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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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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 applies two multi-phase compositional simulators to the Sleipner Benchmark model for simulating CO_2 plume migration in the uppermost layer (Layer 9) in the Utsira Sand. 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%

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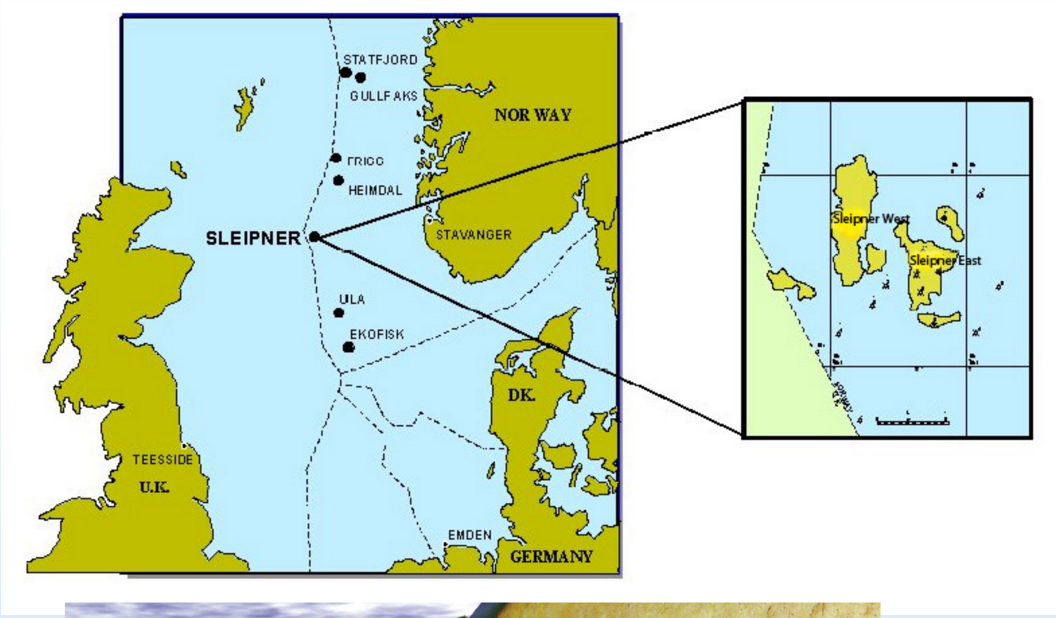
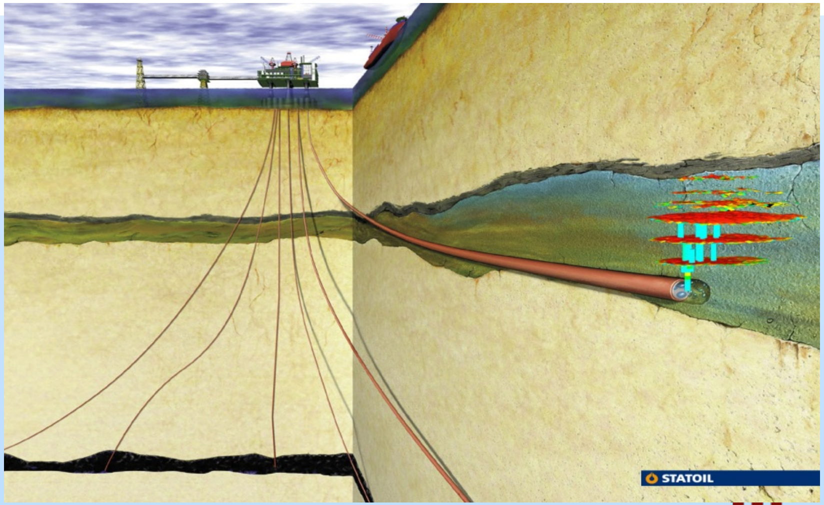
Project Overview Objectives

To assess and reduce uncertainties of model predictions of CO_2 plume migration, trapping mechanisms, and storage capacity estimates through history matching, sensitivity analysis, 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

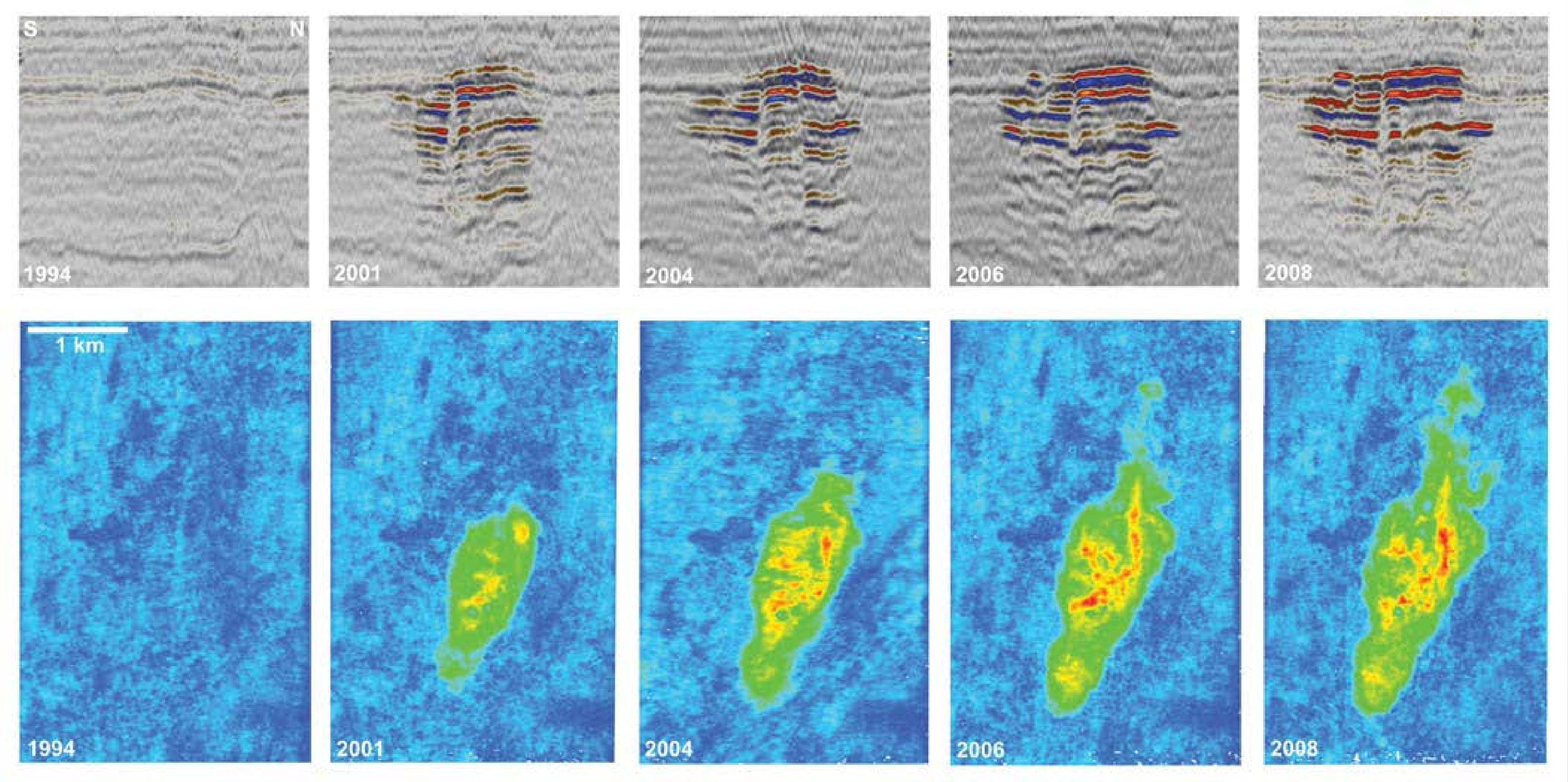




Sleipner CO_2 injection:

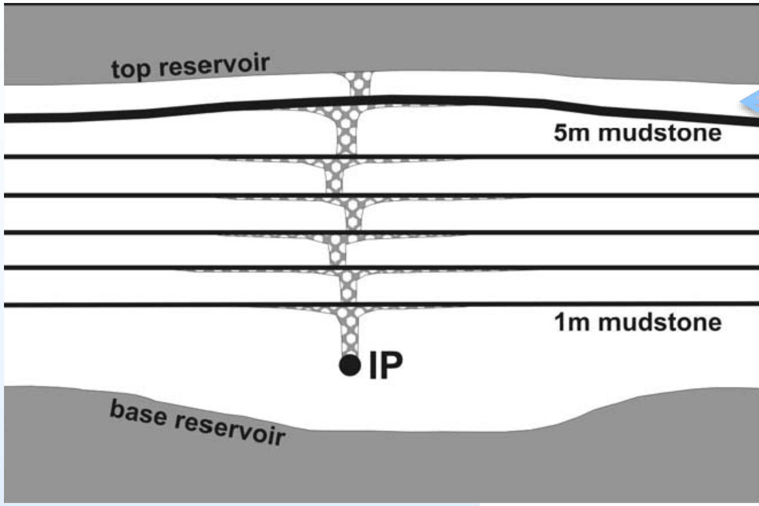
- World's first industrial-scale geological carbon storage project
- In operation since 1996
- 1 million ton CO_2/year
- Storage: Utsira Formation. A saline reservoir 800-1000 meters (2600-3300ft) below the sea floor

