# Multiscale Modeling of Carbon Dioxide ($CO_2$) Migration and Trapping in Fractured Reservoirs with Validation by Model Comparison and Real-Site Applications

## Project Number DE-FE0023323

Karl W. Bandilla

Princeton University

U.S. Department of Energy

National Energy Technology Laboratory

DE-FOA0001037 Kickoff Meeting

November 12-13, 2014

# Presentation Outline

- Benefit to the Program
- Project Overview
- Expected Outcomes
- Organization / Communication
- Tasks / Milestones
- Schedule
- Summary

# Benefit to the Program

## DOE Storage Program goals being addressed:

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

## Project benefits statement:

The project will conduct research under Area of Interest 2, Fractured Reservoir and Seal Behavior, by developing new capabilities for carbon sequestration modeling in fractured reservoirs through improvements in the representation of fracture-matrix flow interactions. This improved representation will increase the accuracy of $CO_2$ and brine migration modeling in fractured reservoirs, allowing for better predictions of the $CO_2$ distribution within the storage reservoir.

# **Project Overview**: Goals and Objectives

## Overall goal:

to develop new modeling capabilities for simulation of $CO_2$ and brine migration in fractured reservoirs by developing more accurate descriptions of flow interactions between fractures and the rock matrix

## Main objectives:

(1) Develop new model for interactions of fracture and matrix flow

(2) Incorporate new model into reservoir-scale simulator

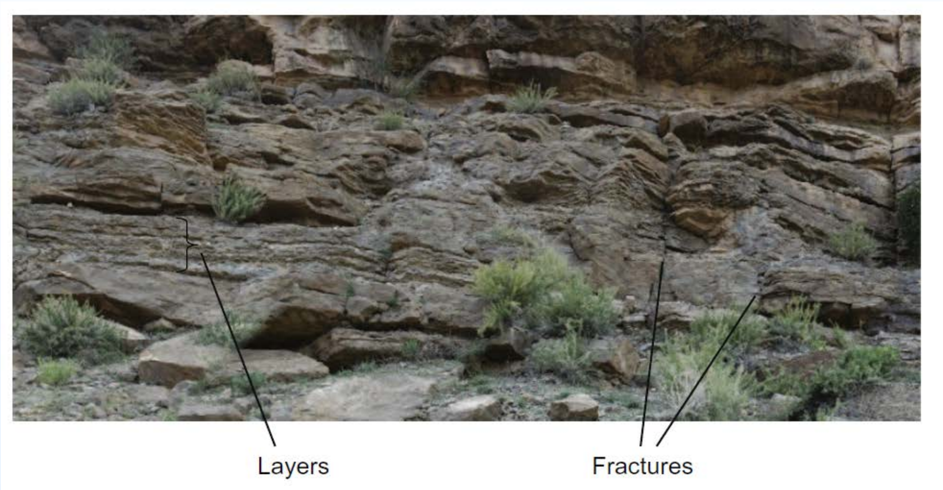
(3) Conduct sensitivity analyses of trapping efficiency and storage capacity using new model

