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Quarterly Status Report: Injection and Reservoir Hazard Management: The Role of Injection-Induced Mechanical Deformation and Geochemical Alteration at In Salah CO2 Storage Project

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Status Report
Quarter End, December 2009

Injection and Reservoir Hazard Management: The Role of Injection-Induced Mechanical Deformation and Geochemical Alteration at In Salah CO_2 Storage Project

WORK PERFORMED UNDER AGREEMENT

LLNL – FEW0149

SUBMITTED BY

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Auspices Statement

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1. EXECUTIVE SUMMARY

The In Salah Gas Project (ISG), a joint venture (JV) of BP, Sonatrach, and StatoilHydro, has two fundamental goals: (1) 25-30 years of 9 bcfy natural gas production from 8 fields in the Algerian Central Sahara, and (2) successful minimization of the associated environmental footprint by capture and subsurface isolation of the excess CO_2 extracted from production streams and subsurface isolation in the Krechba sandstone reservoir. The In Salah project provides an opportunity to study key physical and chemical processes in operational deployment of geological carbon sequestration. The objectives of the research are to study two components relevant to storage effectiveness and operational success at In Salah: Reactive chemistry of the brine-CO2-reservoir-caprock-wellbore system, and the geomechanical effects of large-scale injection on crustal deformation and fault leakage hazards. Results from this work will enhance predictive capability of field performance, provide a new basis for interpretation of geophysical monitoring at In Salah, and provide additional information relevant to the creation of geological sequestration standards. The Joint Industry Partners (JIP: BP, StatoilHydro, Sonatrach) and LLNL will share data and results to achieve the objectives of the proposed work.

The objective of the work performed at LLNL is to integrate LLNL core strengths in geochemistry and geomechanics to better understand and predict the fate of injected CO_2 in the field. The mechanical, chemical and transport properties of the reservoir-caprock system are coupled. We are using LLNL-developed quantitative tools to assess the potential for CO2 migration / leakage caused by injection-induced deformation. The geomechanical work is focused upon fault activation, fluid induced fracturing of the caprock and permeability field evolution of the fractured reservoir. These results will be used in concert with reactive transport calculations to predict the ultimate fate of the CO_2. We will integrate laboratory and reactive transport modeling to assess CO_2 plume migration and partitioning between different trapping mechanisms. Geochemical reactive transport modeling will be used to address multiphase flow (supercritical CO_2 and water), CO_2 dissolution, mineral sequestration, and porosity/permeability changes. The reactive transport portion of the work ultimately couples with geomechanical modeling. In particular, the distribution of the pressure perturbation induced by injection drives the geomechanical response. Subsequently, the geochemical work determines if water-rock interactions eventually enhance or suppress fractures.

A key focus of this work is to establish the site specific interactions of geomechanics, reactive flow and transport. This involves building and refining models of the reservoir and overburden. The models will undergo continual refinement in response to data collected in the field and experiments performed at LLNL and elsewhere.

This project commenced in FY08, with DOE funding starting in April, FY08. We have successfully initiated a cross-disciplinary study of the In Salah CO_2 sequestration project and have met all FY08 and FY09 milestones. Specific accomplishments from this reporting period include:

- Our previous analysis of the uplift above the KB-502 injector has been extended. Firstly, we have continued the simulations out to 3 years post commencement of injection. This period is especially interesting because it includes the shut-in period of that injector. Consistent with observation, our analysis shows a reduction in the mounding about KB-502 post-shut in.

- The wellbore reactive transport model has been revised to include new assumptions concerning cement and formation mineralogy to better match field and laboratory experimental data. The revised model continues to suggest a likely reduction in porosity of an assumed fractured zone existing at the wellbore cement-formation interface. This model was presented at the American Geophysical Union Fall Meeting in San Francisco.

- We prepared presentations and posters for the upcoming JIP Science Advisory Board meeting in Cambridge, U.K. Joseph Morris and Walt McNab will present our latest technical contributions while Bill Foxall has been asked by the JIP serve on the board to provide peer review of the InSAR data.

2. Statement of Project Objectives

OBJECTIVES

The In Salah Gas Project (ISG), a joint venture (JV) of BP, Sonatrach, and StatoilHydro, has two fundamental goals: (1) 25-30 years of 9 bcfy natural gas production from 8 fields in the Algerian Central Sahara, and (2) successful minimization of the associated environmental footprint by capture and subsurface isolation of the excess CO_2 extracted from production streams and subsurface isolation in the Krechba sandstone reservoir. The In Salah project provides an opportunity to study key physical and chemical processes in operational deployment of geological carbon sequestration. The objectives of the research are to study two components relevant to storage effectiveness and operational success at In Salah: reactive chemistry of the brine-CO_2-reservoir-caprock-wellbore system, and the geomechanical effects of large-scale injection on crustal deformation and fault leakage hazards. Results from this work will enhance predictive capability of field performance, provide a new basis for interpretation of geophysical monitoring at In Salah, and provide additional information relevant to the creation of geological sequestration standards. The Joint Industry Partners (JIP: BP, StatoilHydro, Sonatrach) and LLNL will share data and results to achieve the objectives of the proposed work.

SCOPE OF WORK

This study is composed of a comprehensive multi-disciplinary effort that addresses two fundamental challenges to successful geologic CO_2 isolation at In Salah that are equally relevant to the broad range of CO_2 storage scenarios:

1) Quantify CO_2 plume migration and sequestration partitioning among distinct trapping mechanisms within dynamic, complex permeability fields characterized by multi-scale heterogeneity—emphasizing assessment of coupled processes that may lead to early CO_2 breakthrough at production wells.

2) Evaluate geomechanical response and potential supra-reservoir leakage, through faults, fractures and well bores, which may ultimately reach the surface.

The objectives of the study will be accomplished by completing the following activities:

- Construction of reactive transport and geomechanical models
- Batch/mixed flow reactor experiments and modeling
- Plug-flow reactor experiments and modeling
- Field-scale reactive transport modeling
- Fault failure forecasting
- Discrete fracture modeling
- Simulation of microseismicity

Successfully addressing these challenges requires quantitatively representing injection-triggered hydraulic, geochemical and mechanical processes within reservoir, caprock, and well-bore environments. Such representation requires modeling approaches that explicitly integrate these processes. The proposed research will augment and advance the JIP's earlier in-house reservoir simulation work by adding explicit account of permeability evolution due to injection-triggered geomechanical and geochemical processes, which together may lead to significant modification—enhancement or degradation—of reservoir, caprock, and well-bore integrity. Specifically, dynamic pressure perturbations may cause rapid aperture modification of pre-existing faults and fractures through mechanical deformation, while imposed chemical disequilibria may cause concomitant, yet kinetically retarded, aperture modification through fluid-rock mass transfer and dependent volume alteration of bounding matrix blocks. Understanding and quantifying this complex interaction of geomechanical and geochemical contributions to permeability evolution lies at the heart of developing computational capabilities that accurately forecast the long-term isolation performance of CO_2 storage sites.

TASKS TO BE PERFORMED

Our research plan includes reactive transport and geomechanical modeling over a range of scales and builds upon systematic experimentation. We will employ a set of LLNL-developed computational tools well suited to these problems.

Task 1.0 – In Salah Storage Project Data Acquisition, Interpretation, and Information Exchange

Predictive modeling efforts rely on accurate characterization of the subsurface environment. This component of our research will involve obtaining/interpreting available data from the JIP relating to the geochemical, mechanical and hydrologic properties of the reservoir, caprock and overburden. These data will provide a framework for our subsequent experimental and modeling efforts.

Subtask 1.1 Data Acquisition

BP has provided provisional agreement to share various kinds of data with LLNL to execute the tasks discussed above (see below). These data will be provided at the earliest availability in order to give investigators sufficient time to meet key milestones and deliverables. BP will maintain propriety over release and sharing of primary data and BP prior models. Data derived from new simulations of these models will be owned by LLNL, but for a period of 2 years after generation of new derived data and results publication of these data will require formal BP approval.

Critical information required for predictive geomechanical modeling includes the following:

- Orientation and magnitude of the in-situ stress tensor
- 3D fault geometry as interpreted from seismic data and well logs
- Orientation and estimated densities/apertures of pre-existing and drilling-induced fractures
- Reservoir and caprock mechanical constitutive properties
- 3D velocity model
- Structural history
- Waveforms, locations, and source moments from injection-induced micro seismic events

For reactive transport modeling, the preceding list must be augmented to include (ideally) all of the following:

- Porosity/permeability ranges and their degree/style of heterogeneity

- Detailed mineralogy/petrography, including trace silicates/oxides/sulfides, solid-solution compositions (e.g., for clays), cementation characteristics, etc.
- Detailed chemical analyses of the reservoir aqueous phase (major/trace elements)
- Sampling locations for the above data (obtained from core and fluid samples)
- Current pressure-temperature conditions
- CO_2 influx parameters: projected rates, duration, and injection well locations
- CO_2 compositional parameters: impurity concentrations
- Local and regional hydrologic flow gradients
- Capillary entry pressure data for caprock lithologies
- Core samples from the reservoir and caprock for experimental/modeling studies
- Geophysical monitoring data that may delineate plume geometry as a function of time
- Residual CO_2 saturations that characterize the Krechba reservoir
- Location of the initial and current CH_4-water contact

Subtask 1.2 Data Interpretation

We will use the data supplied by the JIP to construct numerical models of the reservoir, caprock, and overburden. Critical components of this process will include incorporating geological structure and heterogeneity into our models and developing boundary and initial conditions that are representative of field conditions. These models will form the basis for our reactive transport and mechanical deformation simulations detailed below.

Subtask 1.3 In Salah Operator Information Exchange

Throughout the duration of the project, we will continue to exchange results and data with the JIP. This ongoing communication will facilitate refinement of our models and provide insights to the JIP regarding future data acquisition.

Task 2.0 Reactive Transport Studies

Our reactive transport studies will combine modeling and experimental components to provide improved predictions of CO_2 plume migration, permeability evolution, and isolation performance at In Salah. Our approach is two-fold: (1) conduct and model batch, mixed-flow, and plug-flow reactor experiments using representative reservoir and caprock samples, and (2) carry out field-scale 2- and 3-D reactive transport simulations of

CO_2 injection into the Krechba reservoir. The proposed research builds upon and extends our Sleipner modeling studies (Johnson et al., 2004a) and CCP-I work on simulating long-term caprock integrity (Johnson et al., 2005a); it also leverages our Frio work (Knauss et al., 2005; Kharaka et al., 2006) and experience conducting integrated modeling/ experimental studies (Johnson et al., 1998, 2005b).

Subtask 2.1 Batch/mixed flow reactor studies

These analyses are designed to assess CO_2-dependent chemical and porosity/permeability evolution (1) in the vicinity of the reservoir/caprock interface, and (2) within both the reservoir and caprock. . For investigating the reservoir/caprock interface, the sample chamber will contain crushed reservoir and caprock material; for investigating completion cement, it will contain an inner cylindrical core of fresh cement surrounded by either crushed Krechba reservoir or caprock material. For both sets of batch and mixed-flow experiments, the chamber will initially be filled with CO_2-saturated brine at field P-T conditions. In the batch (closed system) runs, this initial condition will be allowed to steep over an appropriate time frame; in contrast, the mixed-flow (open system) runs will be characterized by continuous fluid stirring (to minimize compositional gradients), influx, and withdrawal at controlled rates. Thus, the batch experiments represent diffusion-dominated reaction progress (no advective fluid flow; i.e., relatively minimal chemical/permeability evolution), while the mixed-flow experiments represent advection-dominated reaction progress (continuous fluid flow; i.e., relatively maximal evolution). In all of these experiments, fluid chemistry will be sampled during the runs and mineral alteration products will be sampled and analyzed post-mortem. Agreement between measured and predicted chemical and permeability evolution will be optimized by fine-tuning key thermodynamic, kinetic, and hydrologic parameters within uncertainty limits.

Subtask 2.2 Plug-flow reactor studies

This analysis is designed to assess CO_2-dependent chemical evolution along the cement/reservoir, cement/caprock, and reservoir/caprock interfaces as well as permeability evolution within the reservoir and caprock damage zones. The sample chamber will be configured such that one longitudinal half (parallel to flow) is occupied by representative cement and the other is divided into equal-parts crushed Krechba reservoir and caprock material. Metered flow of CO_2-saturated brine will be restricted to the crushed-material half and therefore will interact with cement only along its interfaces with sandstone and shale. This set-up represents a physical analog to the cement contact with reservoir and caprock damage zones; hence, it provides a forum for evaluating chemical evolution that attends advective flow of carbonated brine through these zones as well as its diffusive migration into cement. Data collected to assess such evolution will include time-dependent effluent fluid compositions as well as post-mortem mineralogical and petrographic analyses of cement, sandstone, and shale. Real-time permeability evolution of the sandstone/shale half will be retrieved from data recorded by the differential pressure transducer. Experimental P-T conditions will approximate those of the reservoir/caprock interface at Krechba. Agreement between measured and predicted chemical and permeability evolution will be optimized by fine-tuning key thermodynamic, kinetic, and hydrologic parameters within uncertainty limits.

Subtask 2.3 Field-scale integrated reactive transport and geomechanical studies

Grounded by the preceding work, two sets of field-scale reactive transport simulations will be carried out, each spanning both active-injection and post-abandonment phases of the isolation process. The first set will address plume migration, sequestration partitioning among distinct hydrodynamic, solubility, and mineral trapping mechanisms, and permeability evolution. Here, the focus will be on quantifying the effects of geochemical and geomechanical processes unconsidered within earlier JIP in-house reservoir simulation efforts. Particularly important are their potential impacts on plume arrival time at the gas accumulation, reservoir injectivity, storage capacity, and caprock seal integrity. To the extent feasible (from both technical and proprietary standpoints), 2- and 3-D simulation domains will be consistent with—and possibly extracted directly from—the same site geologic model used in the JIP's earlier in-house reservoir simulation work; i.e., our EarthVision/NUFT interface will be used to translate detailed lithologic heterogeneity directly from the site geologic model into NUFT spatial domains.

In this first set of simulations, the effect of geomechanical processes on reservoir/caprock permeability evolution will be assessed using the unidirectional NUFT/LDEC interface developed under CCP-1 (Johnson et al., 2005a), which translates injection-triggered pressure history into the corresponding effective stress and fracture aperture evolution. This translation will be carried out under the Geochemical modeling task "caprock deformation and fracture", as described below. At present, this geomechanical evolution (LDEC) is not back-coupled into the multiphase flow and reactive transport model (NUFT); i.e., the dependence of permeability, fluid flow, and pressure history on concomitant geomechanical aperture evolution is not represented. As a result, the magnitudes of predicted pressure increase and aperture widening represent upper-limit values, which provide the most critical bound on anticipated performance.

The second set of simulations will address potential CO_2 migration within the localized well-bore environment. In these models, particular attention will be paid to capturing the observed radial extent and pre-injection permeability enhancement of reservoir and caprock well-bore damage zones. The focus will be on quantifying long-term chemical and permeability evolution within these zones, along cement/reservoir and cement/caprock interfaces, and within the cement itself. Particularly significant is potential leakage through gas production well-bore environments, which will ultimately be exposed to the replacement CO_2 accumulation.

Task 3.0 Geomechanical Studies

Fractures and faults are expected to play an important role in plume migration within the reservoir and provide potential pathways for leakage of CO_2 from the reservoir. We will develop discrete fracture network models that are representative of: 1) the known structural geometry of major faults and fractures in and above the reservoir and 2) conceptual models of caprock structure. With these discrete fracture models, we will use LLNL's proprietary LDEC code (Morris et al., 2003; Johnson et al., 2004, 2005a) to calculate fluid-pressure driven deformations of the fractured rock mass at different scales. LDEC can be used to simulate normal and/or shear deformation along individual fractures or faults as well as networks of fractures with arbitrary orientation, length, and mechanical properties. All of the elements (rock blocks) can deform independently potentially resulting in slip and/or dilation of existing fractures due to changing pore pressures. Coupling LDEC with a recently developed discrete-fracture-network flow code (FracHMC) that accommodates stress-induced changes in transmissivity (Detwiler et al., 2006) will provide estimates of changes in effective permeability caused by altered transmissivities of individual fractures within the fracture networks.

Subtask 3.1 Fault/fracture studies

Given the geometry of major faults and fractures in and above the reservoir and estimates of the in-situ stresses, we will use LDEC to forecast the minimum change in effective stress needed to induce slip along portions of the fault (e.g., Wiprut and Zoback, 2002; Chiaramonte et al., 2006). This will require populating the large-scale fracture network model with mechanical properties that are representative of the different formations within the reservoir and overburden. Then, incrementally increasing pore pressures within regions of the reservoir will eventually lead to slip along one or more of the faults in the system. Using this approach, we will develop estimates of failure pressures along fault elements within the reservoir. It is believed that such fault failure events lead to both induced seismicity and the potential for substantial fluid flow along the fault. This analysis will provide estimates of the magnitude of reservoir pressure perturbations likely to cause slip along major faults, resulting in a potentially major leakage pathway. In addition, LDEC simulations of fault slip will provide estimates of seismic source terms resulting from the slip events, which can then be propagated through the overburden (described below) to provide simulated seismic signals at the surface or in boreholes.