Time-lapse seismic images of the CO_2 plume at Sleipner

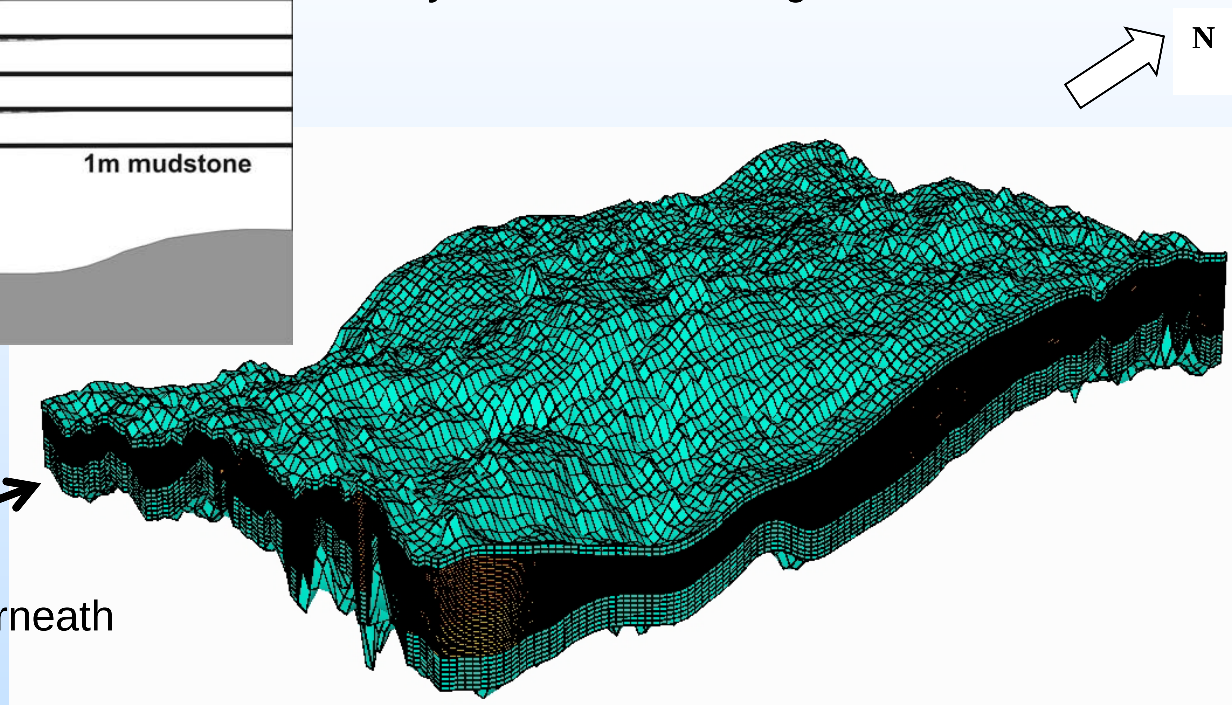


Upper row: N-S seismic section through the plume.
Lower row: plan views of the plume showing total integrated reflection amplitude (Chadwick et al., 2010)

Statoil-IEA Benchmark Geological Model



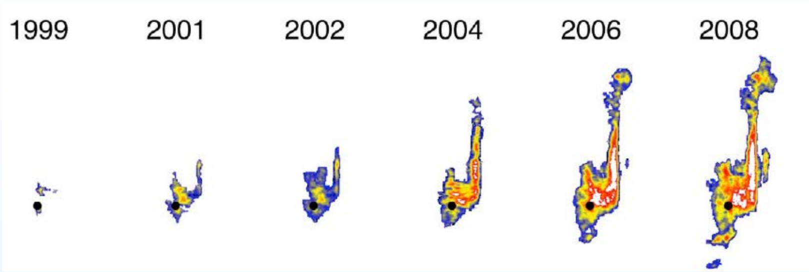
Layer 9 = “Sand Wedge”



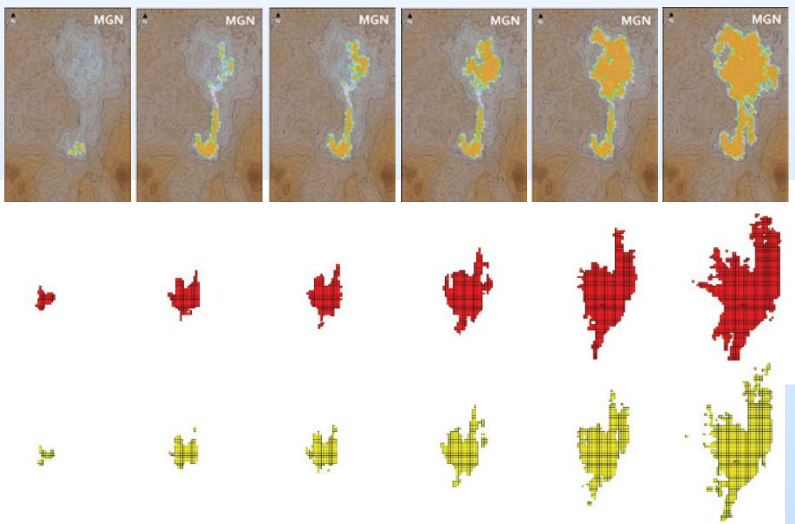
5 m mudstone underneath

- 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.

Previous modeling work



Seismic Response

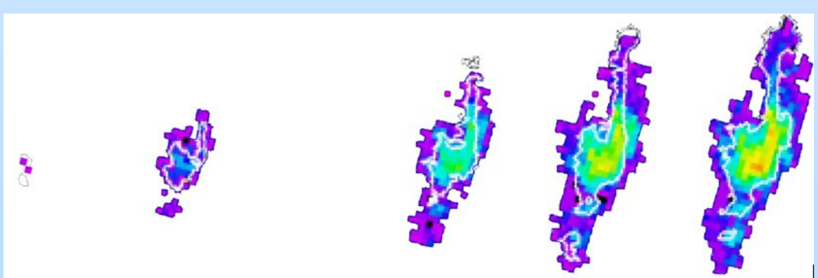


Invasion percolation migration

CO_2 Black Oil Simulator using up-scaled relative permeability curves

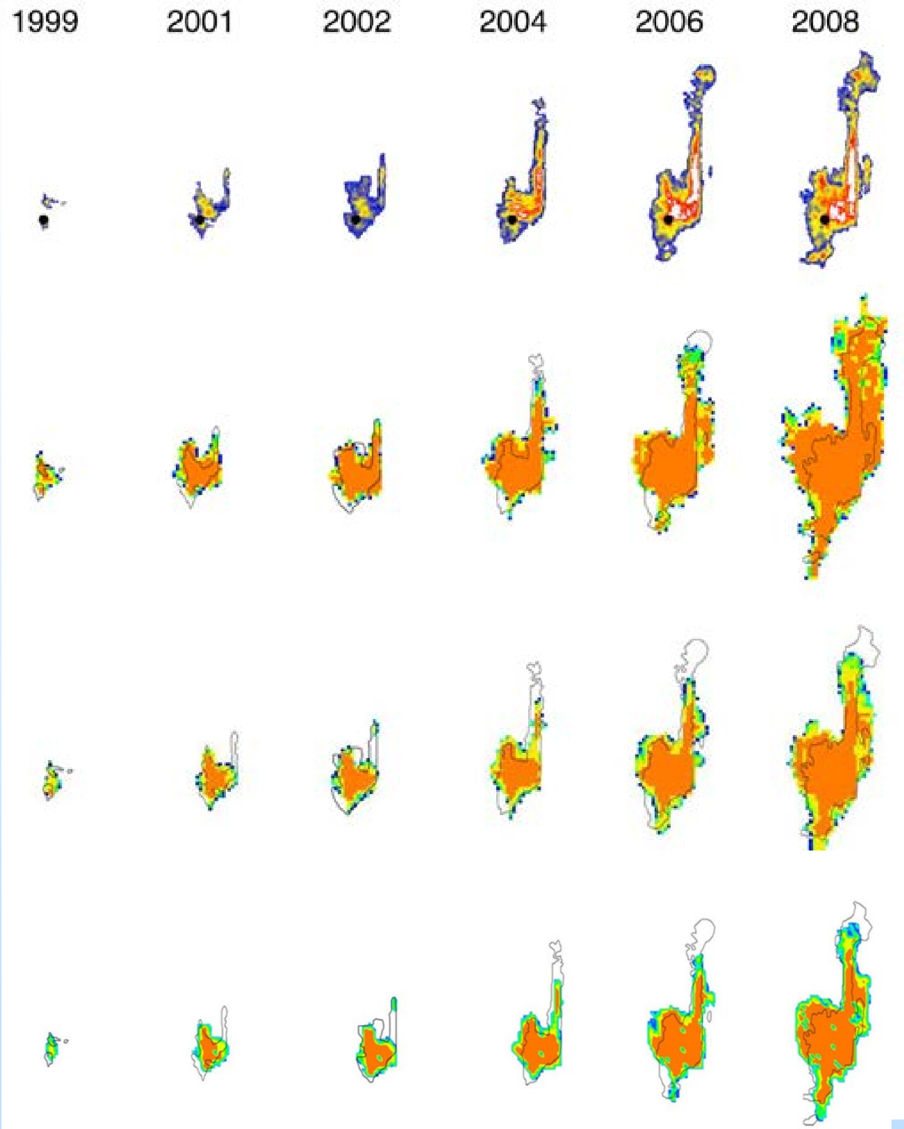
CO_2 Black Oil Simulator using the Vertical Equilibrium option

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



Haukaas et al. (2013)

