Model Complexity and Choice of Model Approaches for Practical Simulations of CO_2 Injection, Migration, Leakage, and Long-term Fate

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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

- Project Goals and Objectives
- Project overview
- Accomplishments
- Summary

Benefit to the Program

- The aim of the project is to develop criteria for the selection of the appropriate level of model complexity for CO_2 sequestration modeling at a given site. This will increase the confidence in modeling results, and reduce computational cost when appropriate.
- 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**.

Project Overview: Goals and Objectives

- Goal: Develop a suite of models, across a broad spectrum of complexity, and determine when simplified models are appropriate for CO_2 sequestration modeling.
- Project objectives:
  - Assemble a suite of models across the range of complexity
  - Compare the performance of models of different complexity when applied to actual sites
  - Develop a set of practical criteria that can guide the choice of model complexity

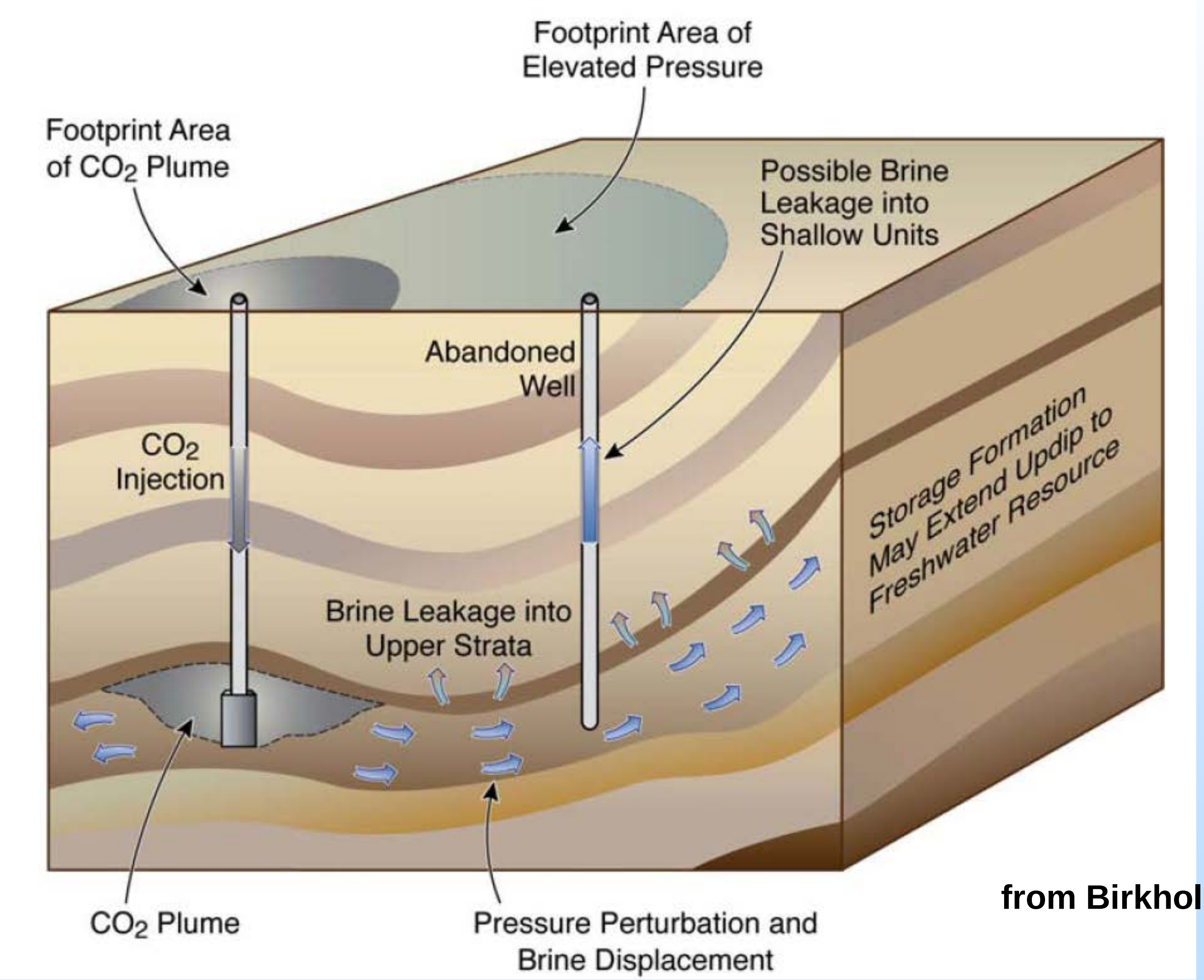
Project Overview: Project Members

- Core members:
  - Princeton University: M. Celia (PI), K. Bandilla, B. Guo, E. Leister
  - Lawrence Berkeley National Lab: J. Birkholzer (co-PI), A. Cihan, S. Finsterle, Q. Zhou
- Affiliates:
  - University of Bergen: J. Nordbotten, E. Keilegavlen
  - CIPR: S. Gasda
  - University of Stuttgart: R. Helmig