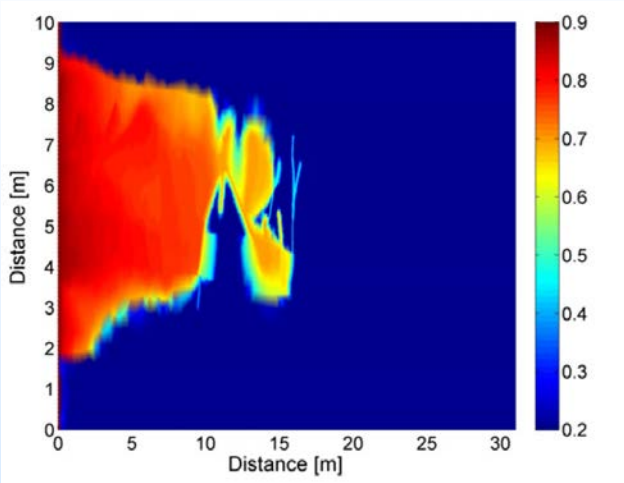
(4) Apply new model to In Salah site

# Objective 1

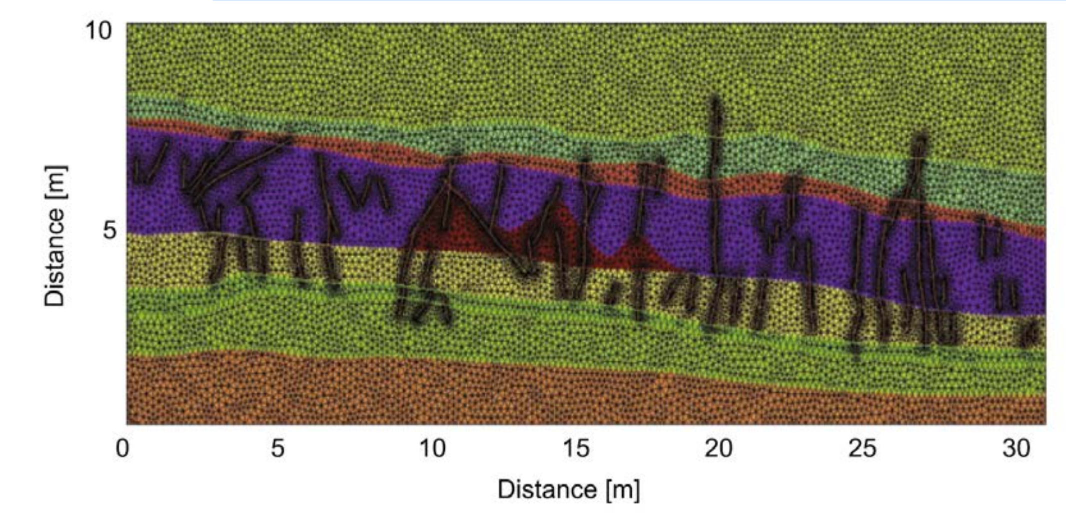
To study the small-scale interactions between fracture and matrix flow using a three-dimensional Discrete Fracture and Matrix modeling approach, and use the results to develop a new version of the Multi-Rate - Dual-Block Dual-Porosity (MR-DBDP) Model.

