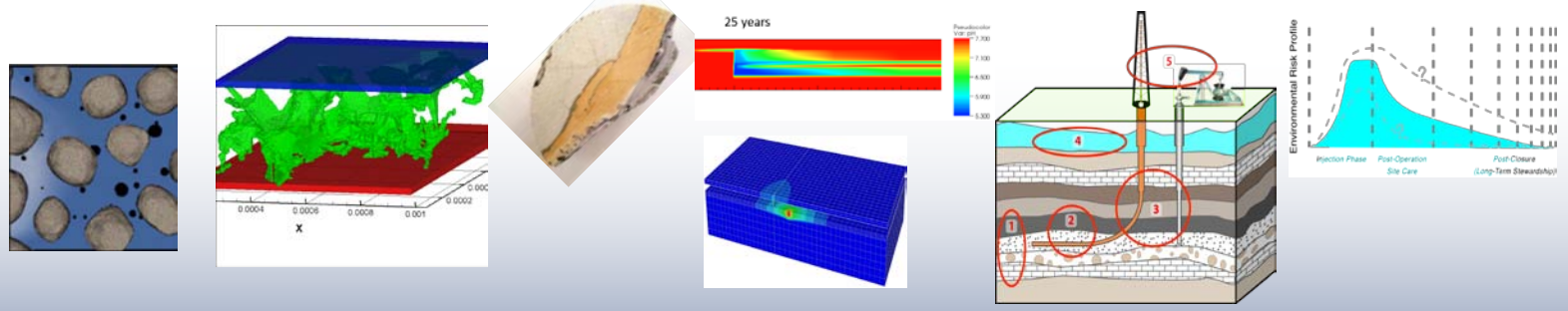
National Risk Assessment Partnership



Identify key physical & chemical phenomena → Predict core- and field-scale processes → Quantify behavior and uncertainties for each subsystem → Calculate risks using integrated assessment models

NRAP Overview

Grant Bromhal & George Guthrie (NETL)

17 November 2011

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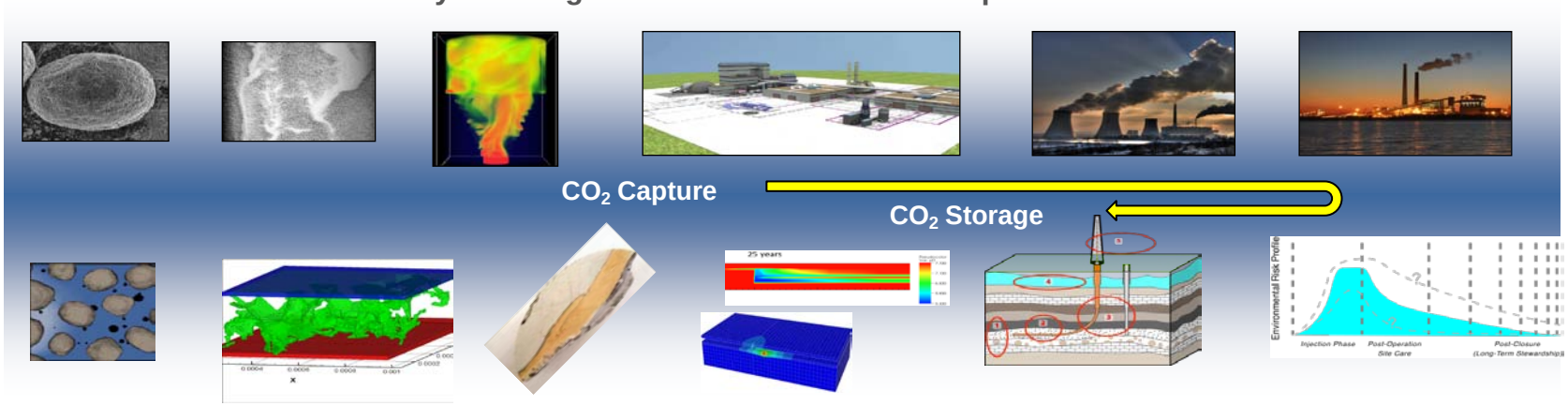
DOE has initiated an effort to leverage its core capabilities in science-based prediction to lower the uncertainty in the business case for CCS.

