National Risk Assessment Partnership:
Quantifying the Behavior of Engineered–Natural Systems for CO_2 Storage

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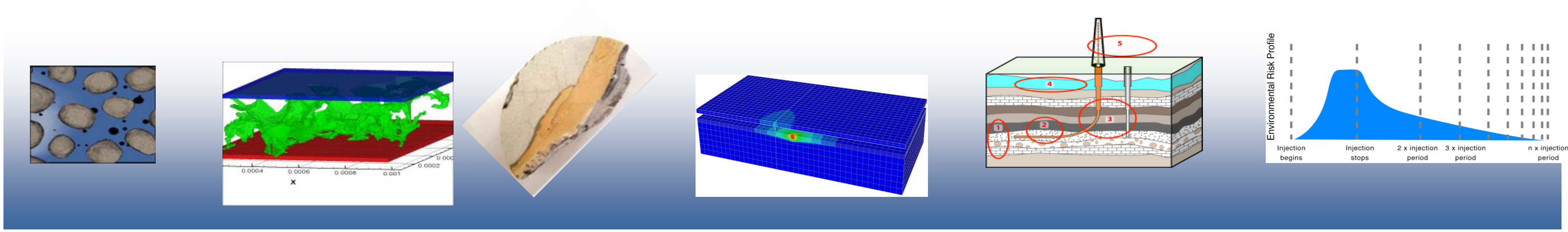
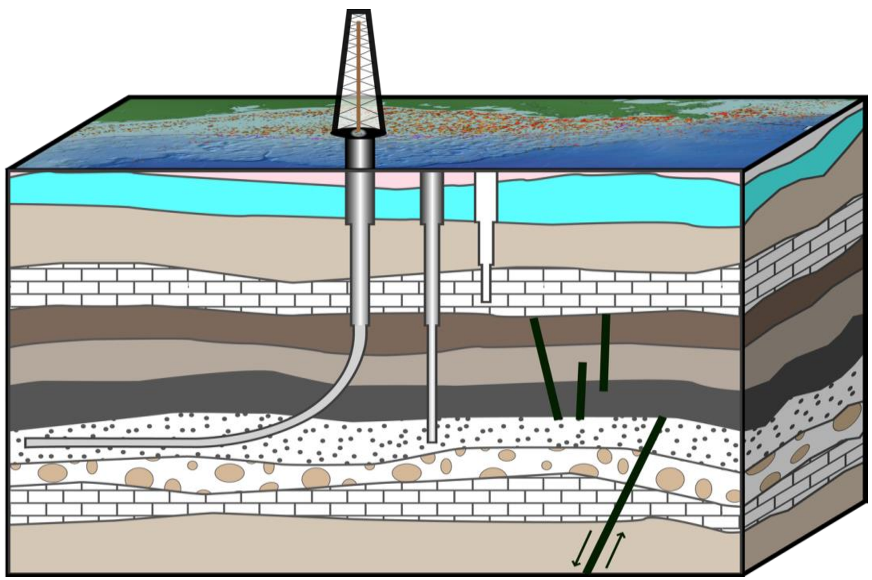
U.S. DOE Office of Fossil Energy

May 2014





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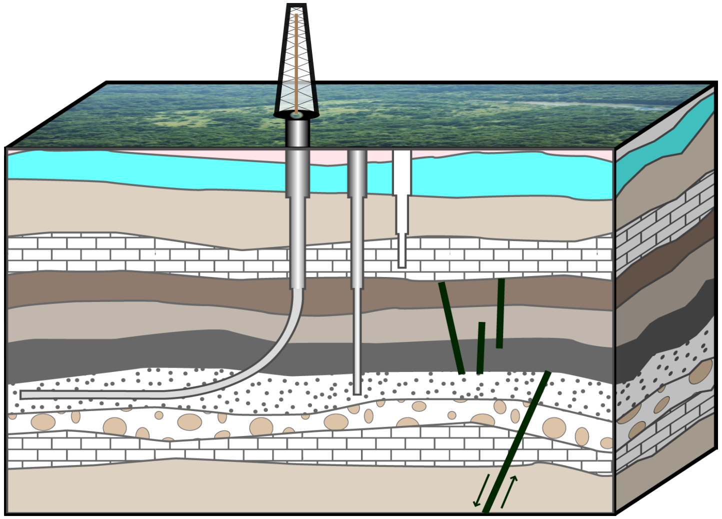
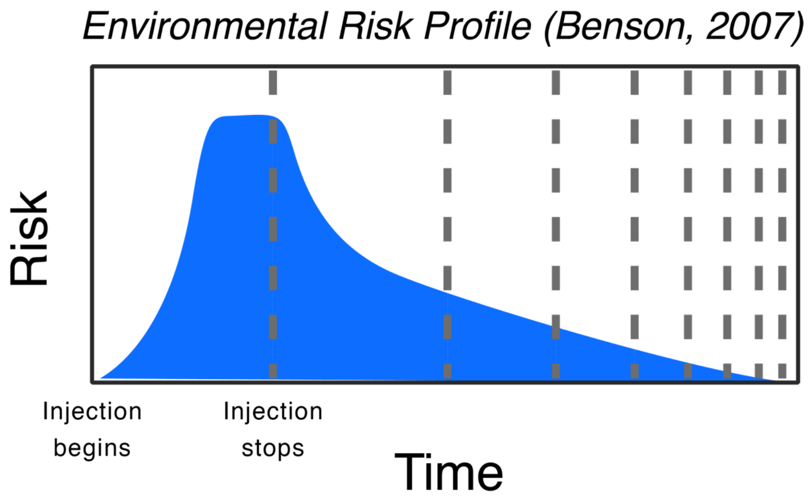
NRAP National Risk Assessment Partnership

National Risk Assessment Partnership:

Quantifying the Behavior of Engineered–Natural Systems for CO_2 Storage

Using science-based prediction to inform decisions tied to a complex and uncertain engineered–natural system.





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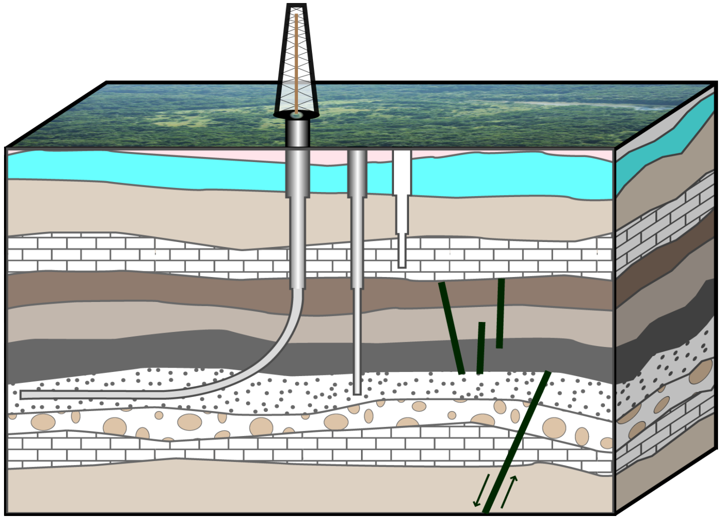
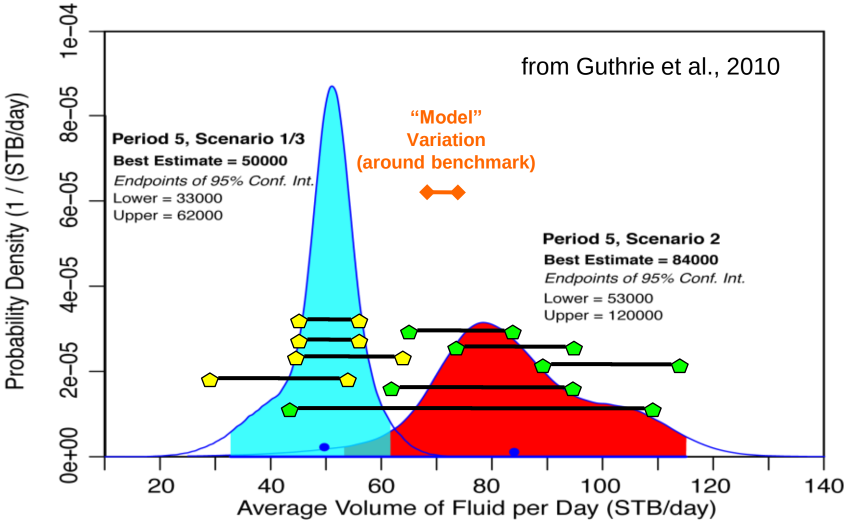
Quantifying the Behavior of Engineered–Natural Systems for CO_2 Storage

Using science-based prediction to inform decisions tied to a complex and uncertain engineered–natural system.

