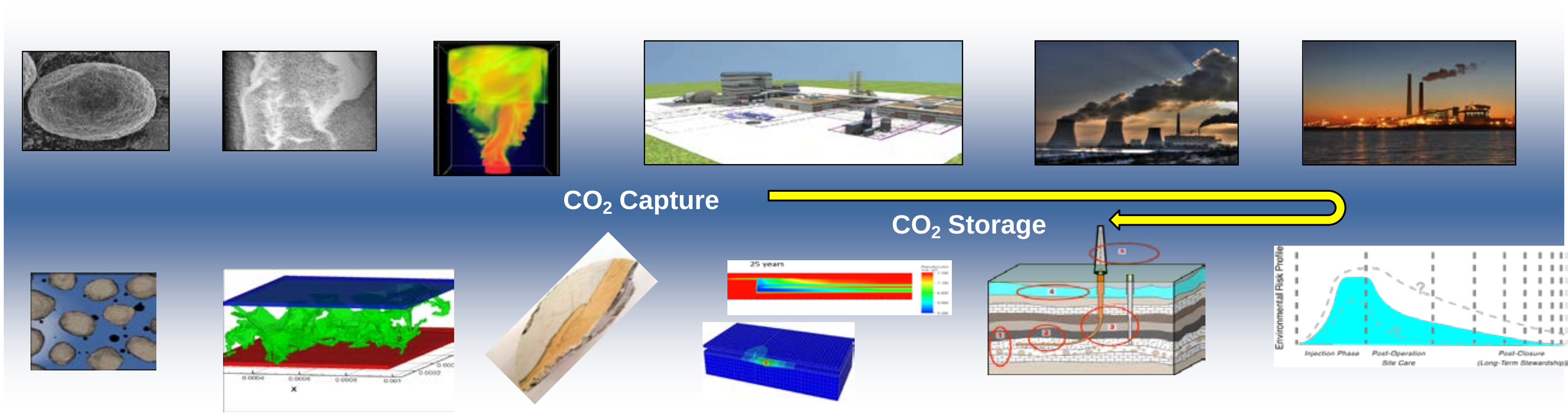
Two DOE initiatives leverage core capabilities in science-based prediction to lower the uncertainty in the business case for CCS.

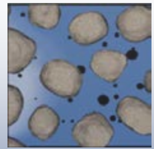
Carbon Capture Simulation Initiative (CCSI)

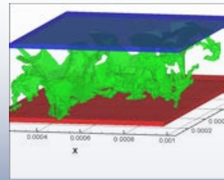
To accelerate the path from concept (bench) to deployment (commercial power plant) by lowering the technical risk in scale up.

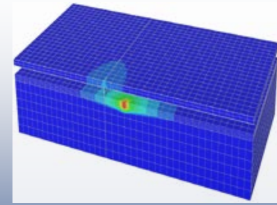


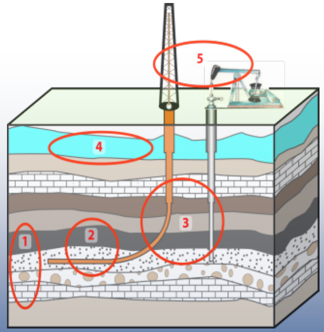
National Risk Assessment Partnership (NRAP)

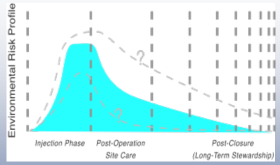
To build confidence in the business case for long-term CO_2 storage by quantifying the storage-security relationships across a range of site characteristics.











National Risk Assessment Partnership

NRAP leverages DOE's competency in science-based prediction for engineered–natural systems to build confidence in the business case for CO_2 storage.

Building toolsets and the calibration & validation data to quantify …

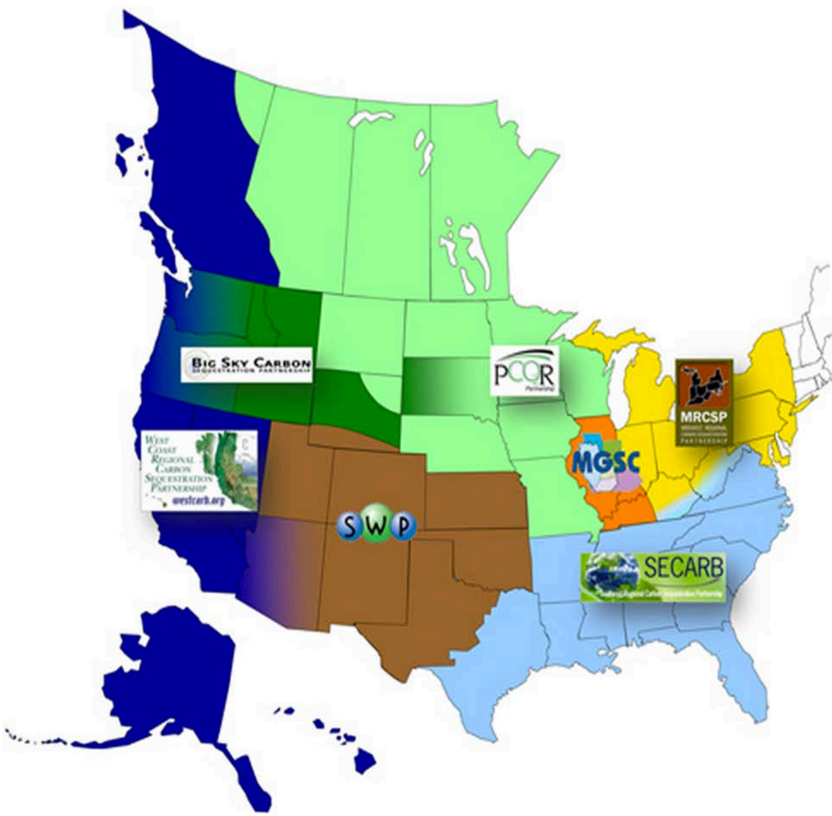
- Potential impacts related to release of CO_2 or brine from the storage reservoir
- Potential ground-motion impacts due to injection of CO_2

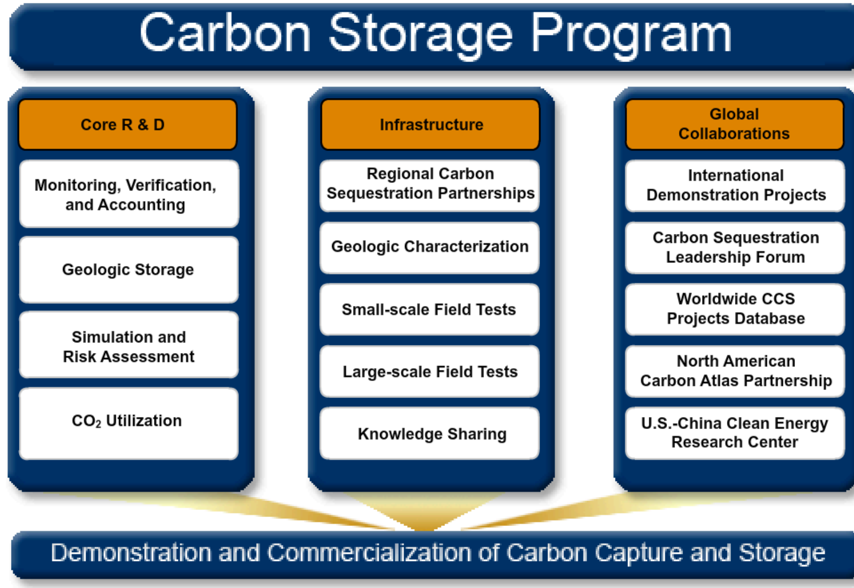
Technical Team

Stakeholder Group

Wade, LLC

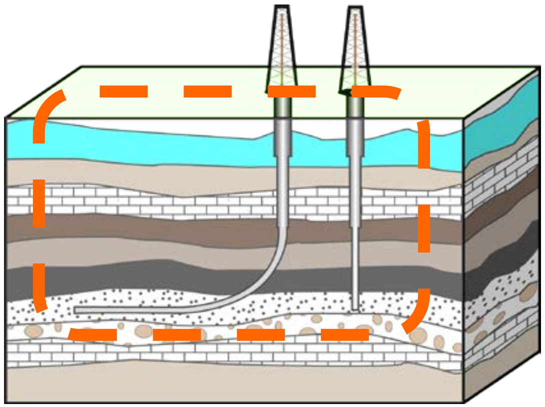
NRAP complements other risk-assessment elements in the Carbon Storage Program





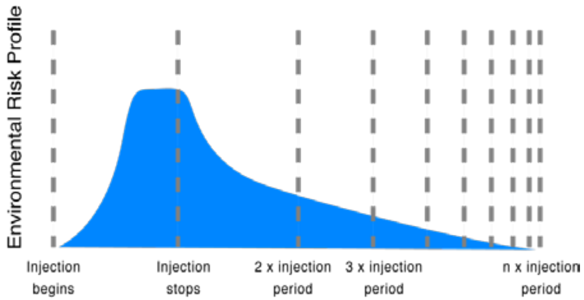
- **Core R&D**
  - Building data and tools to predict and verify CO_2 storage
- **Infrastructure (e.g., RCSPs)**
  - Building data and experience on CO_2 injection in a variety of geological settings
- **NRAP**
  - Integrating data to address cross-cutting relationships
  - Building toolsets and science-base for integrated assessments in order to quantify storage-security relationships

Science-based prediction can build confidence in expected storage security by quantifying system performance for a range of conditions.

