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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 CCS

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Presentation Outline

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

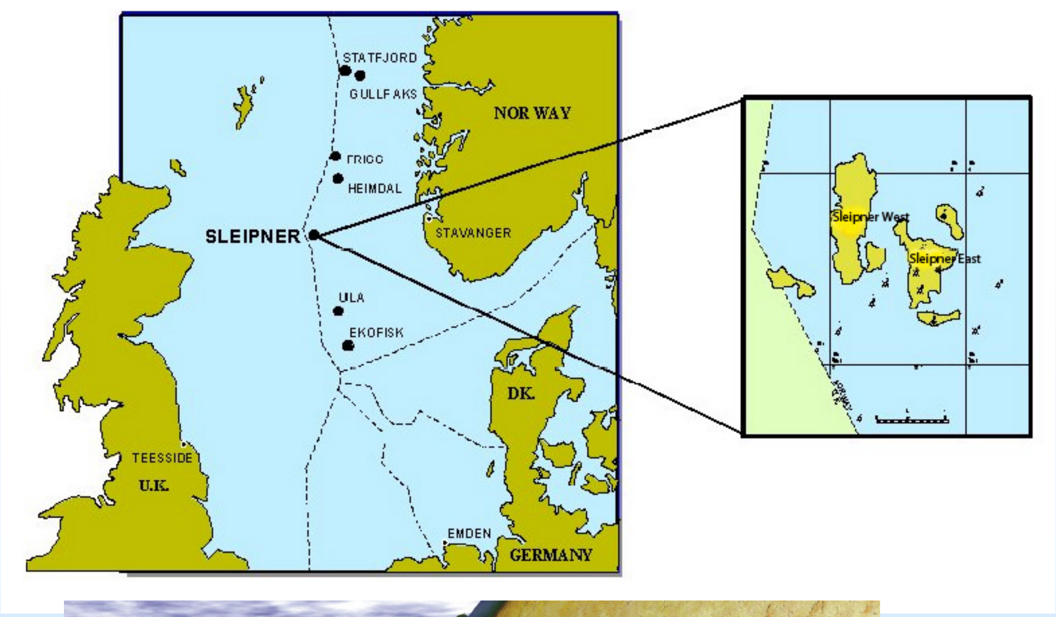
Benefit to the Program

- 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 storage 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

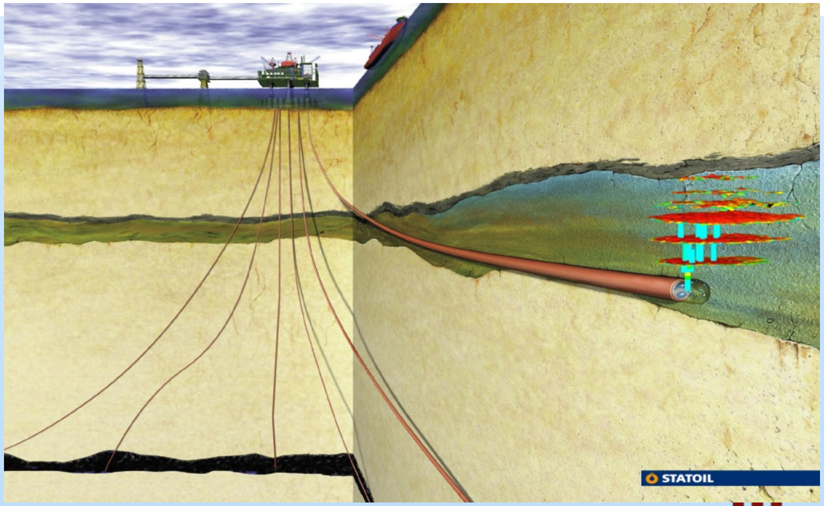
To assess and reduce uncertainties of model predictions of CO_2 plume migration, trapping mechanisms, and storage capacity estimates through history matching and long-term fate modeling of CO_2 through implementing rigorous chemical kinetics and through a number of bounding calculations and sensitivity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

Norwegian Sleipner Project

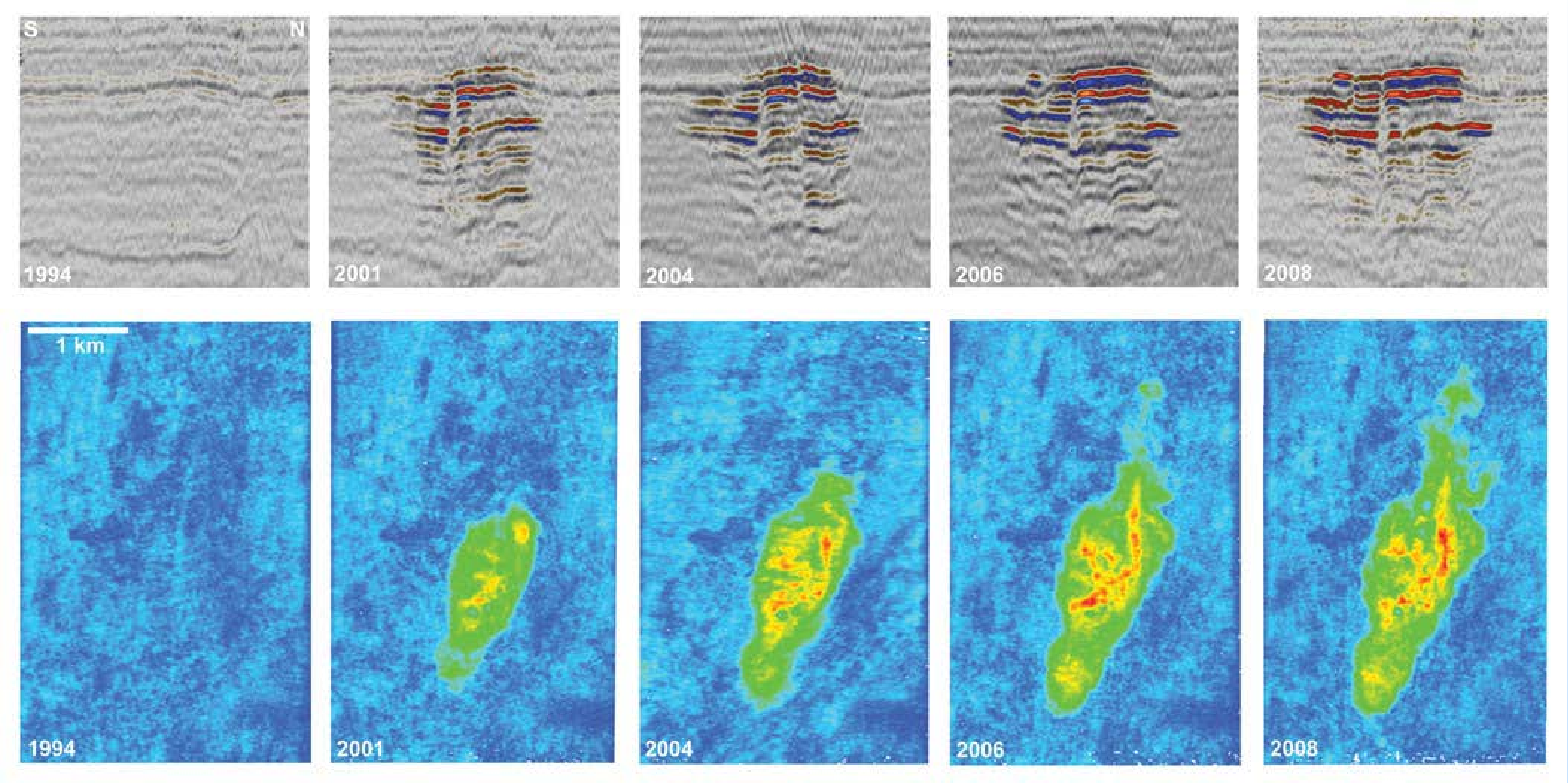


Sleipner CO_2 injection:

- World's first industrial-scale geological carbon storage 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