Injection-induced increases in pore pressure lead to reservoir expansion and deformation of the caprock, which in turn may cause new and/or pre-existing fractures to open by induced tensile (Mode I) or shear stresses (Modes II and III). Furthermore, induced strain along weak discontinuities, such as fractures or bedding planes within the caprock can damage well-bore cements and casing. We will quantify the potential significance of these compromises to seal integrity at In Salah by using LDEC to predict the evolution of fracture apertures that corresponds to that of pore fluid pressure, as predicted by the field-scale reactive-transport modeling task, described above. The distribution and transmissivity of fractures that are created and/or opened by injection-imposed stresses will provide quantitative estimates long-term CO_2 leakage from the reservoir. In addition, a first-order quantitative assessment of aperture evolution due to explicitly integrated geochemical and geomechanical components will be carried out as a fundamental project integration task (see below).

Subtask 3.2 Injection-induced seismicity studies

The outputs from LDEC described above also serve as the basis for seismic modeling. The orientation and magnitude of local stresses, and fracture orientations provide the initial conditions for modeling seismic events. Shear failures, induced by changing pore pressures, produce seismic events that provide source terms for predicting seismograms through wave propagation from the reservoir to the surface. LLNL has developed a new 3D wave propagation code, WPP, that runs much faster and with greater stability than prior codes (Petersson et al., 2006). We will model the failure events as seismic source terms and match the modeled wavefields with seismograms recorded at In Salah. This will provide a tool for inverting microseismic results to better interpret the relation between monitored events and the distribution of CO_2 and pressure at depth.

Task 4.0 Integration of Reactive Transport and Geomechanical Study Results for Field-scale Interpretation

Ultimate enhancement or degradation of reservoir, caprock, and well-bore integrity hinges on the relative impact and rates of concomitant geochemical and geomechanical contributions to permeability evolution in these environments. In lieu of fully (bi-directionally) coupled reactive transport and geomechanical modeling capabilities, we have developed an aperture-based conceptual framework that facilitates explicit integration of these components, which in turn permits first-order predictive assessment of ultimate permeability modification for any site-specific CO_2 injection scenario (Johnson et al., 2003, 2004). In this integration task, results from the field-scale reactive transport and caprock deformation modeling work will be dovetailed within this framework to estimate net permeability evolution due to predicted geochemical and geomechanical contributions at In Salah. The results from both the individual and integrated studies can contribute information to the development of field operational protocols, both in the context of the In Salah site but potentially for broader application internationally.

DELIVERABLES

The following deliverables will be provided:

- Project Management Plan (Due at the start of the FWP)
- Progress Reports (Due Quarterly and shall at a minimum document technical, cost, and schedule status)
- Yearly Topical Reports (Due yearly for FWPs with greater than 18 months duration)
- Conference Papers/Proceedings (A copy of any conference papers/proceedings are required to be submitted)
- Final Scientific/Technical Report (Due at the completion of the FWP, should be a comprehensive document covering all years of the FWP)

BRIEFINGS/TECHNICAL PRESENTATIONS

LLNL will prepare detailed briefings for presentation to the NETL Project Manager. Briefings will be given by LLNL to explain the plans, progress, and results of the technical effort.

3. Major Milestone Status

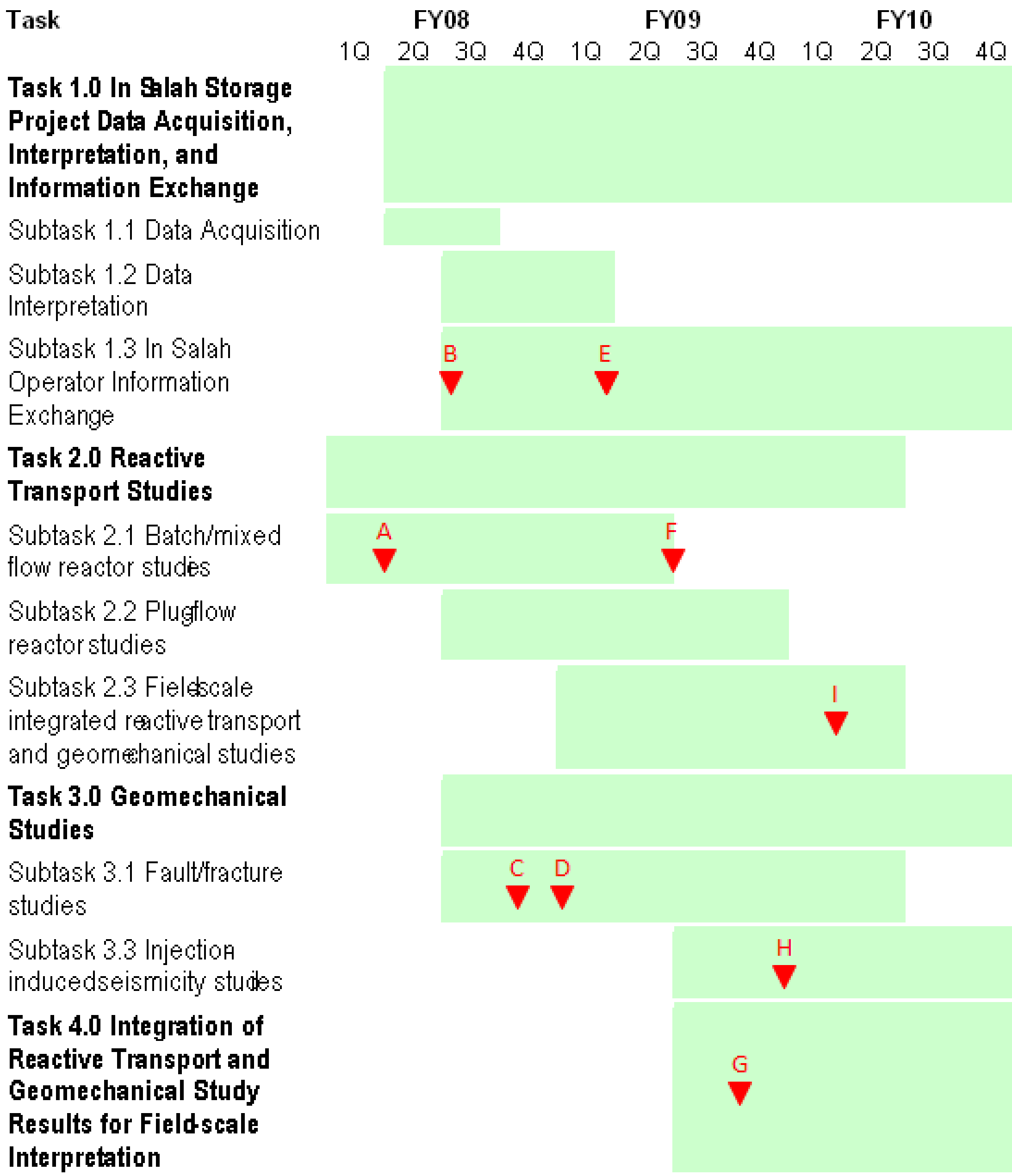
MILESTONE LOG

FY08 Milestone Descriptions	Schedule Request	Completion Date/achievement
A. Initiate design of new experimental reactor apparatus to study In Salah demonstration project reservoir, caprock, and well-bore integrity	12/31/07	MET. A kick-off meeting was held with LLNL investigators to discuss reactor design and reactive chemistry experiments.
B. Establish requirements for In Salah demonstration project data and information exchange through technical meeting with BP	3/31/08 New: 6/30/08	MET. A kick-off meeting was held at LLNL on 6/5/08 with BP/StatoilHydro to exchange data and discuss project goals.
C. Initiate construction of discrete fracture network model for In Salah demonstration project fault/fracture networks in reservoir and overburden	6/30/08	MET: An initial discrete fracture model has been developed using BP data
D. Initiate development of preliminary failure envelope calculations for In Salah demonstration project fault/fracture networks	9/30/08	MET: Initial simulations of fracture response to fluid injection have been performed.

FY09 Milestone Descriptions	Schedule Request	Completion Date/achievement
E. Provide progress update to BP of initial phase of geomechanical and geochemical analysis through technical meeting	12/31/08	MET. BP hosted a workshop on October 15-16, 2008 in London attended by key participants from the JIP and currently-funded researchers. LLNL discussed the status of their results to date and established working relationships with other groups.
F. Complete initial reactor studies of In Salah demonstration project well-bore	3/31/09	Met. The initial series of reactor studies have been completed.

cements		Results documented in this report.
G. Initiate integration of reactive transport and geomechanical study results for In Salah demonstration project fault/fracture networks	6/30/09	Met. We have simulated the geomechanical response of the overburden including fault to the predicted porepressure distribution from the reactive transport calculations
H. Initiate injection induced seismicity study for In Salah demonstration project	9/30/09	Met: We have developed a procedure for converting results from geomechanical simulations into corresponding seismic events

FY10 Milestone Descriptions	**Schedule Request**	**Completion Date/achievement**
I. Complete initial reactive transport simulations of wellbore integrity	12/31/09	Met: We have simulated a number of scenarios involving flow through hypothetical fractures between the cement and caprock.


Task
FY08
FY09
FY10
1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q
Task 1.0 In Salah Storage Project Data Acquisition, Interpretation, and Information Exchange
Subtask 1.1 Data Acquisition
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Task 2.0 Reactive Transport Studies
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I
Task 3.0 Geomechanical Studies
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Subtask 3.3 Injection inducedseismicity studies
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Task 4.0 Integration of Reactive Transport and Geomechanical Study Results for Field-scale Interpretation
G

4. Chronological Listing of Significant Events and Accomplishments

Significant Events

Date	Description
10/18/2009	Susan Carroll presented an invited talk at GSA on the experimental geochemistry and reactive transport modeling efforts.
10/29/2009	Videoconference between LLNL, JIP, and University of Liverpool
11/15/2009	Susan Carroll presented a talk at NETL on the experimental geochemistry and reactive transport modeling efforts.
12/14/2009	(1) Invited presentation by Joe Morris on mechanical deformation at an AGU special session on CO_2 sequestration; (2) wellbore reactive transport model presented at AGU poster session by Walt McNab
12/15/2009	Telecon between LLNL and JIP

Accomplishments

Date	Description
12/2009	(1) Additional temporal extensions to NUFT model; (2) Revisions to the wellbore cement mineralogy realizations in the reactive transport model

5. Reporting Period Summary Accomplishments

In support of Task 1.0, we have participated in teleconferences with members of the JIP, including a videoconference on 29 October. This meeting included participants from the JIP as well as currently-funded researchers from the University of Liverpool. The purpose of the videoconference was to ensure continued communication across participants and to encourage synergies among these different research efforts. In addition, we began preparing presentations and posters for the upcoming JIP Science Advisory Board meeting in Cambridge, U.K.

In support of Task 2.0, additional reactive transport modeling work was conducted to help quantify anticipated changes in porosity, and hence permeability, at the wellbore cement-formation interface. The reactive transport model currently includes a mineralogical model that is consistent with KB-502 mineralogical data as well many of the aqueous phase and solid phase results obtained through our prior laboratory experiments involving cement, Krechba formation materials, simulated Krechba brine, and CO_2. A summary of the modeling approach and results were presented at the Fall Meeting of the American Geophysical Union in San Francisco. Additional experimental results are not available from the reporting period as a result of a laboratory facility move. However, results-to-date were presented at the Geological Society of America Annual Meeting in Portland, Oregon as well as at NETL.

In support of both Tasks 2.0 and 3.0, new NUFT simulations were performed at the reservoir scale. These simulations include the features of earlier model runs (e.g., a hypothetical vertical fault) but have extended our previous analysis of the uplift above the KB-502 injector. The additional simulations include extending the simulation period out to 3 years post-commencement of injection. This period is particularly important because it includes the shut-in period of the KB-502 injector. Our analysis shows a reduction in the mounding about KB-502 post-shut in, which is consistent with observation. This updated model will be used to further investigate potential interactions between the induced fluid pressures from KB-502 and KB-503. As part of this effort, we have also begun refining the model grid based on a new STARS data set.

A summary of previous NUFT and geomechanics modeling results was presented at an invited talk at the Fall Meeting of the American Geophysical Union in San Francisco.

During the reporting period, work continued in support of Task 4.0 (Integration of Reactive Transport and Geomechanical Study Results for Field-scale Interpretation). Specifically, our geomechanical analysis predicts which faults are likely to be conductive and which are expected to act as flow barriers. These results are fed into the reservoir scale simulations to predict the effect upon plume geometry and pressure response within the reservoir. In turn, the reservoir model pore pressure prediction was integrated into a geomechanical model of the overburden to provide a prediction of the associated surface uplift. The current geomechanical simulations include the hydromechanical response due to both fluid in the reservoir and conducting faults.

6.Technical Progress Report

Task 1.0 – In Salah Storage Project Data Acquisition, Interpretation, and Information Exchange

In support of Task 1.0, we have participated in teleconferences with members of the JIP, including a videoconference on 29 October. This videoconference meeting included participants from the JIP as well as currently-funded researchers from the University of Liverpool. The purpose of the videoconference was to ensure continued communication across participants and to encourage synergies among these different research efforts. In addition, we began preparing presentations and posters for the upcoming JIP Science Advisory Board meeting in Cambridge, U.K.

Task 2.0 - Reactive Transport Studies

Overview

The reactive transport modeling task has continued to focus on the wellbore cement-formation interface. The environment surrounding the wellbore is where volumetric changes associated with changes in mineralogy are most likely to affect porosity and permeability, given the reactivity of the cement when exposed to a CO_2-enriched brine. Modeling efforts over the past quarter have involved refining the initial wellbore cement-formation interface model to achieve consistency with field data as well as laboratory results, as presented in previous quarterly reports).

The reactive transport model is based on the geometry and boundary condition definitions shown on Figure 1. CO_2-enriched Krechba brine migrates through a cylindrical damaged/fractured zone at the interface between the wellbore cement and the formation under a constant pressure gradient. Solute transport through the damaged zone occurs by advection and dispersion while transport through the low-permeability wellbore cement and the adjacent formation material occurs through molecular diffusion. The initial cement composition is modeled by equilibrating the Ca-Si-oxides and other constituents (Al_2O_3, $Fe2O_3$, etc.) present in anhydrous Class G cement with the Krechba brine composition, resulting in the formation of portlandite, pseudowollastonite, $MgSiO_3$, and brownmillerite as the principal hydrated cement phases. Upon contact with CO_2-enriched brine, these mineral phases become thermodynamically undersaturated (i.e., favored to dissolve) and are subject to replacement by phases such as calcite and amorphous silica which may become supersaturated and hence precipitate out of solution.

The initial formation mineralogy model is based on the assumption of thermodynamic equilibrium between the Krechba brine chemistry (Table 1) and mineral phases identified through analyses of core collected from drilling of the KB-502 injector well (Figure 2). Two modifications to the reactive transport model include:

- Both pure-phase and solid-solution variations of the mineral assemblage model for carbonate and chlorite phases have been introduced to assist in explaining previous experimental results, specifically Ca, Fe, and Mg chemistry in experiments involving wellbore cement carbonation in combination with formation materials. Specifically, Ca- and Fe-carbonates in the pure phase model are modeled as calcite and siderite, respectively, versus a (Ca,Fe)CO_3 idealized solid solution. For chlorite, the pure-phase Fe- and Mg-end members are represented by daphnite, $Fe_5Al_2Si_3O_{10}(OH)_8$, and clinochlore, $Mg_5Al_2Si_3O_{10}(OH)_8$, respectively, whereas the solid solution model consists of an idealized gradational combination of the two.

- Mineralogical heterogeneities have been included in the formation materials adjacent to the wellbore cement interface. These heterogeneities entail differences in the distributions of major mineral phases such as carbonates, chlorite, and illite and are based on the KB-502 mineralogy data set developed by Armitage (2008).

A comparison of observed and simulated concentrations for key reactive components – calcium, iron, inorganic carbon, magnesium, and silica – is shown on Figure 3. Given variability in the brine composition, the degree of uncertainty as to the identity of all of the relevant specific mineral phases present, and uncertainties inherent in the associated thermodynamic data (and, in particular, the assumption of equilibrium), the modeled initial conditions appear reasonable.

PHREEQC (Parkhurst and Appelo, 1999) and the accompanying LLNL thermodynamic database were used to model all reactions, assuming local equilibrium conditions (i.e., diffusion is the rate-limiting step for reactions in the cement) at an ambient temperature of 95ºC. The reactive transport model was run out to an elapsed time of 2,000 days (5.4 years), representing a cumulative flux of 60 pore volumes of CO_2-enriched brine through the fractured zone.

Table 1. Water quality parameters reported for Krechba Brine samples. Brine chemistry data courtesy of P. Ringrose (StatOil).

