Multiscale Modeling of Carbon Dioxide Migration and Trapping in Fractured Reservoirs with Validation by Model Comparison and Real-Site Applications

Project Number DE-FE0023323

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U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology, Innovation and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

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Presentation Outline

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

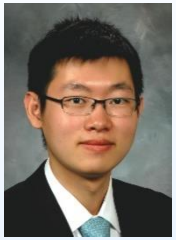
Project participants

Princeton University


Michael Celia


Karl Bandilla


Bo Guo


Yiheng Tao

Lawrence Berkeley National Laboratory


Jens Birkholzer


Quanlin Zhou

Heriot-Watt University


Sebastian Geiger


Florian Doster


Rafael March

Benefit to the Program

- Goal: Develop new capabilities for carbon sequestration modeling in fractured reservoirs through improvements in the representation of fracture-matrix flow interactions.

- Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.

Project Objectives

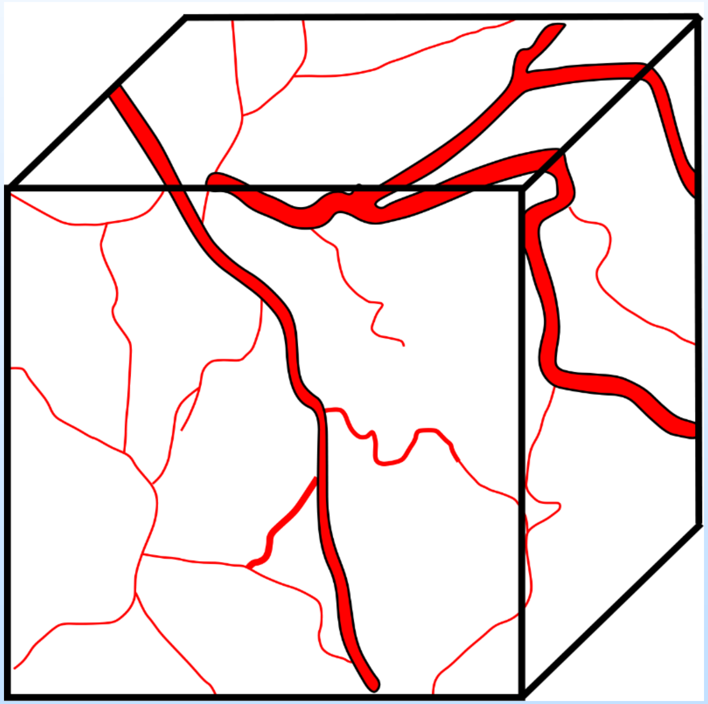
- Develop new models for interactions of fracture and matrix flow
- Incorporate those models into reservoir-scale simulators
- Conduct sensitivity analyses of trapping efficiency and storage capacity using new model
- Apply new model to In Salah site

Project Overview

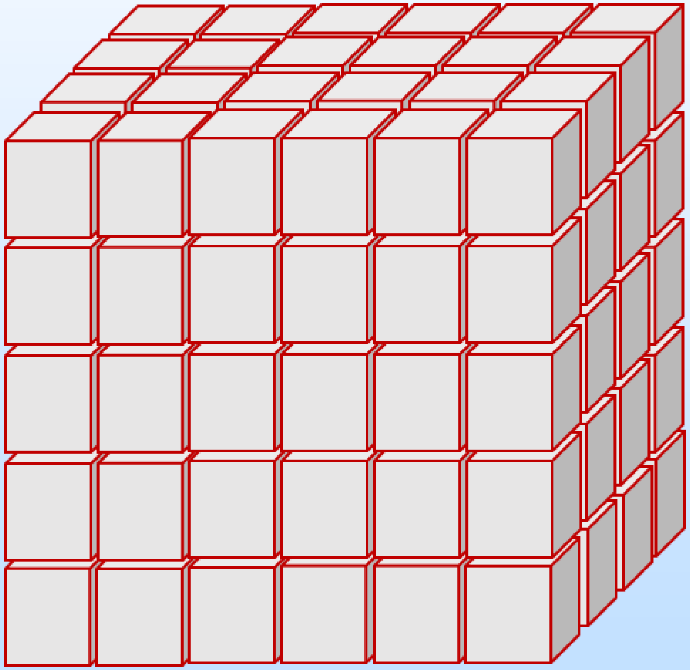
- Dual-continuum models
- Transfer functions
  - Gravity drainage
  - Spontaneous imbibition
- Sensitivity analysis
- Vertically-integrated approach

