An Advanced Joint Inversion System for CO_2 Storage Modeling with Large Data Sets for Characterization and Real-Time Monitoring

Enhancing Storage Performance and Reducing Failure Risks under Uncertainties

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U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS

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Presentation Outline

- Benefit to the program
- Goals and objectives
- Technical status
- Accomplishments to date
- Summary

Benefit to the Program 1/2

In Terms of Program Goals:

"Support industry's ability to predict CO_2 storage capacity in geologic formations …"

-By developing better site characterization methods that can resolve the earth's heterogeneity.

"Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness"

-Yes by developing technologies for monitoring that will guide management and provide timely warnings of risks.

Benefit to the Program 2/2

"Develop Best Practice Manuals for *monitoring, verification, accounting, and assessment*; *site screening, selection and initial characterization*; public outreach; *well management activities*; and *risk analysis* and simulation"

-Though the focus is not the writing of manuals, this research addresses the issues above.

The joint inversion tools system will allow better site selection and more reliable monitoring by utilizing quickly large volumes of data for more reliable estimation.

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Project Overview: Goals and Objectives

- **Goals:** Develop and apply to selected sites a data-utilization toolbox to support decision-making for optimal design and control of CO_2 injection and storage operations, linking *process simulations*, *dynamic monitoring and inversion*, *uncertainly quantification*, and *risk assessment.*
- **Objectives:** Develop, test, and apply advanced algorithms, based on the best statistical and computational technology possible, to perform assimilation of huge data sets, very quickly, working with state of the art simulators, and performing uncertainty quantification.

Technical Status

Advanced tools are available that:

- *Simulate complex multiphysics*
- *Have large data requirements*
- *Are affected by uncertainties in parameters and initial and boundary conditions*

For their successful implementation in the field, these models must **utilize data** to:

- *Estimate parameters, using all available data, and update parameters and state variables as new data are collected during monitoring*
- *Quantify uncertainty*

Technical Status

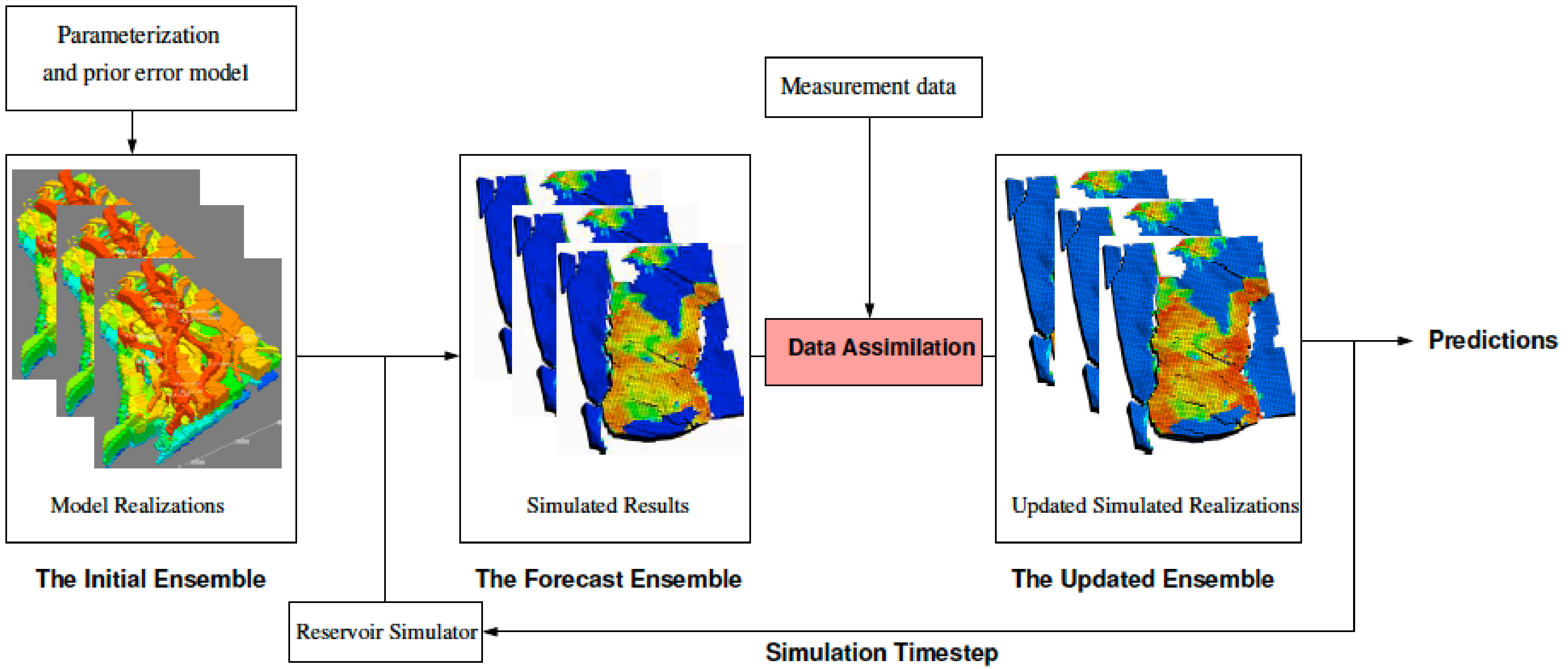
Motivation for our approach

- **The stochastic approach** *provides powerful tools to* ***manage information*** *and* ***quantify uncertainty***
- **Heterogeneity of the earth must be resolved at fine scales** to achieve **more accurate descriptions and more reliable predictions**

Technical Status

- It is virtually impossible to both have high-resolution models, utilize large data sets, and apply the stochastic approach using “textbook” algorithms
- **However, fast linear algebra methods can be developed to achieve accurate yet computationally efficient algorithms for implementing the stochastic approach in very large systems. This is the focus of this project**

