GIS Knowledge Integration for Carbon Sequestration: The Cyberinfrastructure Approach

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Abstract

The temporal and spatial scales involved in carbon sequestration studies require integration of numerous sources of disparate information for decision making and performance assessment. A well-formulated cyberinfrastructure design ensures this integration by providing access to information, problem solving capabilities, and communication. This carbon cyberinfrastructure has five major elements: 1) a knowledge base, consisting of key geospatially referenced databases; 2) links to relevant data sources available through measurement, monitoring, and verification (MMV); 3) links to process models (data/model integration, model coupling); 4) links to higher-level integrative models (system dynamics); and 5) links to computation services, in particular geographic information system (GIS)-based capabilities for analysis and visualization (GIServices, decision support).

We are developing a GIS-based decision support system (DSS) for carbon sequestration studies that examine critical pathways for CO_2 release, specifically borehole failure. The knowledge base links diverse empirical data (e.g., borehole locations, cement degradation, and material properties) with physics-based models of flow and CO_2 reactions to simulate borehole seal failure and the resulting environmental release of CO_2. The methodology for our performance-based decision analysis framework relies on well-defined data models derived from the requirements of component process models. The DSS supports evaluation of spatial and temporal variations in borehole failure as a result of geographic, geologic, and engineering conditions at different boreholes. The data and process model results are abstracted and aggregated to serve as input for system dynamics models that allow decision makers to evaluate critical economic and health impacts of potential CO_2 release.

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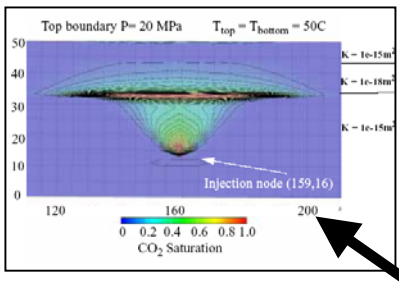
I. Carbon Cyberinfrastructure: The Knowledge Base

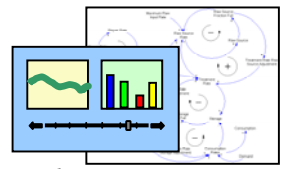
Carbon Cyberinfrastructure *= integrated computing environment that provides access to carbon science information, models, problem solving capabilities, and communication*

Process Models



- Physical models
- Operations models
- Scenario analysis

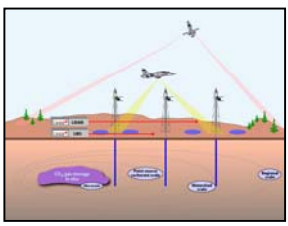
Decision Support



- System Dynamics and Visualization

Knowledge Base
Data Warehouse
Model Warehouse

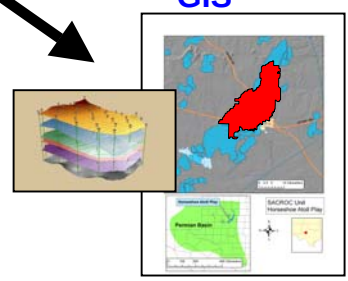
Measurement, Monitoring, & Verification (MMV)



- Remote sensing
- Sensor arrays / networks
- Ground truth

- National Carbon Atlas
- MMV libraries
- Model component archive (inputs, parameters…)
- Scenario libraries

