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Reducing Uncertainties in Model Predictions via History Matching of CO_2 Plume Migration at the Sleipner Project, Norwegian North Sea

Project Number (DE-FE0004381)

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Indiana University

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage
August 21-23, 2012

Organization Chart

- **PRINCIPAL INVESTIGATOR**
- Professor Chen Zhu
- Indiana University

- **Co-Principal Investigator**
- Professor Per Aaggard, University of Oslo, Norway

- **Student/post-doc**
- Peng Lu, Indiana University

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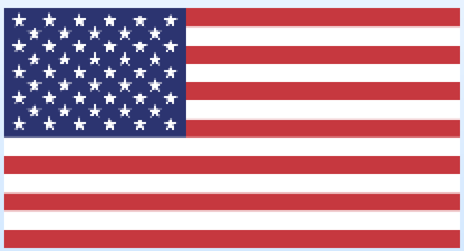
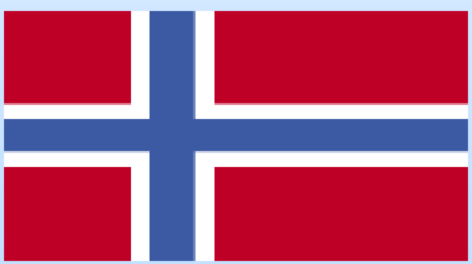
U.S.-Norway Fulbright Foundation for Educational Exchange





Norwegian Center of Excellence: Subsurface CO_2 storage – Critical Elements and Superior Strategy (SUCCESS)

Specific Objectives of This Project:

1. Acquire dataset and track the Sleipner project, one of the best field dataset for U.S. scientists, engineers, and students working on CCUS;
2. Develop a reactive flow reservoir model that matches CO_2 plume migration history;
3. Use the flow model as the basis to develop coupled reactive transport model to simulate water-rock interaction and long-term fate of CO_2 at Sleipner.

TASK 1.0 - PROJECT MANAGEMENT, PLANNING AND REPORTING

TASK 2.0 – DATA ACQUISITION AND INTERPRETATION

TASK 3.0 – HISTORY MATCHING OF CO_2 PLUME MIGRATION WITH A RESERVOIR MODEL

TASK 4.0 – MODELING LONG-TERM CO_2 FATE

Presentation Outline

- Benefits to the program
- Project overall objectives
- Technical status
- Project summary
- Conclusions and future plans

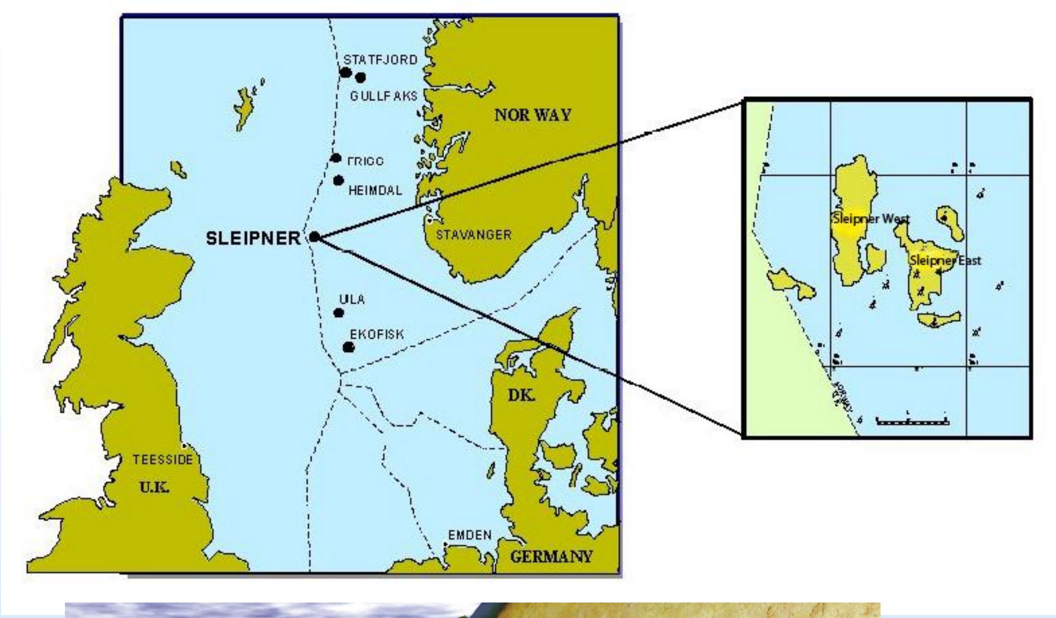
Benefit to the Program

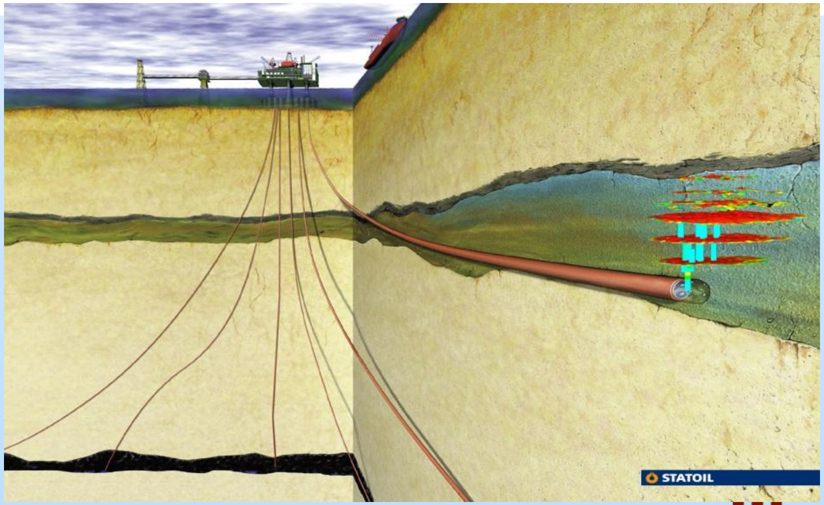
- Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
- Develop technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zones.
- This research project develops a reservoir scale CO_2 plume migration model at the Sleipner project, Norway. The Sleipner project in the Norwegian North Sea is the world's first commercial scale geological carbon sequestration project. 4D seismic data have delineated the CO_2 plume migration history. The relatively long history and high fidelity data make Sleipner one of the best places in the world to conduct multi-phase flow and reactive mass transport modeling of CO_2 migration. This work contributes to the Program's efforts of demonstrating 99% of injected CO_2 remaining in the injected zone and ability to predict storage capacity within ±30%

Project Overview Objectives

To assess and reduce uncertainties of model predictions of CO_2 plume migration, trapping mechanisms, and storage capacity estimates through history matching and long-term fate modeling of CO_2 through implementing rigorous chemical kinetics and through a number of bounding calculations and sensitivity analyses

Norwegian Sleipner Project





Sleipner CO_2 injection:

- World's first industrial-scale geological carbon sequestration project
- In operation since 1996
- 1 million ton CO_2/year
- Storage: Utsira Formation. A saline reservoir 800-1000 meters (2600-3300ft) below the sea floor

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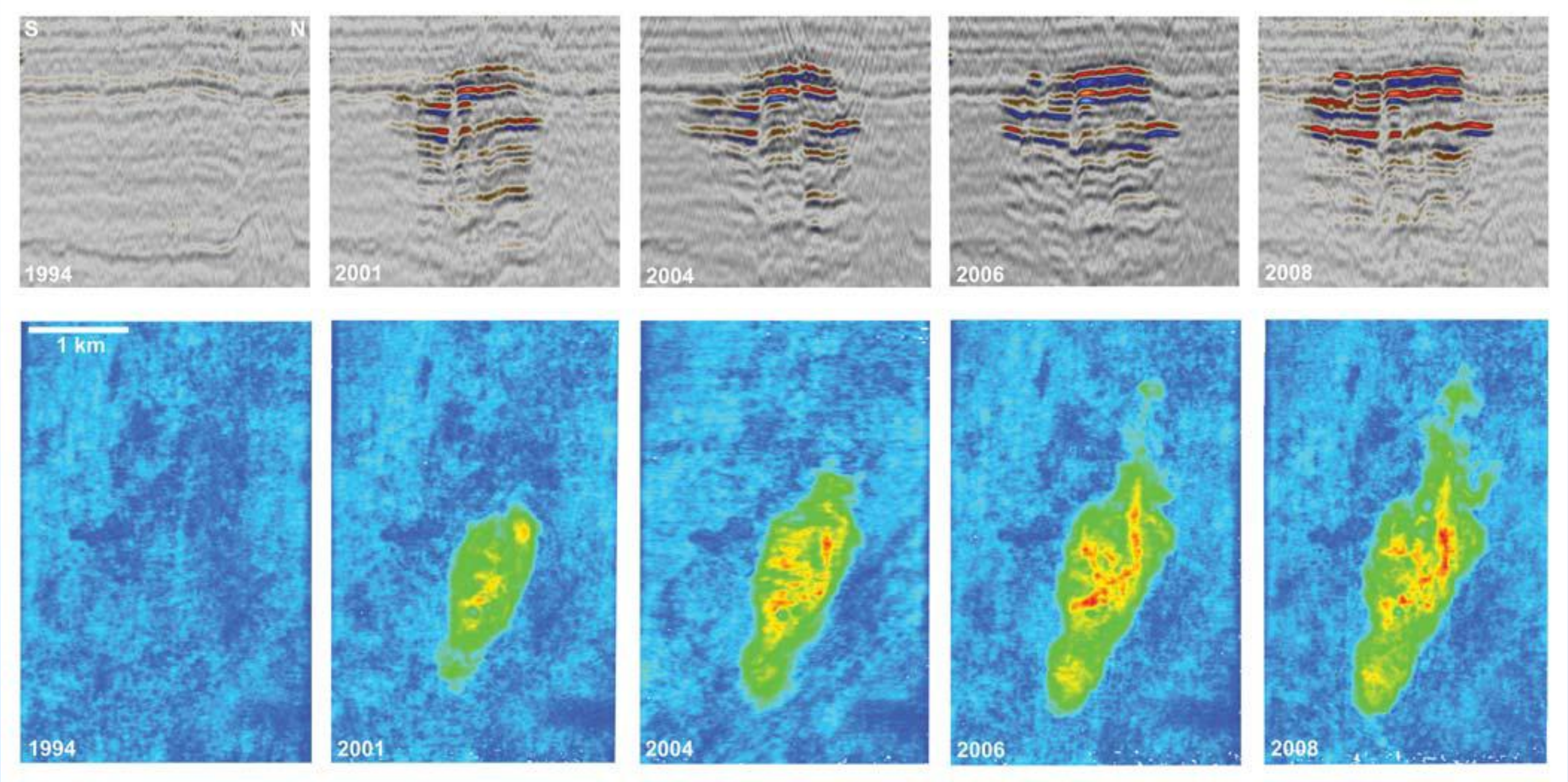
Time-lapse seismic images of the CO_2 plume at Sleipner