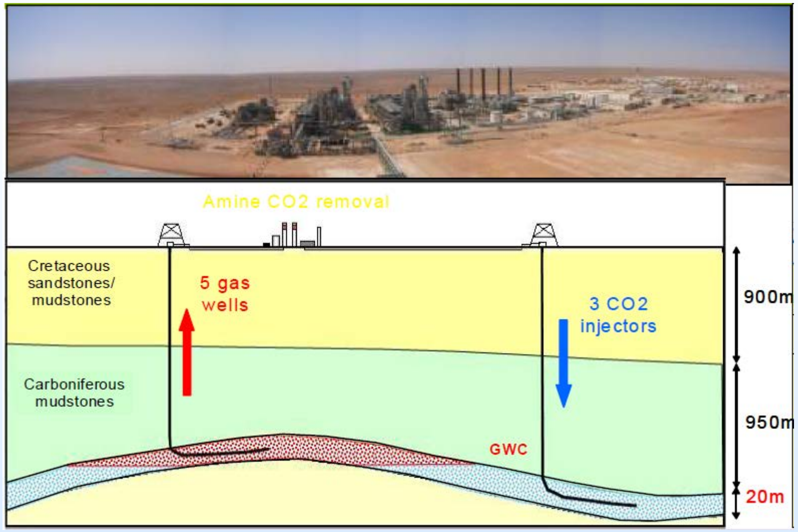
Monitoring Assisted Site Management

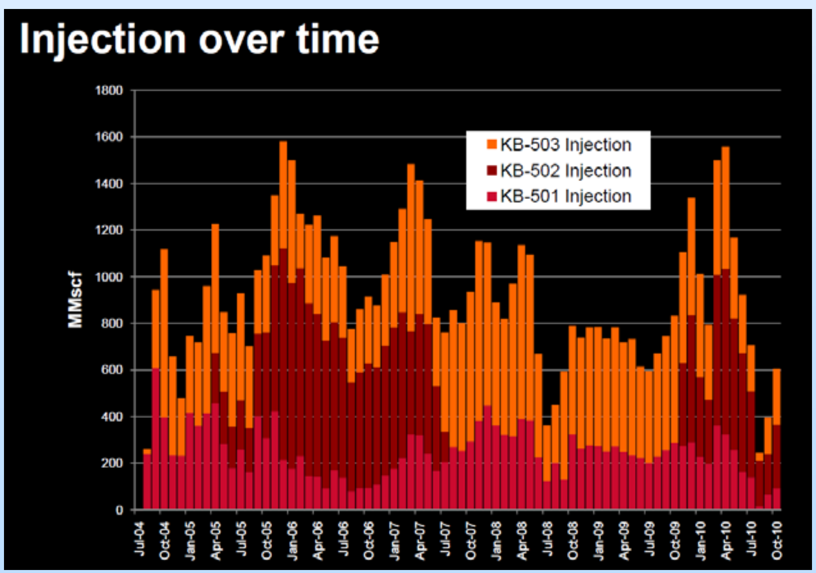


Seiler et al. 2009

- **At each "observation time", update parameters (porosity, permeability) and dynamic state variables (CO_2 saturation, pressure etc.)**

Application to the In Salah Site: CO2 Storage



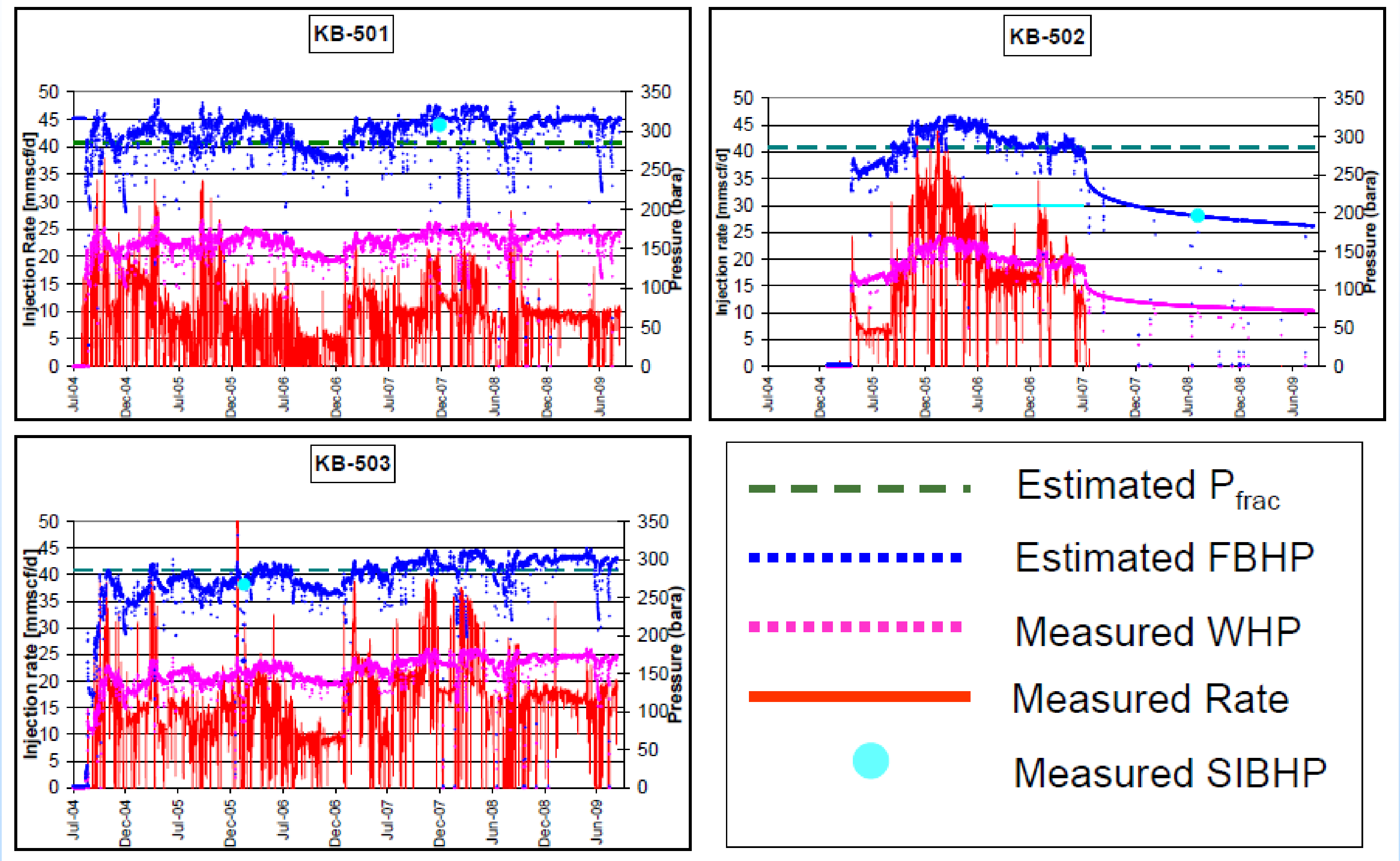


- **Three horizontal injectors of 1000-1500 m long**

- **Injection:**
  - **KB-501: 7/31/2004 - 6/10/2011**
  - **KB-502: 4/13/2005 - 6/10/2011 (7/10/2007 - 11/11/2009 stop)**
  - **KB-503: 8/19/2004 - 6/10/2011**

