National Risk Assessment Partnership:

Leveraging DOE's Science-Based Prediction Capability to Build Confidence in Engineered–Natural Systems

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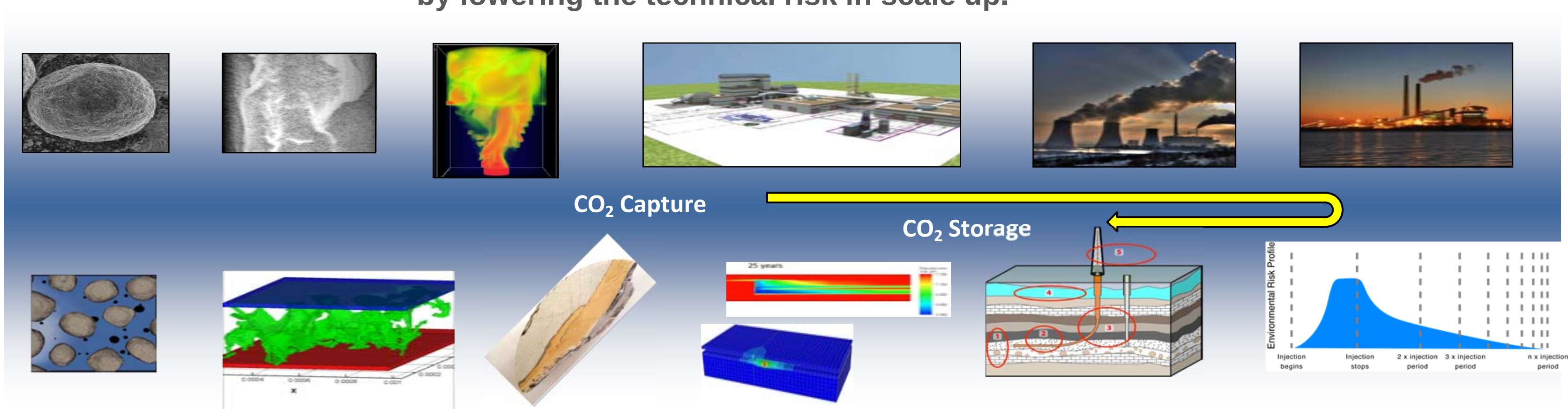
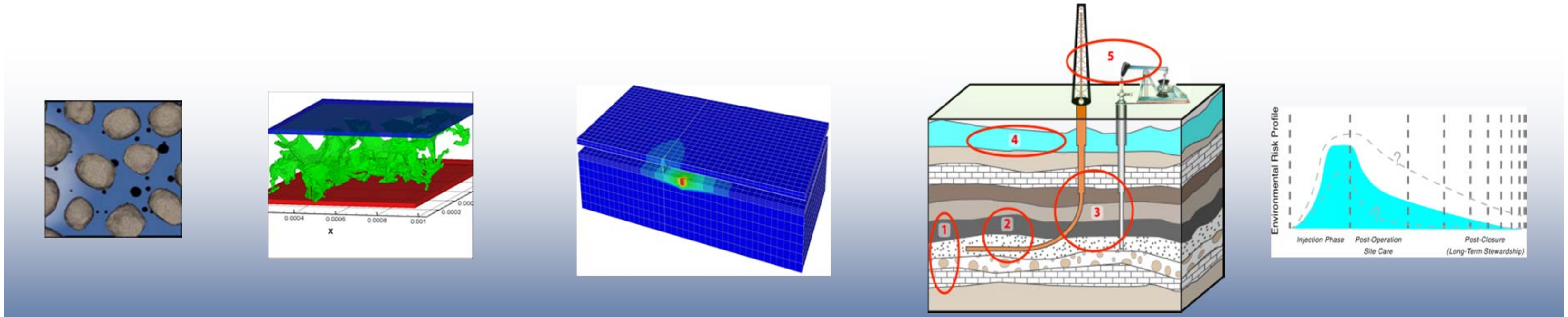
Carbon Capture Simulation Initiative (CCSI)

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 accelerate the path to CCUS deployment through the use of science-based prediction to quantify storage-security relationships, thereby building confidence in key decisions.



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 …

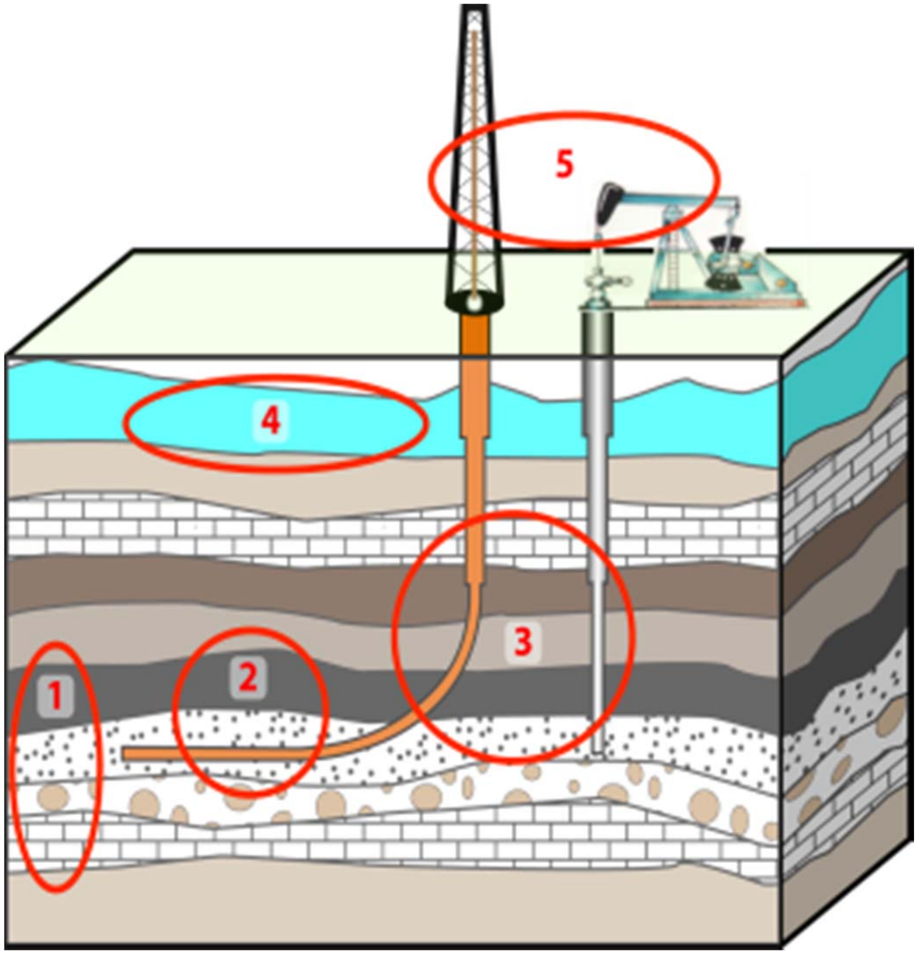
- Potential impacts related to release of CO_2 or brine from the storage reservoir
- Potential ground-motion impacts due to injection of CO_2

Technical Team

NETL-RUA Regional University Alliance
Berkeley Lab
Los Alamos National Laboratory EST.1943
Pacific Northwest National Laboratory
URS

Stakeholder Group

AEP American Electric Power
Blue Source
bp
EPA United States Environmental Protection Agency
ExxonMobil
ieaghg
IEc
MIT
NRDC
Schlumberger
Southern States Energy Board
Stanford University
Texas Railroad Commission
The University of Utah
Wade, LLC
Whiting
Zurich Because change happenz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4
3
2
1

Quantitative Predictions for Planning…

- **Capacity**
- **Long-term storage**
- **Performance**
- **Risk**
- **Monitoring strategies**
- **…**

Must predict fluid flow in porous & fractured media (reservoirs, seals, wells).

Quantitative Predictions for Planning…

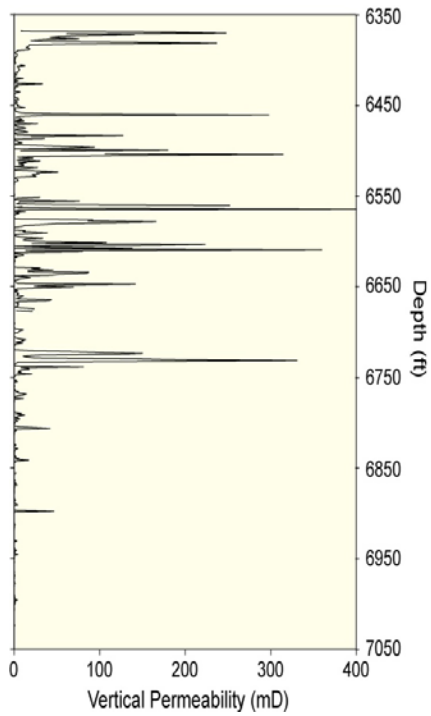
- Capacity
- Long-term storage
- Performance
- Risk
- Monitoring strategies
- …

Must predict fluid flow in porous & fractured media (reservoirs, seals, wells).

Permeability is a first-order parameter in predicting fluid flow.