# Objective 1: methodology (1)



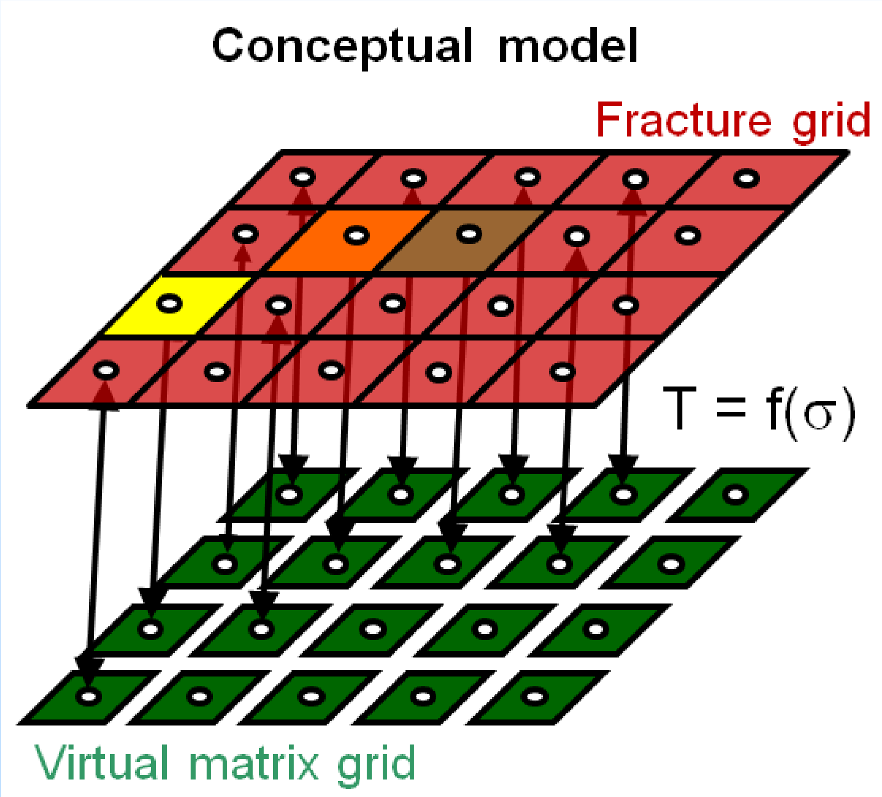




Discrete Fracture Model



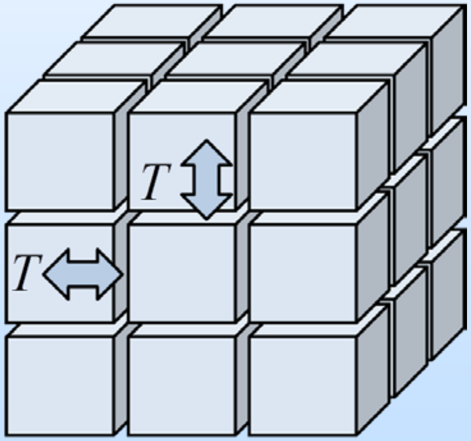
# Objective 1: methodology (2)