GIS

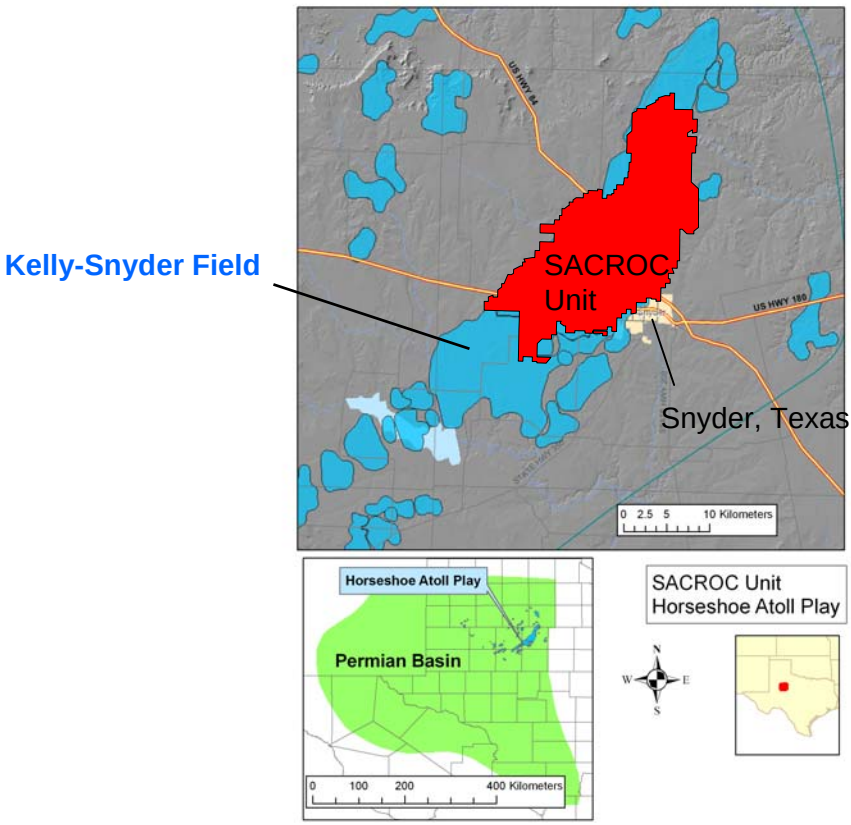


- Data Access
- Data/model integration
- Map-based analysis and visualization

- **data warehouse** access to shared data
- **model warehouse** access to model components and scenario libraries
- **"loose coupling"** of all elements