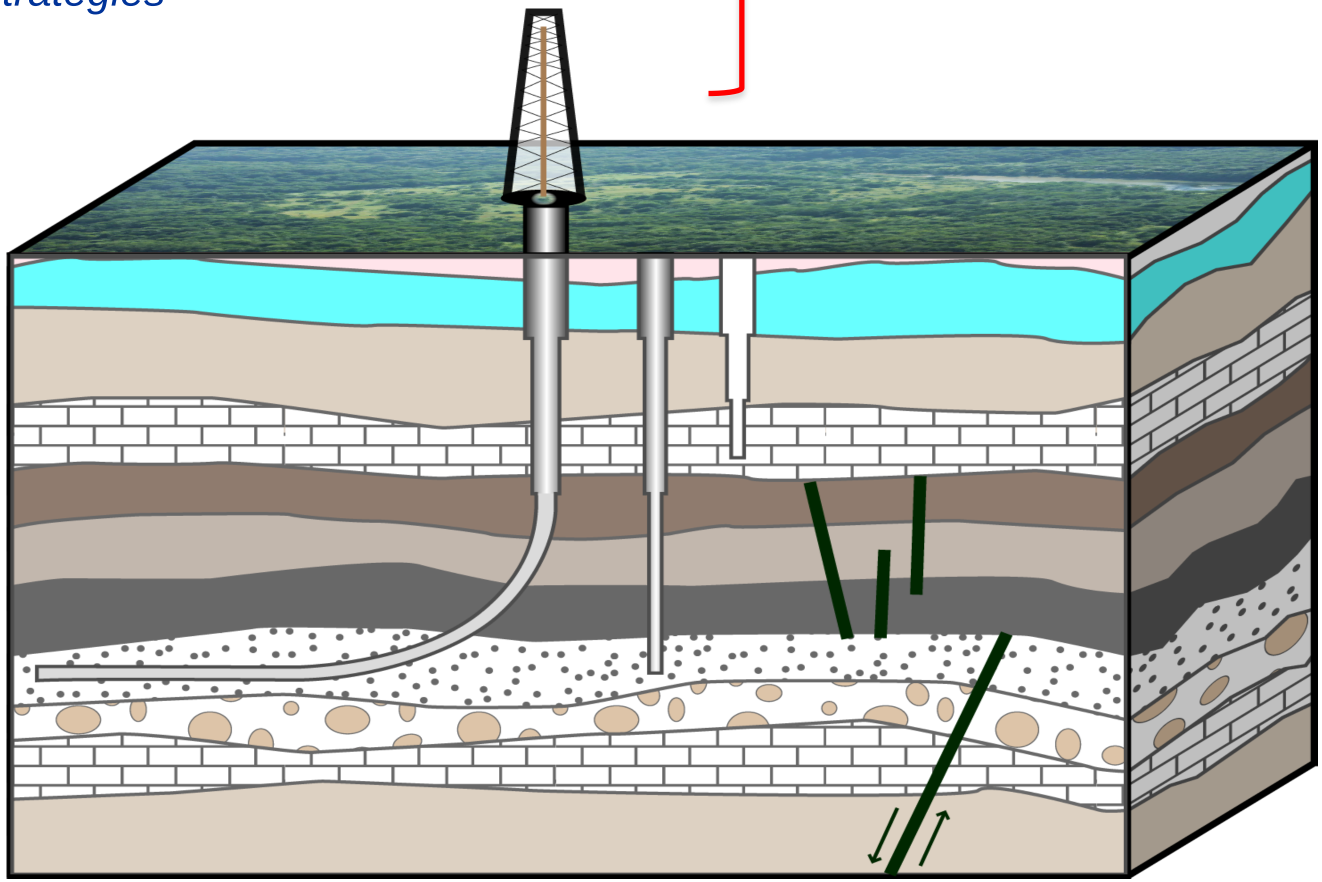




Quantitative Predictions Needed for Planning…

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

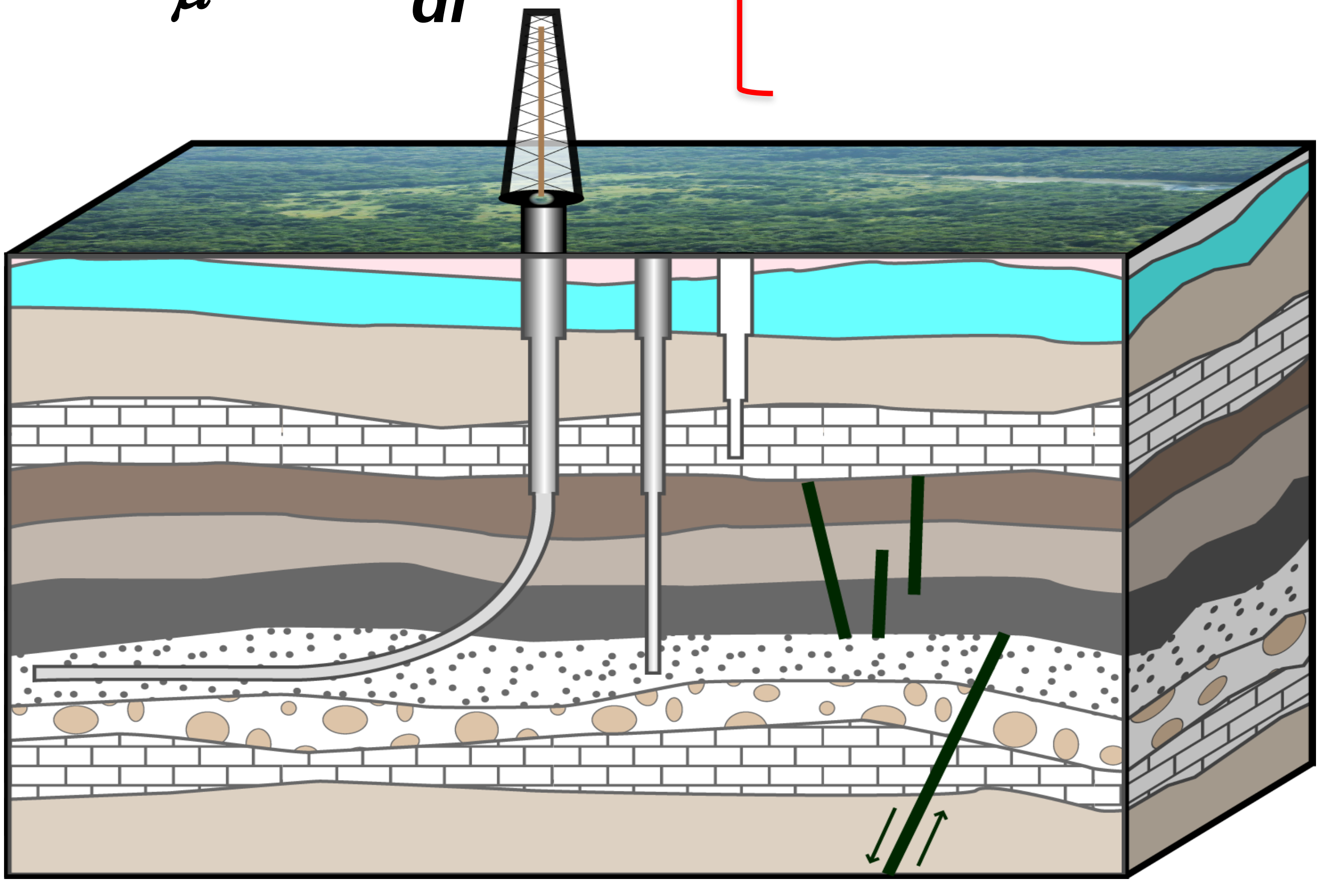
Must predict fluid flow in porous & fractured media.



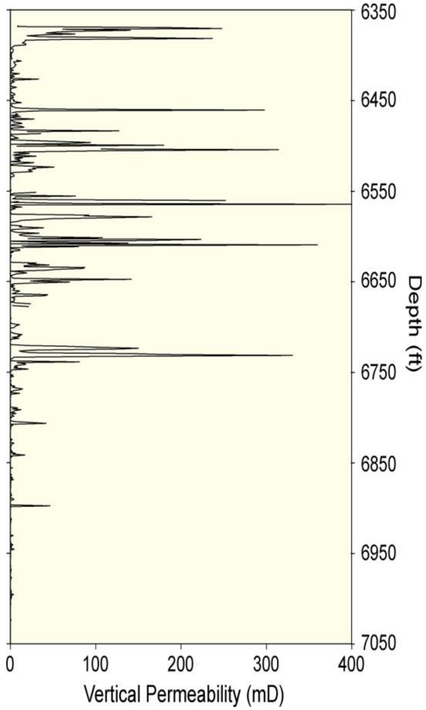
Permeability is a first-order parameter in predicting fluid flow.