Dual Porosity Model

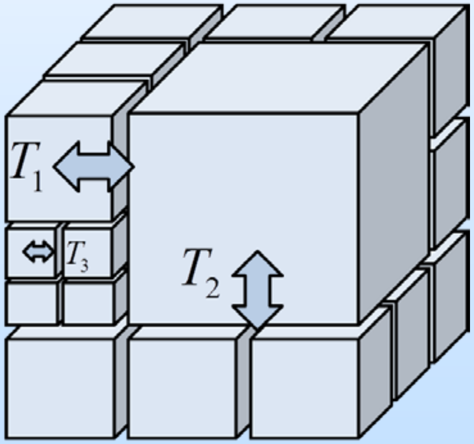


# Objective 1: methodology (3)

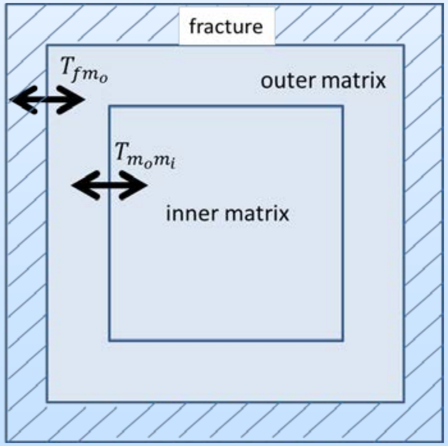
Dual-Porosity Model



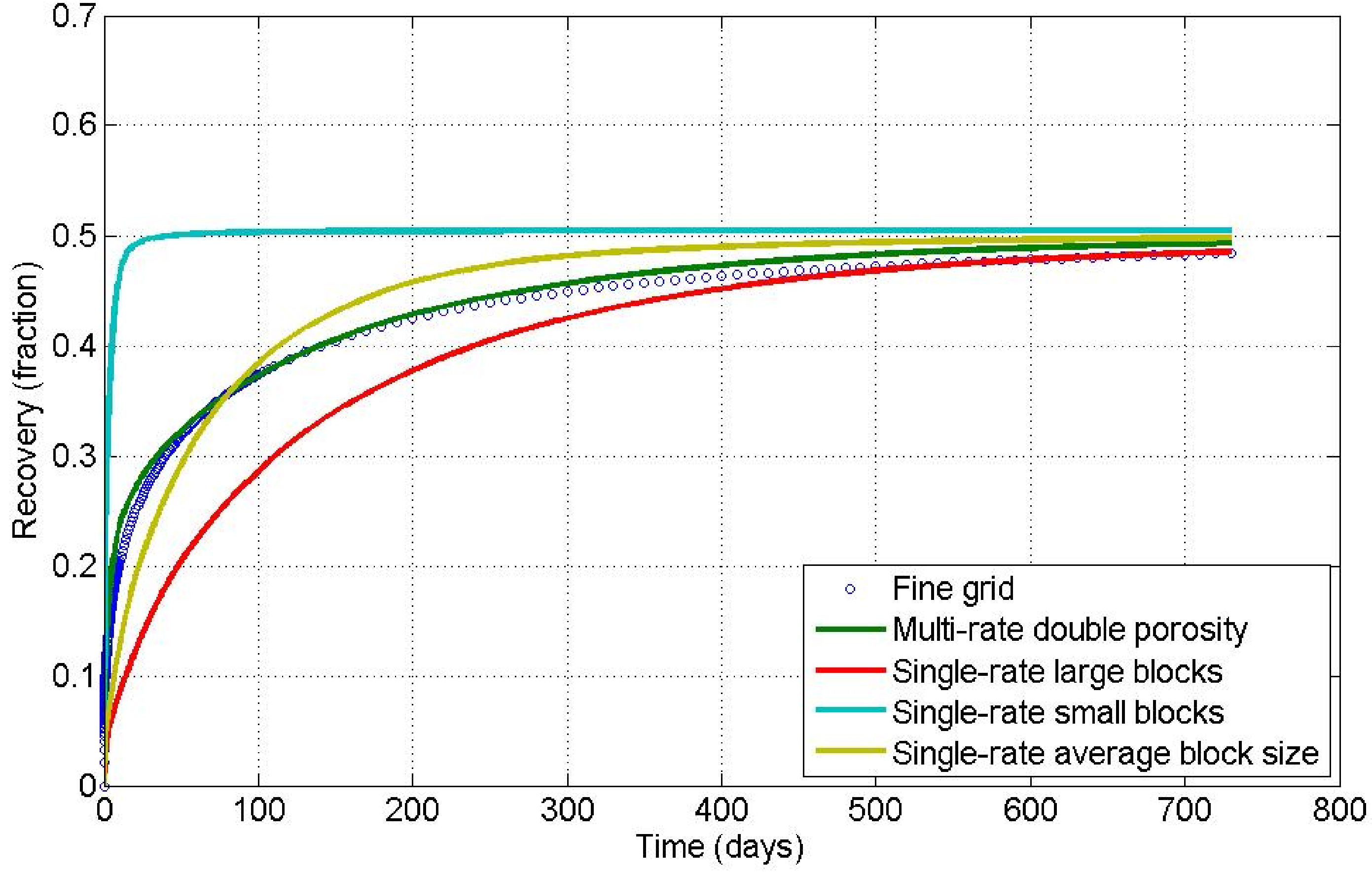

Multi-Rate Dual-Porosity Model




Multi-Rate Dual-Block Dual-Porosity Model



# Objective 1: methodology (4)



# Objective 1: success criteria

- Does the DFM model produce sufficient results to describe the fracture-matrix transfer?

  *Compile catalog of flow profiles over a wide range of expected conditions.*

- Can a MR-DBDP model sufficiently represent fracture-matrix flow interactions?

  *Show that the new model can accurately model the range of flow conditions modeled by the DFM model*

# Objective 2

To incorporate the new Multi-Rate - Dual-Block Dual-Porosity (MR-DBDP) Model into the existing reservoir simulators TOUGH2 and MRST, and to develop a new vertically integrated modeling approach for fractured reservoirs that includes the MR-DBDP formulation.