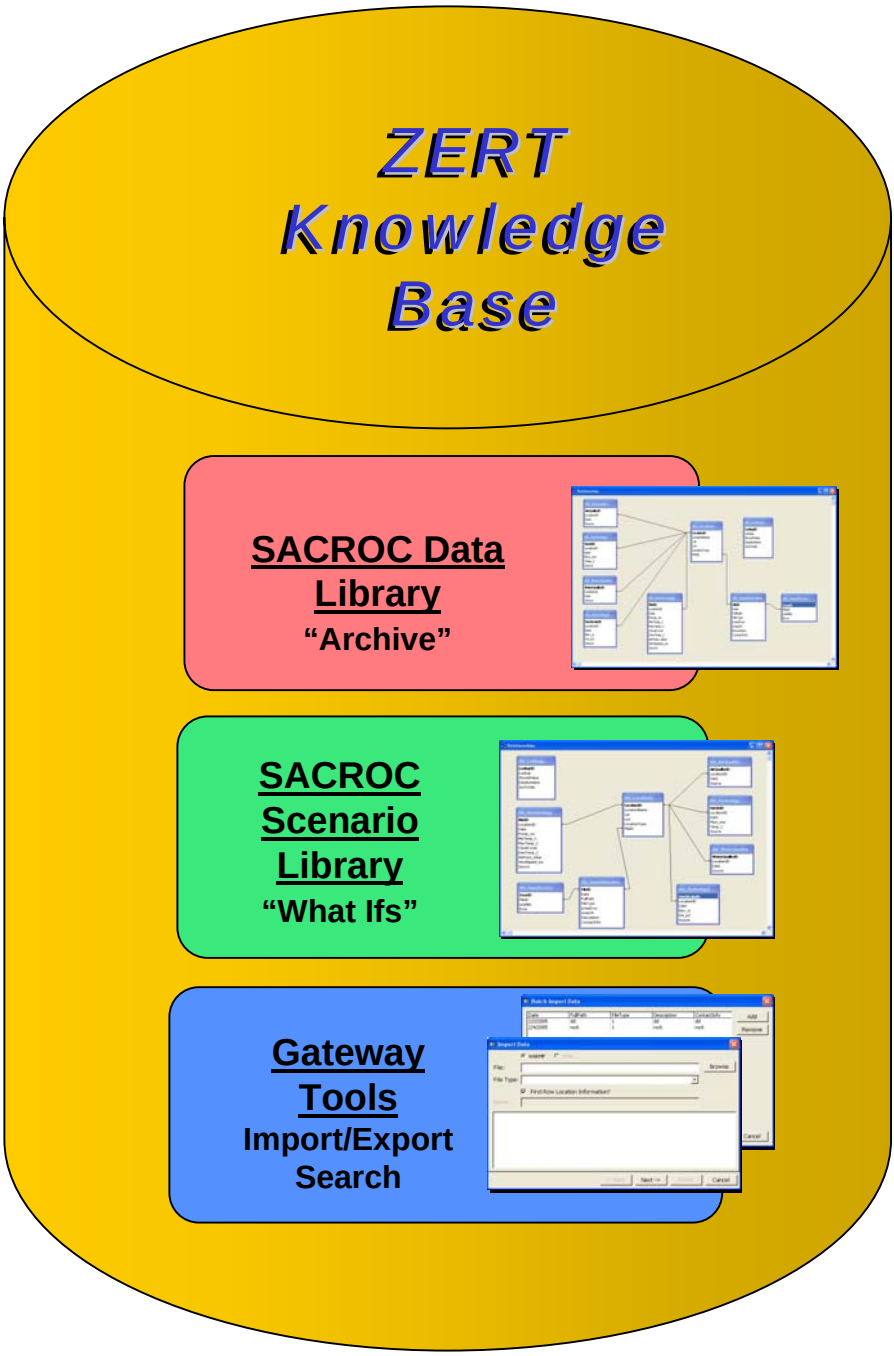
II. Case Study

Borehole Integrity Modeling and CO_2 Migration, SACROC Unit, Texas



Thirty years of CO_2 injection for enhanced oil recovery provides an excellent analog for proposed sequestration of CO_2 in depleted oil reservoirs. LANL studies include lab studies of lateral reentry drill cores (cement, casing, caprock, reservoir); autoclave experiments on cement; batch brine-cement-CO_2 reaction modeling; CO_2 transport modeling; monitoring, measurement, and verification (MMV) R&D; and GIS data-model integration for decision support.

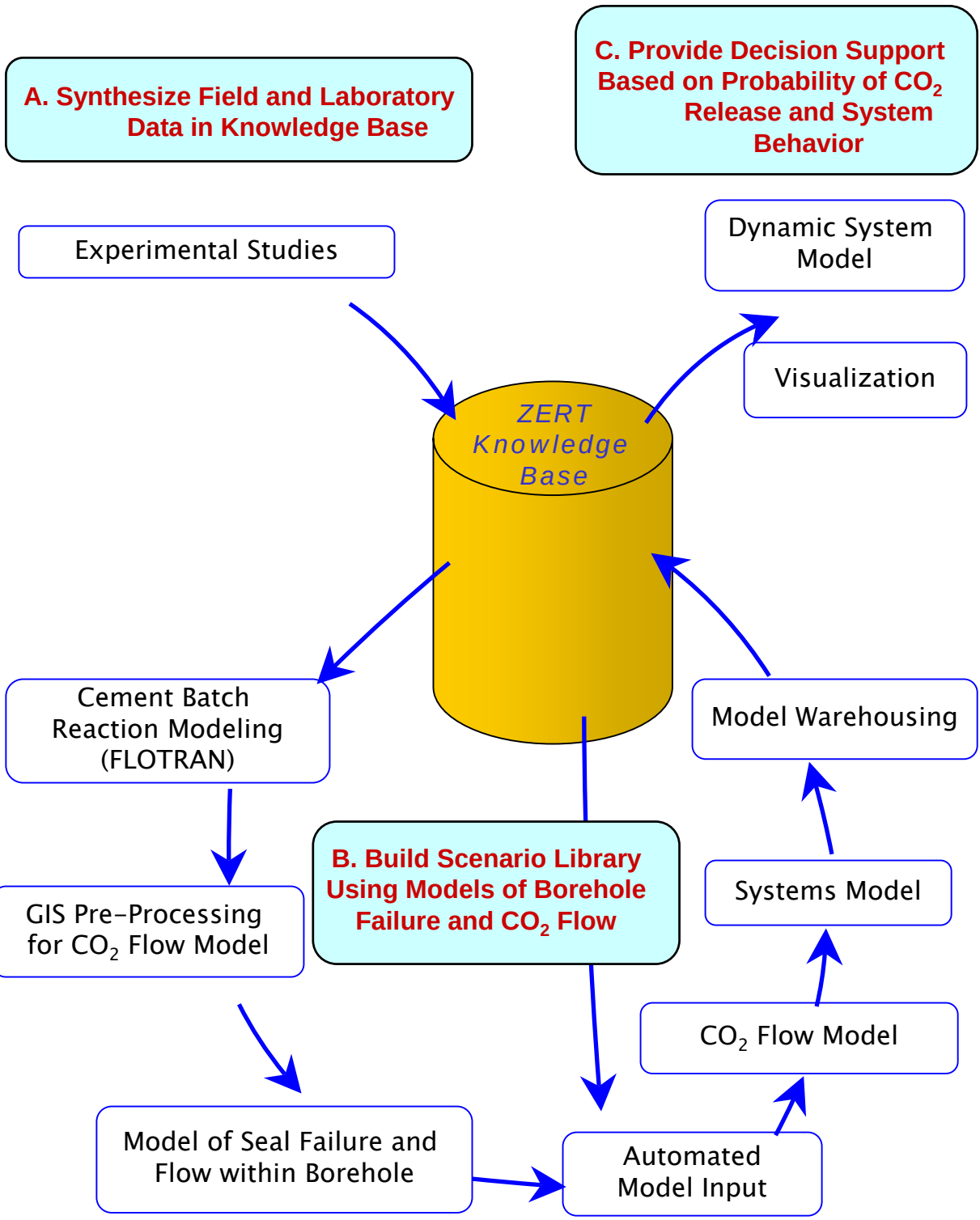
At the core: the Knowledge Base:



- Database tables and linked flat files
- Consistent data sources for analysis, modeling, and reporting

ZERT = Zero Emissions Research and Technology

Overview of Flow of Information within the Borehole Integrity Modeling and CO_2 Migration Study

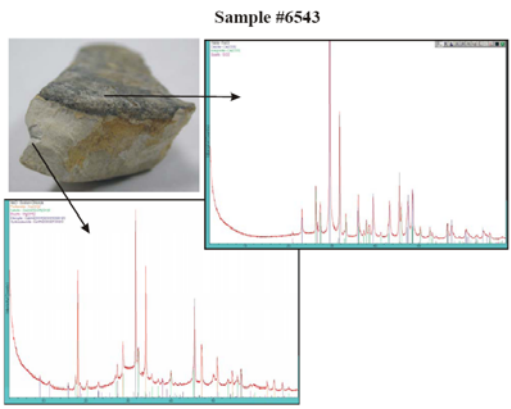


A. Synthesize Field and Laboratory Data in Knowledge Base

Experimental Studies

Core from lateral drilling through well casing-cement-caprock-reservoir in injection and production wells

Autoclave for investigating CO_2-cement reaction at high P,T



XRD analyses of cement and host rock from SACROC core

Cement mineralogy
Cement-host rock reactions

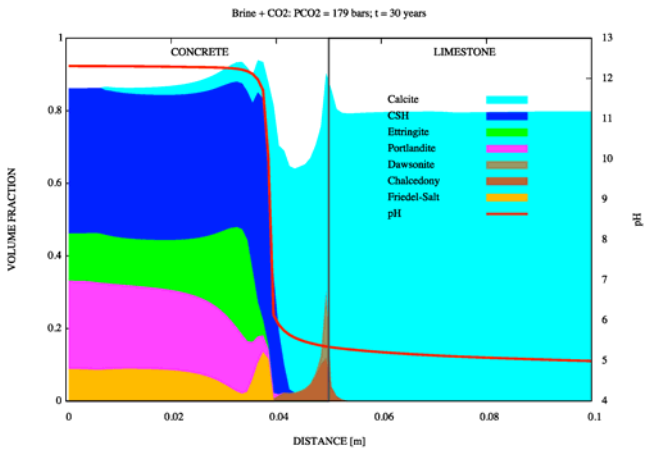
ZERT Knowledge Base

B. Build Scenario Library Using Models of Borehole Failure and CO_2 Flow (Part 1)

ZERT Knowledge Base

Cement mineralogy
Brine chemistry

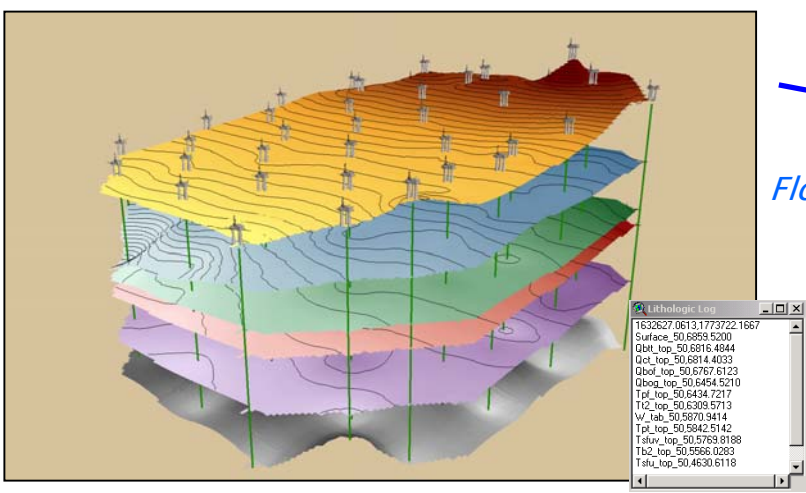
Cement Batch Reaction Modeling (FLOTRAN)