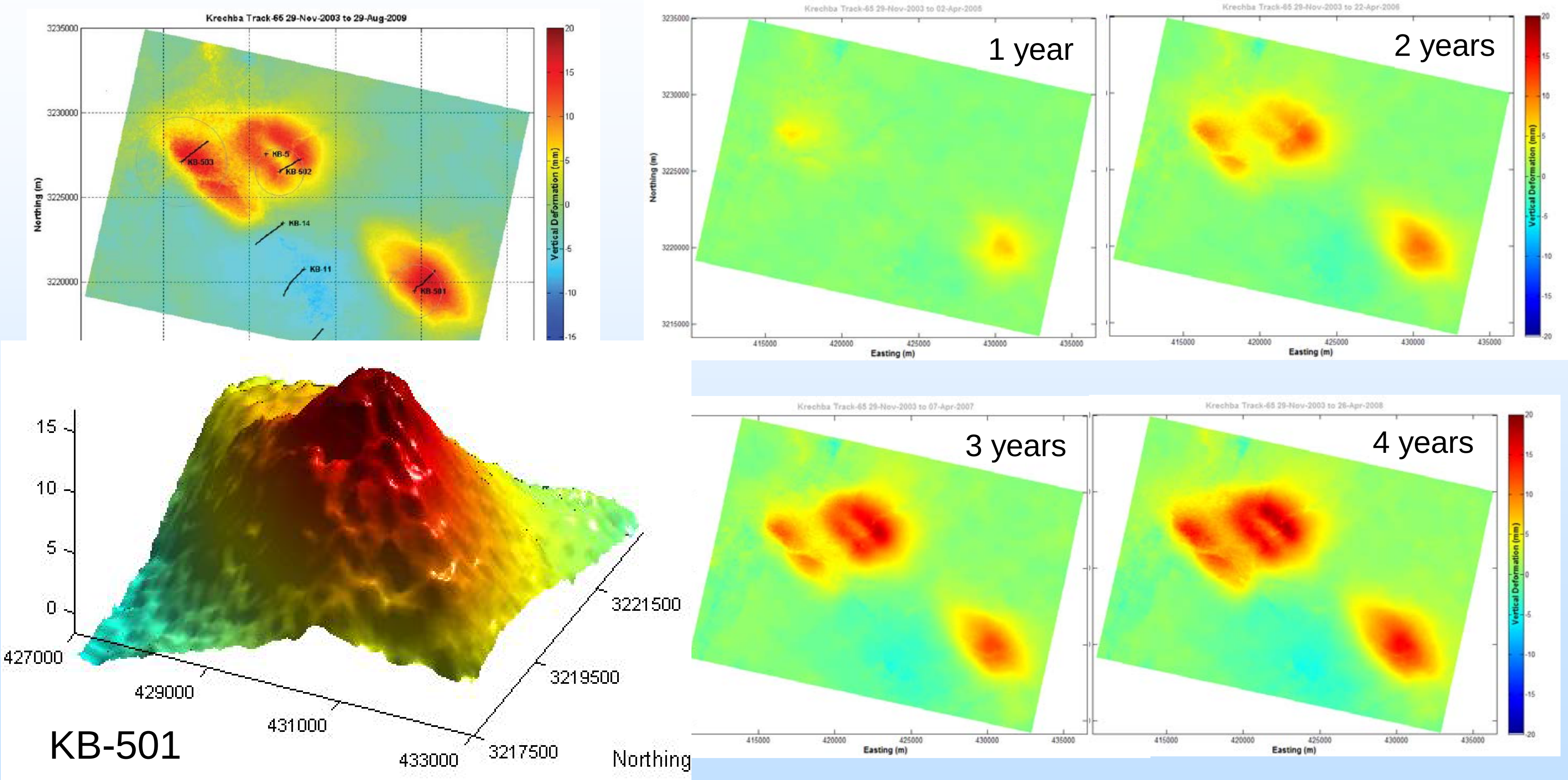
- **Total injected CO_2 is 4.26 Mt by 06/10/2011 (injection stop)**

Application to the In Salah Site: Pressure Monitoring Data



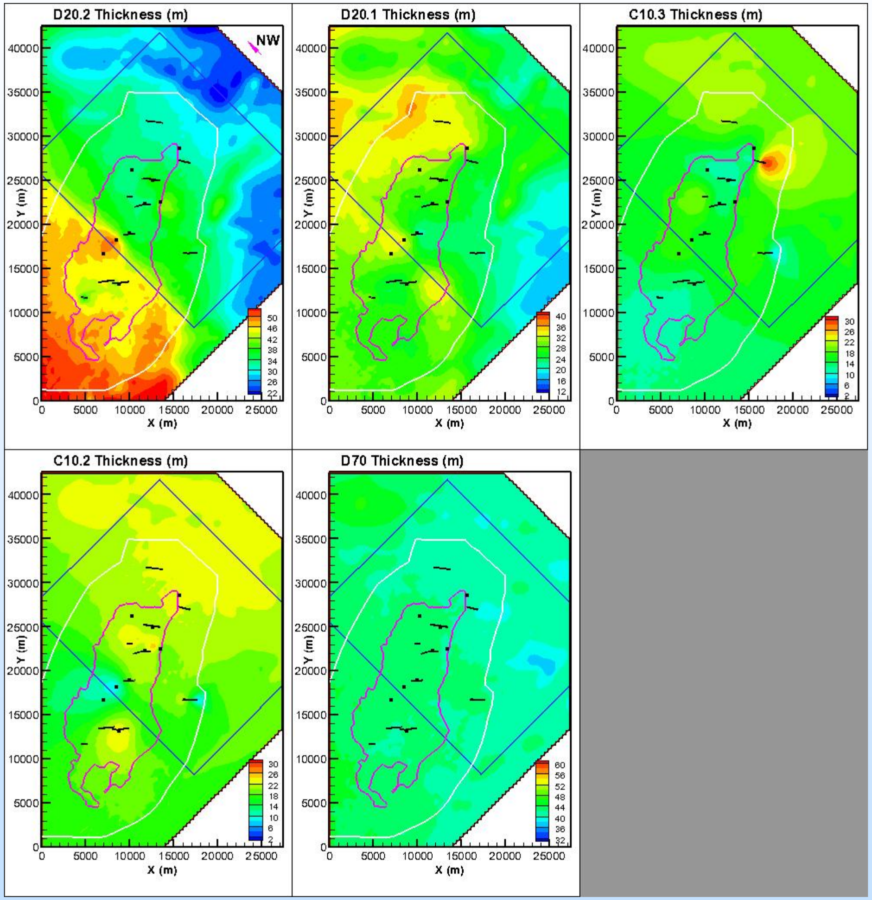
- **Measured well-head pressure WHP is converted to bottomhole pressure (FBHP) for modeling, using shut-in BHP (SIBHP)**

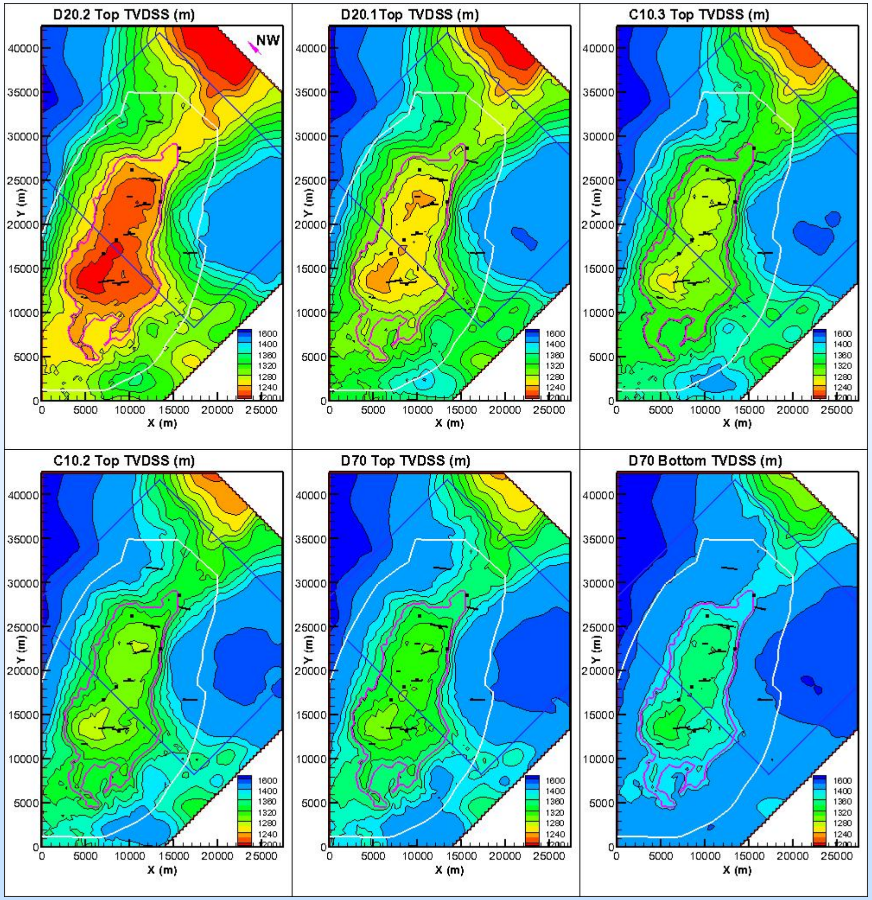
Application to the In Salah Site: InSAR Deformation Data