# Objective 2: methodology (1)

TOUGH2:

- Widely used simulator for carbon sequestration modeling
- Already has dual-porosity capabilities

MRST (MATLAB Reservoir Simulation Toolkit):

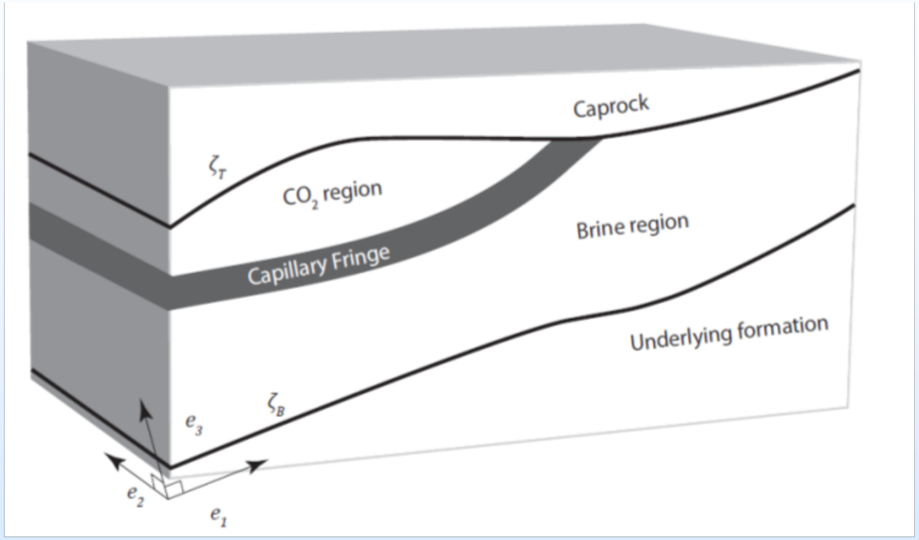
- Open-source simulator
- Dual-porosity capabilities will be added as part of this project

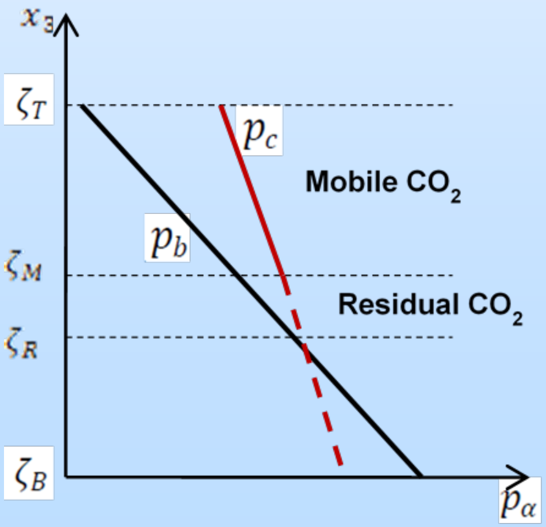
# Objective 2: methodology (2)

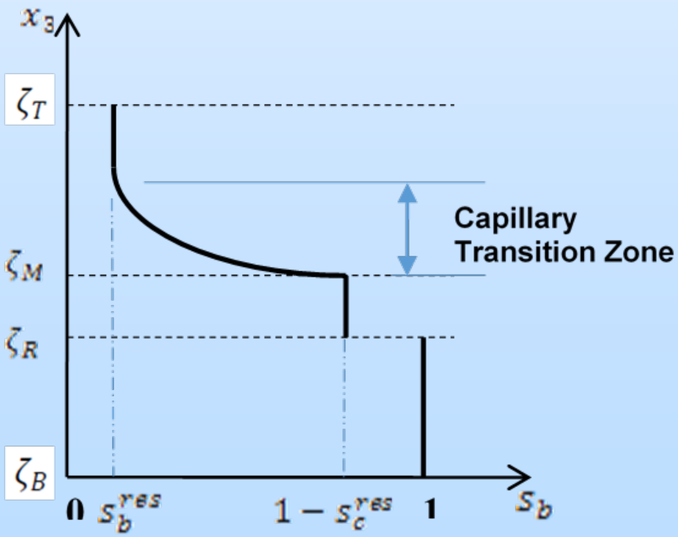
VESA (Vertical Equilibrium with Sub-scale Analytics):

- Numerical vertically-integrated simulator
- Dual-porosity capabilities will be added as part of this project

# Objective 2: methodology (3)



# Objective 2: methodology (4)

- Main assumption: fractures at vertical equilibrium, while matrix is not at equilibrium.
- Dynamic reconstruction of pressure and saturation in the rock matrix.
- Horizontal fluxes between fractures and matrix will be vertically integrated.