Carbon Capture Simulation Initiative (CCSI)

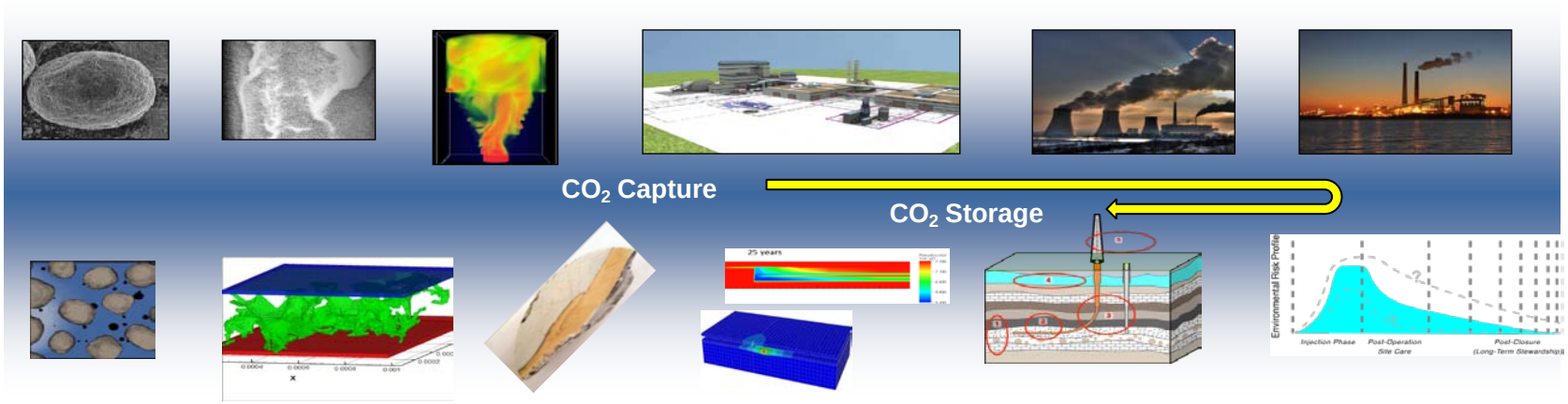
To accelerate the path from concept (bench) to deployment (commercial power plant) by lowering the technical risk in scale up.



National Risk Assessment Partnership (NRAP)

To develop and demonstrate a methodology and toolset for predicting long-term risk profiles that are needed for quantifying potential liabilities at a CO_2 storage project.

CCSI & NRAP utilize a common approach to predict system behavior.



Detailed Models for Components ⇨ **Reduced Order Models** ⇨ **Integration via System Models (with tie to economics)** ⇨ **Monitoring for Verification and Control**

- **Leverage multiple research & commercial codes**
- **Validate using lab and field data**

- **Develop lookup tables & response surfaces (PSUADE); surrogate models (NRAP only)**
- **Validate relative to detailed models**

- **Produce common system models and platform**
- **Quantify uncertainty**

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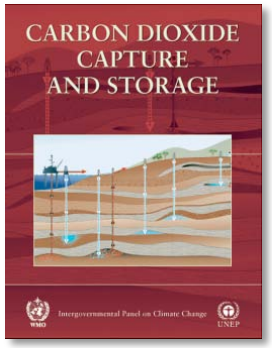
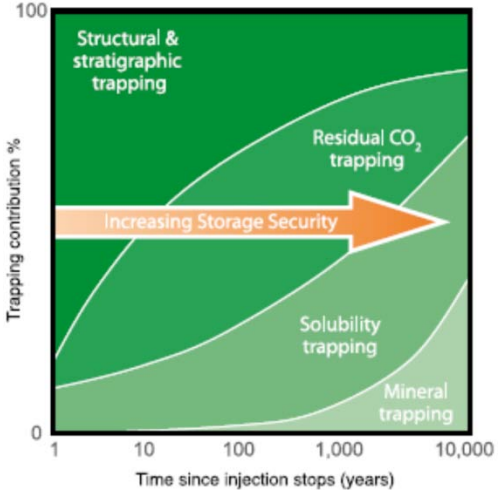
NRAP effort is using science-based prediction to provide a quantitative basis for geologic storage security.



IPCC (2005)

Schematic evolution of trapping mechanisms over time (IPCC, 2005)



Multiple trapping mechanisms reduce CO_2 mobility over time

- structural/stratigraphic
- residual
- solubility
- mineralization; sorption

Risk profiles are expected to decline over time

Various site characterization and operation strategies will promote storage security

- e.g., DOE Best-Practices documents

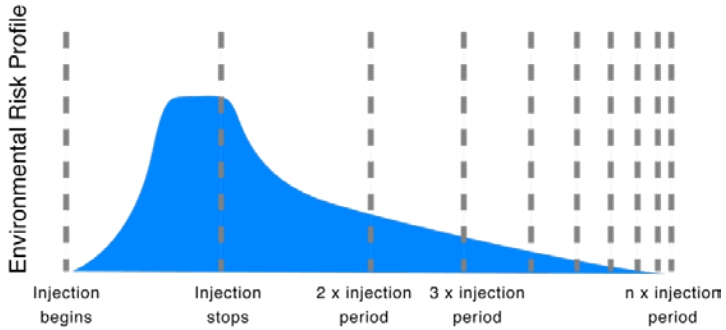
Needs

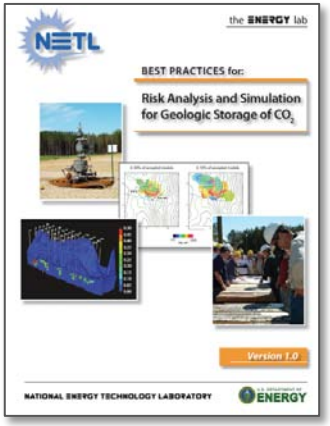
- **Quantify common storage security relationships**
- **Assess validity and nature of relationships over variety of geologic environments**
- **Quantify and reduce uncertainty**