The Dual-Continuum Model

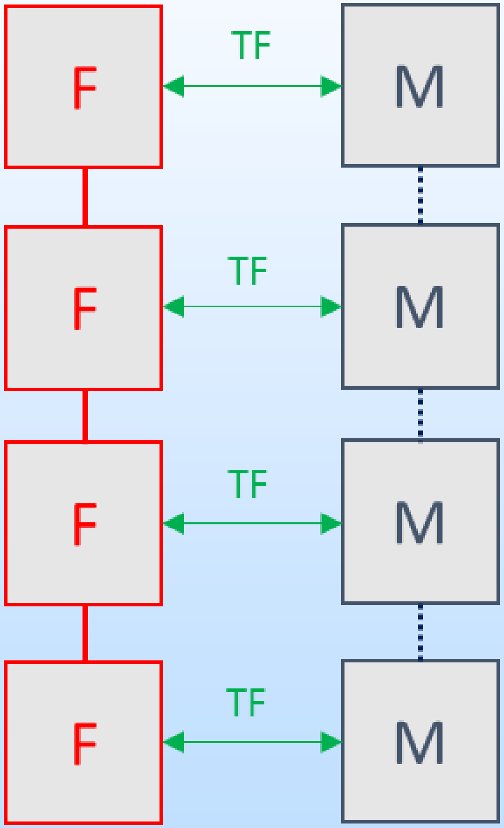
Physical geometry



Idealization: the dual-continuum representation



Conceptual approach



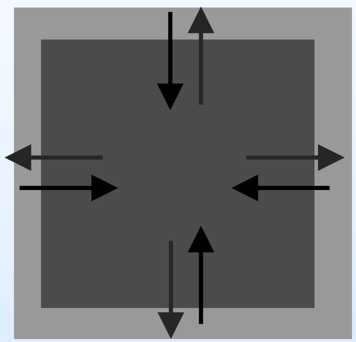
F = Fracture grid-block

M = Matrix grid-block

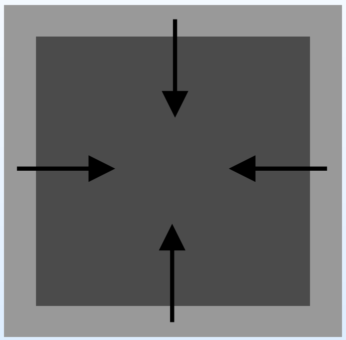
TF = Transfer function

Fracture/Matrix Interaction

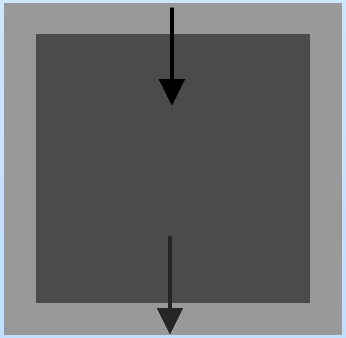
Spontaneous Imbibition



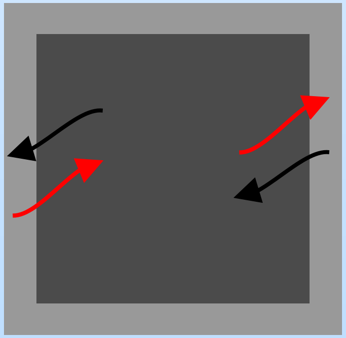
Fluid Compression



Gravity Displacement



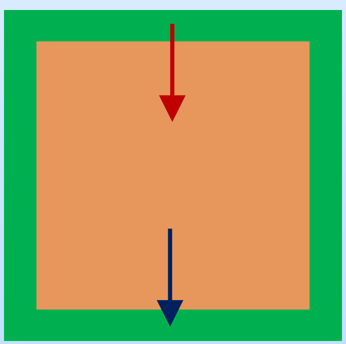
Molecular Diffusion



CO_2 Storage Context

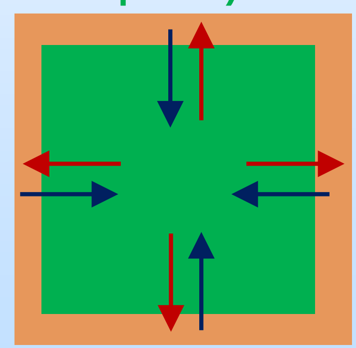
CO_2 Injection Phase: Drainage Process

Fracture filled with supercritical CO_2 (non-wetting phase)
Rock matrix filled with brine (wetting phase)