# Objective 2: success criteria

- Can a dual-porosity approach be implemented in a vertical integration framework?

  *Demonstrate both the algorithm and actual computations, compare to existing dual-porosity simulator.*

- Is the structure of TOUGH2 amenable for implementation of the MR-DBDP model?

  *Demonstrate the implementation of MR-DBDP in TOUGH2 and show modeling results.*

# Objective 2: success criteria

- Can the structure of MRST be adapted for implementation of the MR-DBDP model?

  *Demonstrate the implementation of MR-DBDP into MRST and show modeling results.*

# Objective 3

To investigate $CO_2$ storage capacity and trapping efficiency in site-scale fractured reservoirs with various sensitivity analyses using the newly developed models.

# Objective 3: methodology

- Investigation of different driving forces of fracture-matrix exchange.
- Analysis of sensitivity of storage capacity and trapping efficiency to reservoir geometry and other parameters.
- Assessment of storage and trapping efficiency in a heterogeneous reservoir
- Investigation of impact of injection scenarios on trapping efficiency.

# Objective 4

To apply one or more of the newly developed models to predict the $CO_2$ migration and trapping at the In Salah storage site and to conduct sensitivity analysis of fracture-matrix interactions and compare the simulation results with monitoring data.

# Objective 4: methodology

- Construct a numerical model of the vicinity of well KB-501 using historic injection data.
- Model $CO_2$ injection using one or more of the newly developed simulators with fracture-matrix interaction.
- Investigate uncertainty at In Salah by conducting sensitivity analysis by varying fracture-matrix shape factors.

# Objective 4: success criteria

- Are sufficient data available to construct a geologic model of the In Salah injection, and to represent the injection history? Are there enough monitoring data to validate our new simulators?

  *Compile a list of available data for In Salah injection site, and compare to data needs of simulators and to simulator prediction capabilities.*

