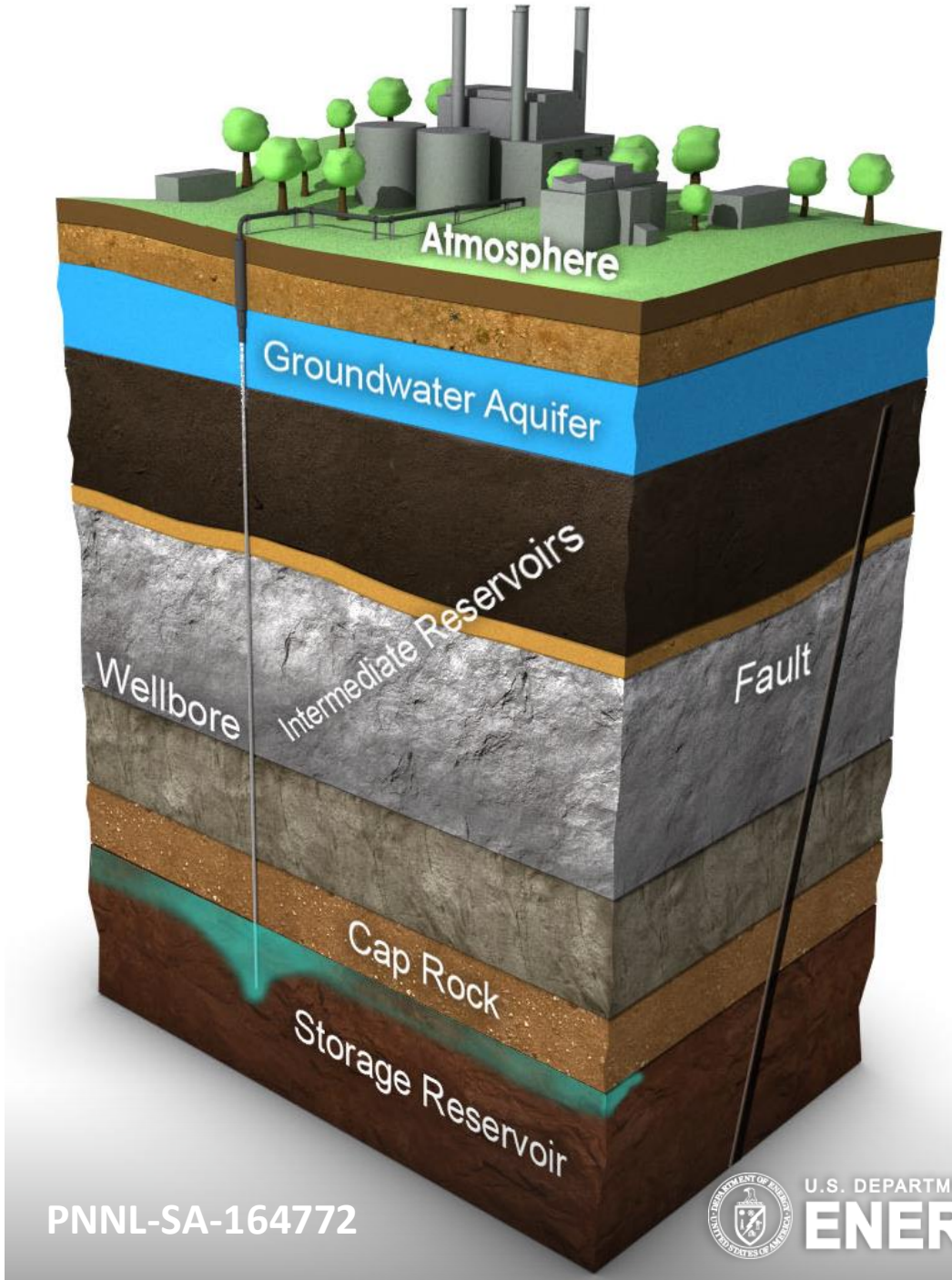
National Risk Assessment Partnership: NRAP Tools and Recommended Practices for Containment Assurance and Leakage Risk Management

Diana Bacon, PNNL
Rajesh Pawar, LANL

August 6, 2021



PNNL-SA-164772

U.S. DOE's National Risk Assessment Partnership

NRAP
National Risk Assessment Partnership

NRAP leverages DOE's capabilities to quantitatively assess and manage long-term environmental risks amidst significant geologic uncertainty and variability.

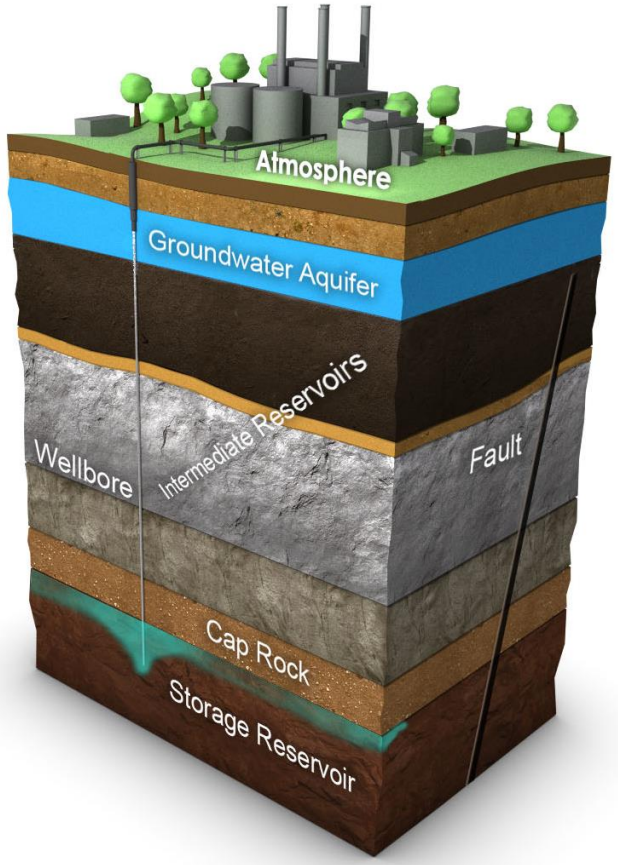
Technical Team

NATIONAL ENERGY TECHNOLOGY LABORATORY

BERKELEY LAB
Lawrence Berkeley National Laboratory

Los Alamos
NATIONAL LABORATORY
EST.1943

Pacific Northwest
NATIONAL LABORATORY



Stakeholder Group

PRINCETON UNIVERSITY

THE UNIVERSITY OF UTAH

ILLINOIS

BATTELLE

USGS
science for a changing world

bp

GLOBAL CCS INSTITUTE

Southern Company

ieaghg

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

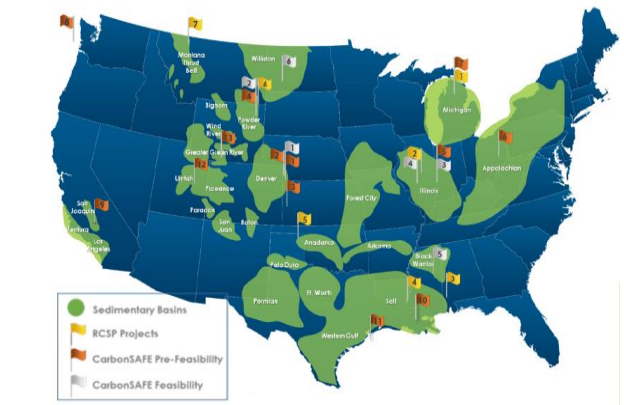
CARBON SEQUESTRATION COUNCIL

NRDC

UNITED STATES Carbon Sequestration Council

Engaging with Key Stakeholders

DOE CarbonSAFE

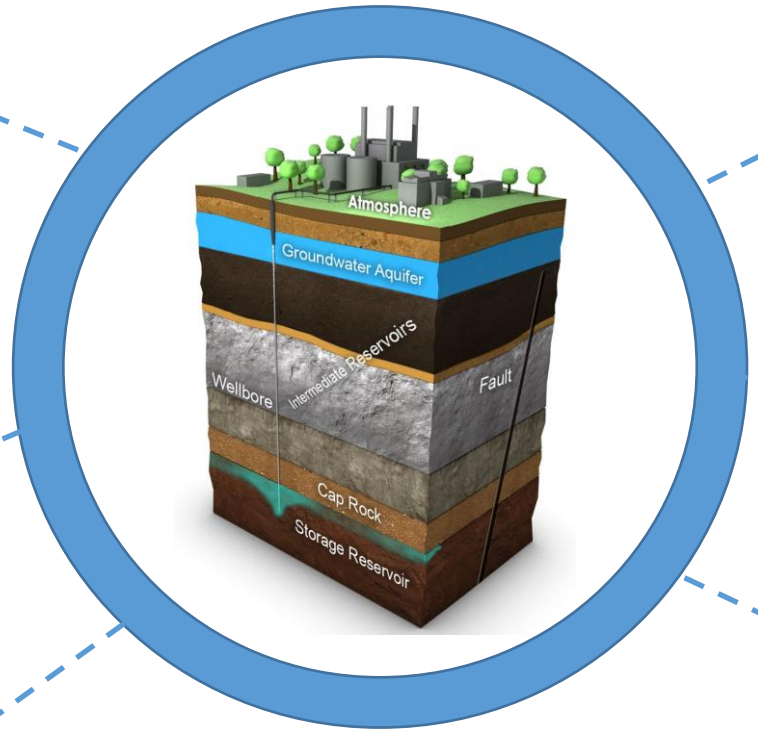


DOE-FECM Regional Initiatives

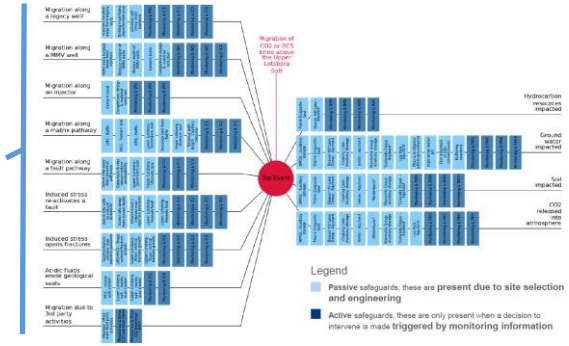
DOE-FECM SMART Initiative

SMART

NRAP
National Risk Assessment Partnership



Industry Best Practices



Bourne et al., 2014

International CCUS RD&D Community

ieaghg

Regulatory Context

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

NORTH DAKOTA OIL AND GAS DIVISION

DEQ

NATIONAL ENERGY TECHNOLOGY LABORATORY

BERKELEY LAB

Los Alamos NATIONAL LABORATORY EST. 1943

Pacific Northwest NATIONAL LABORATORY

Overview and Objectives

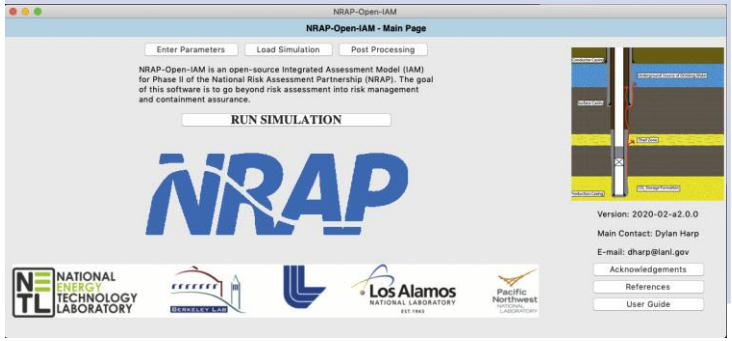
NRAP Tools and Recommended Practices for Containment Assurance and Leakage Risk Management