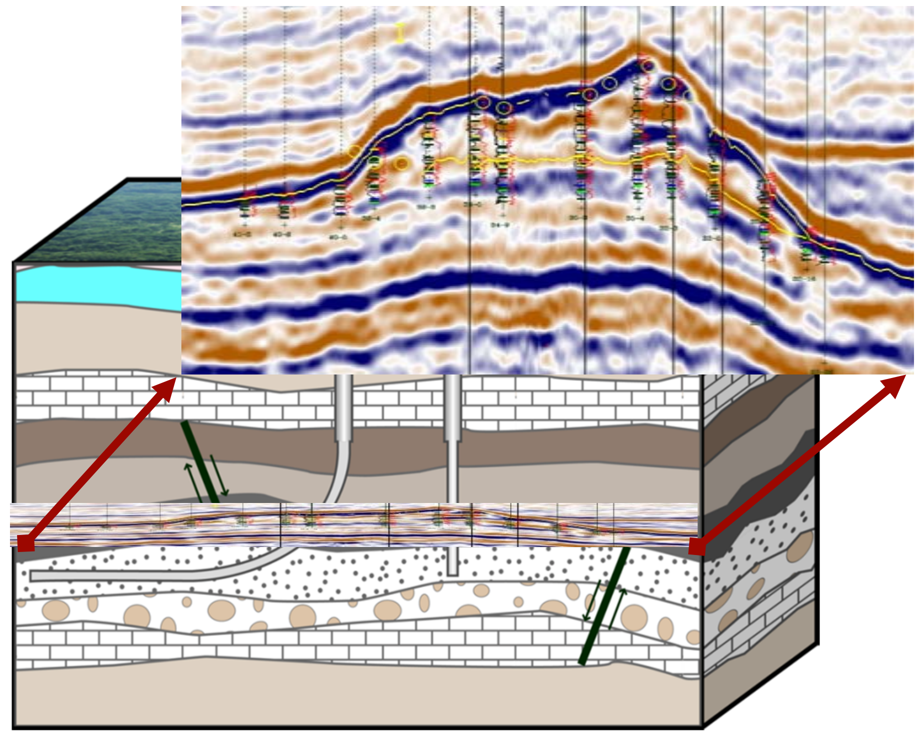
$$\frac{Q}{A} = \frac{k \rho g}{\mu} \frac{dh}{dl}$$

Permeability varies over space and time.



SACROC core data represent ~10^{-10} of the total reservoir volume.

Seismic image through SACROC reservoir.

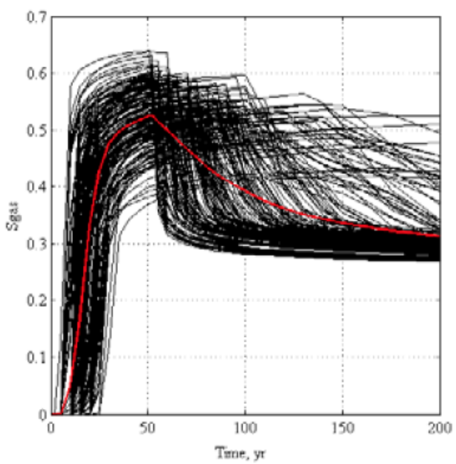


Seismic data do not provide high resolution or high certainty information on permeability.

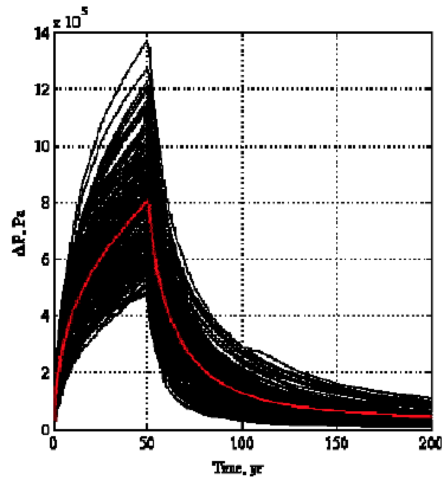
In conventional oil production, permeability fields are refined by history-matching to data from 10's to 1000's of wells.

Different choices of permeability field impact predictions on reservoir behavior.

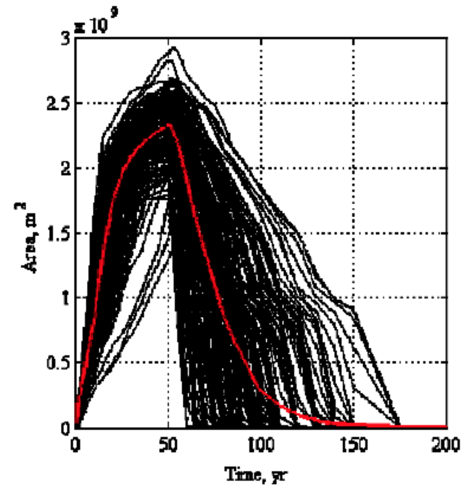
Saturation



Pressure Buildup

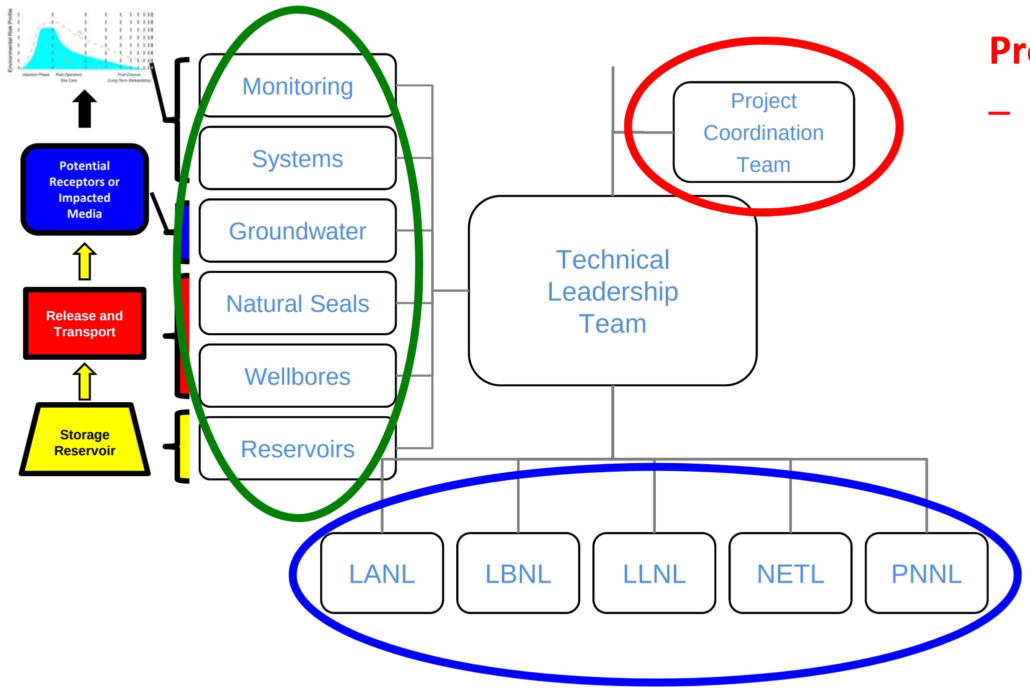


Area of Pressure Buildup



from Wainwright et al. (2012) NRAP-TRS-III-002-2012

NRAP Team Structure



Project Coordination Team

- NETL team that supports the coordination and integration of NRAP; led by <u>project coordinator</u>