Results of this study: Two calibrated models



Seismic response (Boait et al., 2012) = calibration targets

Calibrated Model 1: 1Feeder, T=35 ^{o}C, CH_4=1.8% mol, Anisotropic permeability

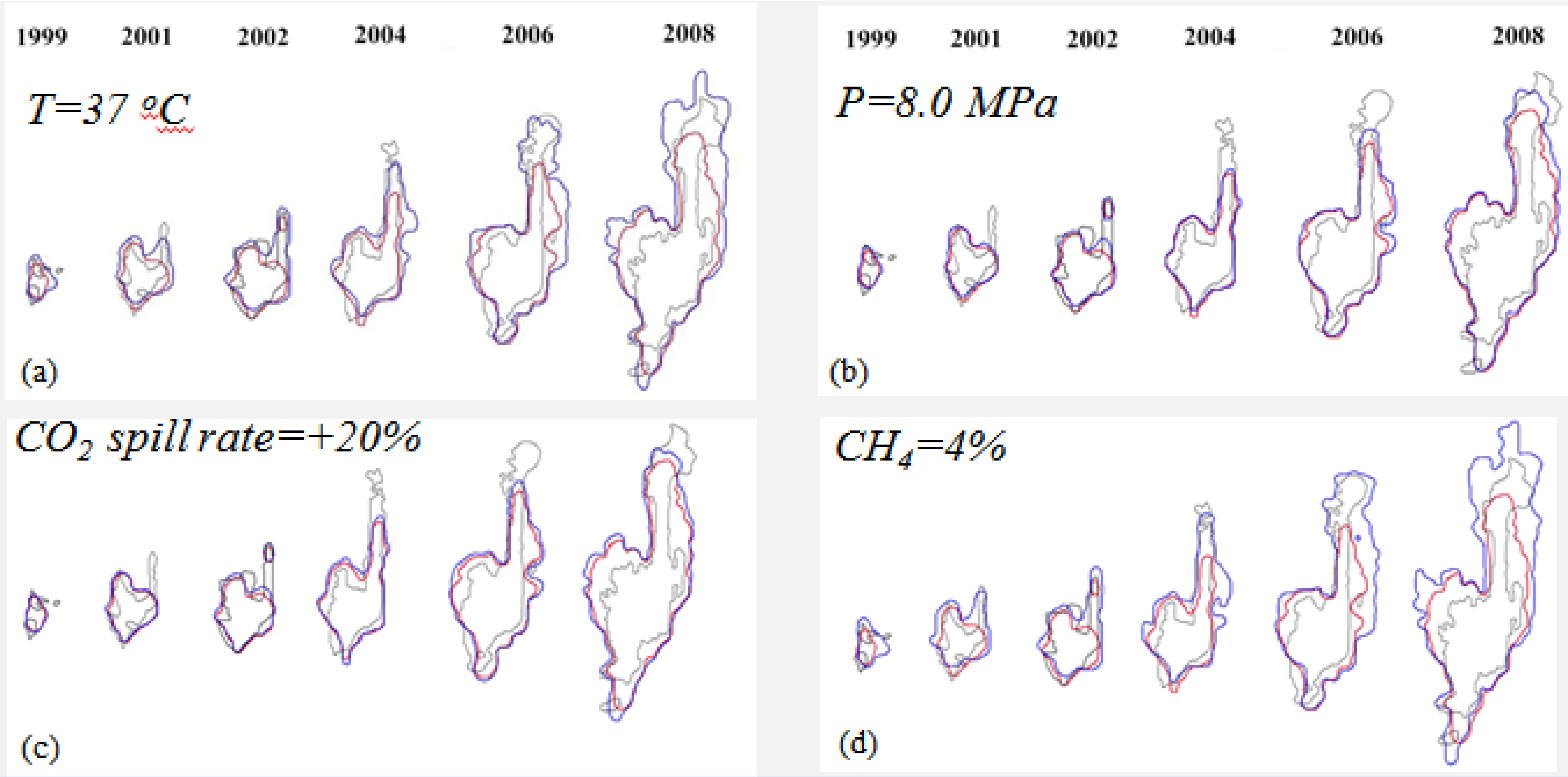
GEM®

Calibrated Model 2: 2 Feeders, Anisotropic permeability

Calibrated Model 2: TOUGH2

Approximate history match can be achieved with widely available multi-phase compositional simulators and parameters reported in the literature

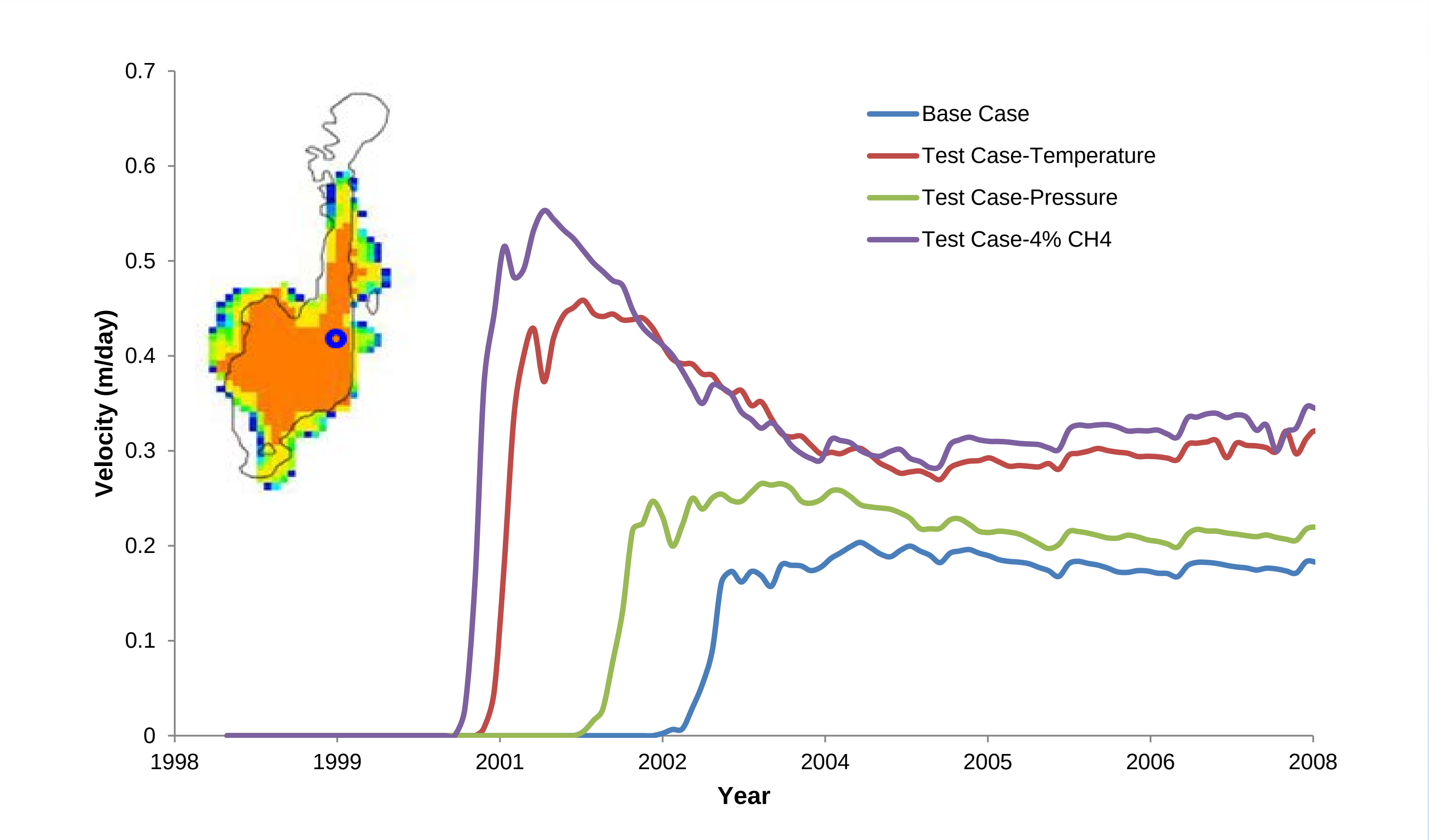
Sensitivity analysis for aerial extent of CO_2 plume



(a)-(d): The black outlines represents CWC observed from 4D seismic (Boait et al., 2012); Red lines represent the Base Case; Blue lines in (a)-(d) represent simulated results of test cases

Base Case: Calibrated model 2 (2Feeders, Anisotropic permeability, with 33.2 ºC and 8.3 MPa)

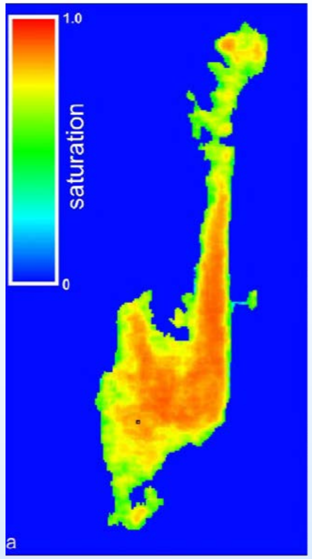
CO_2 velocity along N-S for test cases

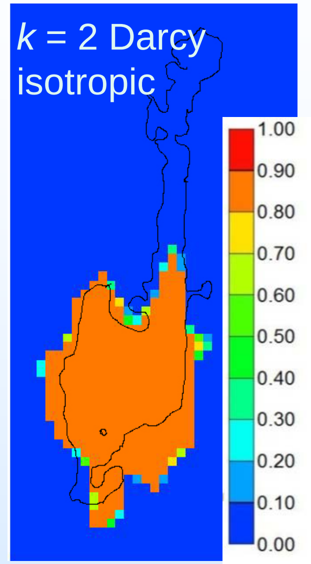


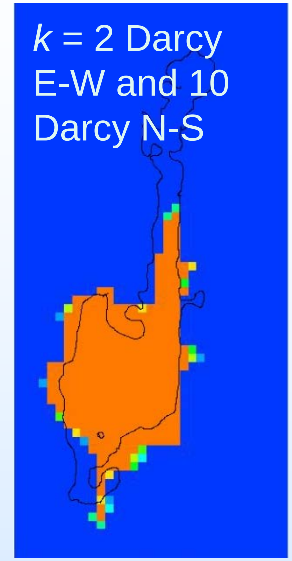
Velocity at the position shown by the circle

First—Applying Permeability Anisotropy
N-S higher permeability supported by geology

Observed extents



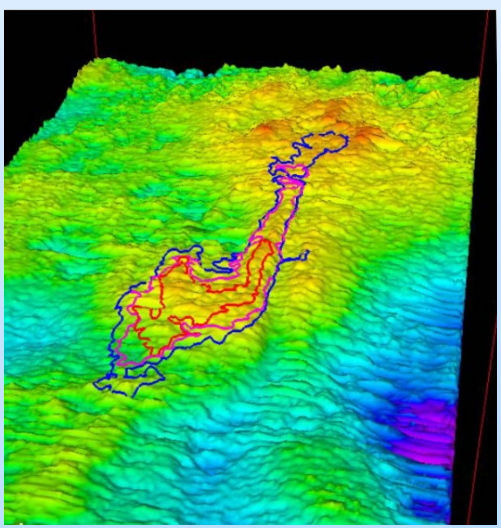


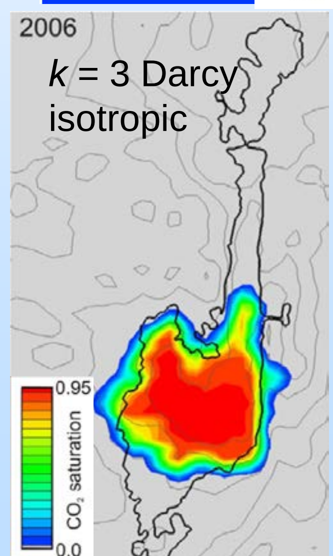


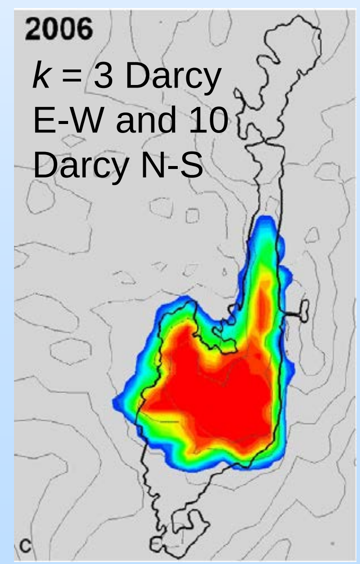
GEM simulation

Cannot achieve the match by adjusting permeability anisotropy alone

Topography of the Layer 9.