- **NRAP Task 2: Containment Assurance**
  - Develop robust, science-based workflows and software tools to:
    - predict containment effectiveness and leakage risk
    - evaluate the effectiveness of leakage risk monitoring, management, and mitigation
- **NRAP Task 5: Validate Risk Assessment Tools and Methodologies Using Synthetic Data and Field Observations**
  - Apply NRAP tools to field experiments and geologic carbon storage projects
  - Collect and develop synthetic datasets for NRAP community use

NRAP Task 2: Containment Assurance

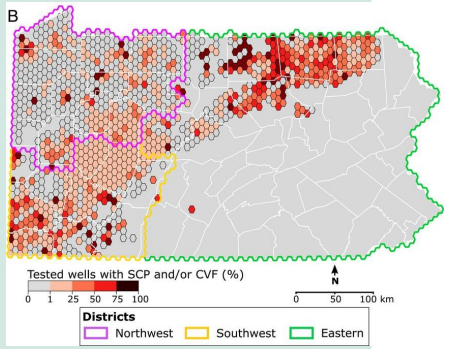
Subtask 2.1 NRAP-Open-IAM - Veronika Vasylkivska (Lead)

- Diana Bacon, PNNL
- Greg Lackey, NETL
- Bailian Chen, LANL
- Yingqi Zhang, LBNL
- Ernest Lindner, NETL
- Seunghwan Baek, PNNL
- Shaoping Chu, LANL
- Nik Huerta, PNNL
- Megan Smith, LLNL
- Gavin Liu, NETL
- Julia de Toledo Camargo, PNNL
- Dylan Harp, LANL



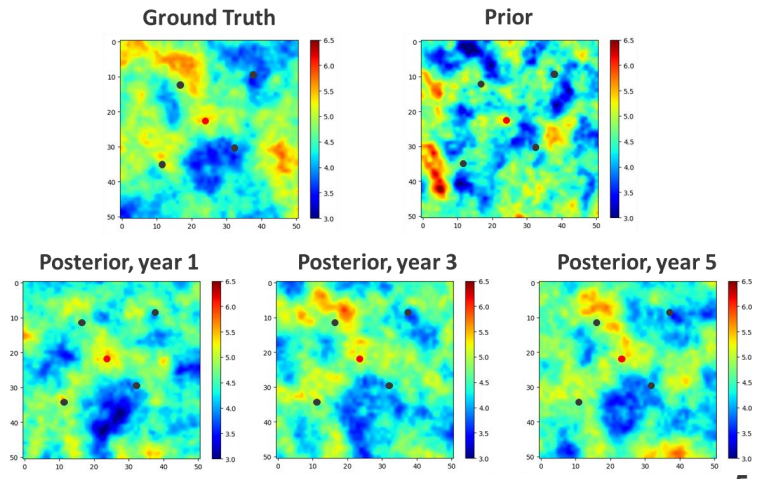
Subtask 2.2 Well Leakage - Jaisree Iyer (Lead)

- Diana Bacon, PNNL
- Ernest Lindner, NETL
- Greg Lackey, NETL
- Kevins Rhino, LLNL
- Megan Smith, LLNL
- Michelle Bourret, LANL
- Seungwhan Baek, PNNL
- Veronika Vasylkivska, NETL
- Mohammad Islam, NETL
- Curt Oldenburg, LBNL
- Nik Huerta, PNNL
- Bill Carey, LANL
- Gavin Liu, NETL
- Xiao Chen, LLNL
- Kenton Rod, PNNL
- Lehua Pan, LBNL
- Susan Carroll, LLNL



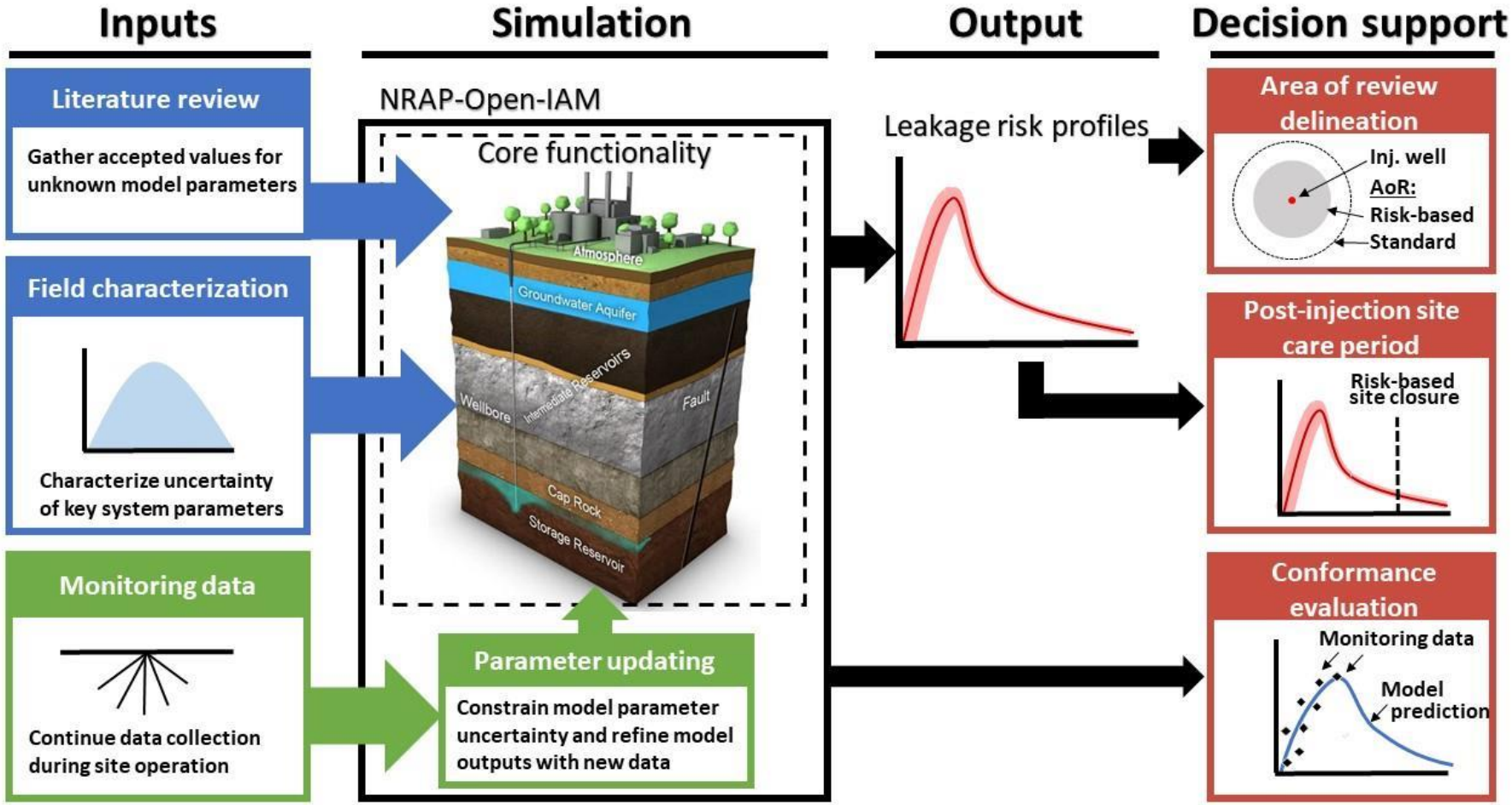
Subtask 2.3 Dynamic Risk - Yingqi Zhang (Lead)

- Abdullah Cihan, LBNL
- Bailian Chen, LANL
- Gavin Liu, NETL



Subtask 2.1: NRAP-Open-IAM Development

Vasylkivska, VR Dilmore, G Lackey, Y Zhang, S King, D Bacon, B Chen, K Mansoor and D Harp (2021). "NRAP-open-IAM: A flexible open-source integrated-assessment-model for geologic carbon storage risk assessment and management." Environmental Modelling & Software **143**.

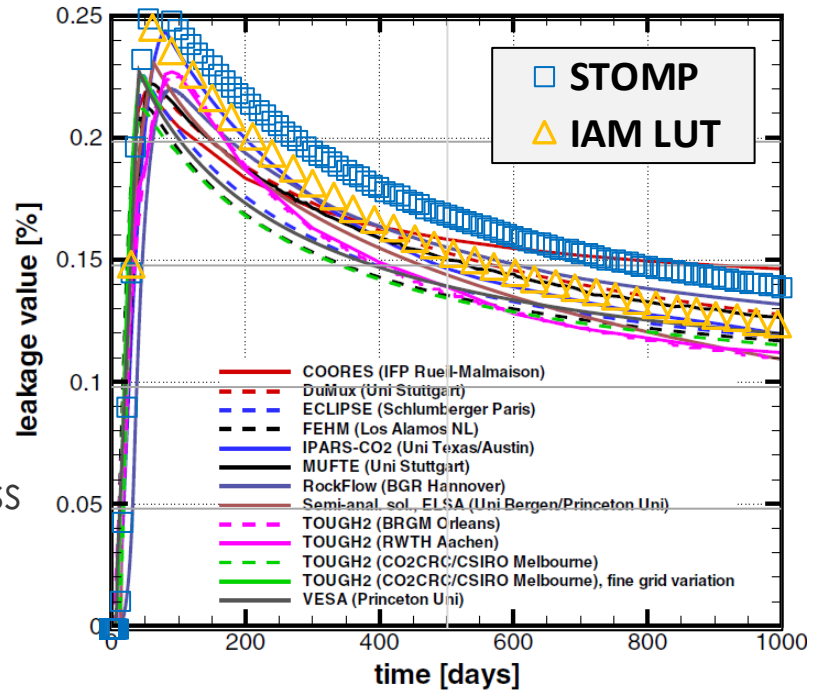


https://gitlab.com/NRAP/OpenIAM

Subtask 2.1: NRAP-Open-IAM

Improving existing component reduced order models (ROMs)

- **Cemented wellbore ROM**
  - Completed: Michelle Bourret, LANL
  - Improves ROM's predictive capability using sub-ROMs
- **Seal ROM[1]**
  - In progress: Ernest Lindner, NETL
- **FutureGen2 Components (Reservoir, Aquifer, AZMI)**
  - Quality Assurance (QA) complete: Diana Bacon, PNNL
  - Updated to constrain plume thickness predictions to aquifer thickness
- **Open Wellbore ROM[3]**
  - QA complete: Diana Bacon, PNNL; Lehua Pan and Curt Oldenburg, LBNL
- **Multisegmented wellbore ROM**
  - QA in progress: Seunghwan Baek, PNNL
  - CO_2 leakage rates predicted by the multisegmented wellbore ROM compare well to several full-physics models on a well-known benchmark problem



H. Class et al. 2009

[1]https://edx.netl.doe.gov/dataset/seal_flux-a-rom-for-flow-through-a-seal-beta-2-4-2021-02-24