Parameter	KB-502z	KB-10
	mg/L	
Al	<3	?
Ba	10	444
Ca	22,400	19,529
Cl	110,250	93,500
Fe	262	290

HCO3	178	371
K	225	550
Mg	5,276	1,526
Na	35,500	34,000
Si	38	16
SO_4	656	3
Sr	506	2,000
pH	5.2	5.52
Density	1.13	1.08

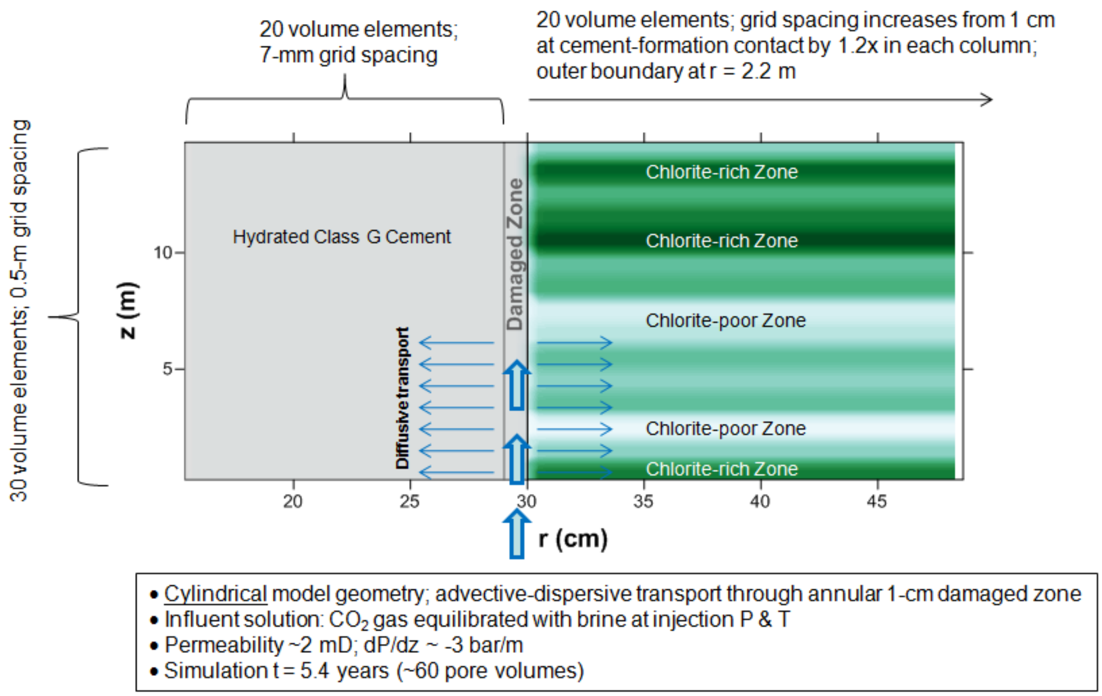

Figure 1. Reactive transport model geometry and boundary condition definitions.

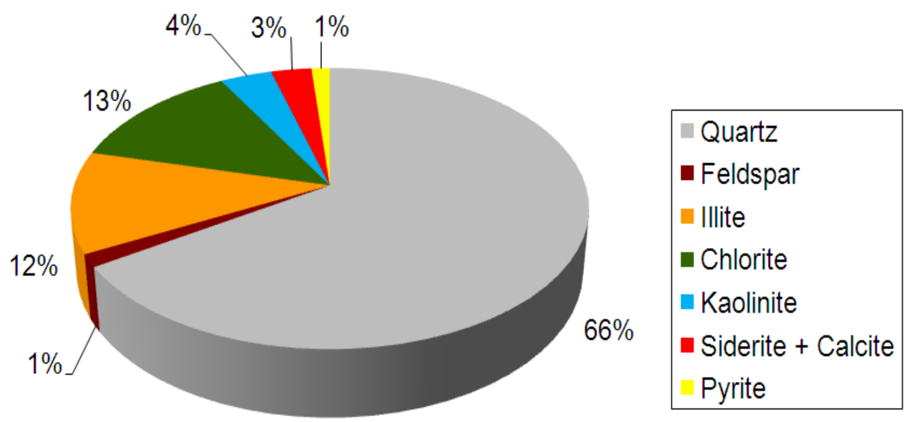

Figure 2. Distribution of mineral phases (by mass), averaged over the core sample intervals evaluated by Armitage (2008).

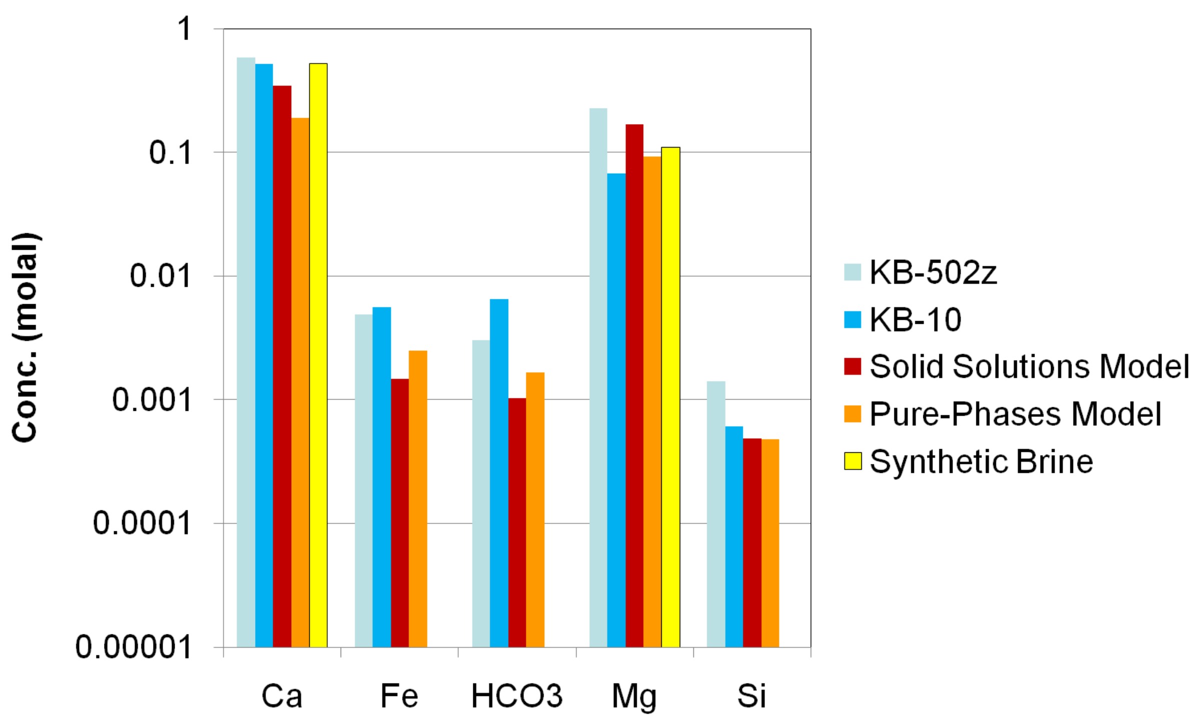

Figure 3. Measured and simulated concentrations of reactive solution components in Krechba brine. Simulated components assume equilibrium with putative mineral assemblage (Figure 2). Synthetic brine concentrations were used as initial conditions in prior experiments.

Model Results

Simulated distributions of the major mineralogical indicators of cement carbonation are shown on Figure 4. The predicted replacement of the original major cement components (portlandite and pseudowollastonite – $CaSiO_3$) by calcite and amorphous silica is supported by previous laboratory studies conducted in the context of the project which identified each of these mineral phases during CO_2 mixing experiments. This mineralogical zonation supports the delineation of the model domain into four regions which can be associated with the prior laboratory results:

- Cement + brine: Cement reacted with brine prior to the introduction of CO_2, represented spatially in the model domain (at t =5.4 years) by the interior fresh cement (i.e., $r < 29$ cm) near the outlet boundary (i.e., $z = 15$ m).
- Cement + sandstone + brine: Formation material adjacent to the wellbore cement interface near the outlet boundary.
- Cement + brine+ CO_2: Carbonated cement near the inlet boundary (i.e., $z = 0$ m).
- Cement + sandstone + brine + CO_2: Formation material adjacent to the wellbore cement interface near the inlet boundary.

Example comparisons between the pure-phase and solid-solution mineralogical models and experimental data for Ca^{2+} and Mg^{2+} are shown on Figures 5 and 6, respectively. Both sets of graphs depict differences in concentration for the particular cation in the above categories versus background. For Ca^{2+}, modeling and experimental results indicate an increase in concentration in brine in contact with the cement prior to introduction of CO_2 (attributable to equilibrium with portlandite), followed by a decline in concentration following contact with elevated CO_2, particularly when formation material is present (attributable to equilibration with calcite). For Mg^{2+}, the pattern of concentration changes is reversed: concentrations decline in contact with cement prior to contact with CO_2 (likely attributable to the formation of an $MgSiO_3$ phase) and increase following introduction of CO_2 (likely attributable to dissolution of Mg-chlorite). However, the predicted increase in Mg^{2+} in the cement + sandstone + brine + CO_2 case has not been observed in the laboratory experiments to date, possibly as a result of kinetic constraints.

For both Ca^{2+} and Mg^{2+}, the solid-solution model results in improved agreement with experimental data only in the specific cement + sandstone + brine configuration (i.e., pre-CO_2 contact). The solid solution model also improves agreement with experimental data with respect to iron (not shown), but these relationships are still being assessed in the context of redox considerations.

The simulated distribution of porosity after 5.4 years, which reflects the integrated volume changes associated with local mineral precipitation and dissolution reactions, is shown on Figure 7. This particular porosity distribution is associated with the solid-solution-based model, but the results from the pure-phase model are very similar. Taken at face value, the porosity distribution suggests a reduction in permeability in the damaged zone downgradient of the boundary inlet. It is important to recognize, however, that this finding depends strongly on the phases included in the model and the associated partial molar volume data.

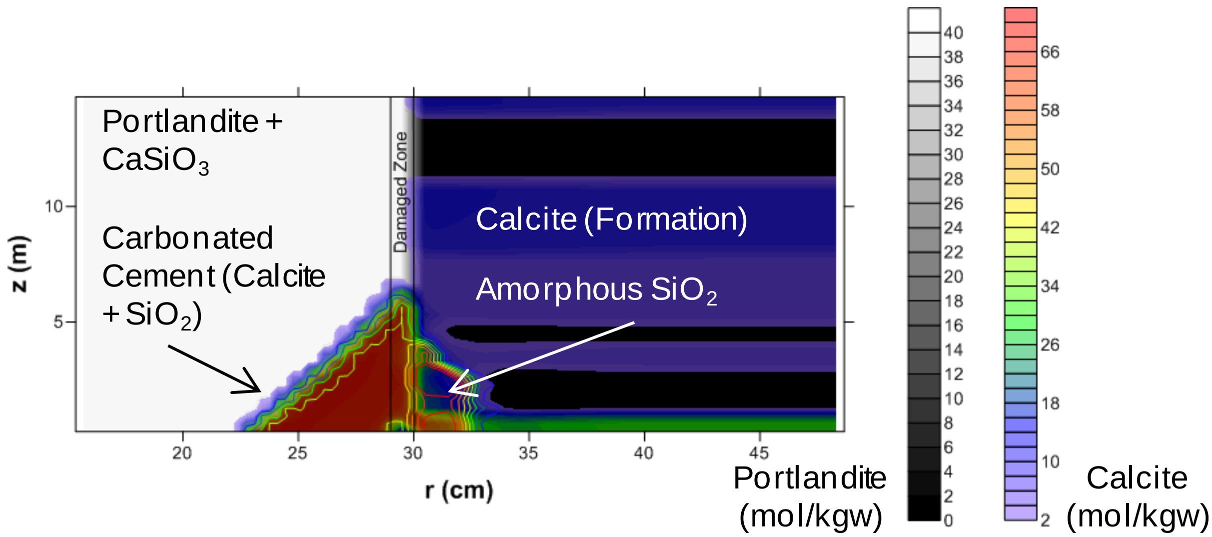

Figure 4. Example model results: mineralogical changes associated with selected silicate and carbonate mineral phases after 5.4 years (approximately 60 pore volumes), solid-solution-based scenario.

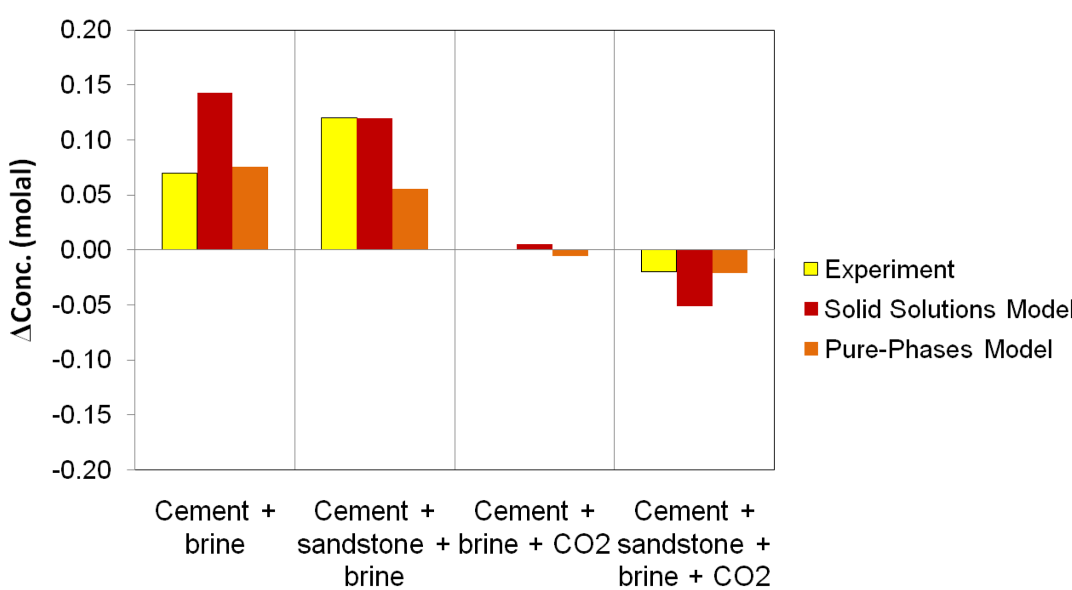

Figure 5. Comparison between modeled and experimentally-measured reactive component concentrations of Ca^{2+} at four locations at *t*= 5.4 years (60 pore volumes): within the cement, near the outlet boundary ("Cement + brine"), within the formation material near the outlet boundary, proximal to the cement-formation interface ("Cement + sandstone + brine"), within the carbonated

cement near the inlet boundary ("Cement + brine + CO_2"), and within the formation material near the inlet boundary, proximal to the cement-formation interface ("Cement + brine + CO_2").

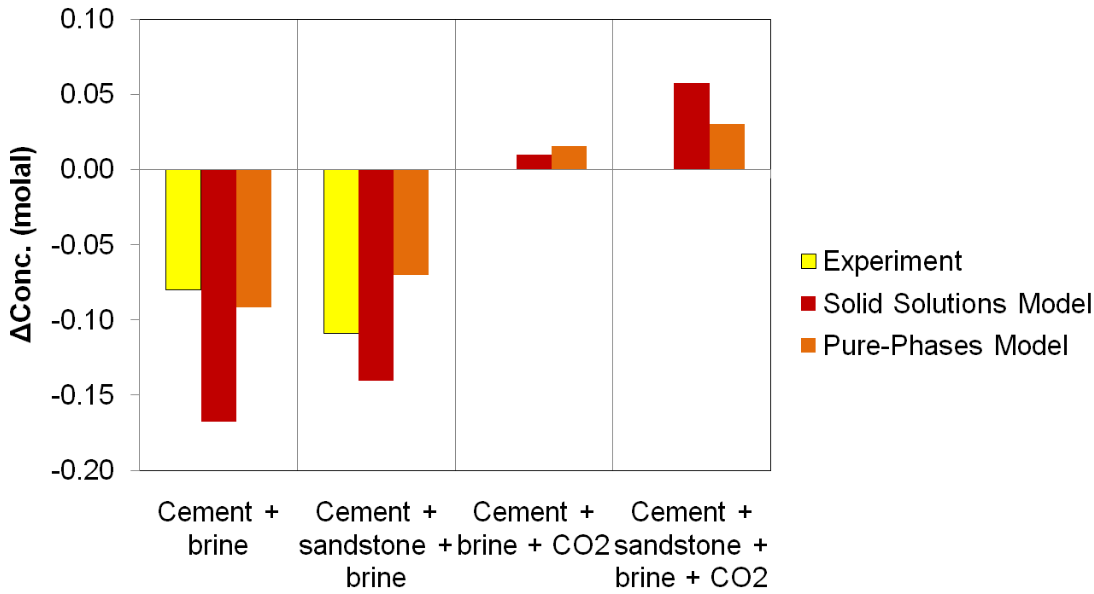

Figure 6. Comparison between modeled and experimentally-measured reactive component concentrations of Mg^{2+} at four locations at *t*= 5.4 years (60 pore volumes): within the cement, near the outlet boundary ("Cement + brine"), within the formation material near the outlet boundary, proximal to the cement-formation interface ("Cement + sandstone + brine"), within the carbonated cement near the inlet boundary ("Cement + brine + CO_2"), and within the formation material near the inlet boundary, proximal to the cement-formation interface ("Cement + brine + CO_2").