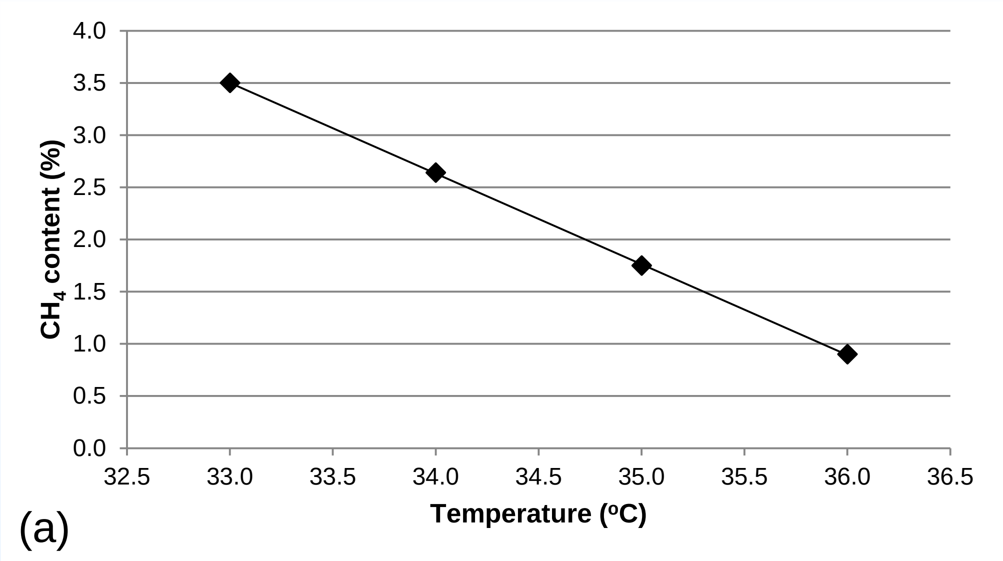






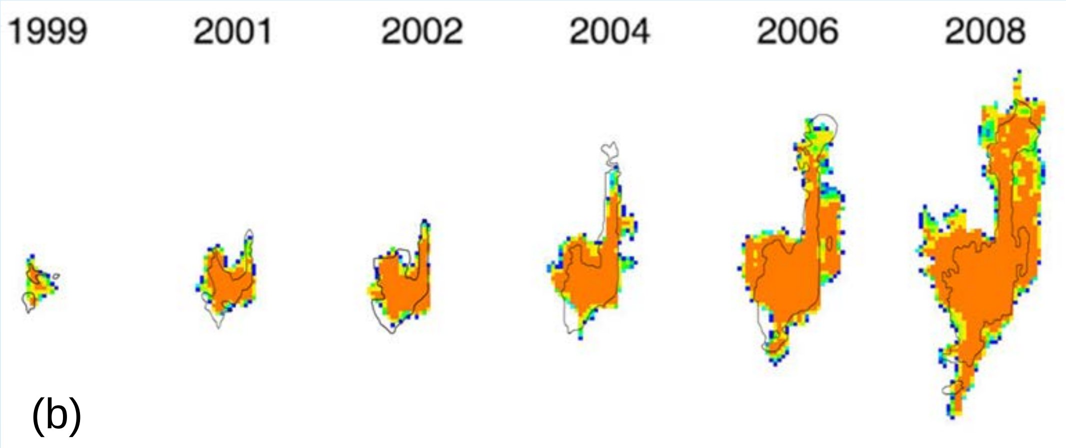
Tough 2 simulations (Chadwick and Noy, 2010)

Calibrated Model 1: A combination of temperature and CH_4



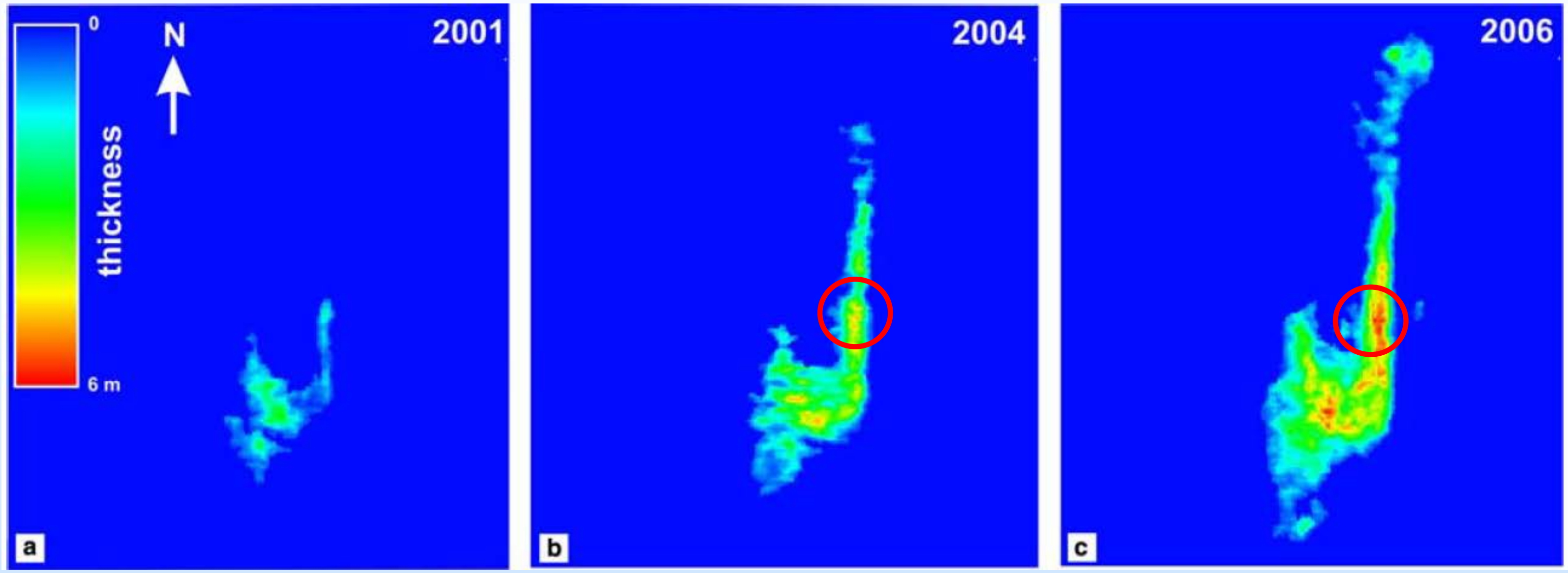
- CO_2 streams contain 1.5-2.5% methane and also butenes, toluenes, and xylenes (BTX) (Arts et al., 2008; Chadwick and Noy, 2010b; Zweigel et al., 2004; Zweigel and Heill, 2003).
- No direct measurements of reservoir ***T*** in Layer 9. ***T*** 31.5 – 35 ^oC in literature

Calibrated model 1: 1Feeder, T=34 ^oC, CH_4=2.7%, Anisotropic permeability



(a) Combinations of T and CH_4 along the line can produce similar good match as "Test Case-1Feeder, T=35 ^oC, CH_4=1.8%" (b) calibrated model 2: 1Feeder, T=34 ^oC, CH_4=2.7%, Anisotropic permeability

Calibrated Model 2: 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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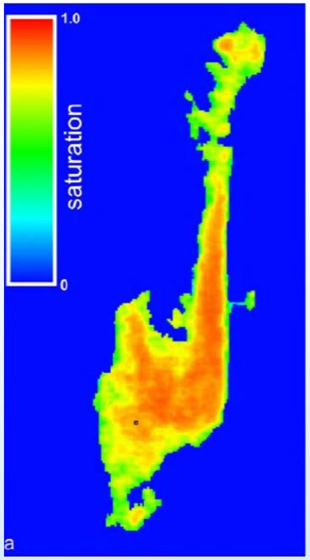
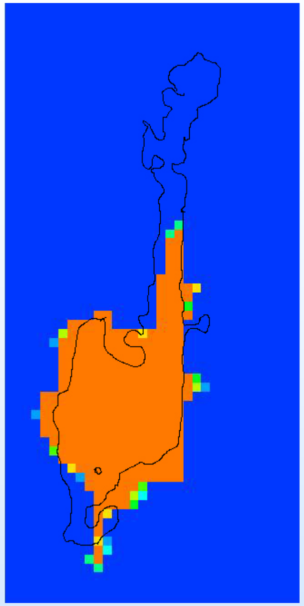
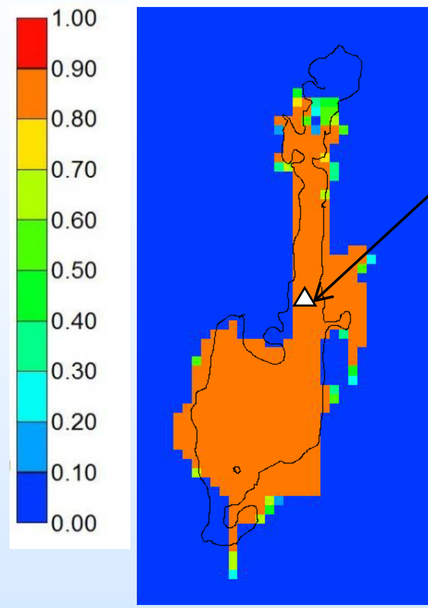
Calibrated Model 2: -Additional Feeder with Permeability Anisotropy