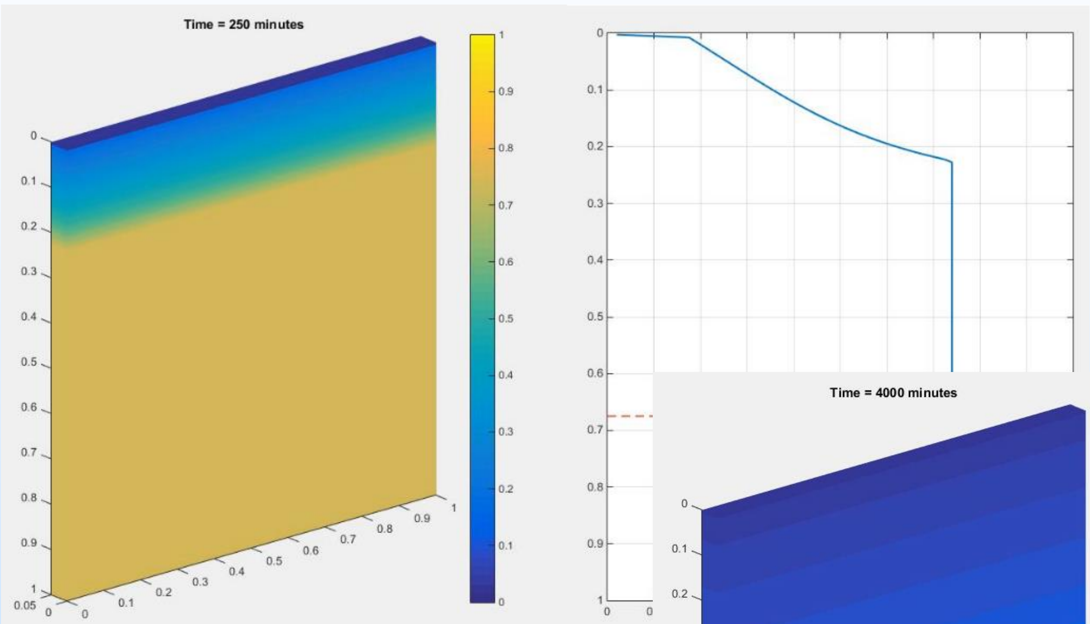
Post Injection Phase: Imbibition Process

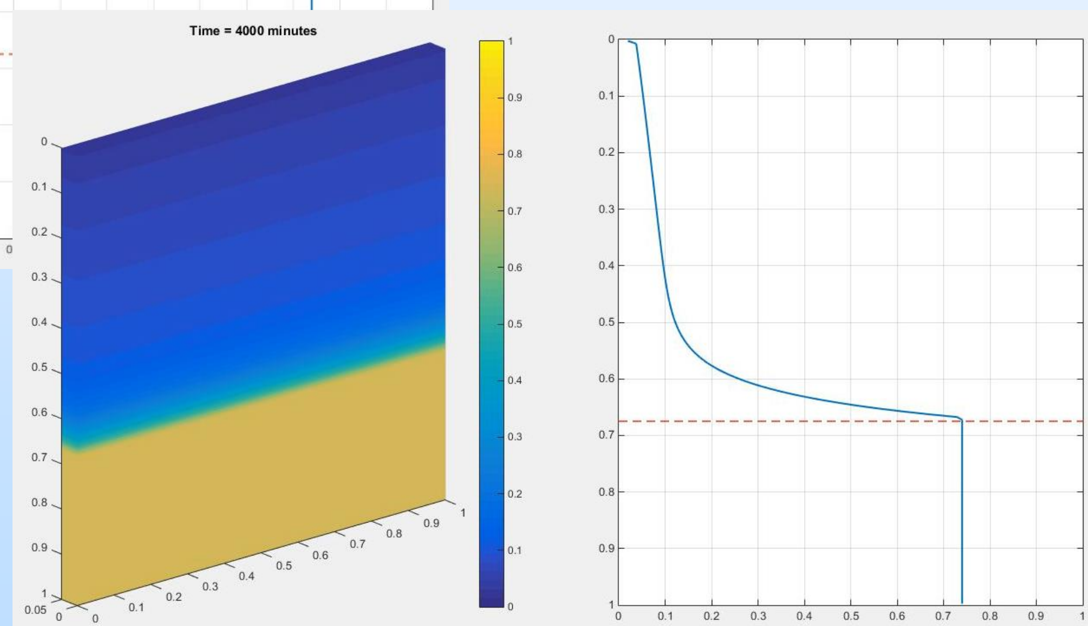
Fracture filled with brine (wetting phase)
Rock matrix filled with supercritical CO_2 (non-wetting phase)