"Observations from engineered and natural analogues as well as models suggest that ***the fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1,000 years."***

"With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO_2 releases if they arise, the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas."

Schematic profile of environmental risk (Benson, 2007)





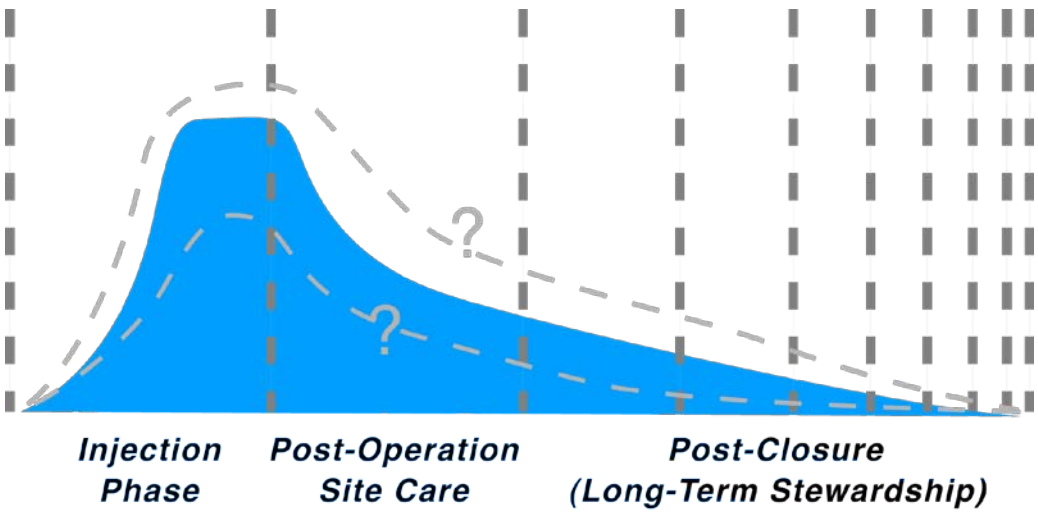
NRAP's efforts address two key risk-related issues that underlie the business case for long-term CO_2.

$$Risk = P_{event} \times C_{event}$$

Liability can occur when a consequence is declared a harm.

operator ⟷ ***regulator***

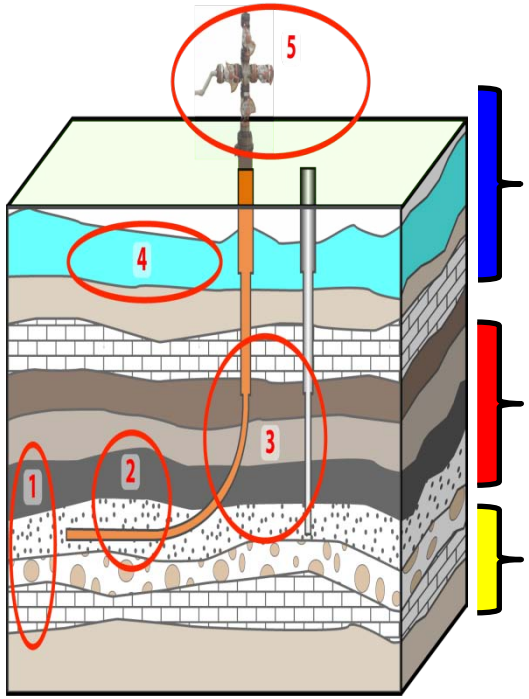
NRAP Results



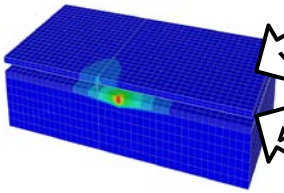
- **Quantification of long-term risk (liability) & uncertainty**
- **Definition of post-operation site-care**
  - time period
  - key monitoring needs (signals to monitor; size of area-of-review)

Approach to quantifying system performance (phase I) relies on integrated assessment models (IAMs).