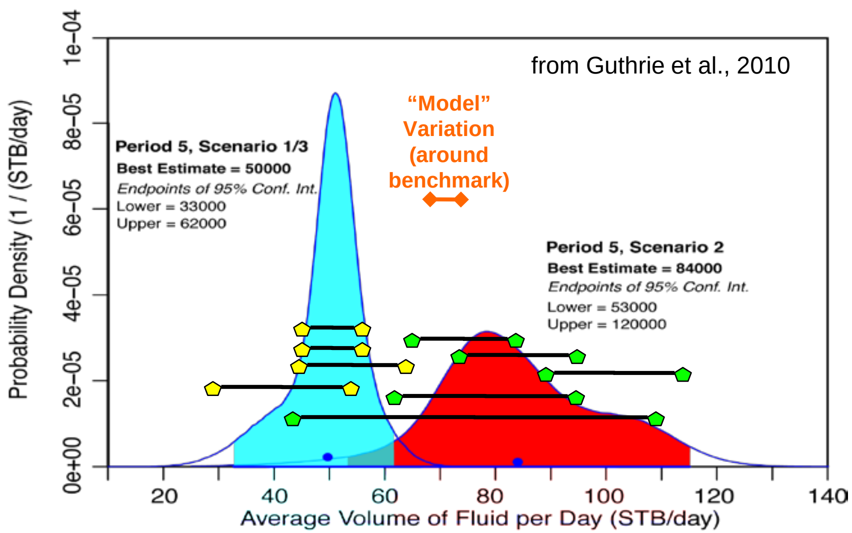


NRAP Goal—to predict storage-site behavior from reservoir to receptor and from injection through long-term storage…

…in order to quantify key storage-security relationships for various site characteristics.

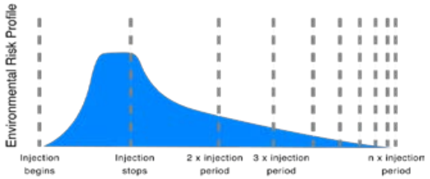


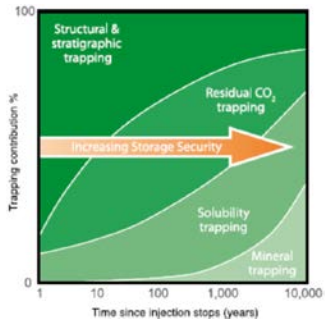
Confidence in uncertain predictions can be built through comprehensive, multi-organizational team assessments.



NRAP is building and applying computationally efficient tools to probe site behavior stochastically, thereby accounting for uncertainties and variability in storage-site characteristics.

NRAP provides an independent technical perspective to inform key decisions across the spectrum of stakeholders.





Spectrum of Stakeholders

Regulators (federal, state)

- Monitoring requirements; injection envelops; wellbore completions

Operators

- Project costs (e.g., liability; wells; monitoring; injection rates)

Insurers (public, private)

- Liability valuation

Public

NRAP Focus to Support Decisions

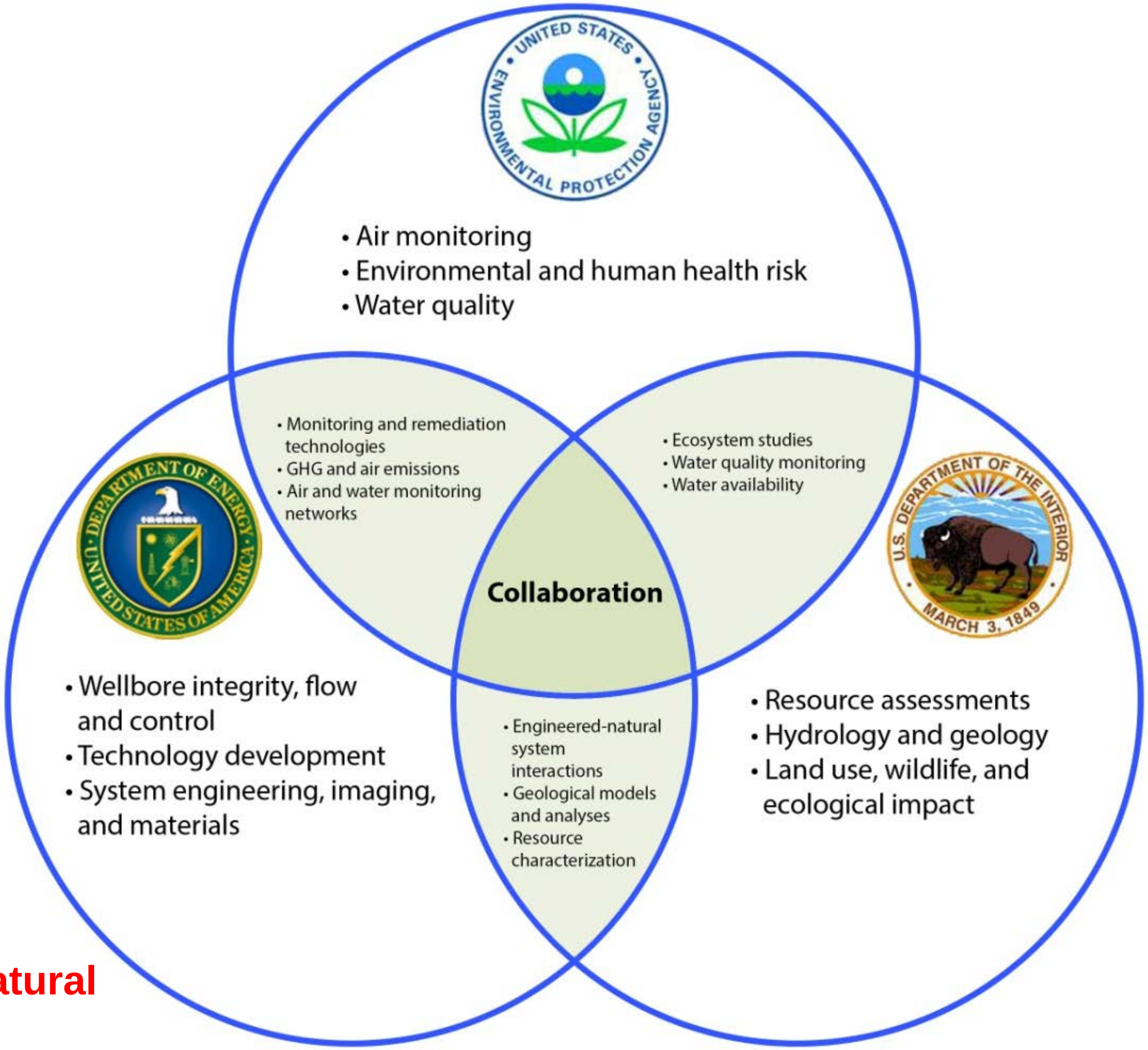
Quantification of storage-security relationships over variety of engineered–geologic conditions

- Likelihood of achieving storage-retention goals (e.g., >99% in 100 yrs)
- Long-term risk profiles (to lower uncertainties in valuation of liabilities)
- Geomechanical behavior (induced seismicity; seal impact)
- Effective and efficient protocols for strategic monitoring and site-specific data needs based on key risk drivers

