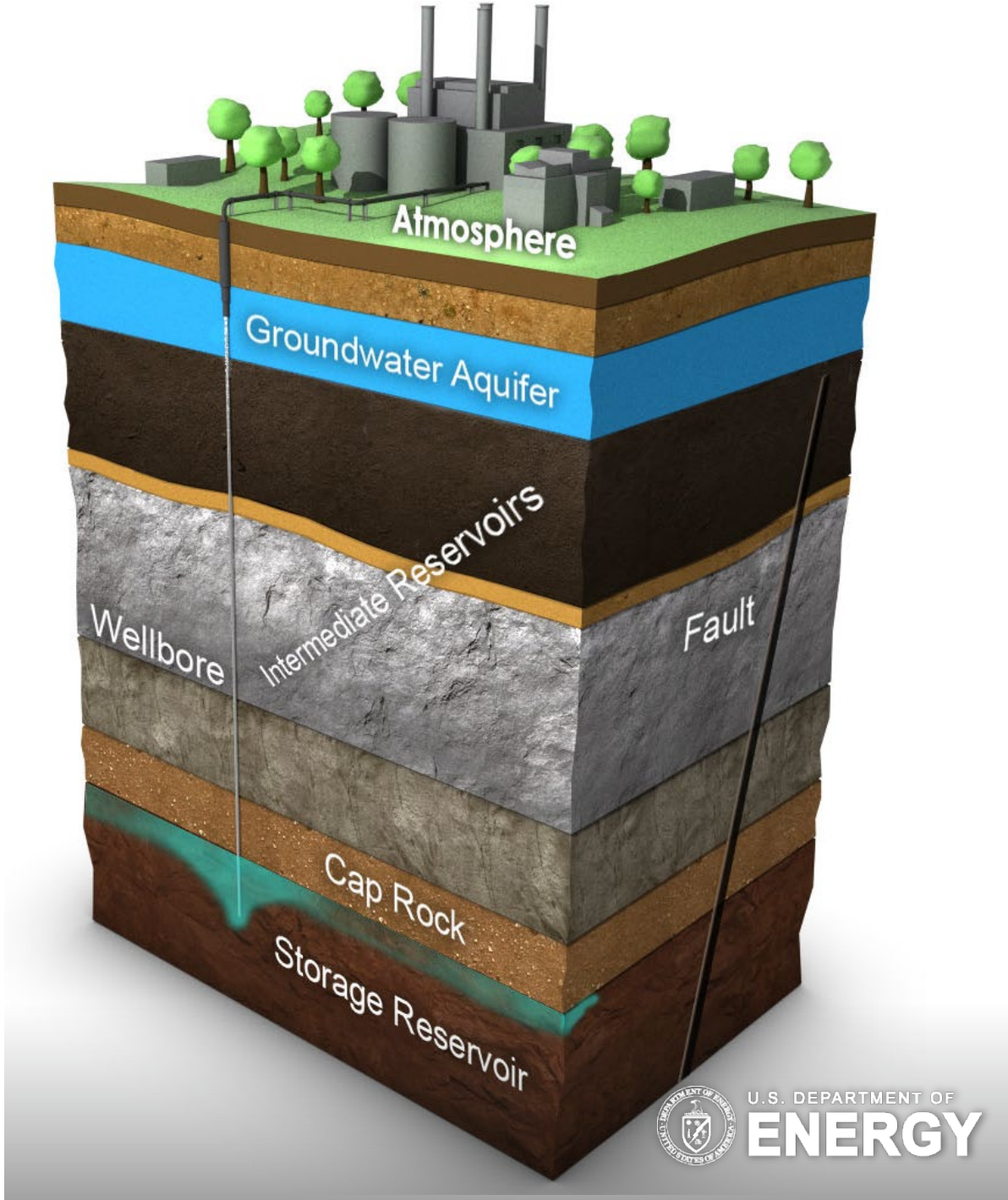
# Assessing monitoring methods for detection of potential leakage at carbon storage sites


Erika Gasperikova, LBNL

Contributors: Xianjin Yang (LLNL), Catherine Yonkofski (PNNL), Robert Dilmore (NETL)



Underground Injection Control Conference and NRAP Workshop, San Antonio, Texas
February 19, 2020

# Outline

- General considerations for geological carbon storage (GCS) site monitoring
- Monitoring design in context of uncertainty
- Estimating monitoring technology detection thresholds
- Design of effective and efficient monitoring

# Uses of Monitoring at a GCS Site

- Site characterization
- Conformance evaluation
- Containment assurance – storage accounting
- Secondary plume detection – risk assessment/decision support
- (Groundwater) resource protection – Class VI permit

# Class VI wells – Criteria and Standards

## 40 CFR 146.90 (d), (g),(i), (j)

**§ 146.90 Testing and monitoring requirements.**

The owner or operator of a Class VI well must prepare, maintain, and comply with a testing and monitoring plan to verify that the geologic sequestration project is operating as permitted and is not endangering USDWs. The requirement to maintain and implement an approved plan is directly enforceable regardless of whether the requirement is a condition of the permit. The testing and monitoring plan must be submitted with the permit application, for Director approval, and must include a description of how the owner or operator will meet the requirements of this section, including accessing sites for all necessary monitoring and testing during the life of the project. Testing and monitoring associated with geologic sequestration projects must, at a minimum, include:

(d) Periodic monitoring of the ground water quality and geochemical changes above the confining zone(s) that may be a result of carbon dioxide movement through the confining zone(s) or additional identified zones including:

(1) The location and number of monitoring wells based on specific information about the geologic sequestration project, including injection rate and volume, geology, the presence of artificial penetrations, and other factors; and

(2) The monitoring frequency and spatial distribution of monitoring wells based on baseline geochemical data that has been collected under §146.82(a)(6) and on any modeling results in the area of review evaluation required by §146.84(c).

(g) Testing and monitoring to track the extent of the carbon dioxide plume and the presence or absence of elevated pressure (e.g., the pressure front) by using:

(1) Direct methods in the injection zone(s); and,

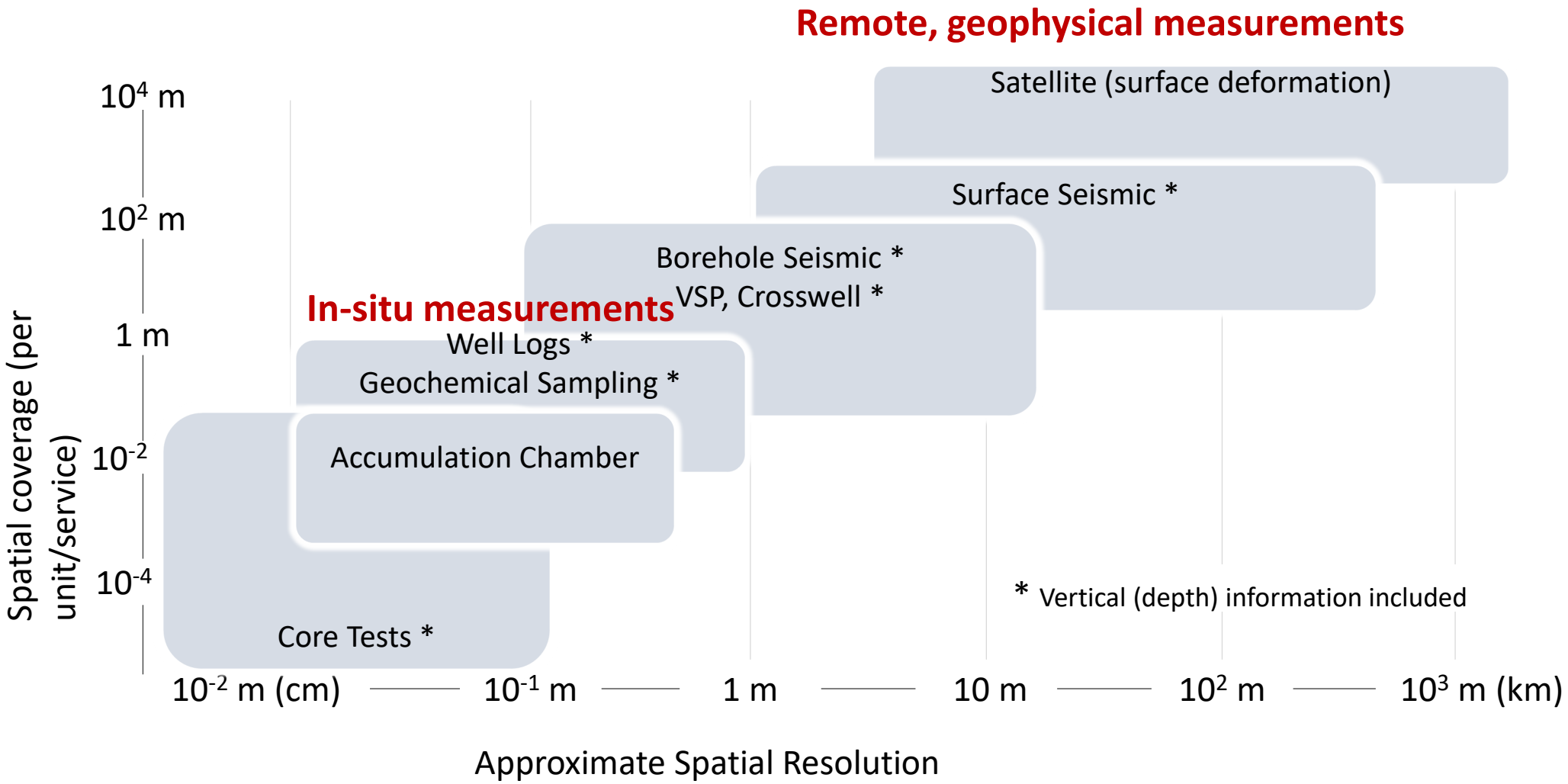
(2) Indirect methods (e.g., seismic, electrical, gravity, or electromagnetic surveys and/or down-hole carbon dioxide detection tools), unless the Director determines, based on site-specific geology, that such methods are not appropriate;

(i) Any additional monitoring, as required by the Director, necessary to support, upgrade, and improve computational modeling of the area of review evaluation required under §146.84(c) and to determine compliance with standards under §144.12 of this chapter;