- **InSAR deformation data show fault zone opening at KB-502;**
- **The data may also show the effect of heterogeneity, providing excellent high-resolution data for stochastic inversion**

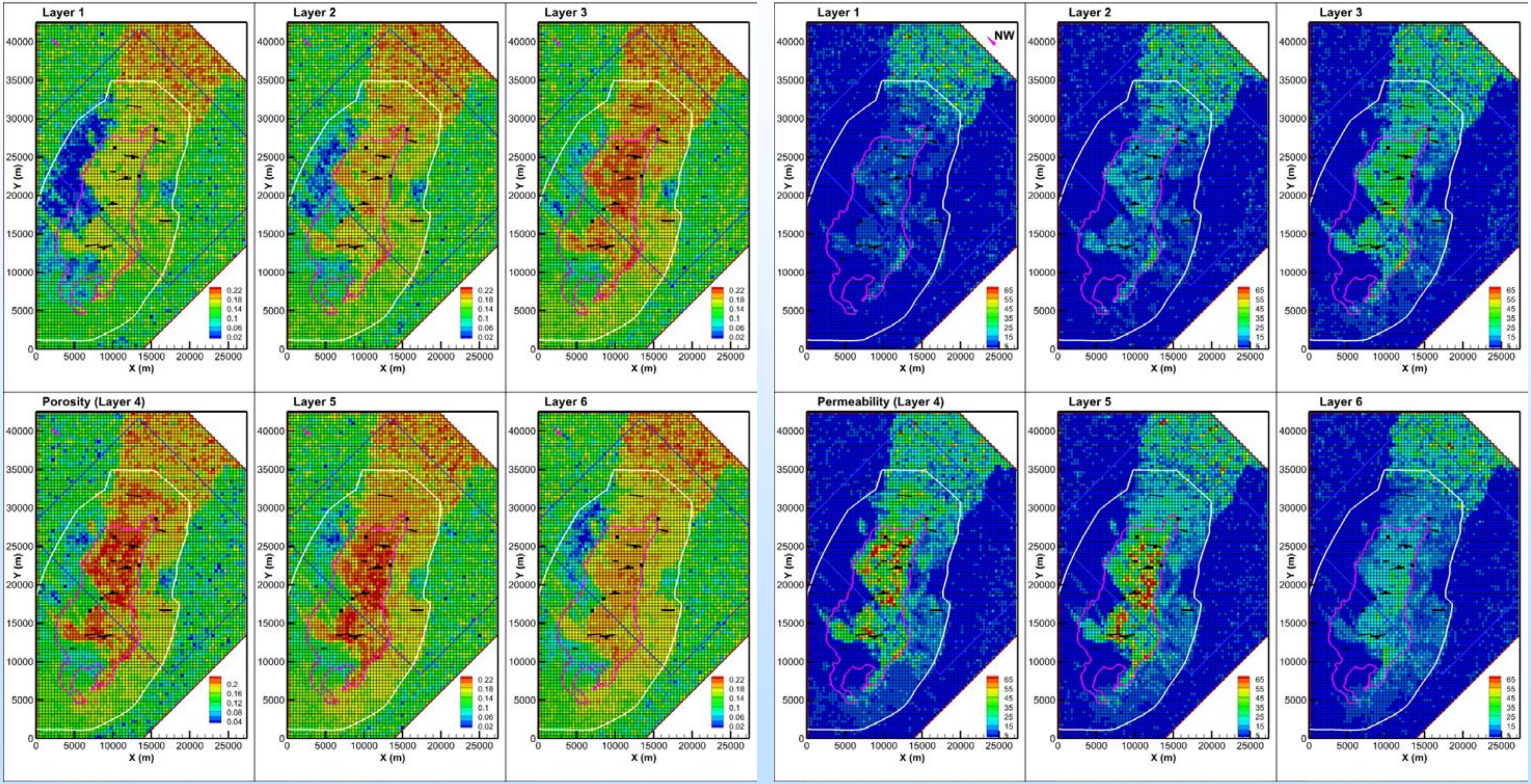
Modeling: 3D Geologic Model (I)





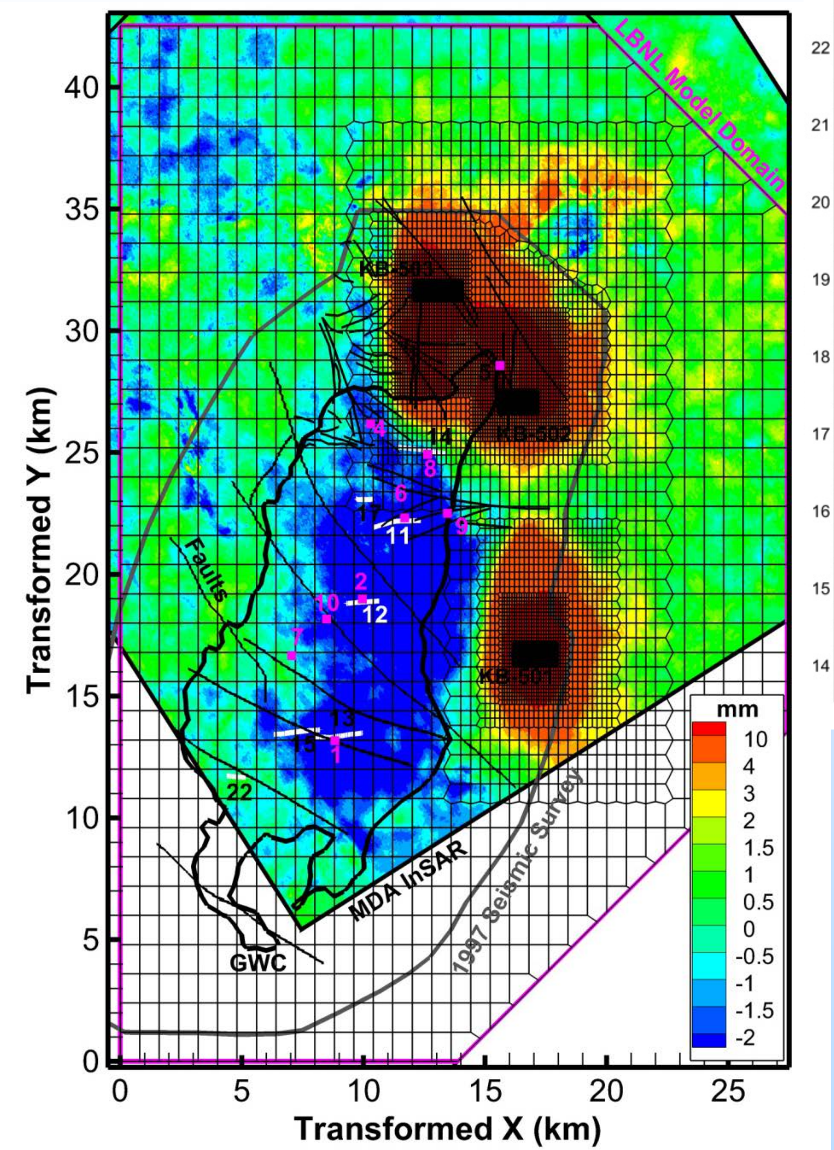
- **The 3D geological model covers the entire strata from the ground surface to the basement rock underlying the storage formation (C10.2), with purple polygon for gas field, white polygon for 1997 seismic survey region**