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

Must predict fluid flow in porous & fractured media.

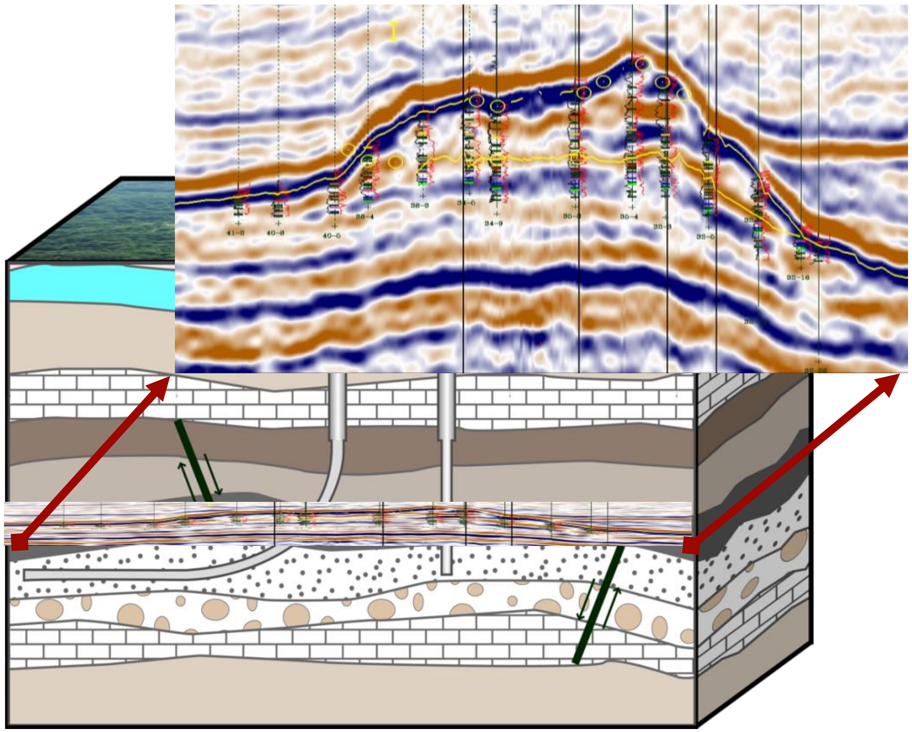


Permeability varies over space and time.



SACROC core data represent ~10–[10] of the total reservoir volume.

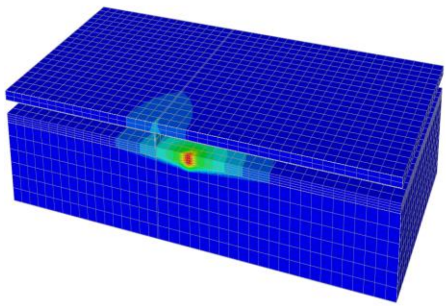
Seismic image through SACROC reservoir.



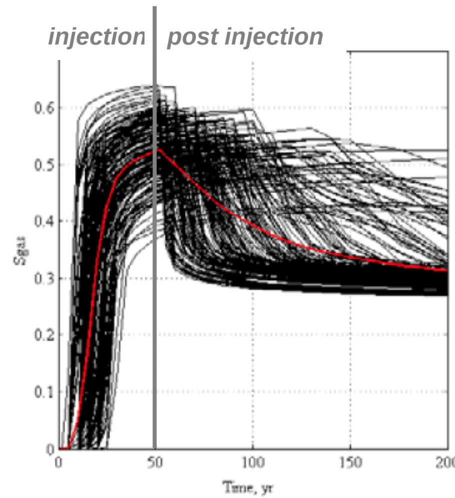
Seismic data do not provide high resolution information on permeability.

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

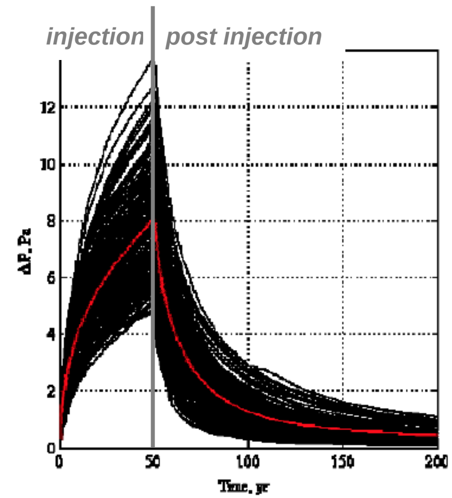
Different choices of permeability (& porosity, …) impact predictions on reservoir behavior.



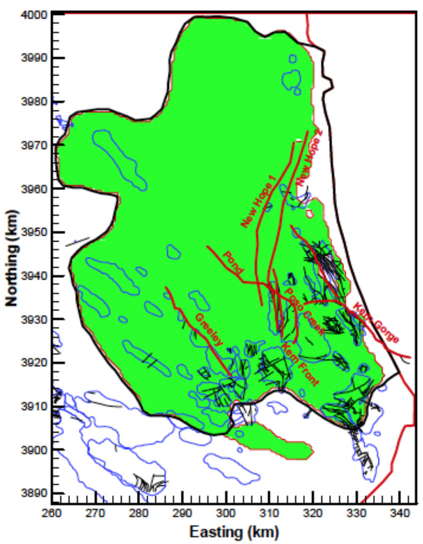
Saturation

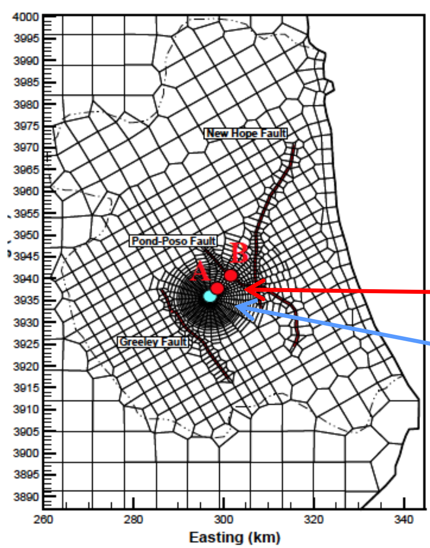


Pressure Buildup



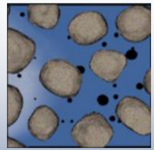
from Wainwright et al. (2012) NRAP-TRS-III-002-2012

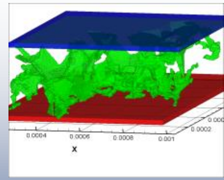


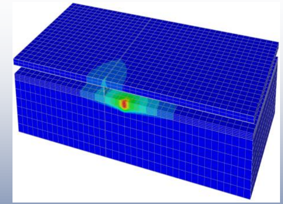


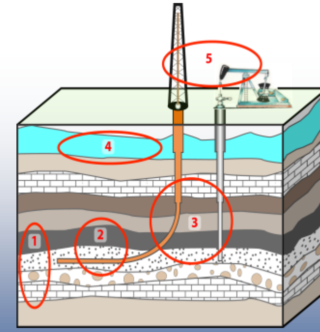
Monitoring location for graph

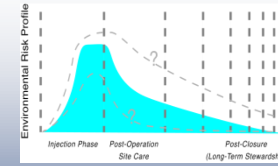
Injection location











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
Berkeley Lab
Los Alamos National Laboratory EST. 1943
Pacific Northwest National Laboratory

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
Whiting
Zurich Because change happenz
The University of Utah
Wade, LLC

Technical Team Leads

- **NRAP Technical Lead**
  - George Guthrie
- **NETL Team Lead**
  - Grant Bromhal
- **Reservoir Lead**
  - Grant Bromhal
- **Wellbore Lead**
  - George Guthrie