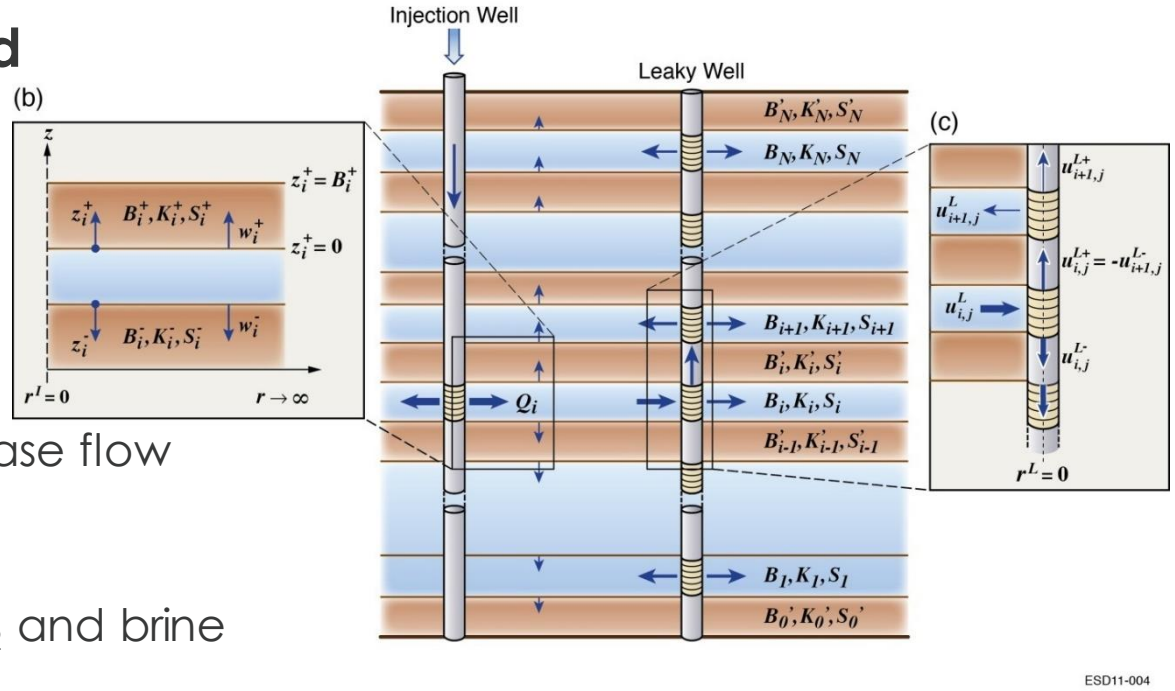
[2]Bacon DH. 2021. *NRAP-Open-IAM: NRAP-Open-IAM: FutureGen2 Component Models*. In press. Richland, WA: Pacific Northwest National Laboratory.

[3]Bacon DH, L Pan, and CM Oldenburg. 2021. *NRAP-Open-IAM: Open Wellbore Component v2.0*. PNNL-31543. Richland, WA: Pacific Northwest National Laboratory.

Subtask 2.1: NRAP-Open-IAM

New Reduced Order Models (ROMs)

- **ROM for leakage through abnormally pressured multilayered reservoir systems**
  - In progress: Abdullah Cihan, LBL
  - Extend analytical solutions for injection and leakage in non-hydrostatic multilayered aquifer systems
- **Analytical Reservoir ROM[1]**
  - Complete: Seunghwan Baek, PNNL
  - Replaces Simple Reservoir ROM to include multiphase flow
- **Generic Aquifer ROM**
  - In progress: Diana Bacon, PNNL
  - Synthetic data-driven deep learning model of CO_2 and brine leakage
- **Oil and CO_2 leakage ROM**
  - In progress: Bailian Chen, LANL
  - Enables leakage estimates at CO2-EOR sites

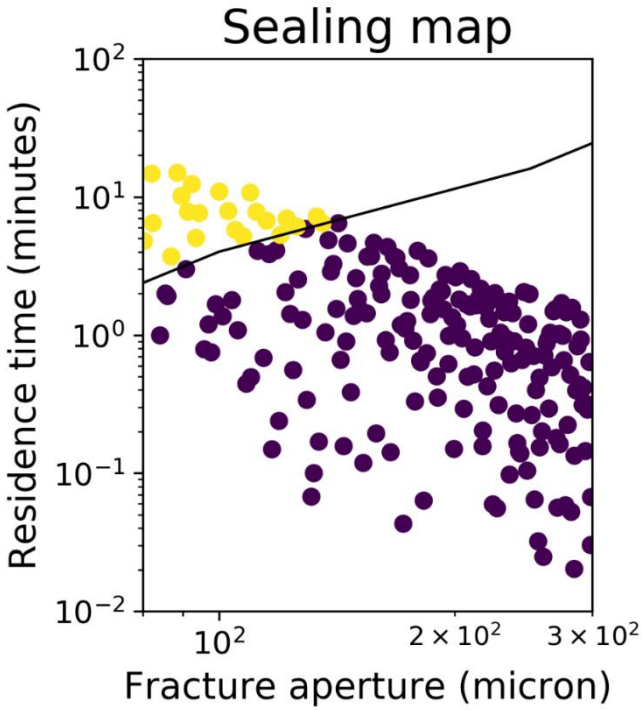


[1]Baek S., D.H. Bacon, and N.J. Huerta. 2021. *NRAP-Open-IAM Analytical Reservoir Model - Development and Testing*. PNNL-31418. Richland, WA: Pacific Northwest National Laboratory.

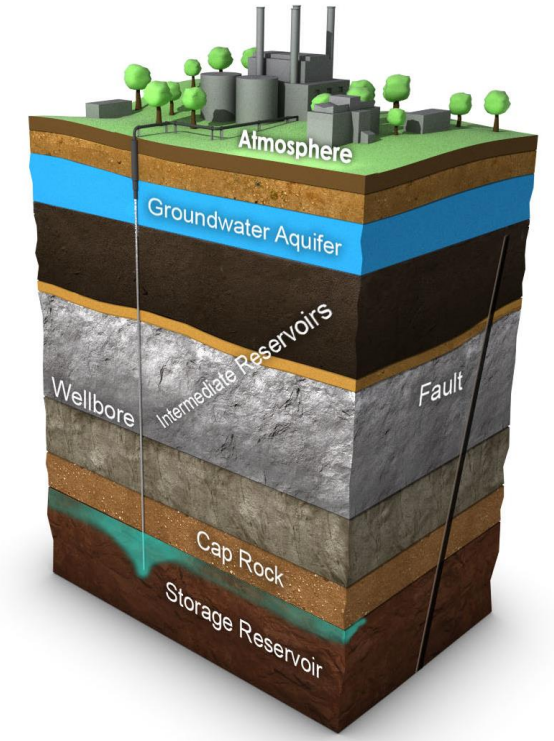
Subtask 2.1: NRAP-Open-IAM

New Reduced Order Models (ROMs)

- **Wellbore Chemical sealing ROM**
  - Completed: Jaisree Iyer, LLNL
  - Published in ES&T[1]
  - Identifies leakage pathways in dam that will seal due to precipitation



- **Fault leakage ROM**
  - In progress: Ernest Lindner, NETL
  - Two-phase flow through faults using Brooks-Corey relative permeability model
  - Available on EDX[2]



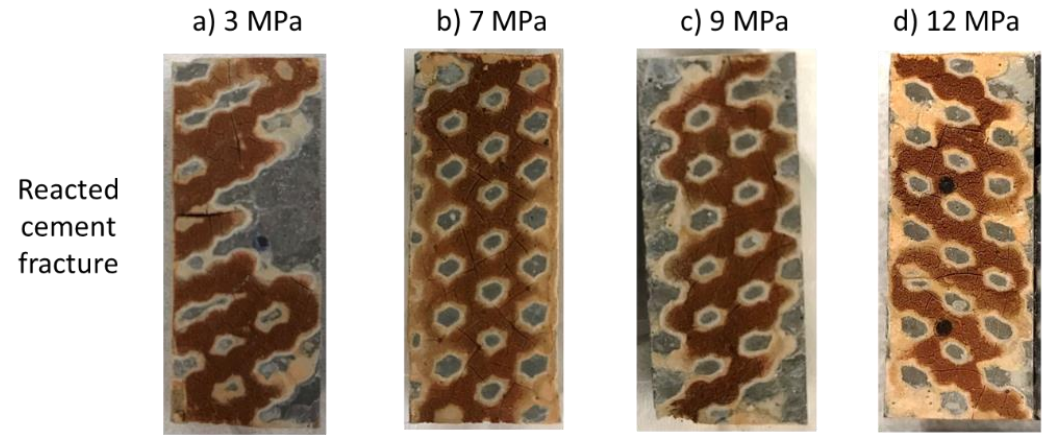
[1]https://pubs.acs.org/doi/abs/10.1021/acs.est.9b05039

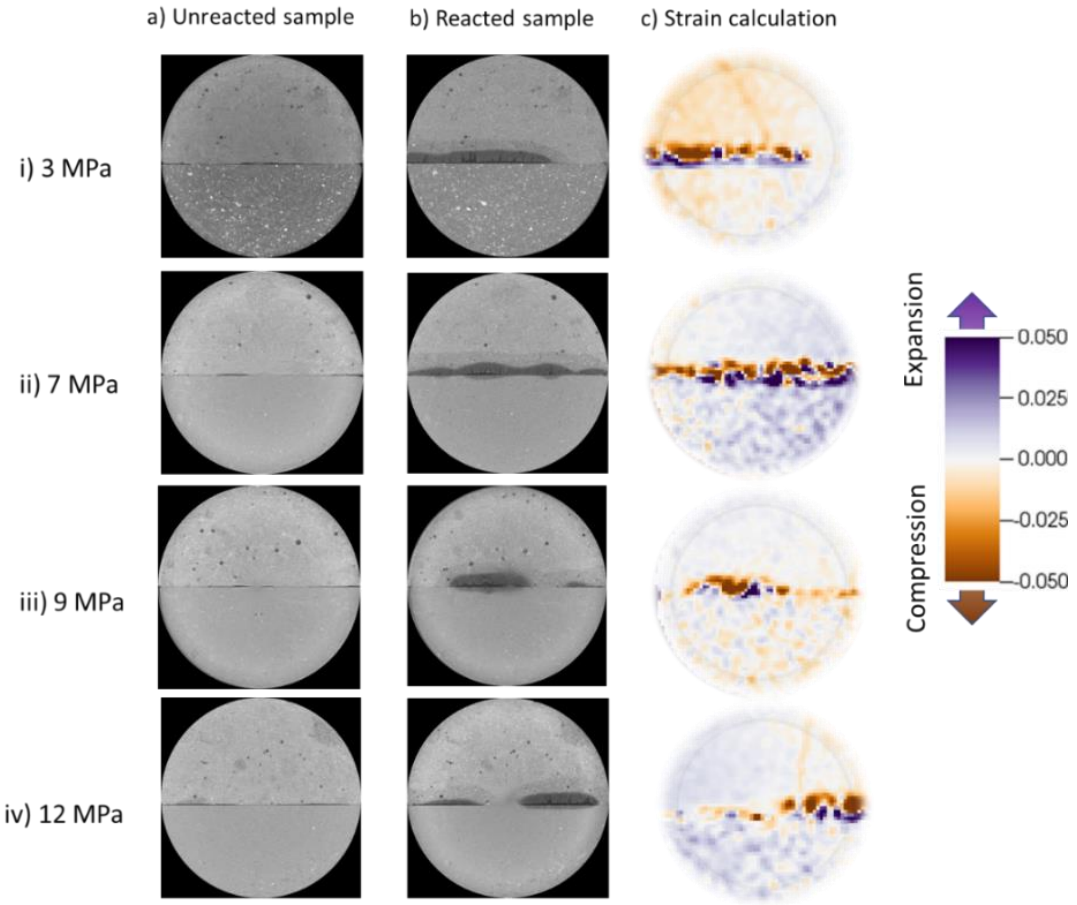
[2]https://edx.netl.doe.gov/dataset/fault_flo-a-reduced-order-model-for-flow-through-a-fault-beta-1-7-version-2021-02-19