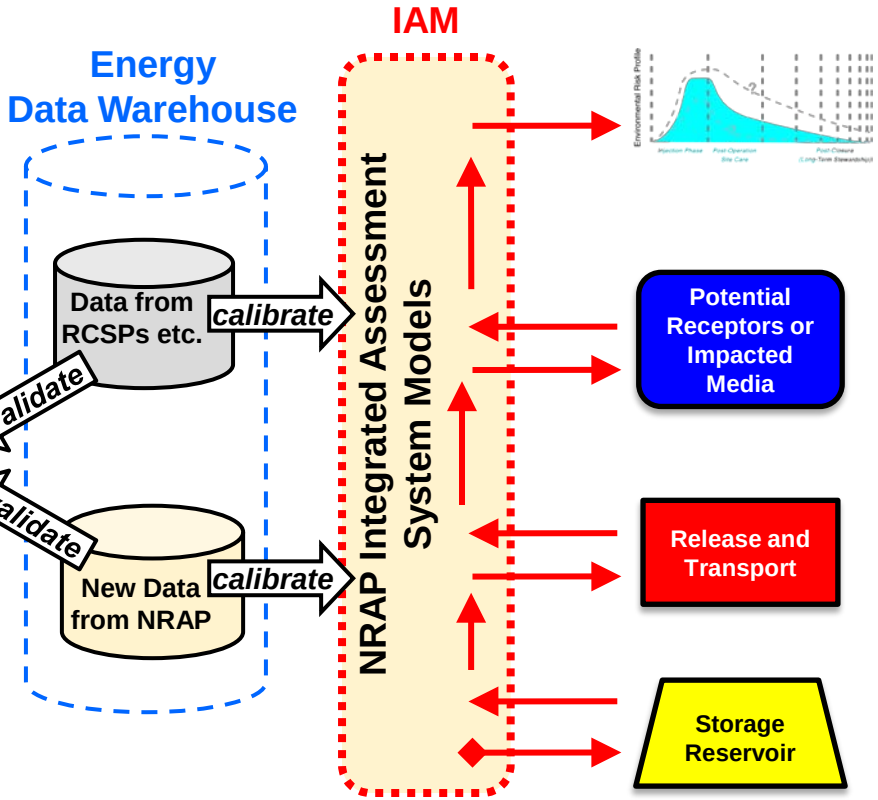
1. Divide system into discrete components



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



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



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

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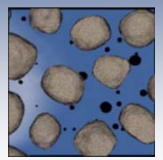
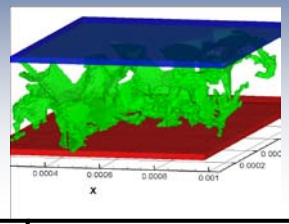
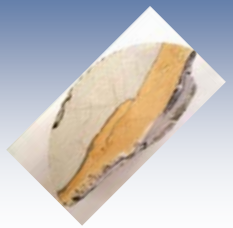
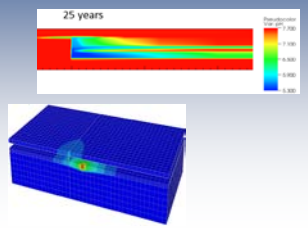
NRAP Phases

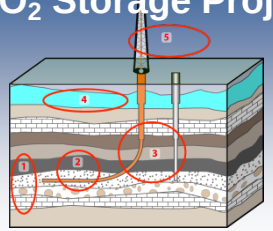
NRAP: Quantification of Risk/Liability for CO_2 Storage Projects

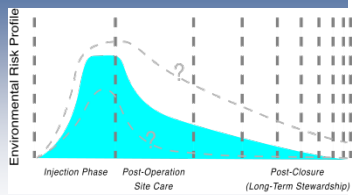












FY2011	FY2012	FY2013	FY2014	FY2015

Phase I

Phase II

Phase III

Risk Profile Quantification

- **Focus**
  - quantification of risk profiles, trapping mechanisms, & uncertainty
- **Approach**
  - development of reduced-order models integrated in system models; validation of component models
- **Products**
  - reduced-order model methodology; calibration data; integrated models