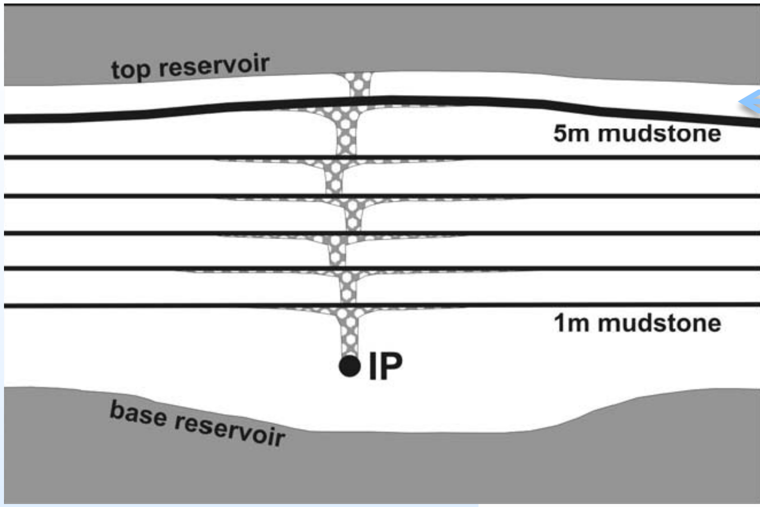


Time-lapse seismic images of the CO_2 plume at Sleipner

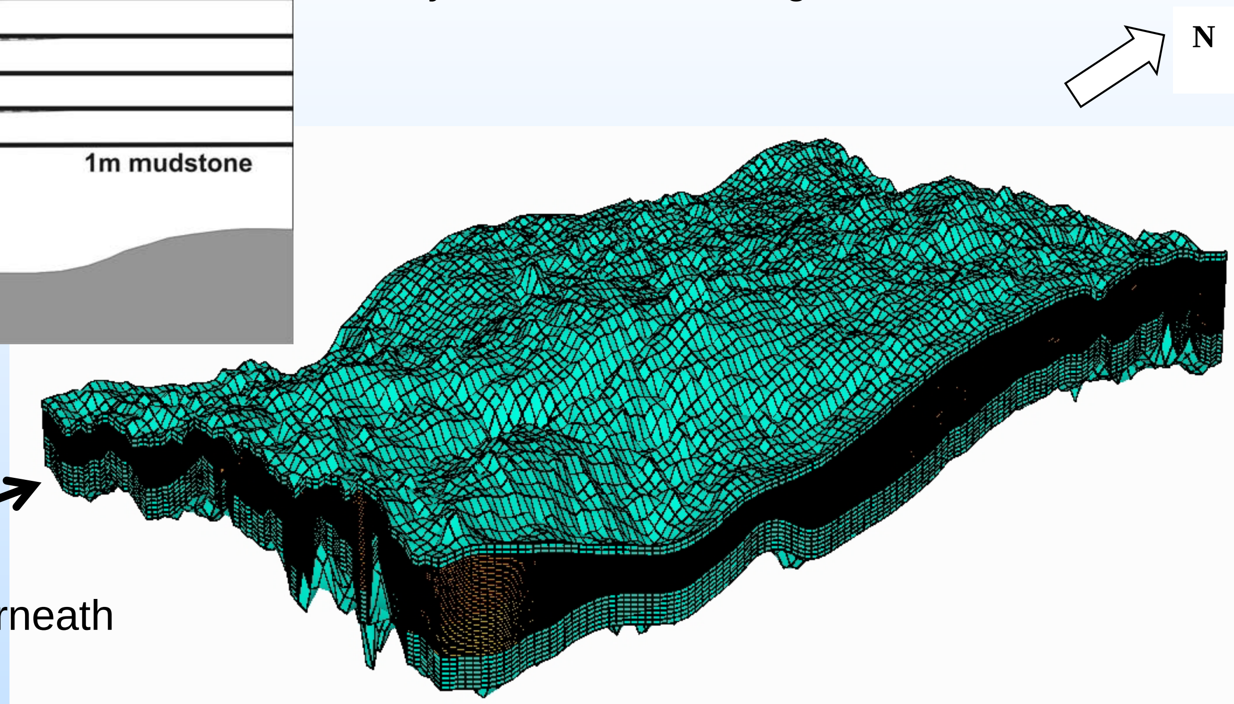


Upper row: N-S seismic section through the plume.
Lower row: plan views of the plume showing total integrated reflection amplitude (Chadwick et al., 2010)

Statoil-IEA Benchmark Geological Model



Layer 9 = "Sand Wedge"

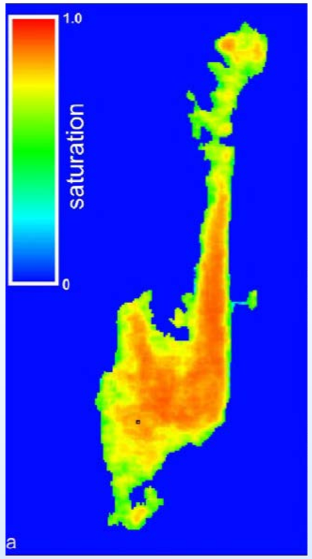


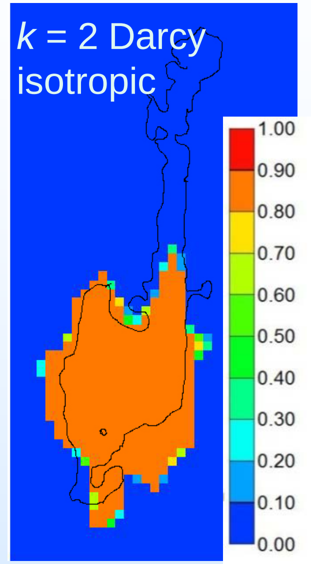
5 m mudstone underneath

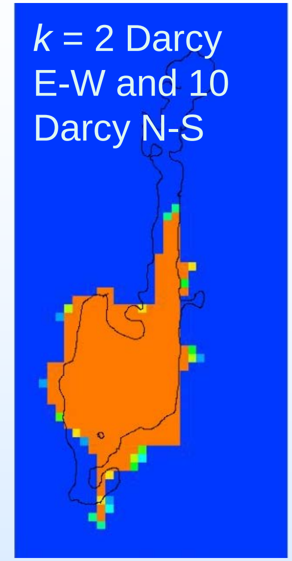
- An area ~ 3 x 6 km
- Grid dimensions: x = 65, y = 119, z = 43; total 332,605 blocks
- The basic grid resolution is 50 m x 50 m.

First Attempt—Applying Permeability Anisotropy

Observed extents



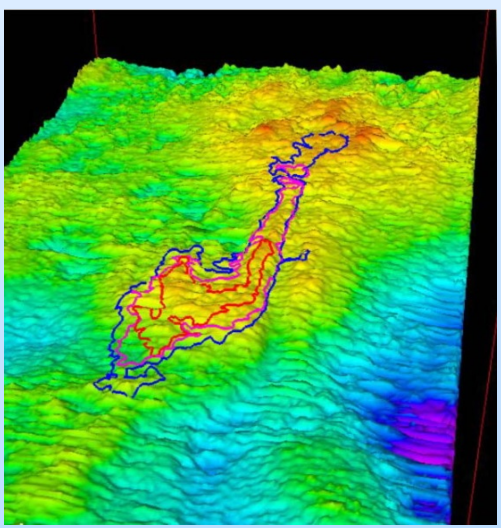


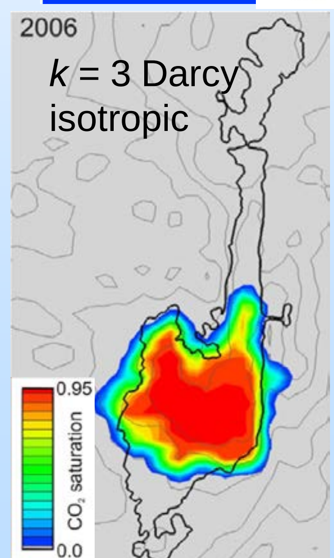


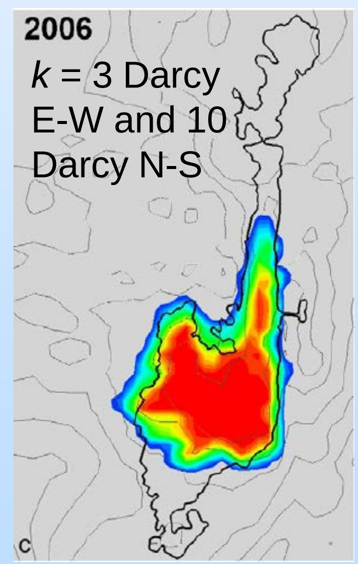
GEM simulation

Cannot achieve the match by adjusting permeability anisotropy alone

Topography of the Layer 9.

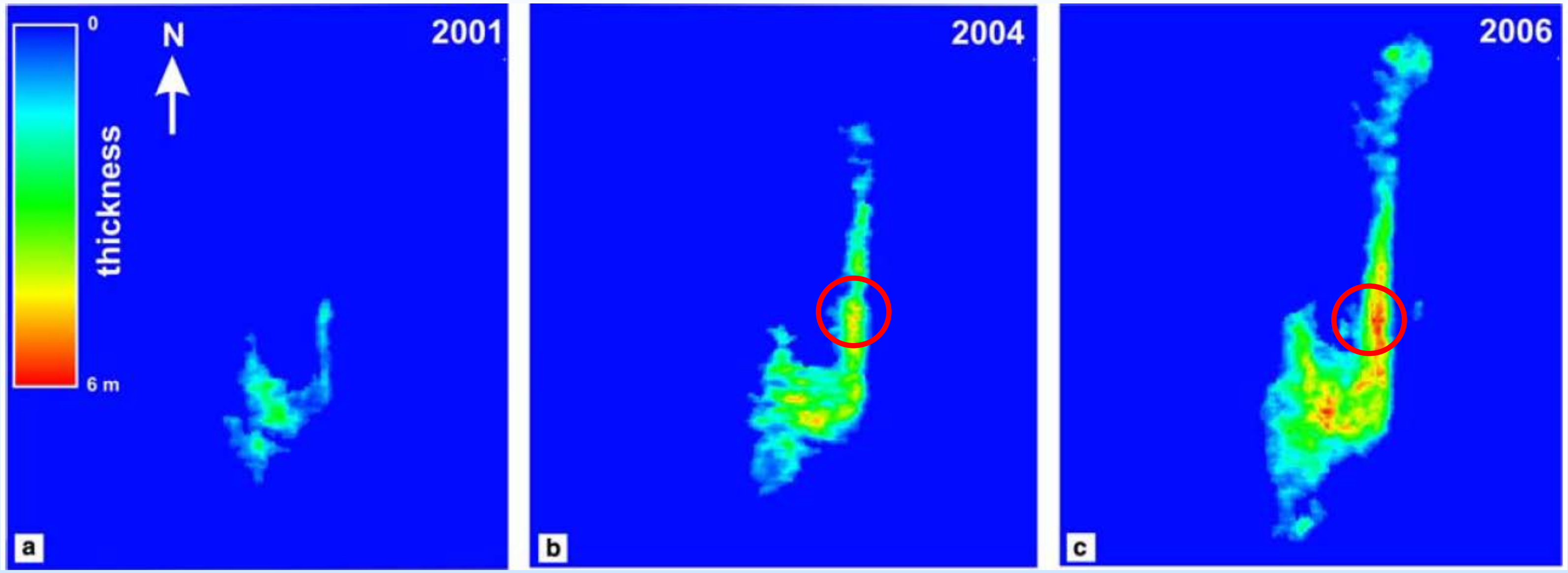






Tough 2 simulations (Chadwick and Noy, 2010)

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.