Project Overview: Technical Status

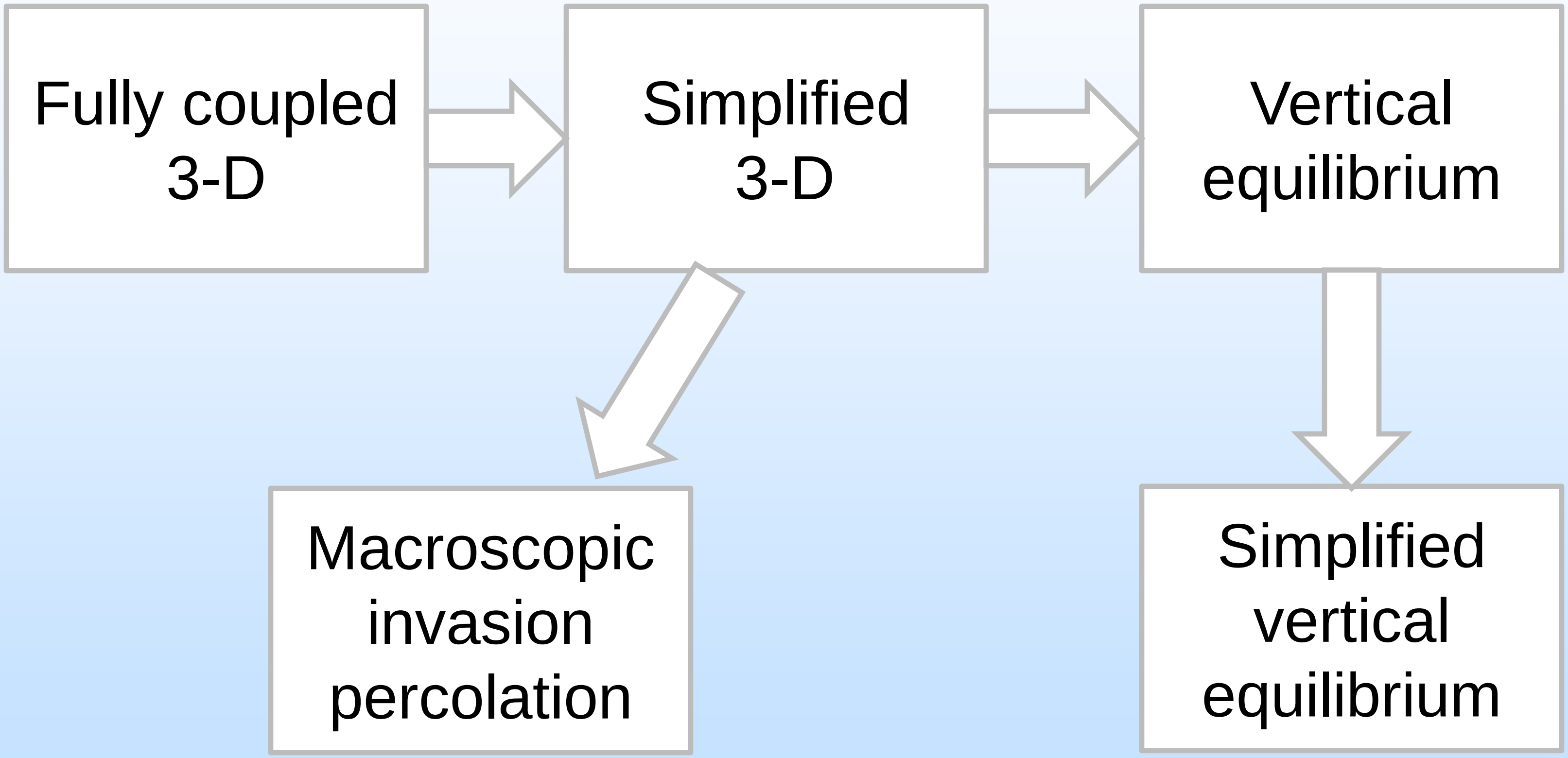
- Spectrum of model complexity
- New algorithm developments
- Site selection
- Model comparison
- Model complexity and design optimization