Upper row: N-S seismic section through the plume.
Lower row: plan views of the plume showing total integrated reflection amplitude (Chadwick et al., 2010)

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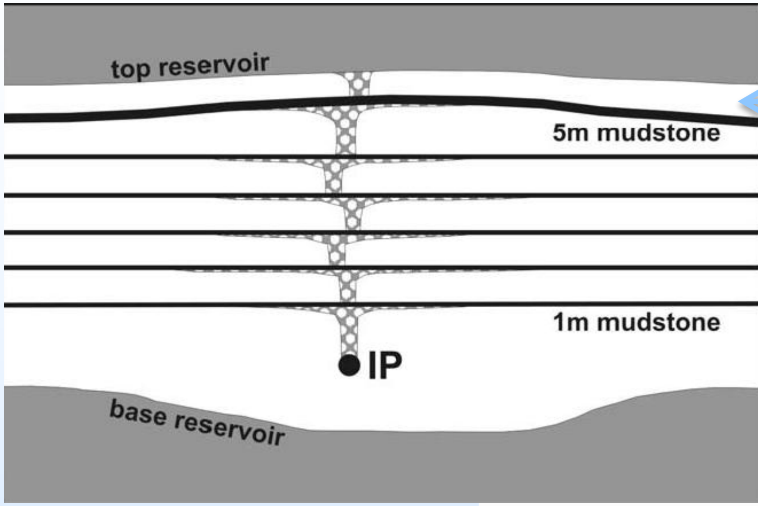
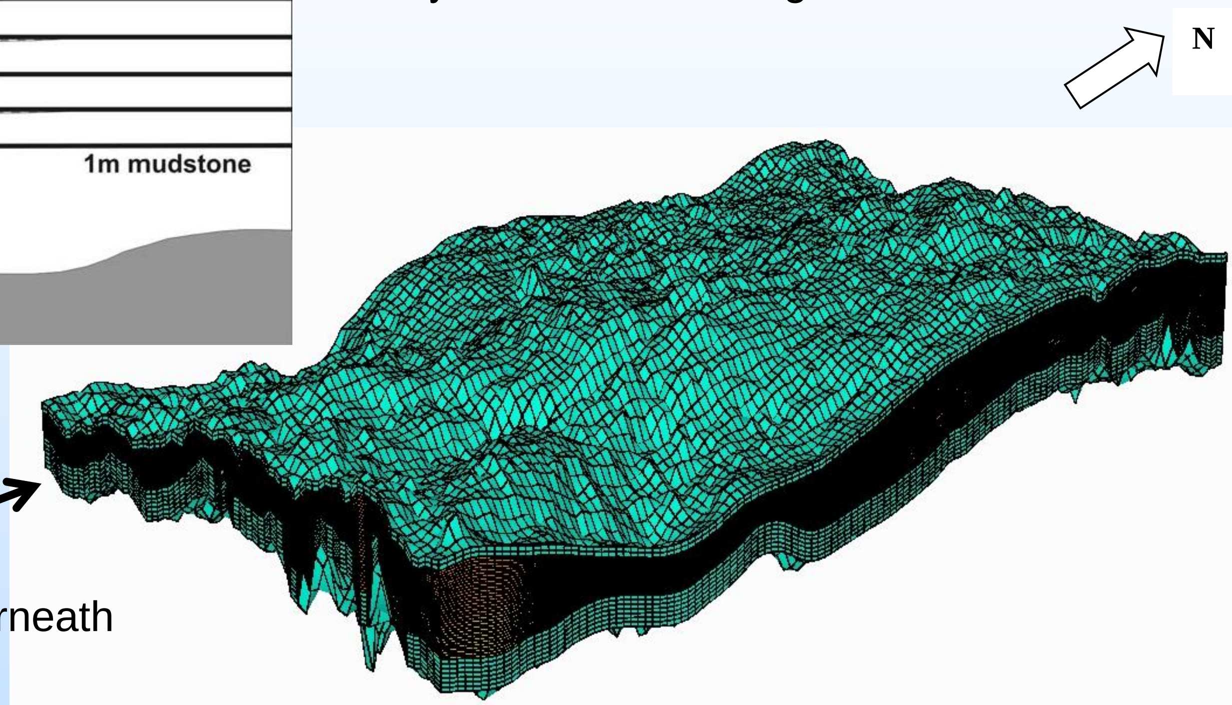
StatOil-IEA Benchmark Geological Model



Layer 9 = “Sand Wedge”



5 m mudstone underneath

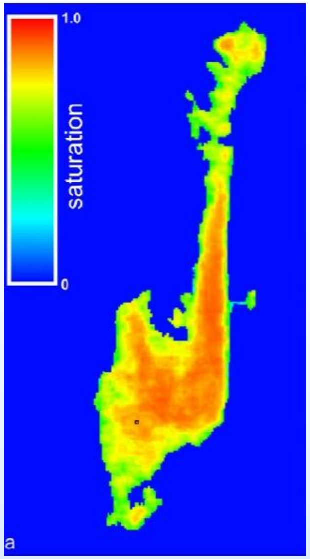
- An area ~ 3 x 6 km
- Grid dimensions: x = 65, y = 119, z = 43; total 332,605 blocks
- The basic grid resolution is 50 m x 50 m.

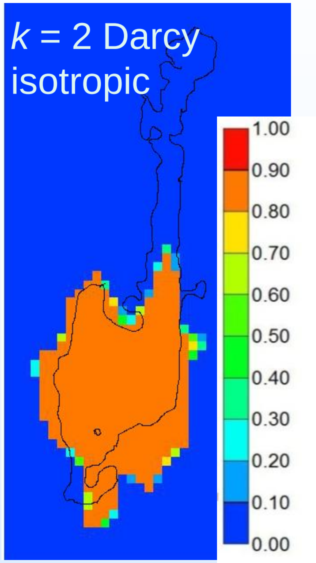
Model Construction and Methods

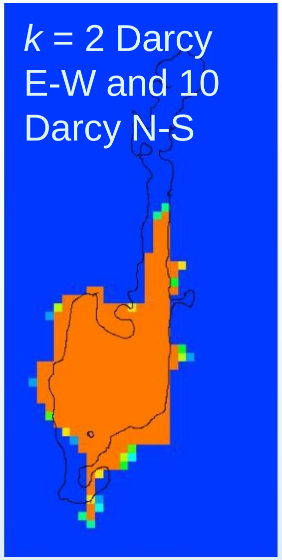
- Reservoir-scale multi-phase reactive flow model for the "Layer 9", because only this layer is clearly resolved on the seismic data
- Immediate contact with the overlying sealing caprock.
  - CO_2 behavior and fate in this layer are determinative to the long-term effectiveness and security of the containment
- Strategy
  - History-match of the CO_2 plume development is essentially an inverse modeling problem but not practical for formal inverse methods
  - We used conditional trial-and-error method
  - Calibrate the locations of major CO_2 conduits/feeders and the permeability anisotropy conditioned to match CO_2-water contacts
  - Subsequently merge into a calibrated model for long-term prediction