CO_2 INJECTION PHASE

CO_2 Injection Phase





Drainage Model

- First-Order Model

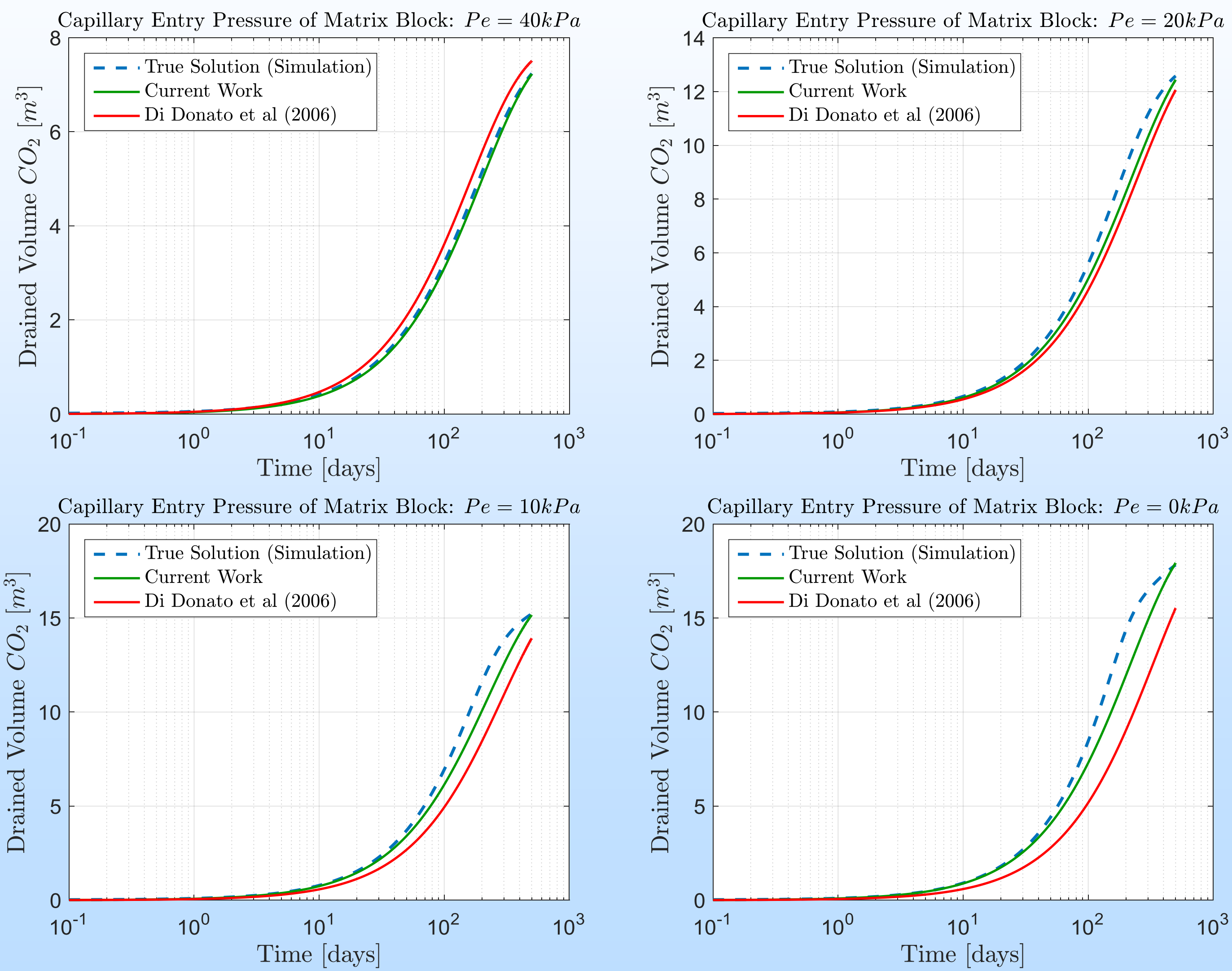
$$V_{CO_2} = V_{CO_2}^{max}(1 - e^{-\tau_D \cdot t})$$

- Dimensional analysis of the 1D fractional-flow equation provides estimate for the characteristic timescales: t_{Dg}, t_{Dc}, t_{Dv}

$$\tau_D = \left(1 - \frac{1}{r}\right)\left(t_{D_g} + t_{D_v}\right) + \left(\frac{1}{r}\right)\left(t_{D_c}\right)$$

with ratio of gravitational to capillary forces: $r = \frac{\Delta\rho g L}{P_e}$