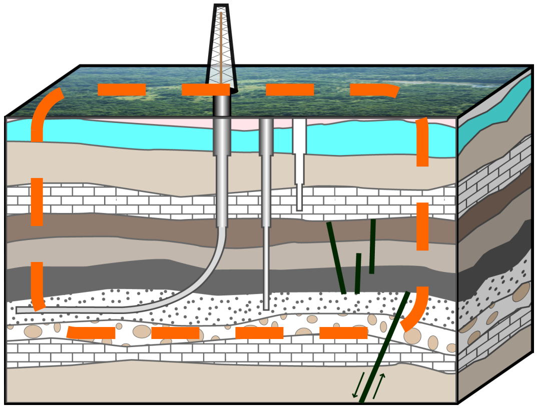
- ***LANL Team Lead***
  - *Rajesh Pawar*
- ***System-Modeling Lead***
  - *Rajesh Pawar*

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

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

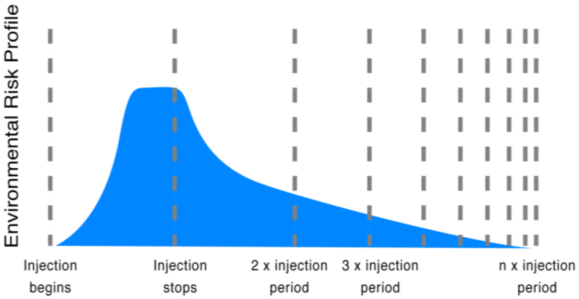
- ***PNNL Team Lead***
  - *Chris Brown*
- ***Groundwater Lead***
  - *Diana Bacon*

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

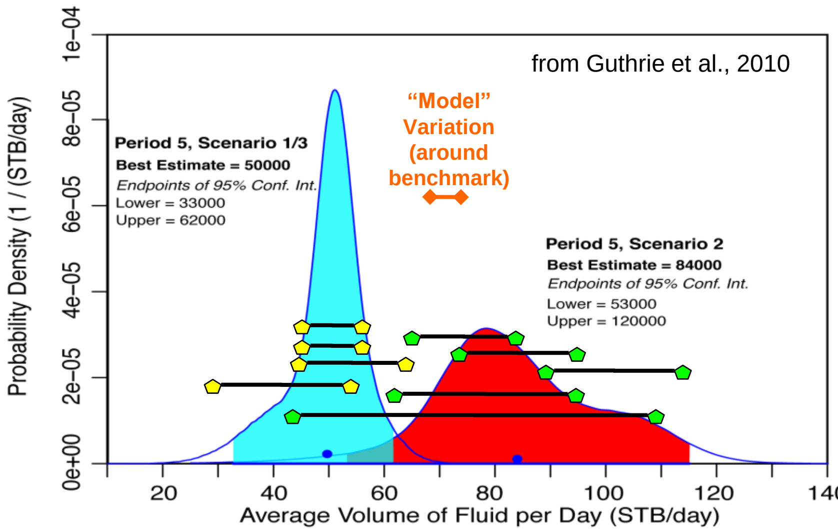


NRAP Goal—to predict storage-site behavior from reservoir to receptor and from injection through long-term storage…

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



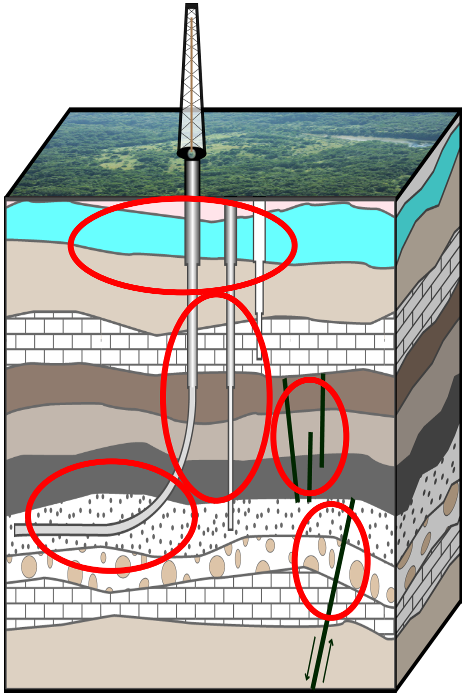
Confidence in uncertain predictions can be built through comprehensive, multi-organizational team assessments.



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

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

A. Divide system into discrete components



System behavior stems from the behavior of individual components.

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

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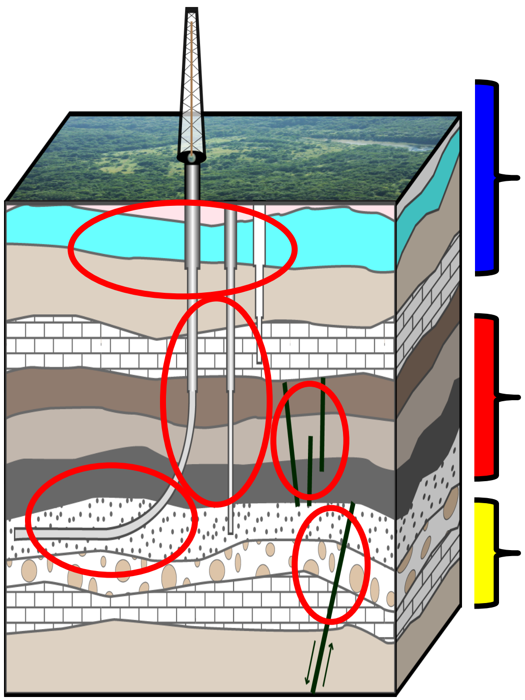
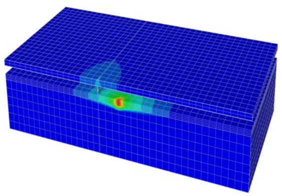


B. **Develop detailed component models that are validated against lab/field data**



Science-based prediction can be used to characterize component behavior for specific conditions.

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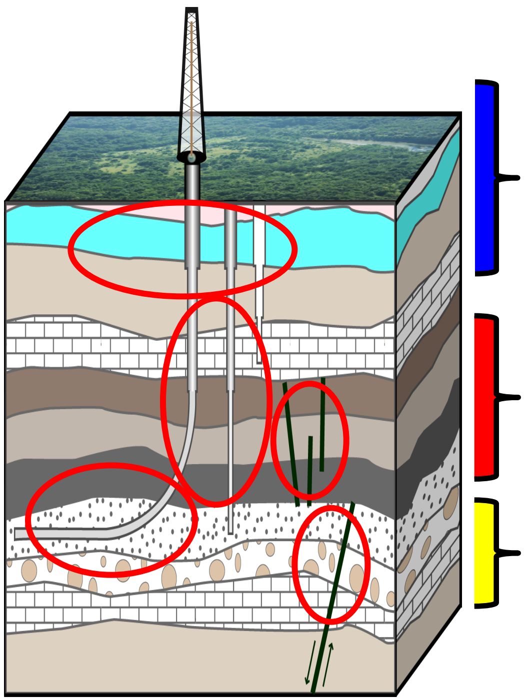

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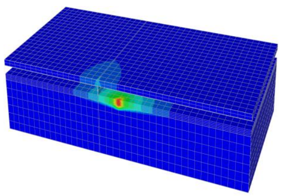
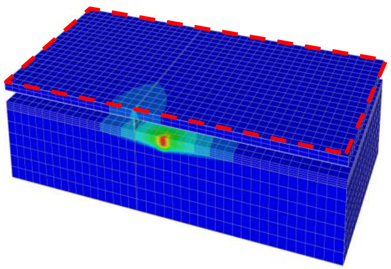


C. **Develop reduced-order models (ROMs) that rapidly reproduce component model predictions**

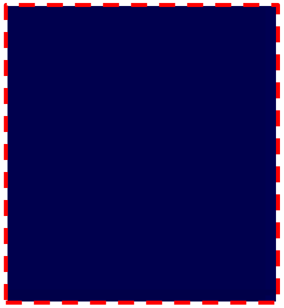


Detailed Simulations

- physics based
- detailed behavior for specific conditions

Calibrate ROM

Validate ROM

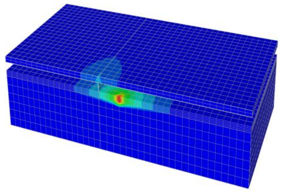


Reduced-order Models

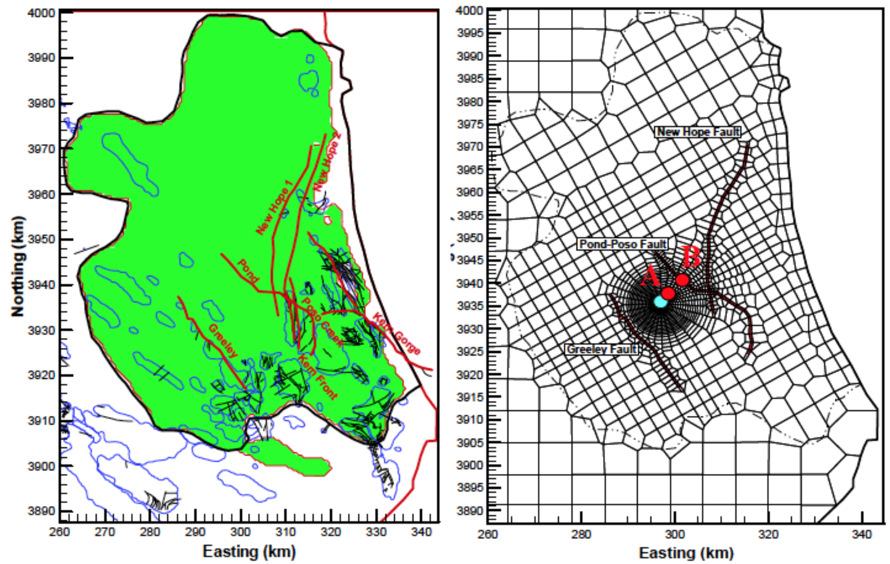
- simplified; rapid
- stochastic behavior for range of conditions