Domain

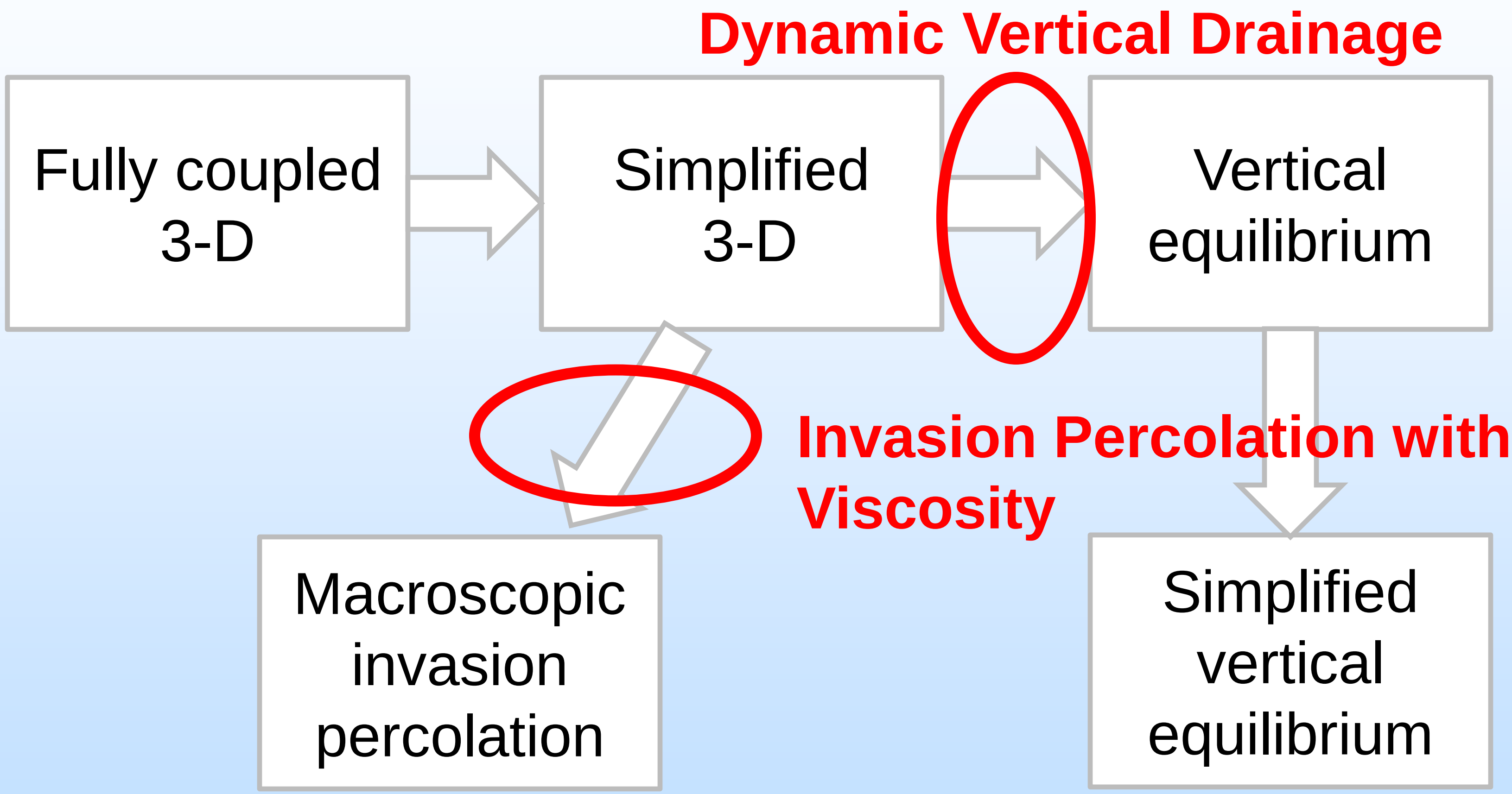


from Birkholzer et al., 2008

Model Complexity



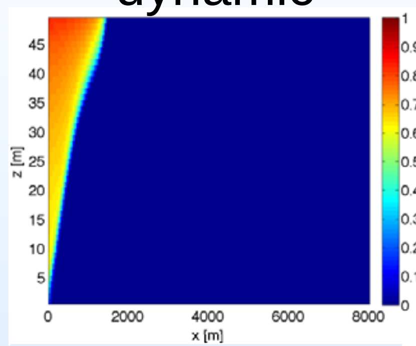
New Algorithms



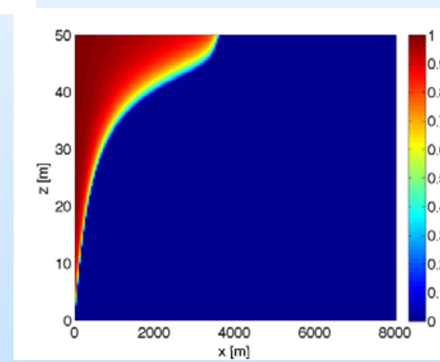
Dynamic Vertical Drainage

simplified 3-D | vertical dynamic | vertical equilibrium

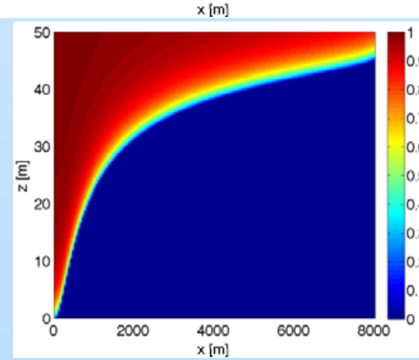
10 years



20 years



50 years

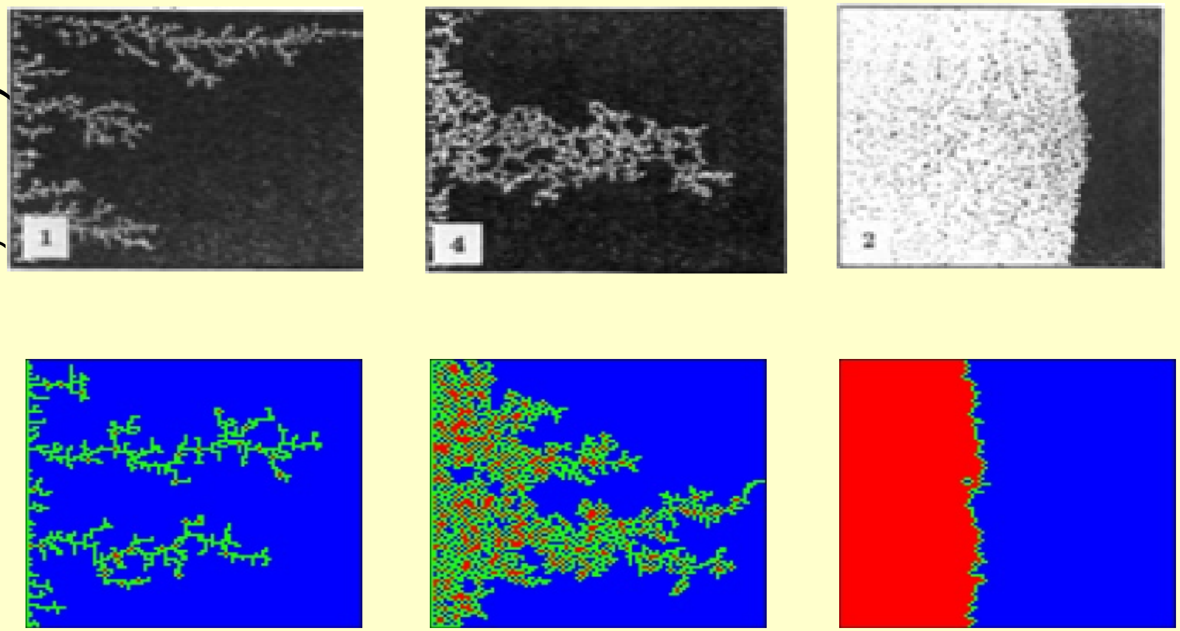


Invasion Percolation

Viscous-Dominated | **Capillary-Dominated** | **Stable**

Experiment (*Lenormand et al., 1988*)