Observed extents 2006

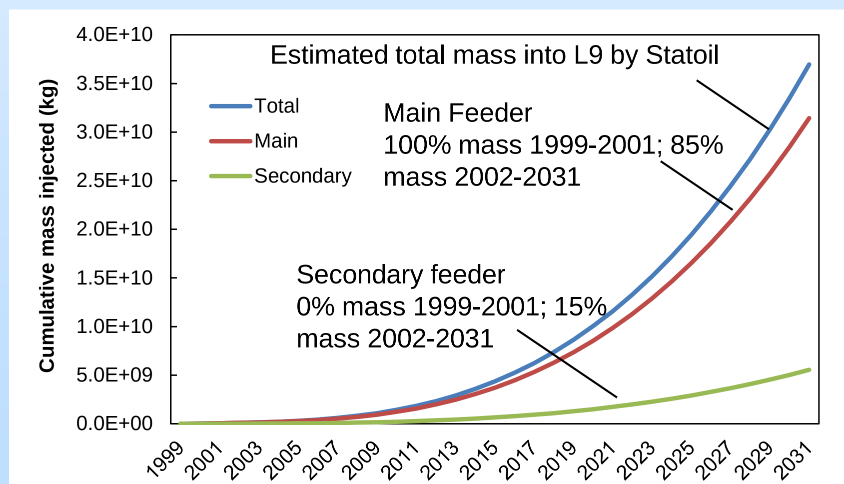


100% CO_2 volume into main feeder



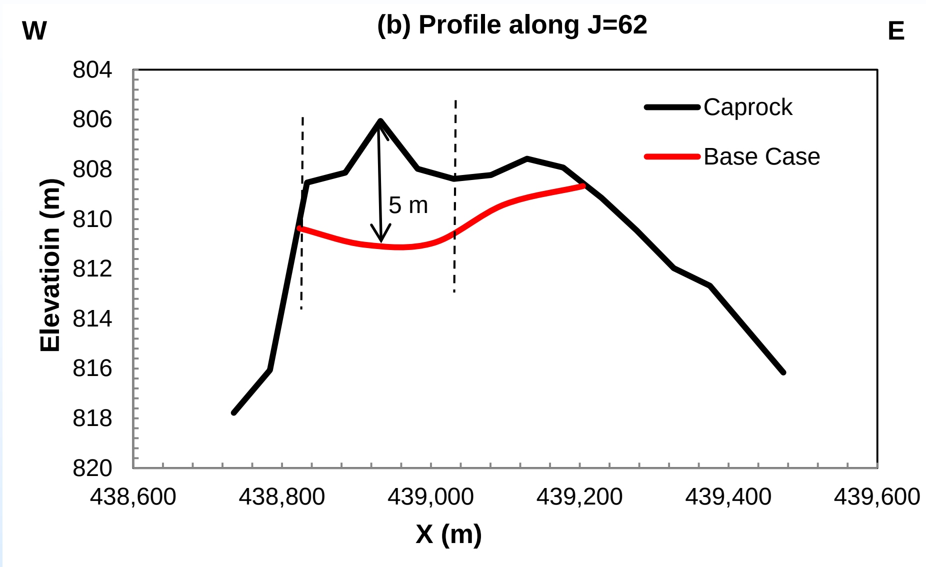
Second feeder

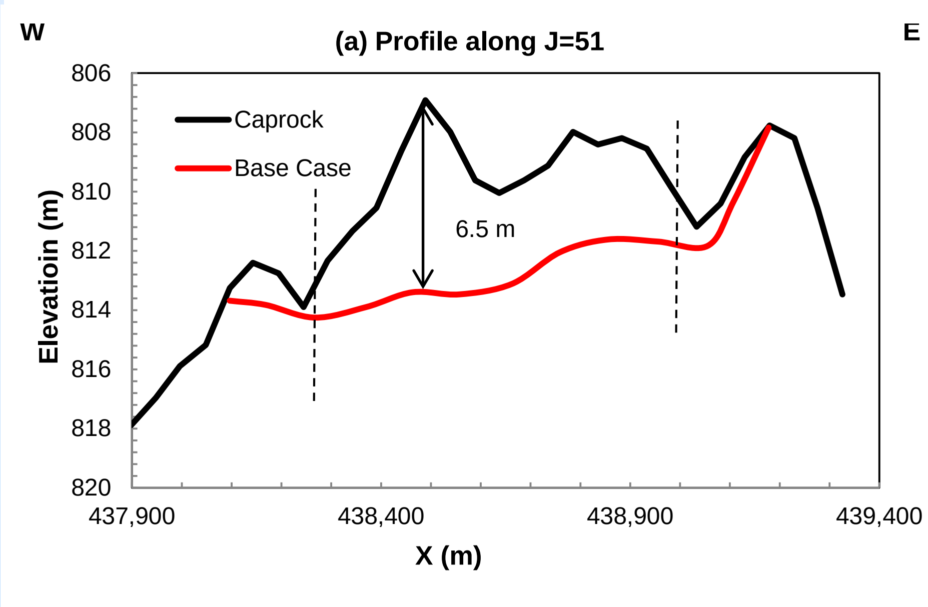
85% CO_2 volume injected into the main feeder and 15% into the second feeder (the triangle) starting from 2002.

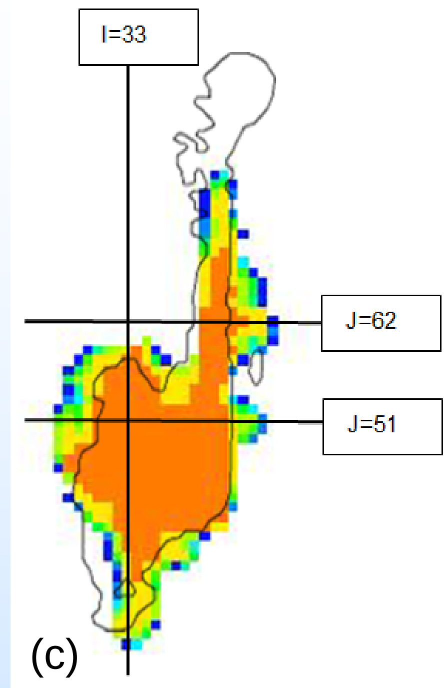


Acceptable results with the second feeder.

Topography uncertainty effect: Vertical profile of the CO_2 plume in 2006



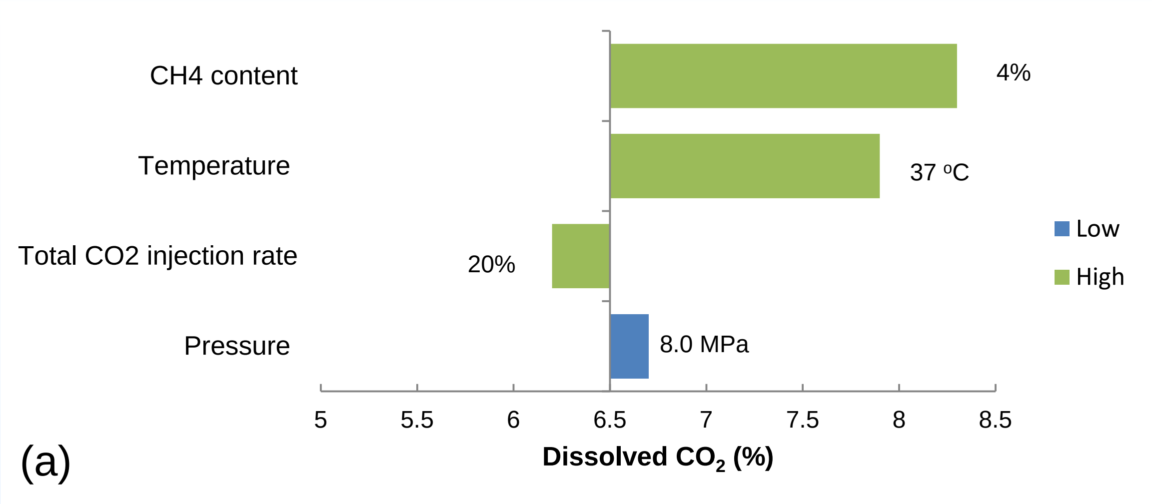




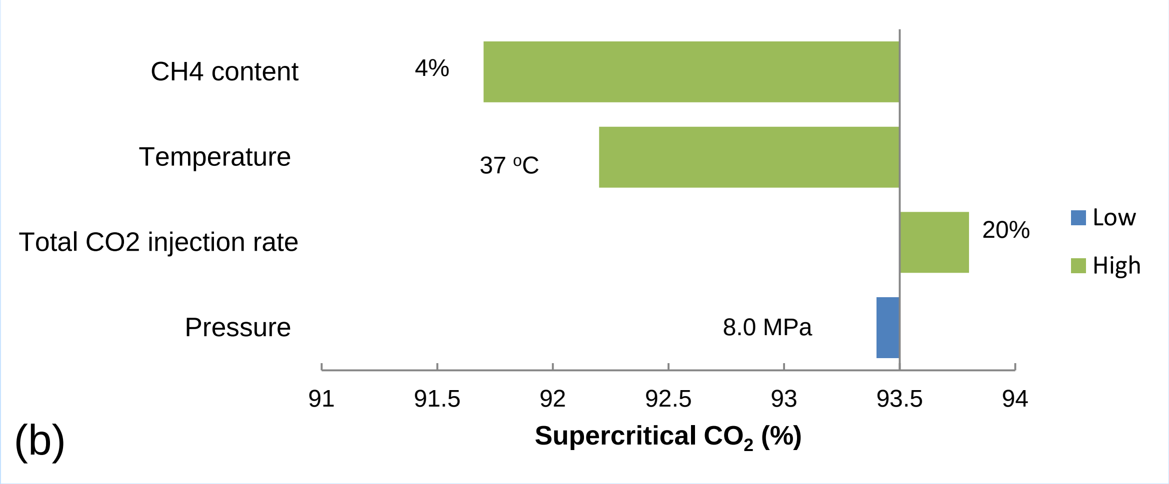
Locations of profiles

(a),(b): red lines: simulated bottom of the CO_2 plume; black lines: the topography of the caprock bottom; vertical black dash lines: the boundary of CO_2 plume