(j) The owner or operator shall periodically review the testing and monitoring plan to incorporate monitoring data collected under this subpart, operational data collected under §146.88, and the most recent area of review reevaluation performed under §146.84(e). In no case shall the owner or operator review the testing and monitoring plan less often than once every five years. Based on this review, the owner or operator shall submit an amended testing

https://www.govinfo.gov/content/pkg/CFR-2019-title40-vol25/pdf/CFR-2019-title40-vol25-part146-subpartH.pdf

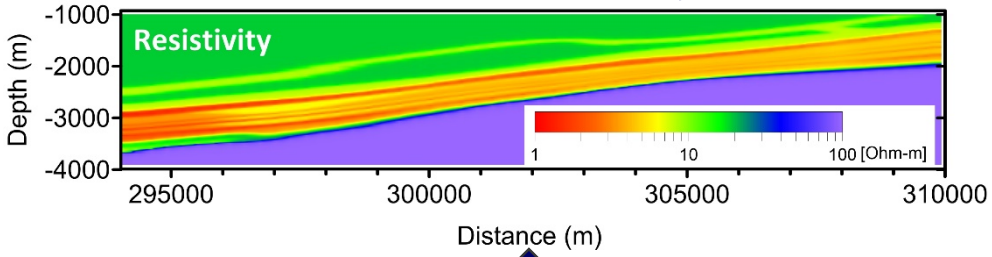
# Monitoring – Spatial Resolution

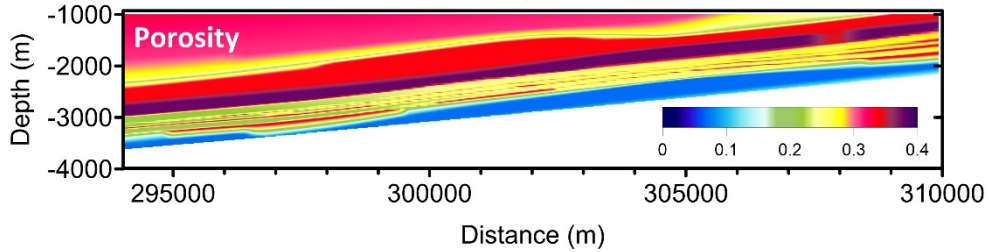


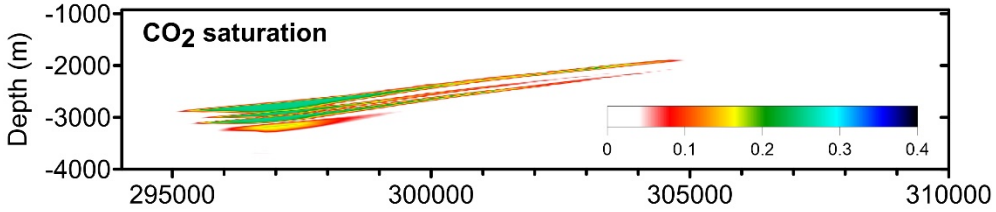
# Geophysical Monitoring

Techniques are **complementary**, as each provides sensitivity that the other technique cannot provide

| Geophysical method | Resistivity/EM | Seismic | Gravity |
|---|---|---|---|
| Geophysical property | resistivity | seismic velocity | density |
| Sensitivity to | fluid properties | changes in bulk properties | density changes |
| Subsurface properties | Lithology, porosity, brine and $CO_2$ saturations | | |
| | Permeability | | --- |
| | --- | Density | |
| | --- | Pressure | --- |
| | Temperature | --- | --- |
| | Brine Salinity | --- | --- |




**Rock-physics or constitutive relationships**

# Optimal Monitoring Design

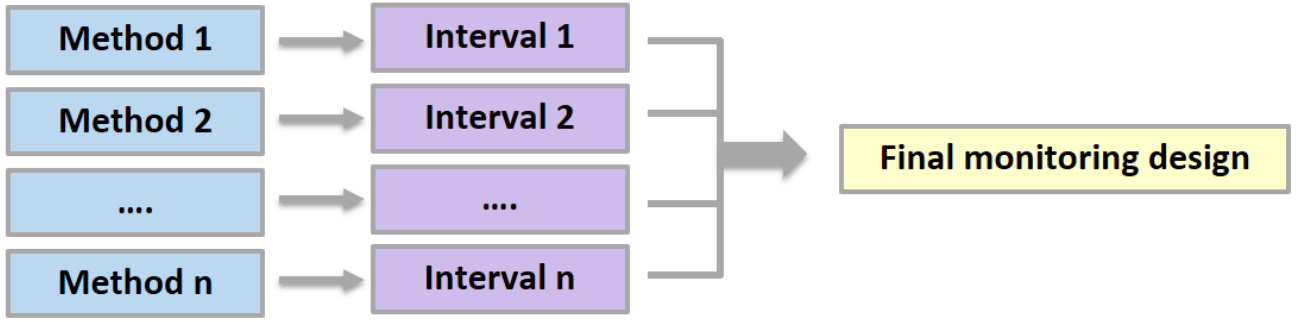
State-of-the-art reservoir monitoring technologies

Pilot/demonstration surveys

**Instrument specifications & sensitivity** → **Measurement noise + Natural background variability + Size of the plume** → **Array design (acquisition geometry & spatial sampling) that captures this change** → **Decide on intervals for repeated surveys (temporal sampling)**

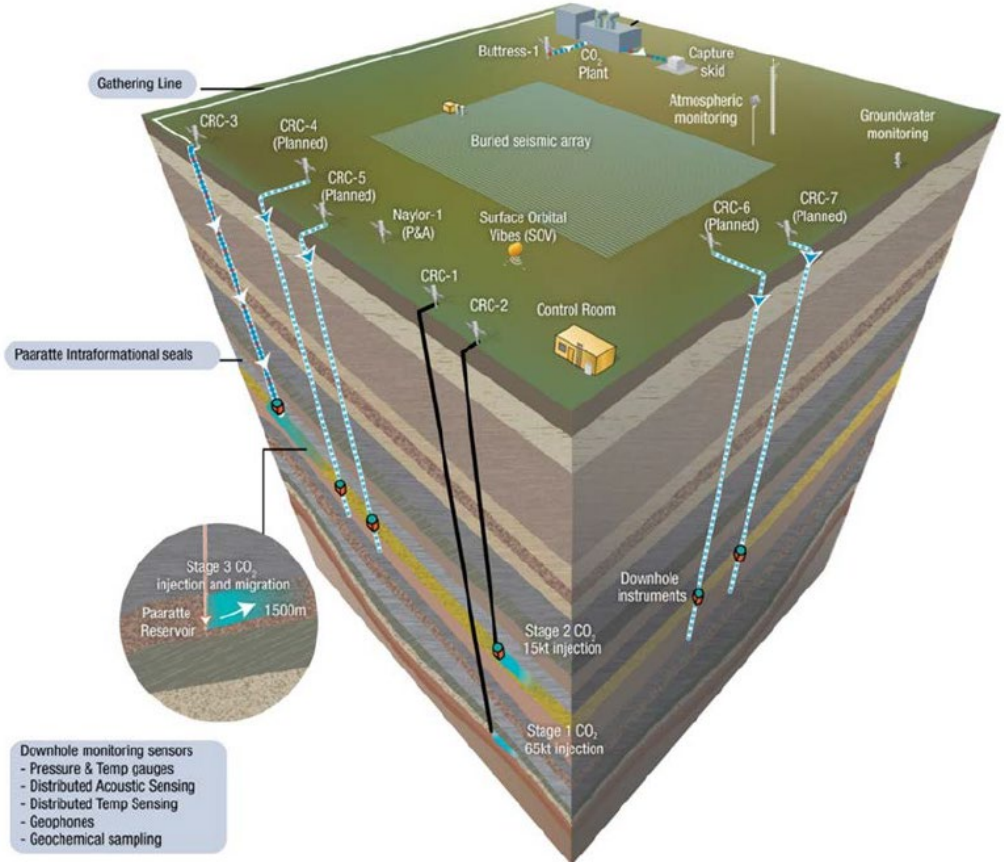
**Done by industry and other DOE-funded programs**

Proximity of sensors to the plume: smaller changes are detectable with sensors closer to the plume