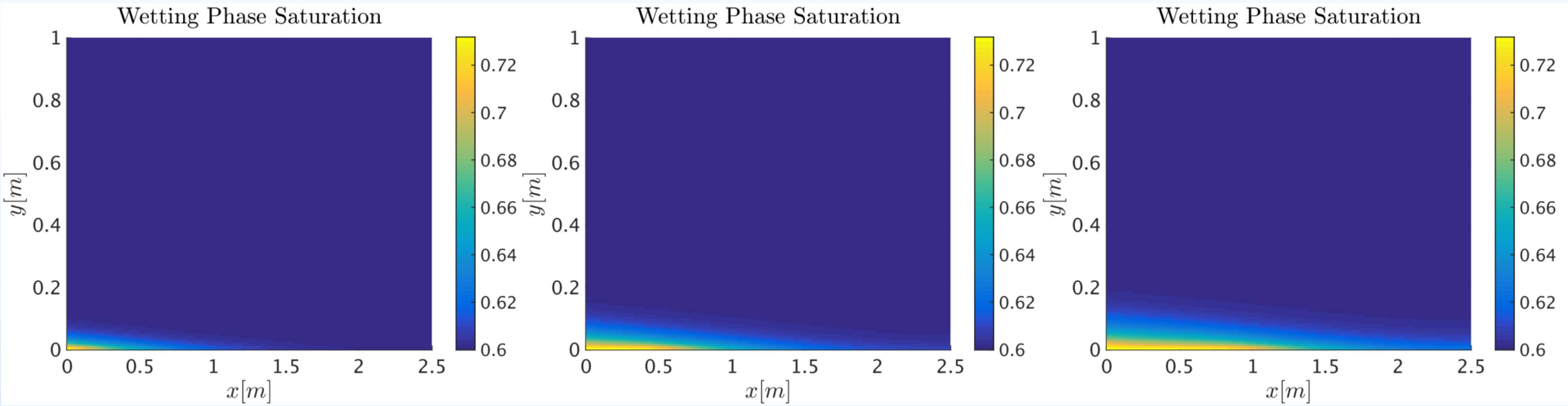
Drainage curves comparison

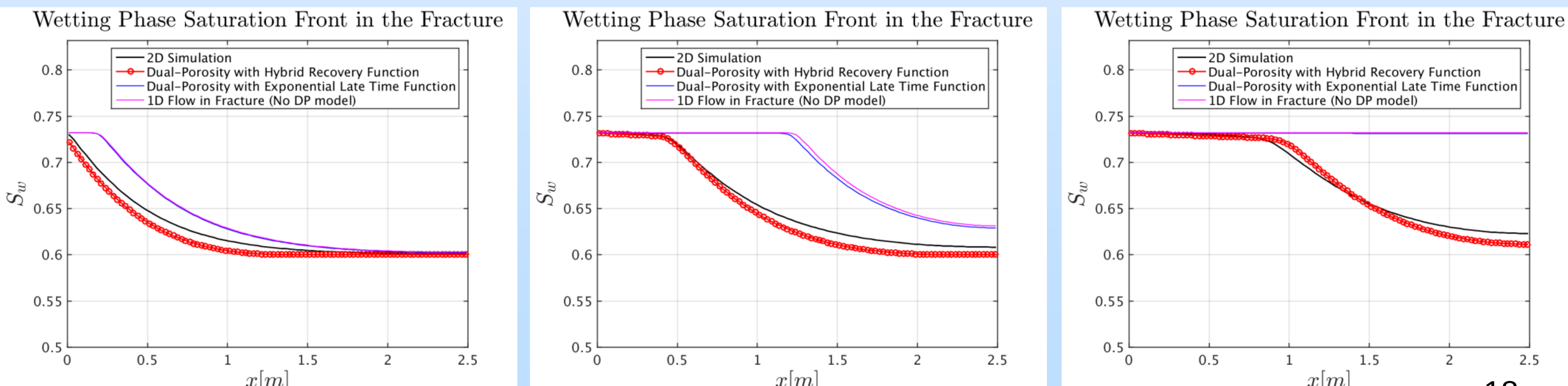


POST INJECTION PHASE

Brine imbibition hybrid model

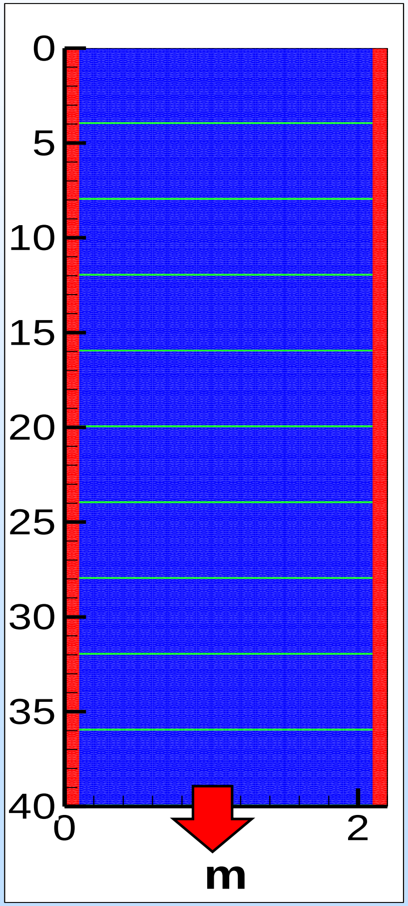
Time



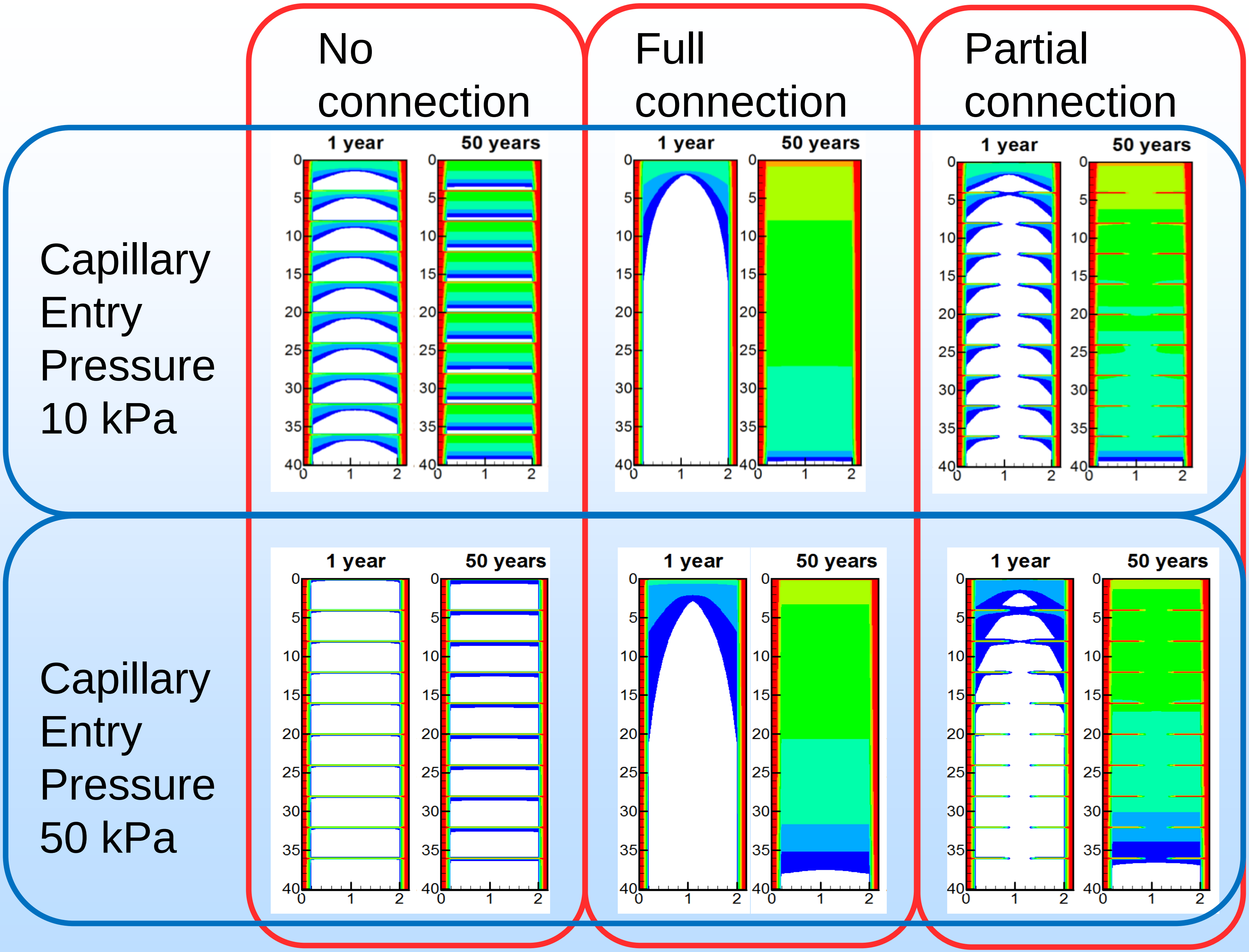


SENSITIVITY ANALYSIS

Vertical block connectivity



- 10 matrix blocks (3.9 m×2 m) and 11 fractures (1 mm)
- Fixed gas pressure + saturation from 2 side fractures
- Three matrix block connectivities:
  - Fully-separated matrix blocks (sugar cubes)
  - No horizontal fractures (match sticks)
  - Partial connectivity (mix of the two above)