Science base to build confidence for decisions

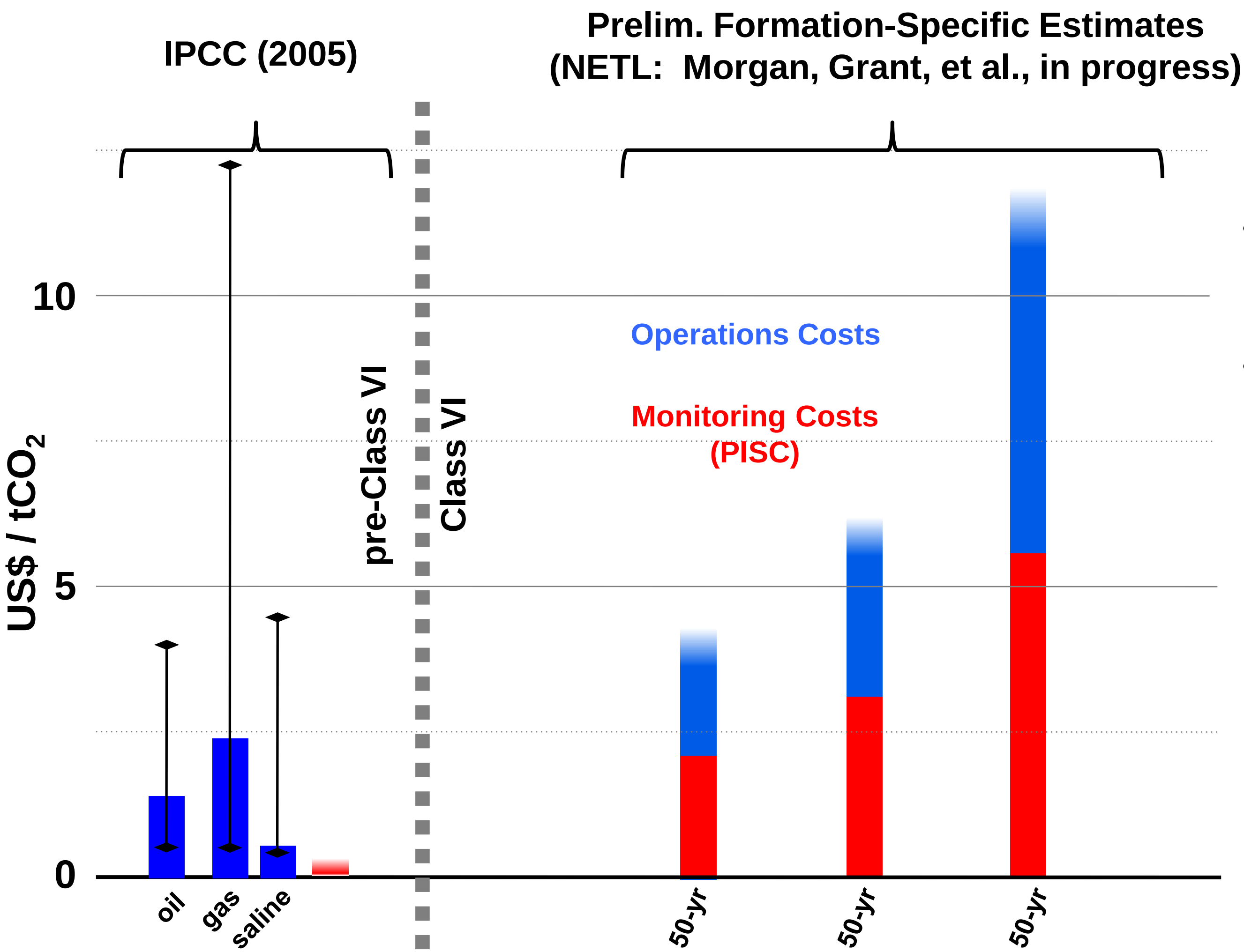
- Trapping mechanisms and risk profiles over a range of geologic environments (including EOR)
- Impact of well completion on leakage risk (e.g., class II/EOR vs. VI/CCS)
- Post-injection behavior (e.g., pressure recovery) for range of sites
- Readily available quantitative relationships/parameters for risk-related phenomena (site- & basin- scale)

Interagency MOU for Unconventional Fossil Resources



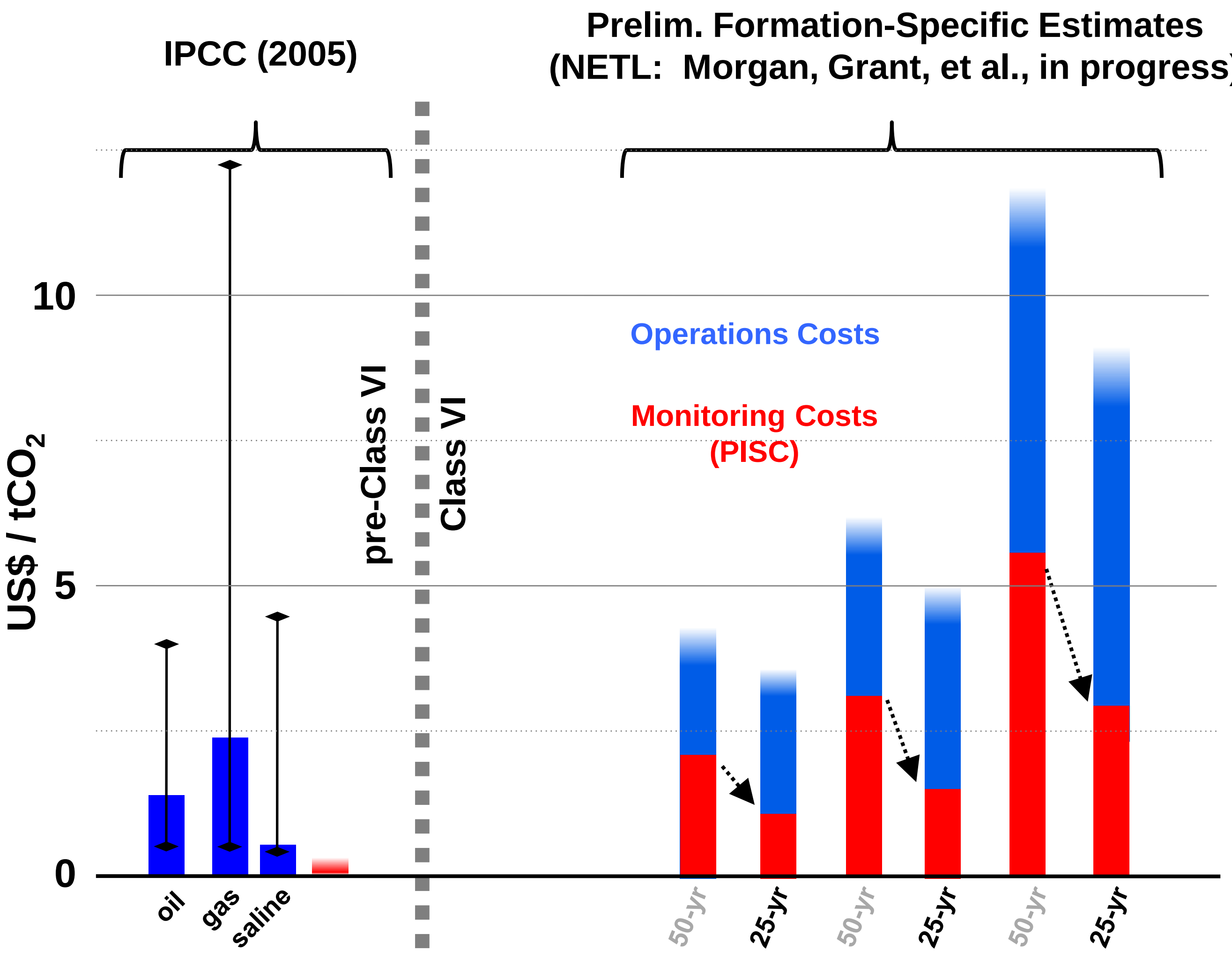
Science-Based Prediction for Engineered–Natural Systems

Early estimates predicted monitoring would be a minor component of storage costs, but Class VI requirements drive monitoring costs up.



- IPCC (2005) estimated post-injection monitoring costs to be <10% of project costs.
- Post Class VI estimates range from 35–50% of total costs, assuming 50-yr period for post-injection site care (PISC).