Sensitivity analysis for CO_2 fate



Structural trapping

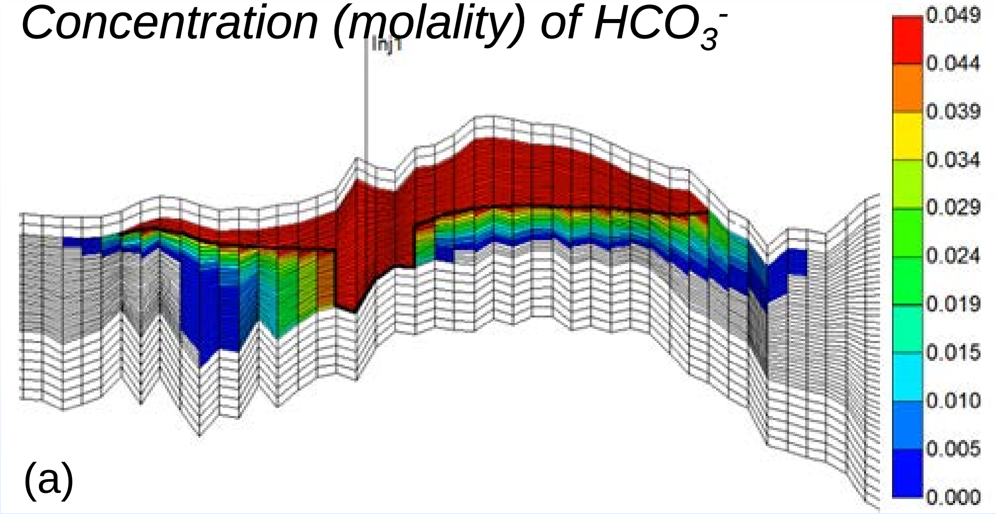


Solubility trapping

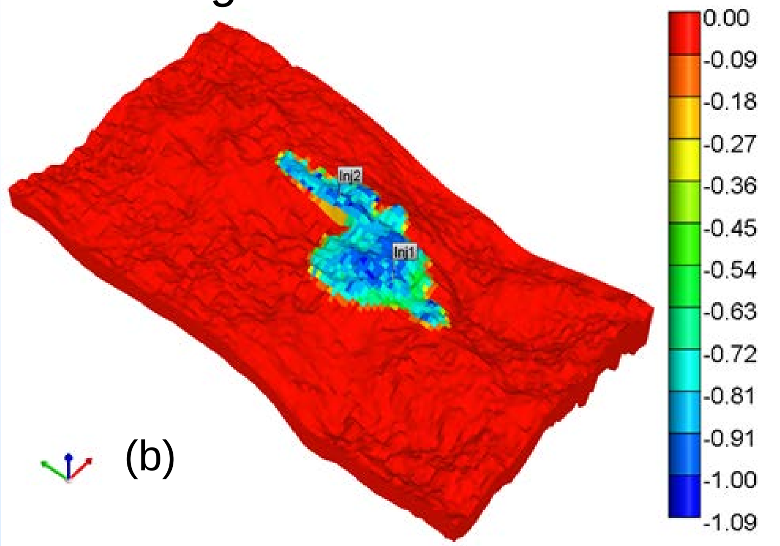
(a),(b): Green color denotes parameter values higher than those in the Base Case and blue color lower than those for the Base Case

Geochemical process in model structure: Geochemical results

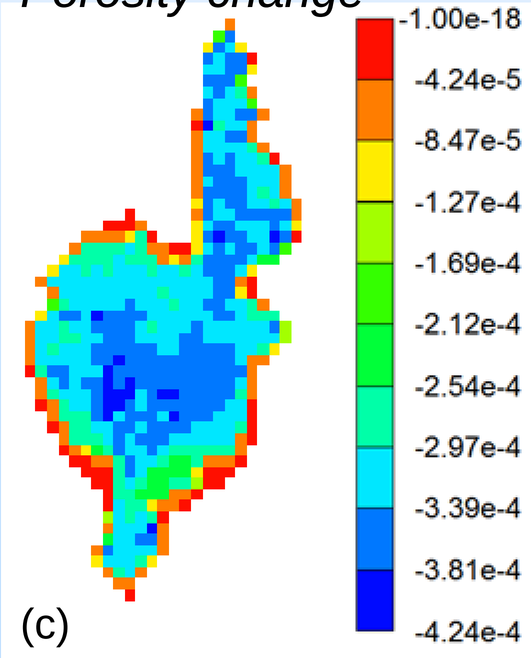
Concentration (molality) of HCO_3^-



Percentage of calcite dissolution

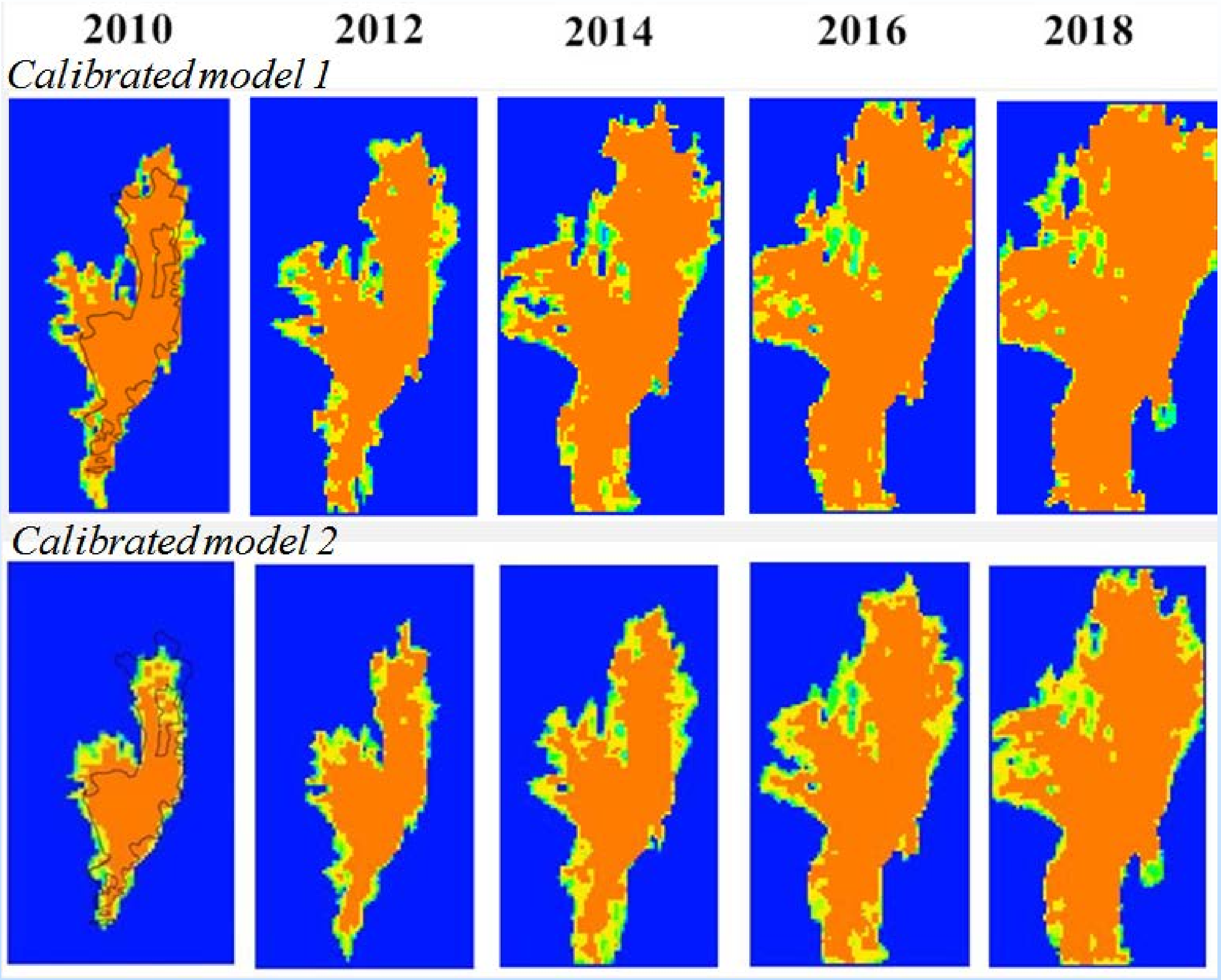


Porosity change



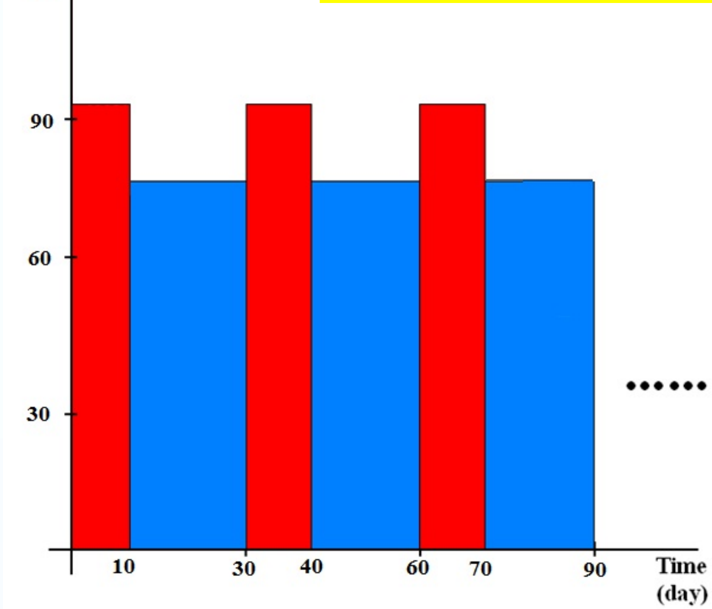
(a) The concentration at the section crossing I=33 (b) distribution at the top sub-layer of Layer 9 in 3D in 2006 (c) distribution at the top sub-layer of Layer 9 in 2006; negative value represents the increase of the porosity due to mineral dissolution.