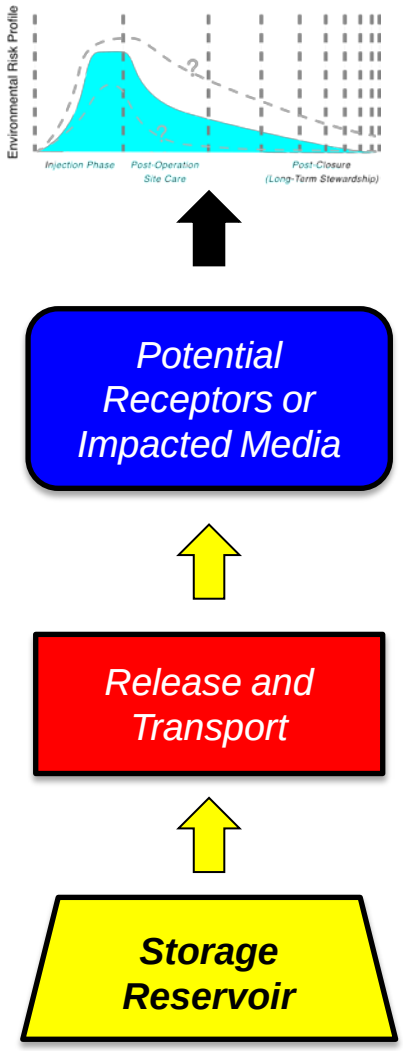
Risk Management Strategies

- **Focus**
  - strategic monitoring and mitigation to verify performance & to lower risk
- **Approach**
  - integration of monitoring/mitigation with risk quantification
- **Products**
  - risk management tools & methodology

Field Tests to Validate System-Level Behavior

- **Focus**
  - field tests to validate system predictions
- **Approach**
  - potential field tests aimed at key data gaps
- **Products**
  - validation data to fill gaps

General NRAP Approach to Predicting Risk



Integrated assessment models (system model) to couple behavior from subsurface systems and to develop risk profiles

- modular to allow connectivity with commercial and research codes
- various methods being assessed for uncertainty quantification at system level (reduced-order models; surrogate models; response surfaces; etc.)

CO_2/brine leakage rates used as boundary conditions in detailed reactive-flow models to calculate dynamic evolution of pH & TDS

- equilibrium-geochemistry, continuum-scale reactive flow
- assessment of impacts from kinetics, co-constituents, organics
- tie to MCLs and other regulatory measures
- use of reduced-order models to address stochastic parameters

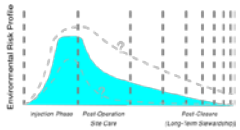
Predicted reservoir pressure/saturation used to calculate potential leakage rates of CO_2 and brine from wells, fractures, and seals

- reduced-order models based on detailed process models coupled with stochastic analysis for uncertainty quantification (UQ)
- coupled geomechanics and geochemistry for time-dependent transmissivity

Detailed reservoir model used to predict pressure & CO_2:brine saturation at reservoir–caprock interface

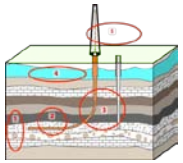
- linkage to existing simulators to predict reservoir behavior over time
- quantitative assessment of time-dependent trapping mechanisms
- use of reduced-order models to address stochastic parameters

NRAP Phase I activities will evolve the risk-profile methodology with three generations of improvements.



FY2011	FY2012	FY2013	FY2014

Phase I



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

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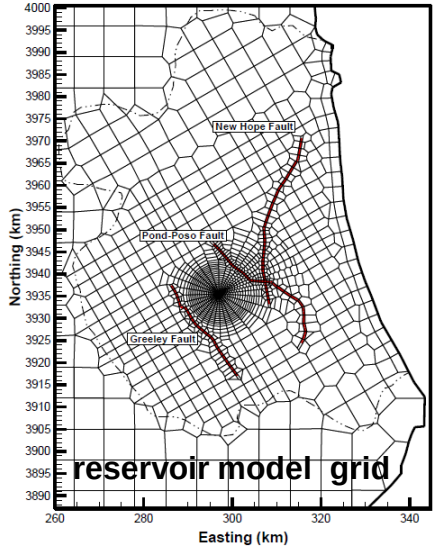
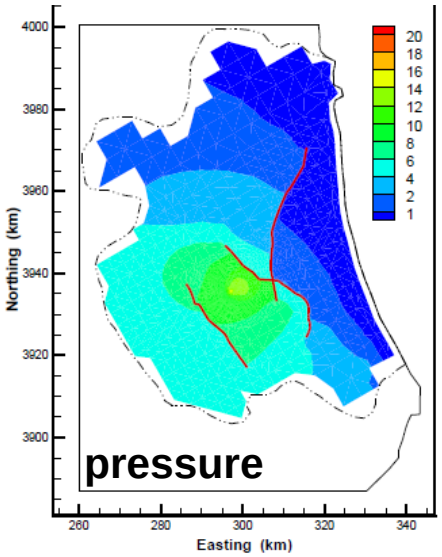
Integration of reservoir behavior through continuum-scale reservoir model to predict pressures and saturations at bottom of caprock.