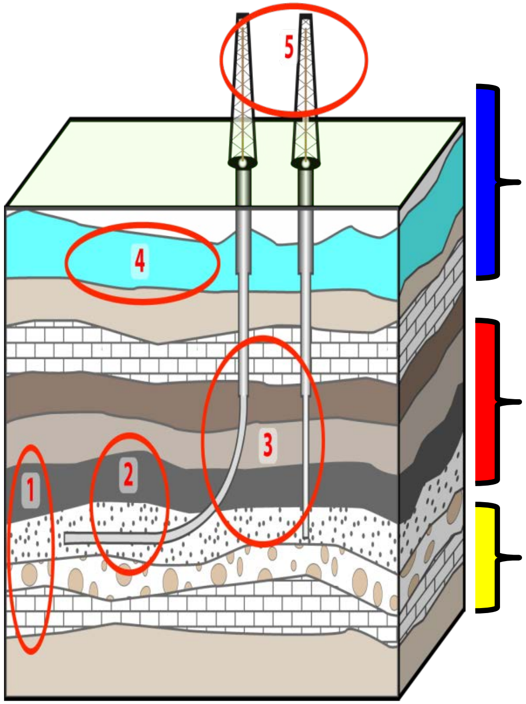
Monitoring costs are primarily driven by three factors: Long time frame, large area of review, frequency/breadth of monitoring.



Reducing monitoring time from 50 years to 25 years significantly reduces costs.

A reduction of 1-2 \$/ton CO_2 would mean a savings of \$50-250 million per project.

NRAP is focused on quantification of two types of potential impacts, based on coupling reservoir behavior to other system components.



Potential
Leakage Impacts
(Atmosphere; Groundwater)

⇧ ***fluid propagation***

Release/Transport of Fluids

⇧ ***fluid propagation***

Reservoir
(plume/pressure evolution)

Potential
Ground-Motion Impacts
(Ground Acceleration)

⇧ ***seismic-wave propagation***

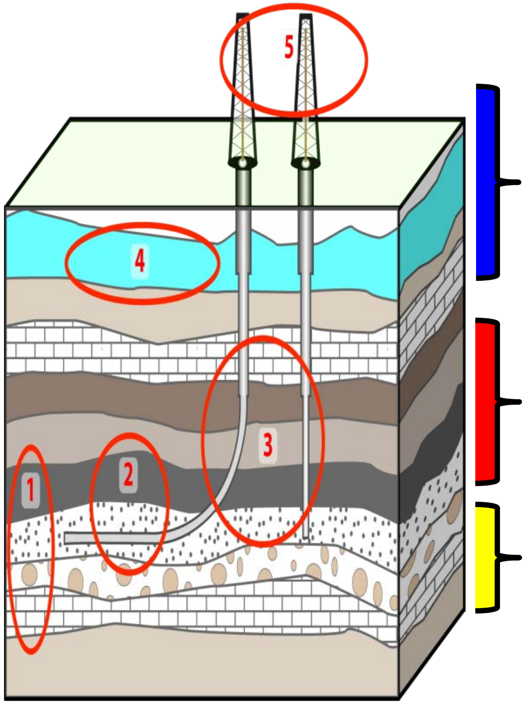
Slip along a Fault Plane

⇧ ***stress/pressure propagation***

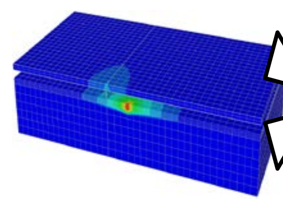
Reservoir
(plume/pressure evolution)

NRAP's approach to quantifying performance relies on reduced-order models to probe uncertainty in the system.

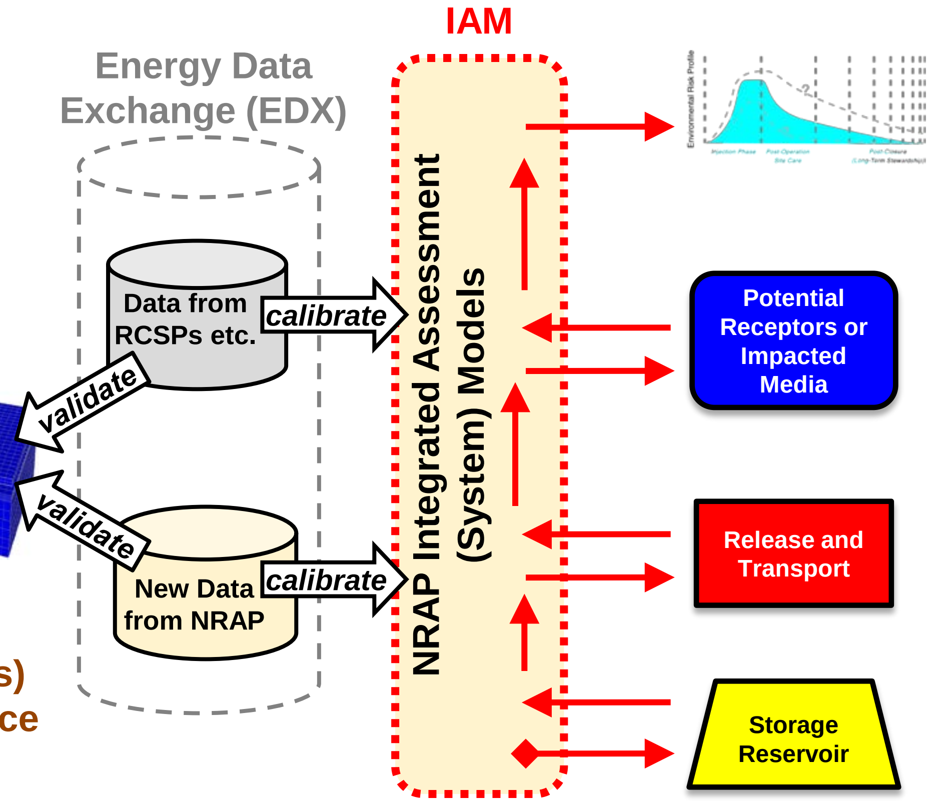
A. Divide system into discrete components



B. Develop detailed component models that are validated against lab/field data



C. Develop reduced-order models (ROMs) that rapidly reproduce component model predictions



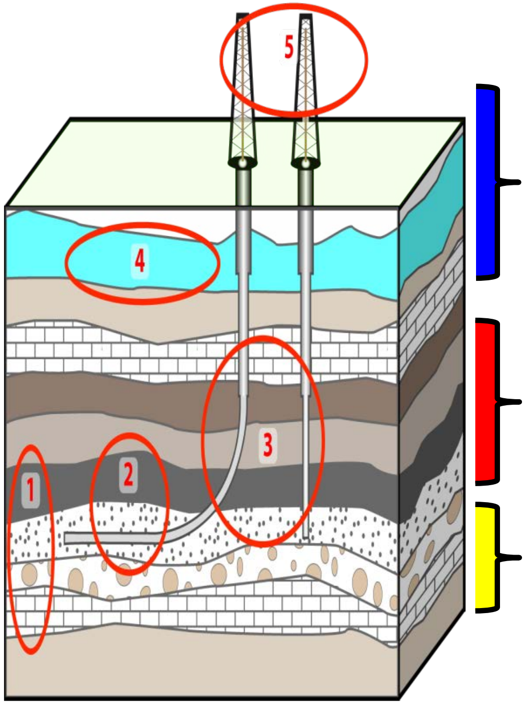
D. Link ROMs via integrated assessment models (IAMs) to predict system performance & risk; calibrate using lab/field data from NRAP and other sources

E. Develop strategic monitoring protocols that allow verification of predicted system performance

NRAP is evaluating a range of approaches to Reduced-Order Models (i.e., Rapid-Performance Models).

	"Kimberlina" Reservoir	"SACROC" Reservoir	"Otway" Reservoir	Wellbores	Fractured Seal	High Plains Aquifer	Edwards Aquifer
Lookup Table				X	X		
Response Surface (via PSUADE)	X					X	X
Analytical Model				X	X	X	X
Polynomial Chaos Expansion		X					
Gaussian Regression	X						
Surrogate Reservoir Model (base on A.I. methods)		X	X				

NRAP is focused on quantification of two types of potential impacts, based on coupling reservoir behavior to other system components.



Potential Leakage Impacts	Potential Ground-Motion Impacts
Potential Leakage Impacts (Atmosphere; Groundwater)	**Potential Ground-Motion Impacts** (Ground Acceleration)
⇧ *fluid propagation*	⇧ *seismic-wave propagation*
Release/Transport of Fluids	**Slip along a Fault Plane**
⇧ *fluid propagation*	⇧ *stress/pressure propagation*
Reservoir (plume/pressure evolution)	**Reservoir** (plume/pressure evolution)

NRAP toolset for ground motion couples reservoir behavior to response of faults/fractures.