Subtask 2.2 Well Leakage

Experimental studies to improve the science behind well leaks at CO_2 storage sites

- **Interplay between stress and flowpath governs permeability evolution of leakage pathways**
  - Completed: Kevins Rhino, LLNL
  - Publication in IJGGC
- **Important chemical interactions upon CO_2 leakage along cement-casing interfaces**
  - In progress: Kevins Rhino, LLNL
  - Probing the impact of different materials and flow rates

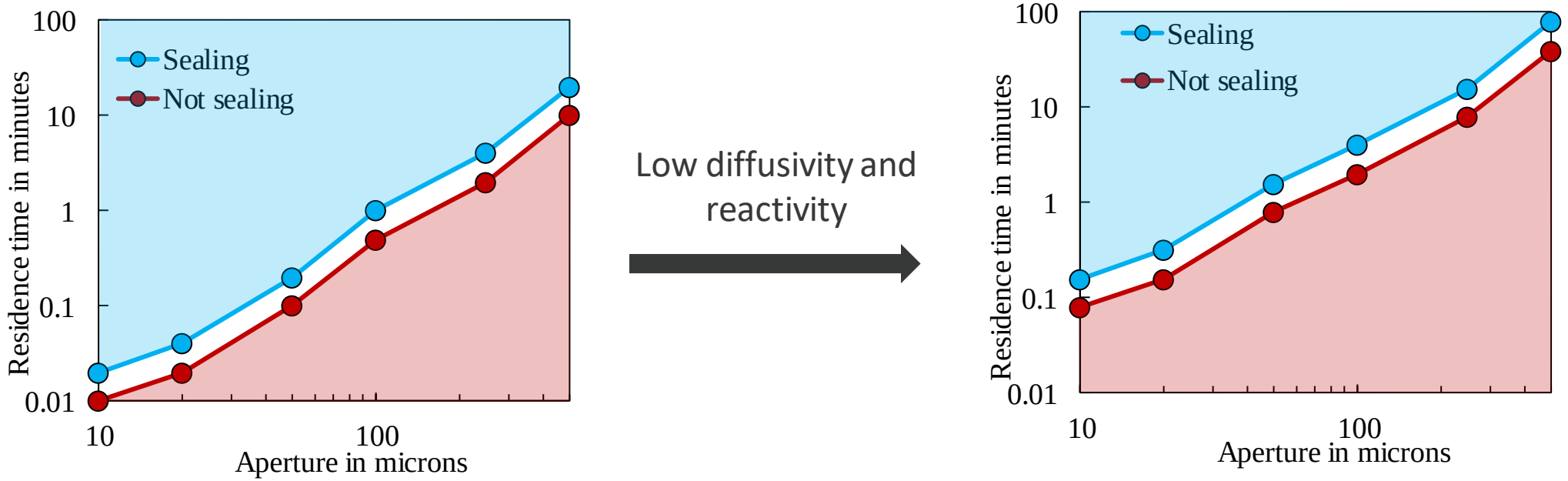




Subtask 2.2 Well Leakage

Modeling studies to improve the science behind well leaks at CO_2 storage sites

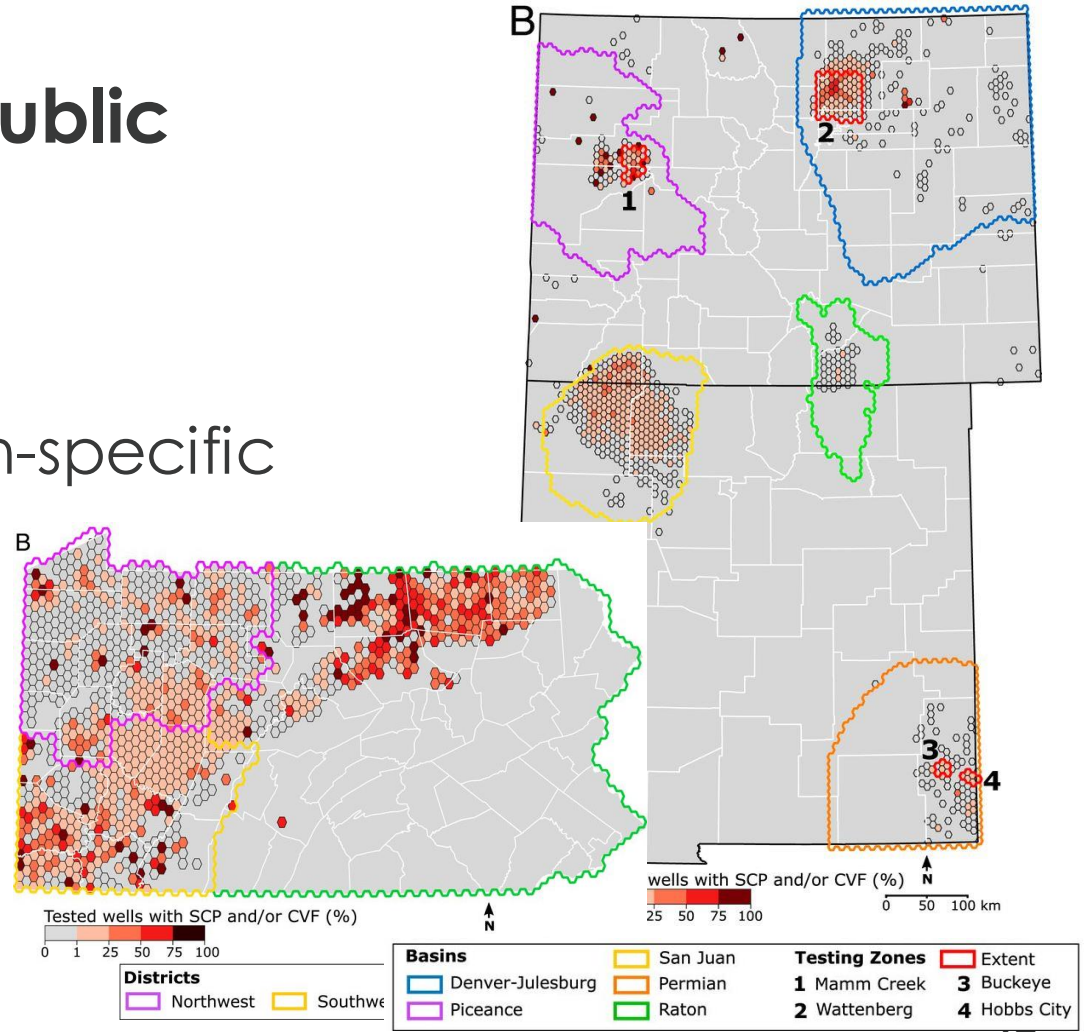
- **Impact of brine concentration, cement composition, diffusivity and reactivity on chemical sealing of leakage pathways**
  - In progress: Jaisree Iyer, LLNL
  - Highest sensitivity to cement diffusivity and reactivity



Subtask 2.2 Well Leakage

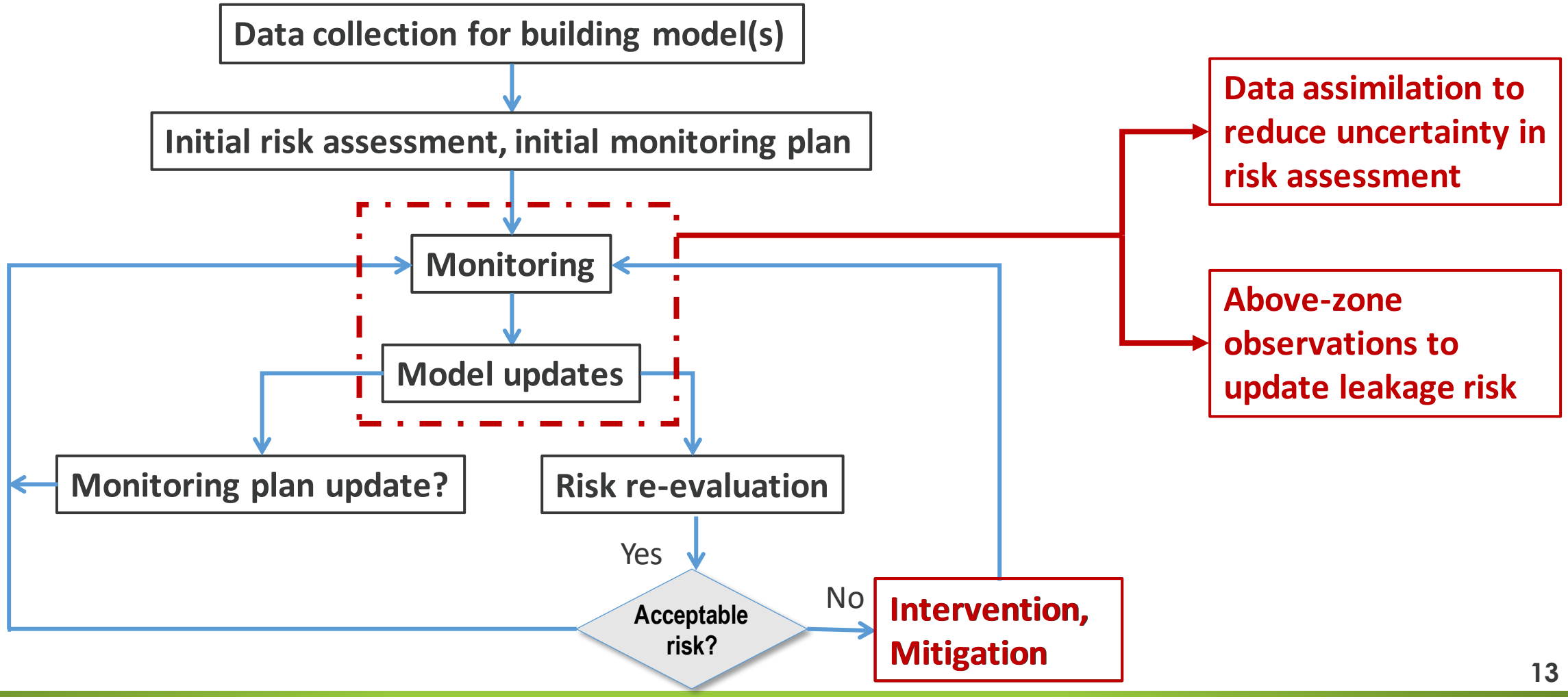
Field studies to improve the scientific understanding of well leaks at CO_2 storage sites