First Attempt—Applying Permeability Anisotropy

Observed extents



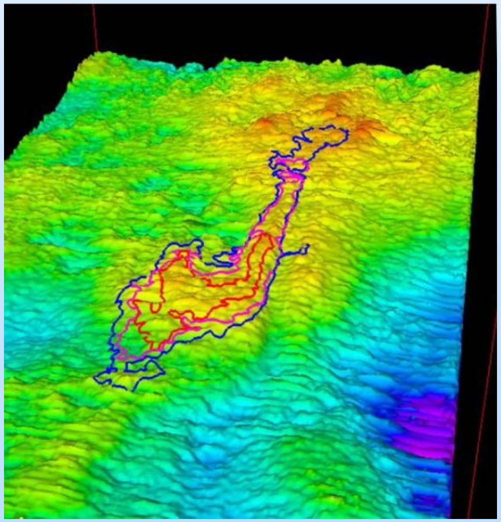


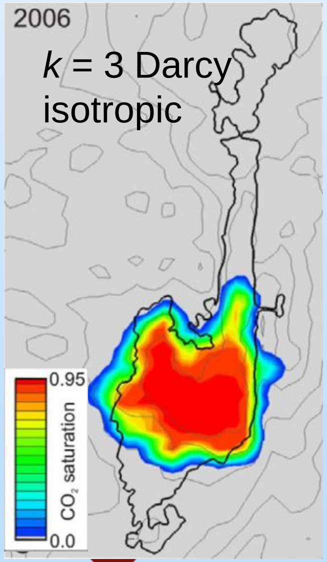


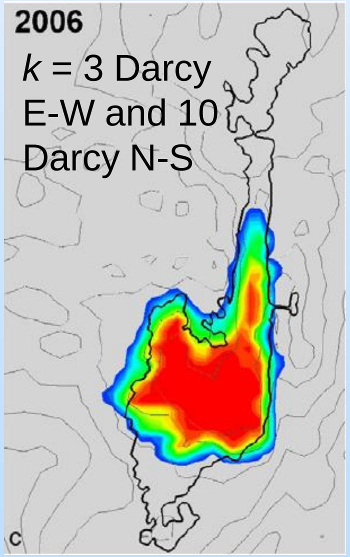
GEM simulation

Cannot achieve the match by adjusting permeability anisotropy alone

Topography of the Layer 9.

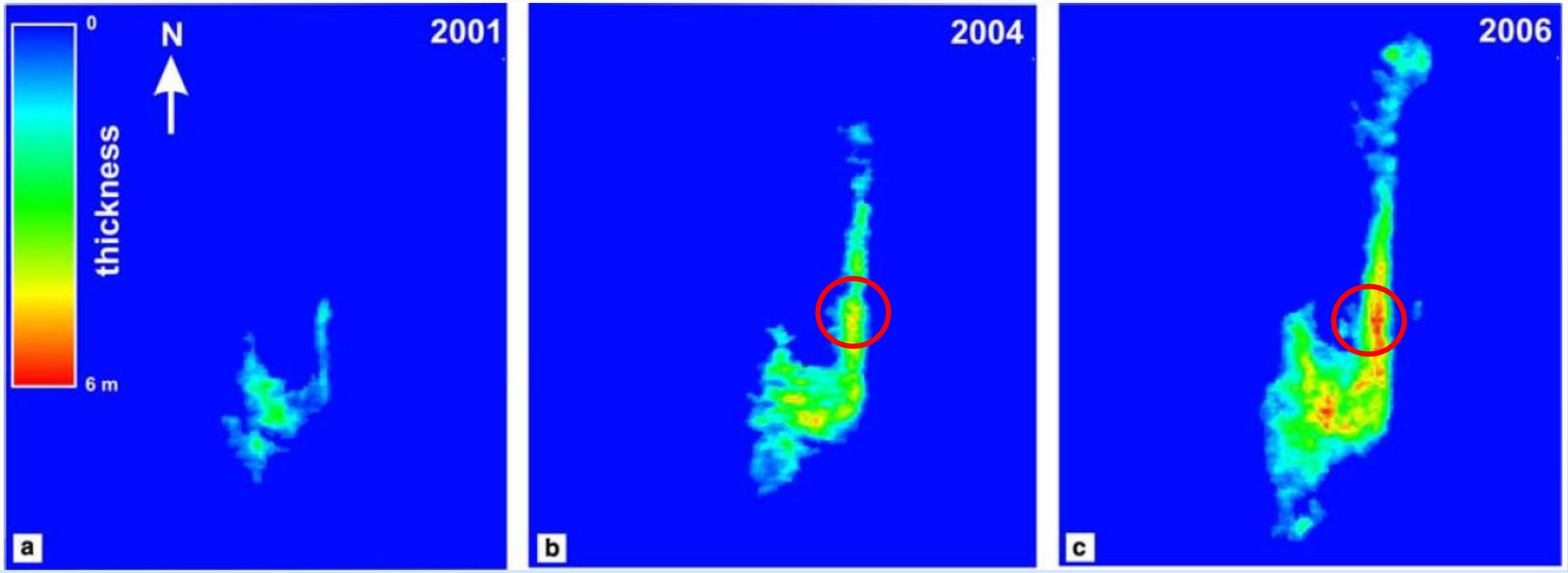






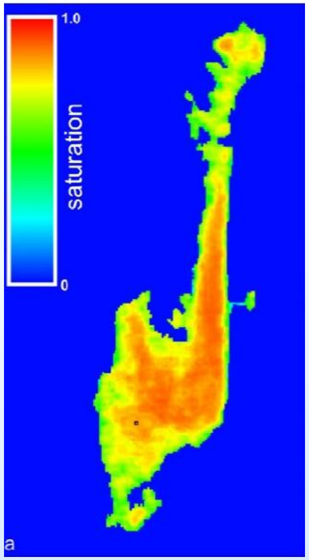
Tough 2 simulations (Chadwick and Noy, 2010)

Second Attempt--Additional Feeder together with Permeability Anisotropy

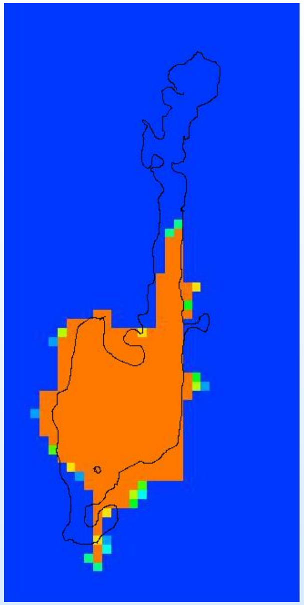


CO_2 plume thicknesses derived from reflection amplitudes (Chadwick and Noy, 2010).
A thick area of CO_2 plume (red circle) is clearly shown in 2004 and 2006 map.
Propose to add a second feeder to that area after year 2001.

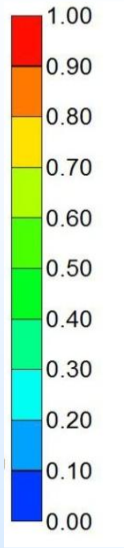
Second Attempt--Additional Feeder with Permeability Anisotropy

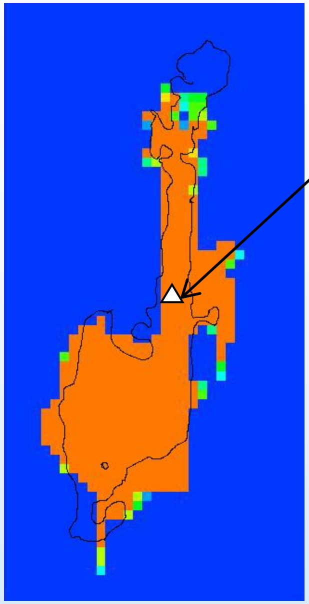


Observed extents 2006



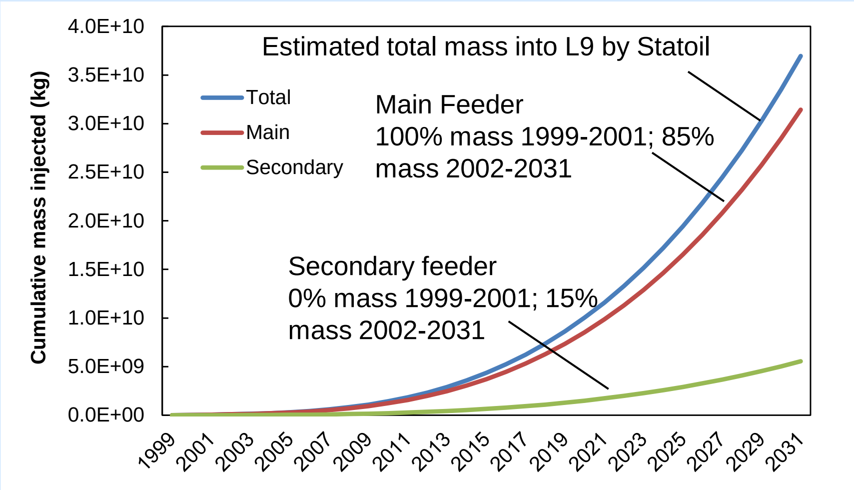
100% CO_2 volume into main feeder





Second feeder

85% CO_2 volume injected into the main feeder and 15% into the second feeder (the triangle) starting from 2002.



Acceptable results with the second feeder.