Tool & Method Development

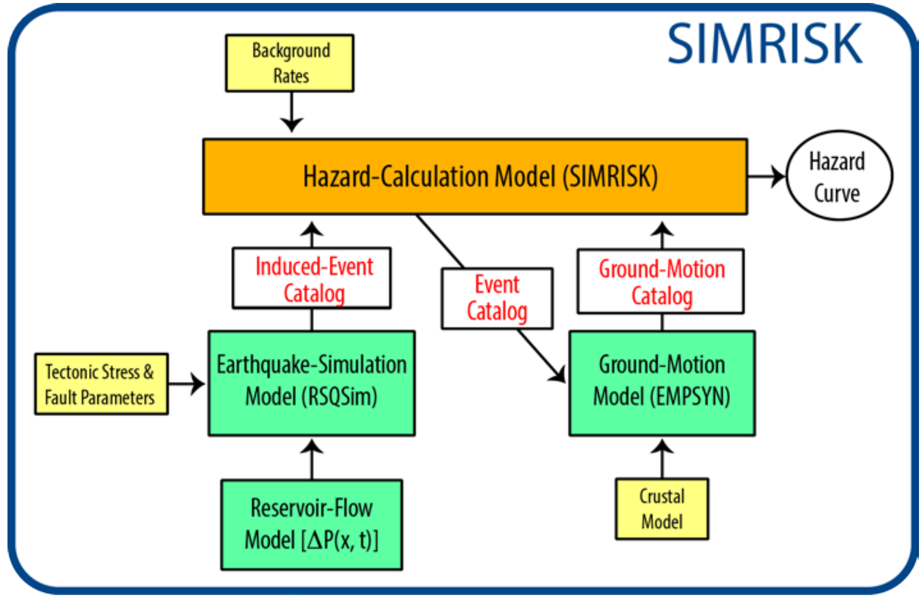
- Adapted widely accepted probabilistic seismic hazard assessment (PSHA) tool for use on induced seismicity

General Trends & Relationships

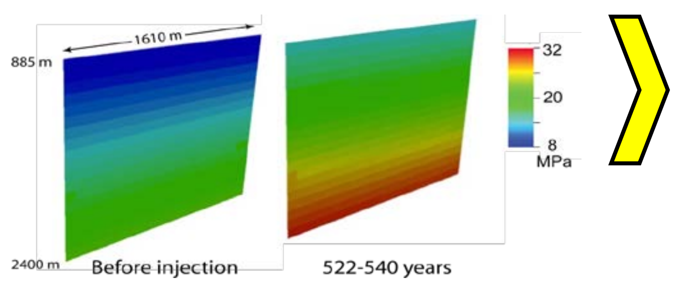
- Rates of occurrence and sizes of earthquakes are determined by tectonic stress and reservoir pressure
  - sensitive to fault permeability and a few key parameters in the law governing the evolution of fault frictional strength

Next Steps

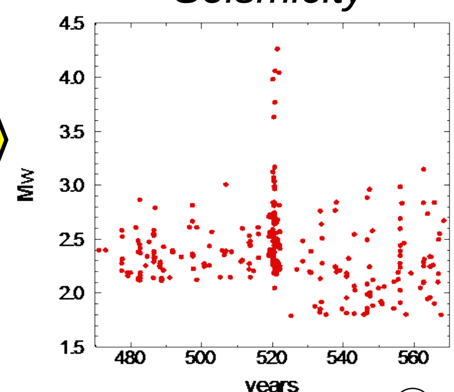
- Multiple faults
- Detailed sensitivity analysis
- Dynamic fault aperture
- Validation of ground-motion calculation



Pore Pressure



Seismicity



NRAP toolset for leakage couples reservoir behavior to the atmosphere and/or aquifers.

Tool & Method Development

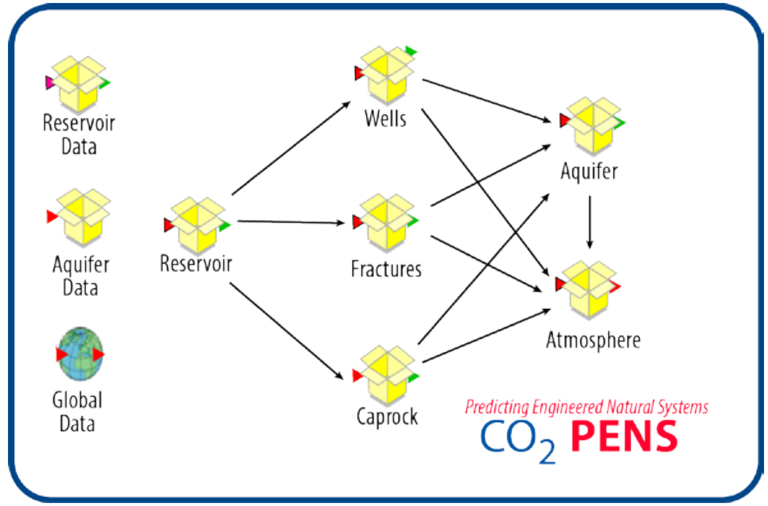
- Developed integrated assessment model for leakage impacts
  - Risk profiles and associated uncertainties for several metrics (atmospheric release and aquifer impacts—ΔpH, ΔTDS, metal release)

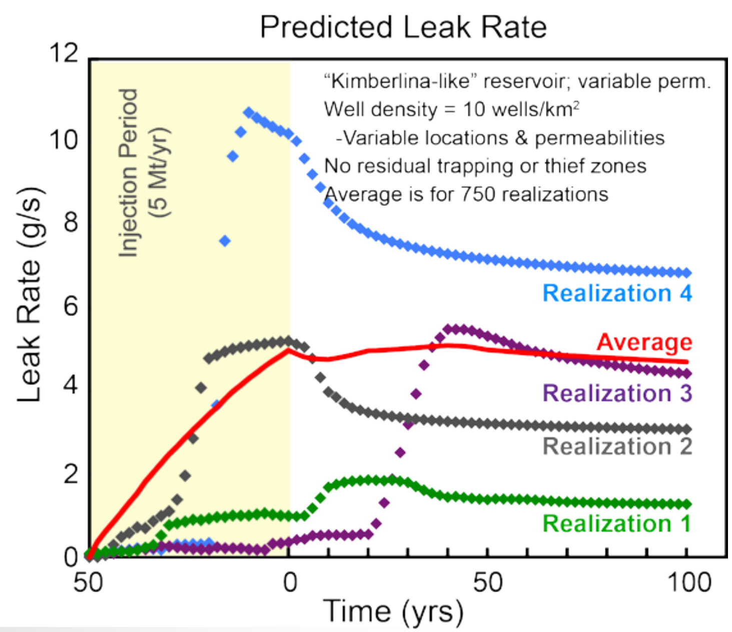
General Trends & Relationships

- Leakage Impacts
  - Uncertainties in wellbore cement permeability dominate overall uncertainties
  - "Risk profiles" show significantly different behavior from reservoir-pressure evolution

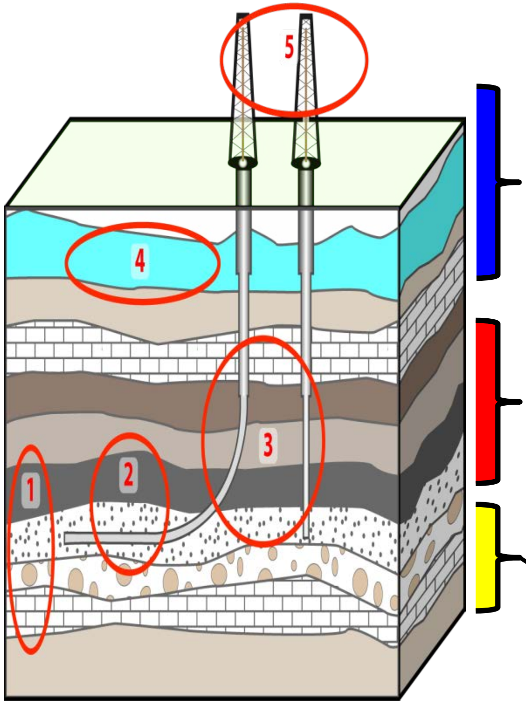
Next Steps

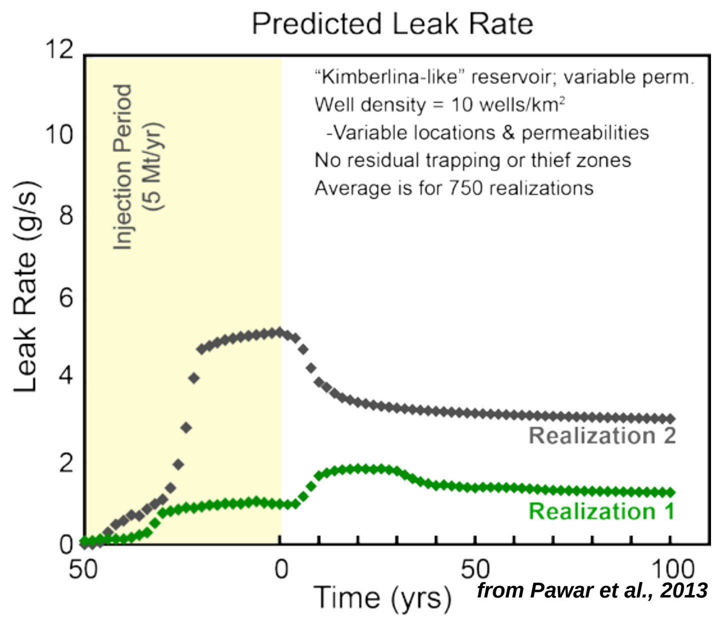
- Added complexities
- Derivative toolsets
- Application to range in conditions