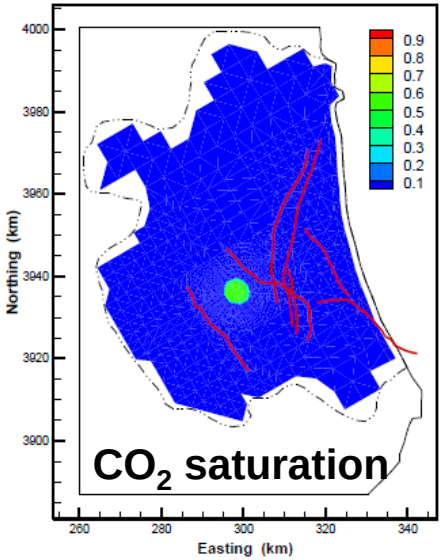


Detailed reservoir models of potential storage formations

Response-surface and/or surrogate models generated for rapid prediction of pressures and saturations throughout the reservoir

Outputs of reduced-order models (ROMs) used as inputs to wellbore and fault leakage models with multiple realizations

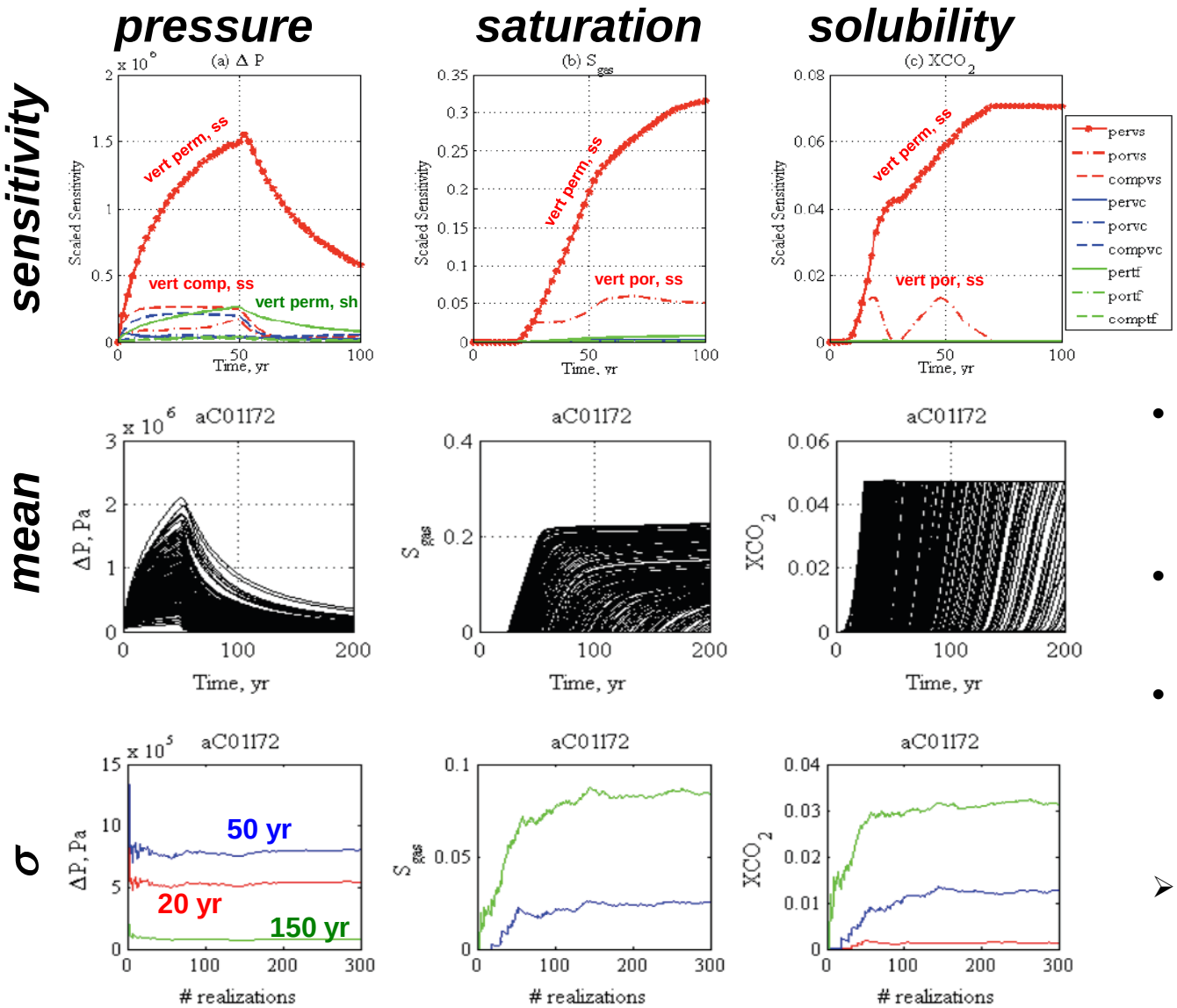




- **high permeability sandstone overlain by low permeability shale**
- **CO_2 injection simulations using detailed model based on potential Westcarb site**
- **50 years injection (5 million t/yr) followed by 150 yrs of relaxation**
- **Nine stochastic parameters: porosity, permeability and compressibility for three reservoir layers each**
- **300 realizations: 54 used for preliminary calculations**

Birkholzer et al. (unpubl.)