Parameters for the Base Case

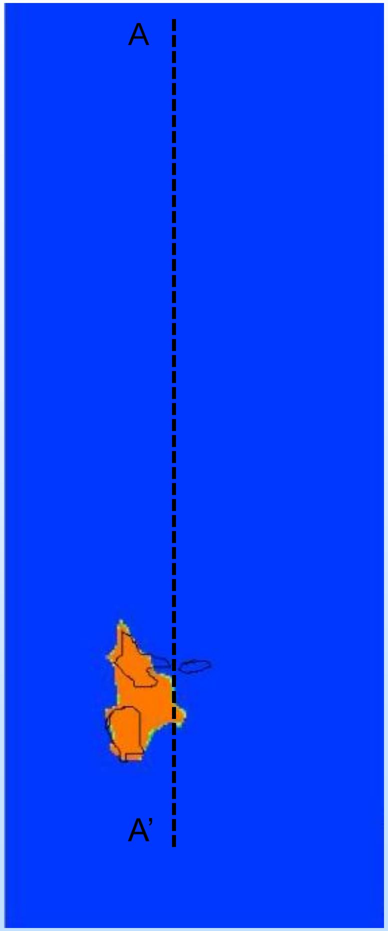
Parameters	Values
Porosity	~ 34-36%
Permeability	Sandstone: ~ 2 Darcy in E-W and 10 Darcy in N-S direction Vertical permeability ~ 1/10 of the horizontal permeability Mudstone: 1e-3 md
Hypothetical feeders	Main: x = 438516; y = 6471210 (Singh et al., 2010); Secondary: x = 438925; y = 6472250
Reservoir temperature	33 ^oC
Initial conditions	Initial pressure of each cell calculated based on determined hydrostatic pressure gradient (reference pressure: 8.6 MPa at 820 m)
Boundary conditions	No-gradient boundary conditions (using infinite large volume for the boundary grid cells so that no variables would change during the simulation in those cells)
EOS for CO_2 properties (solubility and density)	Peng-Robinson EOS (Harvey, 1996)
CO_2 viscosity	Herning and Zipperer (1936); Yoon and Thodos (1970); Jossi et al. (1962)
Relative permeability curves	Upscaled curves based on laboratory measurements (Singh et al., 2010)
Hysteresis	Considered; maximum residue gas saturation of 0.1
Salinity	33500 ppm
Water density	1020 kg/m^3
Brine viscosity	Whitson and Brule (2000); Kestin, et al. (1981)
Grid resolutions	Vertical: 34 vertical sub-layers (~ 0.34 m per sub-layer) for Layer 9 sandstone Horizontal: 50 m x 50 m

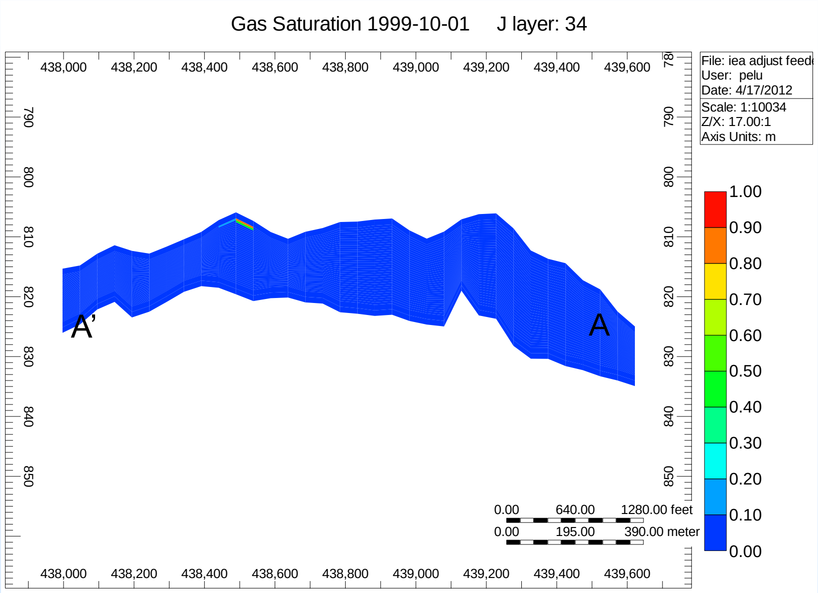
Comparison of Observed vs. Model Predicted CO_2 Plume Extent (Base Case)

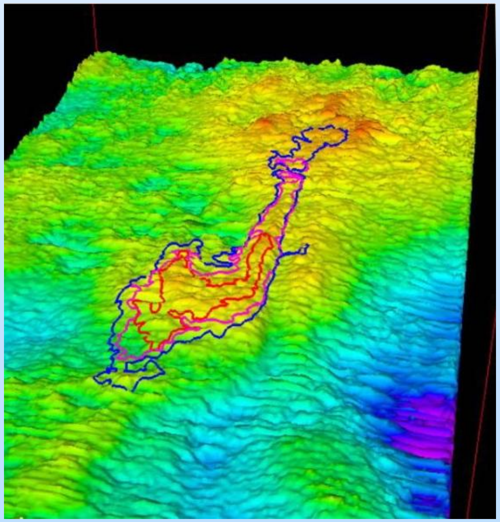
Seismic Response

1999

Model Prediction







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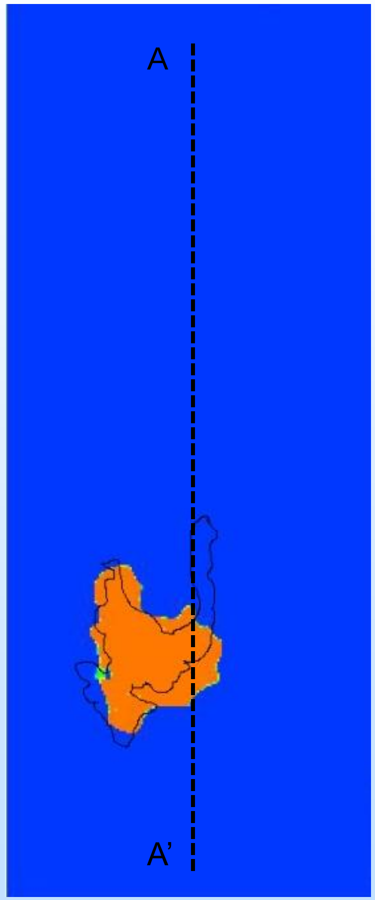
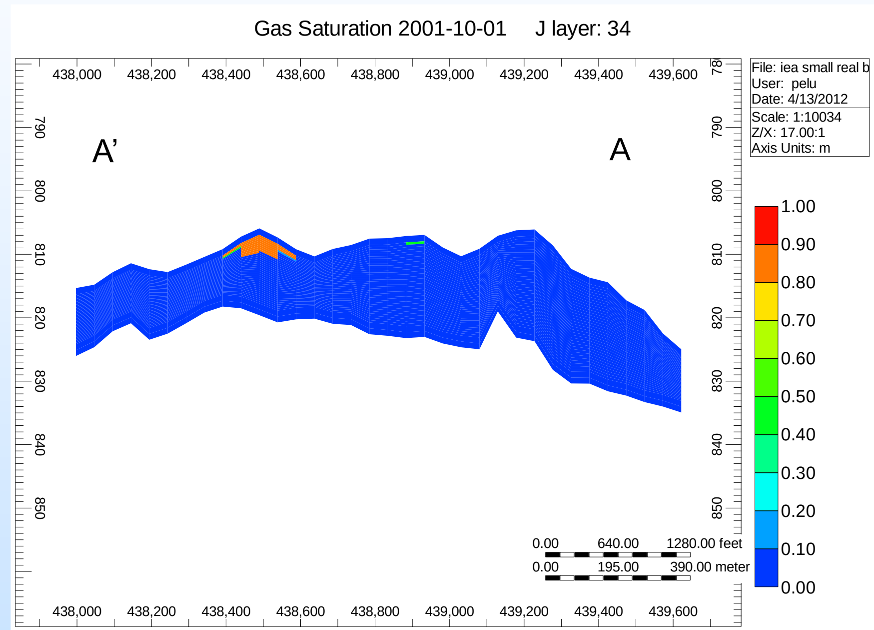
Comparison of Observed vs. Model Predicted CO_2 Plume Extent (Base Case)

Seismic Response

2001

Model Prediction

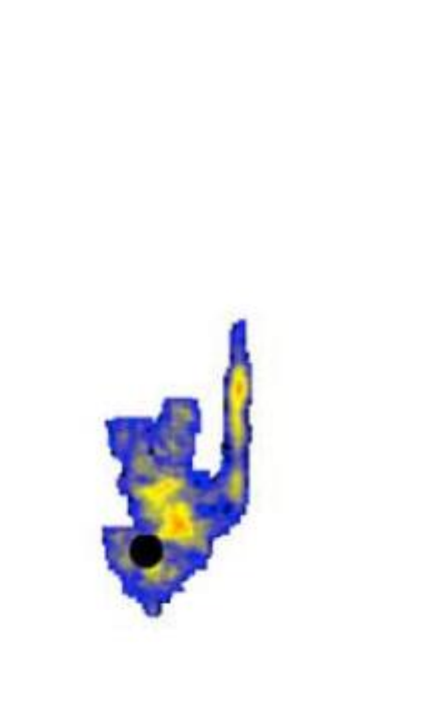




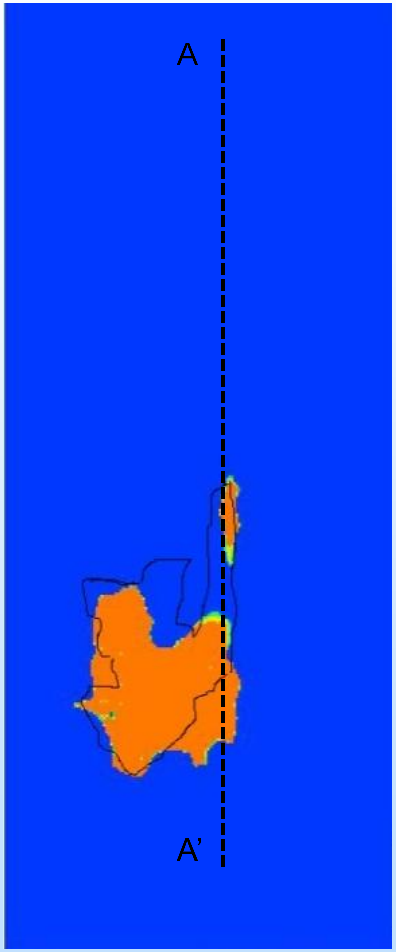
Comparison of Observed vs. Model Predicted CO_2 Plume Extent (Base Case)