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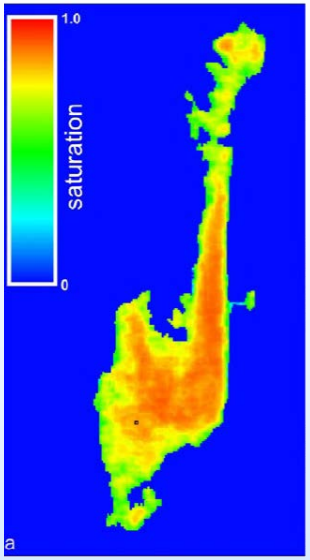
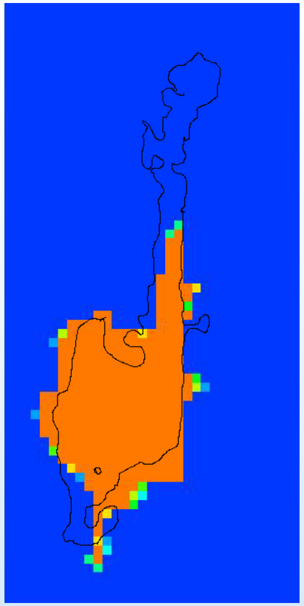
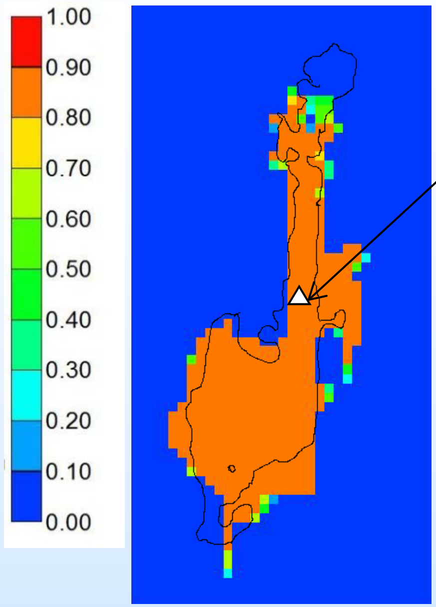
Second Attempt--Additional Feeder with Permeability Anisotropy



Observed extents 2006



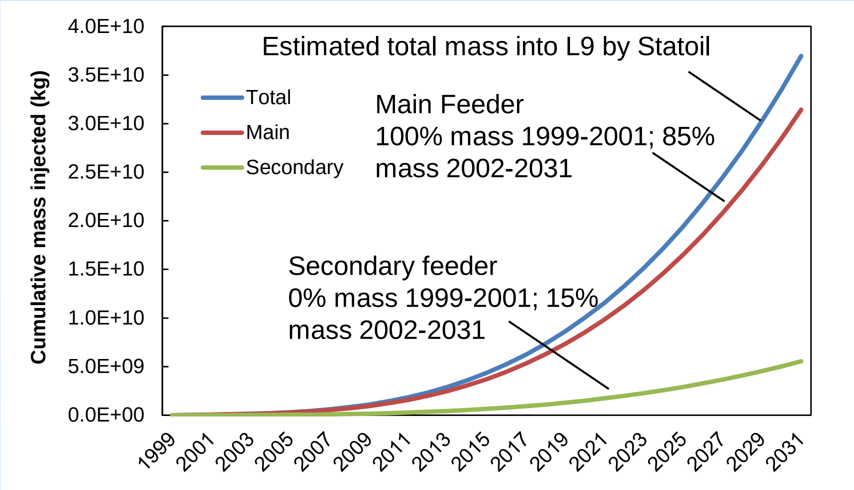
100% CO_2 volume into main feeder



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.

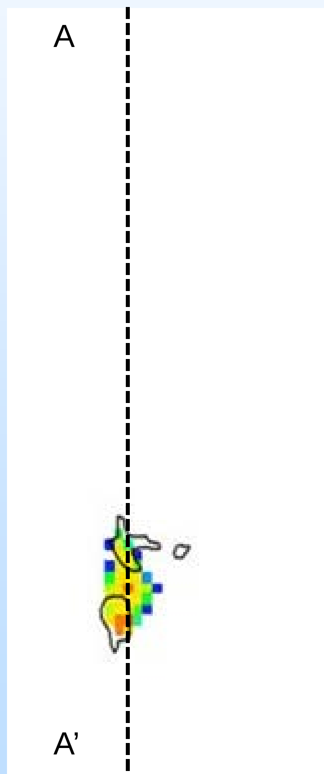


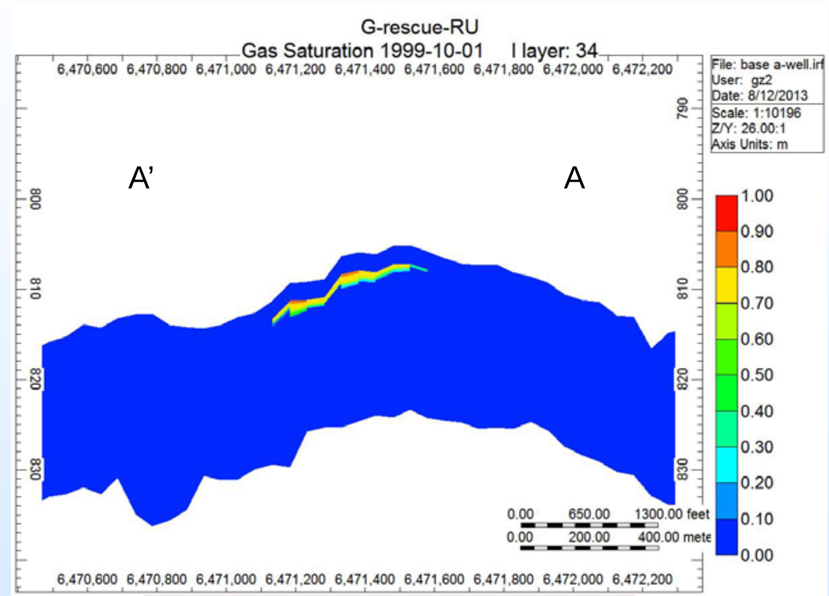
Comparison of Observed vs. Model Predicted CO_2 Plume Extent (Base Case)

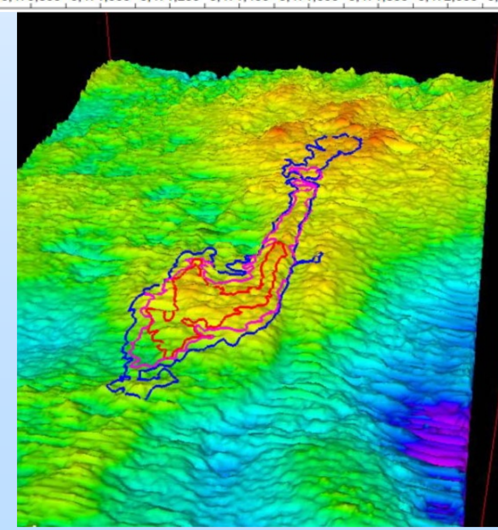
Seismic Response

1999

Model Prediction



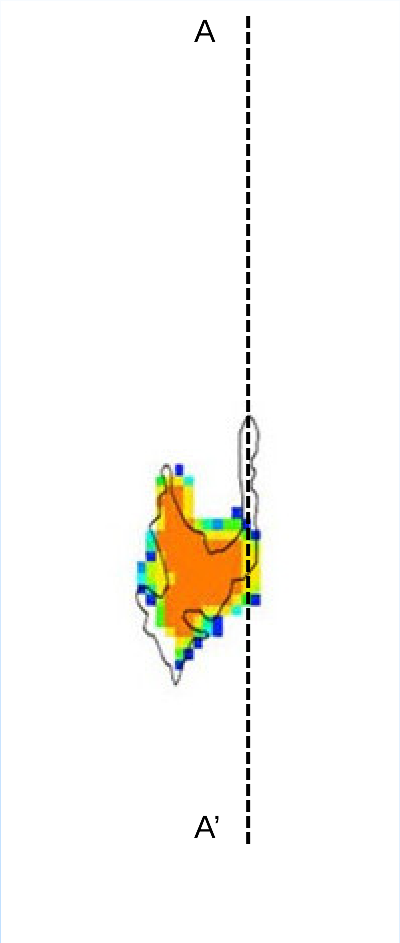


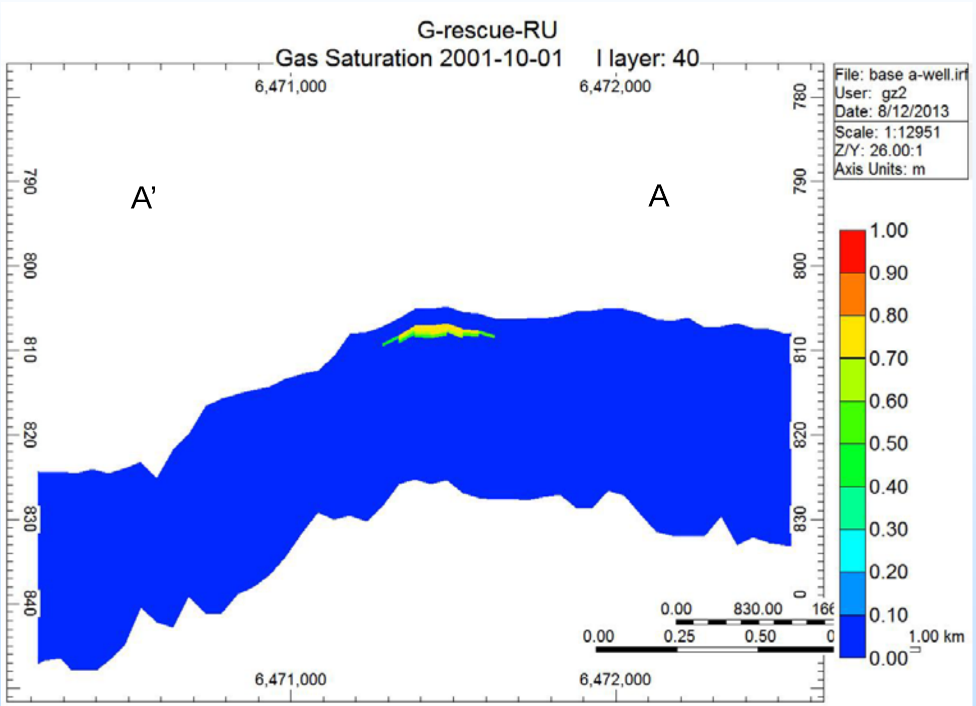


Comparison of Observed vs. Model Predicted CO_2 Plume Extent (Base Case)