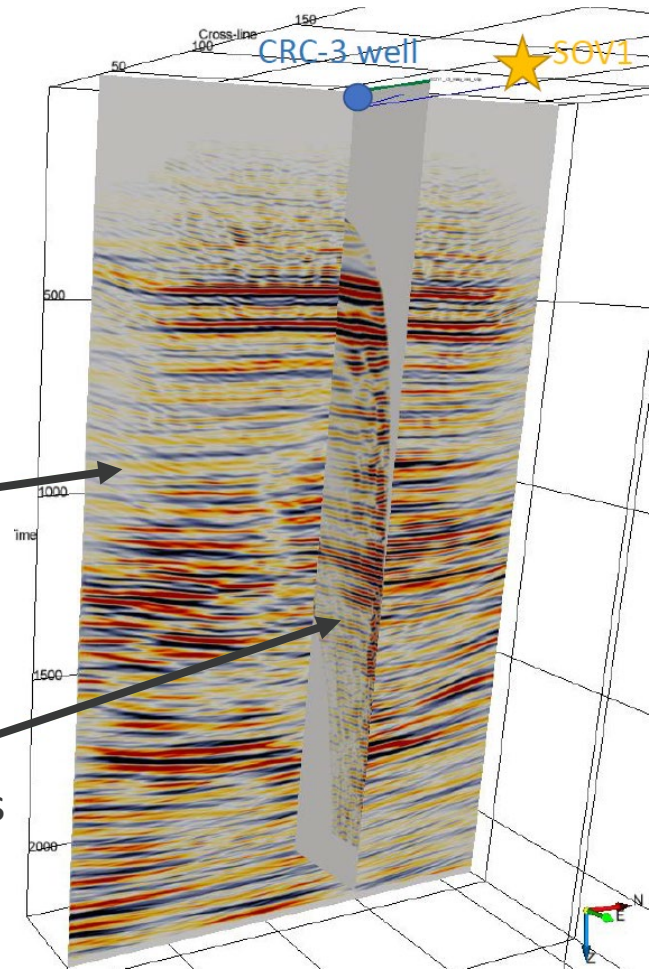

**Site specific, fit-for-purpose monitoring design**

# Advanced Monitoring Systems




Otway, Australia

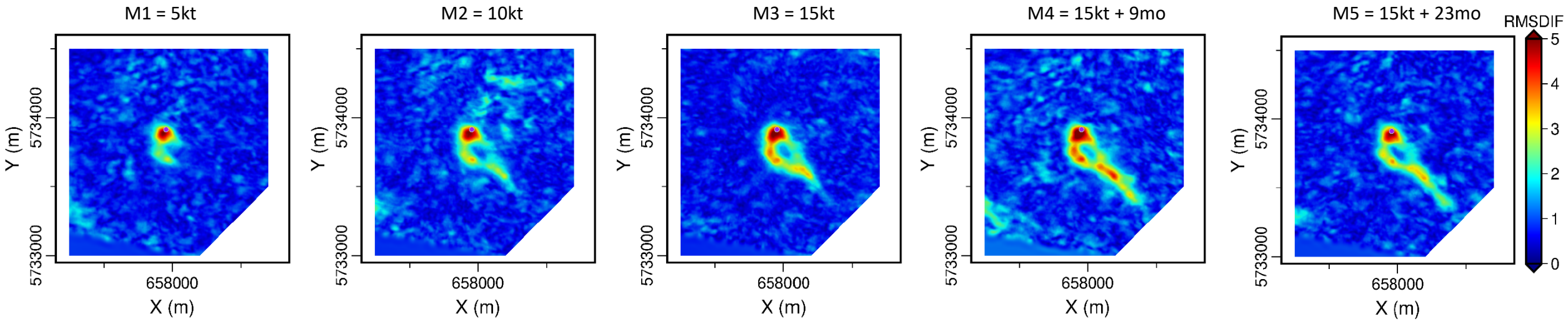
- Continuous/on-demand
- Remotely operated
- Low environmental/ societal impact
- 4D monitoring
- Reduced cost and footprint




(Correa et al., 2019)

# Pilot Projects

- Small injection volumes => can be used as analogs for secondary $CO_2$ plumes
- Verify model results
- Test new technologies
- Test monitoring designs



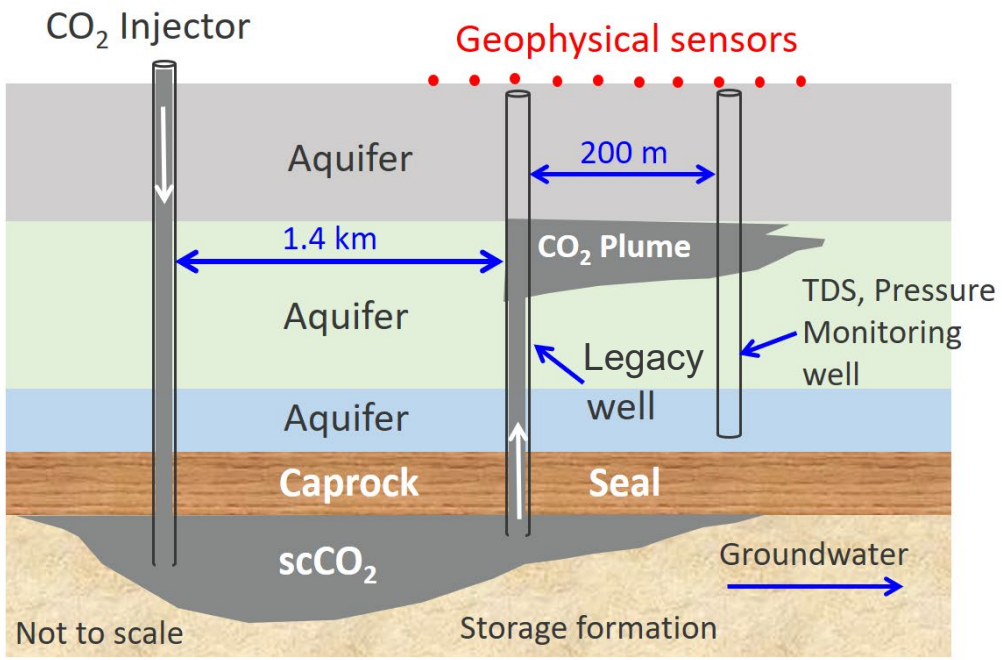

Otway: Time-lapse seismic signals

(Glubokovskikh, 2019)

# Modeling of Geophysical Monitoring

Full spectrum of hypothetical scenarios including those that are highly unlikely

- **Given: $CO_2$ migration through a well with uncertain characteristics (depth, size, saturation distribution)**
- **What is the probability of detecting secondary $CO_2$ plume for various monitoring technologies/deployment?**




Groundwater properties impacted by $CO_2$ leakage:

- Total dissolved solids (TDS)
- Pressure (P)
- $CO_2$ saturation

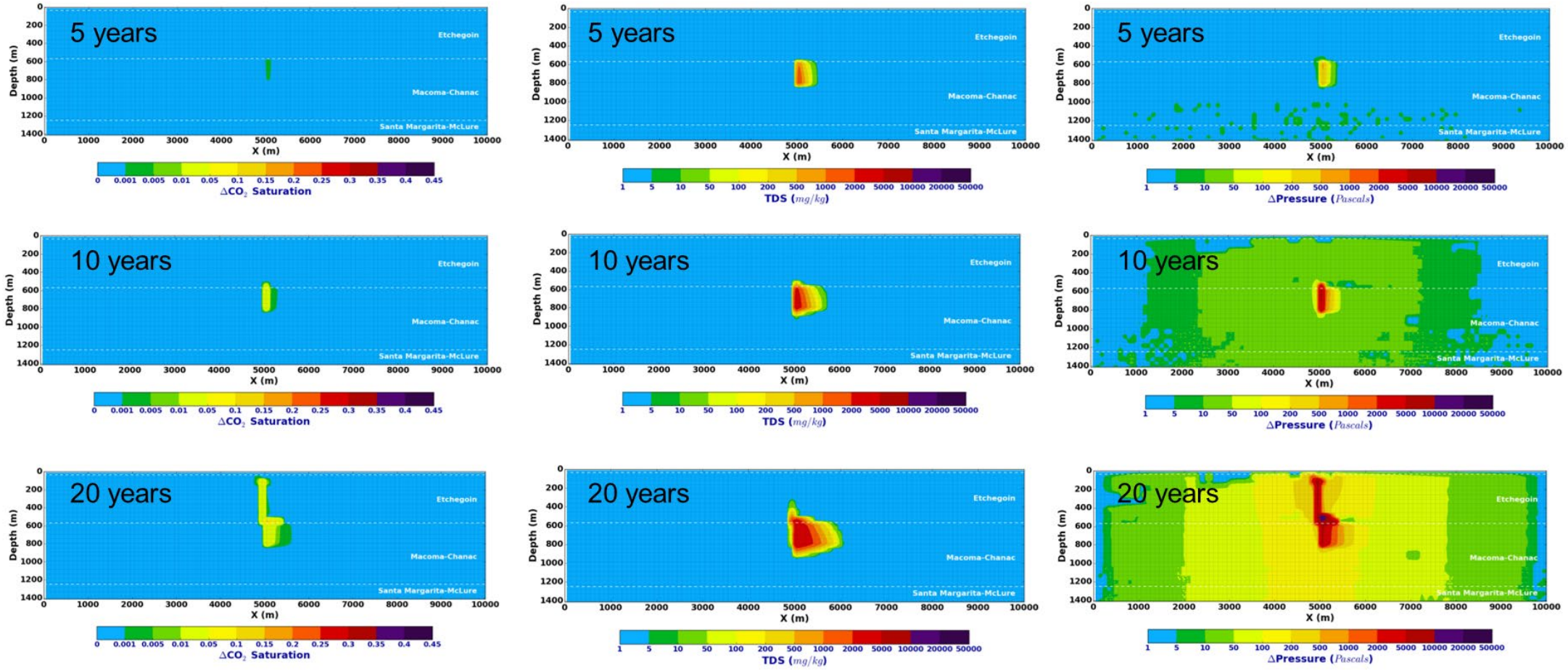
# Approach

Full spectrum of hypothetical scenarios including those that are highly unlikely

1. Stochastic simulation of plumes
2. Model geophysical monitoring for all realizations
3. Evaluate the probability of detecting and time/mass of a secondary plume before detection
4. Assess acceptability of detectability (relative to resource protection and/or decision support)
5. Apply understanding of monitoring technology effectiveness in site-scale monitoring design