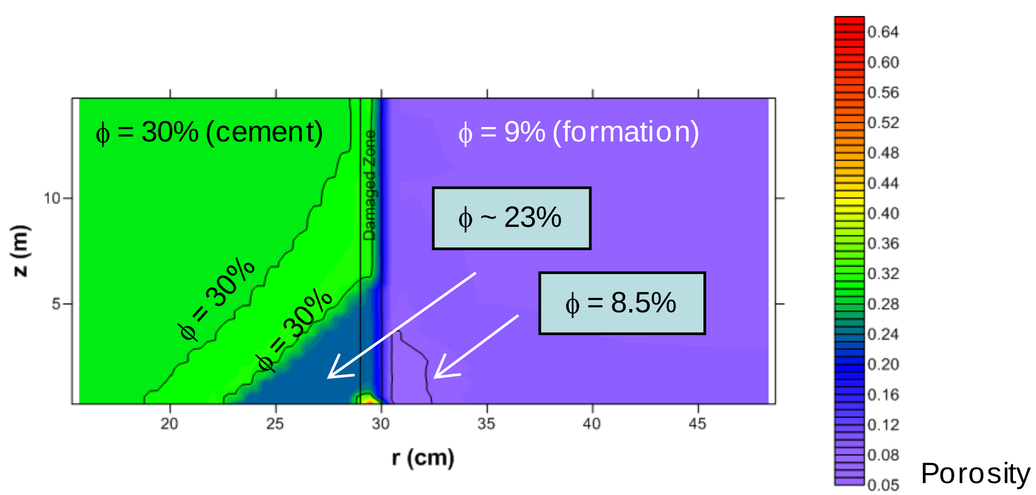

Figure 7. Simulated distribution of porosity at *t*= 5.4 years (60 pore volumes), solid-solution-based scenario.

Geochemical Experiments

There are no new experimental data to report as the geochemistry laboratory was moved to a new facility during the reporting period. New results are anticipated for subsequent reporting periods.

Task 3.0 Geomechanical Studies

Based on the current field-scale flow model at KB-502 region we extended our simulation up to 3 years after the injection starts at the KB-502 well. The pore pressure changes within the reservoir and faults predicted by NUFT modeling were taken as the input to the geomechanical forward model as described in the previous quarter, assuming a fault stiffness of 0.1 GPa/m normal stiffnesses (Figure 8, 9 and 10). These simulations show the expected trend of uplift peaking around the second year and then reducing after that point. This is a consequence of KB-502 being shut-in at that point and the InSAR observations (not shown here) reflect this trend. However, there is also evidence from the InSAR that the deformations due to KB-503 are influencing the KB-502 area and these are not considered by the current model.

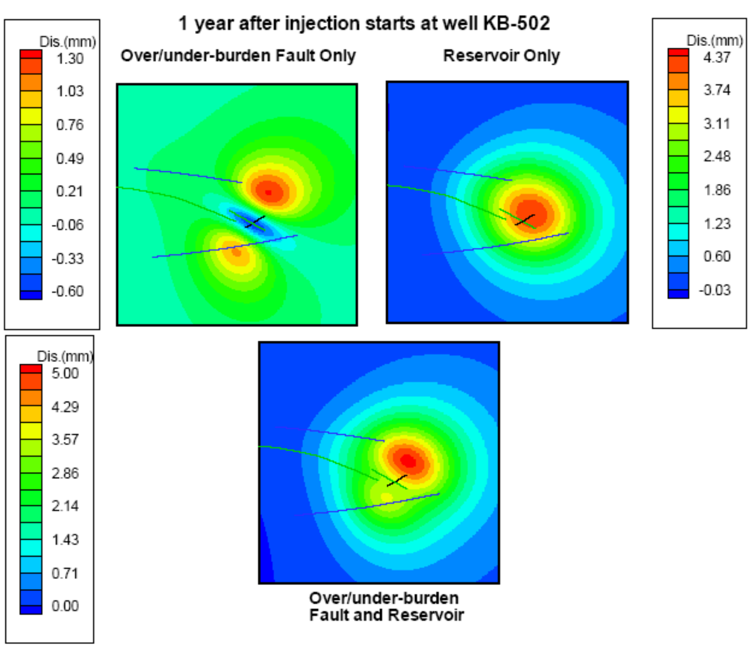

Figure 8: The surface uplift at 1 year after injection starts at KB-502, assuming a normal stiffness of 0.1 GPa/m on the fault.

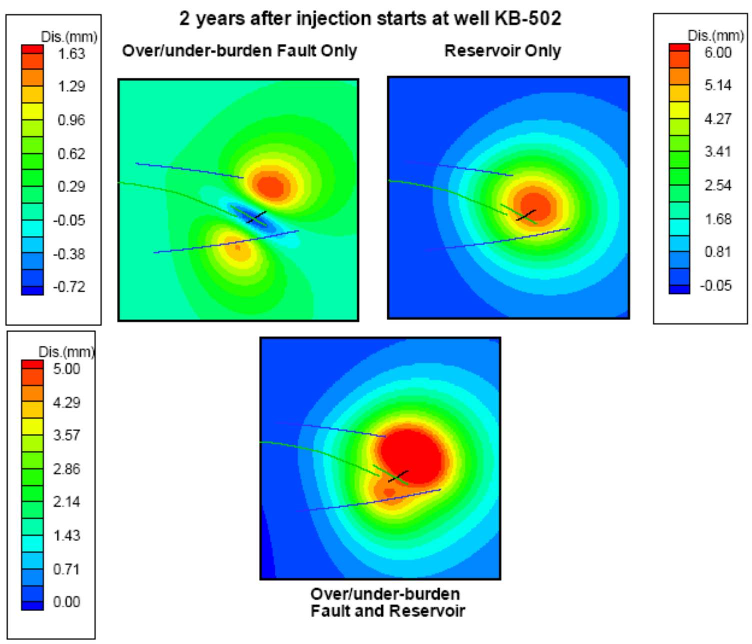

Figure 9: The surface uplift at 2 years after injection starts at KB-502, assuming a normal stiffness of 0.1 GPa/m on the fault.

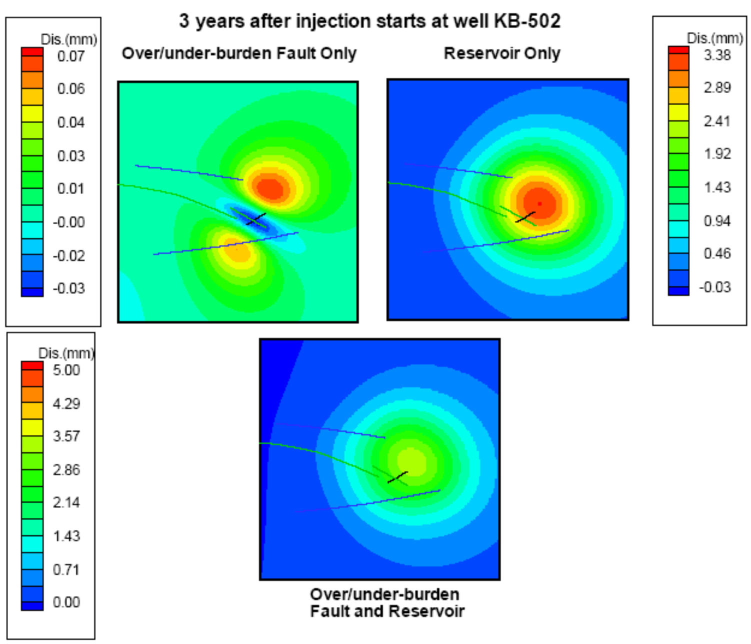

Figure 10: The surface uplift at 3 years after injection starts at KB-502, assuming a normal stiffness of 0.1 GPa/m on the fault.

In addition, we are working with a more extensive model that includes the region about the neighboring KB-503 injector in order to investigate possible interactions between the pressure perturbations about each injector. In the previous quarter, we extended the NUFT mesh to cover this larger domain, however, we had not received the corresponding permeability data from the JIP for this area at that time. Recently we received new STARS model with extended geologic model domain, particularly near KB-503 area. The STARS model has been processed and converted into NUFT model. Figure 11 illustrates the preliminary refined NUFT mesh generated based on STARS data. Currently we are interpreting the preliminary simulation results and further improving the model.

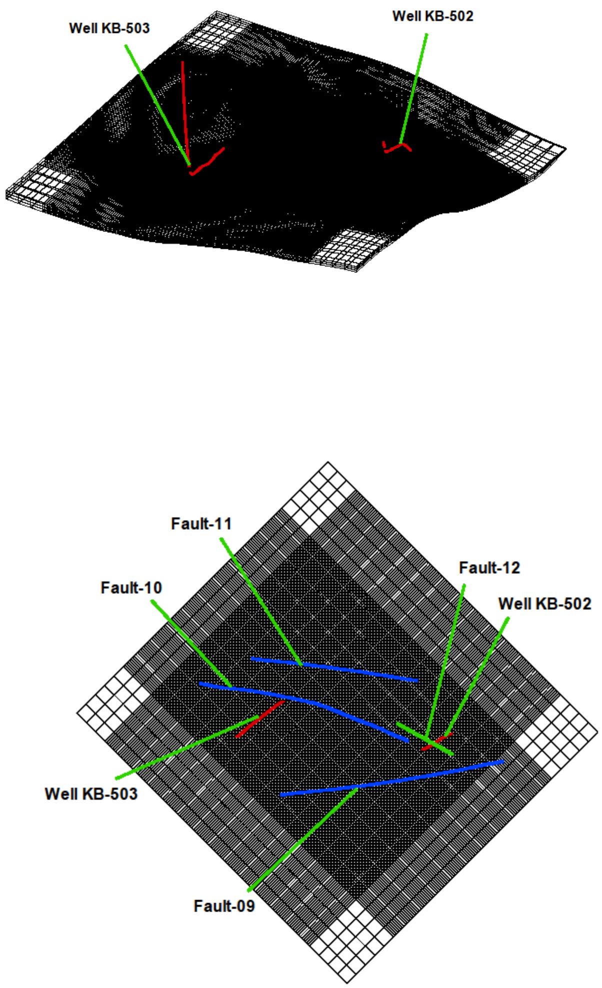

Figure 11: The preliminary refined NUFT mesh generated based on STARS data

Initiation of induced seismicity studies

We have communicated with the JIP and technical partners and have established a mechanism for transferring the microseimic data as it is made available. Only baseline, pre-injection was available for the reporting period and, consequently, no simulations have been performed yet.

Task 4.0 Integration of Reactive Transport and Geomechanical Study Results for Field-scale Interpretation

During the reporting period, preliminary work was also performed in support of Task 4.0. Specifically, geomechanical analysis was used to predict which faults are likely to be conductive and which are expected to act as flow barriers. These results were fed into the reservoir scale simulations to predict the effect upon plume geometry and pressure response within the reservoir. In turn (as reported for Task 3.0), the reservoir model pore pressure prediction was integrated into a geomechanical model of the overburden to provide a prediction of the associated surface uplift.

Acknowledgements

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7. Assessment of Current Status

The project continues to be on time and budget. With an LLNL laboratory move completed, additional experimental geochemistry data will become available to support the reactive transport modeling effort next quarter.

8. Plans for the Next Quarter

New overburden models, fault maps, and microseimic data are expected to become available in the next quarter as a result of recent data acquisitions made by the JIP. The experimental program will continue to focus upon studying the reactivity of rock and cements from the Krechba field; we will explore the feasibility of extending our experimental effort to address *in situ* redox conditions and, separately, a possible flow-through reactor experiment. The geomechanical studies will continue to investigate the mechanical response of the overburden and upper portion of the storage system including progressively more detailed heterogeneity, including the influence of a layered overburden model upon surface deformation. The reservoir model will be extended to include both the KB-503 and KB-502 area using new STARS data. Lastly, it is expected that microseimic data from Krechba will be available in the next quarter and the data obtained will be transmitted to LLNL under existing data sharing agreements.

9. Attachments

Carroll, S. and W. McNab,, “An Experimental and Modeling Study of Wellbore Integrity,” Invited presentation at the Geological Society of America Annual Meeting, October 18th, Portland, Oregon, 18 October 2009.

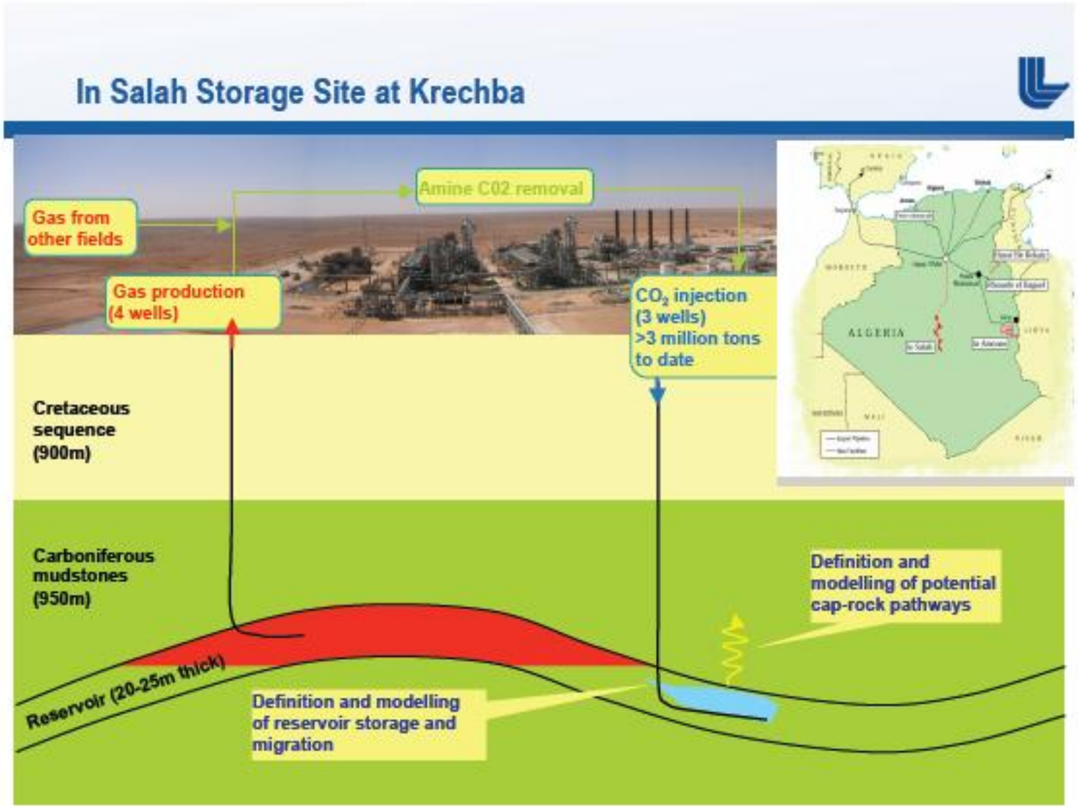
Morris, J., McNab, W., Hao, Y. and Foxall, W., “Hydromechanical Simulations of Surface Uplift due to CO2 Injection at In Salah,” Invited presentation to AGU 2009 Fall Meeting, San Francisco, California, 14-18 December, 2009.

AN EXPERIMENTAL AND MODELING STUDY OF WELLBORE INTEGRITY

October 18, 2009

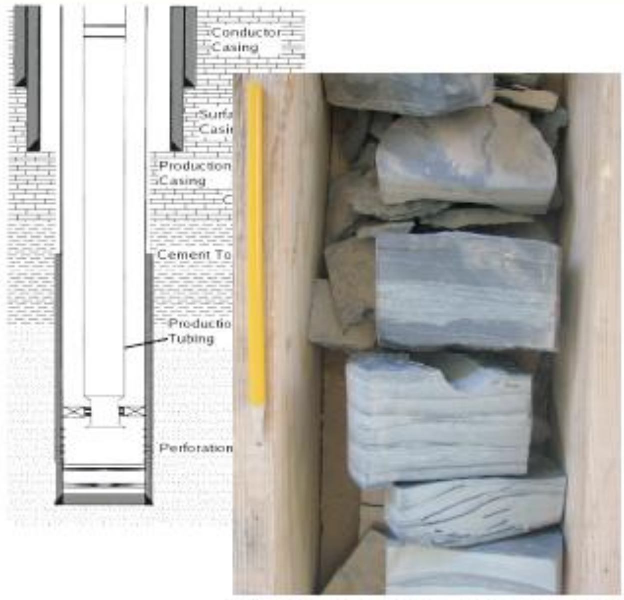
Susan Carroll and Walt McNab
Lawrence Livermore National Laboratory

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551


In Salah Storage Site at Krechba
Amine C02 removal
Gas from other fields
Gas production (4 wells)
CO2 injection (3 wells) >3 million tons to date
ALGERIA
Cretaceous sequence (900m)
Carboniferous mudstones (950m)
Definition and modelling of potential cap-rock pathways
Reservoir (20-25m thick)
Definition and modelling of reservoir storage and migration

Objective: Experimentally measure the geochemical reactions that may impact wellbore integrity at In Salah CO_2 storage site

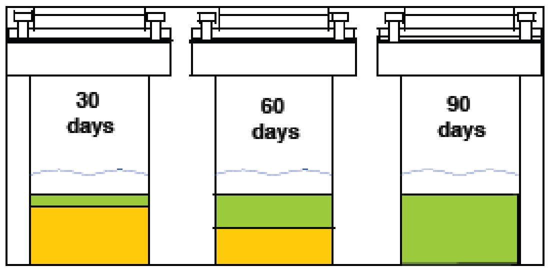
- Experiments
  - Determine the geochemical stability of cement prior to CO_2 injection
  - Determine the geochemical stability of cement + brine + tight sands + CO_2
- Reactive Transport
  - Model the geochemical evolution along the reservoir – cap rock interface