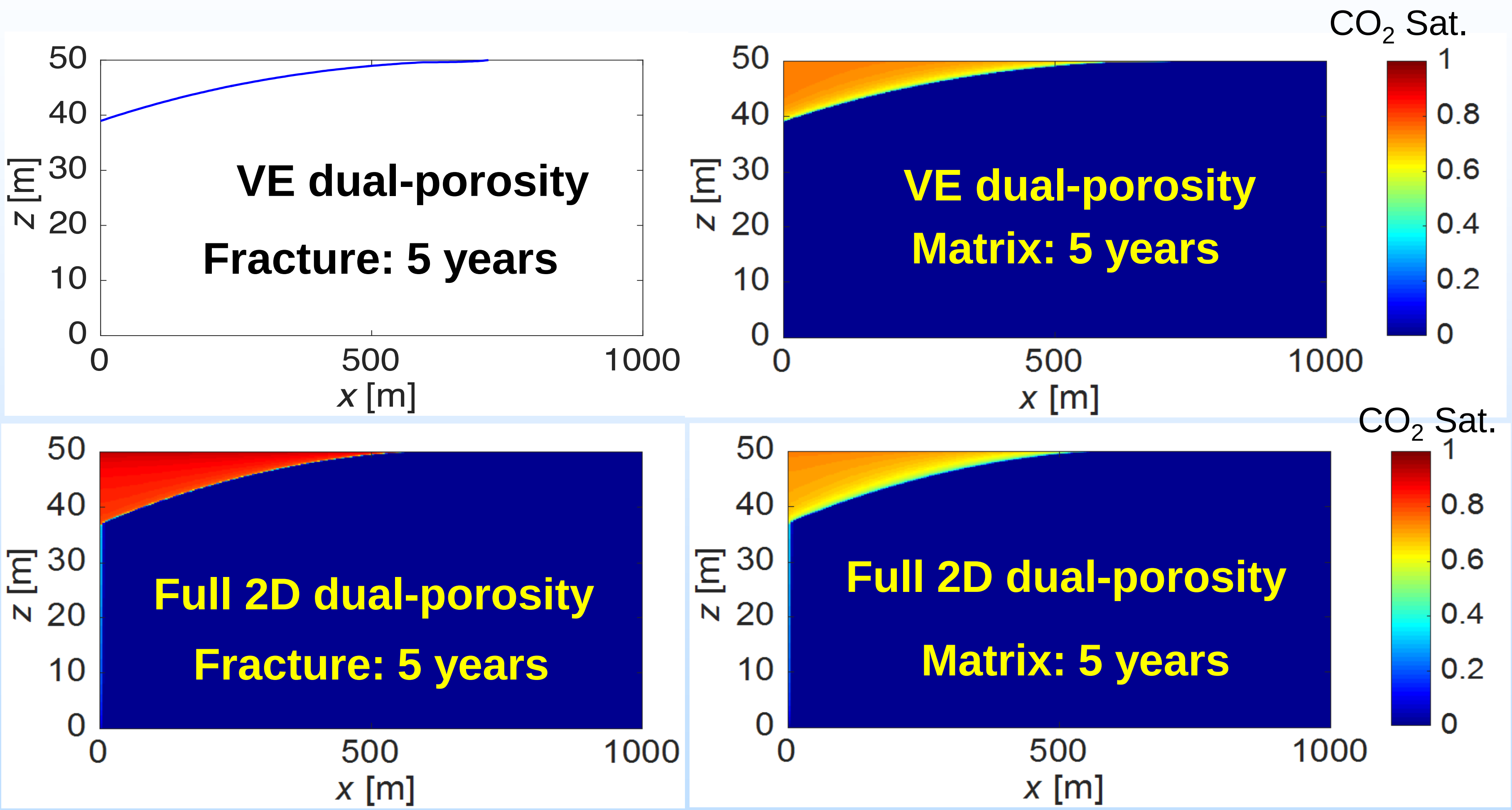

No connection
Full connection
Partial connection
Capillary Entry Pressure 10 kPa
Capillary Entry Pressure 50 kPa
1 year
50 years

VERTICALLY-INTEGRATED APPROACH

Vertically integrated model

- Vertical segregation is fast in the fractures
- Two approaches:
  - Dual-porosity with vertical equilibrium in fractures
  - Dual-permeability with vertical equilibrium in fractures and dynamic reconstruction in matrix

VI dual-porosity model



Conclusions

- Hybrid transfer functions for both initial invasion of CO_2 into matrix and later displacement by brine without tuning parameters
- Matrix block connectivity is important for storage behavior of fractured reservoirs
- CO_2 and brine migration in fractured reservoirs can be modeled using a vertically-integrated approach

Accomplishments to Date

- Development of hybrid transfer function for dual-porosity model for both spontaneous imbibition and gravity drainage
- Implemented and validated single- and two-phase dual-porosity modules and a hysteresis module for MRST
- Updated TOUGH2/ECO2N simulator for better performance for CO_2 storage in fractured media simulations

Accomplishments to Date

- Investigated the impact of matrix block connectivity on CO_2 storage capacity
- Developed analytic solutions for CO_2 storage due to diffusion of dissolved CO_2
- Developed and implemented a vertically-integrated dual-porosity model
- Investigated development of vertically-integrated dual-permeability model

Synergy Opportunities

- The modeling approaches developed in this project should be useful to other projects studying carbon sequestration in fractured formations

Future Plans

- Implement the new transfer functions into TOUGH2, MRST and vertically-integrated simulator
- Continue development of vertically-integrated dual-porosity and dual-permeability models
- Continue to investigate the impact of fracture and matrix block parameters on CO_2 storage capacity
- Apply newly developed modeling approaches to In Salah site

THANK YOU!