Seismic Response

Model Prediction



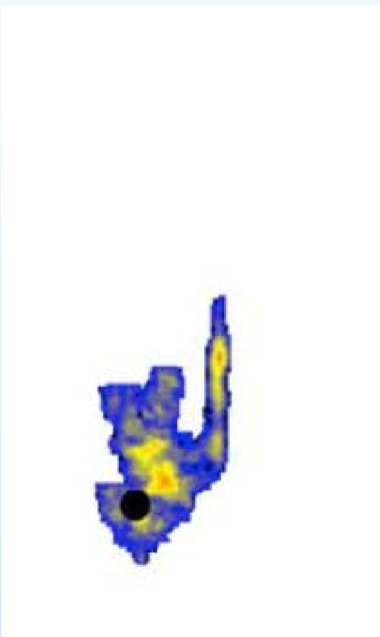


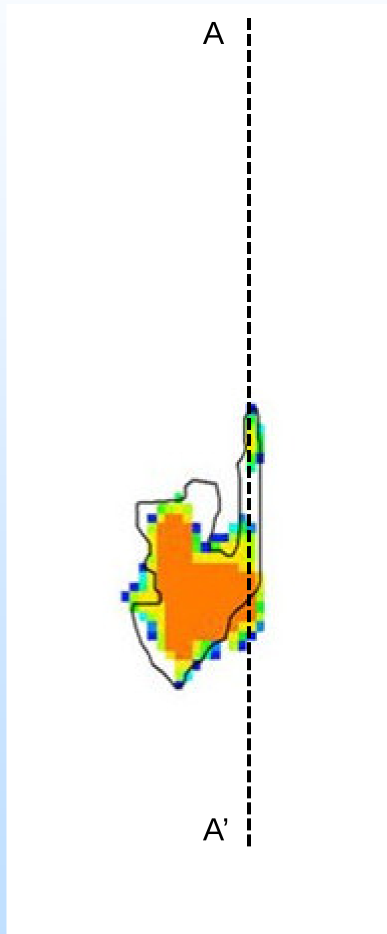
Comparison of Observed vs. Model Predicted CO_2 Plume Extent (Base Case)

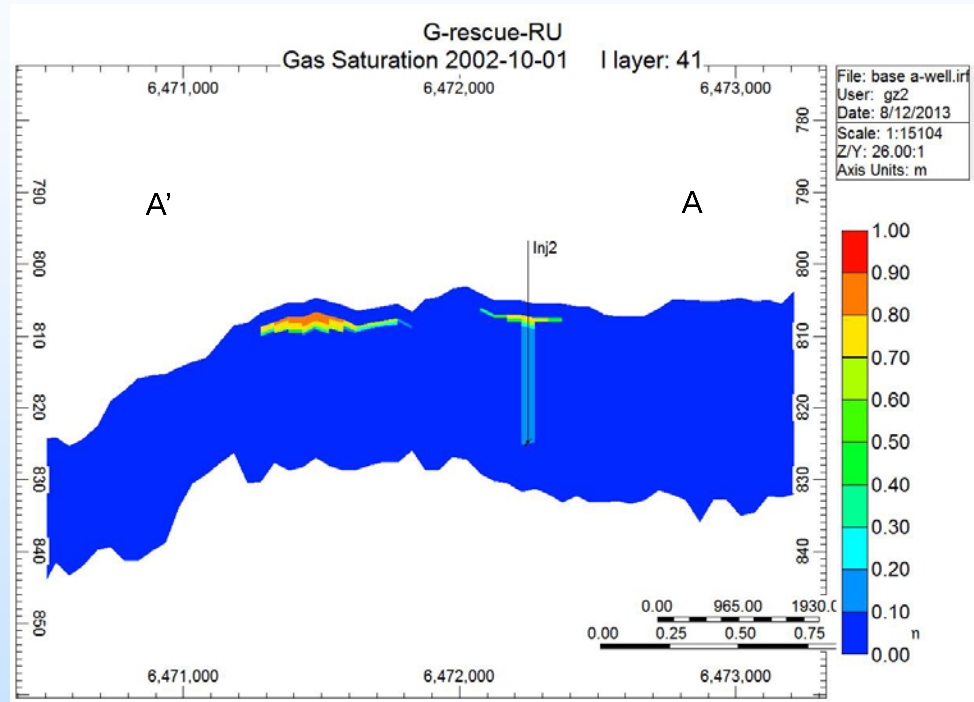
Seismic Response

Model Prediction

2002







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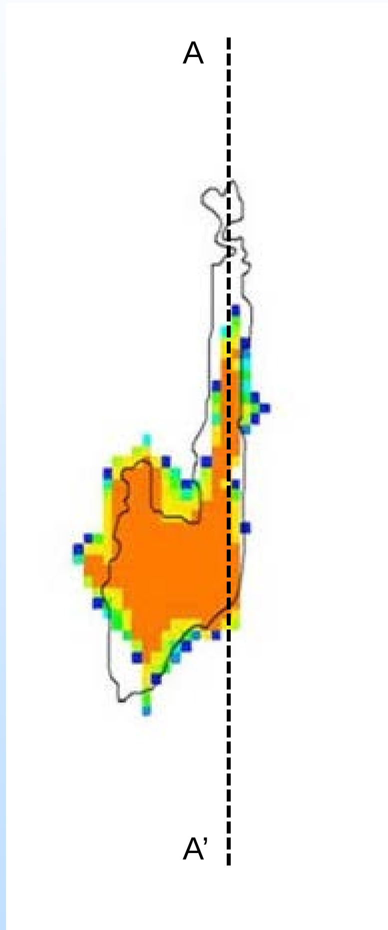
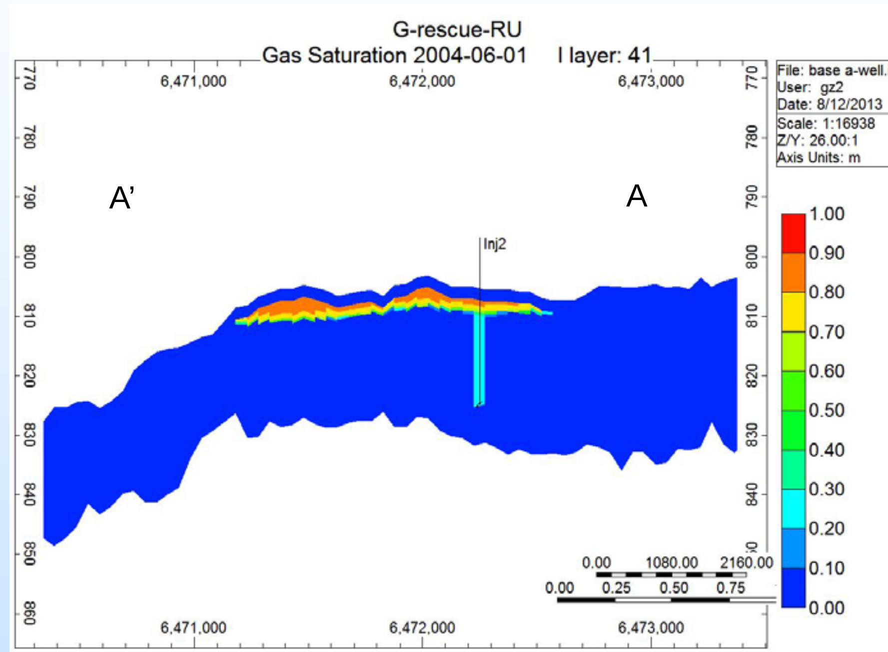
Comparison of Observed vs. Model Predicted CO_2 Plume Extent (Base Case)