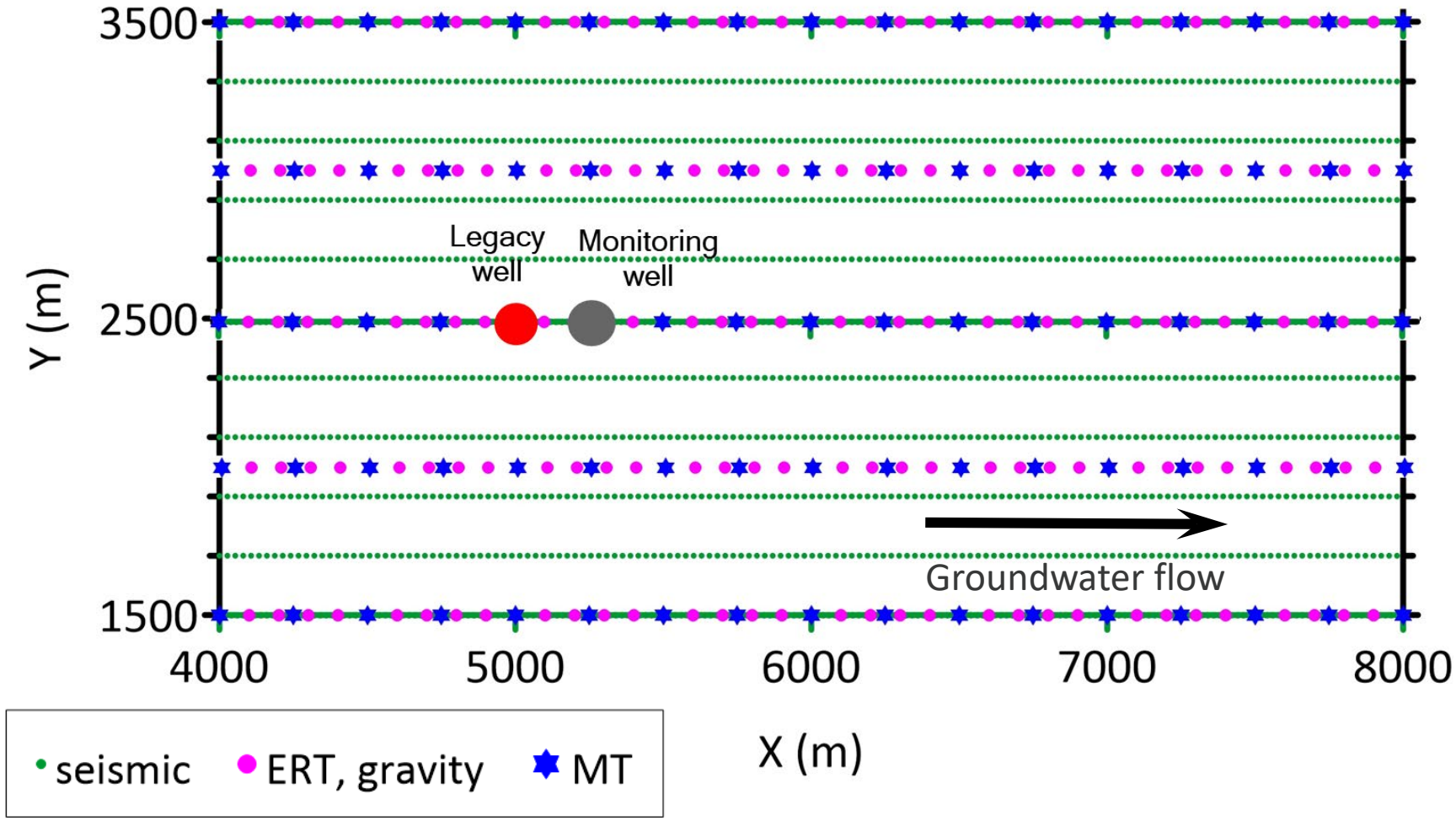
# 1. Stochastic simulation of plumes

Full spectrum of hypothetical scenarios including those that are highly unlikely



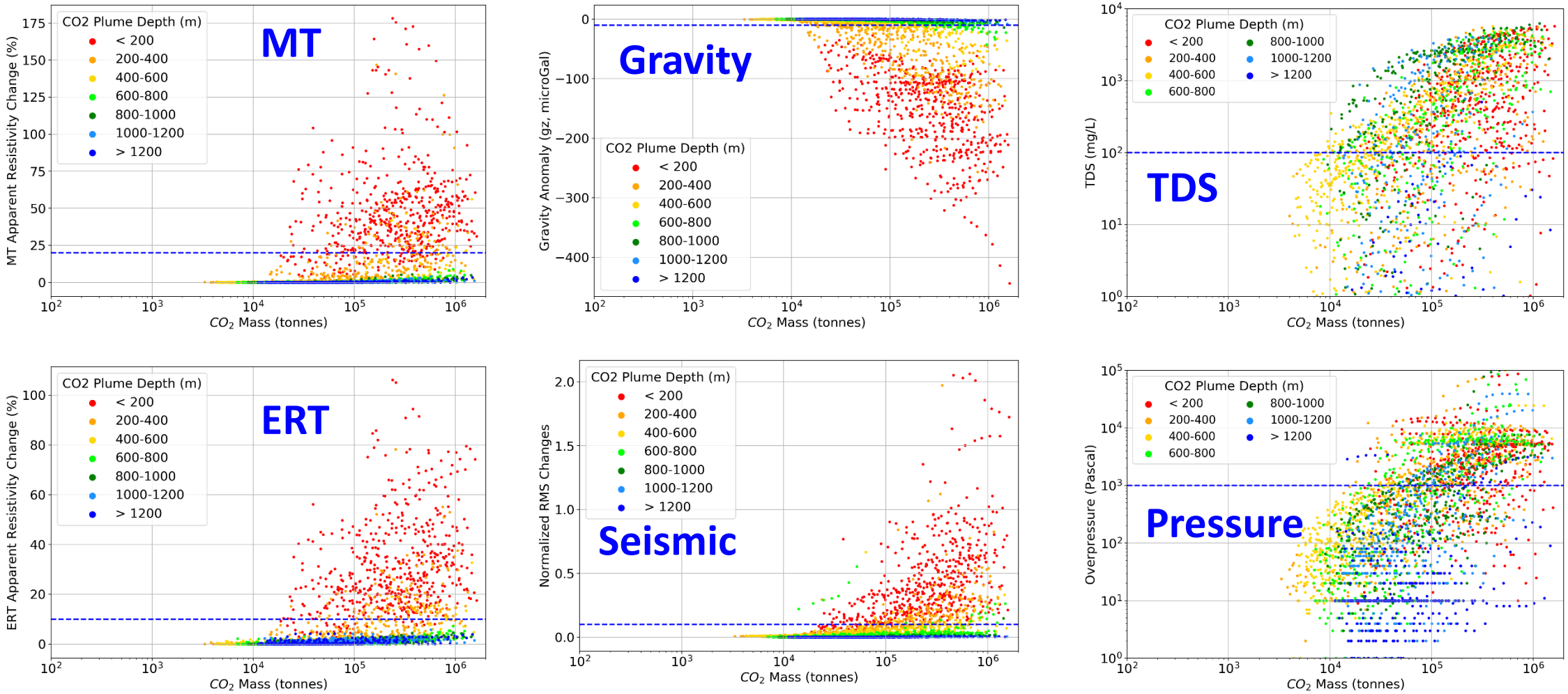

$CO_2$ saturation | TDS concentration | Overpressure

# 2. Model geophysical monitoring

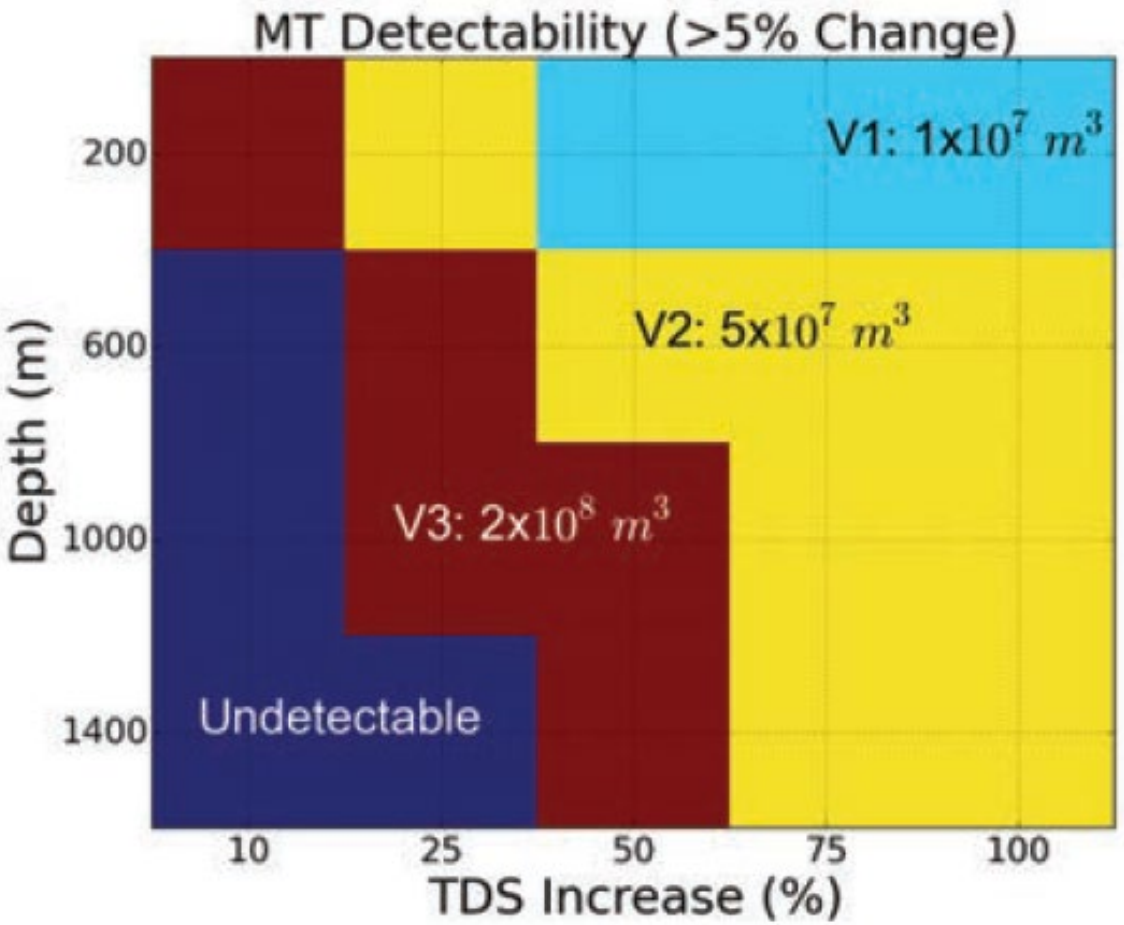



| | |
|---|---|
| MT (Magnetotellurics) | SURFACE |
| ERT (Electrical Resistivity Tomography) | SURFACE |
| Gravity | SURFACE |
| Seismic | SURFACE |
| TDS (Total Dissolved Solids) | DOWNHOLE |
| Pressure | DOWNHOLE |