Preliminary Example from 1st Generation: Reservoir Model UQ



- sensitivity analysis relative to pressure, saturation, & solubility
- 300 realizations to define mean and σ
- results show analysis at one location in reservoir

➢ uncertainty & sensitivity vary over space and time

Wainwright & Birkholzer (unpubl.)

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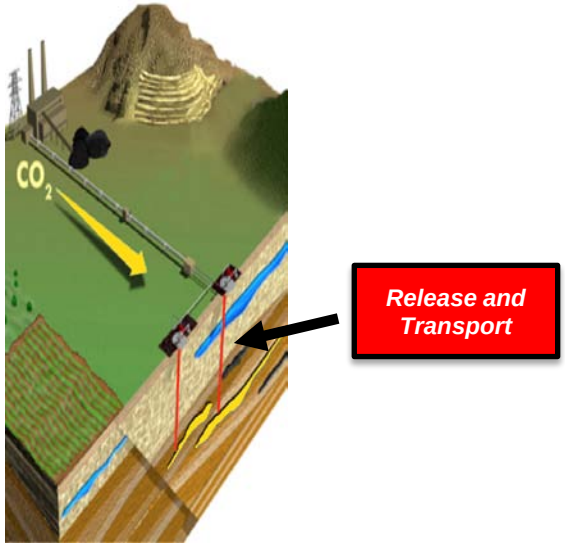
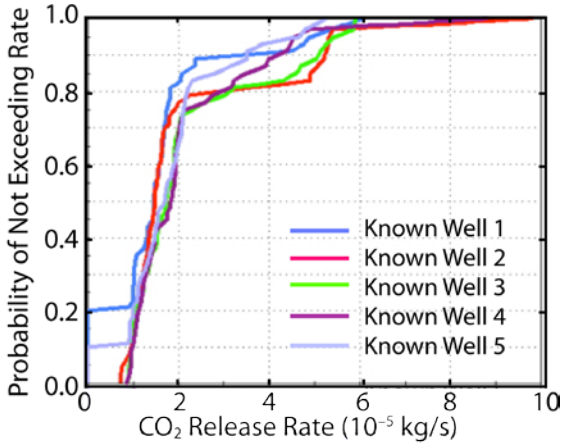
Integration of release processes through wellbore- and fault-release models based on assumed wellbore and fault permeabilities.





CDF for CO_2 leak rate to atmosphere for poorly cemented wells

Wellbore leak-rate is treated as a stochastic variable using Monte Carlo analysis

Wellbores are categorized as well-cemented, poorly-cemented, or open

A single fault leakage model is being used and the permeability is varied stochastically.

Time-dependent CO_2 & brine leakage rates into shallow aquifer are based on multiple realizations

- Open wellbore:
  - Drift-flux model for flow in open pipes using LBL's TOUGH2
  - Non-isothermal, multi-phase CO_2/brine flow including CO_2 phase change
  - 250 different simulations varying bottom hole pressure, CO_2 saturation, wellbore depth and top
  - Look-up table for CO_2 and brine leak rate
- Cemented wellbore:
  - Radial wellbore model using LANL's FEHM
  - Non-isothermal, multi-phase CO_2/brine flow including CO_2 phase change
  - 2000 different calculations varying bottom hole pressure, CO_2 saturation, wellbore depth & top, and cement permeability
  - Detailed (32x32x32x32) lookup table (pressure, saturation, depth and permeability) using LLNL's PSUADE package

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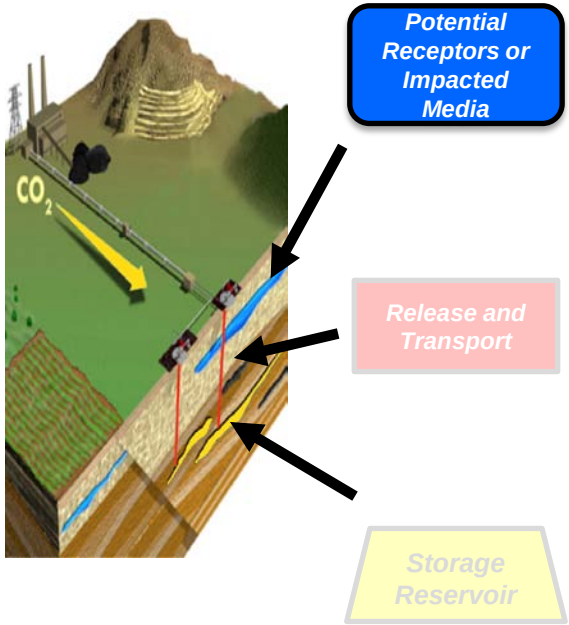
Integration of aquifer processes through equilibrium-geochemistry, continuum-scale, reactive-flow model.