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-element to simplified solution**



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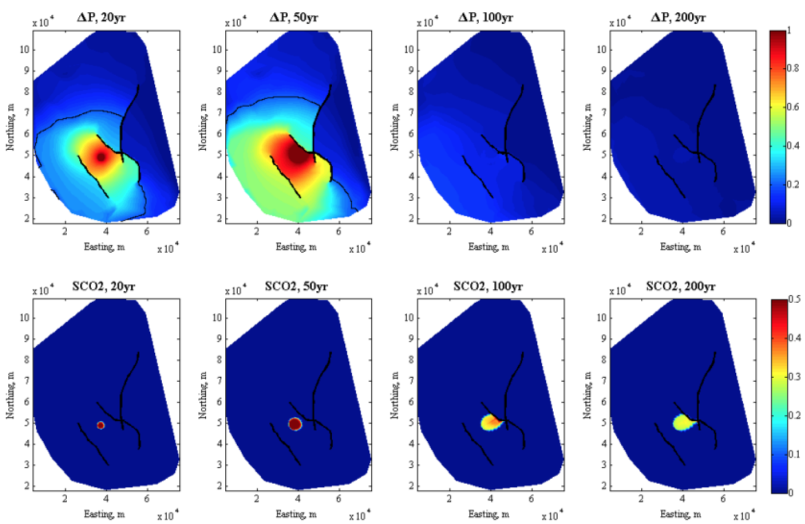
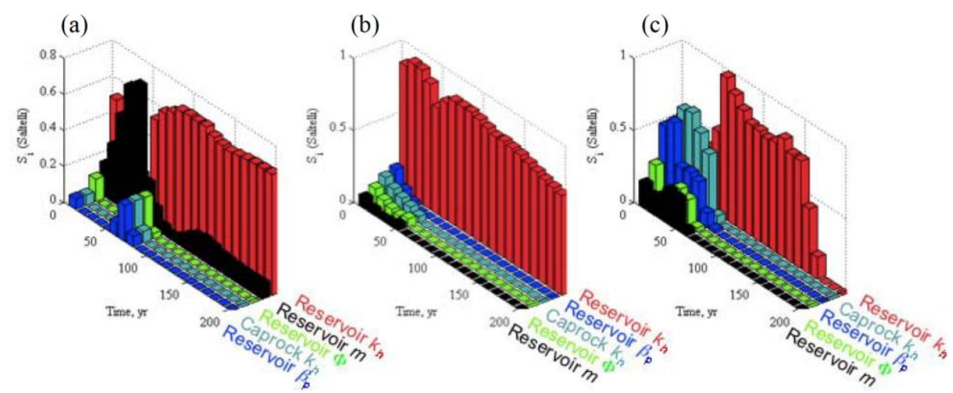




ROM focuses on P and saturation at reservoir-seal interface.

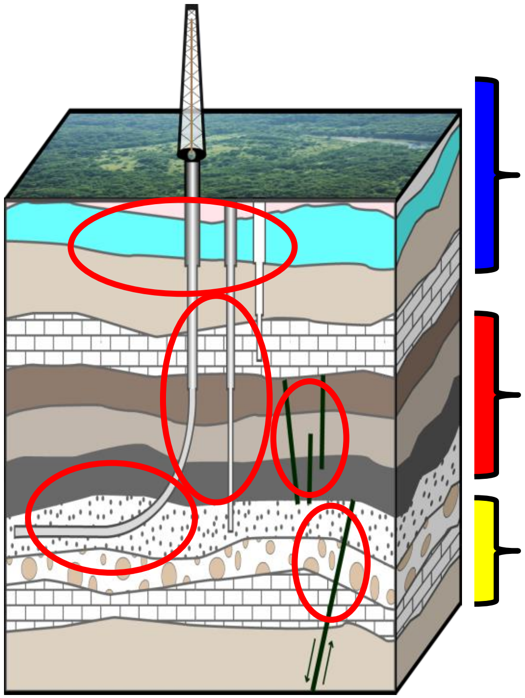
Sensitivity analysis allows ROM to focus only on key variables.

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

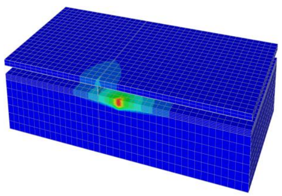
	Layered-clastic Reservoir	Carbonate-reef Reservoir	Clastic, Complex Reservoir	Open & Cemented Wellbores	Fractured Seal	Carbonate Aquifer	Clastic Aquifer
Lookup Table				X	X		
Response Surface (via PSUADE)	X					X	X
Analytical Model				X	X	X	X
Polynomial Chaos Expansion		X					
Gaussian Regression	X						
Surrogate Reservoir Model (base on A.I. methods)		X	X				

NRAP'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



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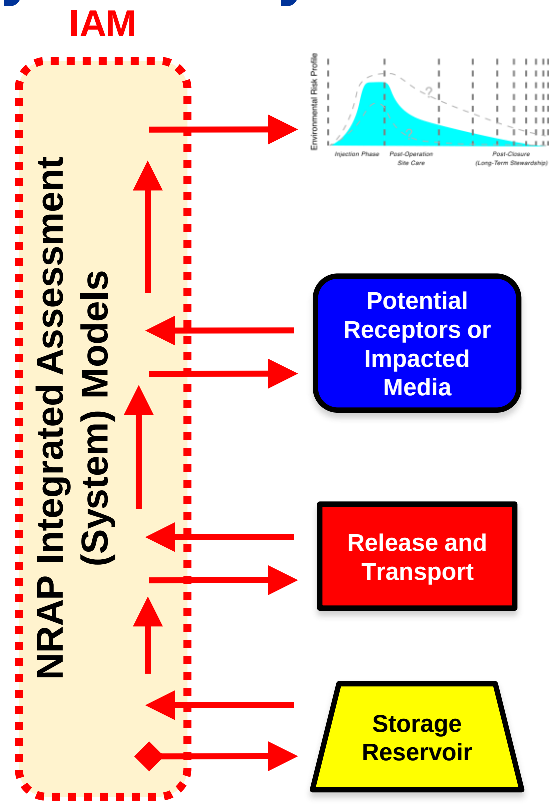

D. Link ROMs via integrated assessment models (IAMs) to predict system performance & risk

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

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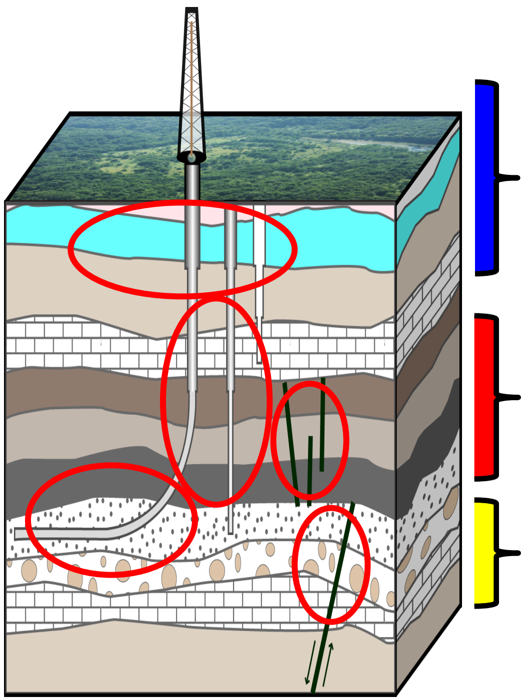