New Growth Model



M=1.80×10^{-5}, Ca=4.95×10^{-7}, Bo=0

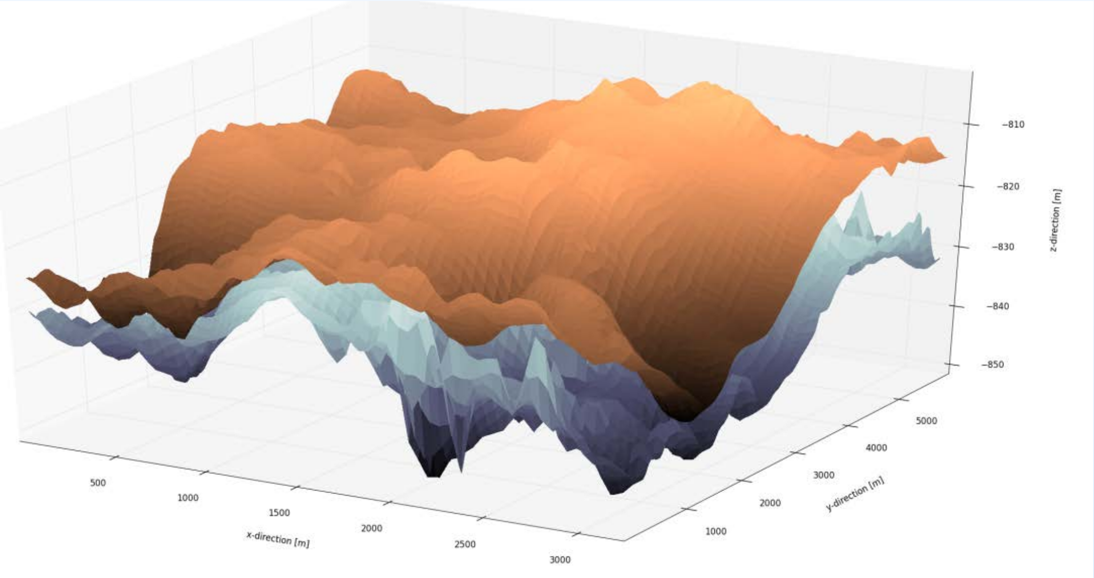
M=1.80×10^{-5} Ca=5.34×10^{-11}, Bo=0

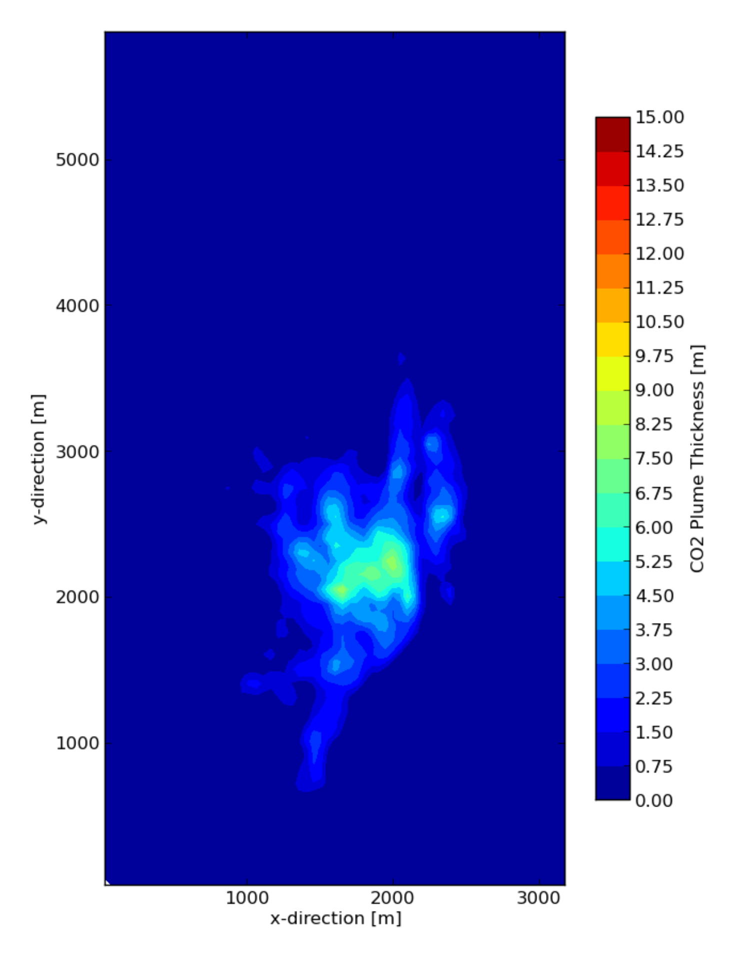
M=100.0, Ca=9.83×10^{-4}, Bo=0