Two different sets of calculations with two groundwater models

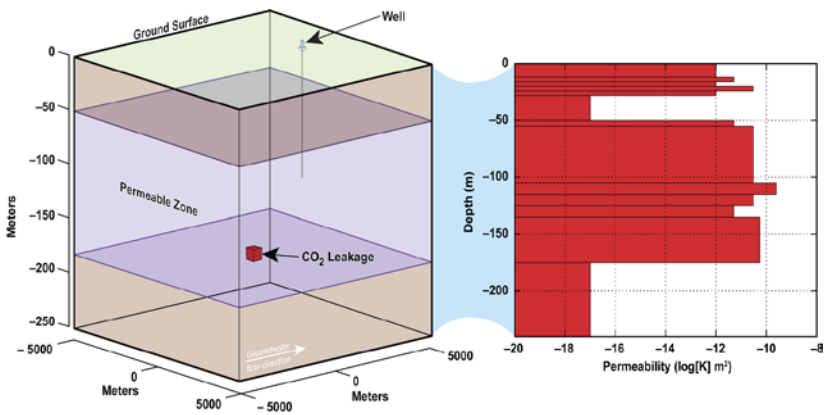
- High Plains aquifer using LLNL's NUFT (Caroll et al., 2009)
- Coastal sandstone aquifer using LBNL's TOUGH2 (Zheng et al, 2009)

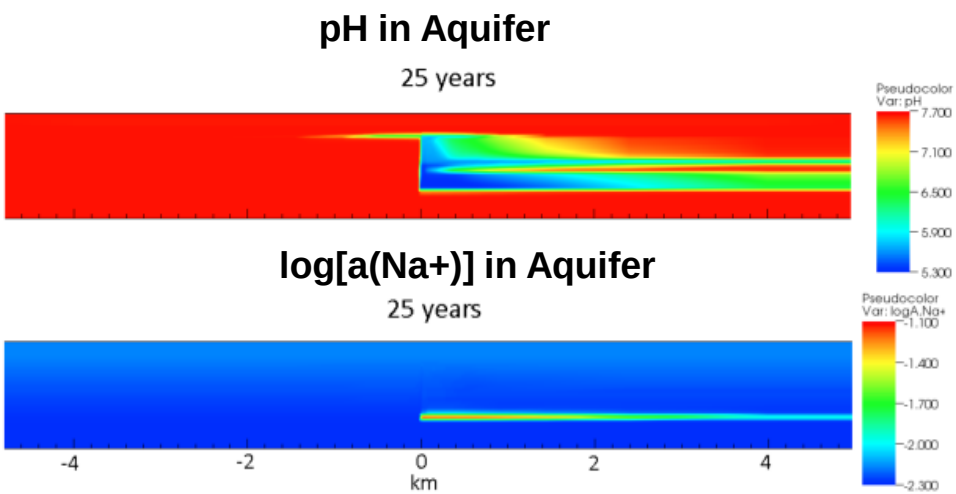
Both models used time-dependent CO_2 & brine leakage rates as boundary conditions to predict time-dependent change in pH and TDS

Reactive transport calculations with assumed mineralogy and fluid compositions

- quartz-calcite aquifer; quartz-feldspar-clay aquifer

Background flow to account for regional groundwater flow





Aquifer Simulations for Preliminary Profiles:
Yue Hao (LLNL), Susan Carroll (LLNL),
Liange Zheng (LBNL), Jens Birkholzer (LBNL)

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Potential Opportunities for Collaboration with Regional Partnerships

- **Reservoirs**
  - Confirmation of model predictions with field data (P, S, state of CO_2 over time)
- **Wellbores**
  - Information on wellbore permeability statistics
  - Characterization of cement integrity after CO_2 exposure
- **Natural Seals**
  - Core samples of natural seals for characterization
  - Data related to faults or fracture networks in caprock materials (e.g., outcrop measurements, seismic data, FMI logs)

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Potential Opportunities for Collaboration with Regional Partnerships

- **Groundwater**
  - Characterization of brine compositions in sequestration formations
  - Field measurements of groundwater and aquifer composition
- **Monitoring**
  - Seismic data sets that address plume extent and pressure changes inside and outside the reservoir
  - Pressure and other monitoring in overlying permeable formation

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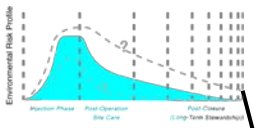
NRAP is a multilab partnership.



Potential Receptors or Impacted Media

Release and Transport

Storage Reservoir

NETL
Cugini

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Thank You!

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