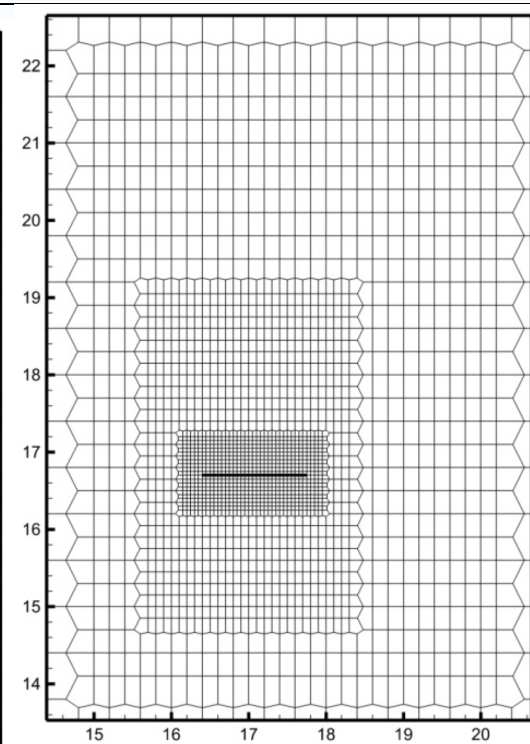
Modeling: Geologic Model (II)

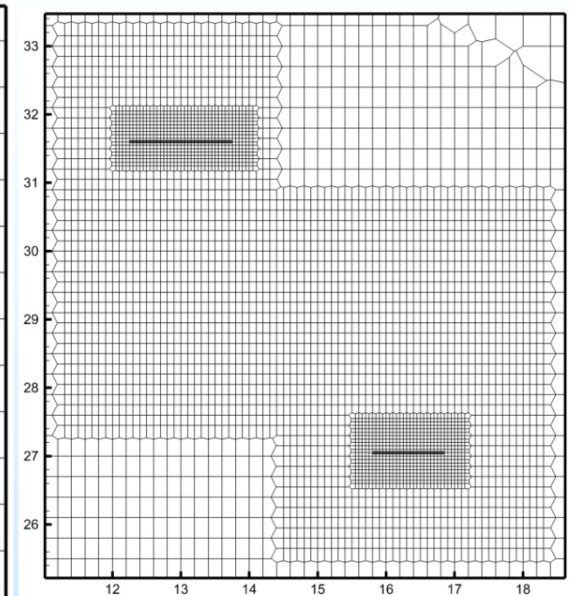


➢ **Porosity (left) and permeability (right) of the six layers of the storage formation (C10.2): the initial geomodel for inversion**

Modeling: 3D Mesh

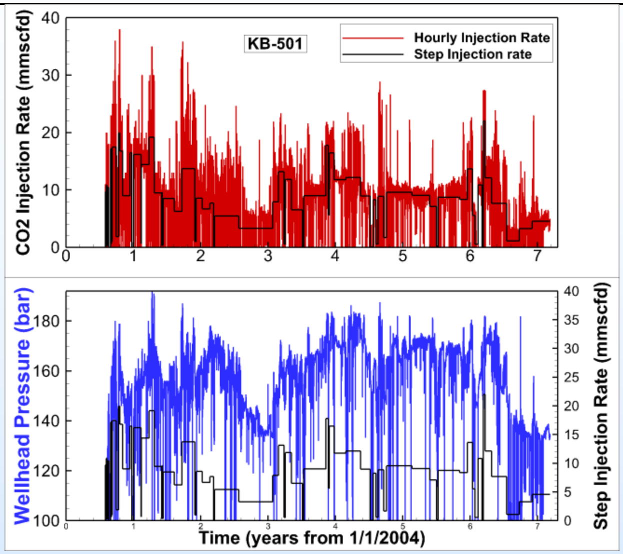




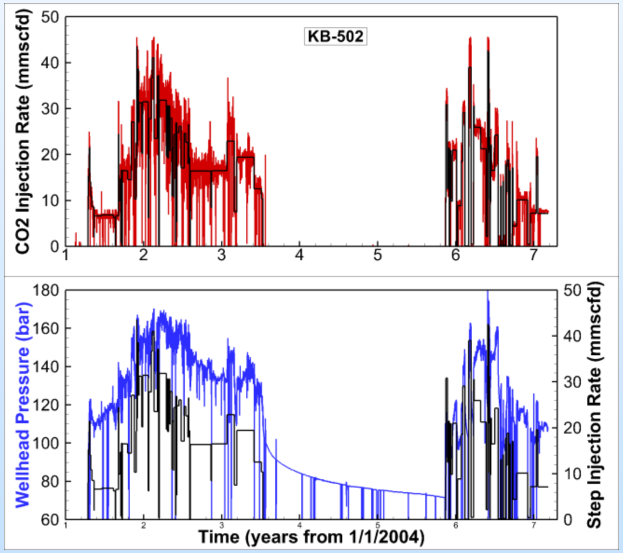


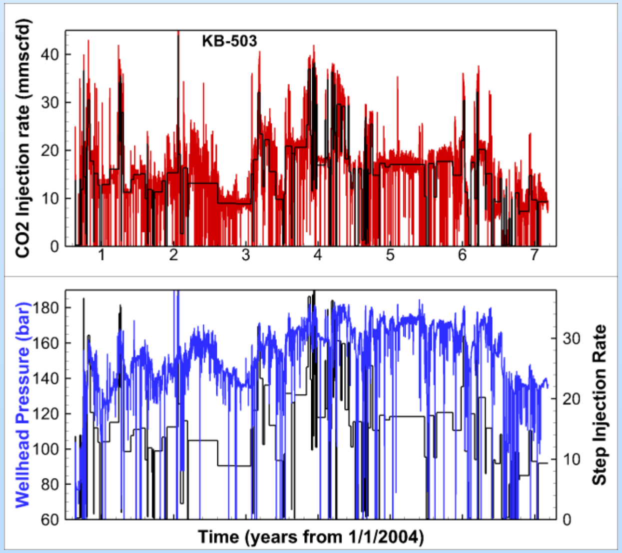
- **The model domain covers a region 27 km × 43 km with surface deformation monitored**
- **Local mesh refinement around the three horizontal wells**