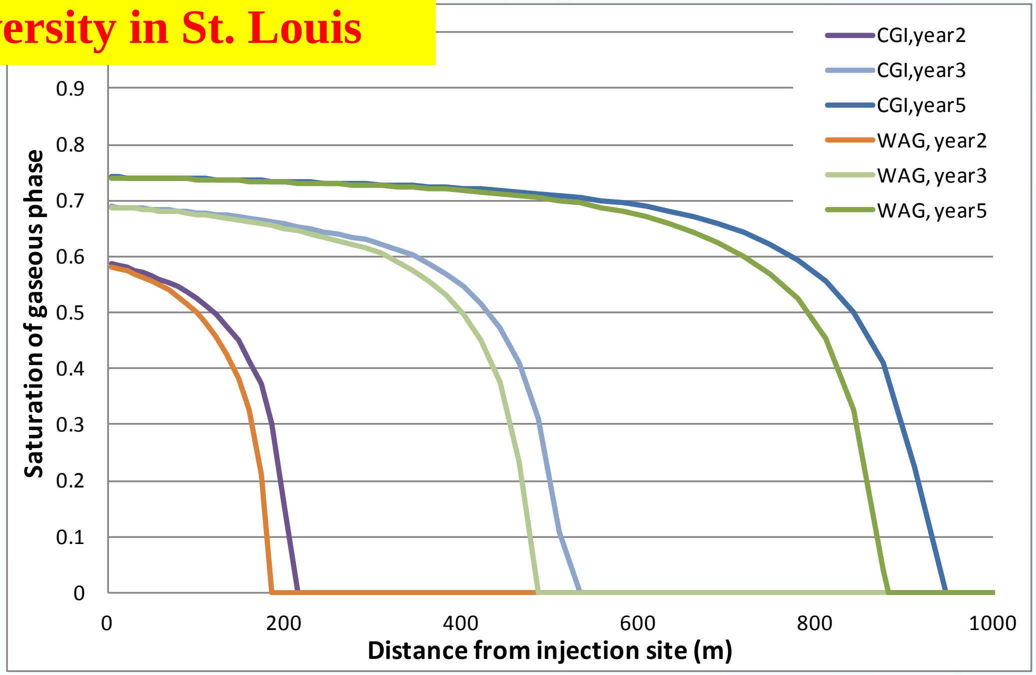
Model Predictions



Water-alternating Gas (WAG) injection– axisymmetric Utsira model

Ramesh Agarwal and Zheming Zhang
Washington University in St. Louis





Optimal WAG pattern, and CO_2 migration for CGI and WAG injection, axisymmetric Utsira formation

	I_{CO2} (kg/s)	I_{water} (kg/s)	*WAG*	*Fitness (m/k ton of water)*
Optimal Value	**95.75**	**75.32**	**0.64**	**0.0251**

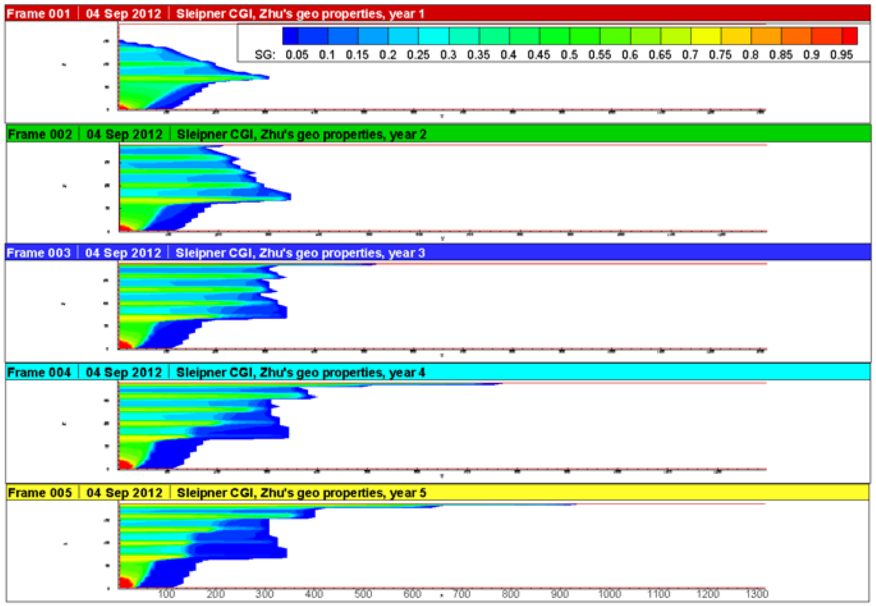
Optimal WAG injection pattern, 2D Utsira formation

CGI		**WAG**				
CO_2 Radial Migration	Dissolution	CO_2 Radial Reduction	CO_2 Radial Reduction Ratio	CO_2 Impact Area Reduction	CO_2 Impact Area Reduction Ratio	Dissolution
946.7 m	**16.89 %**	**65.2 m**	**6.89 %**	**372,095 m^2**	**13.23 %**	**23.43 %**

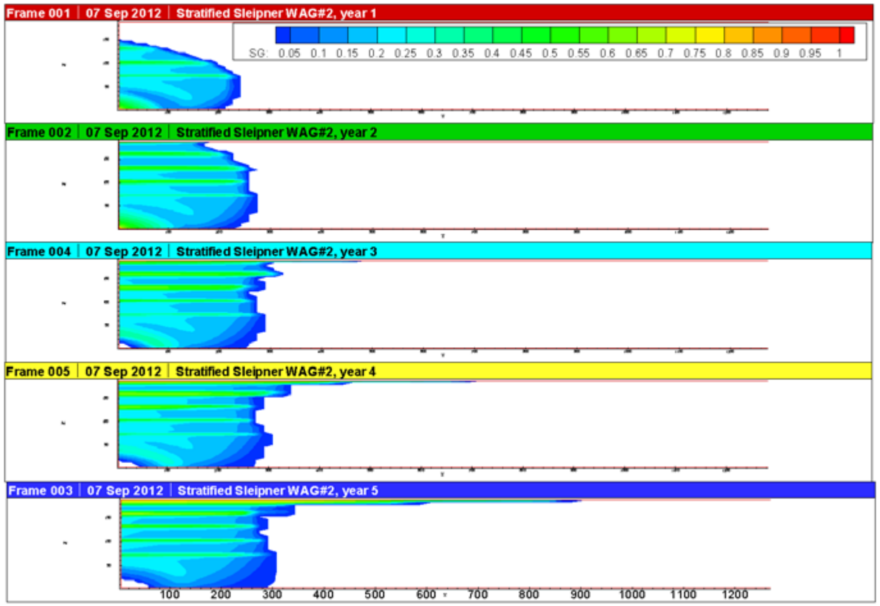
Summary of the best benefits for adopting WAG injection scheme, axisymmetric Utsira formation

WAG injection pattern design – WAG for axisymmetric Utsira formation

Collaboration with
Ramesh Agarwal and Zheming Zhang, Washington University in St. Louis



In situ CO_2 migration for CGI operation, year 1~5



In situ CO_2 migration for optimal WAG operation, year 1~5

Conclusions from Modeling Study

- **Approximate match between simulations based on Sleipner benchmark model and seismic delineated CO_2 plume history can be achieved with two widely available multi-phase compositional simulators**
- **History match is labor and computational intensive, our approximate match resulted from hundreds of simulations on supercomputers**
- **Introducing permeability anistropy is necessary and justifiable based on geology**
- **A combination of reservoir temperature and CH_4 % within the ranges in literature can result in approximate match**
- **Adding second feeder help achieve match with observed plume development**
- **Model-predicted plume thickness, CO_2 saturation, CO_2 solubility, none of them used as calibration targets, are comparable with those based on seismic data interpretations (including mass of CO2 spilled into Layer 9);**
- **Even with a range of uncertain modeling parameters, the predicted fate of CO_2 is within a narrow band, ~93±2% structural/hydrodynamic trapping and ~7±2% solubility trapping**
- **Modeling results provide feedback to monitoring and characterization needs**

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. Simulated multiphase reactive flow in Layer 9 and calibrated two models against 4D plume migration data;
3. Conducting parameter sensitivity analysis;
4. Submitted a manuscript to a peer-referred journal and gave conference presentations;
5. Continuing coupled reactive transport model to evaluate long-term effects on reservoir prosperities by water-rock interactions.