- **New insights into well integrity from public records**
  - Completed: Greg Lackey, NETL
  - Publication in PNAS*
  - Leakage frequencies may not be region-specific
    - Varied between 0.3 and 26 % in this study
  - A much smaller fraction of wells tested can potentially induce leakage outside the well



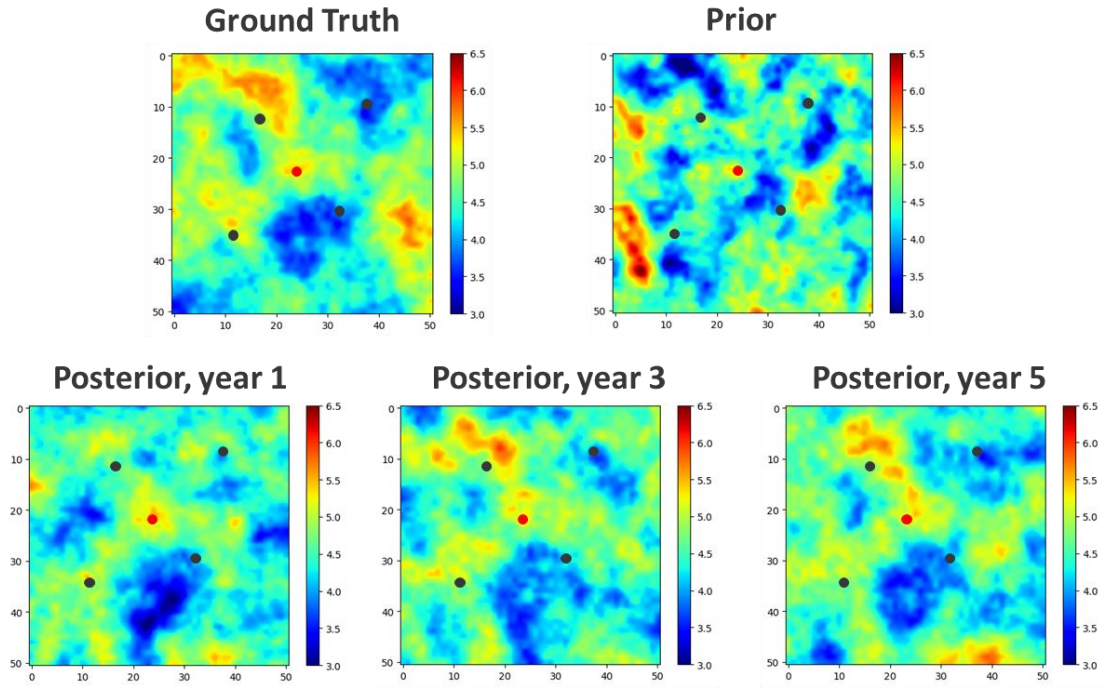
*https://www.pnas.org/content/118/14/e2013894118/

Subtask 2.3 Iterative Risk Assessment and Mitigation

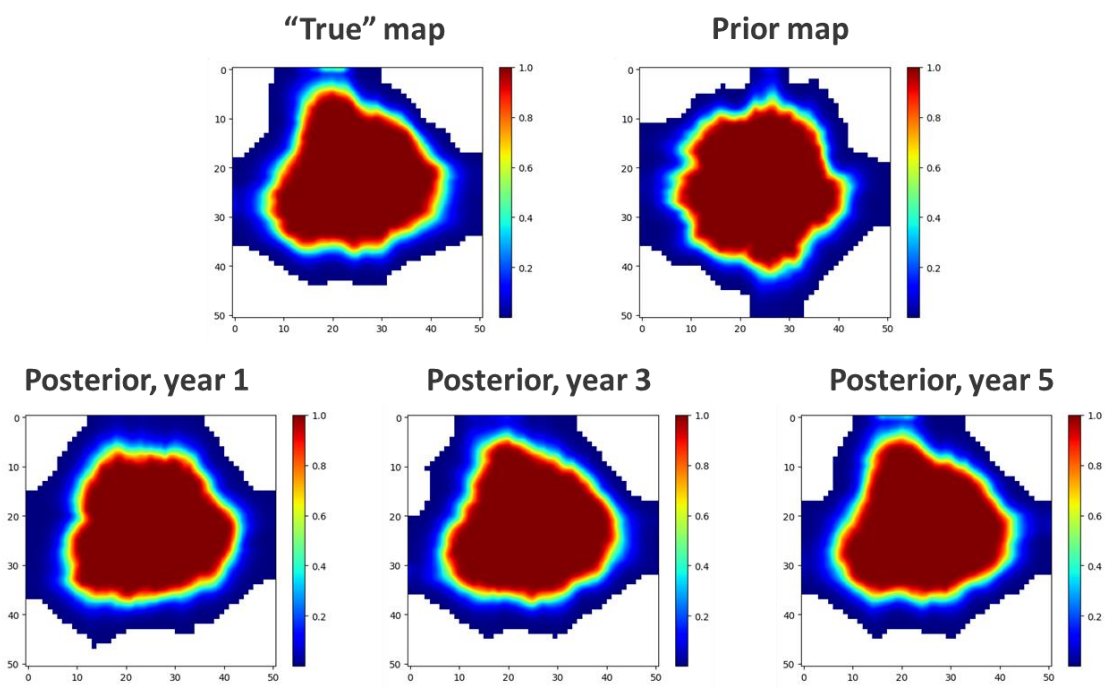


Dynamic risk assessment with spatial measurements

- **Model updated by assimilating CO_2 saturation maps at years 1, 3, and 5 interpreted from 4D seismic**



- **Prediction of CO_2 saturation plume at the end of post-injection**



- Increased similarity between the updated model and the ground truth model with the increased number of seismic surveys.
- Increased predictive accuracy in CO_2 saturation plume with the increased number of seismic surveys.

Workflow: Evaluating Risk Management/Mitigation Scenarios to Inform Risk Management Decisions

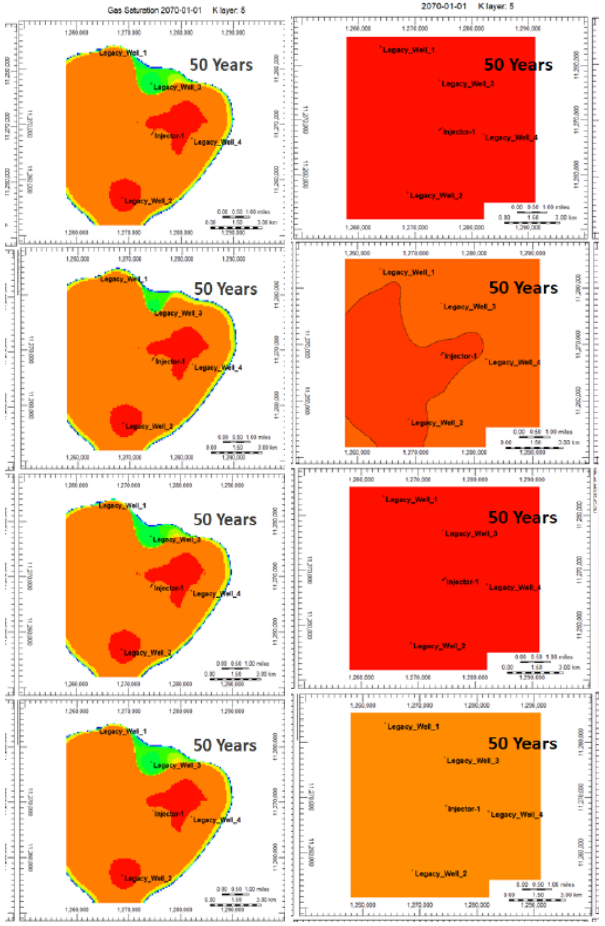
Mitigation Alternative → **Reservoir Simulation** → **NRAP-Open-IAM Calculated Well-Based Leakage to AZMI** → **Monitoring Design and Detectability Analysis** → **Metrics for Alternative Selection**

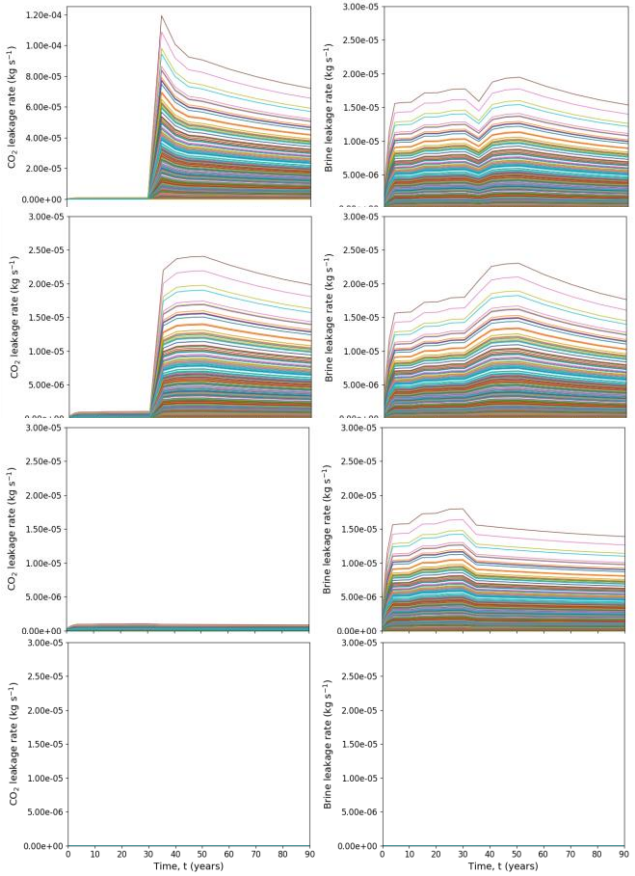
Base Case

Mitigation A

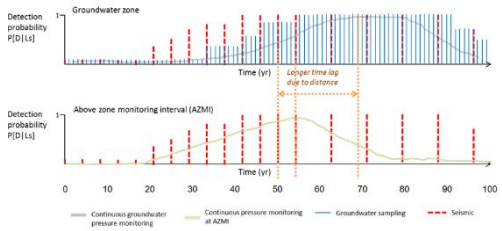
Mitigation B

Mitigation C

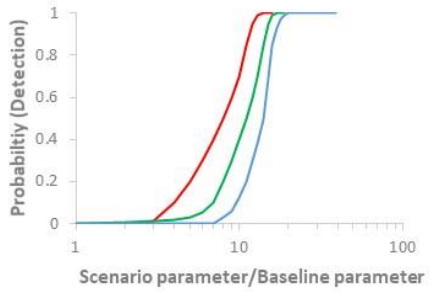




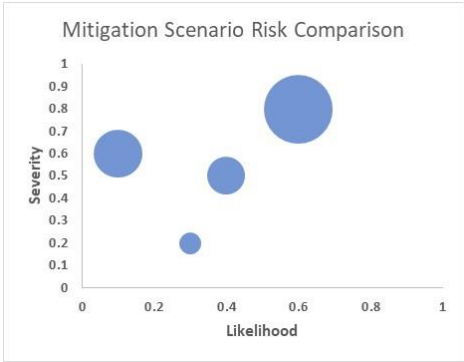
Monitoring Technology and Intensity



Estimate of Leak Detection



Risk Ranking as function of Leakage Likelihood, Severity, and Detectability



Yang, Y. et al., 2015, , Int. J. Greenh. Gas Control

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY | BERKELEY LAB | Los Alamos NATIONAL LABORATORY EST.1943 | Pacific Northwest NATIONAL LABORATORY