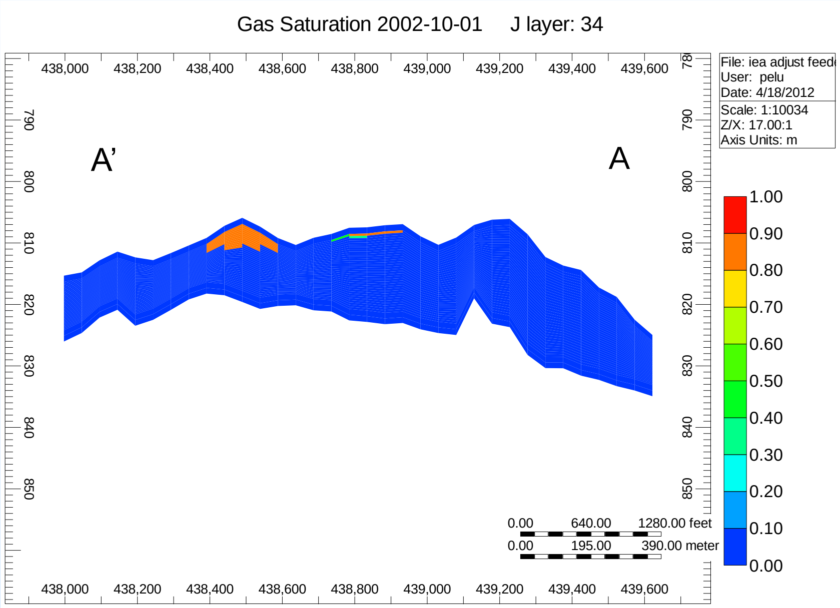
Seismic Response

2002



Model Prediction





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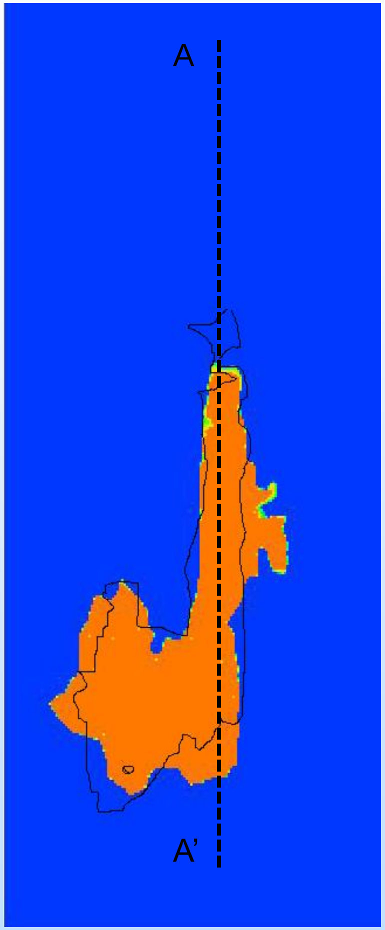
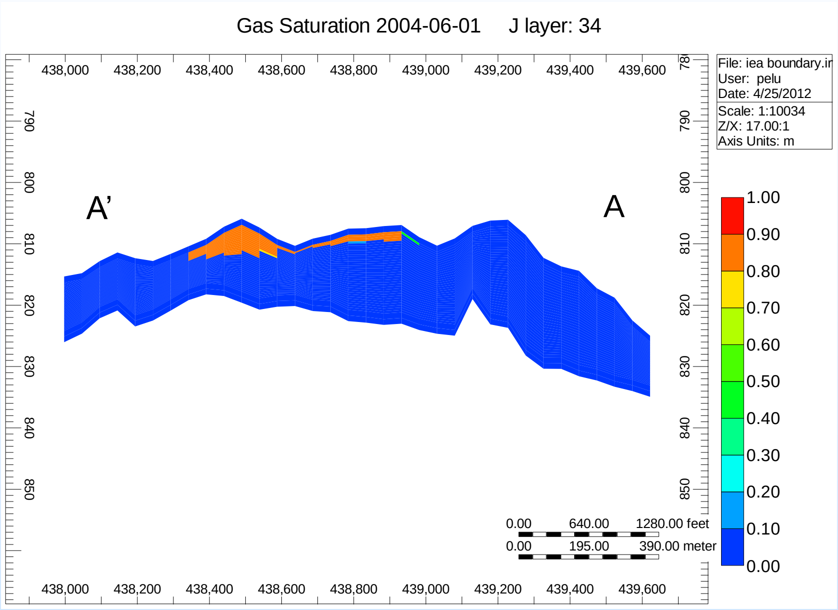
Comparison of Observed vs. Model Predicted CO_2 Plume Extent (Base Case)

Seismic Response

2004

Model Prediction





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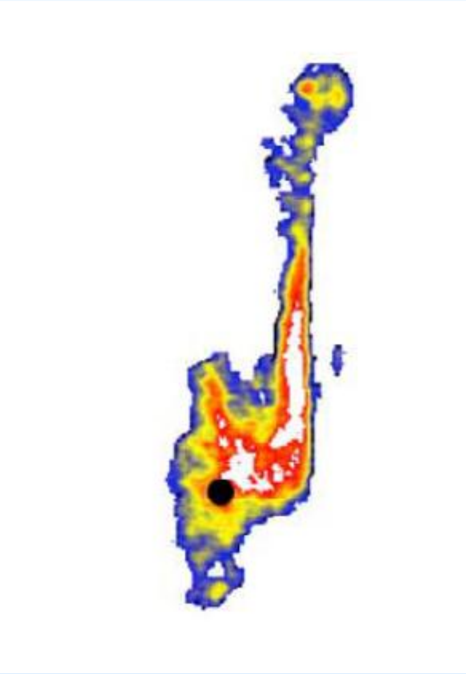
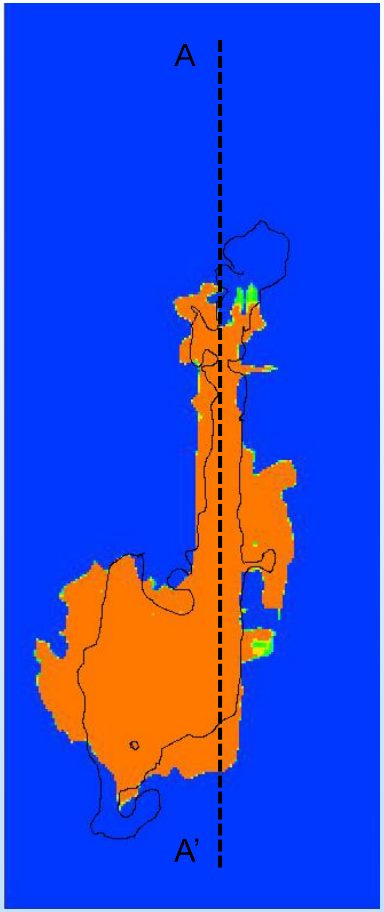
Comparison of Observed vs. Model Predicted CO_2 Plume Extent (Base Case)