Batch model mineralogy results of cement (left half) and brine (right half after 30 years; white = porosity

Cement degradation rates
Φ(t), k(t)

GIS Pre-Processing for CO_2 Flow Model

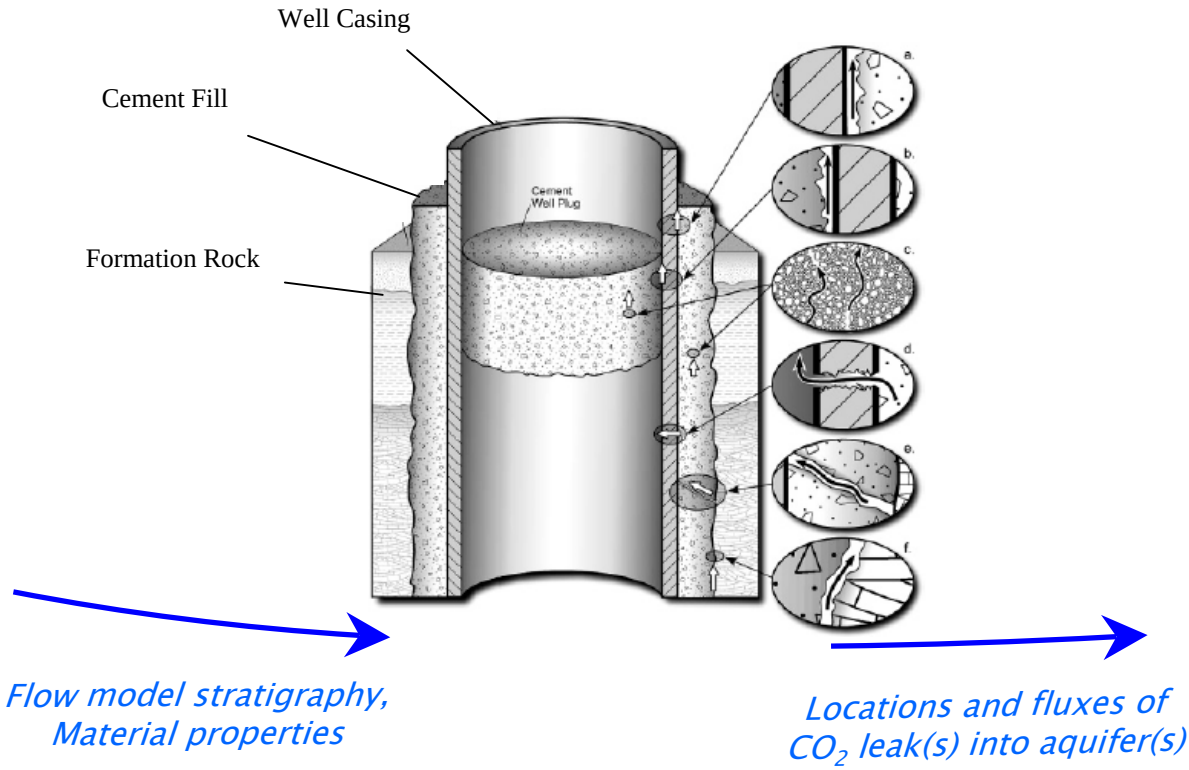


Flow model stratigraphy, Material properties

GIS-based LITHOLOGIC LOG tool constructs local stratigraphy based on borehole location and geologic layers; provides tables of formation top and bottom elevations

B. Build Scenario Library Using Models of Borehole Failure and CO_2 Flow (Part 2)

Model of Seal Failure and Flow within Borehole



Potential leak pathways along an abandoned well; interfaces between formation rock, cement seal, and casing are emphasized (adapted from Nordbotten et al. 2005)