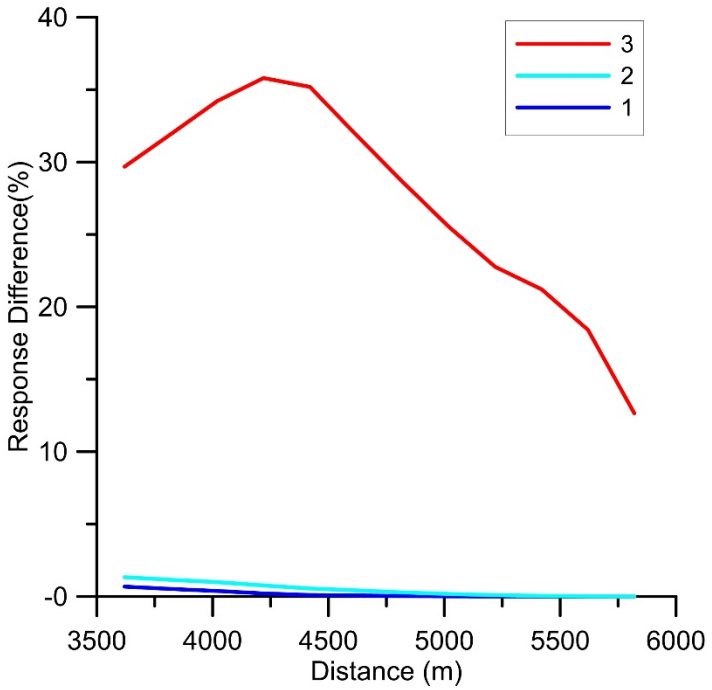
# 2. Model geophysical monitoring



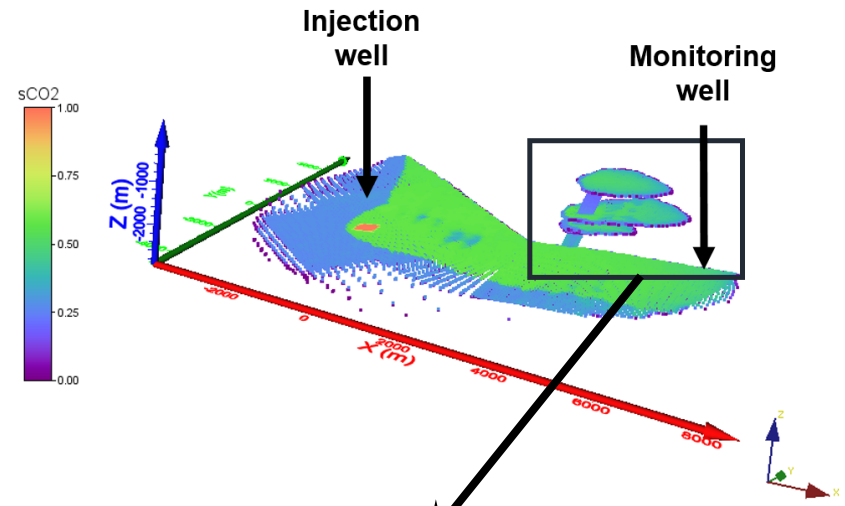
# 3. Evaluate the probability of detection and time/mass of a secondary plume before detection

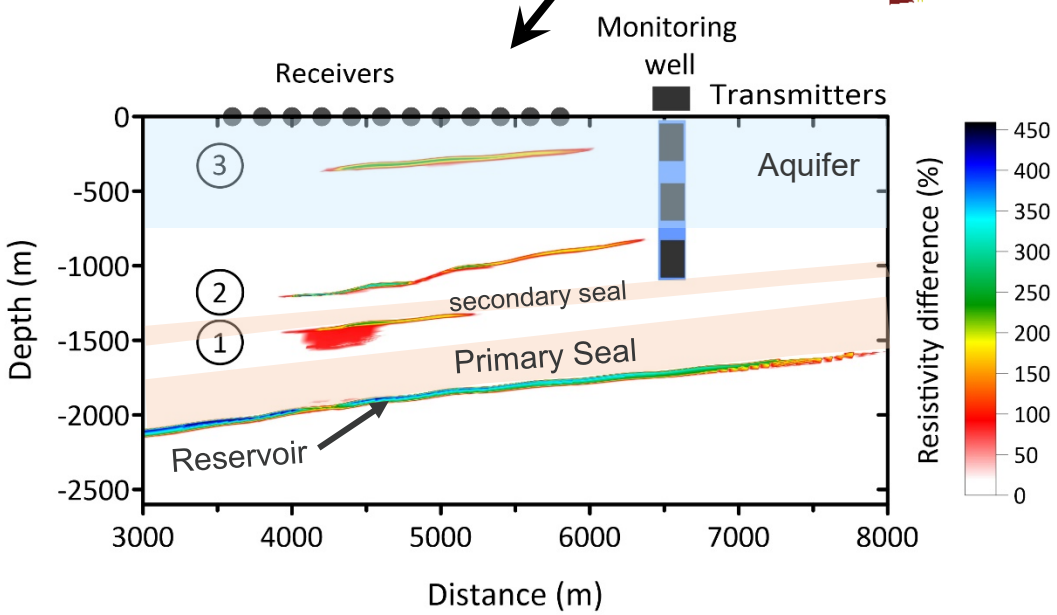


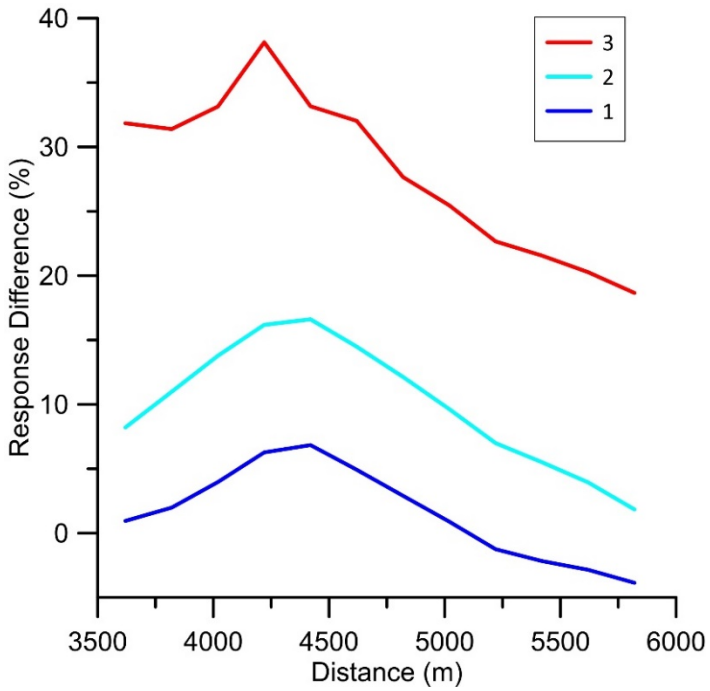
# 4. Fit-for-purpose Survey Design – Detection Thresholds