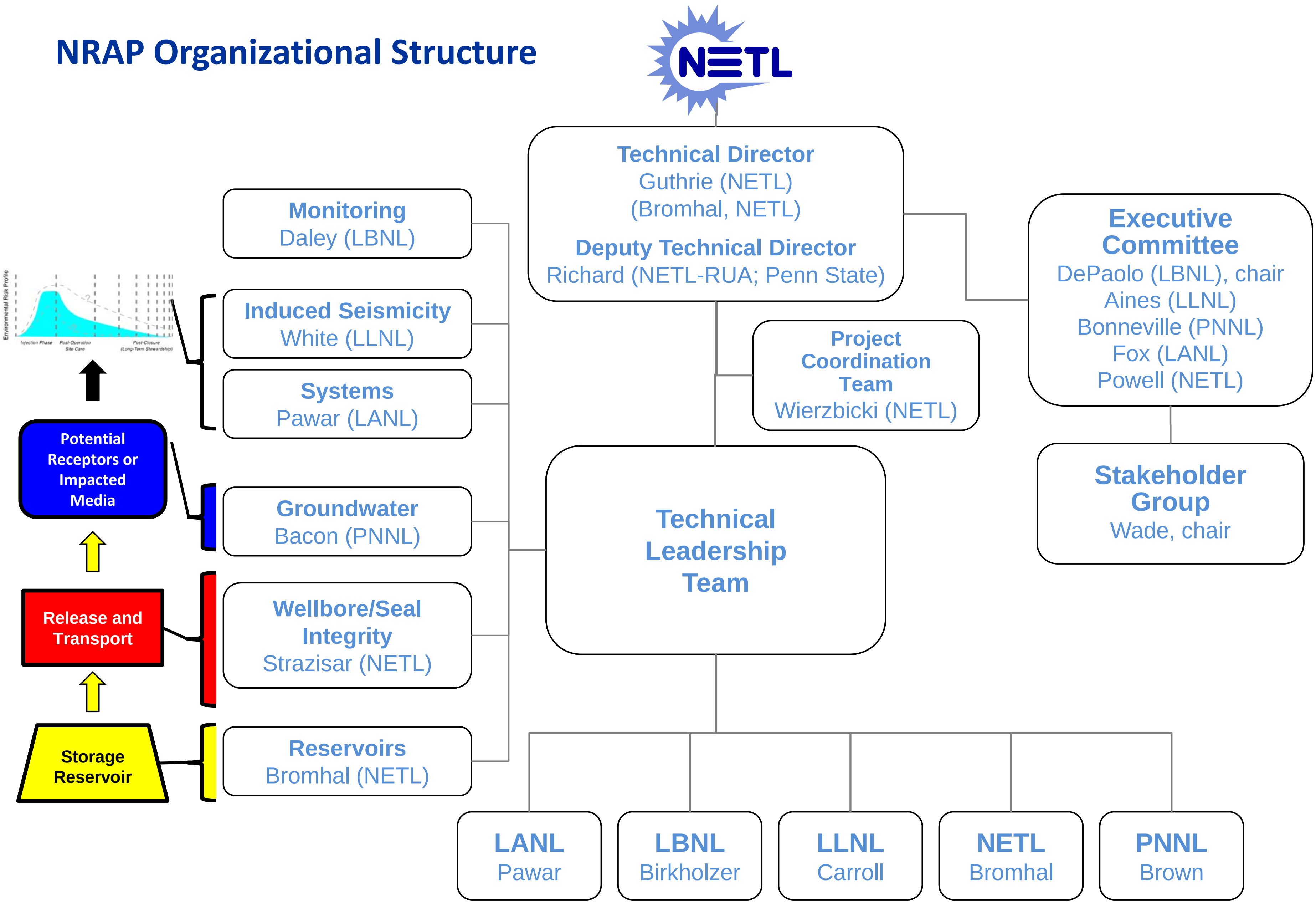
Lab Technical Teams

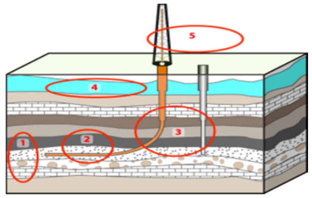
- Multidisciplinary teams at each organization that execute research in support of NRAP goals and plans; led by <u>technical coordinator</u>

Technical Working Groups

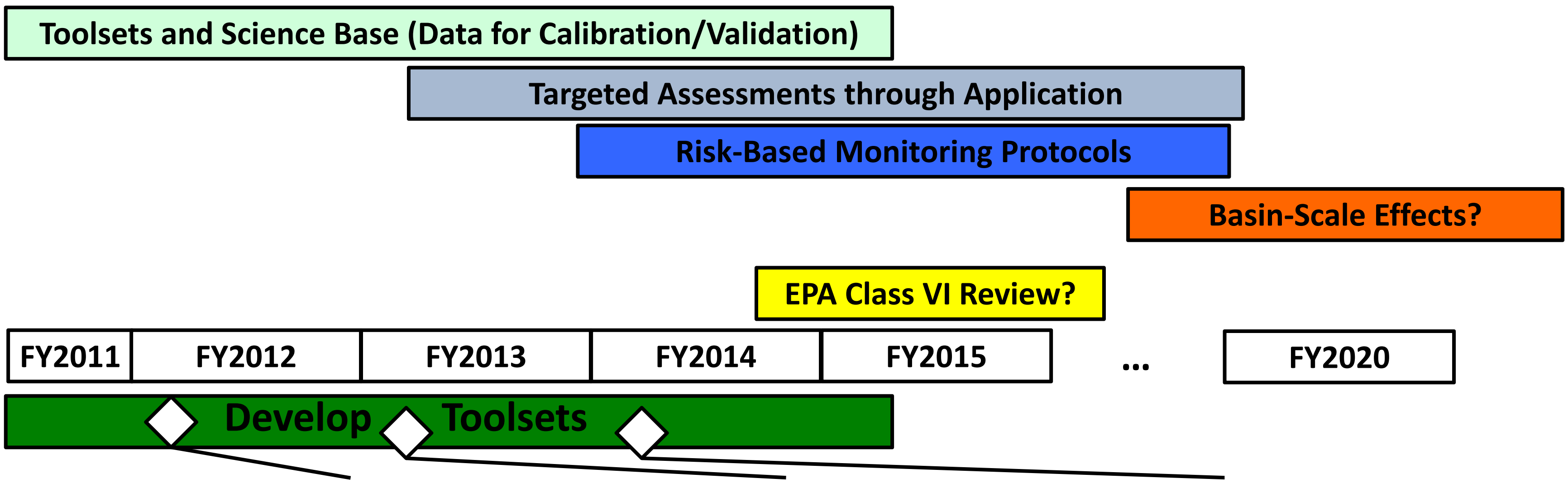
- Inter-lab teams that identify key research needs and that ensure integration across organizations and across working groups; led by <u>working group leader</u>

NRAP Organizational Structure



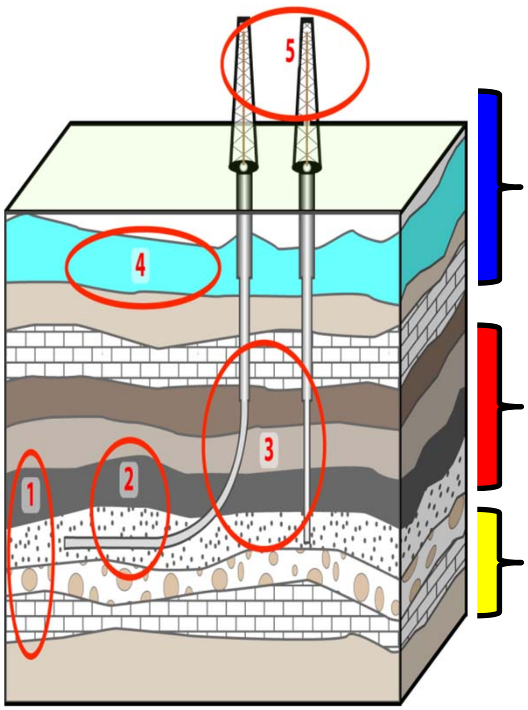


NRAP Tasks and Toolsets



Components	Generation 1	Generation 2	Generation 3
Reservoir	flow only 2 reservoir classes multiple reservoir simulators stochastic permeability	flow & geomechanics 3 reservoir classes (EOR) quantified trapping mechanisms ΔP due to semi-permeable caprock	4 reservoir classes
Release & Transport	wellbores (flow + phase change) faults (flow + phase change) 1D flow into thief zones	wells (flow+chemistry w/ varying permeability; field-based initial state, wellbore failure faults/fractures/caprock (flow+geomechanics; fault-zone complexity) porous flow through overburden	wellbores/fractures (flow, chemistry, geomechanics) coupling of flow in wells, faults, & porous media heterogeneous overburden
Groundwater	TDS, pH equilibrium geochemistry 2 endmember aquifers CO_2 & brine flux	TDS, pH, metals multiple leakage sources	TDS, pH, metals, organics kinetic geochemistry co-constituents redox geochemistry
Induced Seismicity	hazard assessment	hazard and damage risk	hazard, damage and nuisance risk
Atmosphere	total flux only		atmospheric dispersion

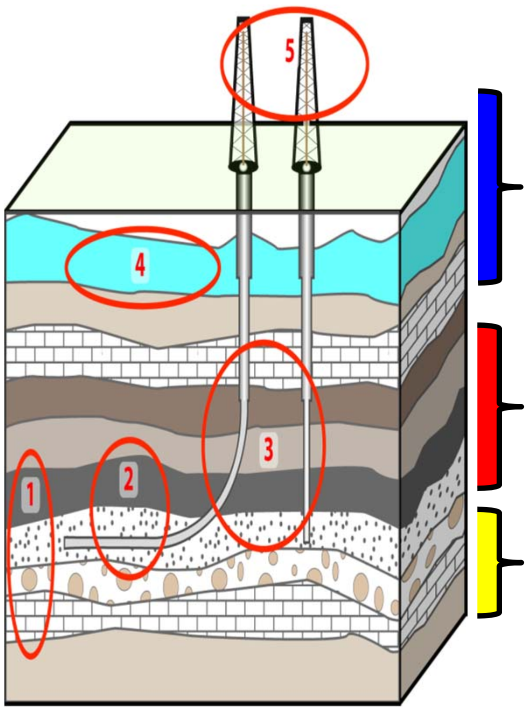
NRAP's approach to quantifying performance relies on reduced-order models to probe uncertainty in the system.



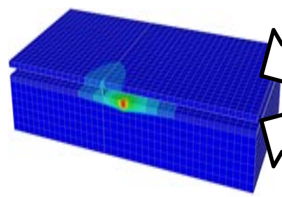
Potential Leakage Impacts (Atmosphere; Groundwater)	Potential Ground-Motion Impacts (Ground Acceleration)
⇧ fluid propagation	⇧ seismic-wave propagation
Release/Transport of Fluids	Slip along a Fault Plane
⇧ fluid propagation	⇧ stress/pressure propagation
Reservoir (plume/pressure evolution)	Reservoir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