Example: What is the expected leak rate for a site with high concentration of legacy wells (but unknown locations & permeability)?





from Pawar et al., 2013

CO_2 SATURATION ***PRESSURE BUILDUP*** ***AREA OF ΔP BUILDUP***

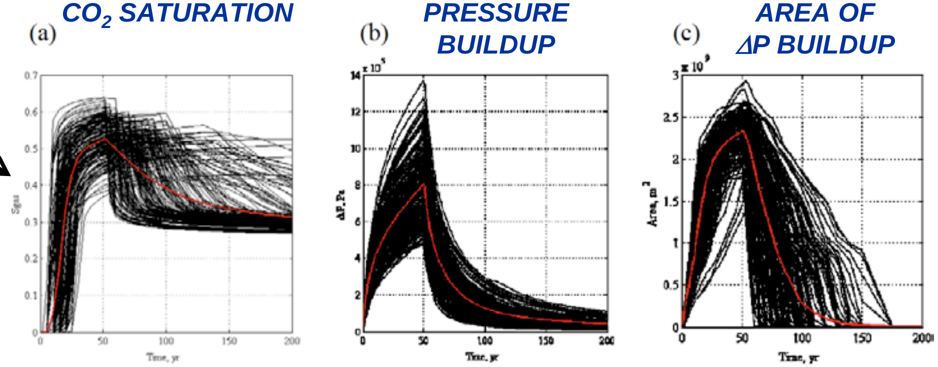
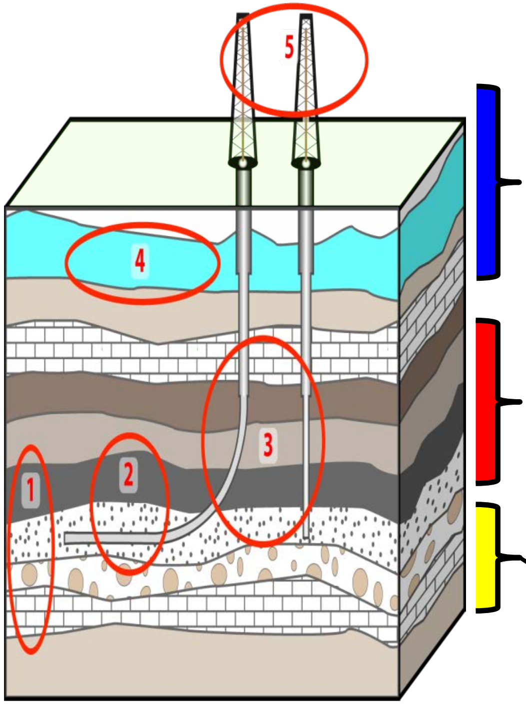
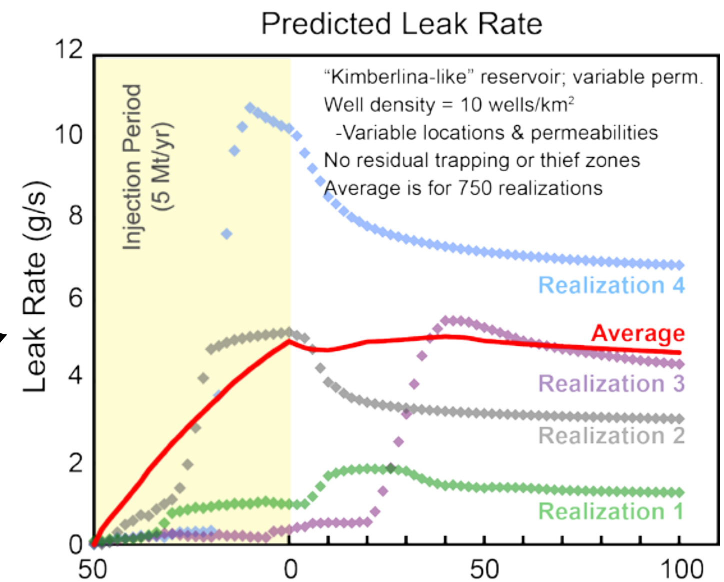


Figure 5: Monte-Carlo simulation results; time profiles of the performance measures: (a) CO_2 saturation (S_{CO2}), (b) pressure buildup (ΔP), and (c) overpressure zone. The red line is the mean at each time slice.

from Wainwright et al., 2012

Storage performance is a reflection of reservoir behavior coupled to the behavior of other system components.





from Pawar et al., 2013

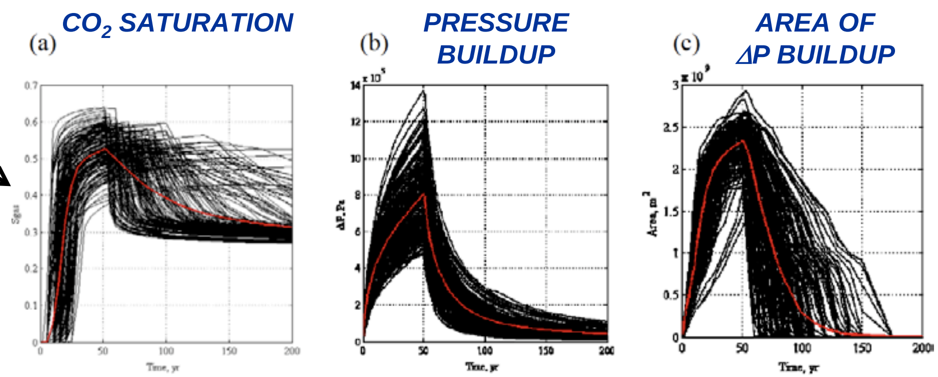
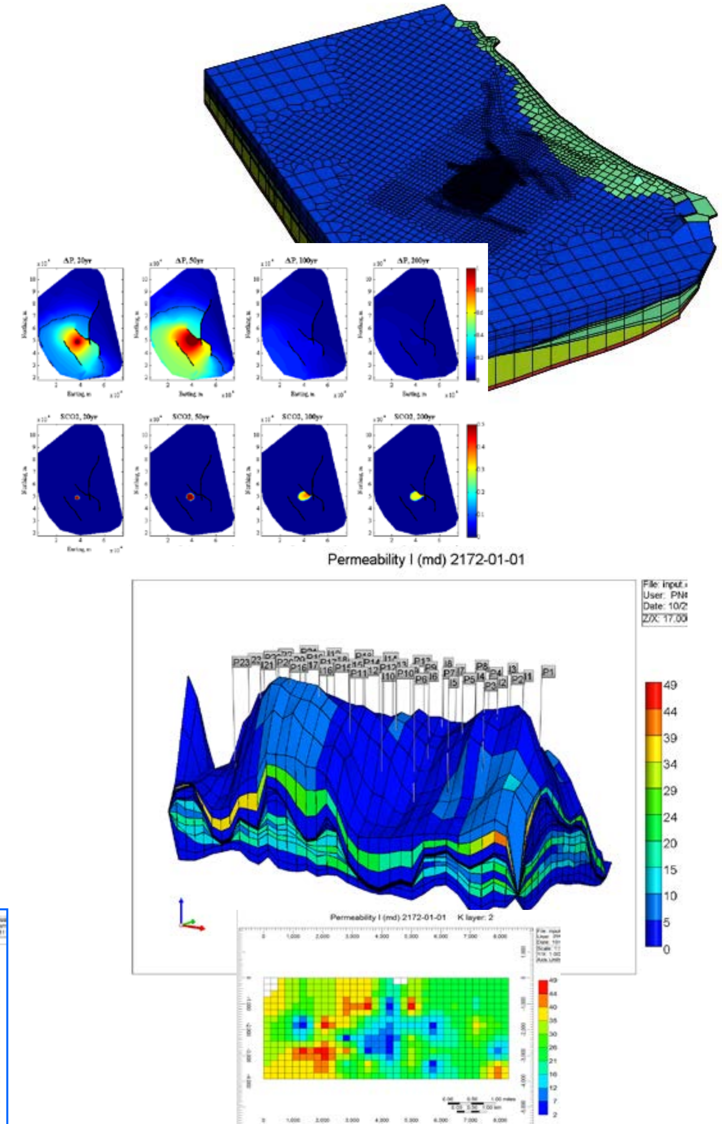


Figure 5: Monte-Carlo simulation results; time profiles of the performance measures: (a) CO_2 saturation (S_{CO2}), (b) pressure buildup (ΔP), and (c) overpressure zone. The red line is the mean at each time slice.

from Wainwright et al., 2012

Reservoir ROM goal is to predict pressures and saturations at the reservoir–seal interface.