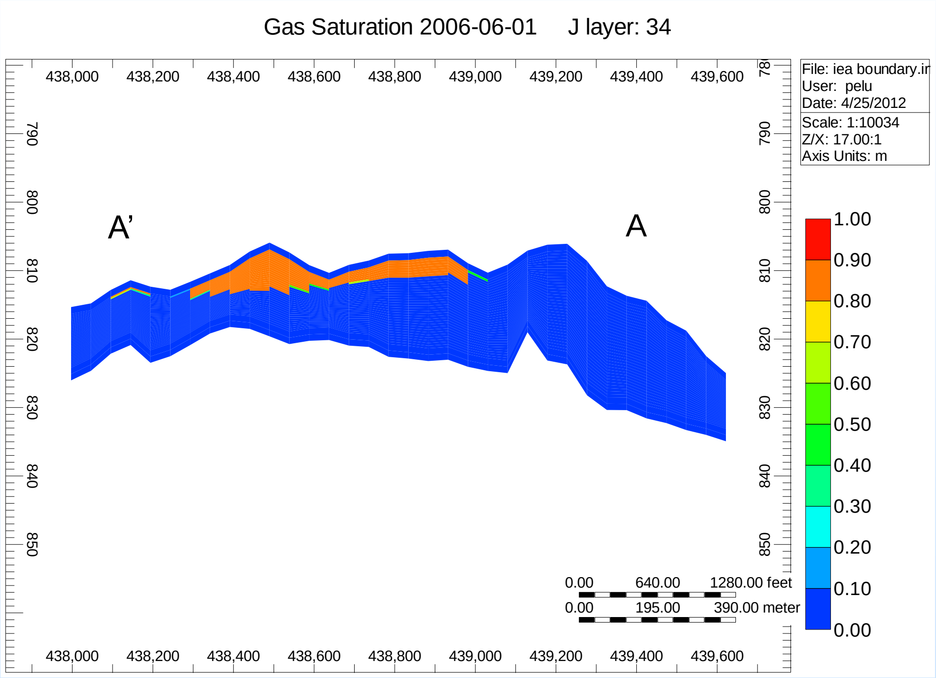
Seismic Response

2006



Model Prediction





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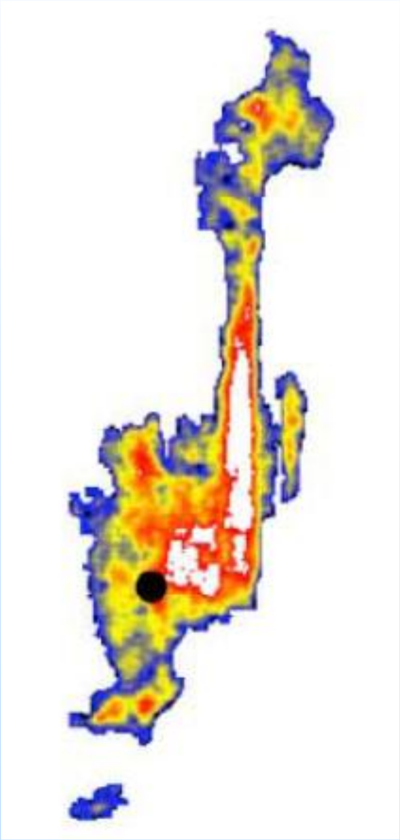
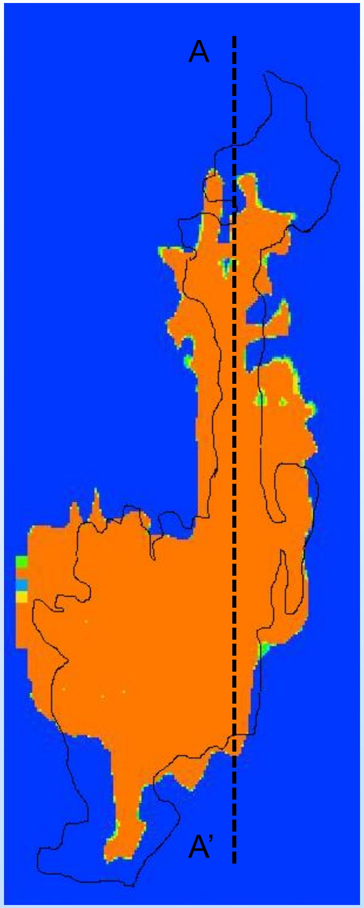
Comparison of Observed vs. Model Predicted CO_2 Plume Extent (Base Case)

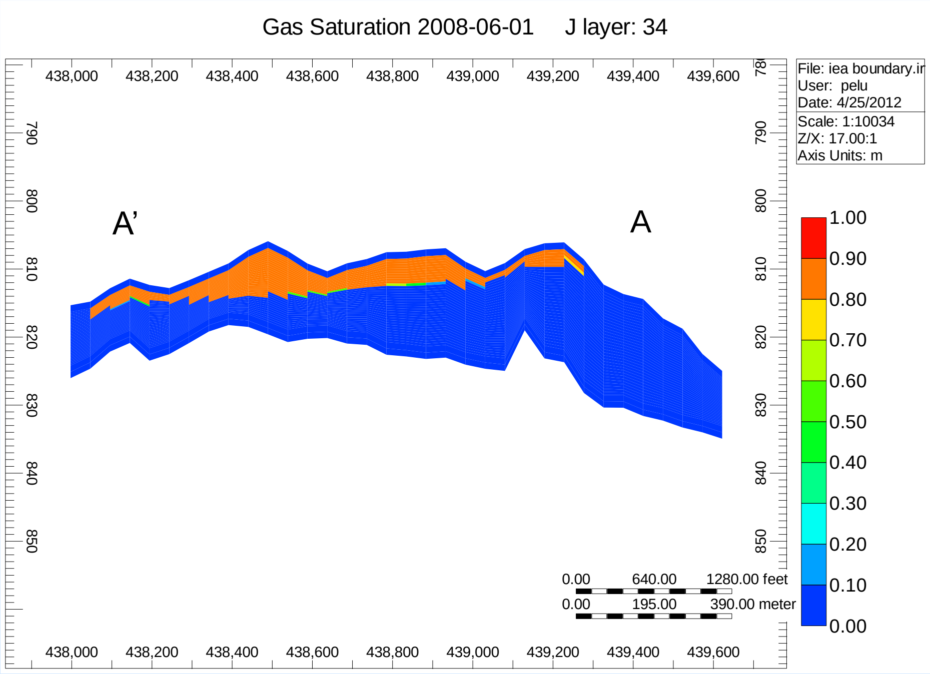
Seismic Response

2008

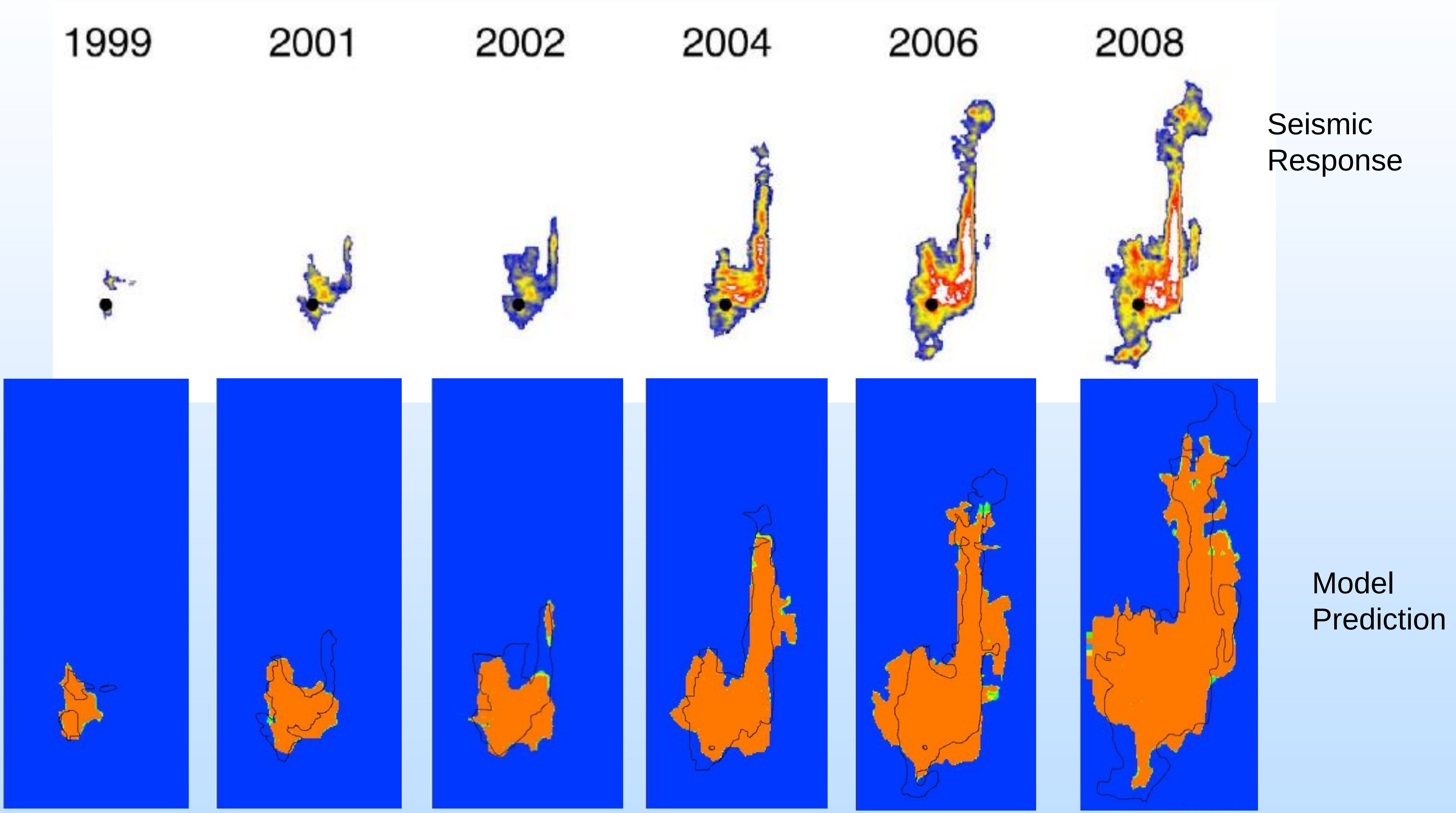


Model Prediction





Overall Comparison (Base Case)