Seismic Response

Model Prediction

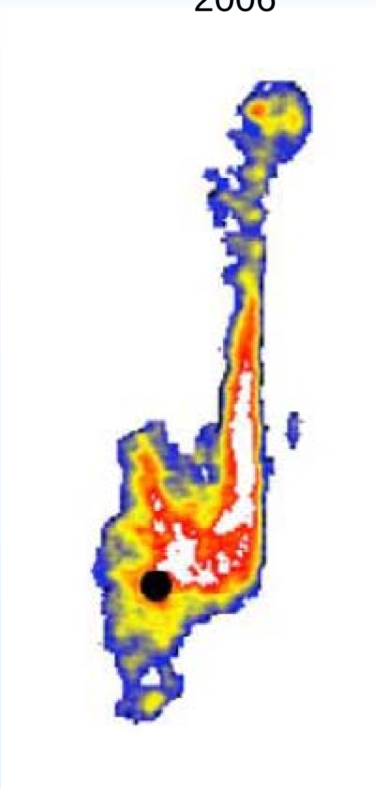




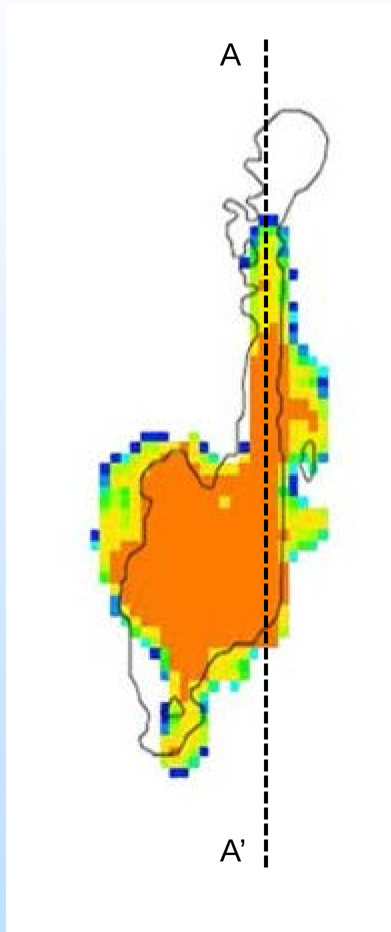
Comparison of Observed vs. Model Predicted CO_2 Plume Extent (Base Case)

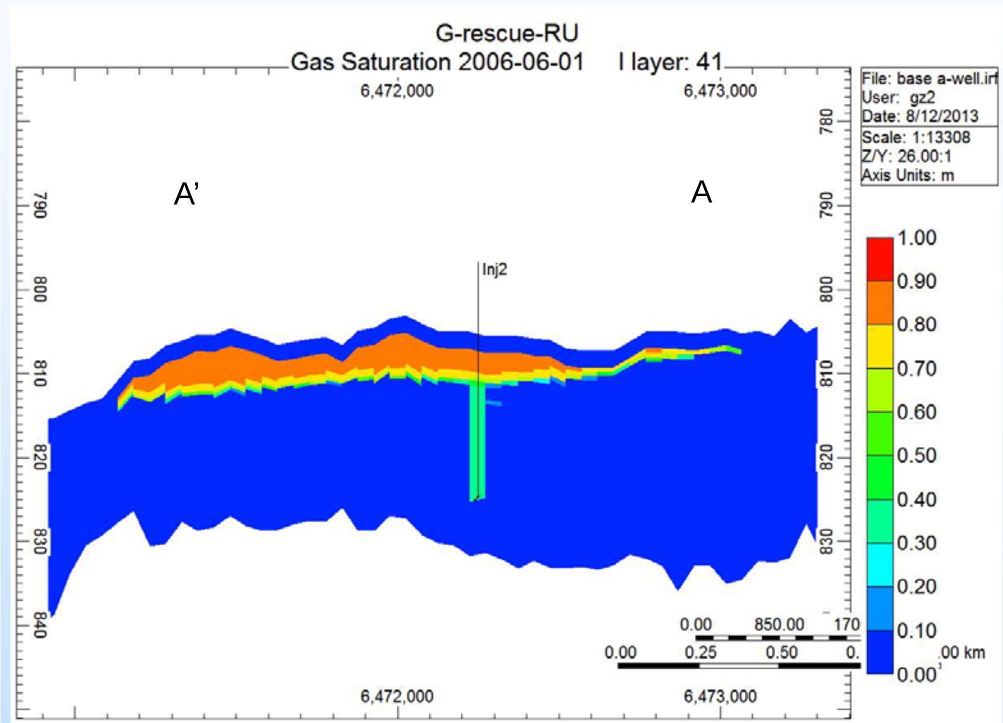
Seismic Response

2006



Model Prediction





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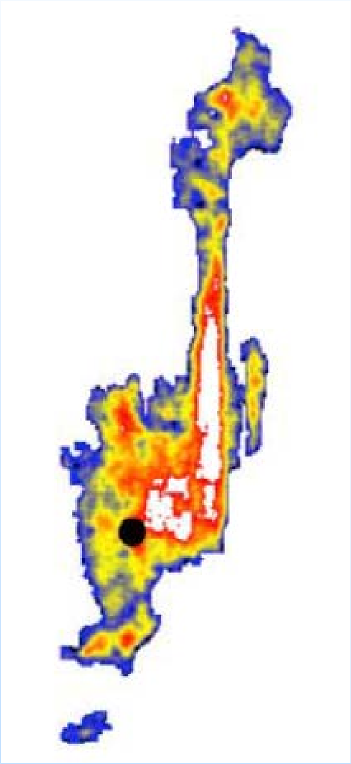
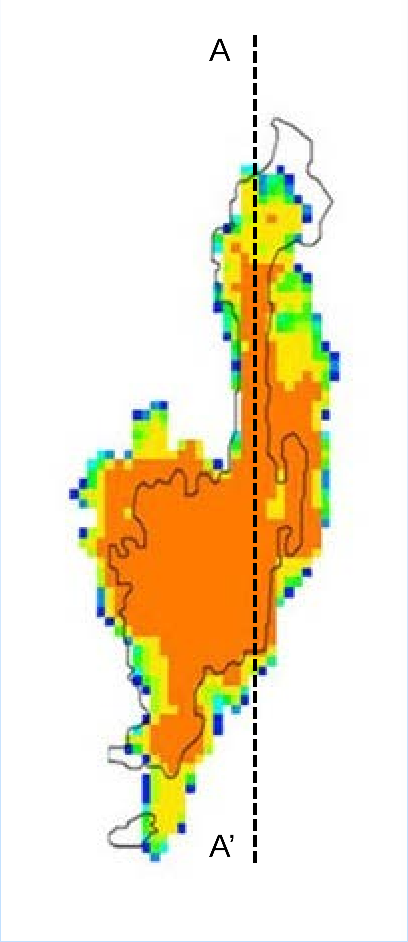
Comparison of Observed vs. Model Predicted CO_2 Plume Extent (Base Case)