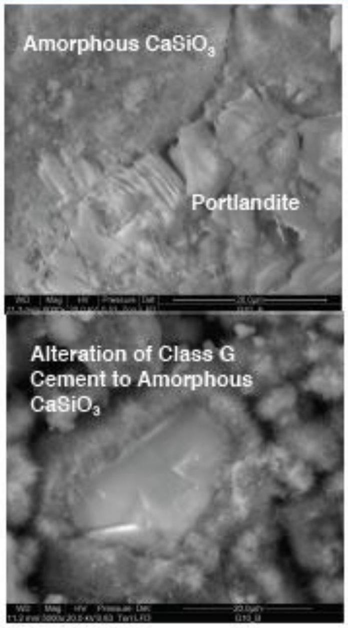
Heterolithic interval from C10.2 reservoir

Measured the solubility controlling phases when Class G cement is reacted at temperature in the absence of CO_2

- Batch Experiments at 95 and 115°C
- Solutions and solids sampled over time
- Starting Materials
  - Class G cement
    - Anhydrous Ca_2SiO_4 and Ca_3SiO_5 oxides
  - Solutions
    - Distilled and De-ionized water
    - 0.13 m $CaCl_2$
    - Synthetic Krechba Brine
  - Additives
    - $CaCl_2$
    - Bentonite
- Solid:Solution
  - 1:5
  - 1:10



Class G cement - brine reactions at KB5 can be modeled with portlandite, amorphous wollastonite, and amorphous enstatite solubility in Krechba brine



Synthetic Krechba Brine

$NaCl = 1.78$ m, $CaCl_2 = 0.55$ m, $MgCl_2 = 0.1$ m

Portlandite

$$Ca(OH)_{2(Portlandite)} + 2H^+ \Leftrightarrow Ca^{2+} + 2H_2O:$$

$$\log K_{95} = 18.4$$

$$\log K_{115} = 17.4$$

Amorphous Wollastonite

$$CaSiO_{3(Amorphous)} + 2H^+ \Leftrightarrow Ca^{2+} + SiO_2(aq) + H_2O$$

$$\log K_{95} = 10.4 \pm 0.1$$

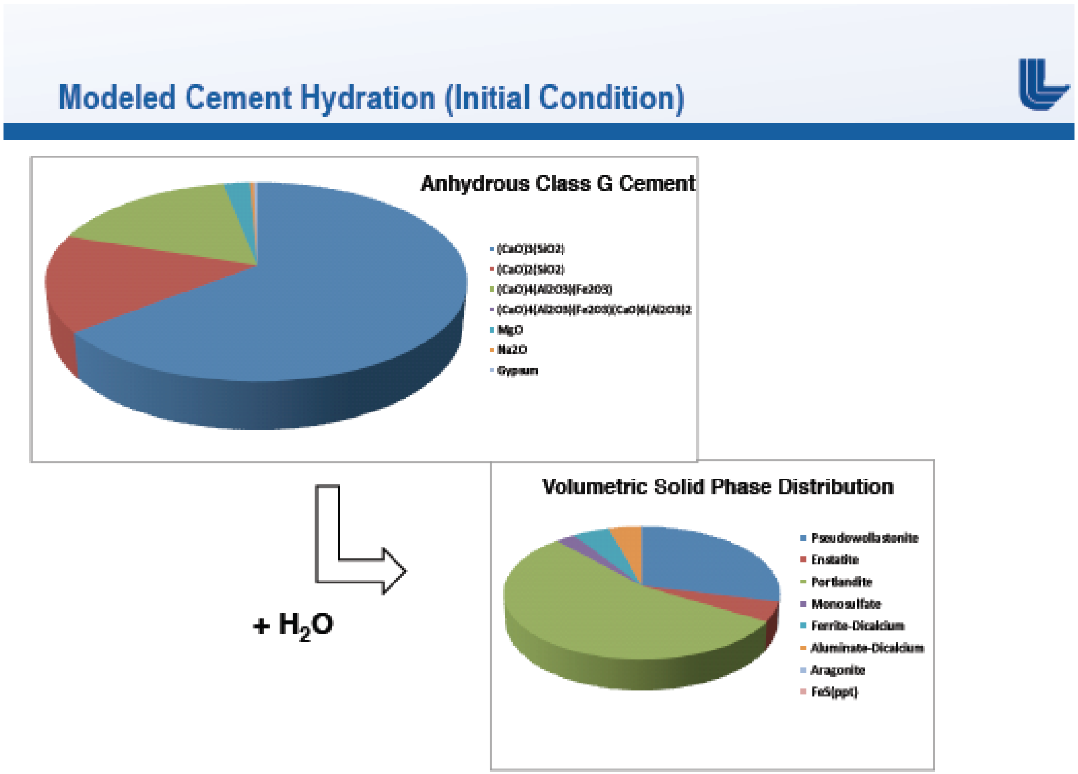
$$\log K_{115} = 11.4 \pm 0.3$$

Amorphous MgSiO3

$$MgSiO_{3(Amorphous)} + 2H^+ \Leftrightarrow Mg^{2+} + SiO_2(aq) + H_2O$$

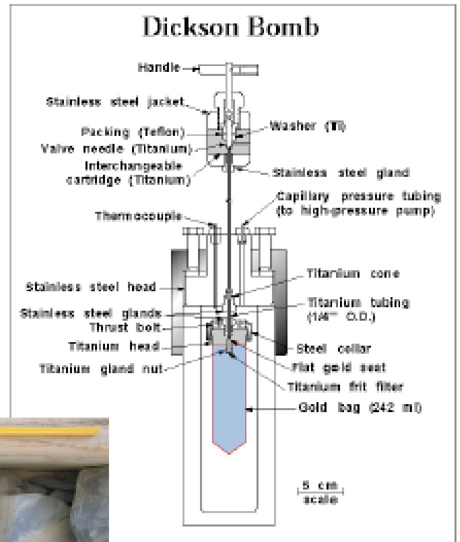
$$\log K_{95} = 5.3 \pm 0.1$$

$$\log K_{115} = 6.7 \pm 0.4$$


Modeled Cement Hydration (Initial Condition)
Anhydrous Class G Cement
(CaO)3(SiO2)
(CaO)2(SiO2)
(CaO)4(Al2O3)(Fe2O3)
(CaO)4(Al2O3)(Fe2O3)(CaO)6(Al2O3)2
MgO
Na2O
Gypsum
+ H2O
Volumetric Solid Phase Distribution
Pseudowollastonite
Enstatite
Portlandite
Monosulfate
Ferrite-Dicalcium
Aluminate-Dicalcium
Aragonite
FeS(ppt)

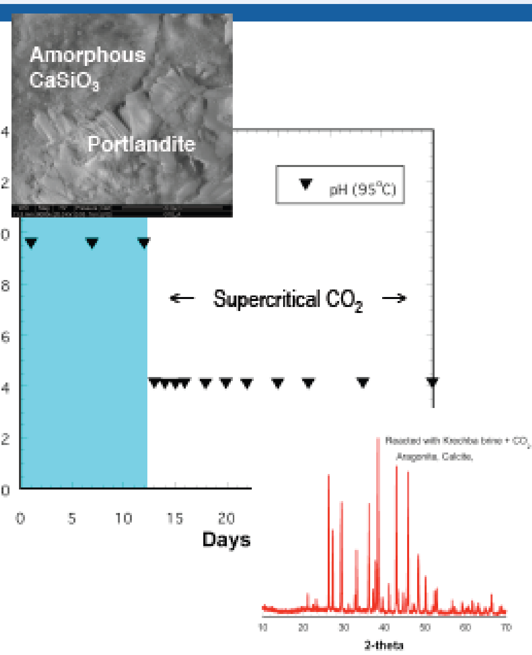
Reaction of Cement + Brine + Cap Rock + CO_2

- Dickson Autoclave
  - Measure reaction progress by changes in solution composition over time and analysis of solids at the end of the experiment
  - Gold reaction vessel and passivated Ti sample head and tube
  - 95°C and 100 bar
- Experimental protocol
  - React solids + brine
  - Inject CO_2 (liquid CO_2 converts to supercritical CO_2 at run conditions)
  - Solids
    - Cement
    - Cement + shale
    - Cement + sandstone

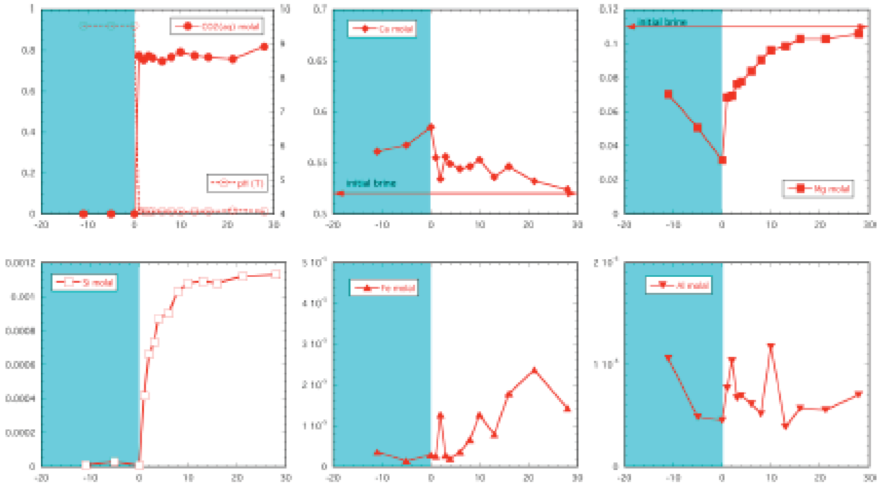


Geochemical Modeling

- Code
  - EQ3/6
  - Yucca Mountain Pitzer database to account for high ionic strength
- Input
  - Measured solution chemistry
  - Temperature and pressure
- pH at T
  - Prior to injection of CO_2
    - pH: equilibrium with portlandite
  - Post injection of CO_2
    - pH: equilibrium with aragonite
- Analyze the solution composition relative to mineral solubility
  - Log Saturation Index



Reaction of cement with CO_2 - rich solutions



days after CO_2 injection

Geochemical modeling suggest that Class G Cement reacts to form calcite, aragonite, and amorphous silica

Portlandite + CO_2 ⇒ Calcite and Aragonite

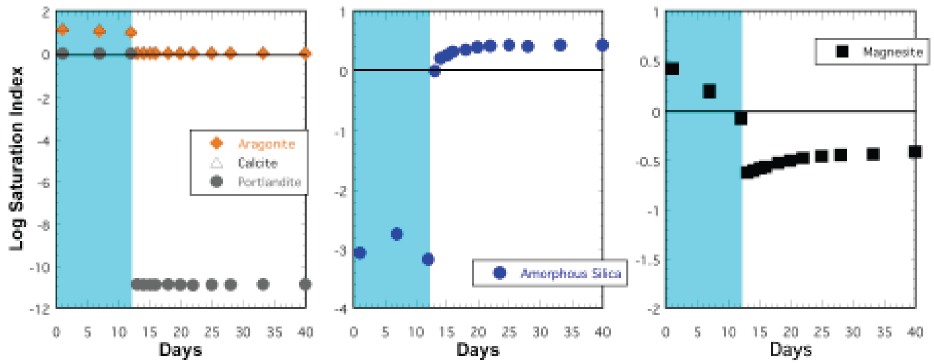
$$Ca(OH)_{2(Portlandite)} + 2H^{+} + HCO_3^{-} \Leftrightarrow CaCO_{3(Calcite/Aragonite)} + 2H_2O$$

Amorphous Wollastonite + CO_2 ⇒ Calcite, Aragonite, and Amorphous Silica

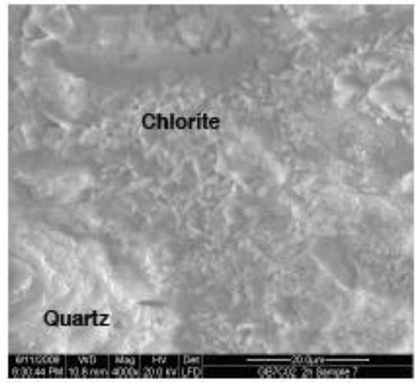
$$CaSiO_{3(Amorphous)} + H^{+} + HCO_3^{-} \Leftrightarrow CaCO_{3(Calcite/Aragonite)} + SiO_{2(Amorphous\ Silica)} + H_2O$$

Poorly Crystaline Mg-silicate + CO_2 ⇒ Dissolved Mg + Amorphous Silica

$$MgSiO_{3\ (Mg\text{-}silicate)} + 2H^{+} \Leftrightarrow Mg^{2+} + SiO_{2(Amorphous\ Silica)} + H_2O$$

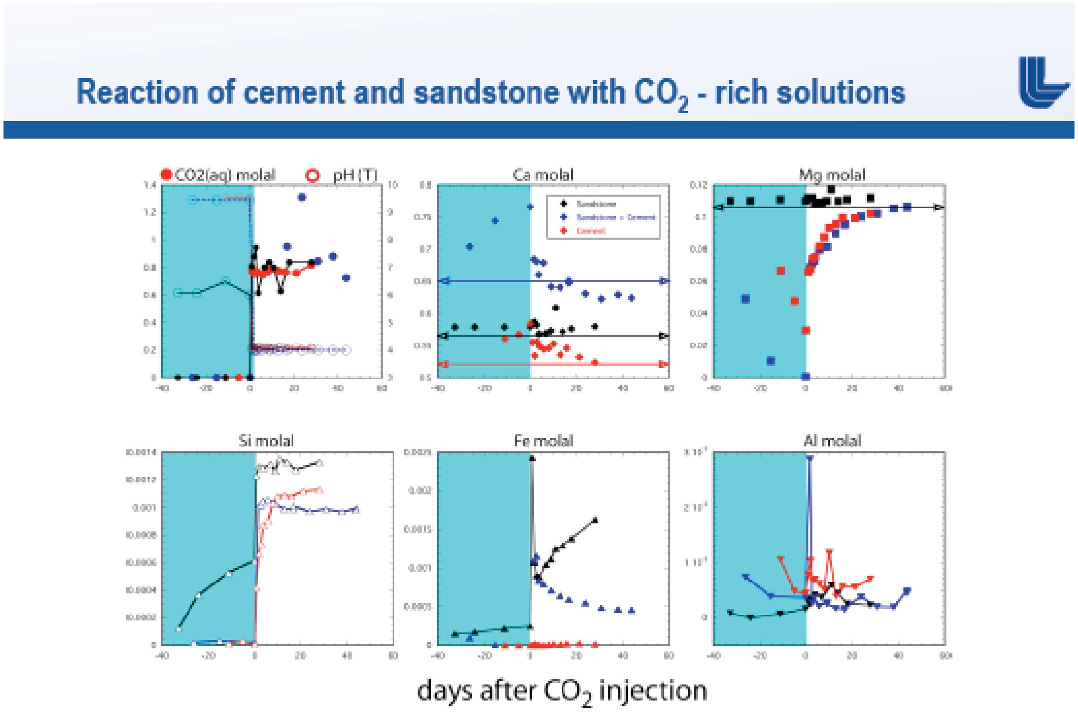


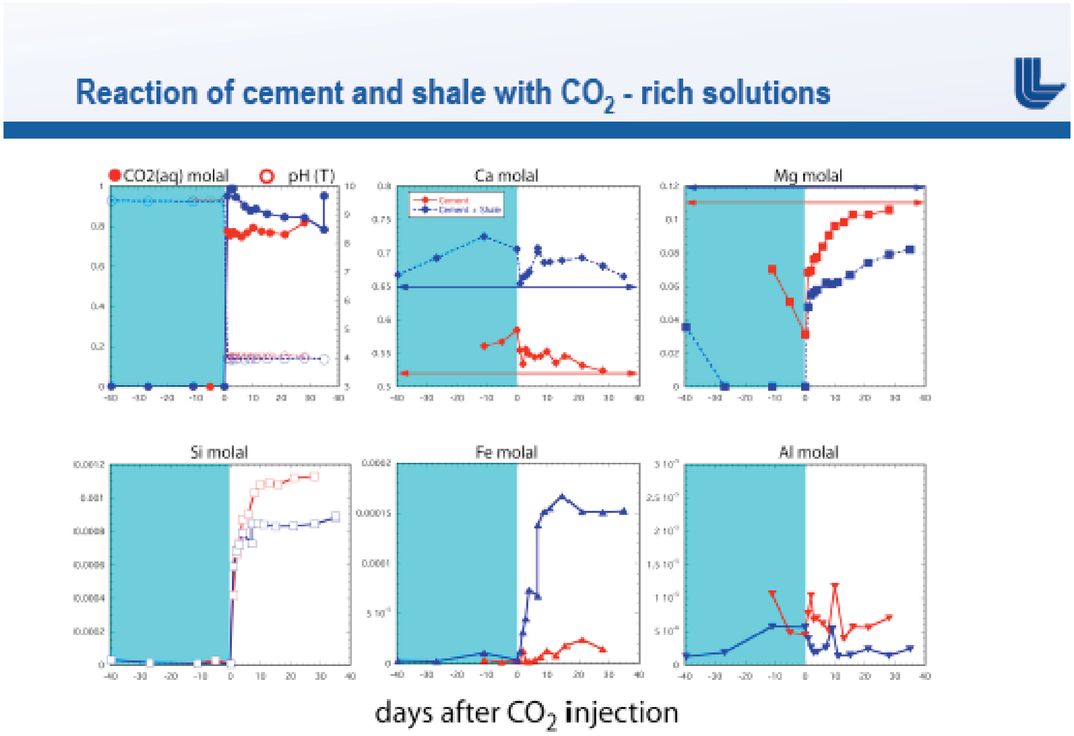
Krechba Sandstone Storage Reservoir: Experimental Model