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

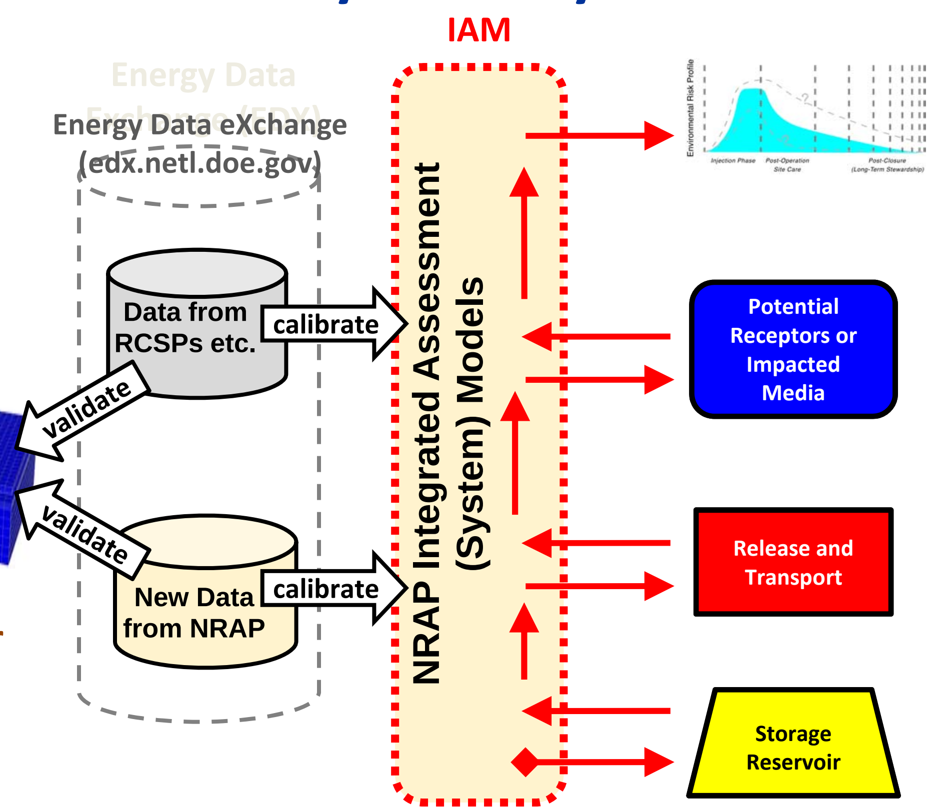
A. Divide system into discrete components



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

Approach to Development of Reduced-Order Models (ROMs):
Case Study at a Candidate Field Site

Sensitivity analysis
Identify key variables that control component behavior

↓

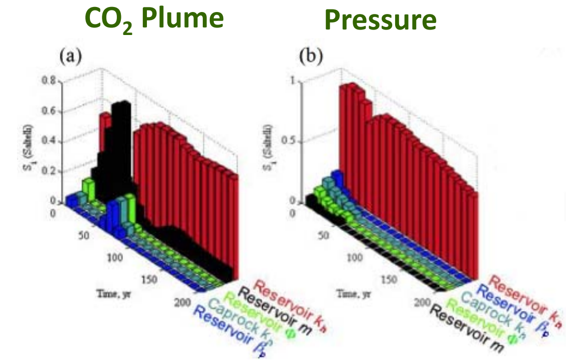
Detailed Simulations
Multiple simulations of detailed component models (reservoir, wellbores, faults, aquifer)

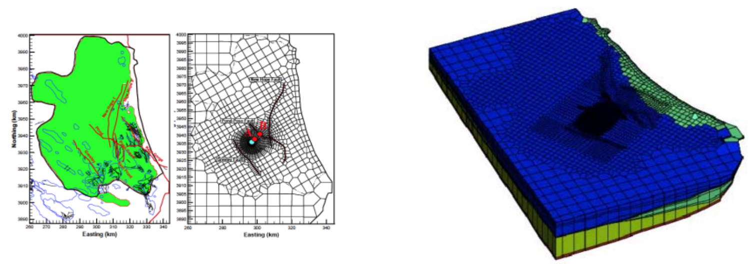
↓

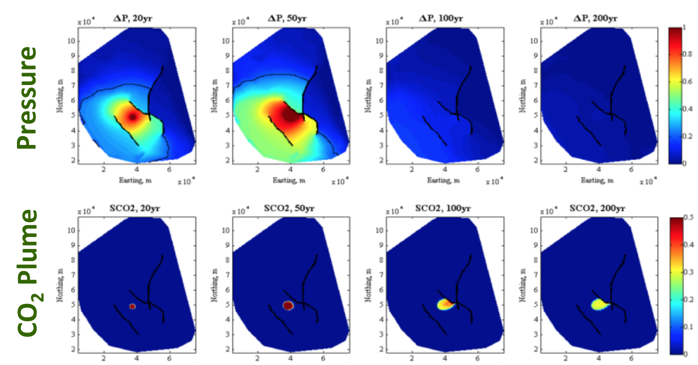
ROM Development
- Look-up tables (LUTs)
- Response surfaces (e.g. via PSUADE)
- Artificial intelligence approaches
- Analytical relationships (e.g., polynomial chaos expansion)

Define Key Parameters for ROM

Validate ROM against simulations



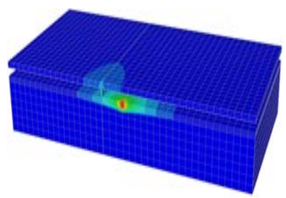




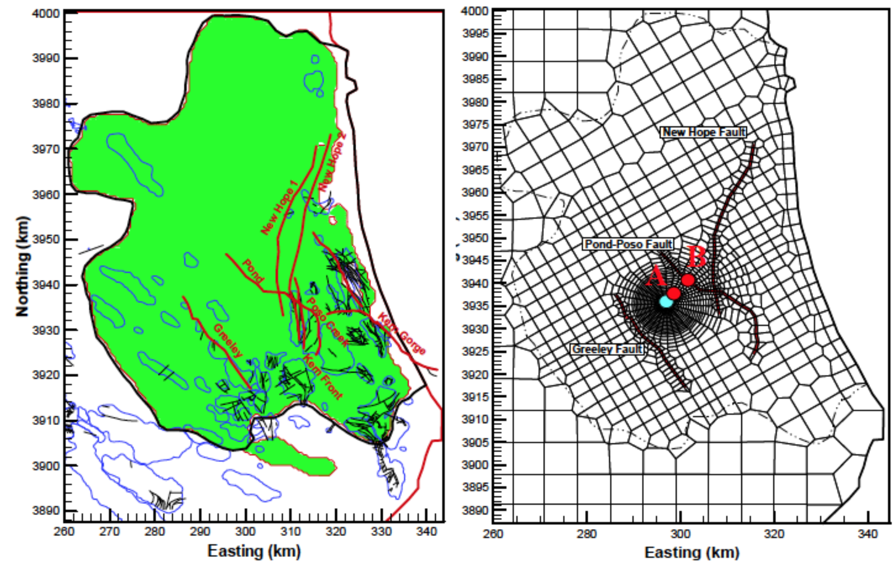
from Wainwright et al. (2012) NRAP-TRS-III-002-2012

Reduced-order models (ROMs) are used to allow rapid evaluation of component behavior over conditions of interest.

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



- **4D (3D+time) to 3D**
- **Only key variables**
- **Finite-volume to simplified solution**



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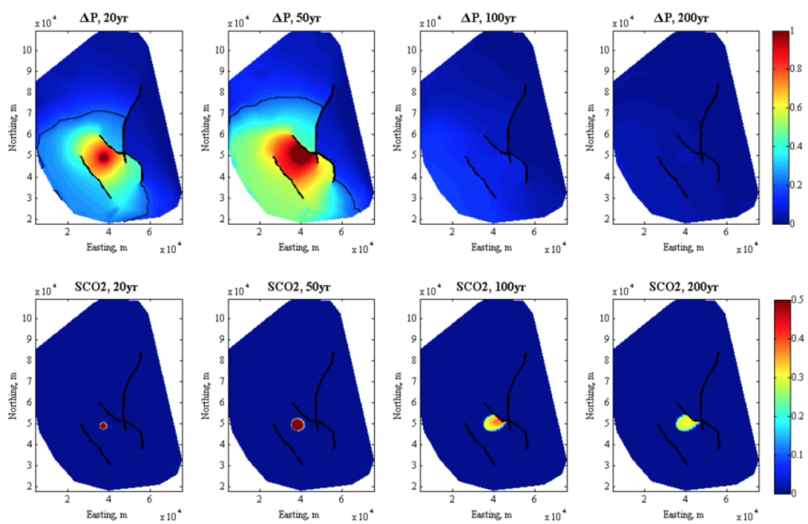
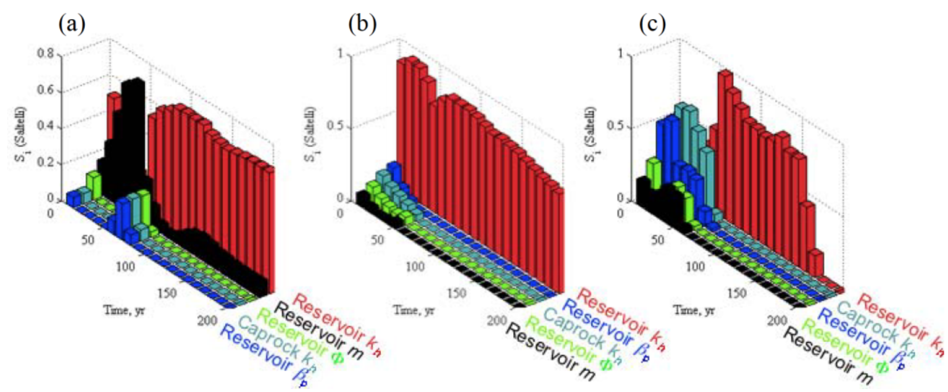


ROM focuses on P and saturation at reservoir-seal interface.

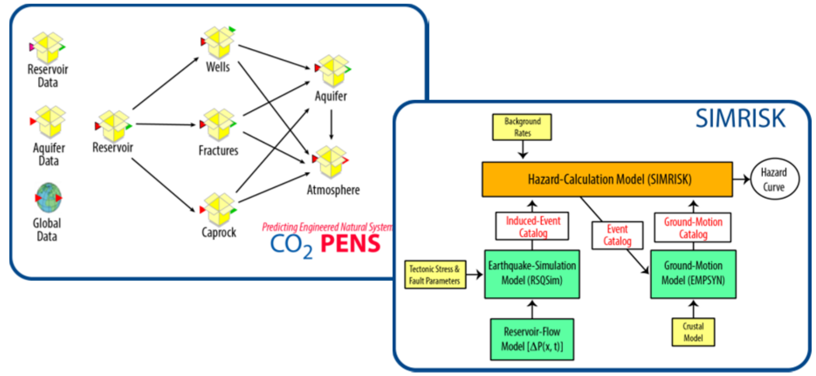


Sensitivity analysis allows ROM to focus only on key variables.