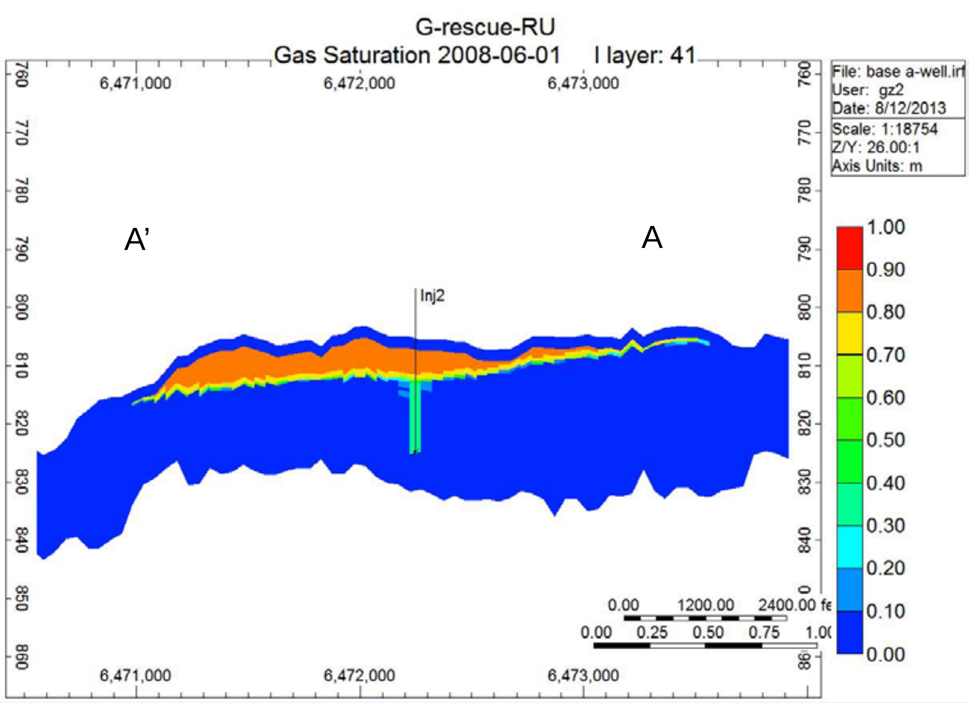
Seismic Response

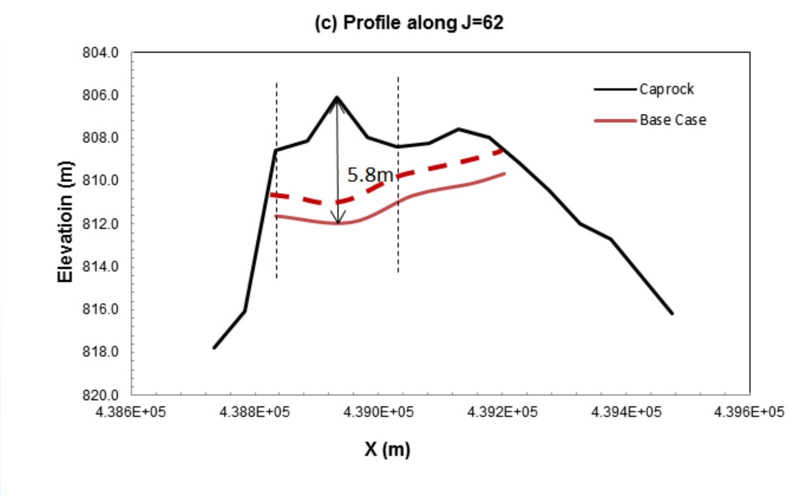
2008

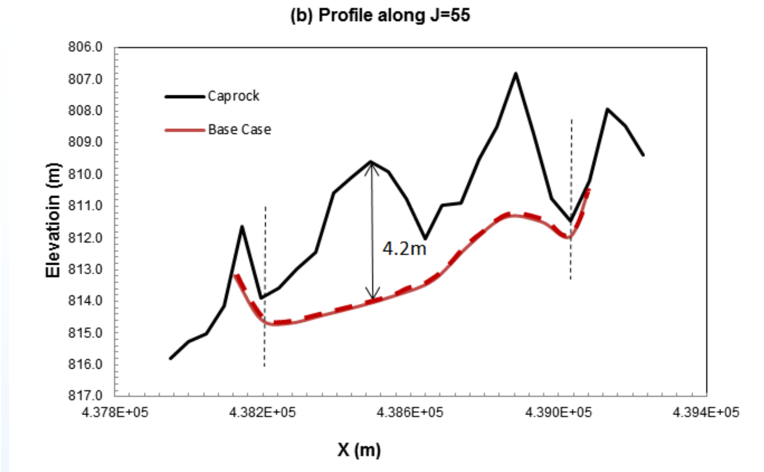


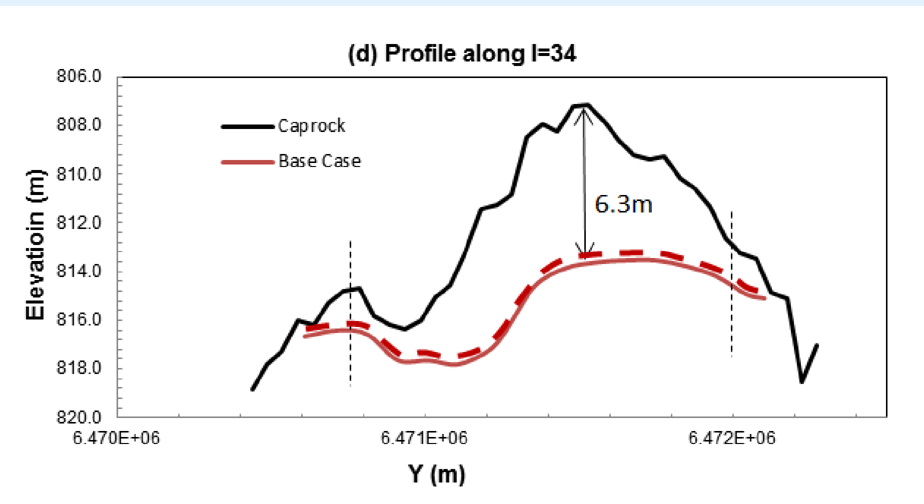
Model Prediction

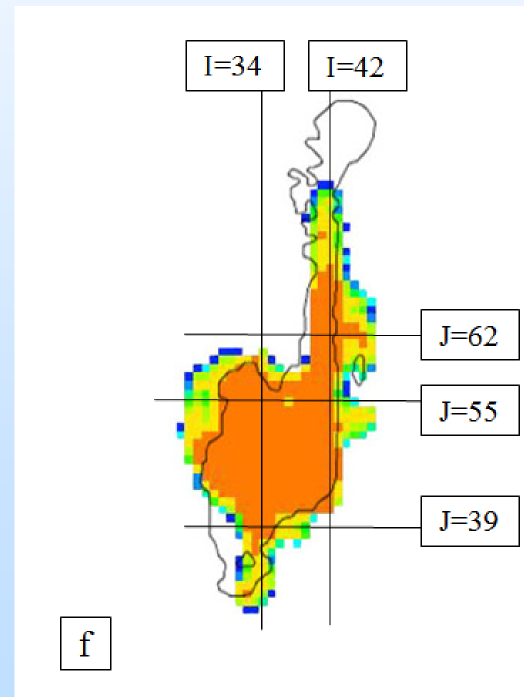




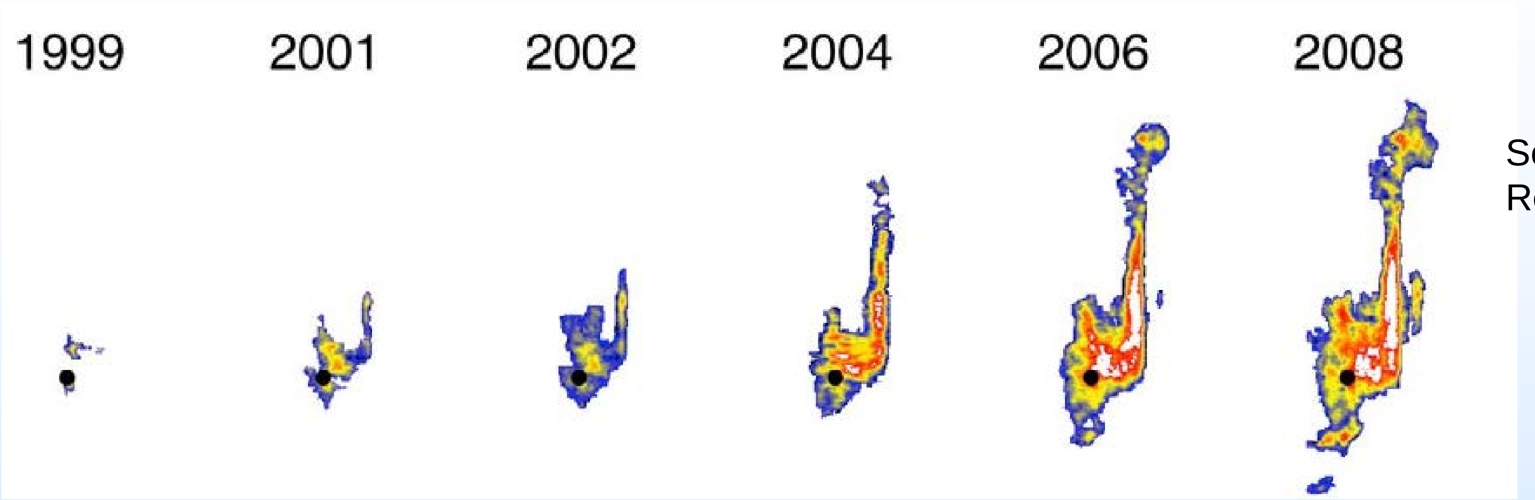

(c) Profile along J=62
Caprock
Base Case
5.8m
Elevatioin (m)
X (m)
804.0
806.0
808.0
810.0
812.0
814.0
816.0
818.0
820.0
4.386E+05
4.388E+05
4.390E+05
4.392E+05
4.394E+05
4.396E+05


(b) Profile along J=55
Caprock
Base Case
4.2m
Elevatioin (m)
X (m)
806.0
807.0
808.0
809.0
810.0
811.0
812.0
813.0
814.0
815.0
816.0
817.0
4.378E+05
4.382E+05
4.386E+05
4.390E+05
4.394E+05

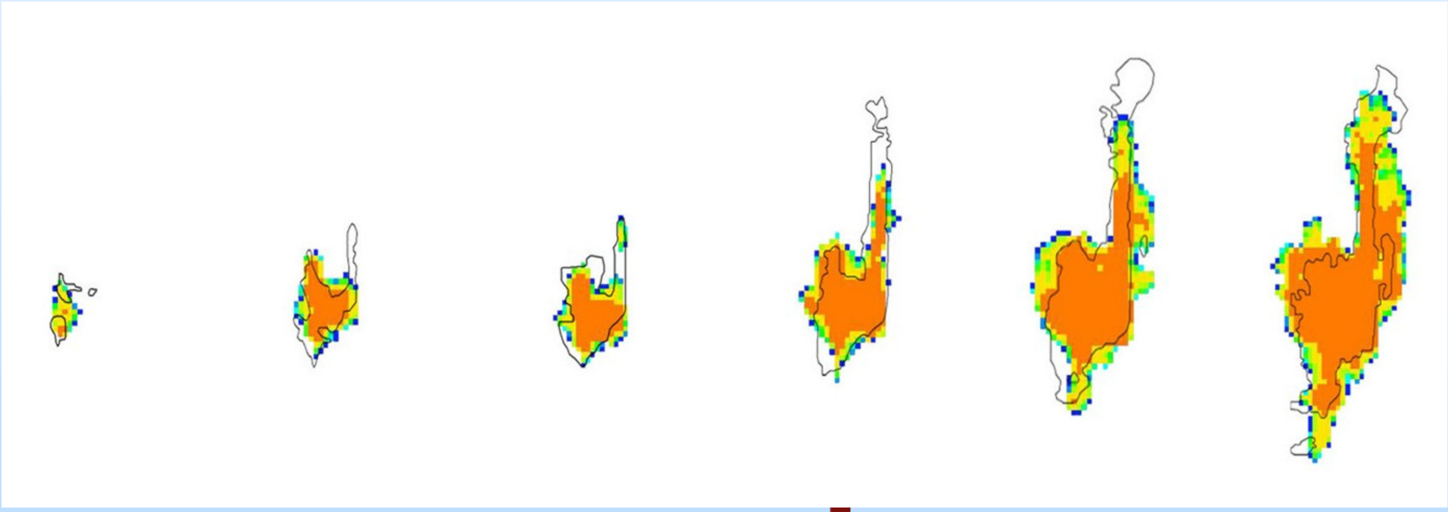

(d) Profile along I=34
Caprock
Base Case
6.3m
Elevatioin (m)
Y (m)
806.0
808.0
810.0
812.0
814.0
816.0
818.0
820.0
6.470E+06
6.471E+06
6.472E+06


I=34
I=42
J=62
J=55
J=39
f

Overall Comparison (Base Case)