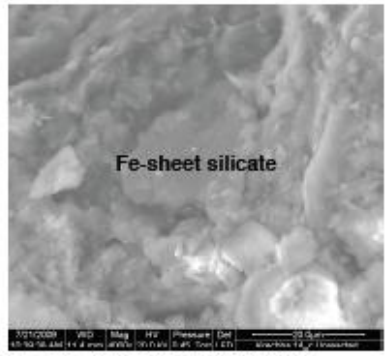
Sample 7, Well KB501

- Quartz 90%
- Chlorite 7%
- Ca-Mg-Fe Carbonate cement
- (Armitage 2008, Ringrose, 2009)


Reaction of cement and sandstone with CO2 - rich solutions
CO2(aq) molal
pH (T)
Ca molal
Mg molal
Si molal
Fe molal
Al molal
days after CO2 injection

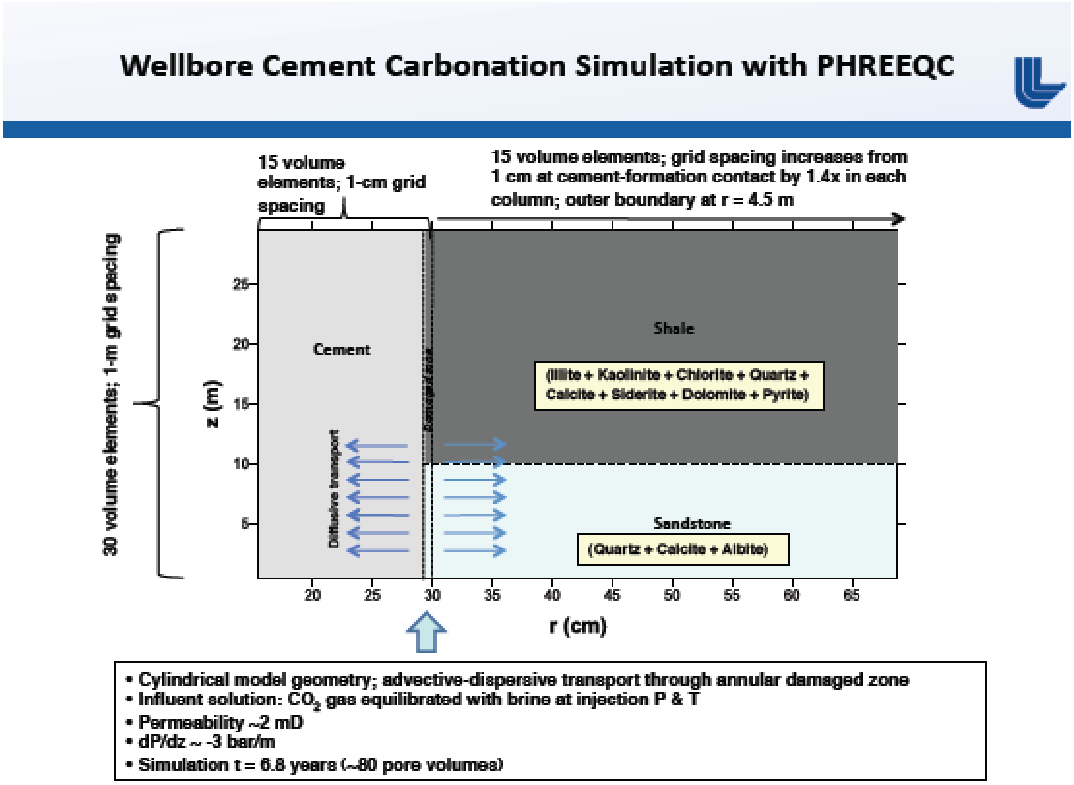

Reaction of cement and shale with CO_2 - rich solutions
CO2(aq) molal
pH (T)
Ca molal
Cement
Cement + Shale
Mg molal
Si molal
Fe molal
Al molal
days after CO_2 injection

Krechba Sandstone Storage Reservoir: Experimental Model

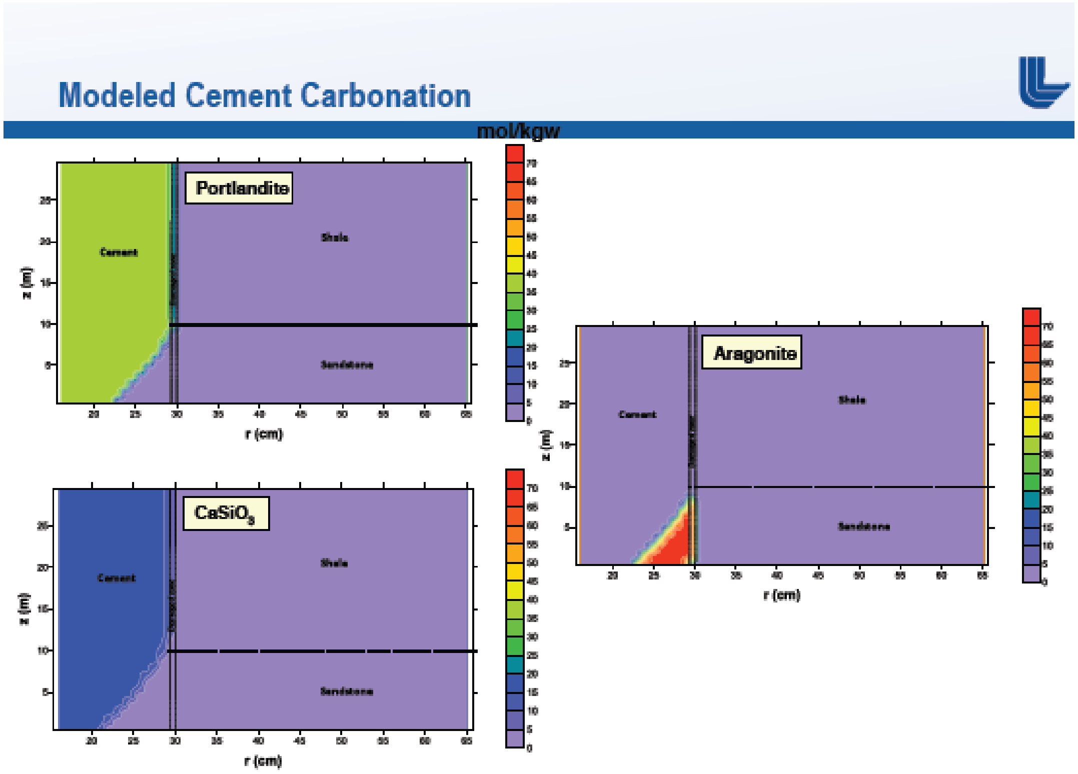


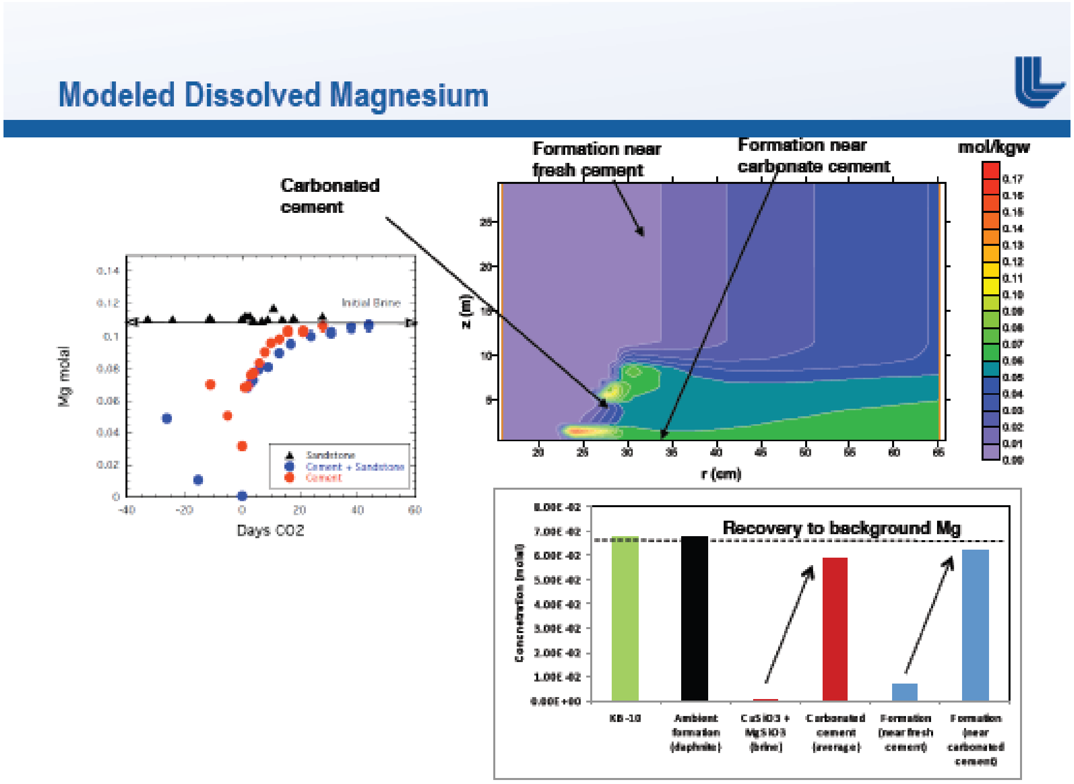
Sample 14, Well KB501

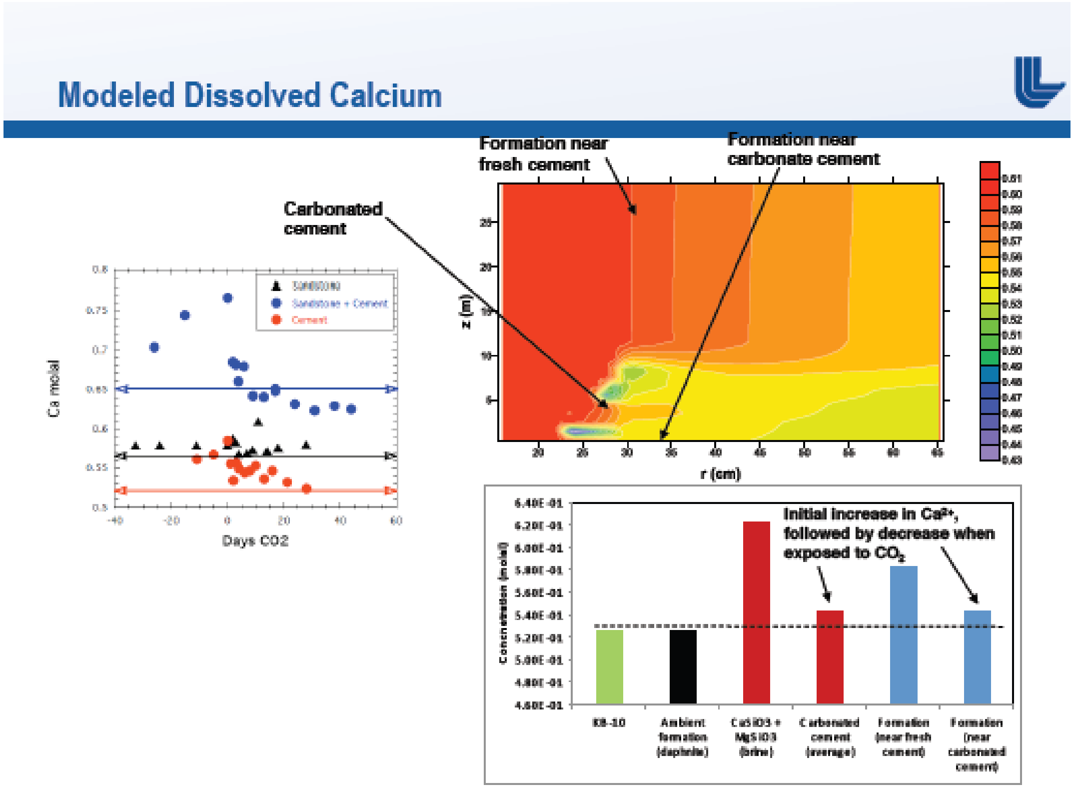
- Quartz 32%
- Illite 40%
- Chlorite 23%
- Kaolinite 7%,Feldspar 2%, Pyrite (trace)
- (Armitage 2008)

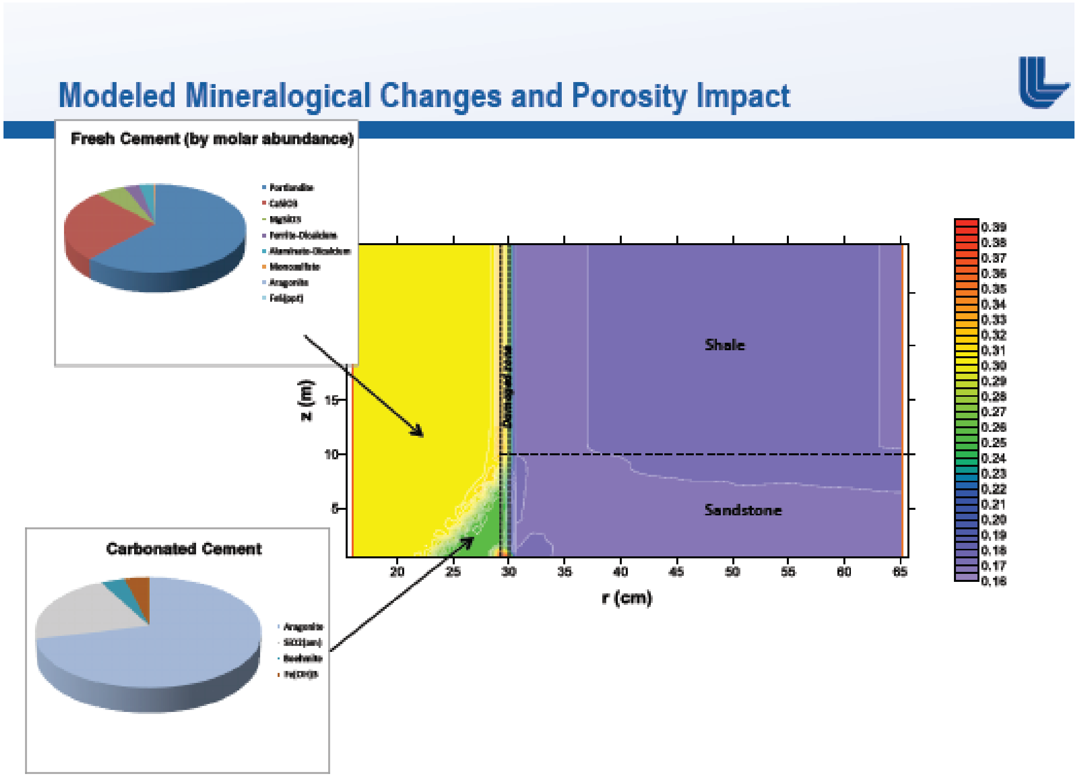


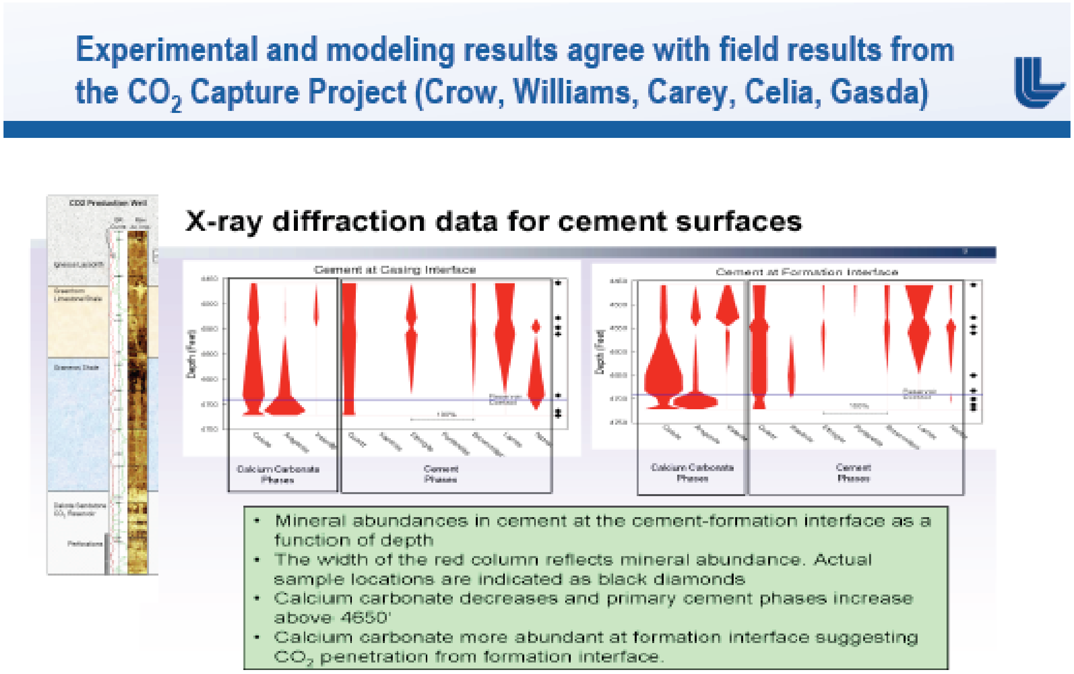
Wellbore Cement Carbonation Simulation with PHREEQC
15 volume elements; 1-cm grid spacing
15 volume elements; grid spacing increases from 1 cm at cement-formation contact by 1.4x in each column; outer boundary at r = 4.5 m
30 volume elements; 1-m grid spacing
z (m)
Cement
Damaged zone
Diffusive transport
Shale
(Illite + Kaolinite + Chlorite + Quartz + Calcite + Siderite + Dolomite + Pyrite)
Sandstone
(Quartz + Calcite + Albite)
r (cm)
• Cylindrical model geometry; advective-dispersive transport through annular damaged zone
• Influent solution: CO_2 gas equilibrated with brine at injection P & T
• Permeability ~2 mD
• dP/dz ~ -3 bar/m
• Simulation t = 6.8 years (~80 pore volumes)