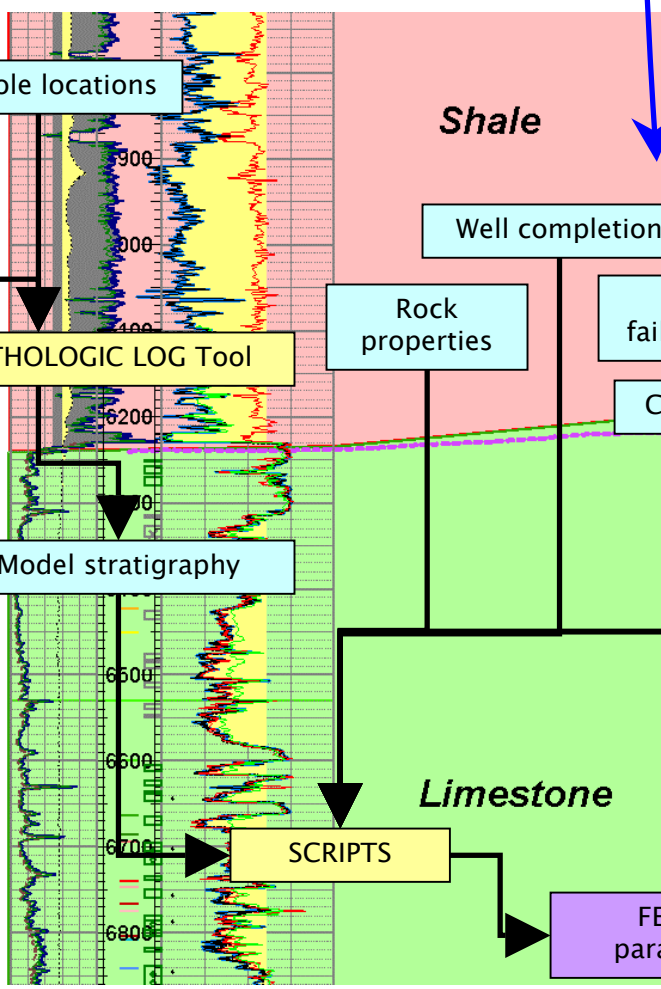
B. Build Scenario Library Using Models of Borehole Failure and CO_2 Flow (Part 3)

ZERT Knowledge Base

Rock properties, Well completion

Locations and fluxes of CO_2 leak(s) into aquifer(s)