Site Selection

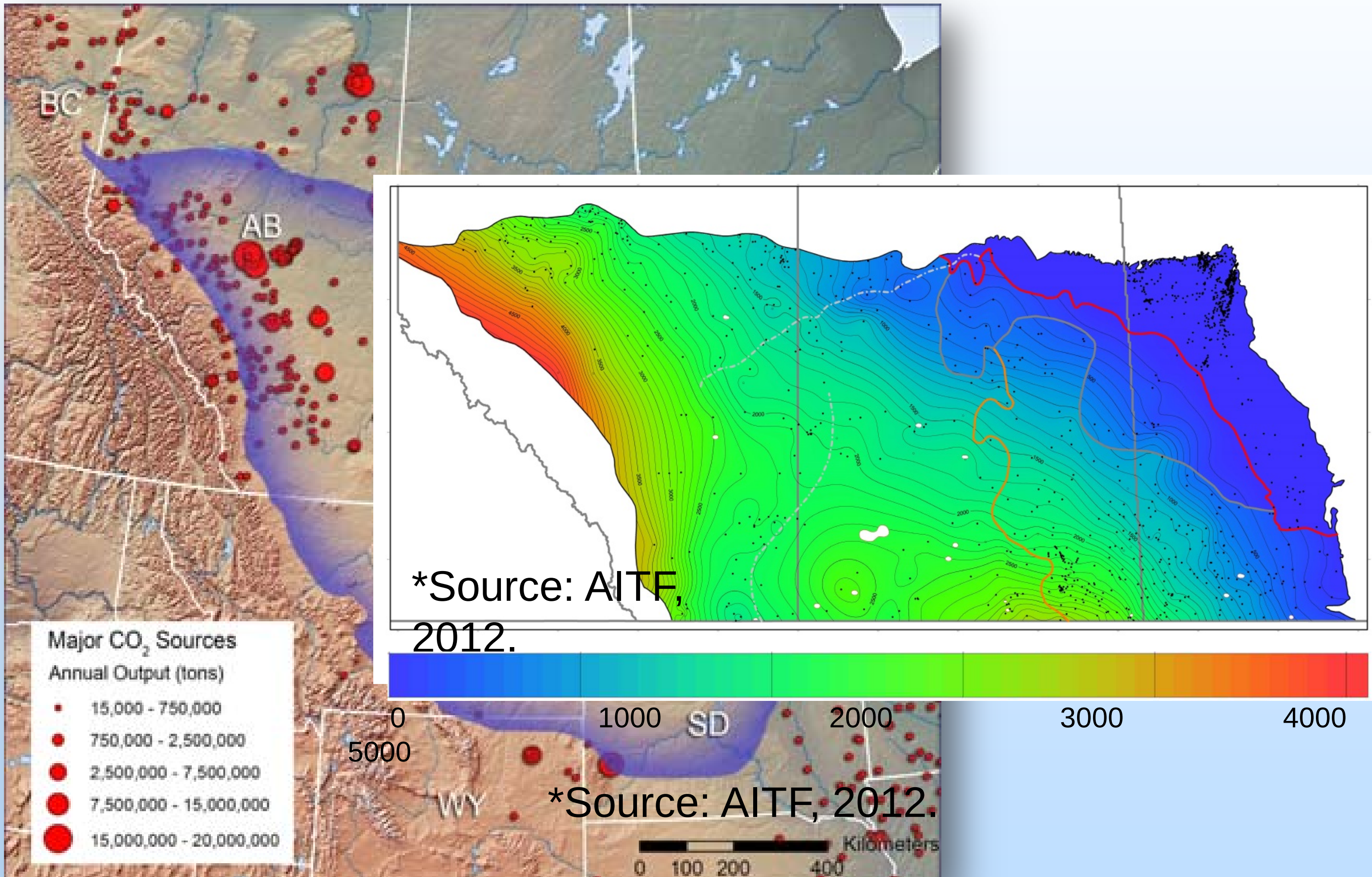
- Sleipner (9th layer of Utsira formation)
- Basal Aquifer
- In Salah
- Ketzin (CO2SINK)
- Cranfield (Phase III Early Test)