Surface configuration

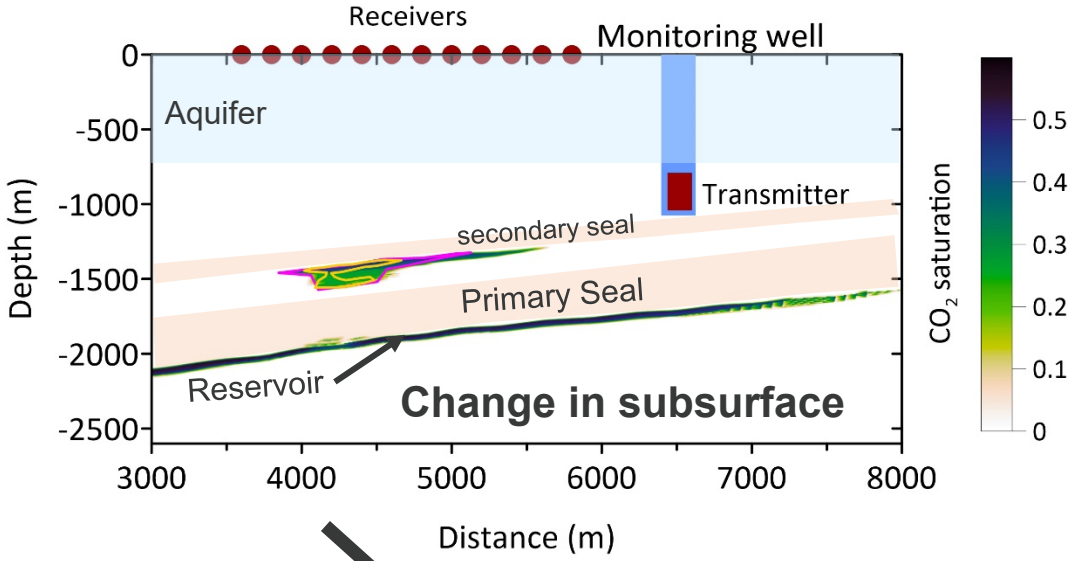


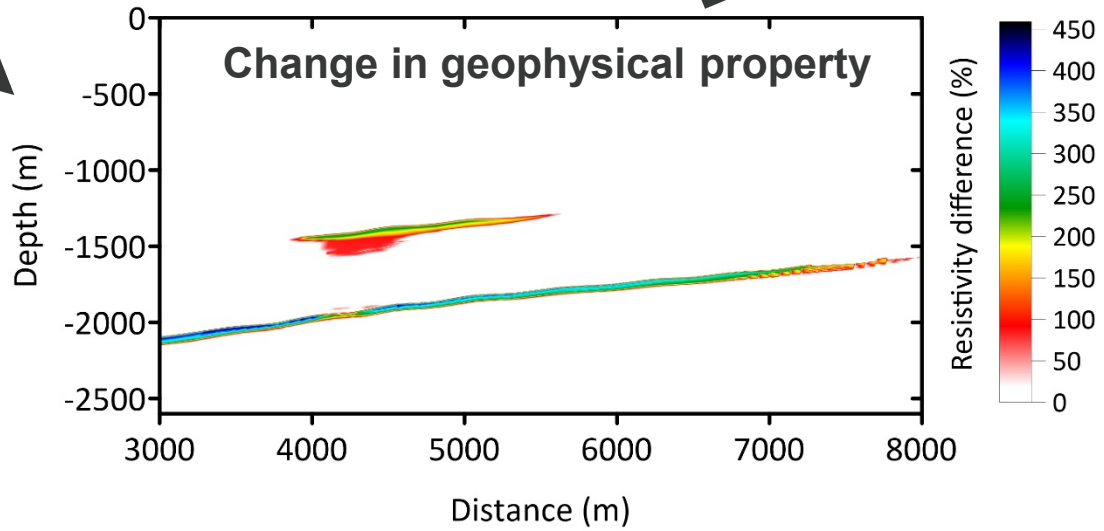



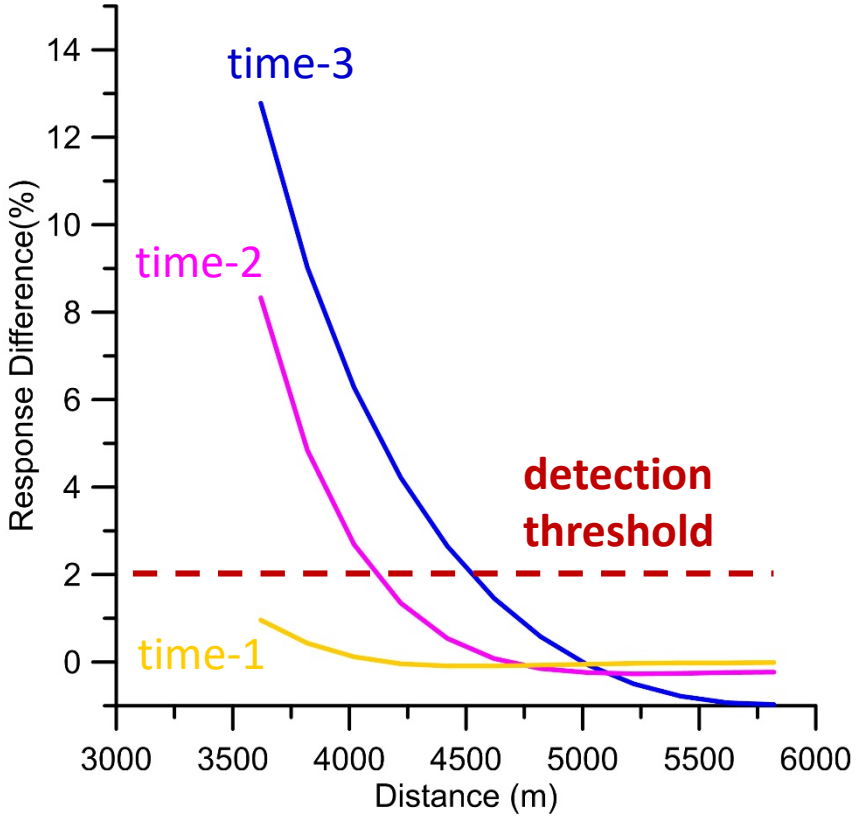




Borehole-to-surface configuration

# 4. Fit-for-purpose Survey Design – Time Intervals

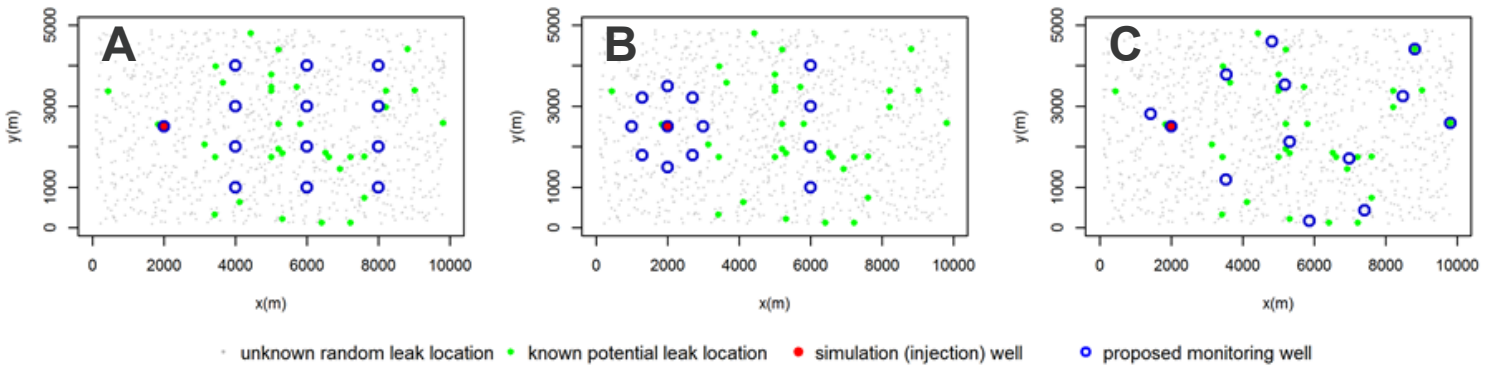


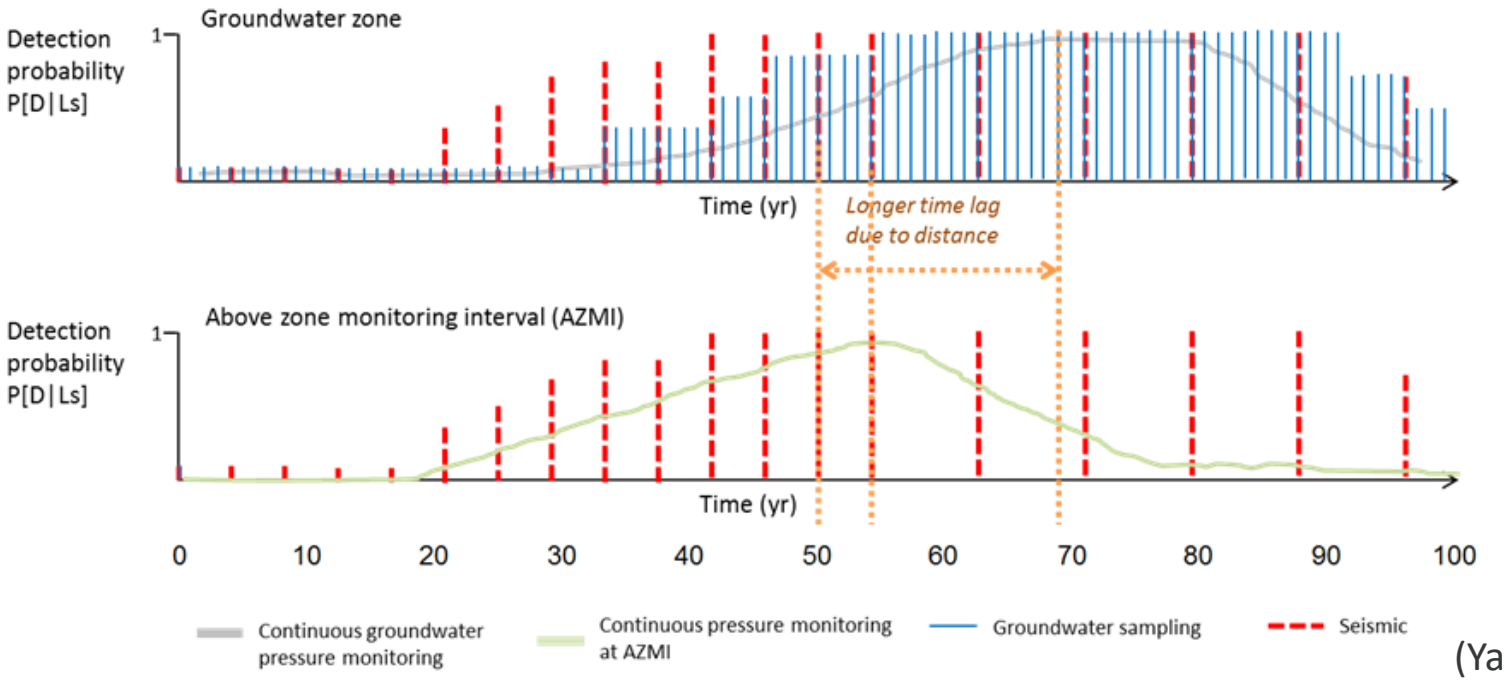




**Time-lapse signal change**

# 5. Risk-based site-scale monitoring design and optimization




Known potential leakage pathways play a central role in designing the monitoring plans




Complementary spatial and time resolutions:

- 3D seismic - to identify high risk zone
- pressure monitoring - more efficient detection in time
- groundwater and soil gas monitoring - to confirm the impact domain

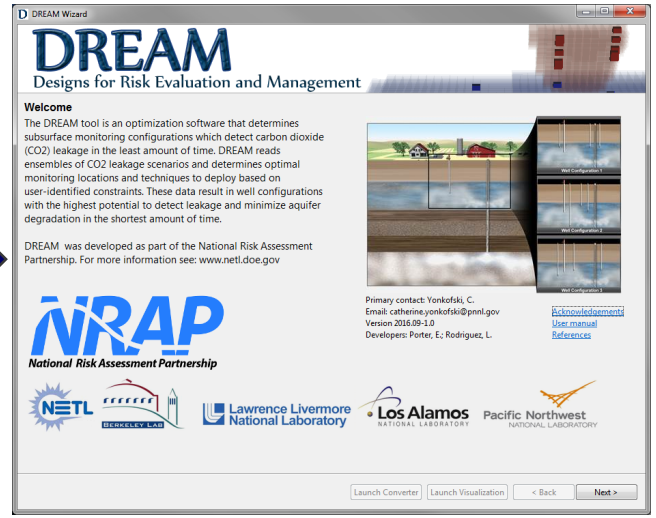
(Yang, Y. et al., 2015)

# DREAM

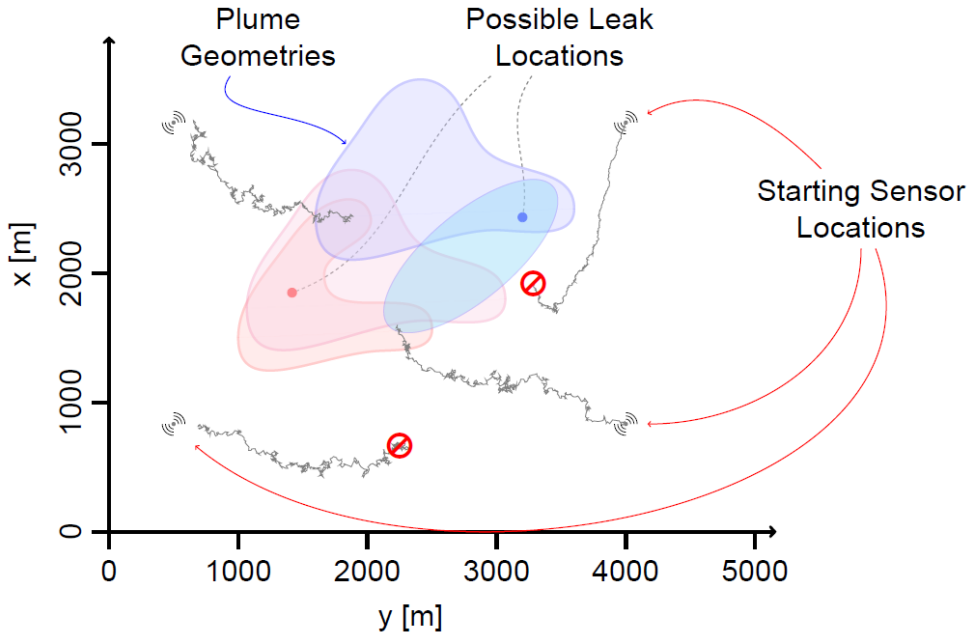
Design for Risk Evaluation and Management