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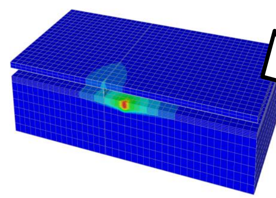
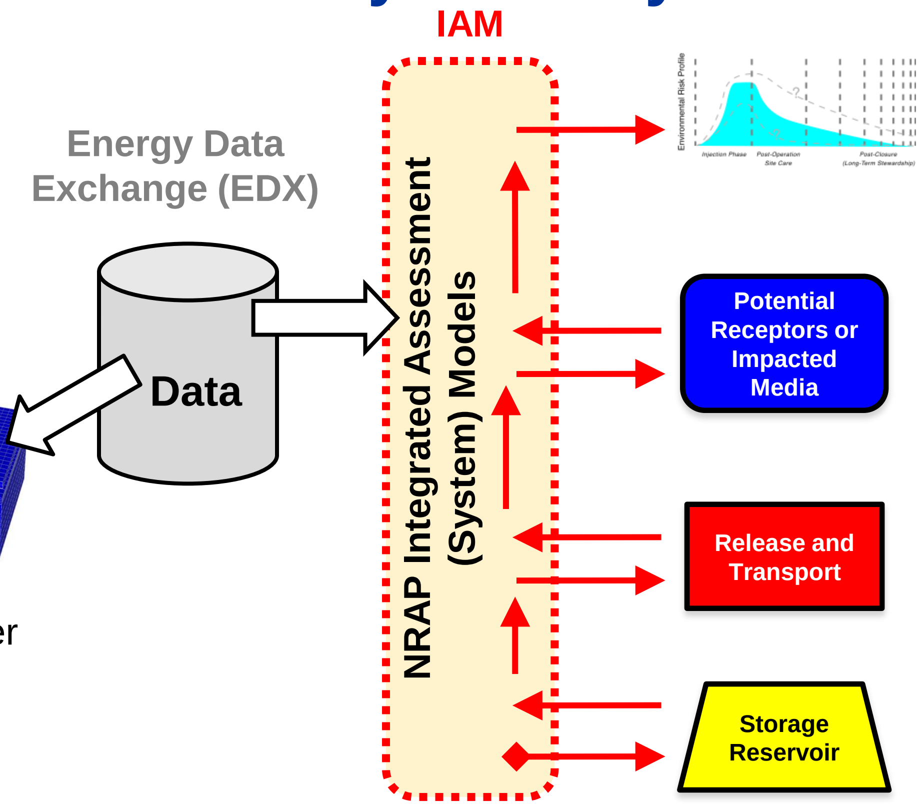


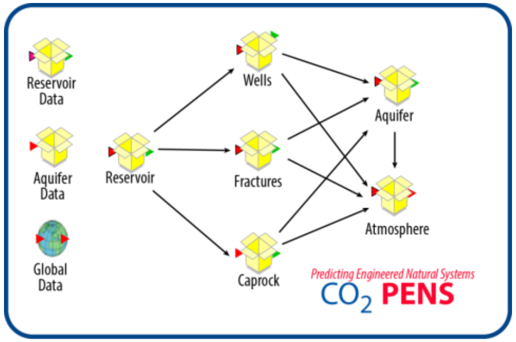


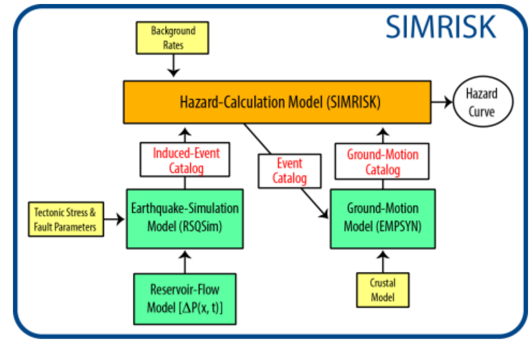
C. Develop reduced-order models (ROMs) that rapidly reproduce component model predictions

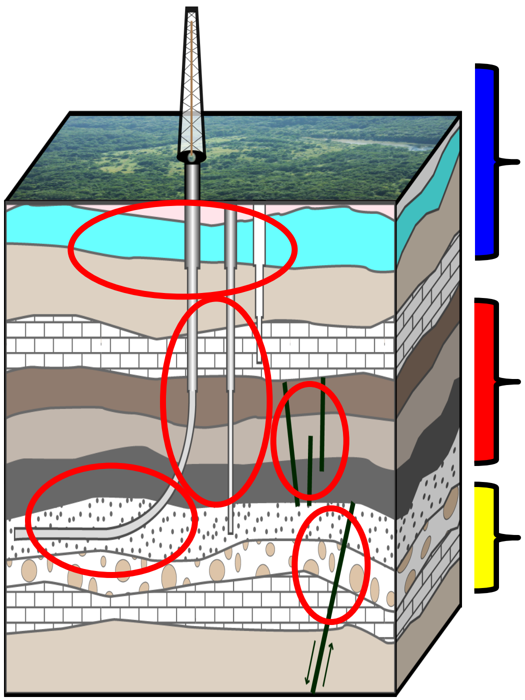
D. Link ROMs via integrated assessment models (IAMs) to predict system performance & risk; calibrate using lab/field data from NRAP and other sources

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

NRAP is focused on quantification of two types of IAMs, 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***

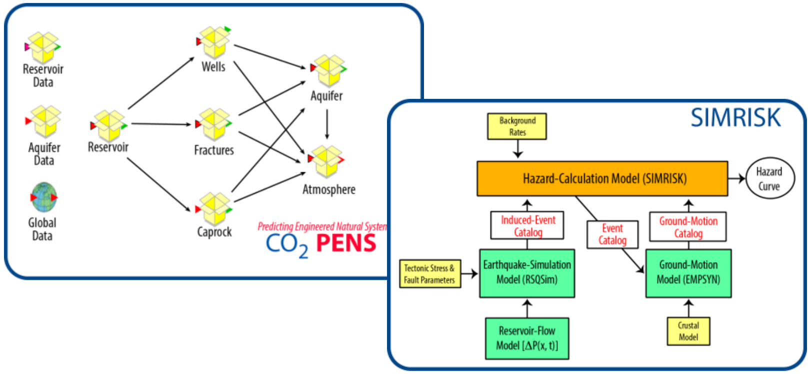
Reservoir
(plume/pressure evolution)

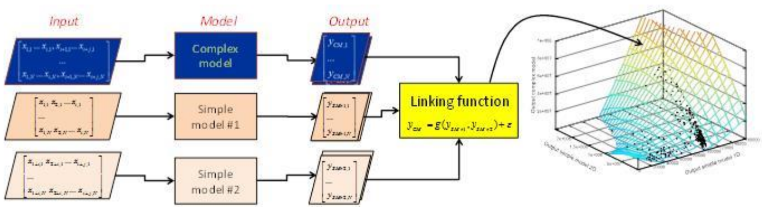
Key NRAP Accomplishments: Building the Toolsets

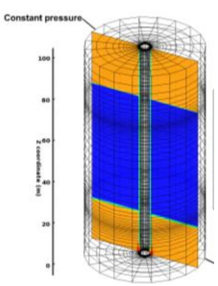
- **Developed first-of-a-kind toolsets for science-based, quantitative evaluation of risks and uncertainties**
  - *Leakage risks (reservoirs to receptors)*
  - *Induced seismic events*

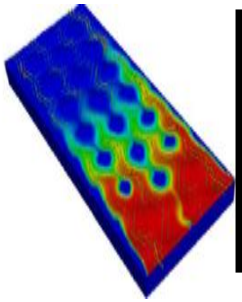
- **Generated first quantitative risk profiles for long-term behavior**

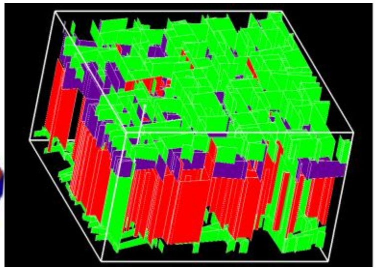
- **Evaluated numerous approaches to reduced-order models (lookup table to artificial intelligence)**
  - *Detailed sensitivity analyses to identify key variables*
  - *Achieve balance between fidelity and speed*
  - *Developed ROMs for:*
    - ✓Reservoir (pressure & CO_2 response)
    - ✓Leakage from wells
    - ✓Leakage through fractures in seals
    - ✓Groundwater impacts (CO_2 & brine influx)