Sleipner Data





Basal Aquifer Data



*Source: AITF, 2012.

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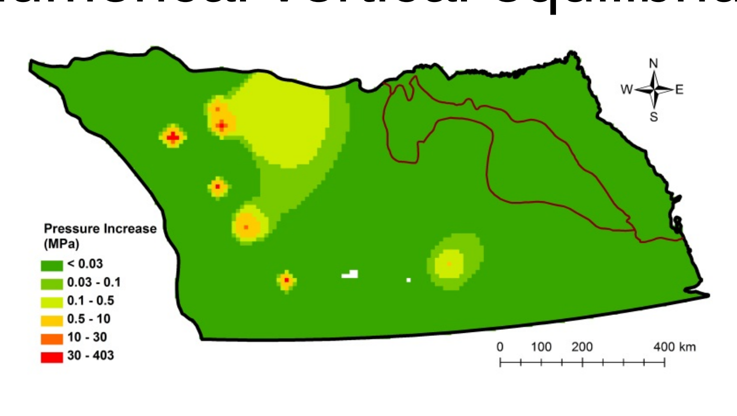
Model Comparison

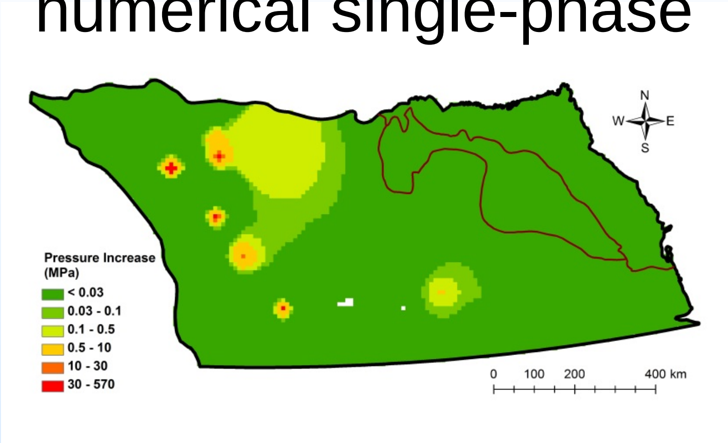
- Compare model results to find criteria for choice of appropriate level of complexity
- Different complexity for different questions:
  - Shape and areal extent of CO_2 plume
  - Areal extent of pressure response
  - Migration of fluids out of injection formation