NRAP Task 5: Validation of Risk Assessment Tools and Methodologies Using Synthetic Data and Field Observations

Subtask 5.1: Risk Assessment and Management Tools and Methodologies Field Validation – Diana Bacon, PNNL (lead)

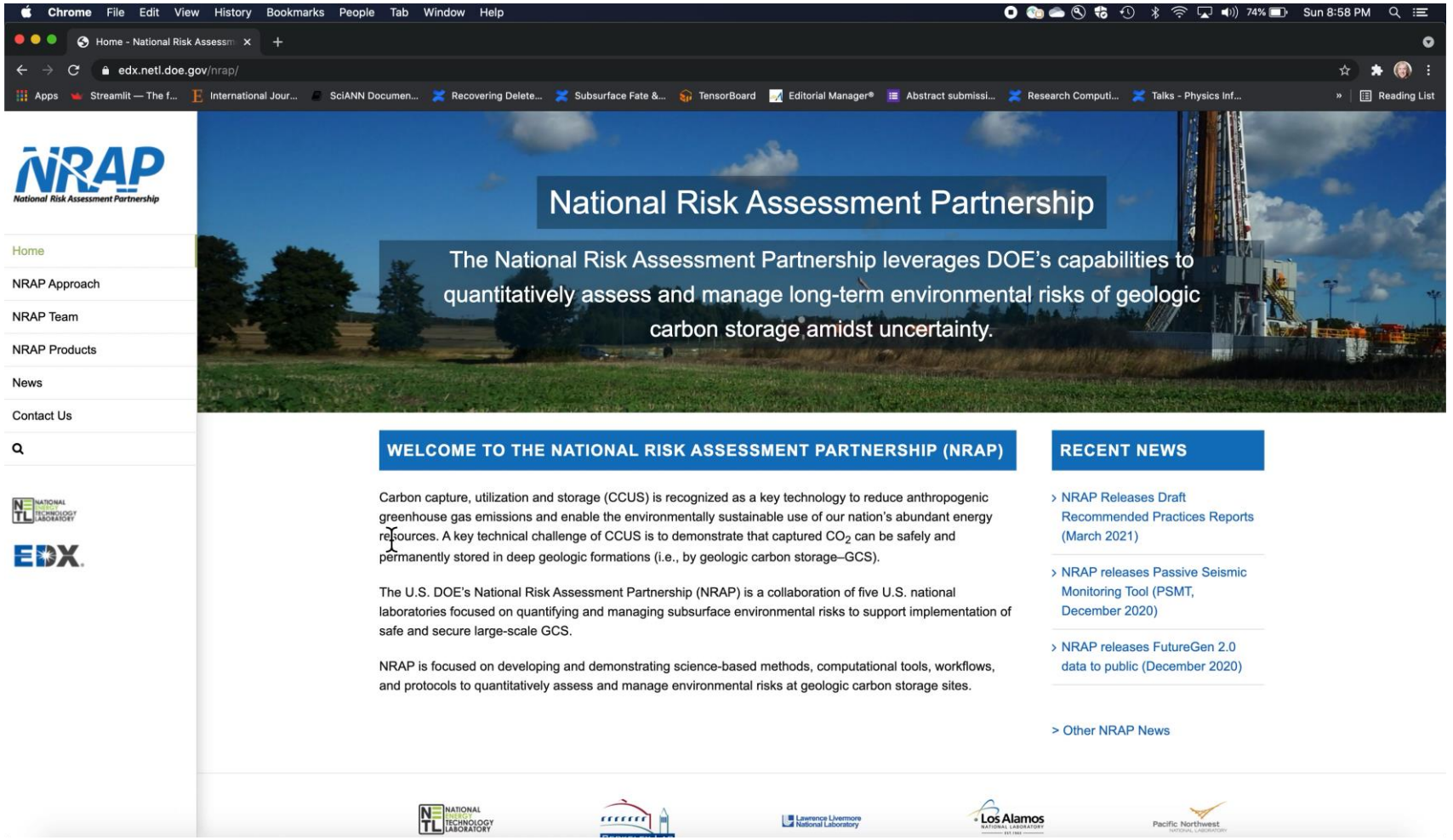
- Brandon Schwartz, PSU
- Shaoping Chu, LANL
- Rajesh Pawar, LANL
- Signe White, PNNL
- Inci Demirkanli, PNNL
- Nik Huerta, PNNL
- Delphine Appriou, PNNL
- Catherine Yonkofski, PNNL
- Susan Carroll, LLNL
- Kayla Kroll, LLNL
- Corrinne Bachmann, LBNL
- Jeff Burghardt, PNNL

Subtask 5.2: Development of Community Data Sets – Kelly Rose, NETL (lead)

- Paige Morkner, NETL
- Andrew Bean, NETL
- Quanlin Zhou, LBNL
- Bin Chen, LBNL
- Liange Zhang, LBNL

NRAP Application Catalog on EDX

N. Huerta, D. Appriou, D. Bacon (PNNL); P. Morkner (NETL); T. Jones, A. Barkhurst (MATRIC)



https://edx.netl.doe.gov/nrap/application-catalog/

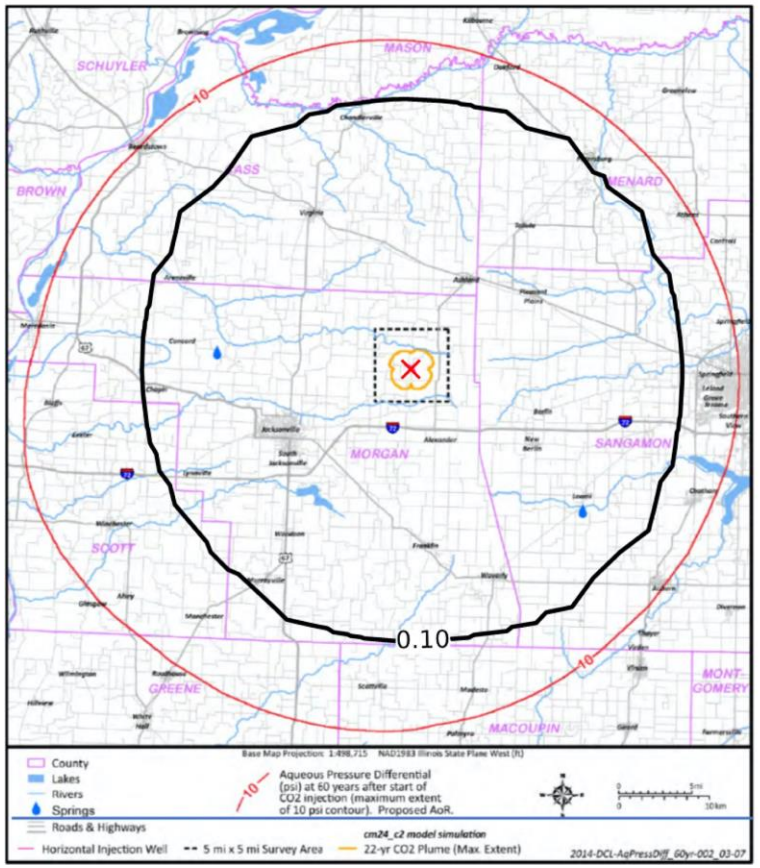
Workflow: Developing a Risk-Based Area of Review

Bacon, DH, DI Demirkanli, and SK White. 2020. "Probabilistic risk-based Area of Review (AoR) determination for a deep-saline carbon storage site", International Journal of Greenhouse Gas Control, 102: 103153. 10.1016/j.ijggc.2020.103153

Key Findings

- Uncertainty in reservoir and aquifer characteristics yields a probabilistic risk-based Area of Review.
- AoR is determined based on the probability of aquifer impacts, rather than just on leakage from an open conduit
- The workflow is demonstrated using characterization and modeling data from a permitted carbon storage project

Risk-Based AoR (0.1 MPa/14.5 psi (black)
Class VI Permit AoR 0.69 MPa/10 psi (red)

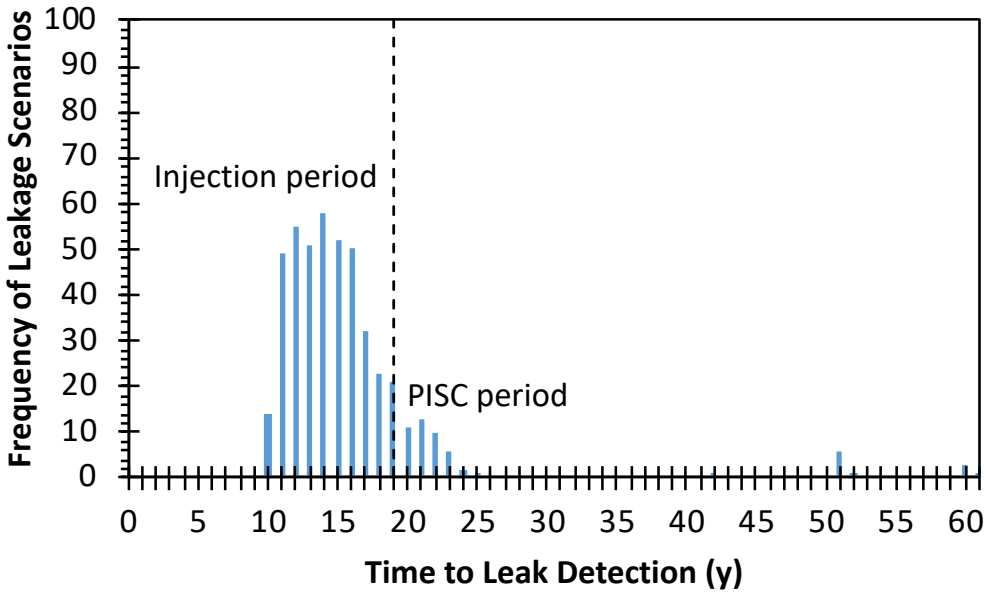


Workflow: Defining a Risk-Based Period of Post-Injection Site Care in Support of Site-Closure Decision-Making

Bacon DH, CMR Yonkofski, CF Brown, DI Demirkanli, and JM Whiting. 2019. "Risk-based post injection site care and monitoring for commercial-scale carbon storage: Reevaluation of the FutureGen 2.0 site using NRAP-Open-IAM and DREAM." *International Journal of Greenhouse Gas Control* 90:102784. 10.1016/j.ijggc.2019.102784.