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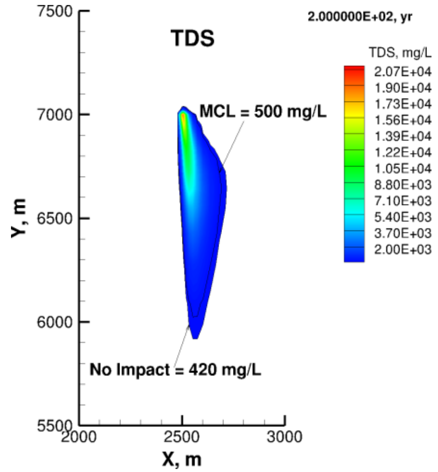
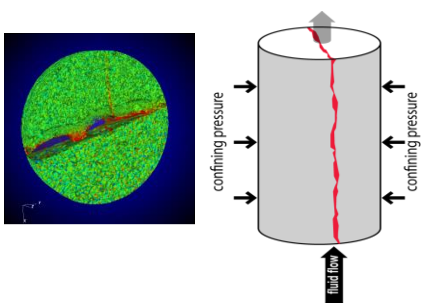
Key NRAP Accomplishments: Building the Science Base

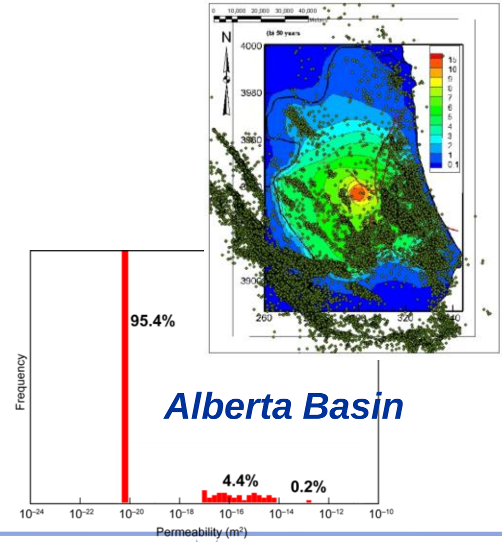
- **Developed underpinning, physics-based models for wellbores and fractures**
- **Demonstrated validity and limitations of de-coupling assumption in integrated assessment models**
- **Established "no-impact" threshold values for two different classes of aquifers representing ~60% of U.S. area**
- **Expanded science base and data needed for model calibration**
    - *Lab studies on cement, shale, aquifers*
    - *Geostatistical studies on wellbore characteristics*

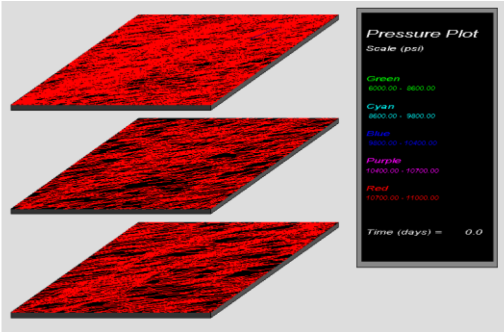


groundwater



wellbores





fractures

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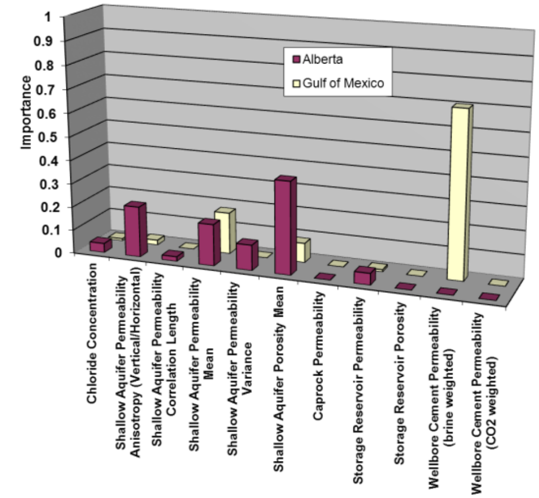
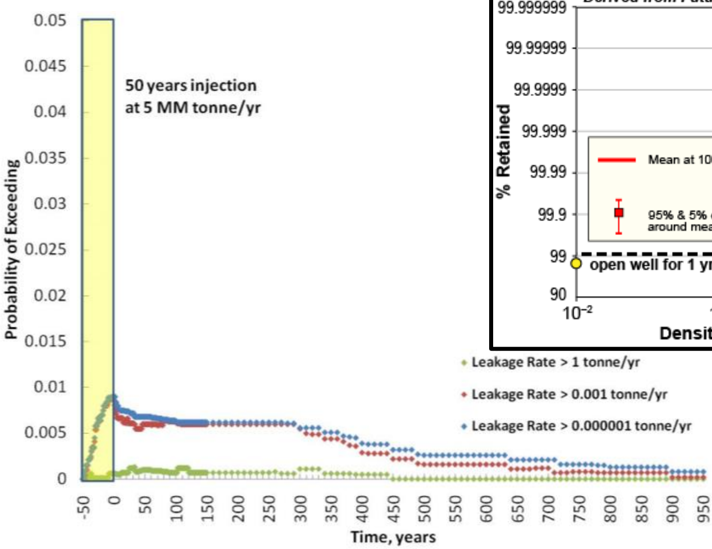
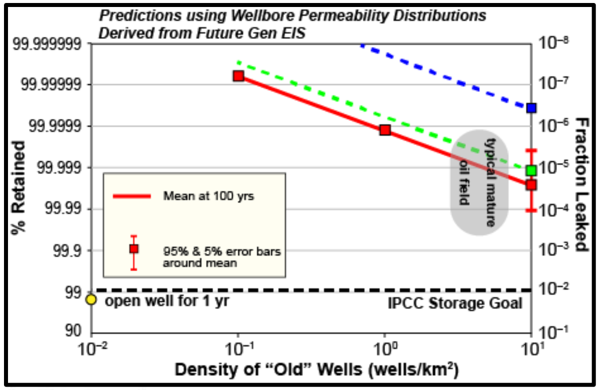
Key NRAP Accomplishments: Applying the Toolsets

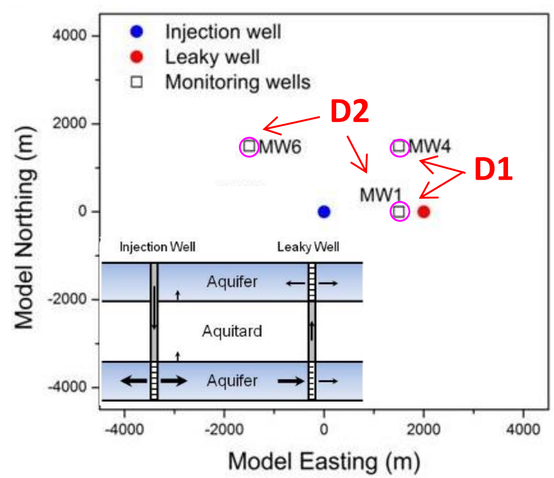
- **Generated first quantitative risk profiles for long-term behavior**
- **Demonstrated use of IAMs to quantitatively identify key subsurface parameters that impact risk at a site**
- **Developed a preliminary technique for risk-based monitoring network design of CO_2 storage sites**