Modeling: Time-Dependent Injection Rate



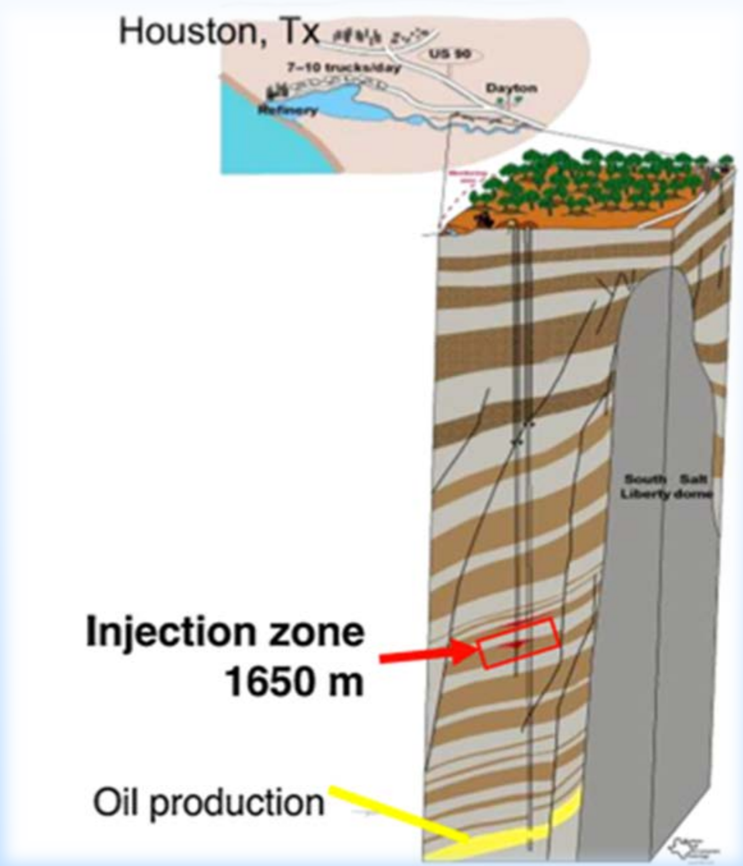
- **CO2 Injection rate varied significantly, leading to large pressure changes**
- **For modeling, the 7-year injection was represented using 90-150 step rates**



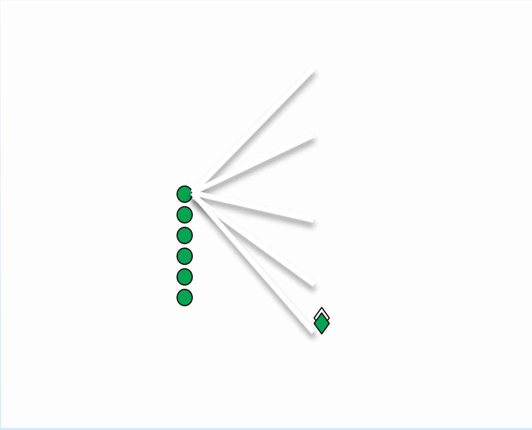


- **To match the observed pressure changes with focus on the dynamics (e.g., fracturing) of the storage system**

FRIO II: CO_2 Injection example



Geology of FRIO II CO2 injection site (Daley et al. 2011)



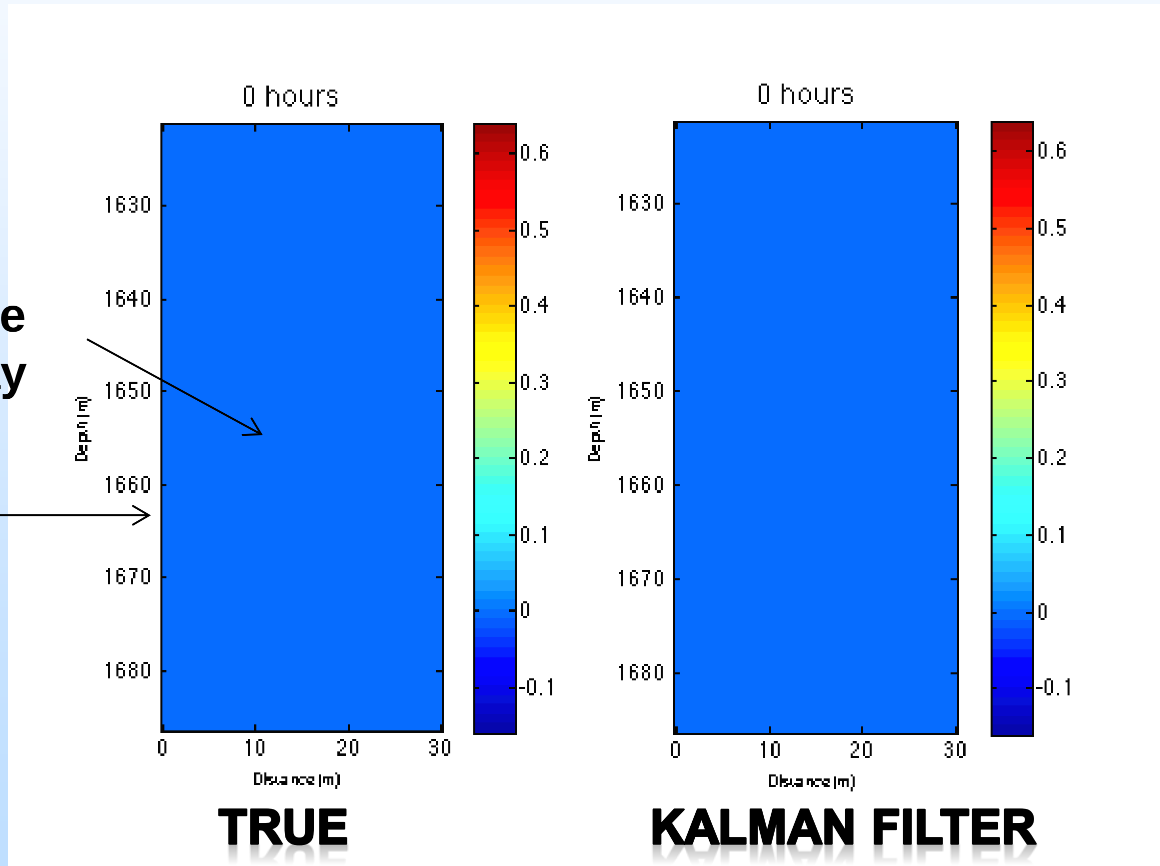
Data Courtesy of LBNL:
Ajo-Franklin
Thomas M. Daley
Christine Doughty