Summary- Key Findings & Lessons Learned

– **Can we predict CO_2 plumes at proposed sites (size, directions) ?**

- **Yes, we can. Accurate enough for AoR?**

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

- **We matched it without using out of ordinary parameters or assumptions, and with two widely available reservoir simulators.**

– **Do we understand CO_2-H_2O multi-phase flow in geological systems?**

- **Reasonably well, (a) we approximately matched the plume migration history; (b) model-predicted CO_2 solubility, CO_2 saturation (?), plume thickness match with geophysical interpretations; (c) plume aerial extent and thickness match with estimated CO_2 spill into Layer 9.**

Summary (continued)

– **Future Plans:**

1) Develop coupled reactive transport model to simulate long-term CO_2 fate
    a) Complete conceptual model and axisymmetric TOUGHTreact modeling of Utsira Sand
    b) Calcite dissolution with reservoir 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

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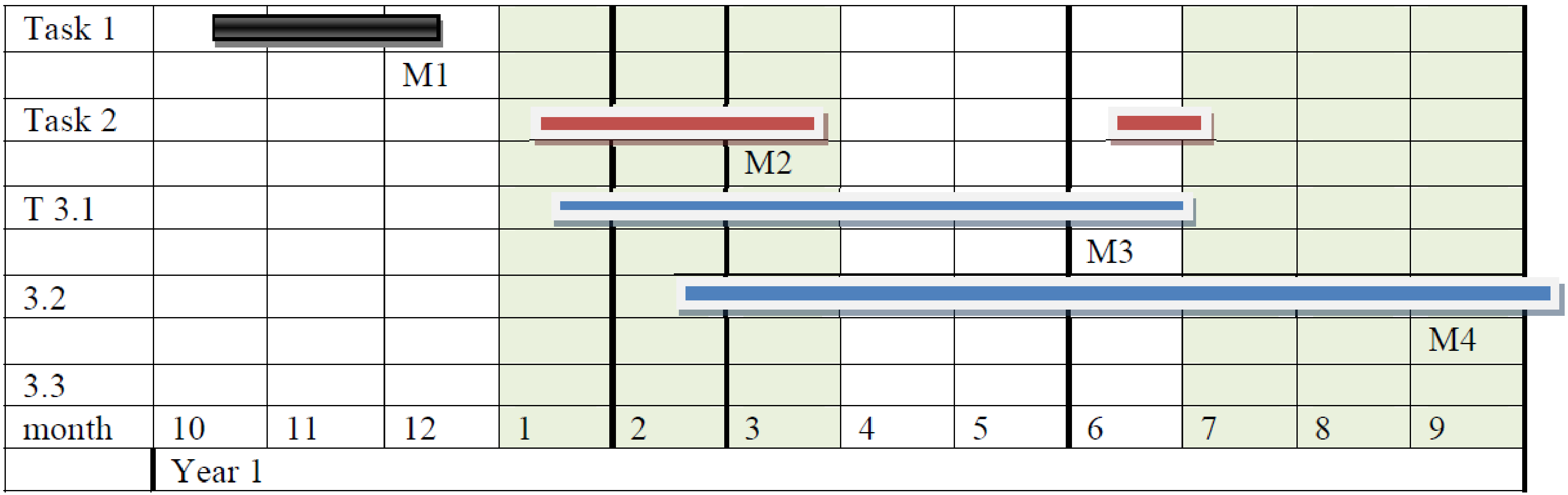
Gantt Chart

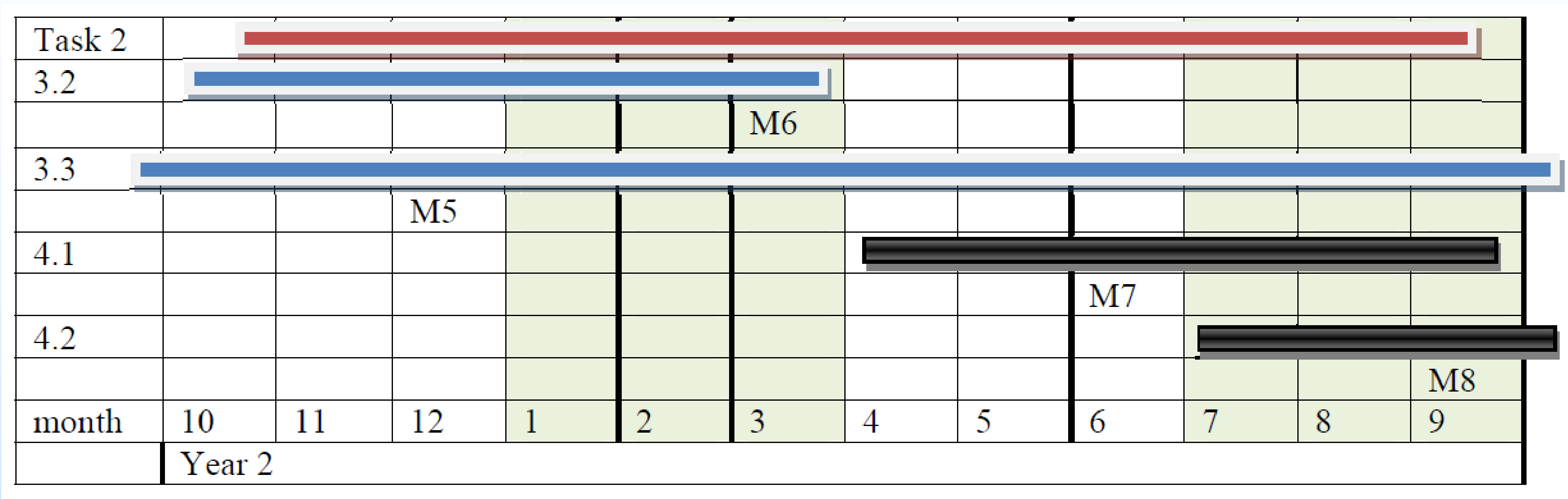


TASK 1.0 - PROJECT MANAGEMENT, PLANNING AND REPORTING

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

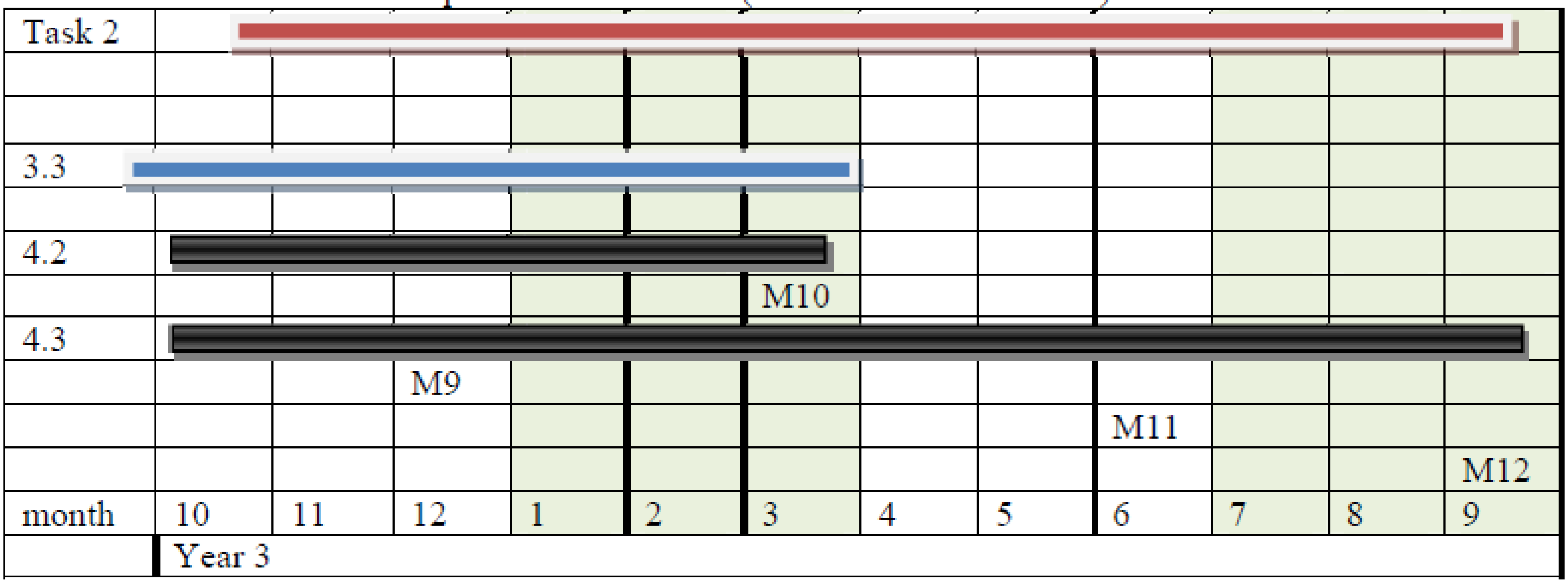
TASK 2.0 – DATA ACQUISITION AND INTERPRETATION

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:

  - Zhu C, Lu P, Zhang GR (submitted after revision August 3, 2014) Benchmark modeling of the Sleipner CO2 plume: Calibration to seismic data for the uppermost layer and model sensitivity analysis. *The International Journal of Greenhouse Gas Control*
  - 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.
  - 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
  - Ji, X. and Zhu, C., 2013, 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.

Bibliography (continued)

- <u>Conference proceeding papers and abstracts</u>:

  - 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.
  - Zhu, C., Lu, P (2013) Coupling of dissolution and precipitation reactions as the main contributor to the apparent discrepancy between lab and field reaction rates. *Procedia of Earth and Planetary Sciences*. (7)948-952, International Symposium on Water-Rock Interaction WRI-14, 4 pages. DOI 10.1016/j.proeps.2013.03.051. PROEPS317
  - Lu, P., Zhu, C., and Aaggard, P. (2012) Reducing Uncertainties in Model Predictions via History Matching of CO2 Plume Migration at the Sleipner Project, Norwegian North Sea, American Institute of Chemical Engineers (AiChe) 2012 Annual Meeting, Pittsburgh, October, 2012.
  - Ji, X. and Zhu C. (2012) Thermodynamic study for CO2 storage in deep saline aquifers. 11th International Greenhouse Gas Control Technology meeting (GHGT-11), November 18-22, 2012, Kyoto, Japan.

Bibliography (continued)

- Conference proceeding papers and abstracts (continued):
  - Ji X. and Zhu C. (2011) A SAFT Equation of State for the Quaternary H_2S-CO_2-H_2O-NaCl System. American Geophysical Union Annual meeting, San Francisco, December 5 -10, 2011.
  - Guanru Zhang, Peng Lu, Chen Zhu, , Zheming Zhang and Ramesh Agarwal. Model Predictions via History Matching of CO_2 Plume Migration at the Sleipner Project, Norwegian North Sea. American Geophysical Union Annual meeting, San Francisco, December 9 -15, 2013
  - Zheming Zhang, Ramesh Agarwal and Chen Zhu, Optimization of CO_2 Storage in Saline Aquifers Using Water-Alternating Gas (WAG) Scheme – Case Study for Utsira Formation. American Geophysical Union Annual meeting, San Francisco, December 9 -15, 2013

Book chapter:

- Ji X and Zhu C (submitted) "CO_2 storage in deep saline aquifers" A chapter in Novel Materials for Carbon Dioxide Mitigation Technology to be published by Elsevier.