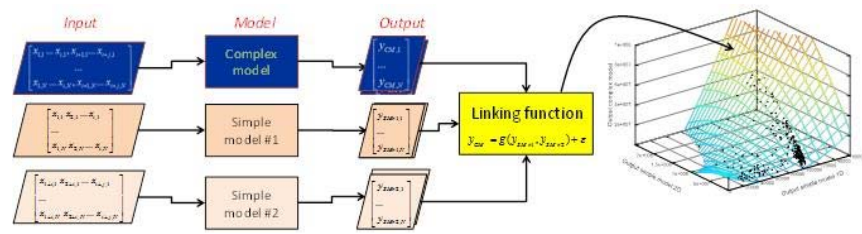
NRAP is evaluating a range of approaches to Reduced-Order Models (i.e., Rapid-Performance Models).

	"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				

Key NRAP Accomplishments: Building the Toolsets

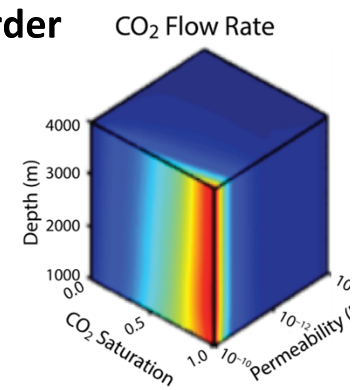


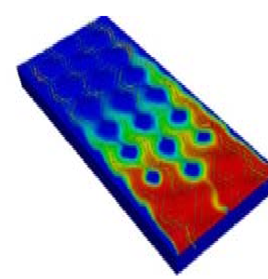
- **First-of-a-kind toolsets for science-based, quantitative evaluation of risks and uncertainties**
  - Leakage risks (reservoirs to receptors)
  - Induced seismic events

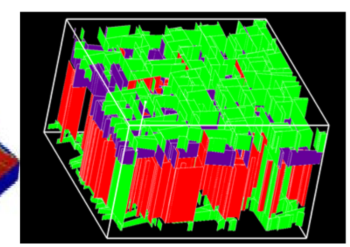


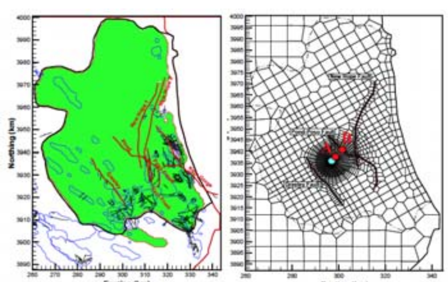
- **Site-specific and adaptable ROMs**
  - Reservoirs (3 classes; 3 injection scenarios)
  - Wellbores (open and cemented)
  - Fractures (discrete and networks)
  - Aquifers (two major types)

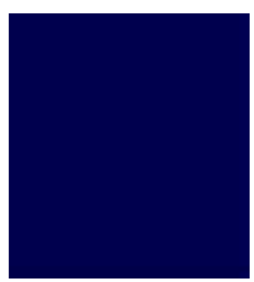
- **Evaluated numerous approaches to reduced-order models (lookup table to artificial intelligence)**
  - Achieve balance between fidelity and speed









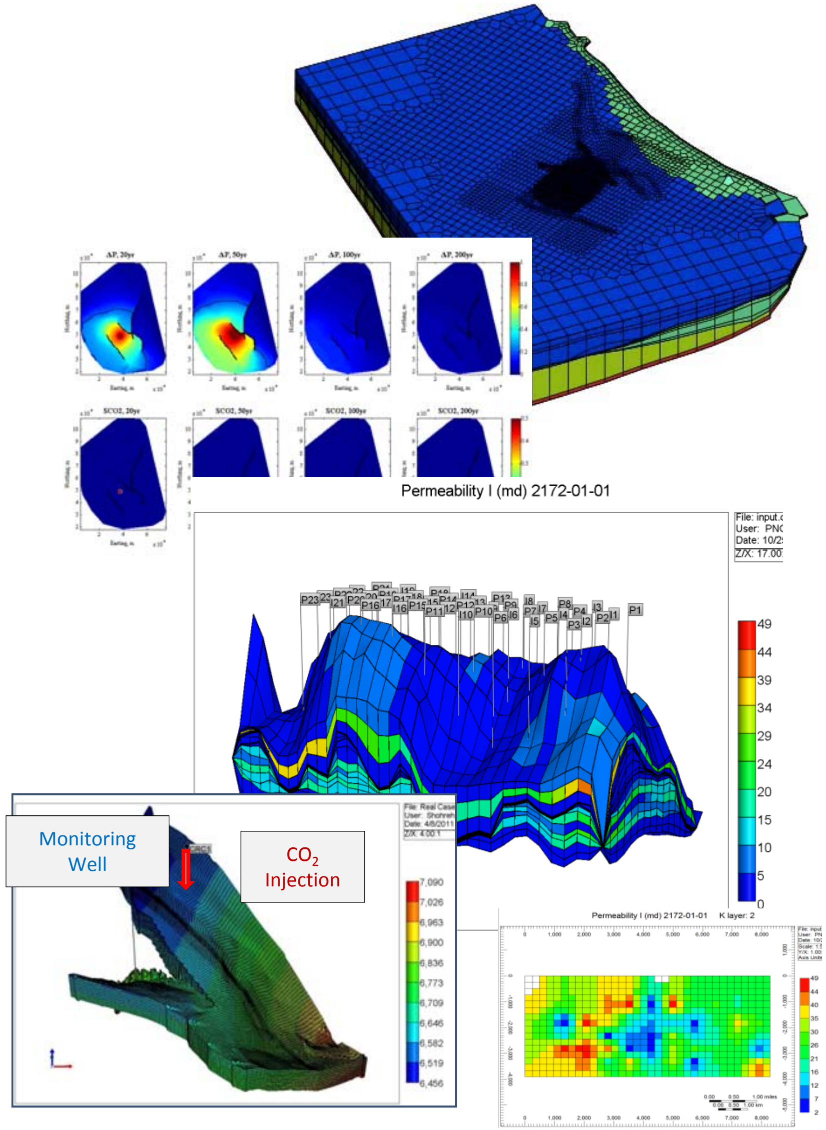


Reduced Order Models (ROMs) for Reservoirs

Purpose: Efficient prediction of P and S at reservoir-seal interface over a range for the most sensitive parameters

NRAP Tool & Method Development

- **ROMs built using reservoir simulation results:**
  - Specific to site and injection conditions
  - Injection through post-injection period
- **ROMs developed for “real” scenarios,**
  but used to capture representative behavior
  - Can be developed for specific sites
- **4 ROM approaches evaluated:**
  - Look up table (LUT)
  - Surrogate reservoir model based on artificial intelligence
  - Polynomial chaos expansion
  - Gaussian process regression



Reduced Order Models (ROMs) for Wellbores

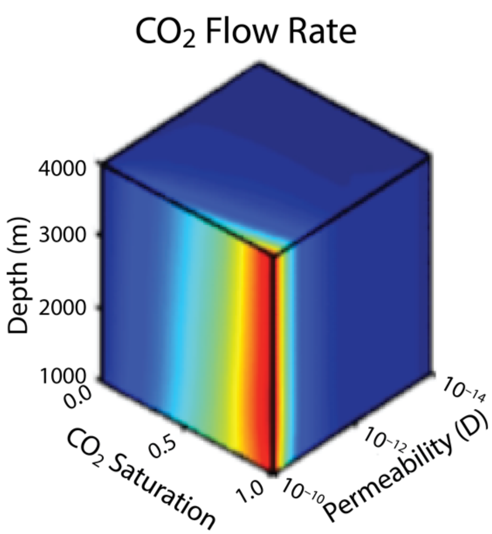
Purpose: Efficient prediction of brine/CO_2 flux given P and S at reservoir-seal interface

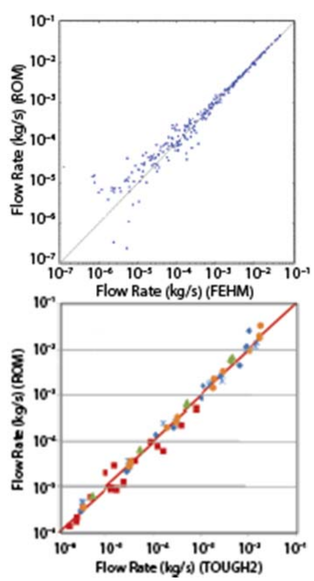
Cemented Wellbores

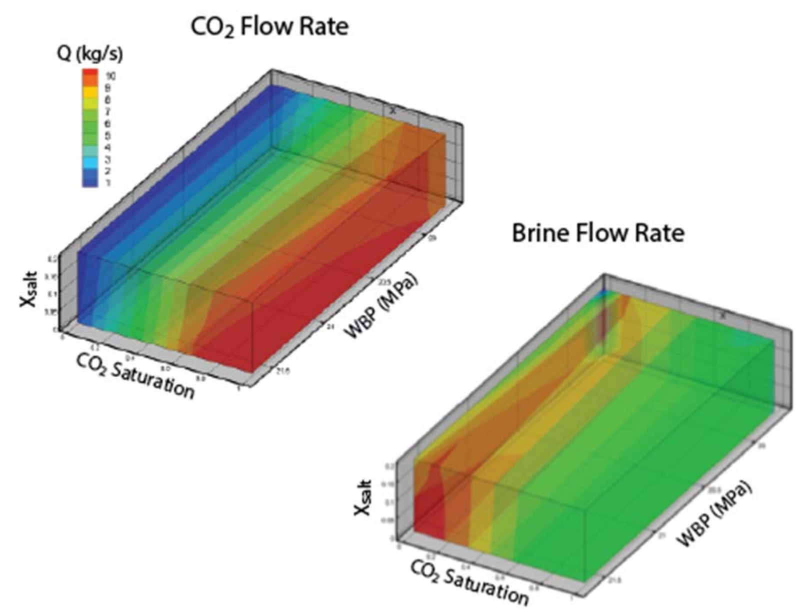
- **Response surfaces based on FEHM & TOUGH2**
- **Functions of depth, permeability, diameter, pressures, & saturations**
- **Decoupling of reservoir–well is valid when $k_{well} < 100 \bullet k_{reservoir}$ & CO_2 saturations are high**