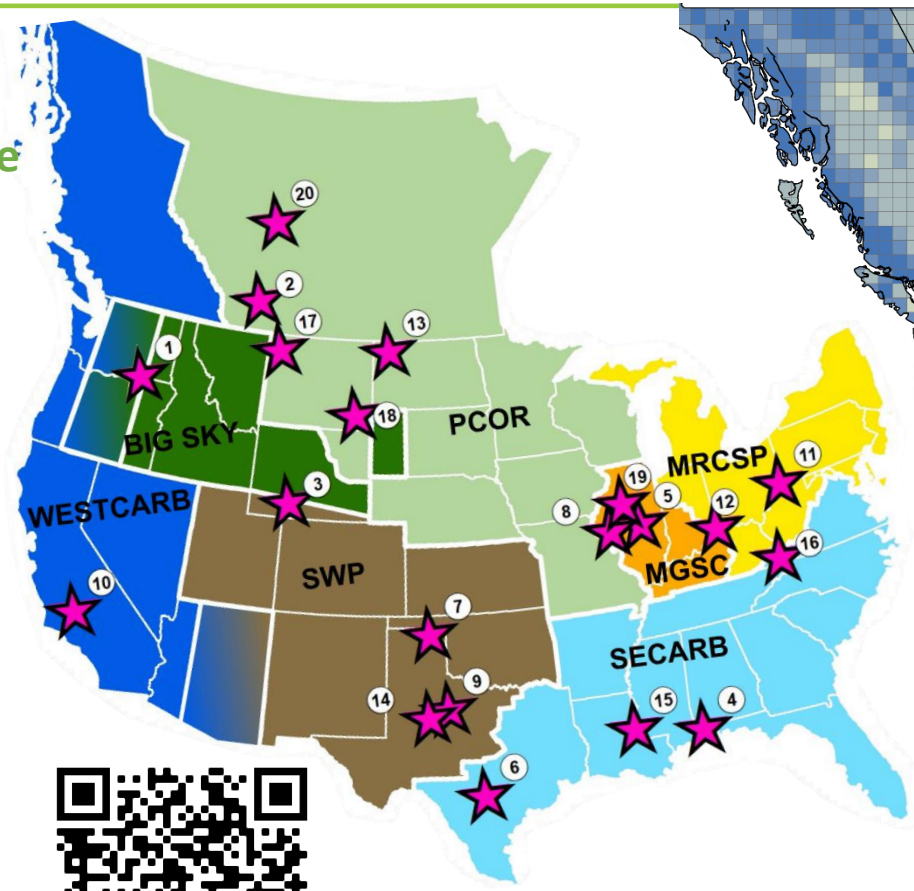
Key Findings

- NRAP-Open-IAM and DREAM were used to determine an optimized monitoring network for a commercial-scale CO_2 storage project
- NRAP-Open-IAM revealed that maximum simulated leakage rates of brine were small and could be detected during the injection phase
- These NRAP tools can be used to define a risk-based, and substantially shorter, PISC period for the site

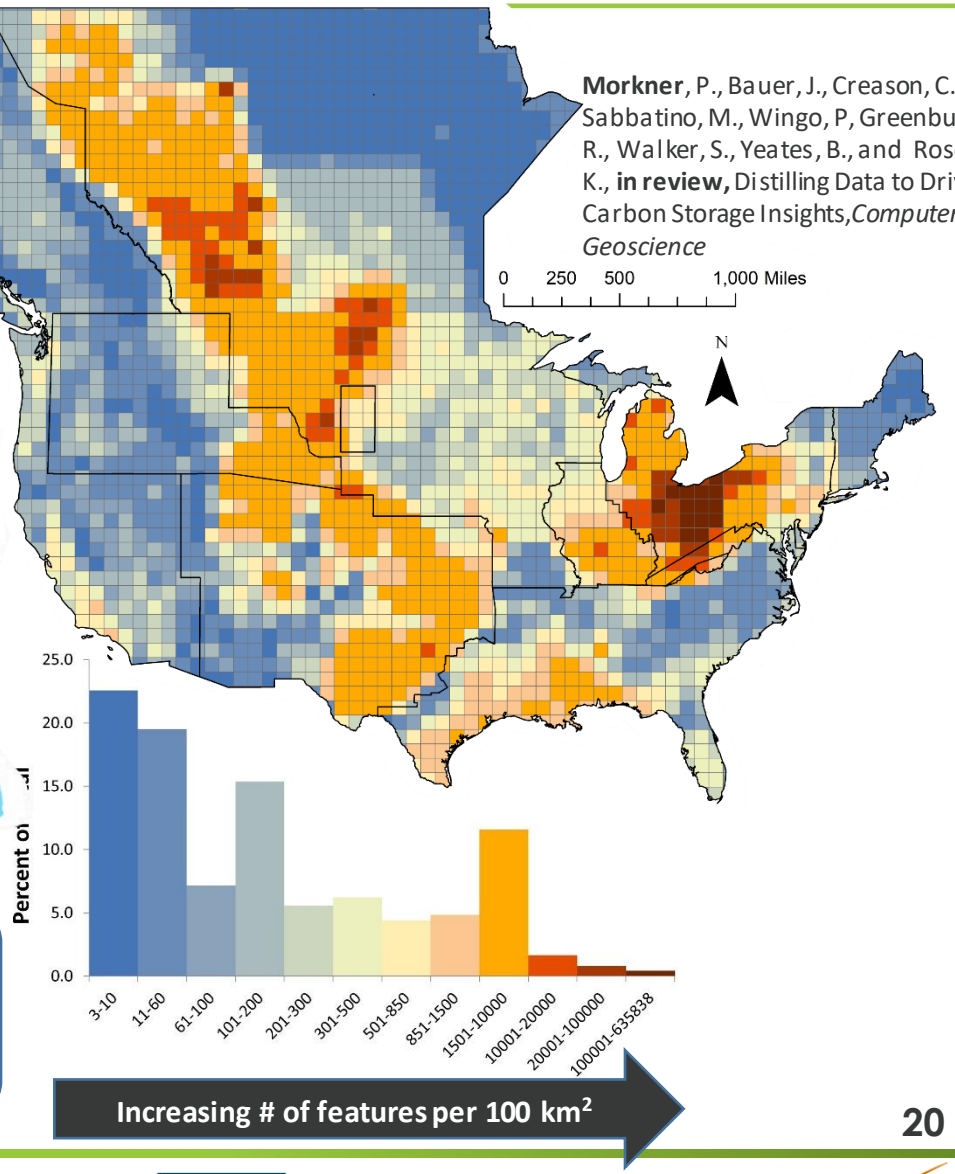


Subtask 5.2: Development of Community Data Sets

- Publishing of **NRAP Community Datasets CCS Site Catalog** on EDX
  - Describing **20 sites which have data available** for testing NRAP tools
- Published **FutureGen 2.0 Technical data** on EDX as community dataset
- Published **5 Kimberlina Datasets** now available on EDX
- **Aided with publishing and cataloged other RCSP and CarbonSAFE data resources**
- Data available for CCS on EDX's spatial data platform, GeoCube



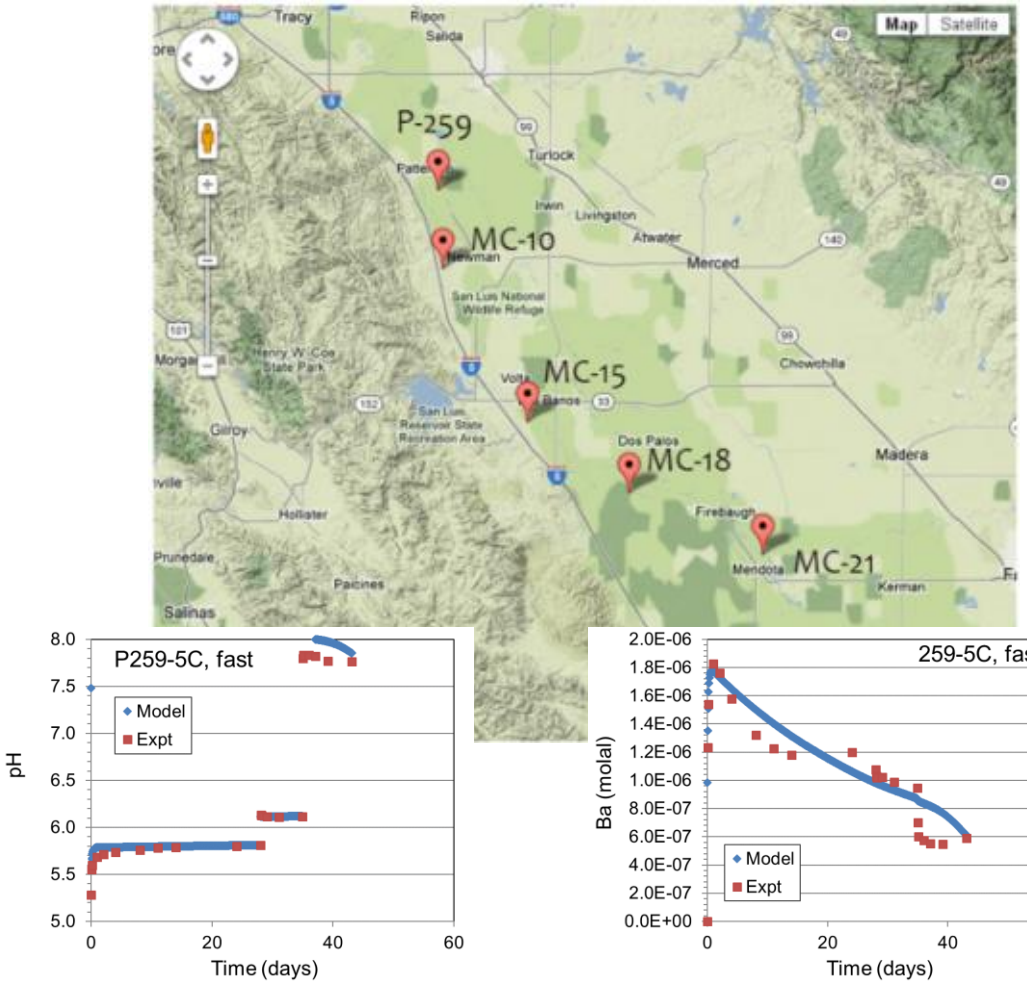
https://edx.netl.doe.gov/dataset/nrap-community-datasets-ccs-site-catalog



Subtask 5.2: Development of Community Data Sets

Liange Zheng, Pierpaolo Marchesini, Tom Daley LBNL

- **Using synthetic data from San Joaquin Valley to demonstrate methodologies**
  - Cores collected from a 50-mile transect of 500-ft deep wells drilled in the San Joaquin Valley was used for a series of batch experiments to study the release of metal under different CO_2 partial pressure.
  - Geochemical models were developed to interpret the data collected from the batch experiments.
  - 2-D reactive transport model with vertical heterogeneity will be developed
  - Global sensitivity analysis based on the 2-D reactive transport model will be established and a reduced order model will be developed.