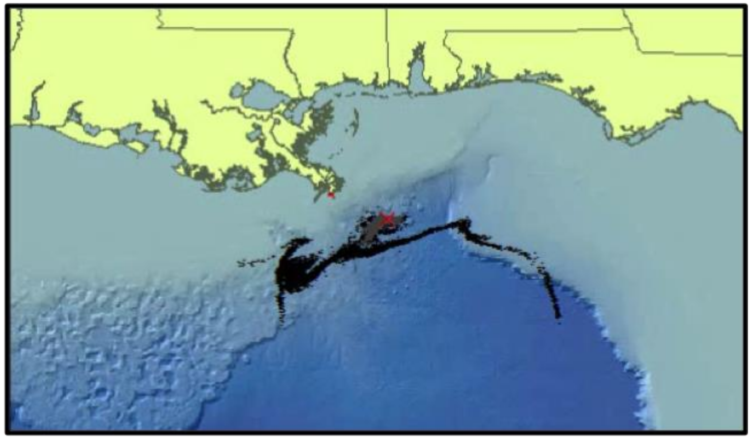


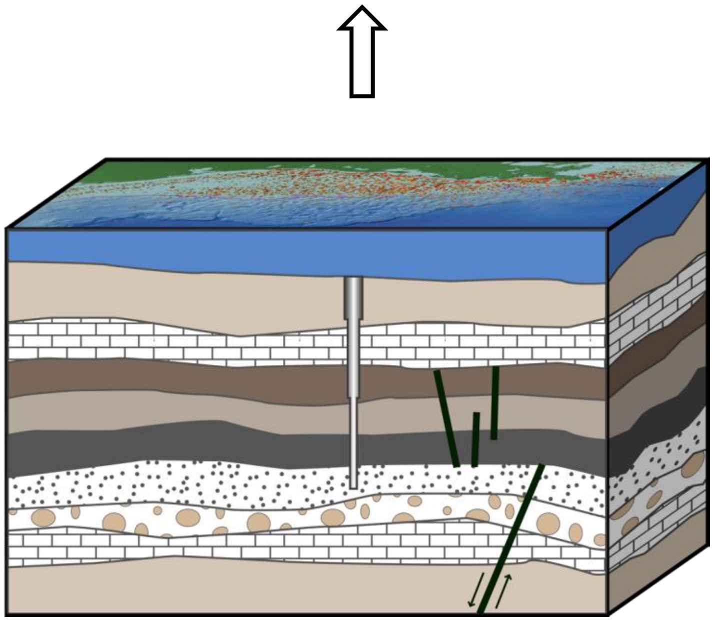


Leaky Storage Cases



BLOSOM takes oil-release input and predicts fate.





Crude Oil, Gas, & Hydrates Models

Chemical and physical properties for crude oil, gases, and hydrates

Multi-Phase Jet/Plume Model

Near-field buoyant jet/plume from blowout

Fate & Transport Model

Transport of oil in far-field until degraded, beached, or settled on sea-floor

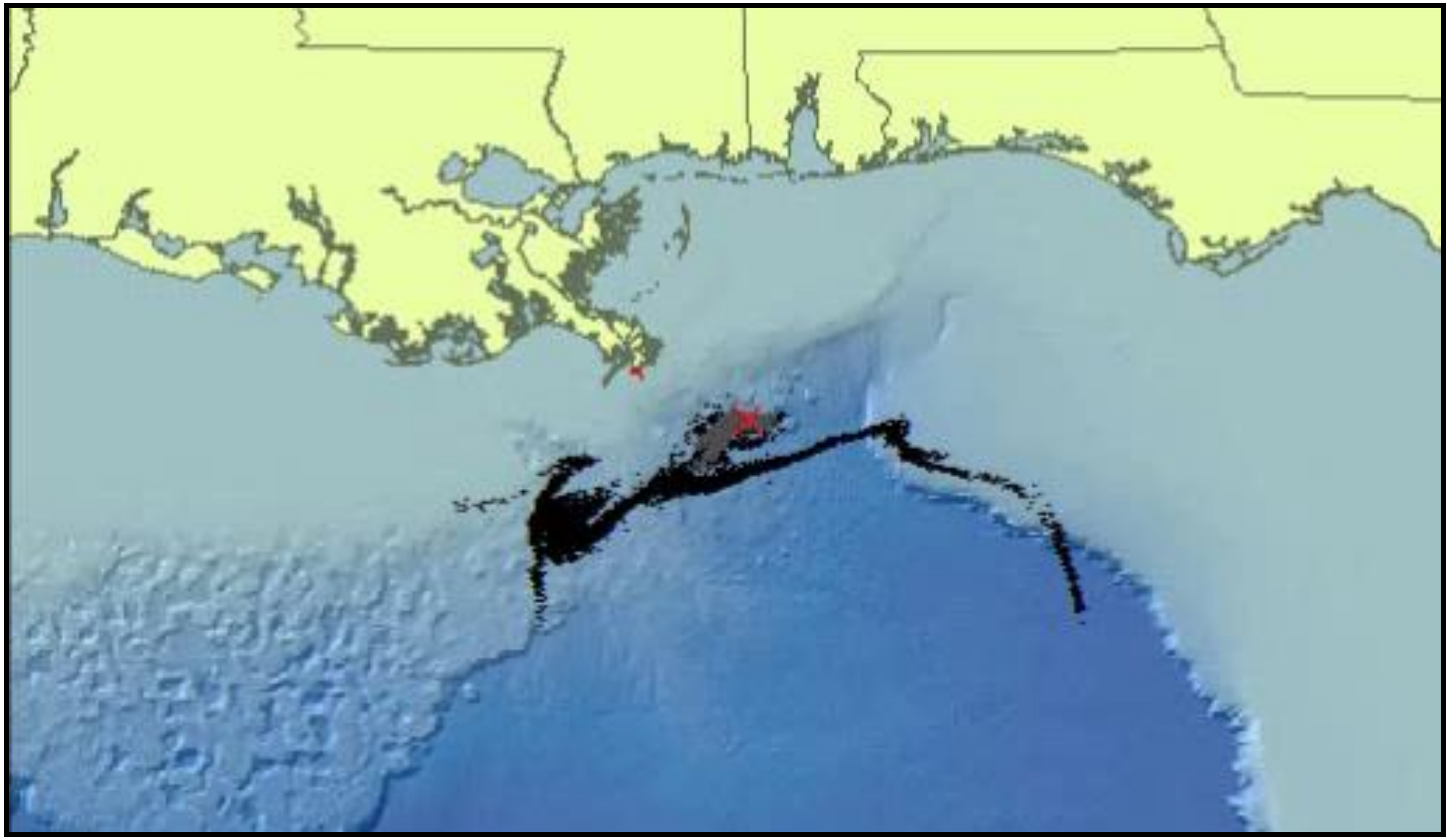
Oil Weathering Model

Degradation and changes in physical properties of crude

Hydrodynamic Handler

Ambient currents and water properties

BLOSOM takes oil-release input and predicts fate.



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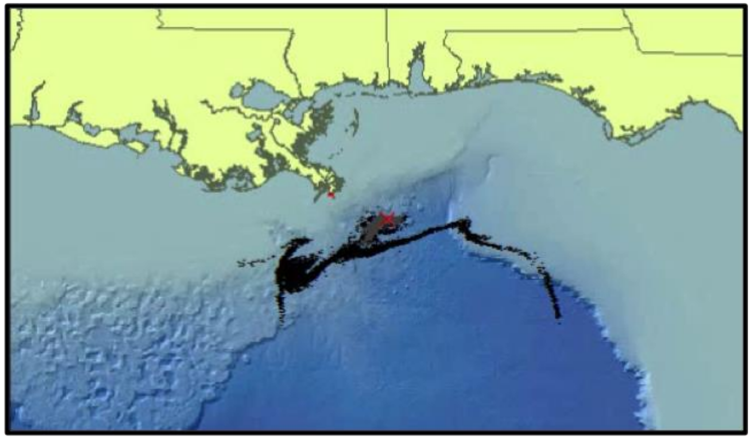

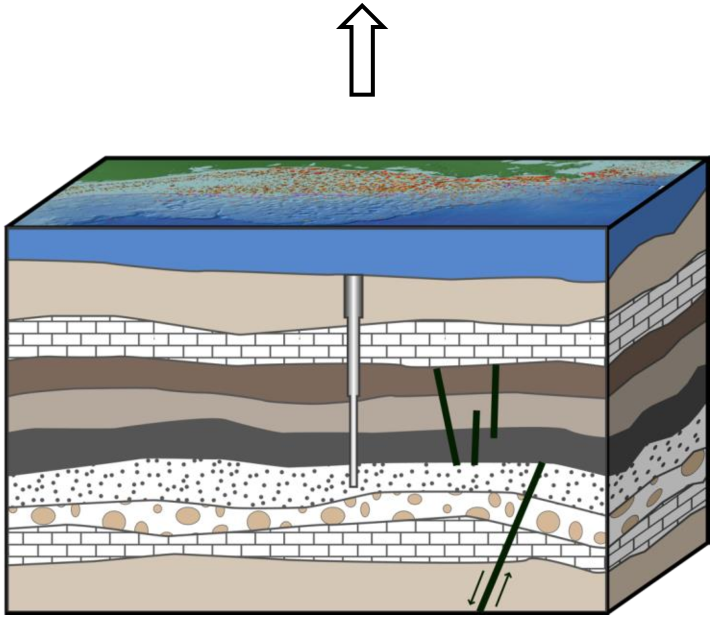

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National Risk Assessment Partnership:

Quantifying the Behavior of Engineered–Natural Systems for CO_2 Storage

Using science-based prediction to inform decisions tied to a complex and uncertain engineered–natural system.