Open Wellbores

- **Response surfaces based on TOUGH2 with drift-flux model**
- **Functions of depth, diameter, salinity, pressures, & saturations**



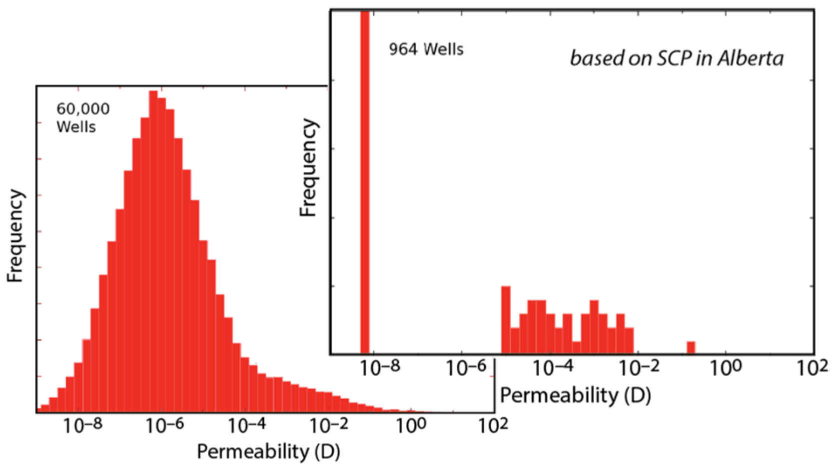


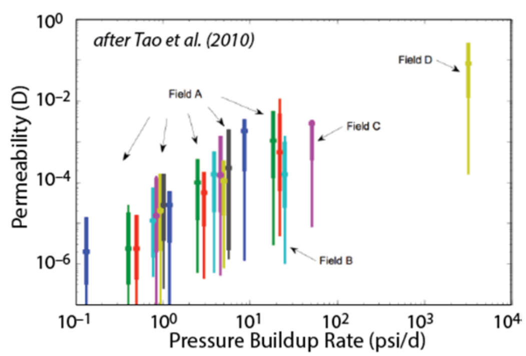


Development of Calibration Data for Wellbores

Effective Permeability

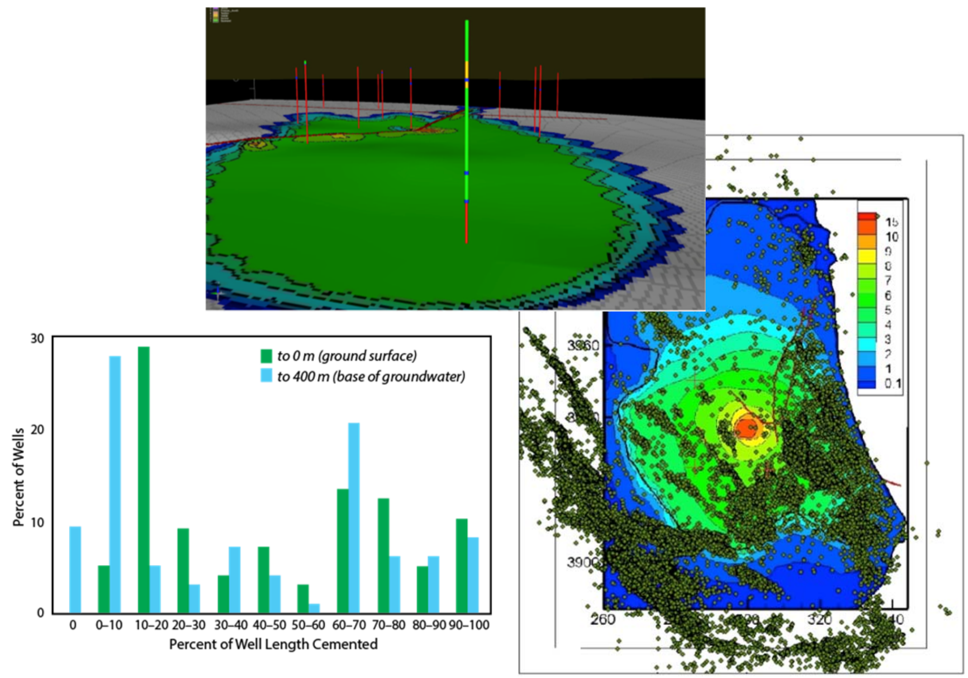
- Development of permeability distributions based on available data





Wellbore Completion Statistics

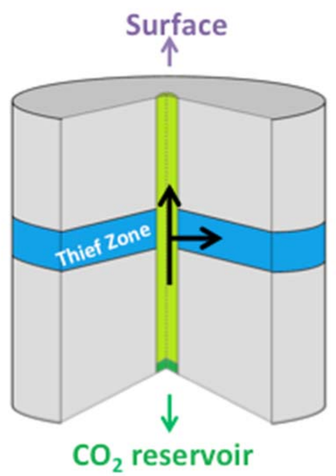
- Case study at California oil/gas reservoir
- Data mining at state-level

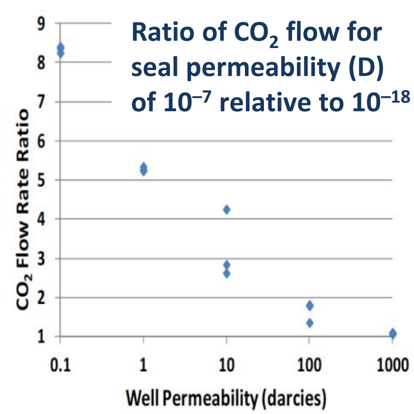


Evaluation of Potential Impacts to Flow Predictions for Wellbores

Impact of Horizontal Flow

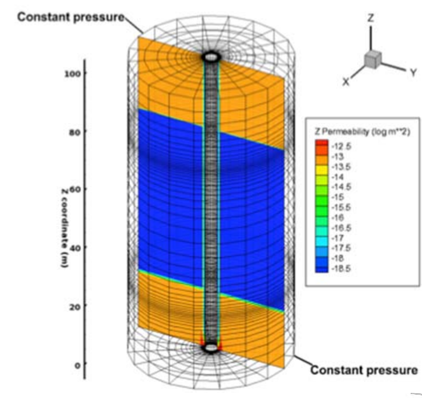
- Thief zones lower flow rates
- Higher seal permeability may increase flow rates

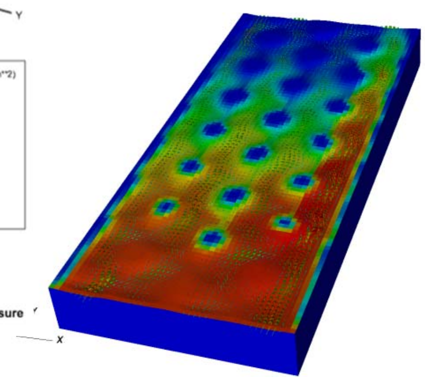


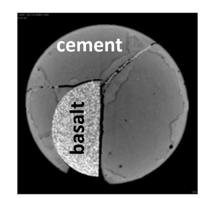


Impact of Geomechanics & Geochemisty

- Physics-based models to predict coupled effects on fractures in cements
- Experimental studies on reactive flow on fractures and interfaces