Automated Model Input



Borehole locations

GIS stratigraphic surfaces

GIS-Based LITHOLOGIC LOG Tool

Model stratigraphy

Well completion

Rock properties

Borehole failure criteria

Cement properties

SCRIPTS

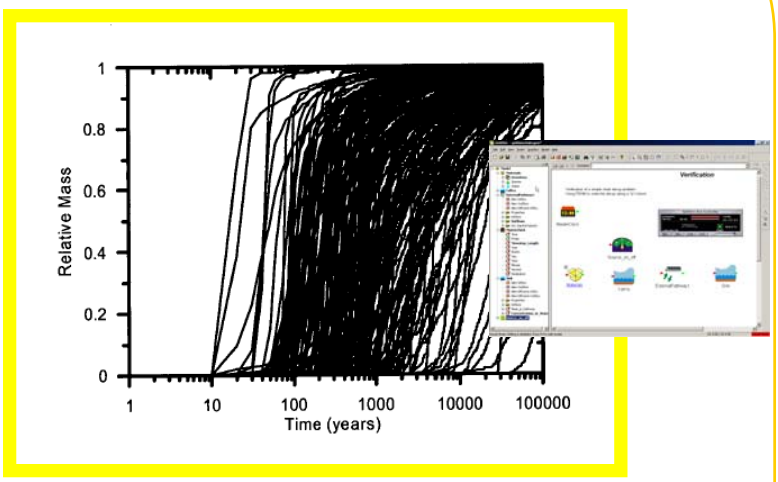
FEHM input parameter files

FEHM
CO_2 / water / heat / reaction / stress / flow model

B. Build Scenario Library Using Models of Borehole Failure and CO_2 Flow (Part 4)

Systems Model

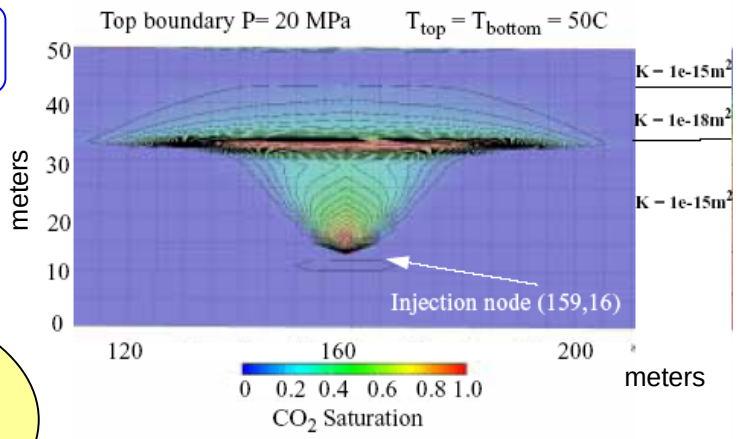
For each model realization:
- CO_2 migration rate, extent
- CO_2 release rate



GoldSim:
- stochastic input sampling
- composite probability of CO_2 migration and release

CO_2 Flow Model

FEHM
CO_2 / water / heat / reaction / stress / flow model

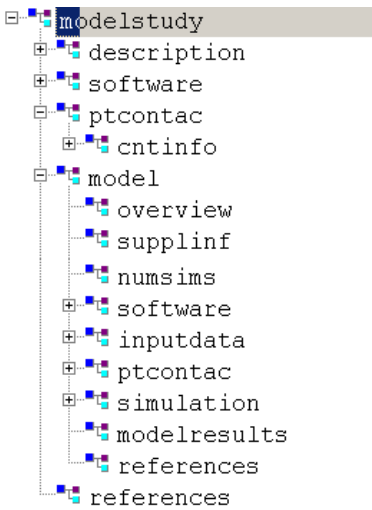


2-D FEHM calculation of CO_2 flow in reservoir (2.6×10^4 kg CO_2, 3000 days)

ZERT Knowledge Base

B. Build Scenario Library Using Models of Borehole Failure and CO_2 Flow (Part 5)

Model documentation



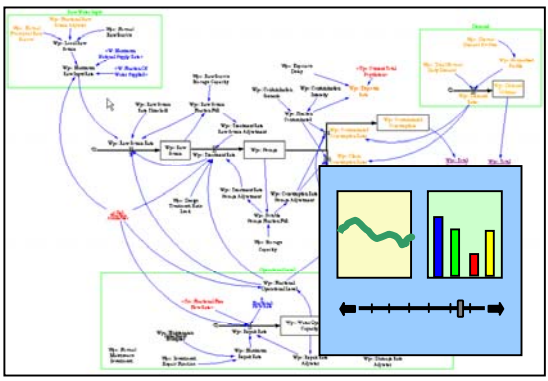
Model Warehousing

Model documentation (metadata) using XML

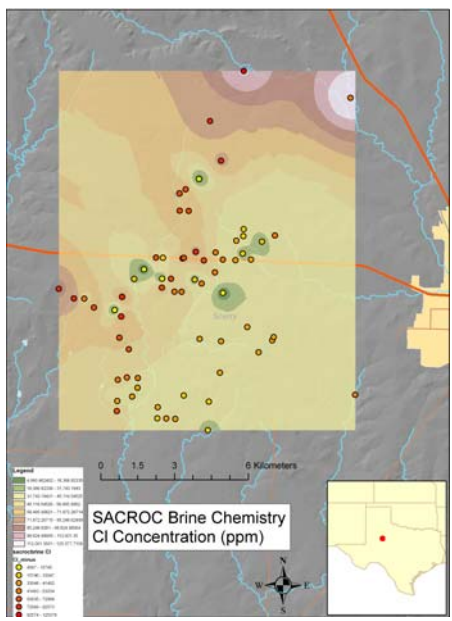
For each model realization:
- CO_2 migration rate, extent
- CO_2 release rate