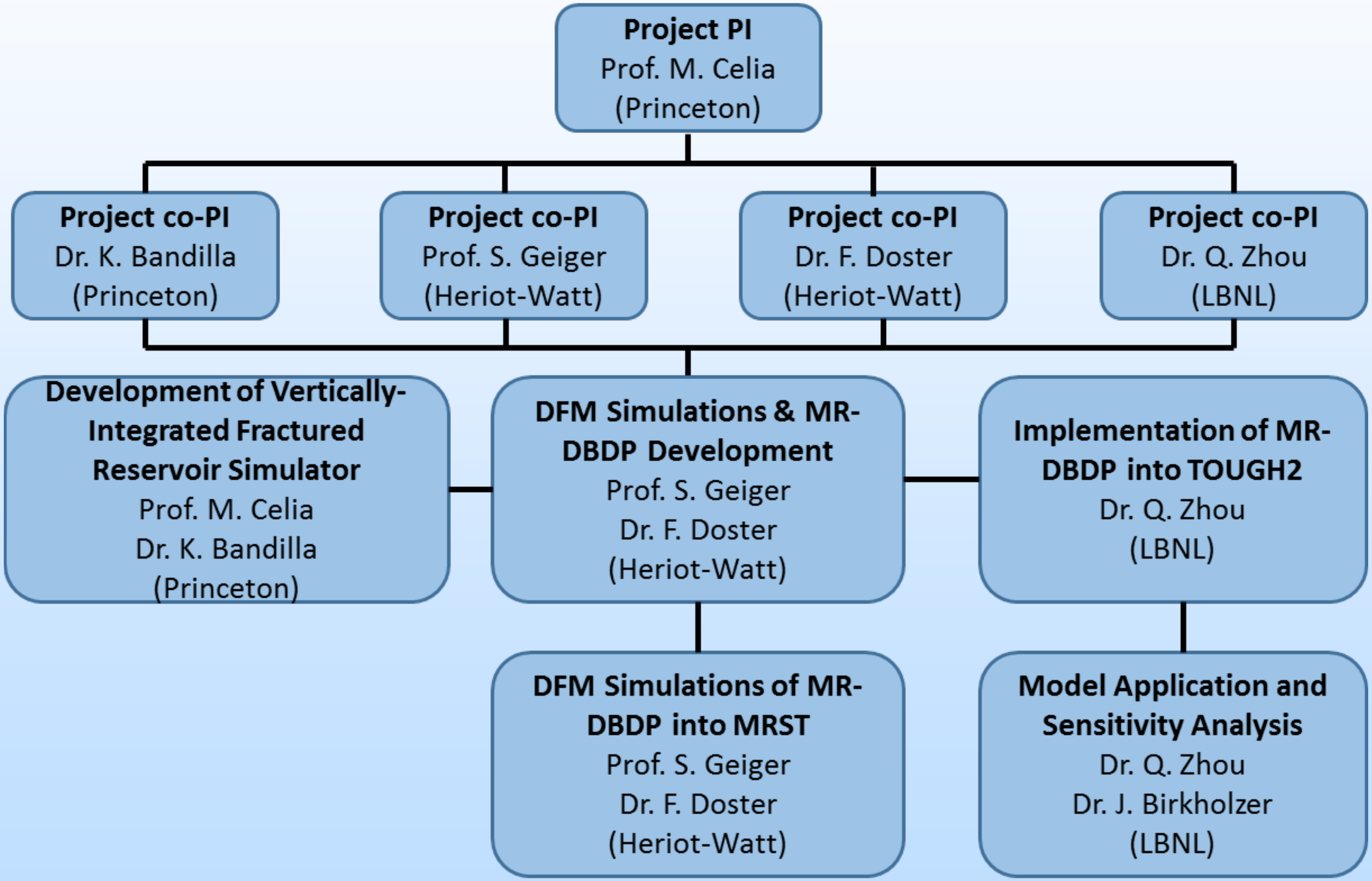
# Expected Outcomes (1)

- Development of a new MR-DBDP Model with an Analytical Transfer Function to Capture the Essential Fracture-Matrix Flow Transfer Processes during $CO_2$ Injection.
- Development of a vertically-integrated dual-porosity model.

# Expected Outcomes (2)

- Application of new modeling approach to the In Salah site and validation using monitoring data.
- Implementation of the MR-DBDP model into the vertically-integrated dual-porosity model and the two existing reservoir simulators TOUGH2 and MRST.

# Organization Chart



# Communication Plan

- The research is divided between three institutions:
  - Princeton University
  - Heriot-Watt University
  - Lawrence Berkeley National Lab
- Team members will communicate through regular phone conferences and at scientific meetings such as the AGU Fall Meeting.

# Task/Subtask Breakdown (1)

- Task 1.0 - Project Management, Planning and Reporting
  - Subtask 1.1 - Project Management Plan
  - Subtask 1.2 - Project Planning and Reporting
- Task 2.0 – Model Multiphase $CO_2$ Brine Flow Using a DFM Model for a Variety of Conditions
- Task 3.0 – Development of a new MR-DBDP Model with an Analytical Transfer Function to Capture the Essential Fracture-Matrix Flow Transfer Processes during $CO_2$ Injection

# Task/Subtask Breakdown (2)

- Task 4.0 – Development of a New Simplified Simulator including the new MR-DBDP Model, and Incorporation of the MR-DBDP Model into the Existing Reservoir Simulators MRST and TOUGH2
  - Subtask 4.1 – Develop New Simulator Incorporating Fracture-Matrix Transfer Behavior into a Vertically-Integrated Framework
  - Subtask 4.2 – Implementation of the MR-DBDP model into the OpenSource simulator MRST and performance of a series of proof-of-concept simulations
  - Subtask 4.3 – Implementation of the MR-DBDP Model into TOUGH2