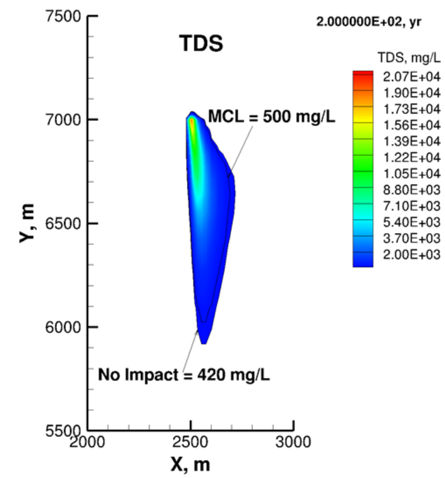




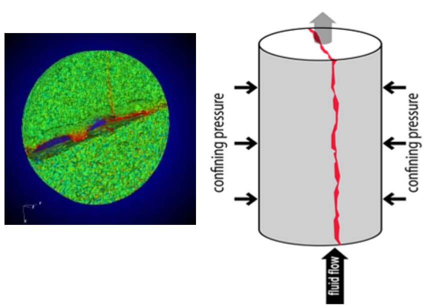


Key NRAP Accomplishments: Building the Science Base

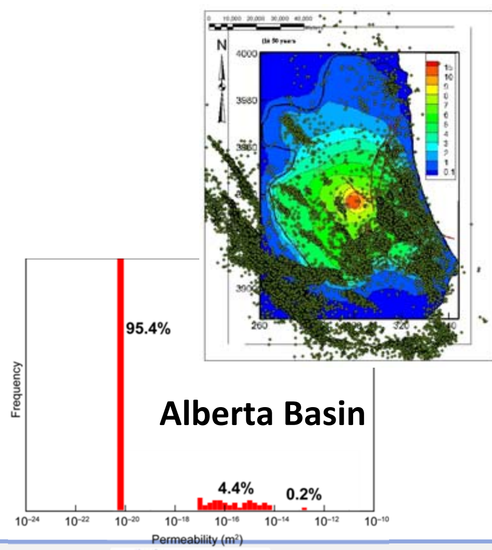
- **Developed underpinning, physics-based models for wellbores and fractures**
- **Demonstrated validity and limitations of de-coupling assumption in integrated assessment models**
- **Established "no-impact" threshold values for two major classes of aquifers**
- **Expanded science base and data needed for model calibration**
    - Lab studies on cement, shale, aquifers
    - Geostatistical studies on wellbore characteristics
    - Natural analog studies on reservoirs/aquifers

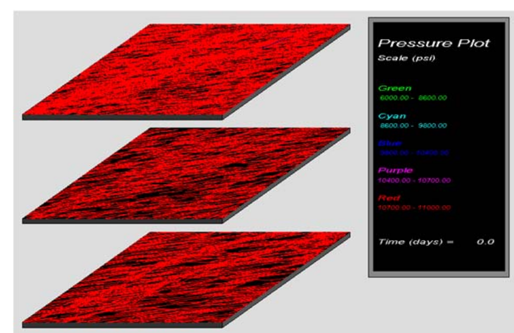


groundwater



wellbores

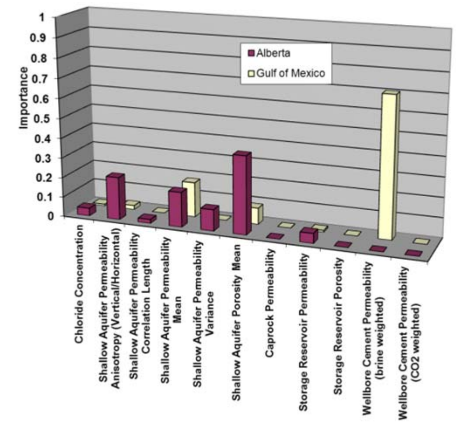


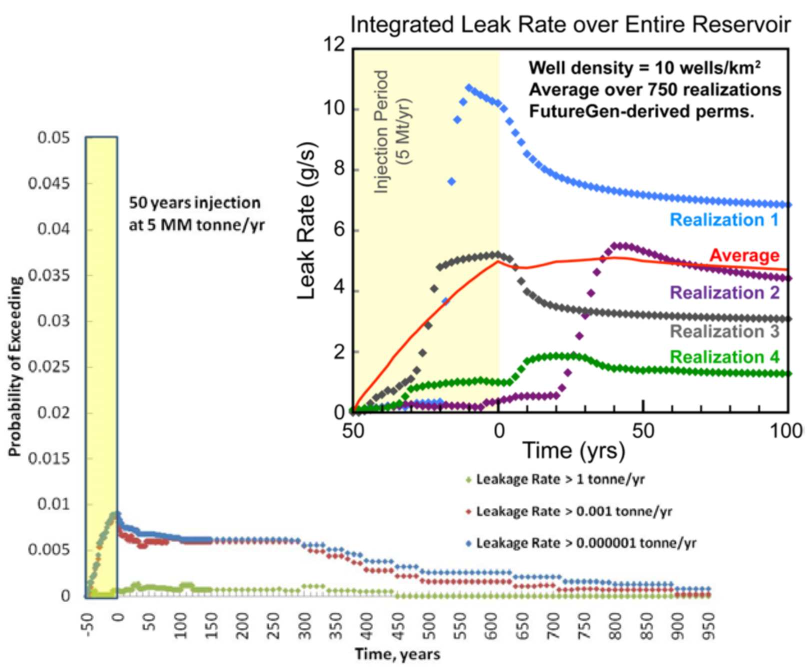


fractures

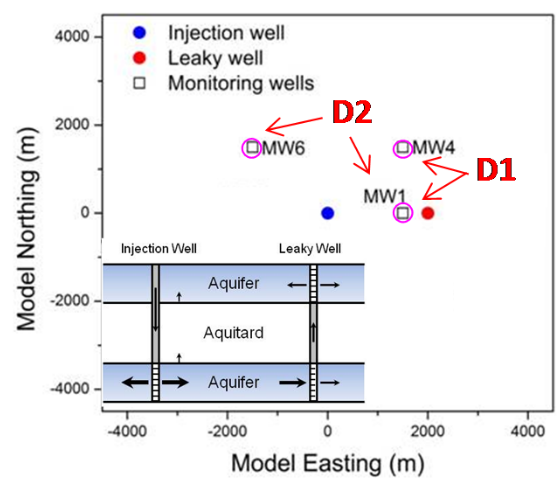
Key NRAP Accomplishments: Applying the Toolsets

- **Generated first quantitative risk profiles for long-term behavior**
  - Route to quantifying probability of meeting containment goals
- **Demonstrated use of IAMs to quantitatively identify key subsurface parameters that impact risk at a site**
- **Developed a preliminary technique for risk-based monitoring network design of CO_2 storage sites**





Leaky Storage Cases



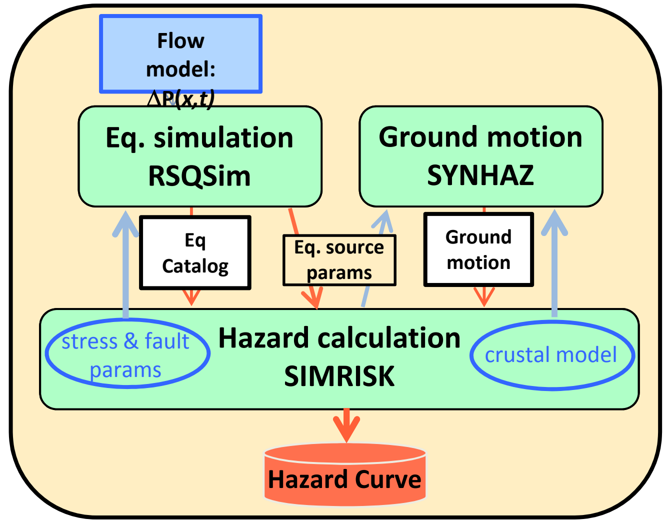
Key NRAP Accomplishments/Results: Induced Seismicity

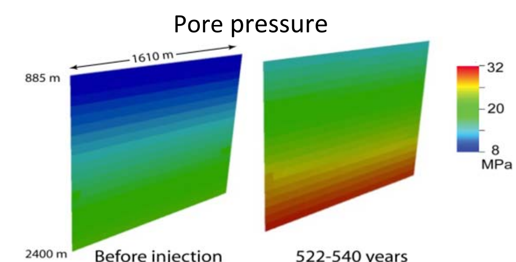
Tool & Method Development

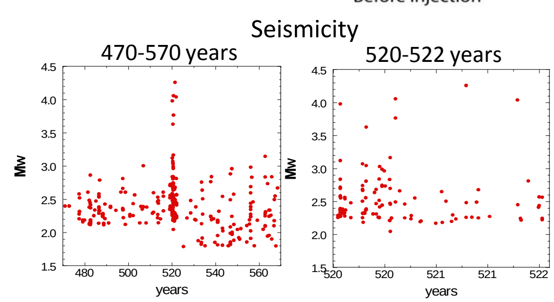
- Developed a probabilistic seismic hazard assessment (PSHA) tool for induced seismicity
  - adapted widely accepted conventional PSHA approach
- Extending development to assess damage and nuisance (felt event) risks
  - demonstration application to realistic CO_2 injection scenarios based on In Salah (Algeria)

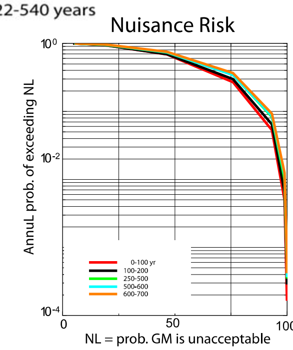
General Trends & Relationships

- 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
- Risk of CO_2 leakage may be coupled to slip on faults during earthquakes