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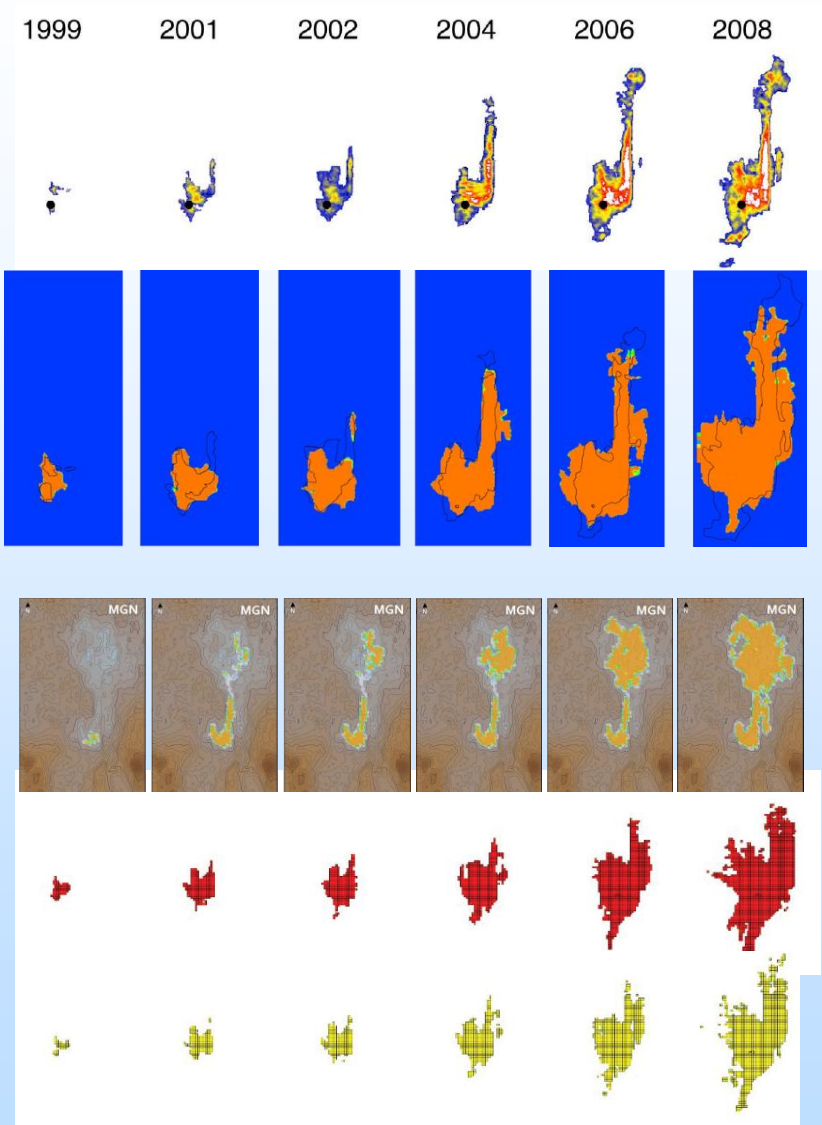
Model Comparison



Seismic Response

Model Prediction

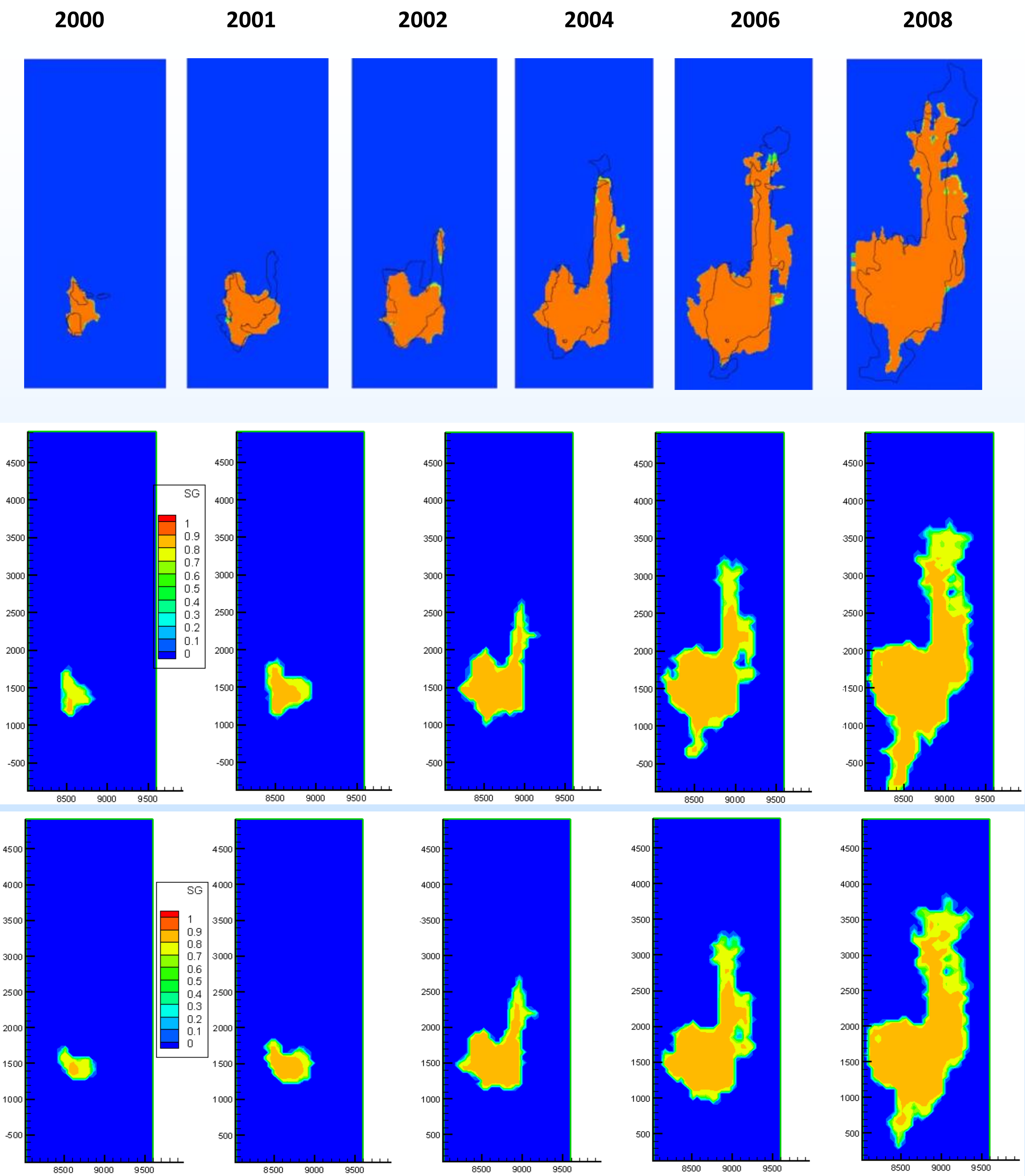
This Study

Invasion percolation migration

CO_2 Black Oil Simulator using upscaled relative permeability curves

CO_2 Black Oil Simulator using the Vertical Equilibrium option

Singh et al. (2010) using Eclipse 100/300



Simulators used

GEM

Tough2 with exactly the same parameters

Tough2, with slight modification of feeder locations

Tough2 simulation in collaboration with Professor Madesh Agarwal and Zheming Zhang

Conclusions from Modeling Study

- Geological structures have the most prominent control on CO_2 migration
- Introducing permeability anistropy is wholly justifiable based on geology
- Adding another feeder is critical in order to model the N-S extension and is justifiable (Chadwick and Noy, 2010; Singh et al., 2010).
- Our modeling results provide an excellent basis for addressing the accuracy of storage capacity estimates
  - ➢ Plume thickness compared well with those derived from reflection amplitudes
  - ➢ Fraction of dissolved CO_2 (9%) is comparable with that based on seismic data interpretation (5-10%)
- Predictive model based on our history-matched model will be compared with newly acquired data from on-going Sleipner project.
  - ➢ Uncertainty estimation

Accomplishments to Date

1. Acquired datasets for the Sleipner project, one of the best field dataset for U.S. scientists, engineers, and students working on CCUS. Fulfilling the international/global collaboration program need;
2. Developed a multiphase reactive flow reservoir model of Layer 9 for the Sleipner project and our simulation results matched well with geophysical monitoring data on historic CO_2 plume migration;
3. Initiated coupled reactive transport model to evaluate long-term effects on reservoir prosperities by water-rock interactions.

Summary

- **Key Findings**: Developed a multiphase reactive flow reservoir model of Layer 9 for the Sleipner project and our simulation results matched well with geophysical monitoring data on historic CO_2 plume migration. Simulations results include the extent of CO_2 plume migration, gas saturation, thickness of the CO_2 accumulations, and CO_2 solubility in brine, all of which are within the range of geophysics data based observations and interpretations
- **Lessons Learned**: Our results so far show that good match can be obtained with a set of reasonable parameters.