Modeled Cement Carbonation
mol/kgw
Portlandite
CaSiO3
Aragonite
Cement
Shale
Sandstone
z (m)
r (cm)


Modeled Dissolved Magnesium
Carbonated cement
Formation near fresh cement
Formation near carbonate cement
mol/kgw
Mg molal
Days CO2
Initial Brine
Sandstone
Cement + Sandstone
Cement
z (m)
r (cm)
Recovery to background Mg
Concentration (molal)
KB-10
Ambient formation (diaphite)
CaSiO3 + MgSiO3 (brine)
Carbonated cement (average)
Formation (near fresh cement)
Formation (near carbonated cement)


Modeled Dissolved Calcium
Formation near fresh cement
Formation near carbonate cement
Carbonated cement
Ca molal
Days CO2
Sandstone
Sandstone + Cement
Cement
z (m)
r (cm)
Initial increase in Ca^{2+}, followed by decrease when exposed to CO_2
Concentration (molal)
KB-10
Ambient formation (daphnite)
CaSiO3 + MgSiO3 (brine)
Carbonated cement (average)
Formation (near fresh cement)
Formation (near carbonated cement)


Modeled Mineralogical Changes and Porosity Impact
Fresh Cement (by molar abundance)
Carbonated Cement
Shale
Sandstone
z (m)
r (cm)
Damaged zone


Experimental and modeling results agree with field results from the CO_2 Capture Project (Crow, Williams, Carey, Celia, Gasda)
X-ray diffraction data for cement surfaces
Cement at Casing Interface
Cement at Formation Interface
Depth (Feet)
Calcium Carbonate Phases
Cement Phases
• Mineral abundances in cement at the cement-formation interface as a function of depth
• The width of the red column reflects mineral abundance. Actual sample locations are indicated as black diamonds
• Calcium carbonate decreases and primary cement phases increase above 4650'
• Calcium carbonate more abundant at formation interface suggesting CO_2 penetration from formation interface.

Next Steps: Model the fracture growth/healing at the cement - formation interface

- Integration of
  - Detailed mineralogy, porosity, and permeability of the tight sands caprock (Univ. Liverpool)
  - Experimental results (LLNL, Univ. Liverpool)
    - Solubility constants
    - Reaction rates
  - Geomechanics (LLNL)
  - Reactive transport modeling (LLNL)

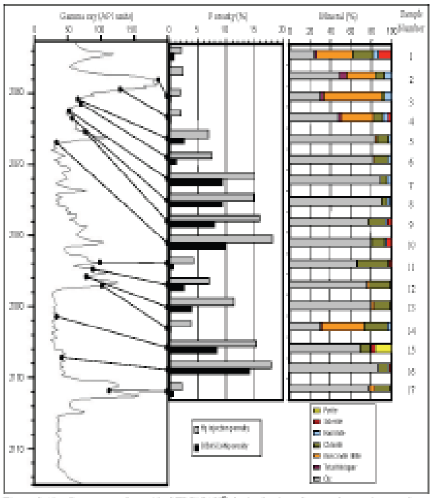


Figure 3-12 - Gamma ray log with QEMSCAN® derived mineralogy and porosity together with Hg-injection porosity values. **Armitage, 2008**

LLNL-PRES-420347

Hydromechanical Simulations of Surface Uplift due to CO_2 Injection at In Salah

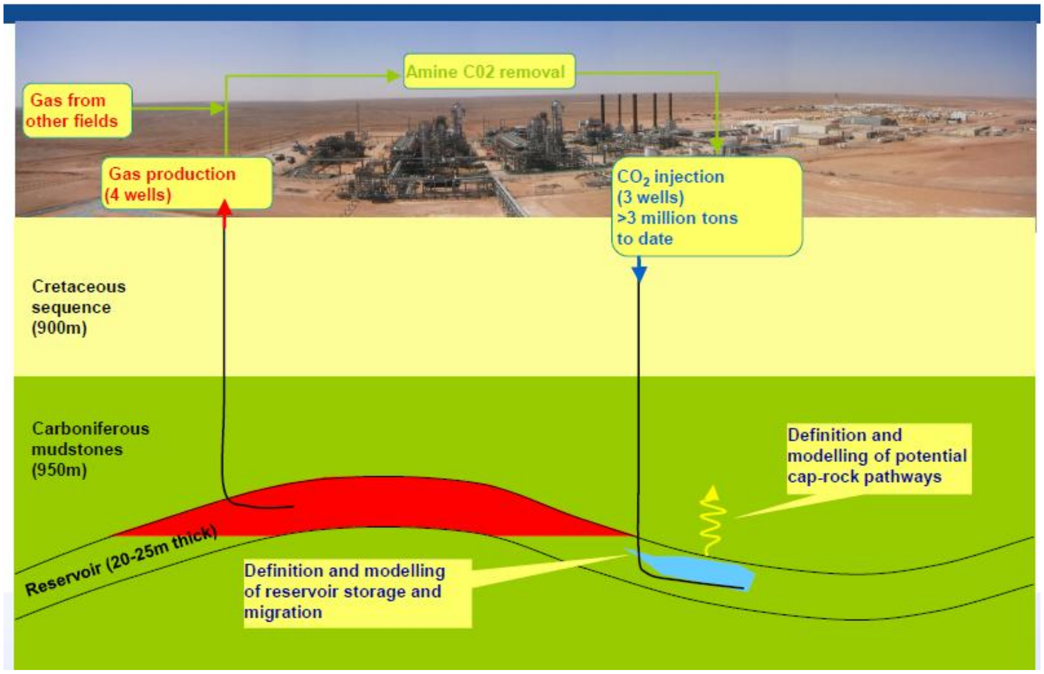
2009 AGU Fall Meeting
H11J-02; December 14, 2009; 8:15 AM

Joseph P. Morris,
Yue Hao, William Foxall and Walt McNab

Lawrence Livermore National Laboratory

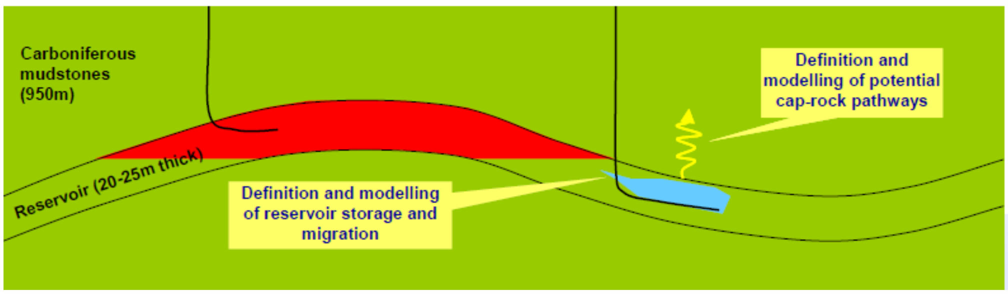
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

In Salah Storage Site at Krechba



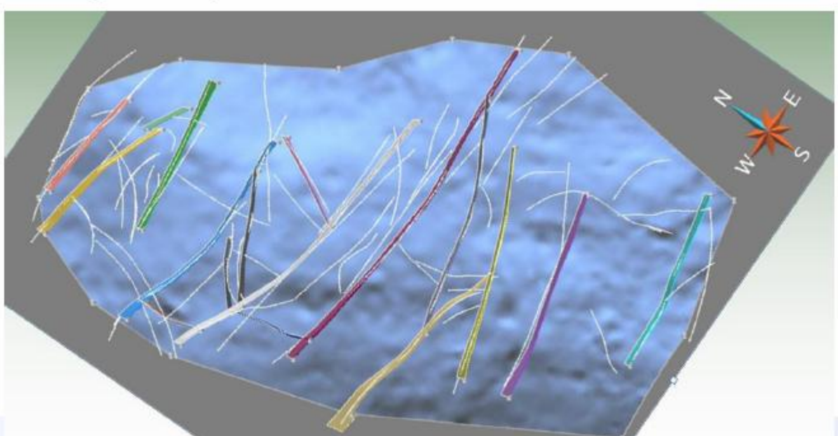
Fractures/faults are key for understanding CO_2 fate at Krechba

- **Reservoir is "thin" and over lying caprock is "thick"**
  - **Injection pressures are high (~10MPa)**
- **Reservoir and base of caprock is fractured**
- **There are also some faults within the reservoir**
- **Some CO_2 will reside in lower portion of caprock:**
  - **What is the ultimate volume available to us?**
  - **What risks are there to containment if we open fractures at base of caprock during injection?**
- **Understanding the evolving fracture/fault networks within the reservoir and caprock at Krechba is key to predicting the long-term fate of the CO_2**



We have studied the stability of combinations of fracture networks and faults

- Fault network for the storage system
  - No faults observed in the caprock/overburden
  - Fault map courtesy of the In Salah Gas JIP



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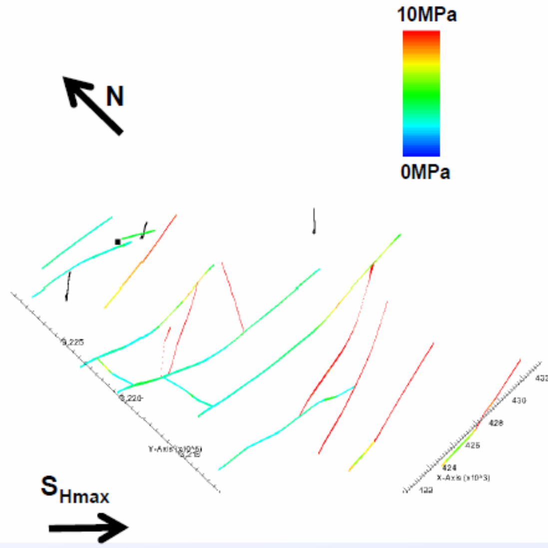
Critical stress analysis: Evaluate change in pore pressure that induces failure for given in situ stress state

- Estimate of change in pore-pressure that will result in shear failure of faults
- Identifies which faults are likely flow conduits or barriers
  - Only as good as your fault and in situ stress characterization



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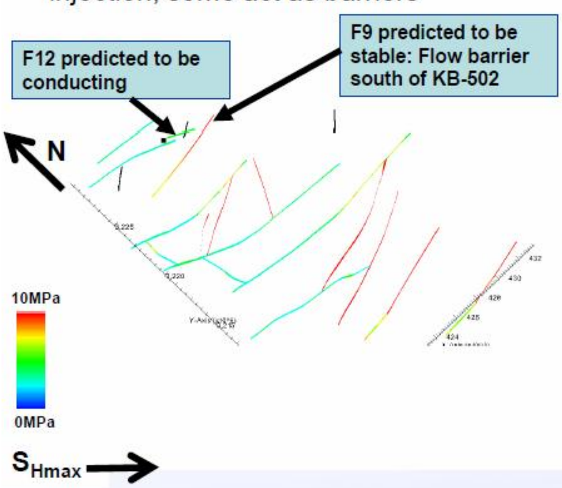
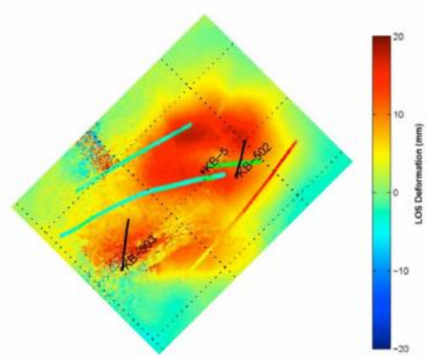
Some features of observed surface uplift appear consistent with faults identified by critical stress analysis

- Some faults in vicinity of KB-502 can be expected to be conductive during injection, some act as barriers





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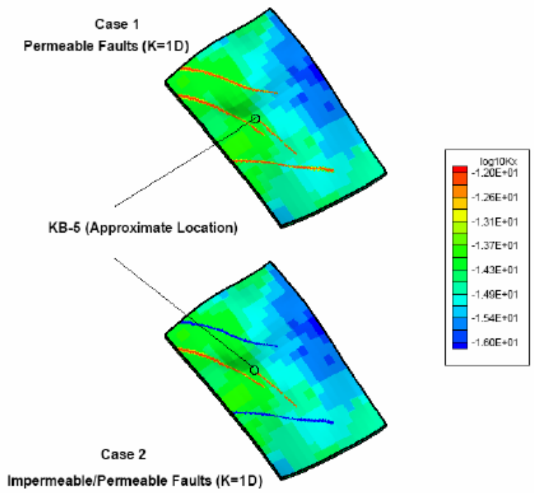
NUFT Reservoir Models: Permeability Profile with Faults
Exploring the effect of fault conduits and barriers

This model assumes the faults exist only within the reservoir

i.e.: No fault extends into overburden or underburden

Permeability field is based upon reservoir model provided by the In Salah JIP



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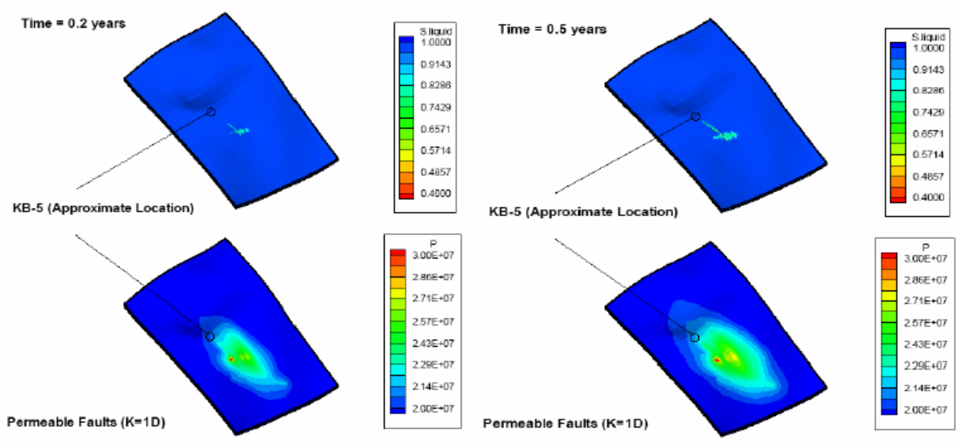
Fault F12 provides a fast flow path:
Observe early arrival at KB-5 well, consistent with observation

Case 1: Permeable Faults (K = 1 Darcy)