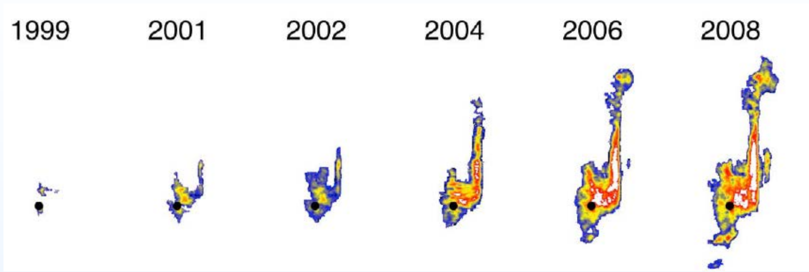


Seismic Response

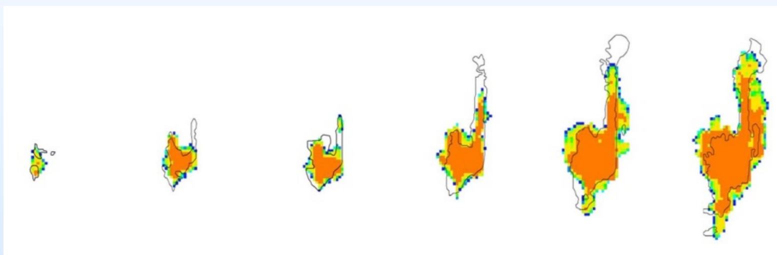


Model Prediction

Model Comparison

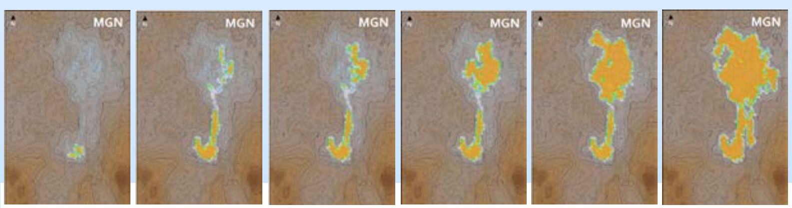


Seismic Response

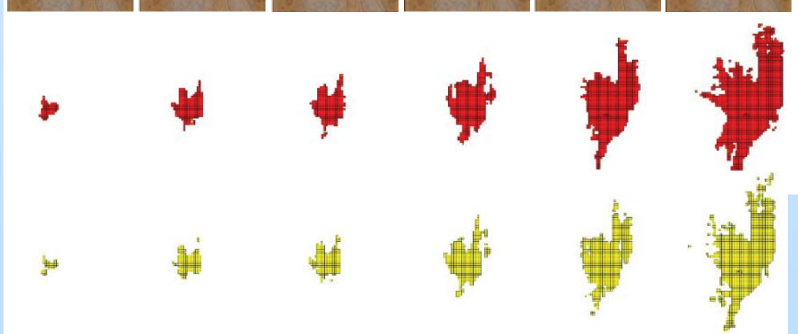


Model Prediction

This Study



Invasion percolation migration

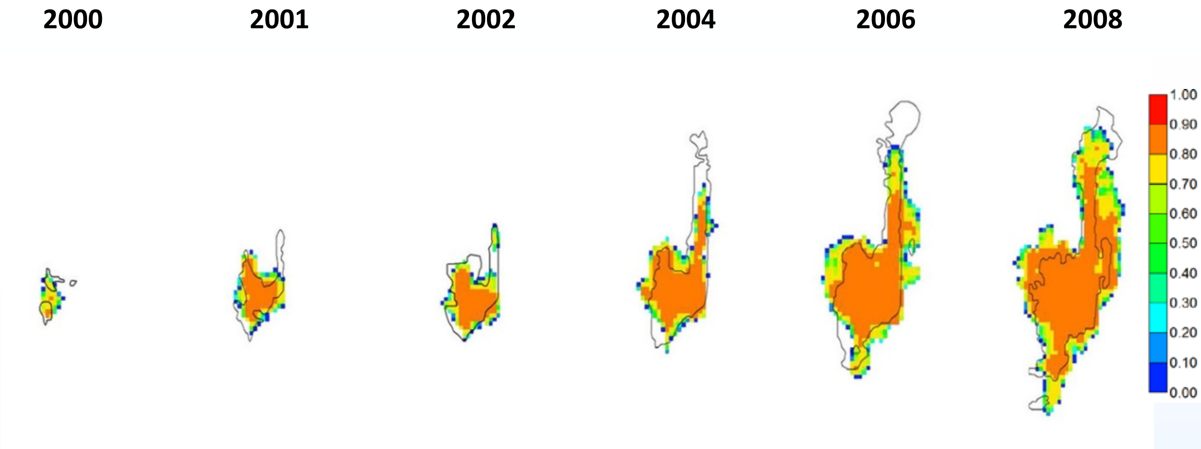


CO_2 Black Oil Simulator using up-scaled relative permeability curves

CO_2 Black Oil Simulator using the Vertical Equilibrium option

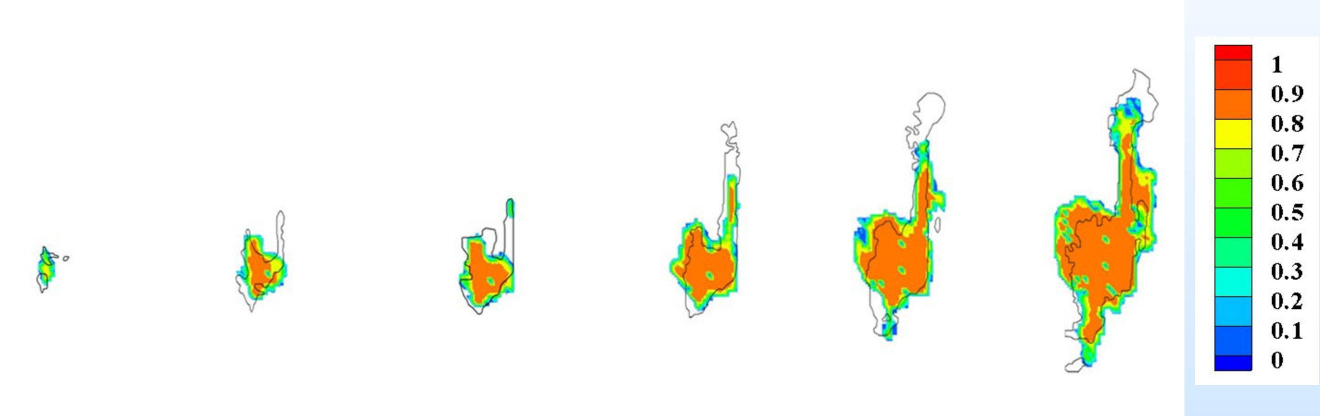
Singh et al. (2010) using Eclipse 100/300

Simulators used



GEM

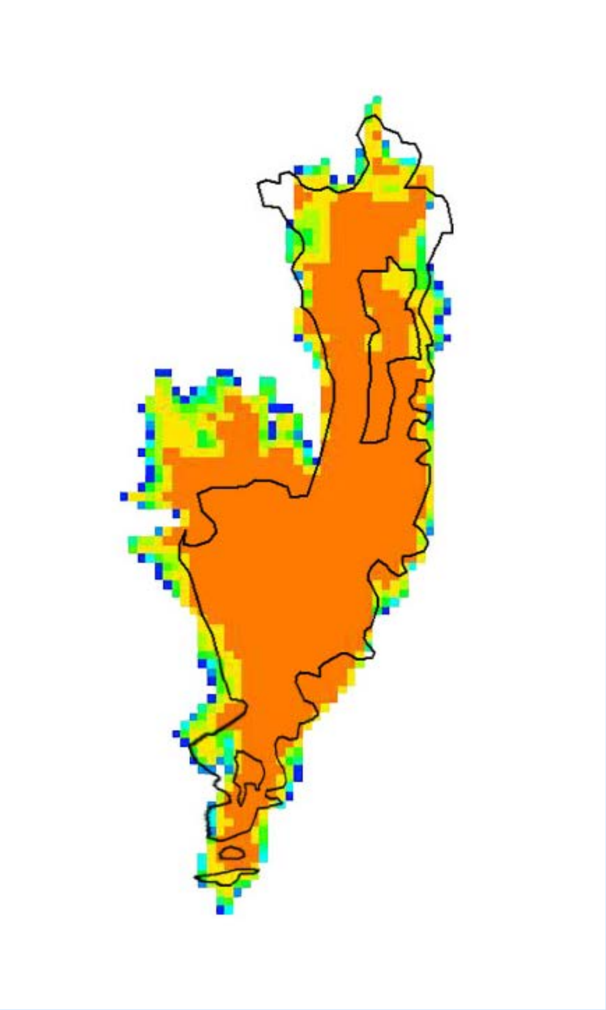
Max. Sg=0.87 in 2006



Tough2 with the same parameters

Max. Sg=0.83 in 2006

Purple: Tough2
Red: GEM



-Model calibrated to 2008 (data available);

-Model prediction 2010 (observation data black outline)

Conclusions from Modeling Study

- Introducing permeability anistropy is necessary and justifiable based on geology
- Adding another feeder is critical in order to model the N-S extension (Chadwick and Noy, 2010; Singh et al., 2010).
- Model-predicted plume thickness, CO_2 saturation, fraction of dissolved CO_2 dissolved are comparable with those based on seismic data interpretations (with estimated mass of CO2 spilled into Layer 9);
- The model calibrated to 2008 predicted 2010 plume extent reasonably.

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 that successfully matched 4D plume migration in Layer 9;
3. Prepared a manuscript that has received DOE approval for publication; Multiple conference presentations.
4. Currently conducting parameter sensitivity analysis;
5. Initiated coupled reactive transport model to evaluate long-term effects on reservoir prosperities by water-rock interactions.