Summary (continued)

– **Future Plans**:

1) To make forward predictions into the future. StatOil has already obtained the 2010 seismic survey data. They are collecting 2012 data. Therefore, the predicted results can be compared to newly acquired data. These comparisons give assessments of uncertainties of storage capacity estimates.
2) Predictive modeling to 2023, and 1000 years later (?);
3) Connect reactive flow reservoir model to optimization routines to improve history match, evaluate factors affect plume migration, and best ways to contain plume (in collaboration with Professor Madesh Agarwal and Zheming Zhang);
4) Develop coupled reactive transport model to simulate long-term CO_2 fate, in anticipation of drilling and coring
    1) Complete conceptual model and axisymmetric TOUGHTreact modeling of Utsira Sand
    2) Port the conceptual geochemistry model into the calibrated multi-phase reactive flow model Layer 9 geometry

Hypothesis: Models have over-predicted mineral dissolution – precipitation reactions. Using realistic rate laws would see much less reactions

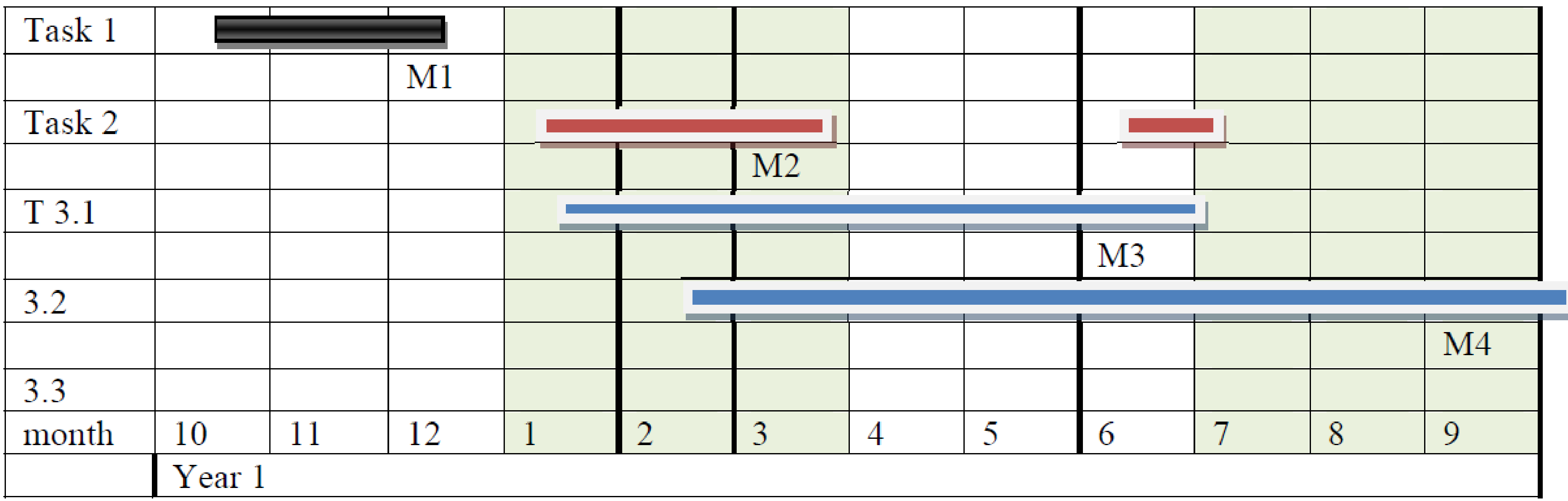
Appendix

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

Organization Chart

- **PRINCIPAL INVESTIGATOR**
- Professor Chen Zhu
- Indiana University
-
- **Co-Principal Investigator**
- Professor Per Aaggard
- University of Oslo

Gantt Chart



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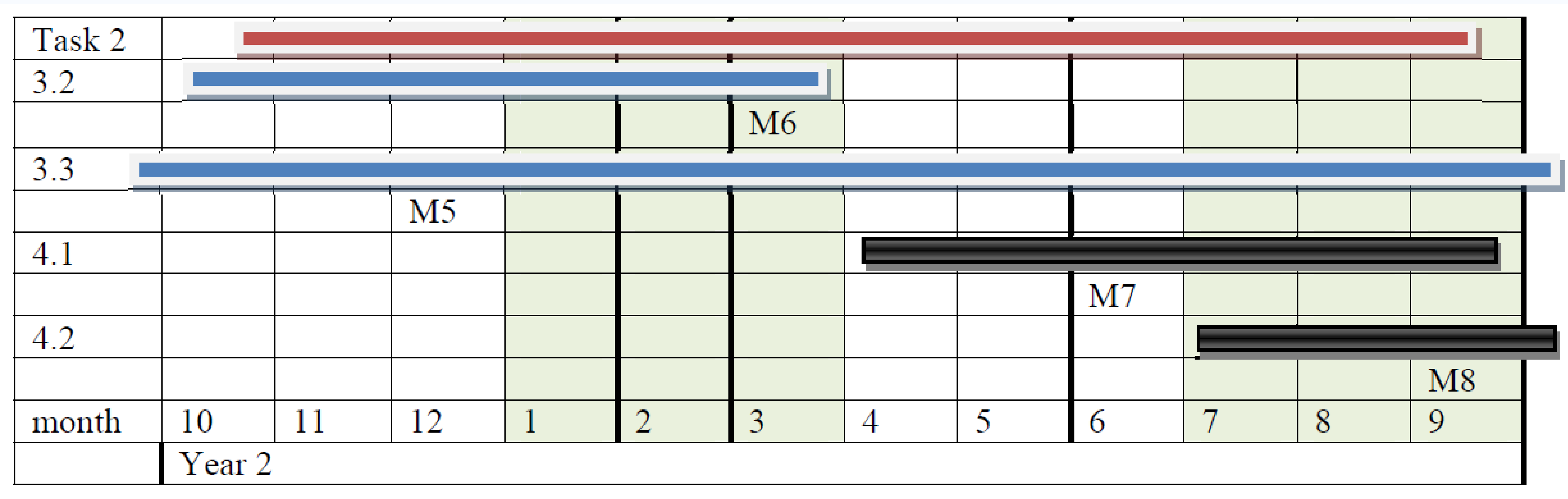
Gantt Chart



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Gantt Chart

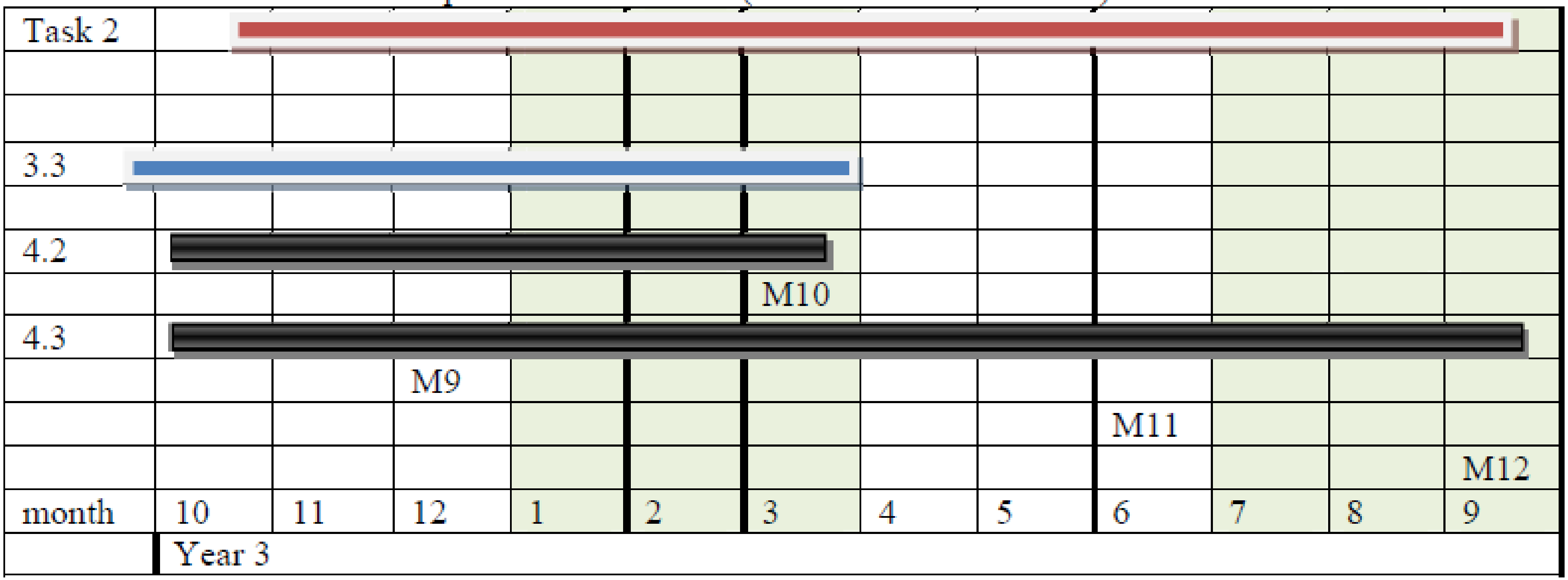

Chart 1. Timeline of the completion of the Tasks (M stands for milestones).

TASK 3.0 – HISTORY MATCHING OF CO_2 PLUME MIGRATION WITH A RESERVOIR MODEL

TASK 4.0 – MODELING LONG-TERM CO2 FATE

Bibliography

- Injection of co-contaminants: Equation of State for CO_2-H_2S-H_2O-NaCl

- Peer-reviewed journal articles:

  - Ji, X. and Zhu, C., 2012, Predicting possible effects of H_2S impurity on CO_2 transportation and geological storage. Environmental Science & Technology. dx.doi.org/10.1021/es301292n.
  - Ji, X. and Zhu, C., 2012, A SAFT Equation of State for the Quaternary H_2S-CO_2-H_2O-NaCl system. Geochimica et Cosmochimica Acta v.91, p. 40–59, http://dx.doi.org/10.1016/j.gca.2012.05.023.
  - Liu, Y., P. Lu, C. Griffith, Y. Soong, S. W. Hedges, H. Hellevang, C. Zhu, 2012, CO2-caprock-brine interaction: Reactivity experiments on Eau Claire Shale and a review of literature. The International Journal of Greenhouse Gas Control, v.7, p.153–167, doi.org/10.1016/j.ijggc.2012.01.012.
  - Lu, P., Fu, Q., Seyfried Jr., WE, Jones, K., and **Zhu**, C., Coupled alkali feldspar dissolution and secondary mineral precipitation in batch systems: 2. Effects of CO_2 and implications for carbon sequestration. ***Applied Geochemistry*** Doi 10.1016/j.apgeochem.2012.04.005