FRIO II: CO_2 Injection example

- **Early leakage detection**

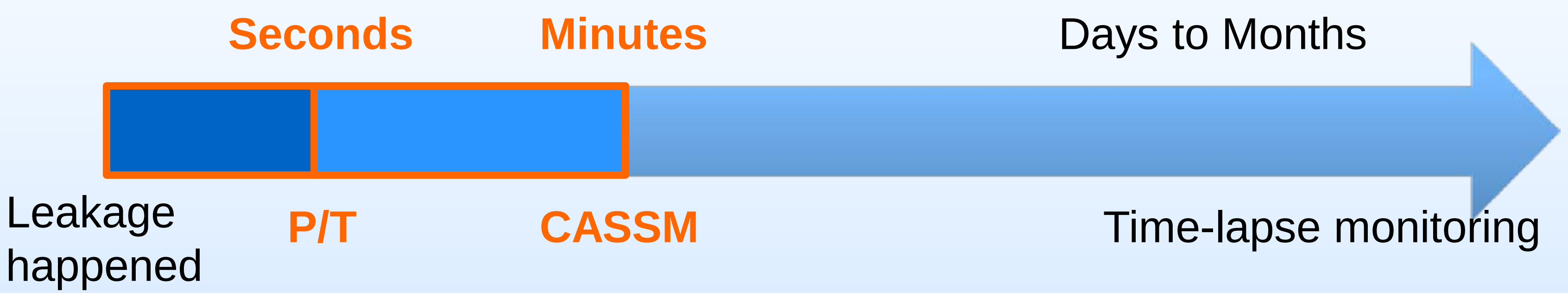
Leakage pathway

Injection point

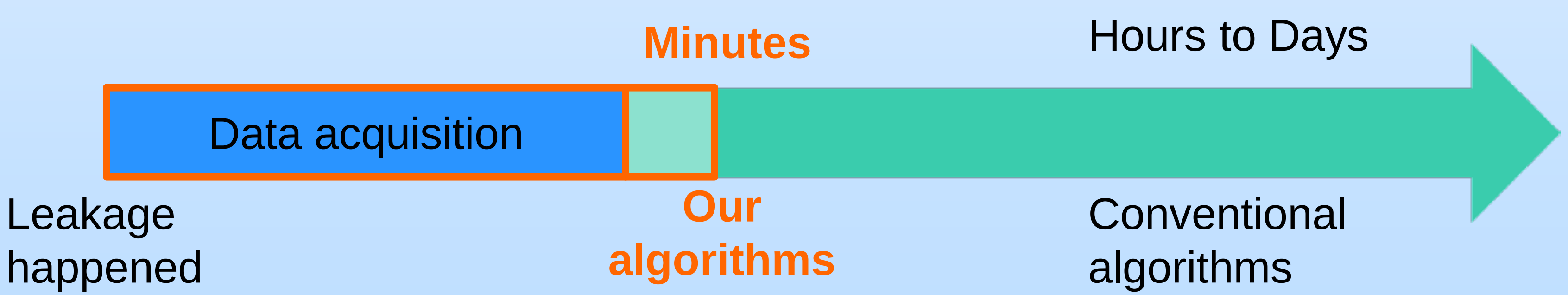


Enable *Real-time* Monitoring

- **Fast data acquisition**



- **Fast data processing (N >> p)**



N: number of unknowns **p:** number of data

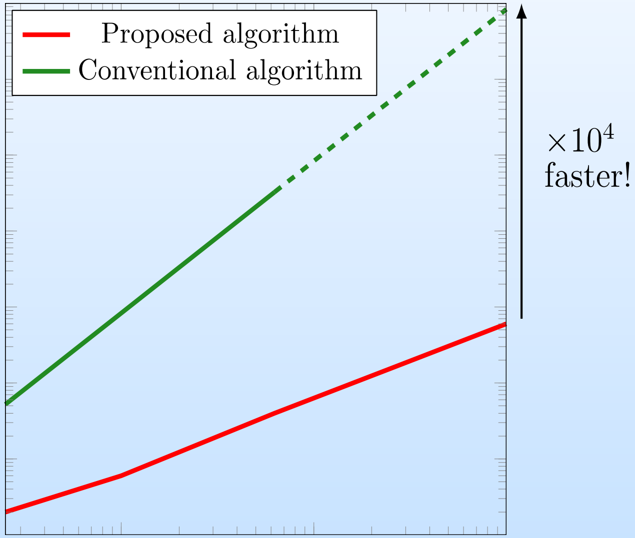
Scalability is the key…

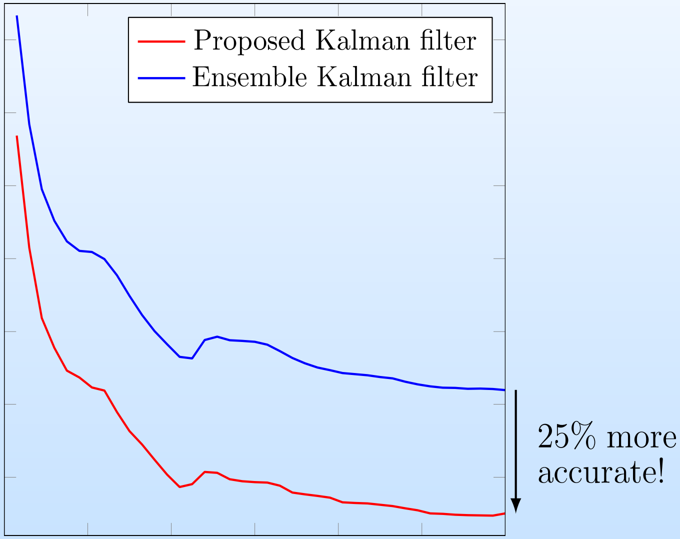
- **We use fast linear algebra**
  - **FFT, Fast Multipole Methods, Hierarchical Matrices …**
  - **Computational cost that is close to linear in the size of the problem**

- **We develop software**
  - BBFMM2D - Black Box Fast Multipole Method in two dimensions. Available at: http://sivaramambikasaran.github.io/BBFMM2D/
  - FLIPACK - Fast Linear Inversion PACKage. Available at: http://sivaramambikasaran.github.io/FLIPACK/

Hierarchical Kalman filter (HiKF)

Computationally efficient for real-time monitoring O(N):
1 million unknowns within minutes on a single-core CPU





Li,J.Y., Ambikasaran, S., Darve, E.F., Kitanidis, P.K. (2013) A Kalman filter powered by H-matrices for quasi-continuous data assimilation problems, *Water Resour Res*, submitted

Accomplishments to Date

1. Static inversion: Developed methodology for fast inversion exploiting hierarchical matrices (paper published)
2. Static inversion: Extended 1. by adding orthogonal decompositions (paper to be submitted)
3. Dynamic data assimilation: Developed HiKF for special cases of near continuous tracking of plumes (paper submitted)
4. Generalized method in 3. for other dynamic systems (published in Ambikasaran’s dissertation, paper to be submitted)
5. Published on the web two software libraries.

Summary 1/2

Key Findings:

– The design and management of CO_2 storage facilities rely on the timely use of large data sets of diverse data. But conventional methods are not suited to handle such large volumes of data.