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Appendix

Organization Chart

- **Project PI**
  Prof. M. Celia
  (Princeton)
  - **Project co-PI**
    Dr. K. Bandilla
    (Princeton)
  - **Project co-PI**
    Prof. S. Geiger
    (Heriot-Watt)
  - **Project co-PI**
    Dr. F. Doster
    (Heriot-Watt)
  - **Project co-PI**
    Dr. Q. Zhou
    (LBNL)
    - **Development of Vertically-Integrated Fractured Reservoir Simulator**
      Prof. M. Celia
      Dr. K. Bandilla
      (Princeton)
    - **DFM Simulations & MR-DBDP Development**
      Prof. S. Geiger
      Dr. F. Doster
      (Heriot-Watt)
      - **DFM Simulations of MR-DBDP into MRST**
        Prof. S. Geiger
        Dr. F. Doster
        (Heriot-Watt)
    - **Implementation of MR-DBDP into TOUGH2**
      Dr. Q. Zhou
      (LBNL)
      - **Model Application and Sensitivity Analysis**
        Dr. Q. Zhou
        Dr. J. Birkholzer
        (LBNL)

Gantt Chart

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

Fiscal Year	BP 1				BP 2						BP 3	
Quarter	1	2	3	4	1	2	3	4	5	6	3	4
Task 1: Project Management, Planning and Reporting												
Subtask 1.1: Updated Project Management Plan	MS											
Subtask 1.2: Project Planning and Reporting	MS											
Task 2.0: Detailed DFM modeling of CO2 and brine				MS								
Task 3.0: Development of MR-DBDP model with analytic transfer function						MS						
Task 4.0: Development of new simulator capabilities												
Subtask 4.1: Development of vertically integrated simulator					MS					MS		
Subtask 4.2: incorporate new MR-DBDP into MRST simulator												MS
Subtask 4.3: incorporate new MR-DBDP into TOUGH2									MS			
Task 5.0: Model demonstration and sensitivity analysis												
Subtask 5.1: Investigation of driving forces												
Subtask 5.2: Sensitivity Analysis								MS				
Subtask 5.3: Storage and trapping in heterogeneous reservoir										MS		
Subtask 5.4: Investigation of injection scenarios												
Task 6.0: Simulator application to In Salah												
Subtask 6.1: Site-specific model development										MS		
Subtask 6.2: Migration and Trapping modeling										MS		1
Subtask 6.3: Sensitivity analysis												MS

Bibliography 1

- Bandilla, K.W. (2015). Multiscale Modeling of Carbon Dioxide (CO_2) Migration and Trapping in Fractured Reservoirs with Validation by Model Comparison and Real-Site Applications. Presented at the Carbon Storage R&D Project Review Meeting in Pittsburgh, Pa (8/18-8/20/15).
- Doster, F. (2015). Multi-scale multi-physics modelling of multi-phase flow phenomena in porous media. Presented at the Non-linearities and Upscaling in Porous Media (NUPUS) Conference in Freudenstadt, Germany (9/8 – 9/12/2015).

Bibliography 2

- March, R. (2015). Analytical Solutions and Numerical Models for Early- and Late-time Imbibition in Fractured Reservoirs. Presented at the Foundation CMG Summit in Calgary, Canada (9/15 - 9/16/2015).
- March, R. (2015). Analytical Solutions and Numerical Models for Early- and Late-time Imbibition in Fractured Reservoirs. Presented at the Challenges and Advancement in Reactive Flow and Carbonate Reservoir Simulation workshop at Heriot-Watt University.

Bibliography 3

- March, R. (2015). Imbibition in multiple continuum representations of fractured porous media: Early and late time behavior. Presented at the 2015 American Geophysical Union Fall Meeting in San Francisco, CA (12/14-12/18/2015).
- Zhou, Q. (2015). A Hybrid Continuum-Discrete Scheme for Simulating CO_2 Migration and Trapping in Fractured Sandstone Reservoirs. Presented at the 2015 American Geophysical Union Fall Meeting in San Francisco, CA (12/14-12/18/2015).

Bibliography 4

- Doster, F. (2015). Full Pressure Coupling for Geo-mechanical Multi-phase Multi-component Flow Simulations. Presented at the Scottish Carbon Capture and Storage conference in Edinburgh, Scotland (10/28/2015).
- March, R. (2015). Modelling CO_2-Storage in Fractured Porous Media: Early and Late Time Behaviour during Imbibition in Dual-Continua Representations. Presented at the Scottish Carbon Capture and Storage conference in Edinburgh, Scotland (10/28/2015).

Bibliography 5

- March, R. (2016). Geological Storage of CO_2, Fractured Reservoirs and much more…. Presented at Penn State University in State College, PA (4/20/2016).
- March, R. (2016). Group Meeting Princeton. Presented at Princeton University in Princeton, NJ (5/6/2016).
- March, R. (2016). Modelling and Simulation of Geological Storage of CO_2 in fractured formations. Presented at the Institute of Petroleum Engineering Workshop in Edinburgh, UK (6/28/2016).

Bibliography 6

- March, R., F. Doster, and S. Geiger (2016). Accurate early and late time modelling of counter-current spontaneous imbibition, *Water Resources Research,* accepted 14 July 2016, DOI: 10.1002/2015WR018456.
- March, R., F. Doster, and S. Geiger (2016). Assessment of Fractured Reservoirs as Potential Candidates for CO_2 Storage. In preparation.
- March, R., F. Doster, and S. Geiger (2016). Modelling of Buoyancy-Driven Transfer duration CO_2 Storage in Fractured Formations. In preparation.