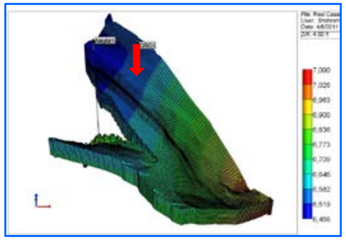


Tool & Method Development

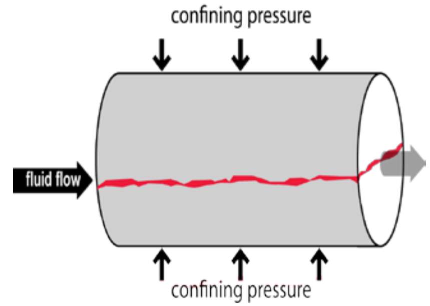
- Produced ROMs for three reservoirs
  - "Kimberlina-like"; sandstone w/ interbedded shale & shale caprock; 5 Mt/yr CO_2 (fixed) over 50 yrs injection; 150 yrs relaxation
  - "Otway-like"; sandstone gas reservoir; up to 0.5 Mt injection (variable rate) for 10 yrs; 500 yrs of relaxation
  - "SACROC-like"; history-matched multiple well injection over 50 yrs; 1000 yrs of relaxation; carbonate reef EOR site
  - **Use of ROMs allow easy tailoring to specific sites**
- Preliminary evaluations for 4 ROM approaches
  - Simple look up table
  - Surrogate reservoir model based on artificial intelligence
  - Polynomial chaos expansion
  - Gaussian regression analysis

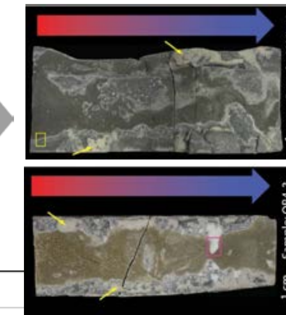
General Trends & Relationships

- Pressure and saturation at reservoir-seal interface is sensitive to only a few key subsurface parameters
  - Caprock permeability is key in predicting pressure relaxation



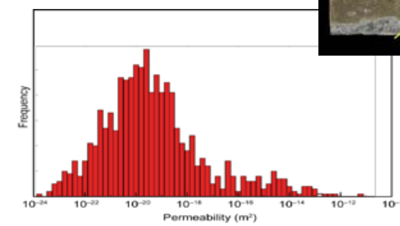
Wellbore ROM goal is to predict fluid flux through wells given pressures & saturations at reservoir–seal interface.





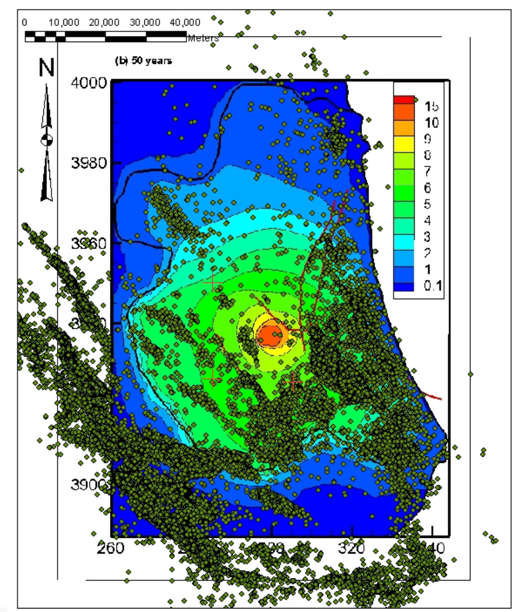
Tool & Method Development

- Produced ROMs for two types of wellbores
  - **Open wellbores**, based on coupled well–reservoir model (Drift-Flux Model) (250 simulations for 4 uncertain parameters)
  - **Cemented wellbores** with uniform permeability along wellbore but permeability can be changed; ROM is 32x32x32x32x32 LUT from PSUADE output derived from radial wellbore model implemented in FEHM (2000 simulations for 5 uncertain parameters)
- Developed preliminary wellbore statistics
  - Permeability distributions
  - Wellbore geospatial characteristics (age, depth, completion state)



General Trends & Relationships

- Decoupled well–reservoir IAM approach is reasonable but conservative for large permeability contrast (i.e., over estimates leakage)
- Important trends based on age and purpose (e.g., exploratory wells vs. production wells)
- Preliminary relationships between reactive-flow conditions and permeability evolution



U.S. DEPARTMENT OF ENERGY

NETL-RUA Regional University Alliance

Los Alamos NATIONAL LABORATORY

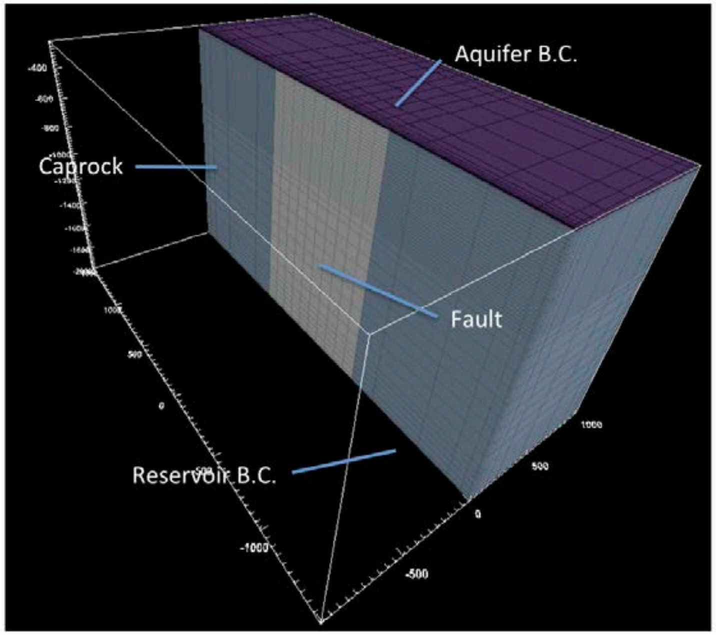
Pacific Northwest NATIONAL LABORATORY

NRAP National Risk Assessment Partnership

Fractured-seal ROM goal is to predict fluid flux through seal given pressures and saturations at reservoir–seal interface.

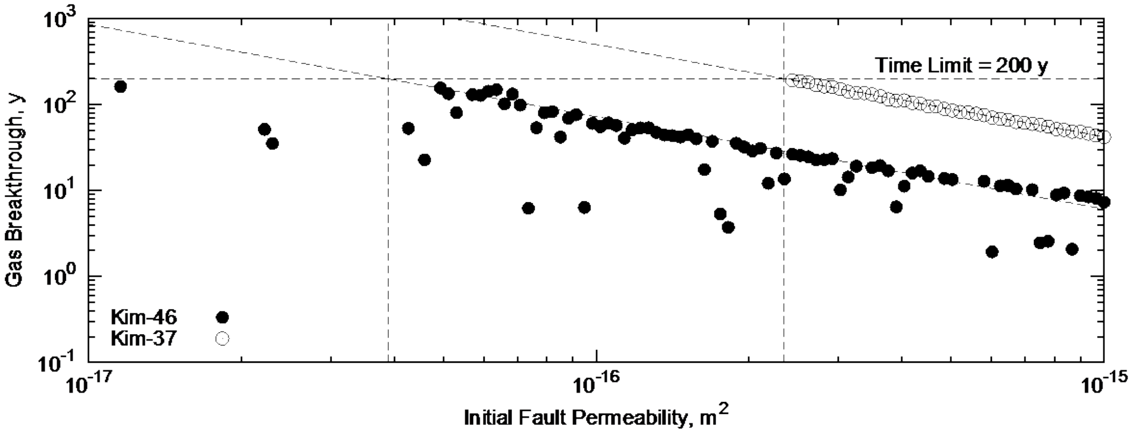
Tool & Method Development

- Produced 2 ROMs for fractured caprock
  - **Single leaking fracture** connecting reservoir to aquifer; based on detailed coupled flow-geomechanics simulator with full compositional behavior (including phase transition from super to sub-critical, geomechanical permeability enhancement due to fault-slip)
  - Leaky caprock resulting from **multiple fractures**; based on discrete fracture simulator; capable of using statistical input on fracture properties, such as density, aperture, orientation; geomechanics capability not implemented until next generation.