Initial Basal Aquifer Comparison

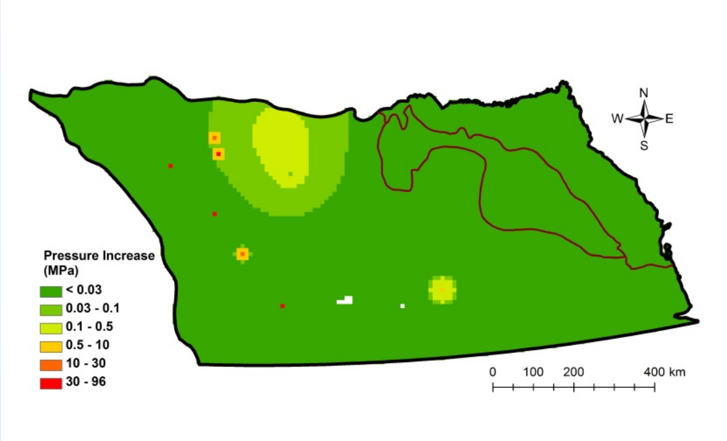
numerical vertical equilibrium



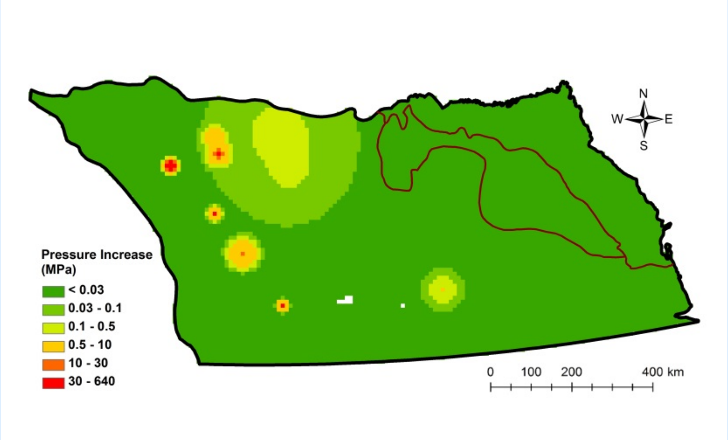
numerical single-phase



semi-analytic vertical equilibrium

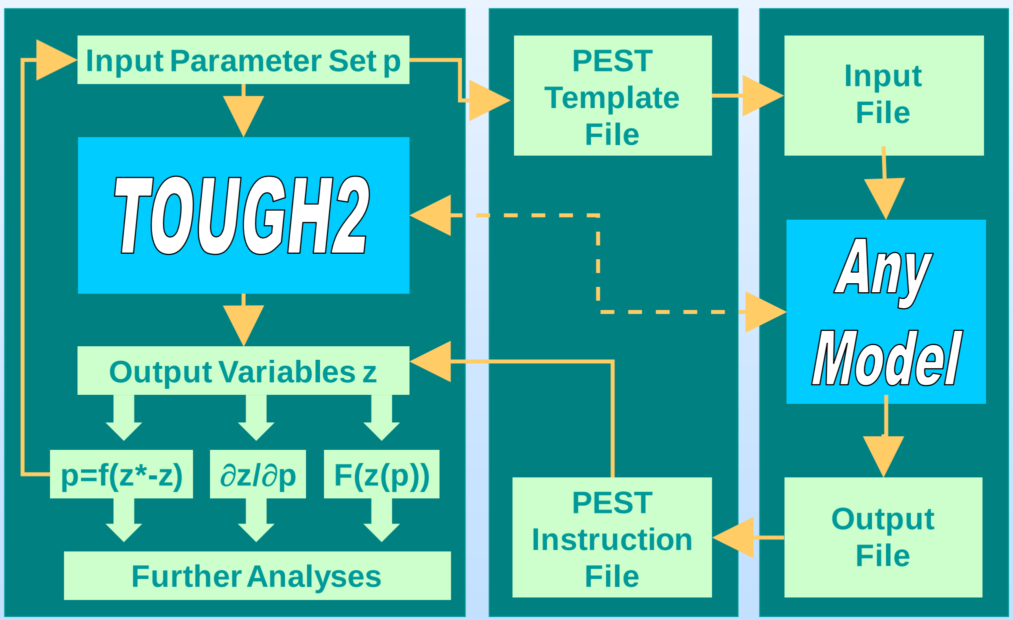


analytic single-phase (Theis)



Optimization

- Provides inverse modeling capabilities for multi-phase simulator TOUGH2 or, via PEST interface, other forward prediction tools
- iTOUGH2 involves a suite of global and local optimization methods



Forward Predictors

(1) Analytical Solutions

(2) Vertically Integrated Numerical Two-Phase Flow Models

- Sharp-Interface Models
- **Vertically Integrated Multi-Phase Models**
- **CO_2 migration in complex and heterogeneous systems**

(3) Simulator TOUGH2

- Multi-phase flow in full 3D systems

Increasing Realism

Increasing Efficiency

Accomplishments to Date

- Established research team and distributed responsibilities.
- Completed review of existing CO_2 sequestration modeling approaches and their application to actual sites.
- Collected and analyzed data for Sleipner and Basal Aquifer.
- Completed study on the impact of model complexity on basin-scale pressure response in the Basal Aquifer.

Accomplishments to Date (cont)

- Developed, implemented and tested vertical drainage dynamics algorithm.
- Developed and implemented algorithm for macroscopic invasion percolation modeling including viscous effects.

Conclusions

- Vertical drainage dynamics algorithm improves the vertical-equilibrium approach and is able to accurately predict CO_2 plume migration under many practical conditions.
- Single-phase sufficient for basin-scale pressure response, but semi-analytic solutions are likely not sufficient.

Future Plans

- Data collection for additional sites
- Improve vertical drainage dynamics algorithm
- Improve viscous invasion percolation algorithm
- Model comparison
- Development of best practices manual

THANK YOU!