– Hierarchical and matrix factorization methods from fast linear algebra produce algorithms that are faster and require less storage by **orders of magnitude**

Summary

Lessons Learned:

– "It seems that there is always a better (faster, with less storage, more accurate) way to solve a problem"

Future Plans:

– Continue algorithm development
– Develop software libraries for code utilization
– More emphasis on actual sites and data of more diverse nature

Appendix

– These slides will not be discussed during the presentation, but are mandatory

Organizational Chart

PI: Peter Kitanidis

Task 2: Stochastic Inversion Development
Task Lead: Peter Kitanidis[1]
Participants: Eric Darve[1], Sivaram Ambikasaran[1] & Judith Li[1]

Task 3: Efficient Algorithms and GPUs
Task Lead: Eric Darve[1]
Participant: Sivaram Ambikasaran[1], Keni Zhang[2]

Task 1: Project Management and Planning
Task Lead: Peter Kitanidis[1]
Participants: Eric Darve[1] & Quanlin Zhou[2]

Tasks 4 & 5: Methodology Testing/Application
Task Lead: Quanlin Zhou[2] & Peter Kitanidis[1]
Participants: Xiaoyi Liu[2], Judith Li[1], Jens Birkholzer[2]

[1]Stanford University, [2]Lawrence Berkeley National Laboratory

Project Team

At Stanford University:

- **Sivaram Ambikasaran, PhD candidate in Computational and Mathematical Engineering**
- **Judith Li, PhD candidate in Civil and Environmental Engineering**

At Lawrence Berkeley National Laboratory:

- **Jens Birkholzer, will collaborate on mathematical modeling issues**
- **Keni Zhang, will collaborate on high-performance computing and the use of TOUGH2 model**
- **Xiaoyi Liu will collaborate on both forward modeling and inversion**

Gantt Chart

Quarter	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1.0. Project Management/Planning												
Subtask 1.1: Project Management Plan	A											
Subtask 1.2:Project Planning and Reporting		B										
Task 2.0. Development of Stochastic Inversion Methods						D1						
Subtask 2.1. Development of Fast Bayesian Inverse Methods				C_1								
Subtask 2.2. Development of Efficient Joint Inversion Methods for Dynamic Monitoring												
Subtask 2.3. Fusion of Results from Separate Inversion of Multiple Different Data Sets												
Task 3.0. Development of Efficient Inversion Algorithms						D2						
Subtask 3.1. Algorithms for Solving Large Dense Linear Systems				C_2								
Subtask 3.2. High-Performance Implementation using GPUs												
Task 4.0. Testing of the Joint Inversion Methodology for a Synthetic Geologic Carbon Storage Example								E2				
Subtask 4.1. Generation of the "True" Fields of Porosity and Permeability of the Heterogeneous Storage Formation												
Subtask 4.2. Generation of the Simulated Data of Hydro-Tracer-Thermal Tests and CO2 Injection Test							E1					
Subtask 4.3. Joint Inversion of the Simulated Data												
Task 5.0. Application of the Methodology to Test Sites												F3,F 4
Subtask 5.1 Application to Test Site One											F1	
Subtask 5.2 Application to Test Site Two												F_2

Project Workplan/SOPO Project Tasks

- Task 1: Project Management and Planning
  - Subtask 1.1: Project Management Plan
  - Subtask 1.2: Project Planning and Reporting
- Task 2.0: Development of Stochastic Inversion Methods
  - Subtask 2.1: Development of Fast Bayesian Inverse Methods
  - Subtask 2.2: Development of Efficient Joint Inversion Methods for Dynamic Monitoring
  - Subtask 2.3: Fusion of Results from Separate Inversion of Multiple Different Data
- Task 3: Development of Efficient Inversion Algorithms
  - Subtask 3.1: Algorithms for Solving Large Dense Linear Systems (FDSPACK + Low Rank Approximations)
  - Subtask 3.2: High-Performance Implementation using GPUs in TOUGH+CO2

Project Workplan/SOPO Project Tasks

- Task 4.0: Testing of the Joint Inversion Methodology for a Synthetic Geologic Carbon Storage Example
  - Subtask 4.1: Generation of the “True” Fields of Porosity and Permeability of the Heterogeneous Storage Formation
  - Subtask 4.2: Generation of the Simulated Data of Hydro-Tracer-Thermal Tests and CO_2 Injection Test
    - Subtask 4.2.1: Creation of the Simulated Data for Hydro-Tracer-Thermal Tests Prior to CO_2 Injection
    - Subtask 4.2.2: Creation of the Simulated Data for CO_2 Injection Test
  - Subtask 4.3: Joint Inversion of the Simulated Data
- Task 5.0: Application of the Methodology to Test Sites
  - Subtask 5.1 – Application to Test Site One
  - Subtask 5.2 – Application to Test Site Two

Project Deliverables

- 1. Task 1.0 – Project Management Plan
- 2. Task 2.0 – Developed inversion algorithms and their demonstration cases, with the final joint inversion tool system, as documented in a quick-look report.
- 3. Task 3.0 – Developed fast large linear system solvers with different computational algorithms as documented in a quick-look report.
- 4. Task 4.0 – Test results of the joint inversion methodology for a synthetic Geologic Carbon Storage example as documented in a quick-look report.
- 5. Task 5.0 – Test results of application of the methodology to field test sites as documented in a quick-look report.
- 6. Task 5.0 – Validation of developed computational tools performance and cost as documented in quick-look report.
- 7. Project Data – Data generated as a result of this project shall be submitted to NETL for inclusion in the NETL Energy Data eXchange (EDX), https://edx.netl.doe.gov/.

Bibliography

List peer reviewed publications generated from project:

Ambikasaran, S., Li, J.Y. Darve, E. F., and Kitanidis P. K. (2013), Large-scale stochastic linear inversion using hierarchical matrices, *Computat Geosci, published online, doi:* 10.1007/s10596-013-9364-0, also available at: http://www.stanford.edu/~sivaambi/

Li, J. Y., Ambikasaran, S., Darve, E. F., and Kitanidis, P. K. (2013), A Kalman filter powered by H-matrices for quasi-continuous data assimilation problems, *Water Resour Res, in review.*

Liu, X.; Zhou, Q.; Kitanidis, P. K. & Birkholzer, J.. Fast Iterative Implementation of Large-Scale Nonlinear Geostatistical Inverse Modeling, Water Resour. Res., 2013, in review.

Kitanidis, P. K., (2013), Geostatistical approach to inverse problems for very large dimensional problems, to be submitted soon.

Modeling: Forward Modeling & Inversion (FY14)

- **Forward modeling:**
  - **Site-specific model for the entire model domain and three injection wells**
  - **Submodels will be created to focus on KB-501 or KB-502/503 regions**
  - **Forward modeling will be conducted to simulated the pressure and surface deformation responses to the time-dependent injection for the site-scale model and the submodels**
- **Inversion**
  - **The geologic model developed by BP using all site-characterization data will be used as initial guess of the “true” geologic model**
  - **The “true” geologic model will be obtained through our stochastic joint inversion to match the pressure and high-resolution deformation data**