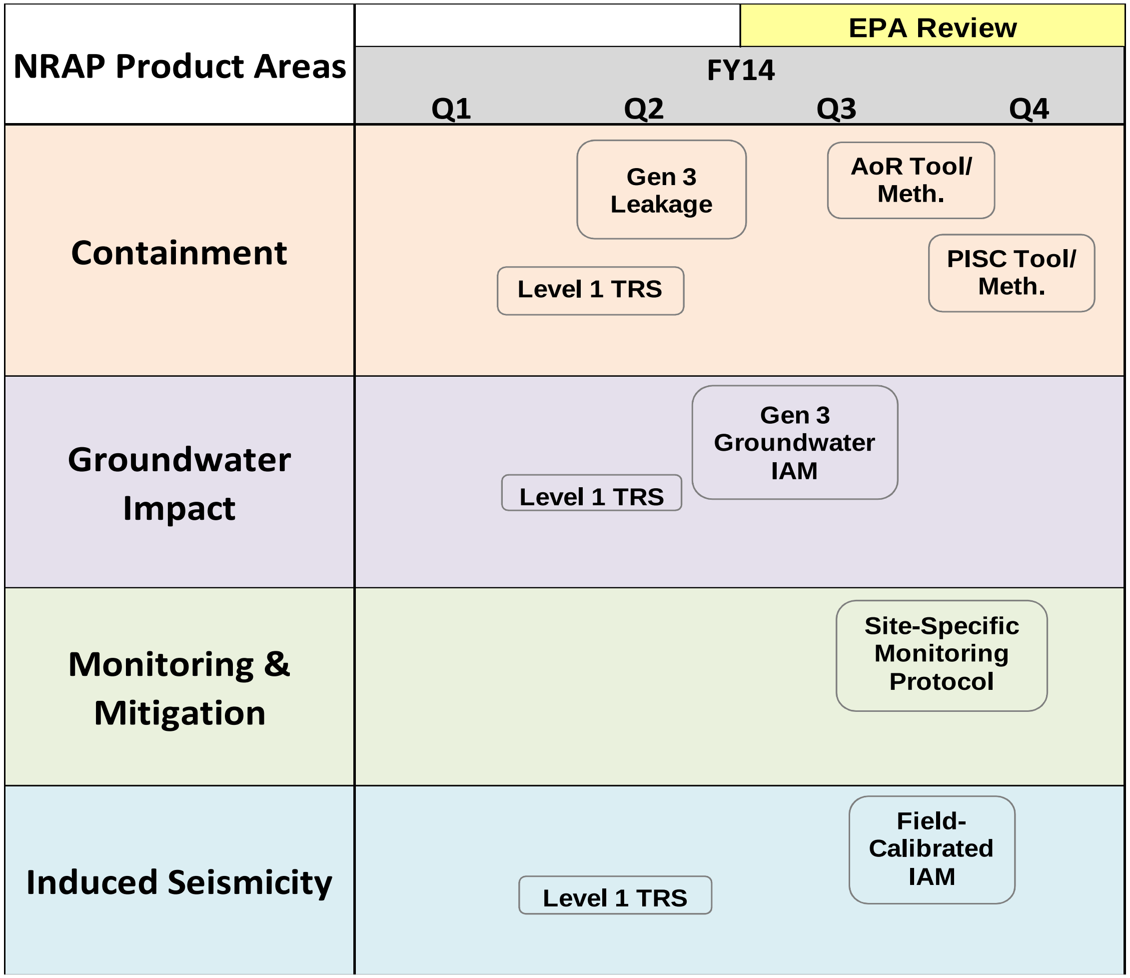








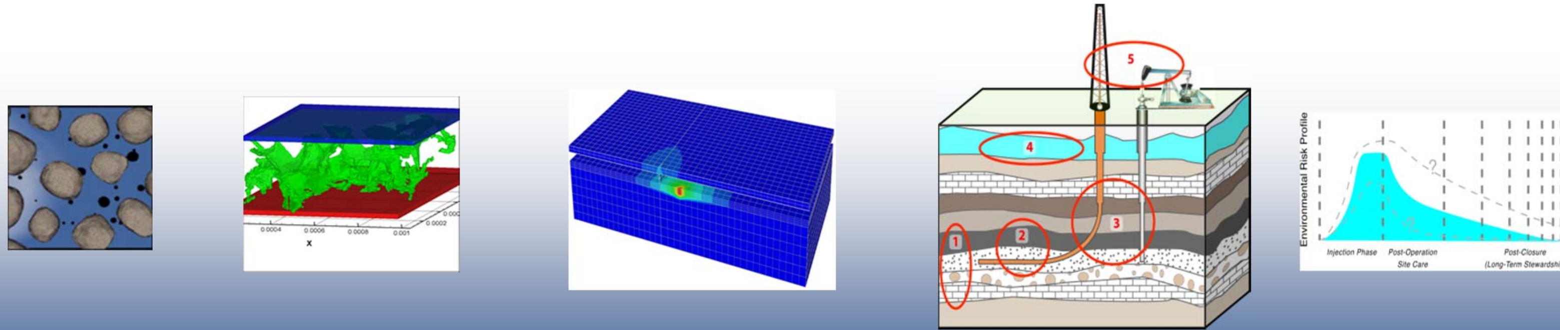
NRAP FY14 Overview



- **Complete third generation toolsets for quantifying long-term performance**
- **AoR & PISC tools for facilitating dialog during the permitting process**
- **Risk-based monitoring protocols for verification (operators, regulators, …)**
- **Field-calibrated toolset for forecasting induced seismic risk to aid operators and regulators (e.g., confidence in injection envelops)**

Using simulations to predict behavior of reservoirs for various scenarios and conditions (AoR and PISC).

- **Two underlying questions**
  - How does a reservoir's performance change as a function of injection volumes and rates?
  - How does a reservoir respond as a function of time when injection stops?
- **Two performance metrics for the reservoir tie to potential risks of concern**
  - Risks of concern include ensuring protection of groundwater and avoiding induced seismicity
  - Performance metrics include evolution of pressure and CO_2 plumes
- **Near-term focus**
  - Use reservoir simulators to predict pressure and CO_2 distributions
    - Focus on two major reservoir categories
    - Explore sensitivity to key variable/unknown characteristics (ϕ, $k_{reservoir}$, k_{seal}, etc.)
    - Determine response as a function of injection rate and volume
  - Calculate large matrix of scenarios; analyze pooled results to identify general trends
- **Longer-term focus**
  - Apply to other reservoir types
  - Use data to develop a streamlined protocol for an AOR and PISC tool
  - Evaluate simplified analytical model vs. reduced-order model based on reservoir simulations
  - Evaluate tiered risk-based AoR Framework



National Risk Assessment Partnership

Using science-based prediction of engineered–natural systems to inform decisions for CO_2 storage

Questions?

NETL-RUA Regional University Alliance
Berkeley Lab
Los Alamos National Laboratory EST. 1943
Pacific Northwest National Laboratory

Technical Team Leads

- **LBNL Team Lead**
  - Jens Birkholzer
- **Monitoring Lead**
  - Tom Daley

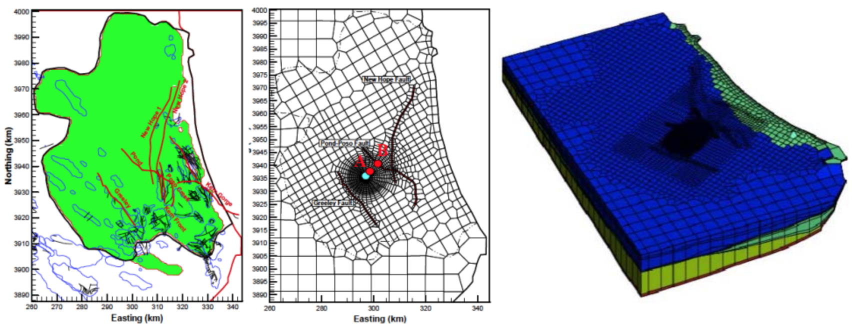
- **LLNL Team Lead**
  - Susan Carroll
- **Induced-Seismicity Lead**
  - Josh White

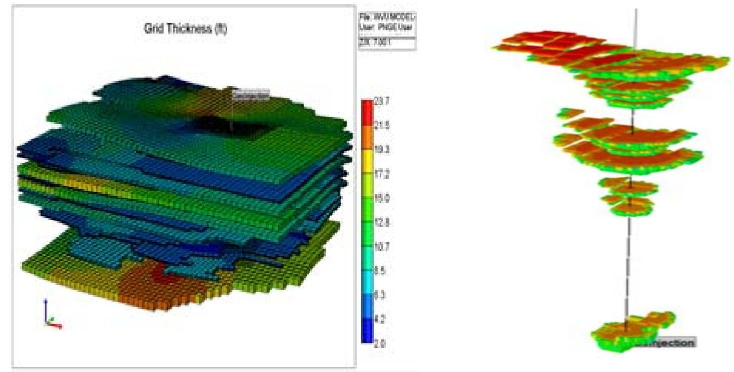
- **NETL Team Lead & Reservoir Lead**
  - Grant Bromhal
- **Migration Pathways**
  - Brian Strazisar

- **LANL Team Lead**
  - Rajesh Pawar
- **System-Modeling Lead**
  - Rajesh Pawar

- **PNNL Team Lead**
  - Chris Brown
- **Groundwater Lead**
  - Diana Bacon

Initial Reservoirs for AoR and PISC Studies





- **Unbound Sandstone Reservoir**
  - Sandstone formation
  - No lateral structural trap
  - Horizontal or dipping units bound by caprock
  - Homogeneous, moderate permeability
- **Based on generic reservoir off structure**
  - Initial geologic model developed in TOUGH2
- **Single, vertical injector**
  - Perforated along entire reservoir interval
  - Constant-rate injection
  - Varying Injection Rates
  - Varying Injection Times
  - Post Injection: Monitoring pressures and CO2 at various time points

- **Domal, Multilayer Sandstone Reservoir**
  - Multilayer sandstone formation
  - Domed structural bound by shale caprock
  - Heterogenous, variable layer permeability
- **Based on candidate site from RCSP, ARRA**
  - Citronelle-like conditions in reservoir
  - Initial geologic model leveraged from RCSP and ARRA project and developed in CMG
- **Single, vertical injector**
  - Multiple perforations along reservoir interval
  - Constant rate injection with pressure constraint
  - Varying Injection Rates
  - Varying Injection Times
  - Post Injection: Monitoring pressures and CO2 at various time points