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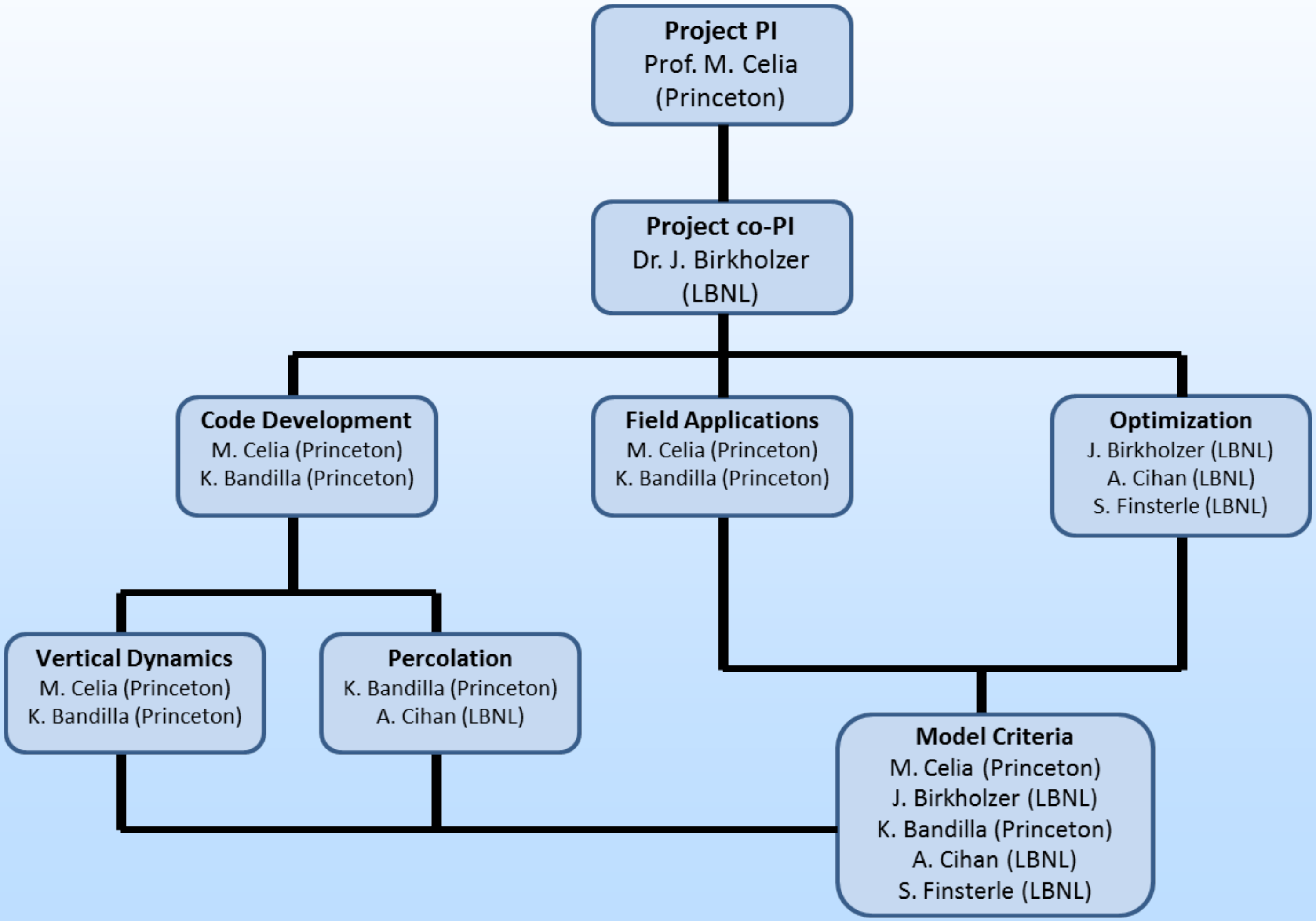
Appendix

Organization Chart



Gantt Chart

	BP1 (2012-2013)				BP2 (2013-2014)				BP3 (2014-2015)			
	1 10/1 -12/31	2 1/1 – 3/31	3 4/1 – 6/30	4 7/1 – 9/30	1 10/1 -12/31	2 1/1 – 3/31	3 4/1 – 6/30	4 7/1 – 9/30	1 10/1 -12/31	2 1/1 – 3/31	3 4/1 – 6/30	4 7/1 – 9/30
Task 1: Proj Mgmt and Planning												
Subtask 1.1: PMP And KickOff	MS											
Subtask 1.2: Project Planning and Reporting												
Task 2: Development Of New Models												
Subtask 2.1: Review And Analyze Existing Models			MS									
Subtask 2.2: Models with Vertical Drainage Dynamics				MS			MS					
Subtask 2.3: New Percolation Model					MS			MS				
Task 3: Model Existing Injection Operations					MS		MS	MS		MS		
Task 4: Optimization Models							MS		MS	MS		
Task 5: Criteria for Model Complexity											MS	

light grey: accomplished; dark grey: planned; MS: mile stone

Bibliography

- Huang, X., Bandilla, K.W., Celia, M.A., Bachu, S., (under review), Basin-scale modeling of CO_2 storage using a cascade of models of varying complexity. International Journal of Greenhouse Gas Control.
- Celia, M.A., Nordbotten, J.M., Bandilla, K.W., Gasda, S., Guo, B., 2012, Multi-scale Modeling and Model Complexity in CO_2 Sequestration Simulations; invited talk; presented at American Geophysical Union 2012 Fall Meeting, San Francisco, CA, 3rd-7th of December 2012.
- Guo, B., Bandilla, K.W., Celia, M.A., 2012, Inclusion of Vertical Dynamics in Vertically-integrated Models for CO_2 Storage; poster; presented at American Geophysical Union 2012 Fall Meeting, San Francisco, CA, 3rd-7th of December 2012.