General Trends & Relationships

- Brine leakage at early times. For low permeability faults, gas leakage may not be seen for decades.
- Key uncertainty is fault permeability behavior, and its evolution with slip or dilation.



Groundwater ROM goal is to predict evolution of impact plumes for various leak scenarios.

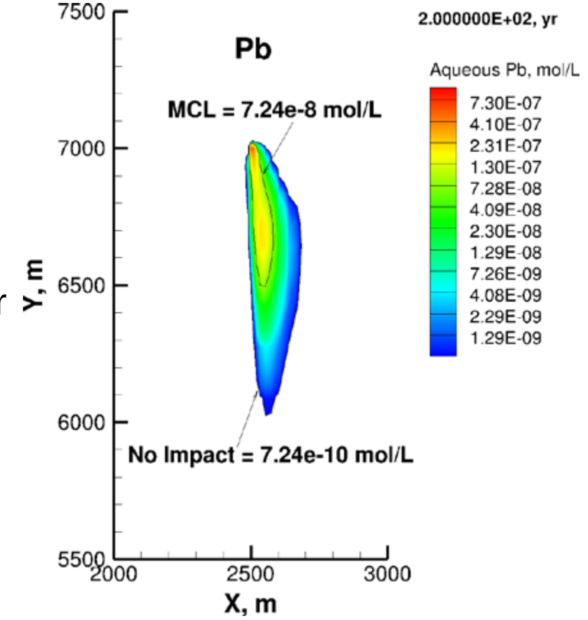
Tool & Method Development

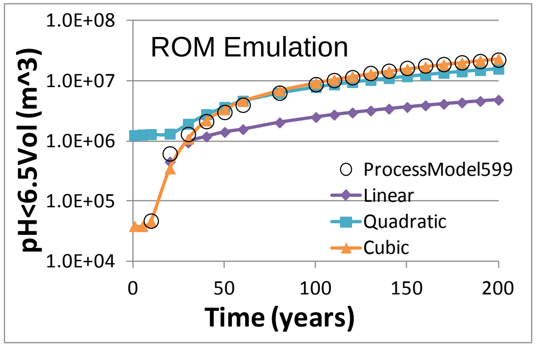
- Suite of ROMs for two aquifer types
  - **Chemical-Hydraulic linking function** to lower computation load for derivation of ROM; quadratic and cubic ROMs best
  - **No-impact thresholds**
  - Relationships to assess impact of metal-transport by brine on aquifer chemistry (for Cd, As, Pb, Cr)

General Trends & Relationships

- Unconfined Limestone Aquifer:
  - Leak rates are most significant parameters for pH, TDS and trace metal concentrations, but carbonate equilibria and clay sorption are also important
  - Significant return of CO_2 to atmosphere (half of simulations have atmospheric leak rate >80% of wellbore leak rate)
- Confined Sandstone Aquifer:
  - Adsorption/desorption is the most important process that controls trace-metal impacts due to the intrusion of CO_2
  - 0.01–0.1% of the CO_2 in the aquifer leaks to atmosphere

Limestone Aquifer





Monitoring goal is to develop strategies and protocols based on risk and uncertainty quantification.

Field and Lab Tests

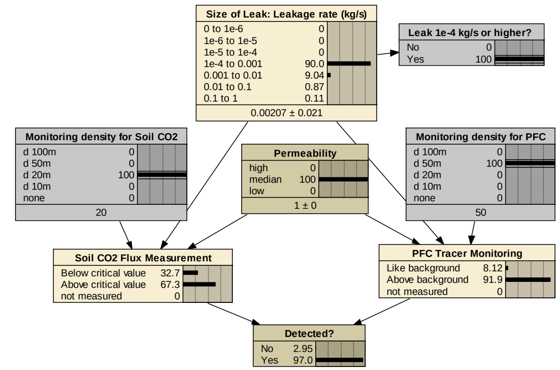
- Quantify uncertainties and improve resolution
  - VSPs, joint inversion, electrical techniques for groundwater; lab measured properties at conditions

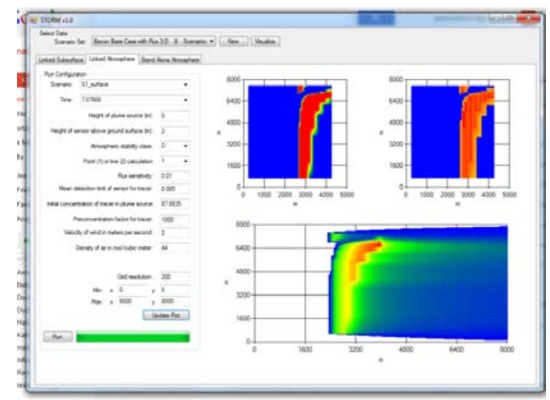
Modeling–Monitoring Integration

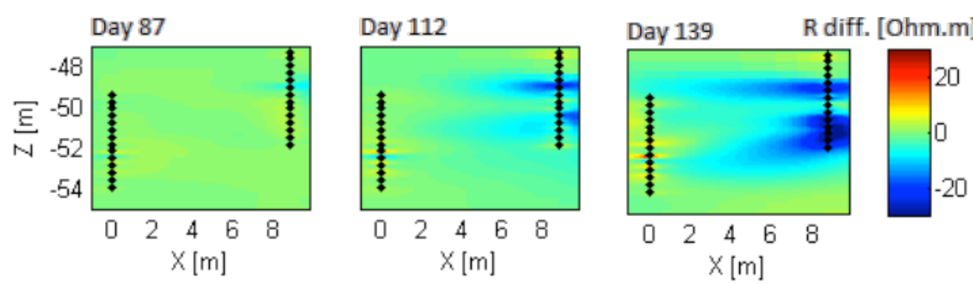
- Efficient techniques to identify key risk variables
- Efficient techniques to optimize network design

General Trends & Relationships

- Flexible grid is more efficient
- AZMI pressure monitoring improved when combined with pressure monitoring in reservoir
- Electrical monitoring provides early indication of groundwater plumes

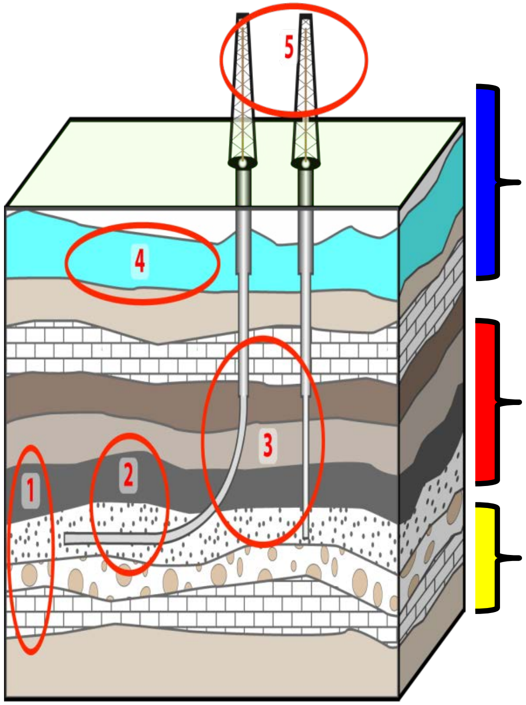




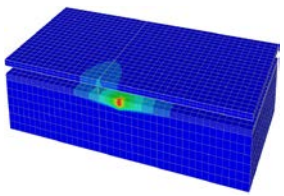


NRAP's current focus includes risk-based monitoring strategies and tools.

A. Divide system into discrete components



B. Develop detailed component models that are validated against lab/field data



C. Develop reduced-order models (ROMs) that rapidly reproduce component model predictions

D. Link ROMs via integrated assessment models (IAMs) to predict system performance & risk; calibrate using lab/field data from NRAP and other sources

E. Develop strategic monitoring protocols that allow verification of predicted system performance

- **Area of review**
- **Post-injection site care**
- **No-impact thresholds for aquifers**
- **Sampling frequency**
- **Monitoring frequency**
- **Key risk-related parameters**