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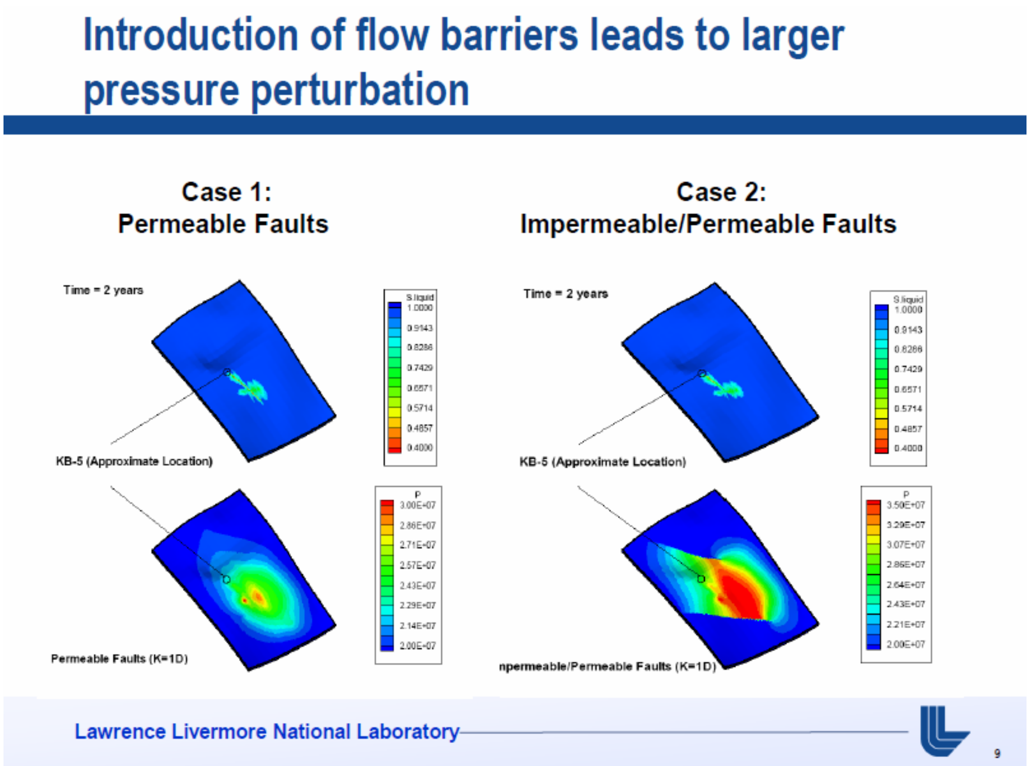
Introduction of flow barriers leads to larger pressure perturbation
Case 1:
Permeable Faults
Case 2:
Impermeable/Permeable Faults
Time = 2 years
KB-5 (Approximate Location)
Permeable Faults (K=1D)
npermeable/Permeable Faults (K=1D)
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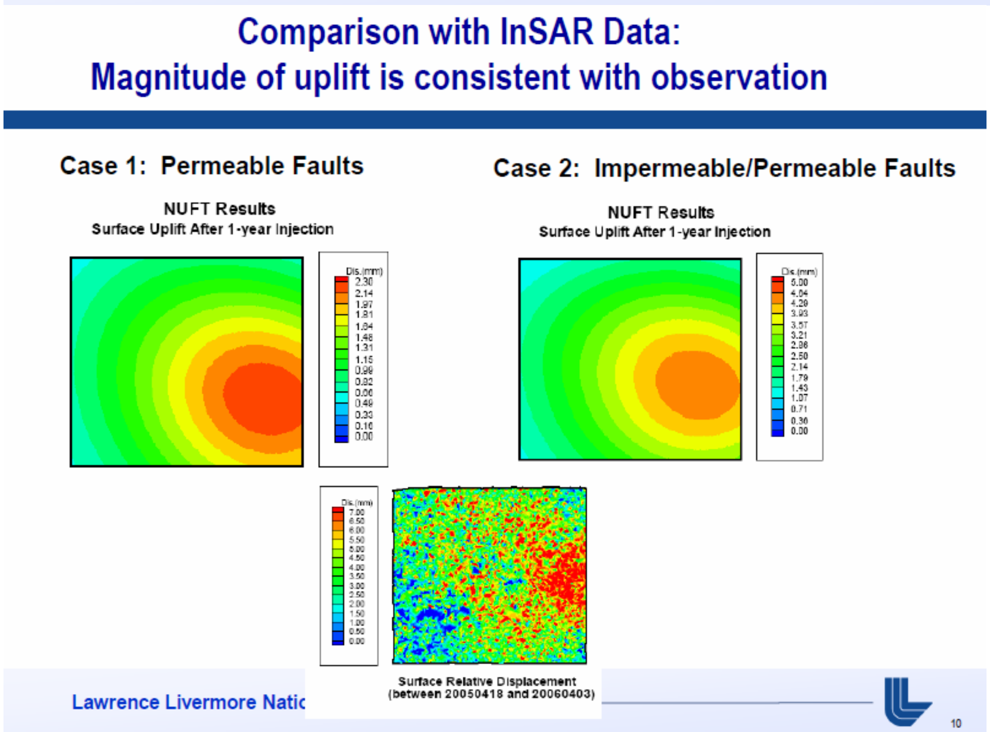
Comparison with InSAR Data:
Magnitude of uplift is consistent with observation
Case 1: Permeable Faults
Case 2: Impermeable/Permeable Faults
NUFT Results
Surface Uplift After 1-year Injection
NUFT Results
Surface Uplift After 1-year Injection
Surface Relative Displacement
(between 20050418 and 20060403)
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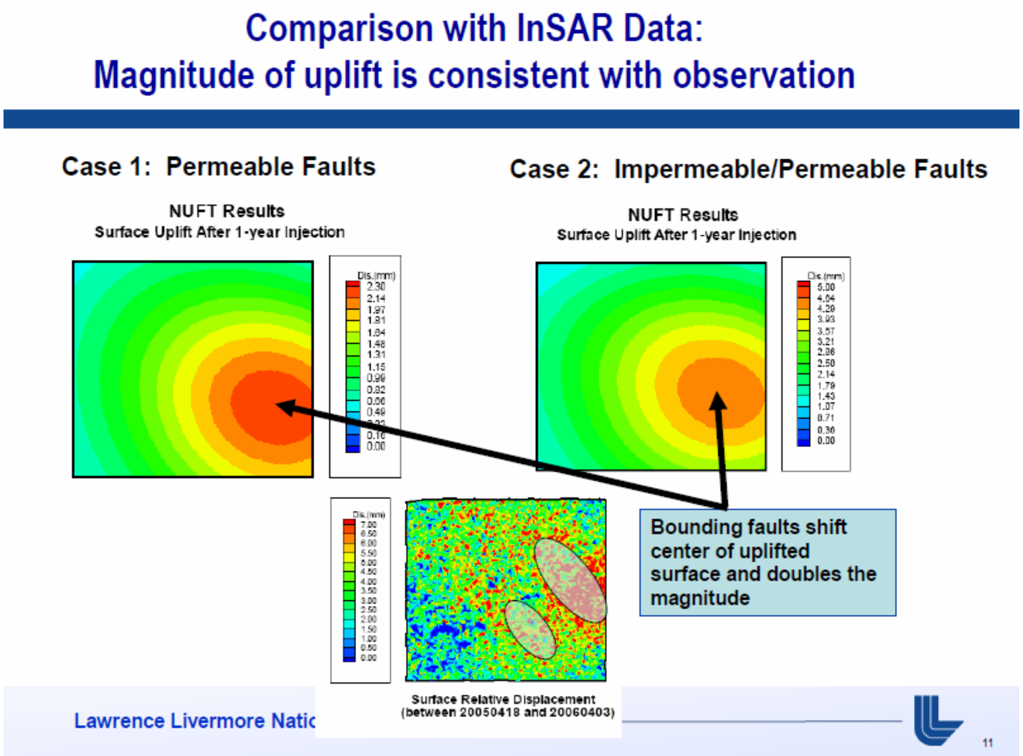
Comparison with InSAR Data:
Magnitude of uplift is consistent with observation
Case 1: Permeable Faults
NUFT Results
Surface Uplift After 1-year Injection
Case 2: Impermeable/Permeable Faults
NUFT Results
Surface Uplift After 1-year Injection
Bounding faults shift center of uplifted surface and doubles the magnitude
Surface Relative Displacement
(between 20050418 and 20060403)
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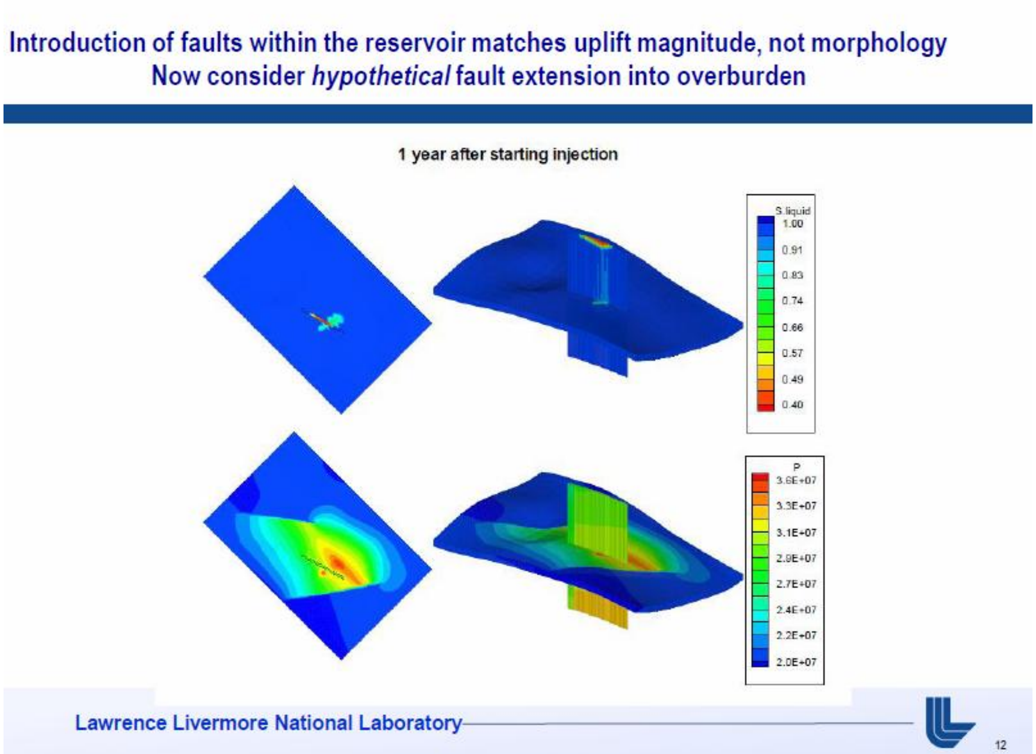
Introduction of faults within the reservoir matches uplift magnitude, not morphology
Now consider hypothetical fault extension into overburden
1 year after starting injection
S.liquid
1.00
0.91
0.83
0.74
0.66
0.57
0.49
0.40
P
3.6E+07
3.3E+07
3.1E+07
2.9E+07
2.7E+07
2.4E+07
2.2E+07
2.0E+07
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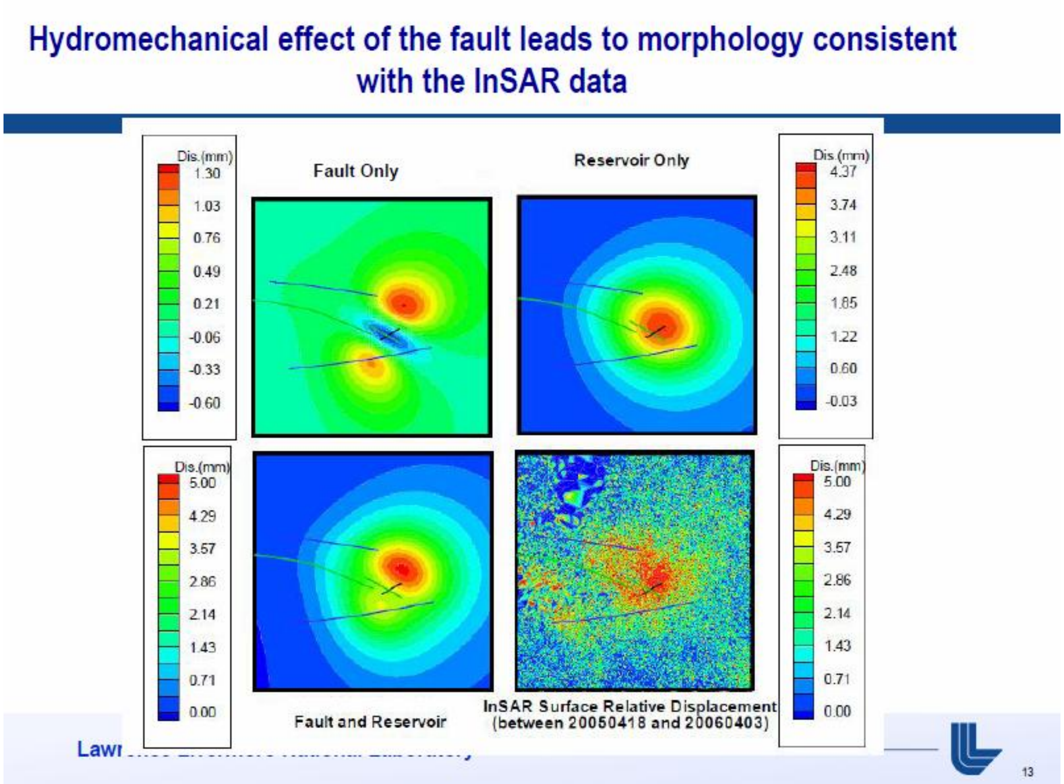
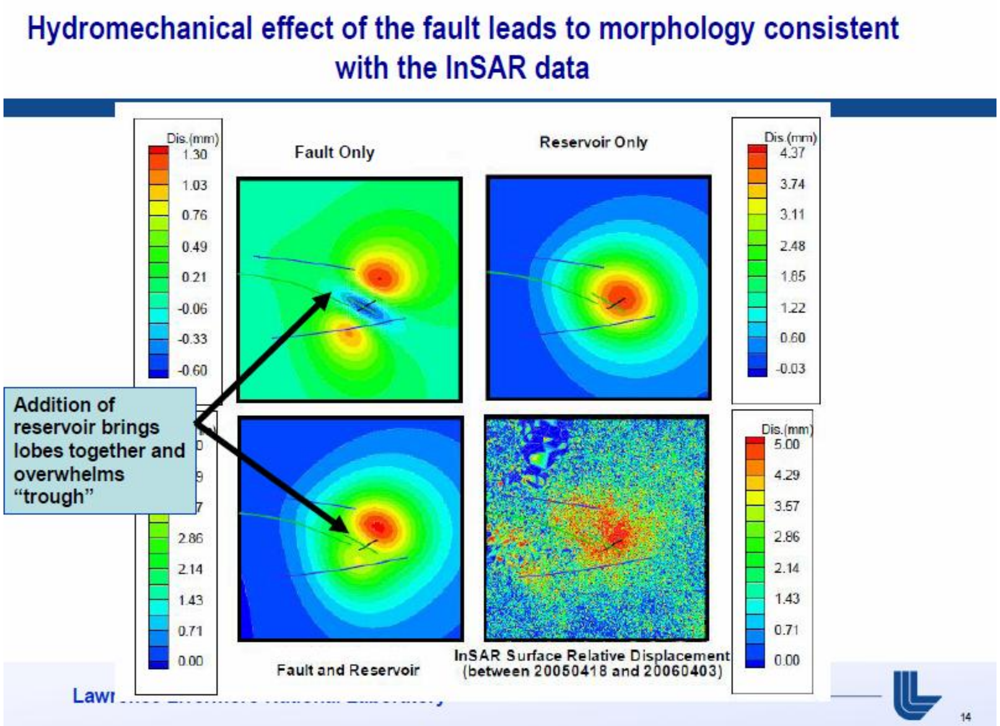

Hydromechanical effect of the fault leads to morphology consistent with the InSAR data
Fault Only
Reservoir Only
Dis.(mm)
1.30
1.03
0.76
0.49
0.21
-0.06
-0.33
-0.60
Dis.(mm)
4.37
3.74
3.11
2.48
1.85
1.22
0.60
-0.03
Dis.(mm)
5.00
4.29
3.57
2.86
2.14
1.43
0.71
0.00
Fault and Reservoir
InSAR Surface Relative Displacement
(between 20050418 and 20060403)
13

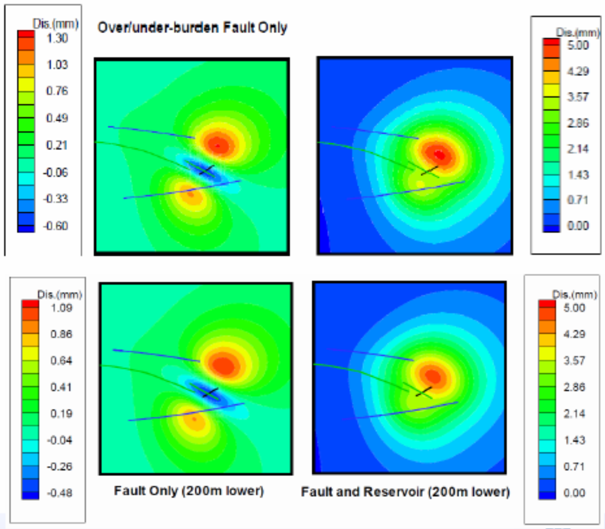

Hydromechanical effect of the fault leads to morphology consistent with the InSAR data
Fault Only
Reservoir Only
Addition of reservoir brings lobes together and overwhelms "trough"
Fault and Reservoir
InSAR Surface Relative Displacement
(between 20050418 and 20060403)
14

A key question: How sensitive are we to the vertical location of the fault?

The answer: **Not very**

There are small differences between the baseline and case of fault *lowered* 200m

I.e.: It is difficult to discern whether fault is in overburden or only underburden



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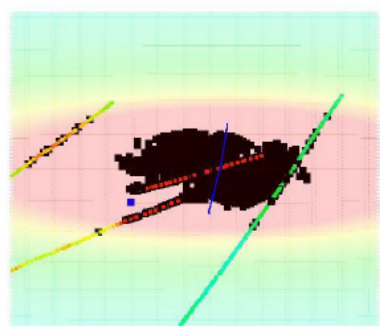
Summary and future work

- Faults in vicinity of KB-502 are expected to act as flow conduits and barriers
  - Consistent with observations of CO_2 breakthrough
- Flow within reservoir predicts *magnitudes* of uplift consistent with observation
- *Hypothetical* flow into vertically extended fault at the storage level reproduces magnitude and *morphology*
  - Surface deformation is not sensitive to vertical fault location
- Future work:
  - We've also looked at predicting shear failure within the combined fracture/fault network
    - Investigate magnitude of events associated with injection and compare against future microseismic observations
  - Consider the response of the overburden in more detail (based on new 3D seismic)
  - Work to interpret ongoing InSAR data acquisitions



Prediction of shear failure in fracture/fault network at KB-502

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Acknowledgements

- Funding
  - JIP (a consortium of BP, StatoilHydro and Sonatrach)
  - DOE Fossil Energy

- Data was provided by the JIP.

- Special thanks to P. Ringrose (StatoilHydro) and Rob Bissell (BP) for the detailed geological models.

- We have reports documenting geomechanical and geochemical studies in detail

For more details please contact:
morris50@llnl.gov