Data and model results from the batch experiments

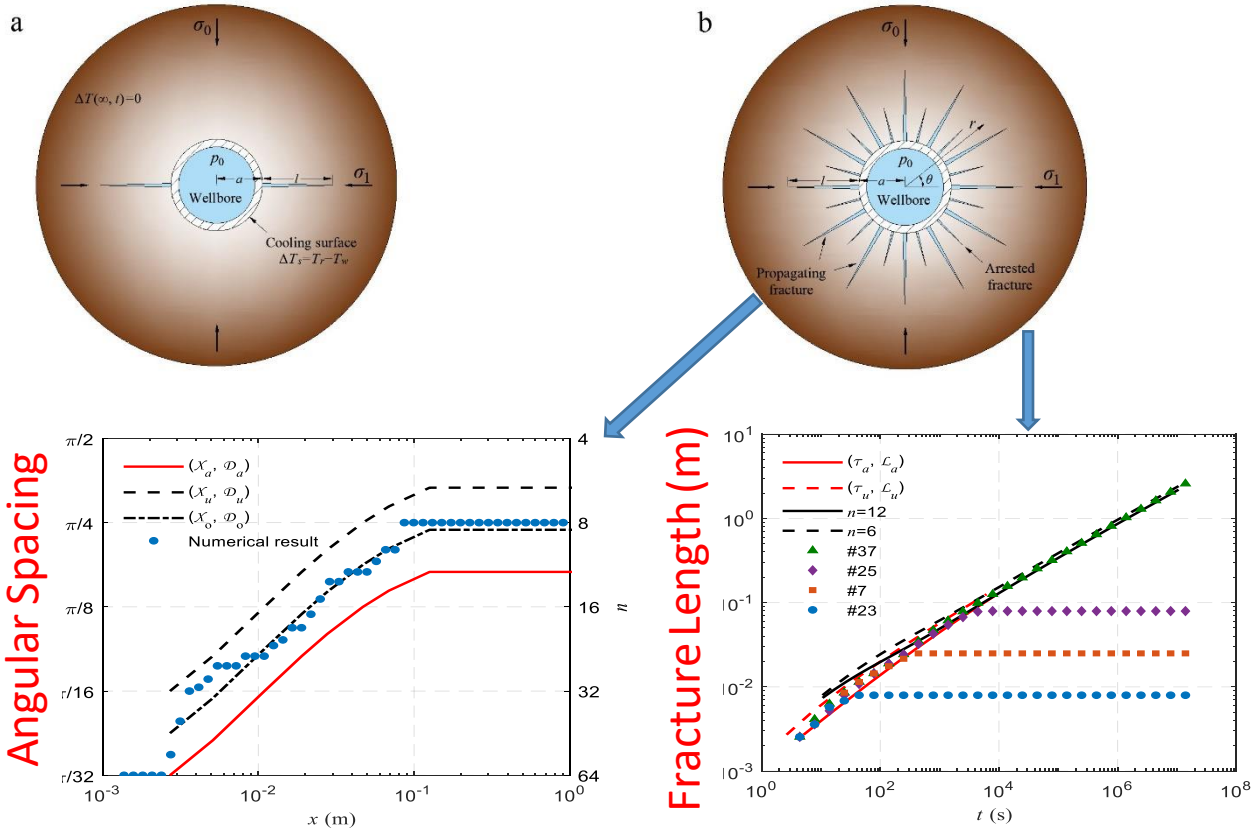
Subtask 5.2: Development of Community Data Sets

Bin Chen & Quanlin Zhou, LBNL

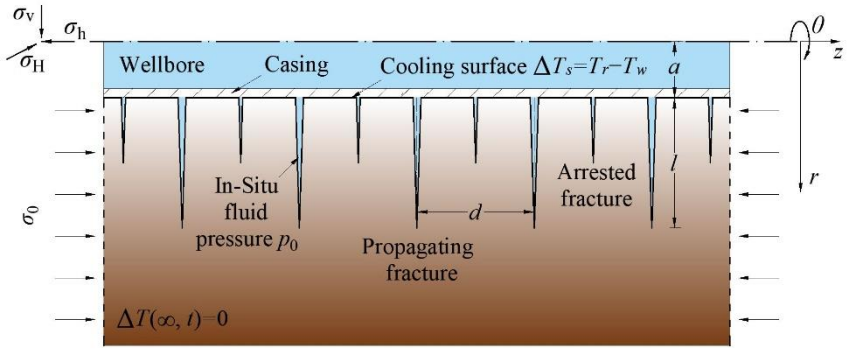
- **Vertical Well Fracturing** (Chen & Zhou, 2021a)
  - Longitudinal thermal fractures
  - Solutions for isotropic/strongly anisotropic stresses

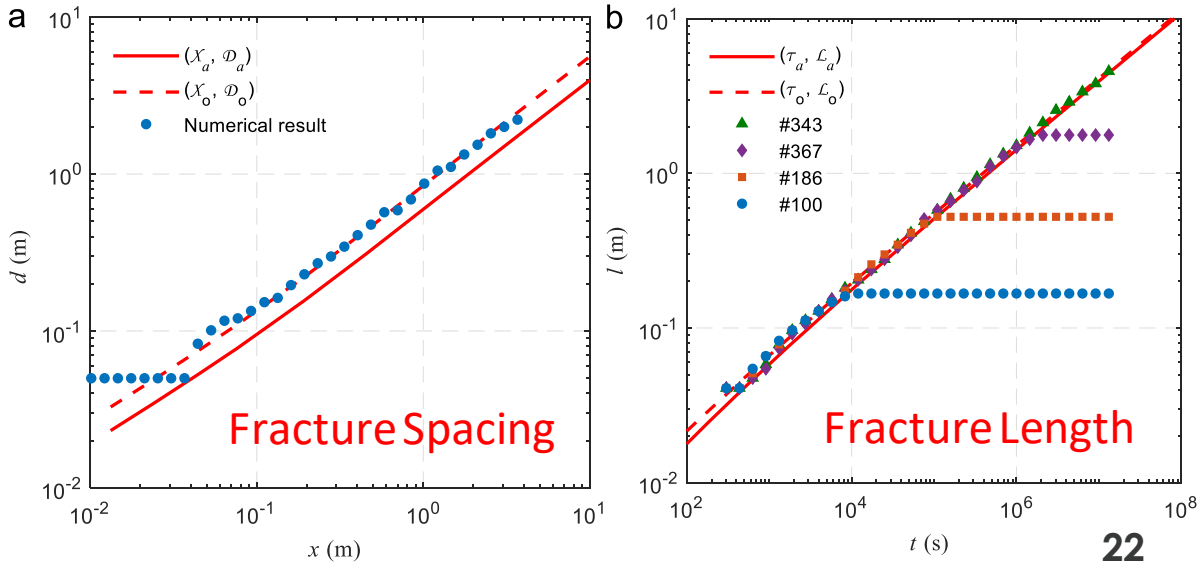
Two-Wing Fractures

Dynamically Spaced Multiple Fractures



- **Horizontal Well Fracturing** (Chen & Zhou, 2021b)
  - Parallel radial, transverse thermal fractures





Key Findings

NRAP Subtask 2.1 **NRAP-Open-IAM**

- **NRAP-Open-IAM software development continues to improve its accuracy and applicability for enabling risk-informed analyses**
- **Ongoing QAQC work**
  - updates, debugs and benchmarks the existing components
  - documents quality through technical reports and updates to software documentation
  - improves quality and user engagement through additional tests and example problems
- **Development of new components and decision support functionality expands capabilities**
- **Addressing community feedback improves user engagement**

Key Findings

NRAP Subtask 2.2 **Well Leakage**

- Generated experimental data sets that quantify the change in flow, chemical and mechanical properties of damaged interfaces in the wellbore
- Developed models that predict leakage through damaged wells
- Quantified occurrence of well integrity issues using information in regulatory databases
- Developed ROMs to quantify leakage through wells, seals and faults at CO_2 storage sites

Key Findings

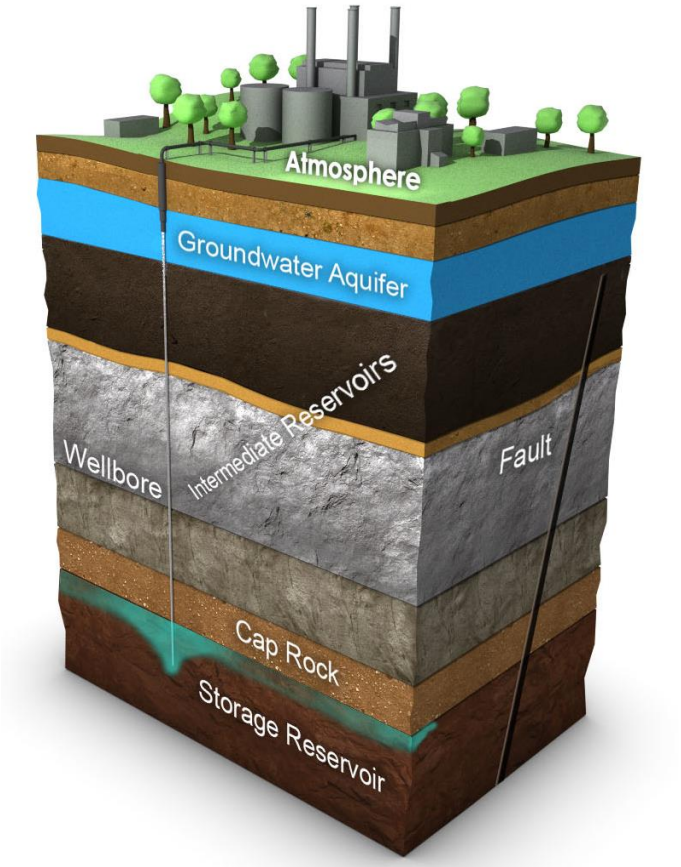
NRAP Subtask 2.3 **Dynamic Risk**

- ES-MDA-GEO can effectively assimilate the monitoring data to reduce the uncertainty in risk metrics
- Updated model is closer to the ground truth model with the increased number of seismic surveys
- Predicted CO_2 plume is more accurate with the increased number of seismic surveys
- A monitoring-based risk mitigation, decision making workflow is developed and demonstrated (https://www.netl.doe.gov/energy-analysis/details?id=8b2e9210-e2a2-4ede-b865-dd2b59bf0d7a)
- Well-based leakage risk mitigation strategies were illustrated using NRAP-Open-IAM
- Risk metrics with intensity, leakage detection, ranking in risk priority number was demonstrated

Key Findings

NRAP Subtask Task 5.1 **Field Validation**

- **NRAP Tool and Recommended Practice Applications**
  - provide a valuable resource for operators and stakeholders to understand the utility of the tools
  - allow the NRAP team to validate the underlying theory and approach for a given tool
  - elicit feedback from users to improve the tools
- **New probabilistic risk-based Area of Review application**
  - Determined AoR based on the probability of aquifer impacts, rather than just on leakage from an open conduit



Key Findings

NRAP Subtask Task 5.2 **Community Datasets**

- To date, over 1.16TB of carbon storage relevant open data has been made publicly available on EDX, and that number keeps growing
- The NRAP Community Datasets CCS Site Catalog, published in fall of 2020, outlines the datasets from 20 field sites which serve as community datasets, including preservation and improved access to over 6000 files published for the FutureGen 2.0 Technical data release
- New datasets related to aquifer reactivity and thermal fracturing are under development

Phase II Remaining Milestones

National Risk Assessment Partnership Tasks 2 & 5

- **NRAP Task 2: Containment Assurance**
  - Complete analysis on leakage risk mitigation scenario evaluation.
  - Decide if beta-testing results and feedback warrant transitioning NRAP-Open-IAM to final version release.
  - Complete draft NRAP-Open-IAM quality assurance documentation.
  - Complete summary of containment assurance/leakage risk accomplishments.
- **NRAP Task 5: Validation of Risk Assessment Tools and Methodologies Using Synthetic Data and Field Observations**
  - Complete draft final catalog of NRAP tools field validation.

Thank you!

Comments and Questions:

NRAP@NETL.doe.gov

NRAP Website: https://edx.netl.doe.gov/nrap/

Sign up for NETL EDX: https://edx.netl.doe.gov/user/register