## INPUT

- Output from:
  - Subsurface full-physics simulators (e.g., STOMP, NUFT, TOUGH2)
  - NRAP-Open -IAM
- Number of sensors
- Type of the sensors
- Technology detection limits
- Possible locations
- Costs/budget




- Iterates across possible plume scenarios
- Uses a computationally-efficient simulated annealing approach

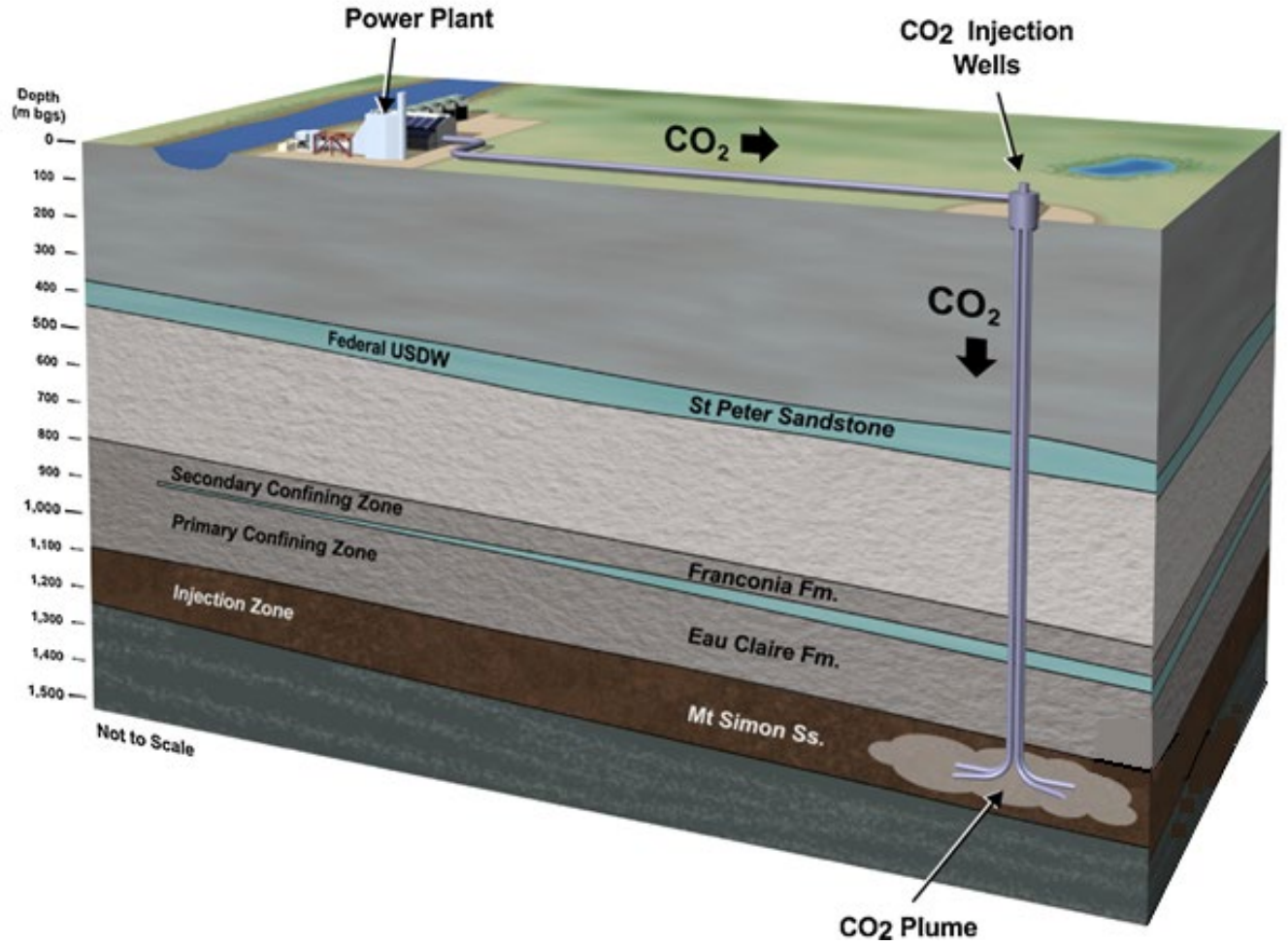


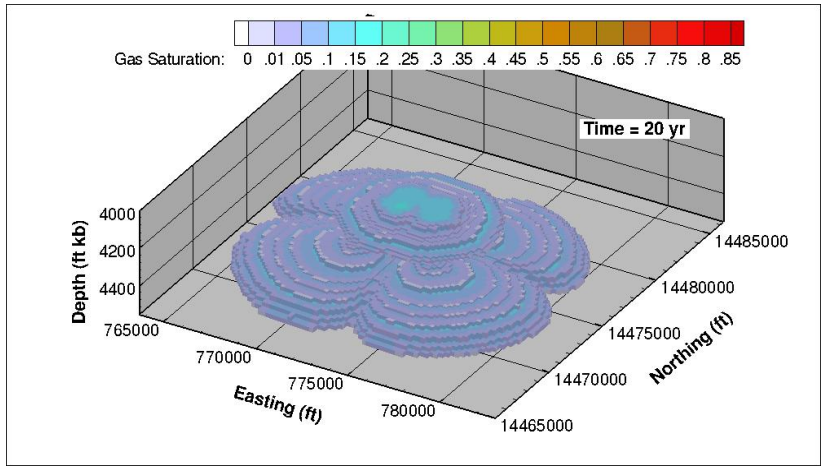

## OUTPUT

- Effective and efficient monitoring network
- Configuration with the lowest time to detection of the plume

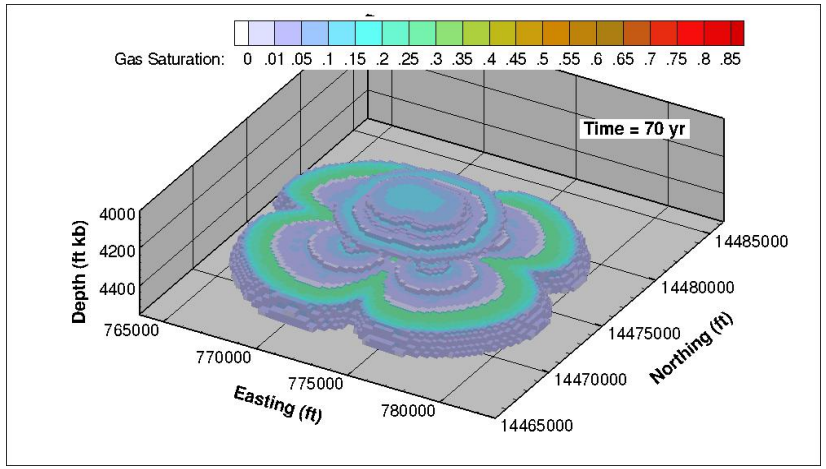
# FutureGen 2.0 Case Study (Illinois Basin)

UIC Class VI Permit Application



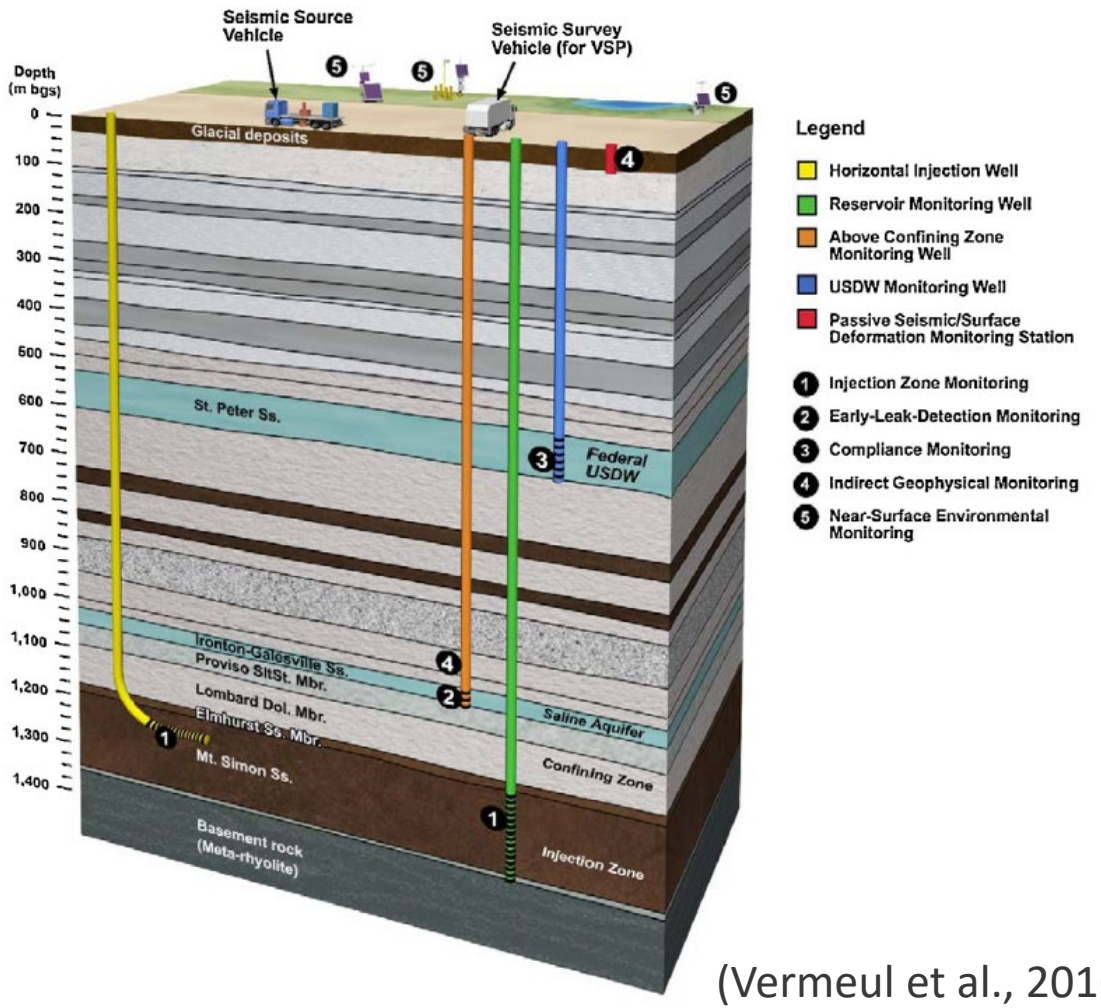

End of injection




50-years later

# FutureGen 2.0 – Monitoring network

## Original Monitoring Plan



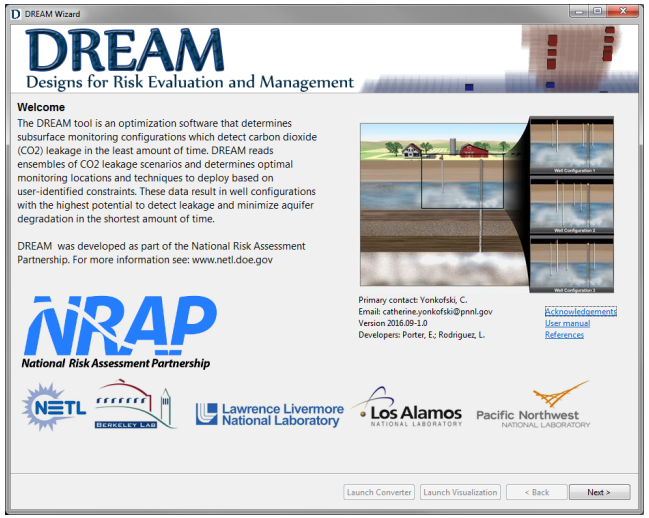

(Vermeul et al., 2016)