Summary- Key Findings & Lessons Learned

– **What takes to match the 4D CO_2 plume history at Sleipner?**

- **We can achieve a good match without using out of ordinary parameters or assumptions, and we used two widely available reservoir simulators.**

– **What model produced?**

- **Approximate match with the 4D plume boundaries, via adjusting permeability & anistropy and feeders;**
- **Predictions (without parameter adjustments) matched well with seismic data based estimates (a) CO_2 solubility, (b) CO_2 saturation, (c) plume thickness; and by extension, (d) estimate of CO_2 spilled into Layer 9.**

– **Lessons Learned**: **Sleipner project is an excellent candidate for demonstration that reservoir simulation of CO_2 plume migration can be achieved with a set of reasonable parameters.**

Summary (continued)

– **Future Plans**:

1) **Publish the results of plume history match modeling in peer-reviewed journals;**
2) **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

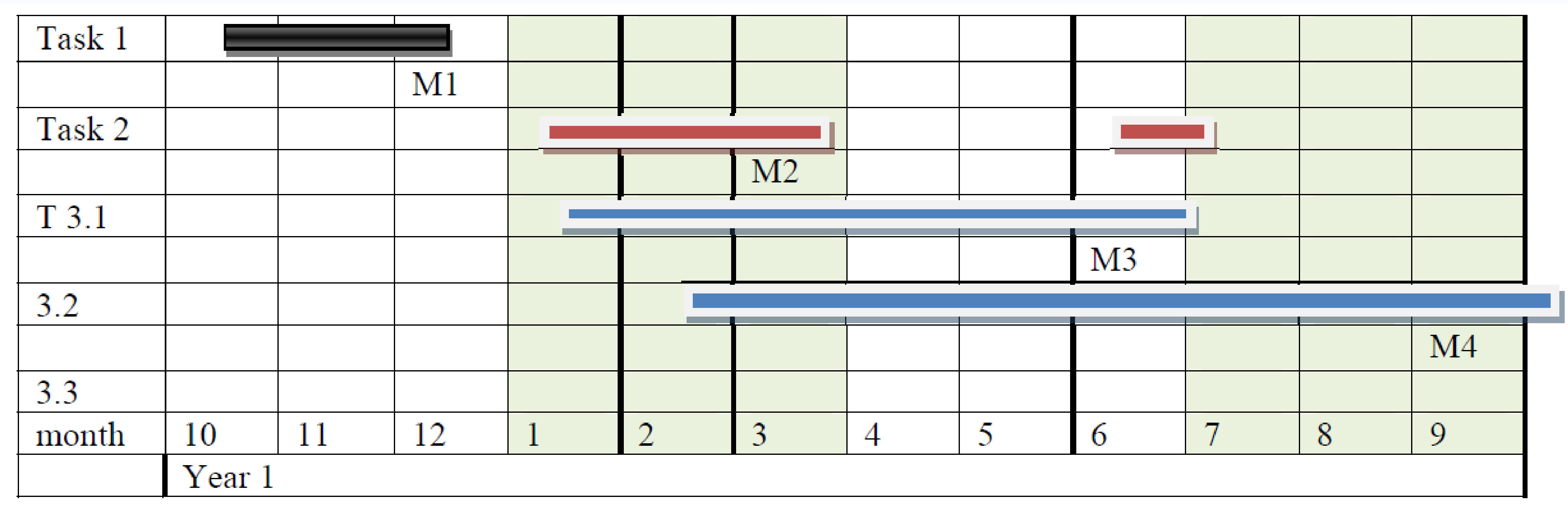
Appendix

– 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

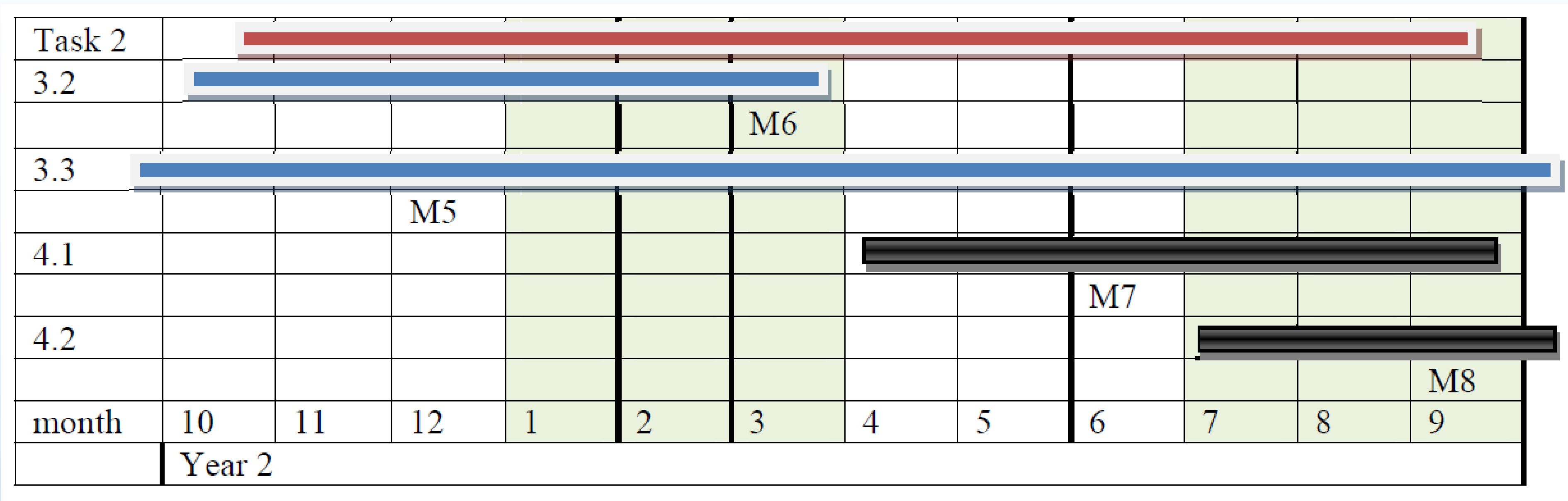


TASK 1.0 - PROJECT MANAGEMENT, PLANNING AND REPORTING

TASK 2.0 – DATA ACQUISITION AND INTERPRETATION

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

Gantt Chart



TASK 1.0 - PROJECT MANAGEMENT, PLANNING AND REPORTING

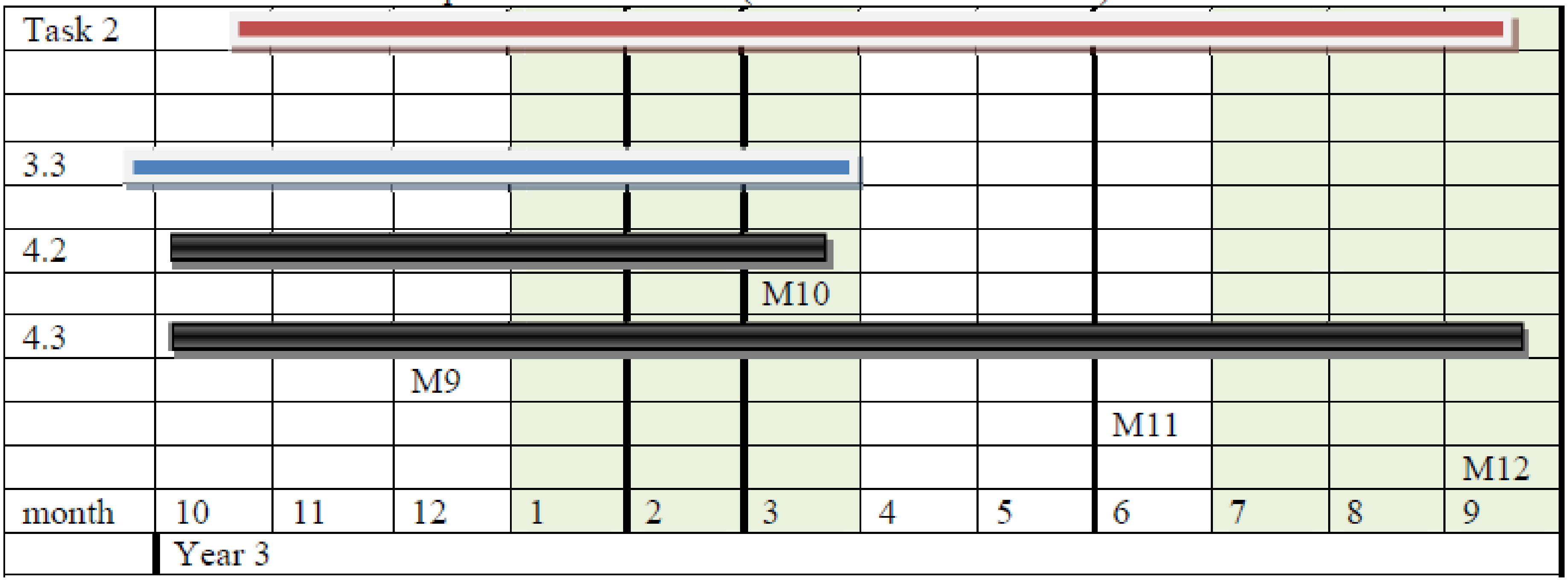
TASK 2.0 – DATA ACQUISITION AND INTERPRETATION

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

TASK 4.0 – MODELING LONG-TERM CO2 FATE

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

- Peer-reviewed journal articles:

  - Ji, X. and Zhu, C., 2013, 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. (2013) 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

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- Conference proceeding papers and abstracts:
  - Ji, X. and Zhu, C (2013) A SAFT Equation of State for the H2S-CO2-H2O-NaCl system and applications for CO2 - H2S transportation and geological storage. *Energy Procedia.* 12 pages.
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