C. Provide Decision Support Based on Probability of CO_2 Release and System Behavior

Dynamic System Model



VenSim: Economic models, infrastructure, risk assessment

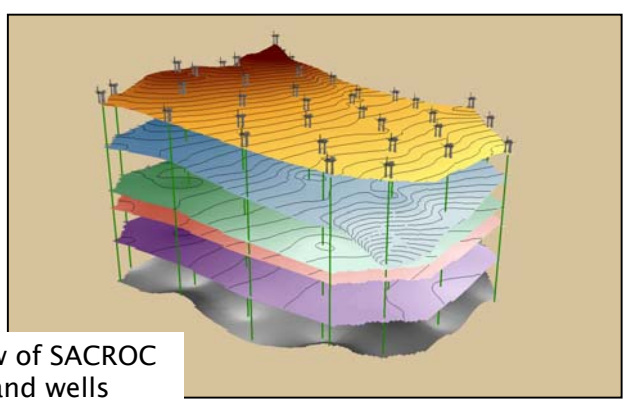


Visualization

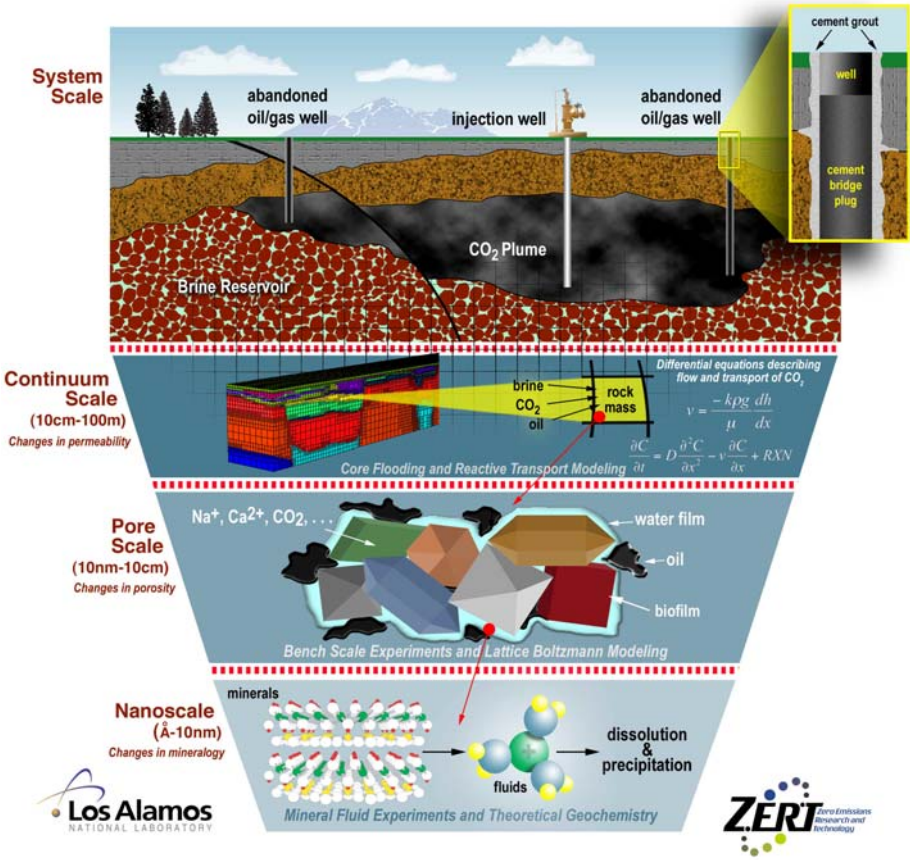
GIS: visualization of data and model results in a geographic framework

Abstracted model results

ZERT Knowledge Base



ArcScene view of SACROC stratigraphy and wells



GIS provides scale transitions among field, laboratory, and modeling activities.

IV. Conclusions

- **GIS** provides framework for **decision support cyberinfrastructure**: data management, model pre-processing and coupling, and visualization.
- **Knowledge Base** integrates field and laboratory data, MMV, and numerical modeling.
- **Systems Models** abstract higher level behavior: risk assessment, management options, and economics.
- **Borehole integrity case study** integrates data and models for evaluation of potential CO_2-release pathways at SACROC Unit.

Collaborators

LANL EES Division: EES-6, EES-9
LANL C Division: C-ADI, C-INC, C-CSE
U.S. DOE / NETL
Idaho National Laboratory
Pacific Northwest National Laboratory
Sandia National Laboratory
NATCARB / Univ. of Kansas
Montana State University

Big Sky Carbon Sequestration Partnership
Southwest Carbon Sequestration Partnership
Kinder Morgan CO_2 Company, L.P.
South Dakota School of Mining and Technology
University of Wyoming
University of Utah
New Mexico Tech
Colarado School of Mines
Princeton University

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