| | Above Confining Zone (ACZ1; ACZ2) | USDW (USDW1) |
|---|---|---|
| **No. of Wells** | 2 | 1 |
| **Total Depth (ft)** | 3,470 | 2,000 |
| **Zone** | Ironton Sandstone | St. Peter Sandstone |
| **Instrumentation** | Fiber-optic (microseismic) cable cemented in annulus; P/T/SpC probe in monitored interval | P/T/SpC probe in monitored interval |

# FutureGen 2.0 – DREAM

## INPUT

- NRAP-Open-IAM output (480 simulations)
- Sensors and detectability based on FutureGen
- Incrementally increasing budget; limited at 8 wells



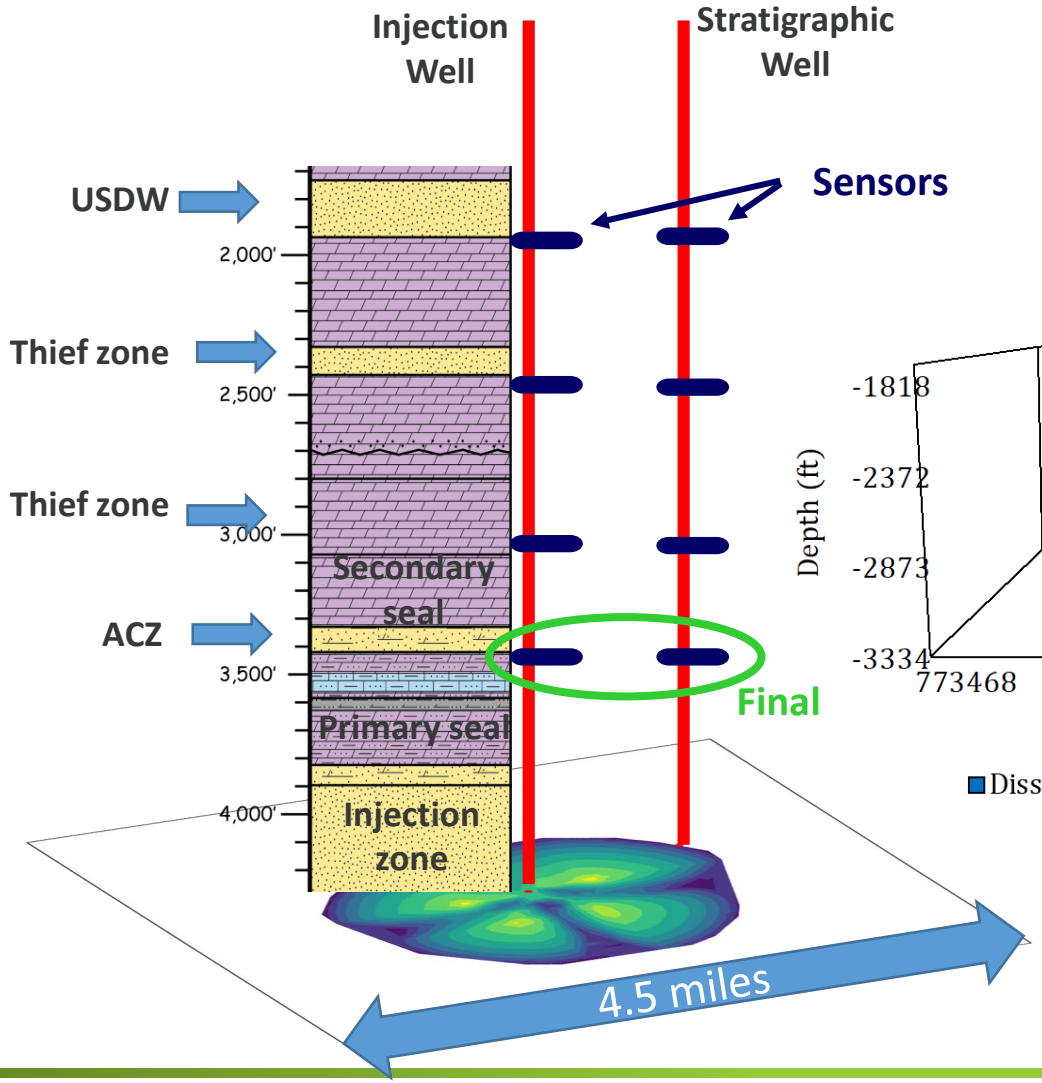

## OUTPUT

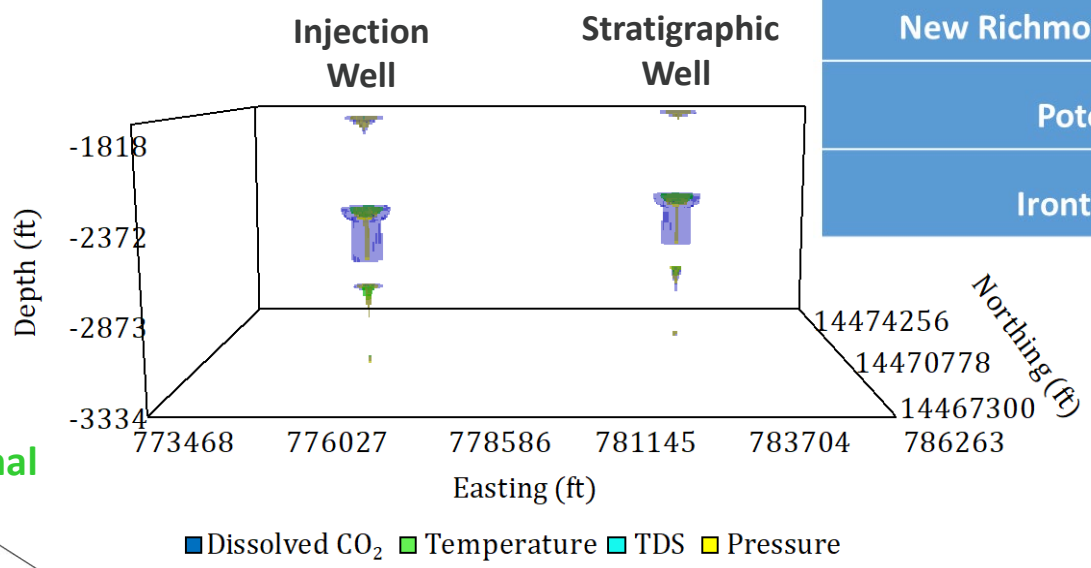
- Effective and efficient monitoring network
- Configuration with the lowest time to detection of the plume

| | Table A.5 & A.7 (FutureGen Industrial Alliance, 2013a) | | | | NRAP-Open–IAM | |
|---|---|---|---|---|---|---|
| | Min | Max | Unit | Precision +/- | Indicator | Threshold |
| Pressure | 0 | 2500 | psi | 0.065% | relative | 0.00065 |
| Temperature | 0 | 150 | F | 0.03% | relative | 0.0003 |
| DIC | 0.2 | -- | mg/L | 20% | relative | 0.2 |
| pH | 2 | 12 | pH | 0.2 | absolute | 0.2 |
| TDS | 10 | -- | mg/L | 10% | relative | 0.1 |

# FutureGen 2.0 – DREAM - Time to detection

DREAM optimized monitoring plan




| Monitoring Unit | Injection Well | Stratigraphic Well |
|---|---|---|
| | TTD (y) | TTD (y) |
| St. Peter | 4.9 | 16.7 |
| New Richmond | 3.9 | 15.7 |
| Potosi | 2.9 | 14.7 |
| Ironton | 1.6 | 12.6 |

Most sensitive indicators: pressure and dissolved $CO_2$

Over $10M in avoided costs for installation, sampling, and decommissioning of the third well

# Conclusions

- **Optimal monitoring** program utilizes **both direct** (pressure, temperature, fluid sampling) and **indirect** (geophysical) **monitoring methods**.
- **Geophysical measurements** produce proxies for saturation and mass that, when properly calibrated and interpreted, are **robust quantitative estimates** of these **key storage parameters**. **Value of information** (VOI) is expected to play a **role in selection of monitoring tools**.
- **Site-specific cost/benefit** approach to selecting post-injection **monitoring techniques** should be developed in association with a **quantitative risk assessment.**

# Acknowledgements

This work was completed as part of National Risk Assessment Partnership (NRAP) project. Support for this project comes from the U.S. Department of Energy (DOE) Office of Fossil Energy's Crosscutting Research Program. Work at Lawrence Berkeley National Laboratory was completed under the U.S. DOE Contract No. DE-AC02-05CH1123. Work at National Energy Technology Laboratory was performed under Field Work Proposal No. 1022407. Work at Pacific Northwest National Laboratory was supported under the U.S. DOE Contract No. DE-AC05-76RL01830. The work by LLNL was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344, Lawrence Livermore National Security, LLC and this presentation was reviewed and released as LLNL-PRES-804186.