# Task/Subtask Breakdown (3)

- Task 5.0 – Model Demonstration and Sensitivity Analysis for Large-Scale Fractured Reservoirs to Assess $CO_2$ Storage Capacity and Trapping Efficiency
  - Subtask 5.1 – Simulation of an Idealized Large-Scale Homogeneous Fractured Reservoir: Investigation of Driving Forces for Fracture-Matrix Interactions
  - Subtask 5.2 - Sensitivity Analysis of Reservoir Geometry and Properties: Storage and Trapping Efficiency Assessment
  - Subtask 5.3 - Assessment of Storage and Trapping Efficiency in Heterogeneous Fractured Reservoir
  - Subtask 5.4 - Improvement of $CO_2$ Trapping Efficiency via Optimal Injection Scenarios

# Task/Subtask Breakdown (4)

- Task 6.0 – Application of the VESA, TOUGH2-MR-DBDP and/or MRST-MR-DBDP Models to the In Salah $CO_2$ Storage Site
  - Subtask 6.1 - Site-Specific Model Development: the Base Case with the Historic Injection Scenario
  - Subtask 6.2 - Modeling $CO_2$ Migration and Trapping for the Base Case
  - Subtask 6.3 - Sensitivity Analysis of Different Fracture-Matrix Interaction Scenarios and Comparison with Monitoring Data

# Decision Points (1)

| Decision Point | Success Criteria |
| --- | --- |
| Does the DFM model produce sufficient results to describe the fracture-matrix transfer? | Compile catalog of flow profiles over a wide range of expected conditions. |
| Can a MR-DBDP model sufficiently represent fracture-matrix flow interactions? | Show that the new model can accurately model the range flow conditions modeled by the DFM model |
| Can a dual-porosity approach be implemented in a vertical integration framework? | Demonstrate both the algorithm and actual computations, compare to existing dual-porosity simulator. |

# Decision Points (2)

| Decision Point | Success Criteria |
|---|---|
| Is the structure of TOUGH2 amenable for implementation of the MR-DBDP model? | Demonstrate the implementation of MR-DBDP in TOUGH2 and show modeling results. |
| Can the structure of MRST be adapted for implementation of the MR-DBDP model? | Demonstrate the implementation of MR-DBDP into MRST and show modeling results. |
| Are sufficient data available to construct a geologic model of the In Salah injection, and to represent the injection history? Are there enough monitoring data to validate our new simulators? | Compile a list of available data for In Salah injection site, and compare to data needs of simulators and to simulator prediction capabilities. |

# Milestones (1)

| Task/ Subtask | Milestone Title | Planned Completion Date | Verification method |
|---|---|---|---|
| 1.0 | Project Management Plan | 31/10/14 | PMP file |
| 1.0 | Kickoff meeting | 12/31/2014 | Presentation file |
| 2.0 | Initial results from DFM modeling study | 9/30/2015 | Quarterly progress report describing modeling conditions |
| 3.0 | Development of new MR-DBDP model for $CO_2$ injection modeling | 3/31/2016 | Quarterly progress report giving details of the new MR-DBDP model |

# Milestones (2)

| Task/ Subtask | Milestone Title | Planned Completion Date | Verification method |
|---|---|---|---|
| 4.1 | Development and initial results for vertically-integrated dual-porosity model | 12/31/2015 | Quarterly progress report describing the vertically-integrated algorithm and showing initial modeling results |
| 4.1 | Development and initial results for vertically-integrated MR-DBDP model | 3/31/2017 | Quarterly progress report detailing the implementation of the MR-DBDP model into the vertically-integrated model |

# Milestones (3)

| Task/ Subtask | Milestone Title | Planned Completion Date | Verification method |
| --- | --- | --- | --- |
| 4.2 | Implementation of MR-DBDP model in an OpenSource simulator | 9/30/17 | Quarterly progress report describing the implementation of MR-DBDP into existing OpenSource simulator |
| 4.3 | Implementation of MR-DBDP model in TOUGH2 | 3/31/16 | Quarterly progress report describing the implementation of MR-DBDP into TOUGH2 simulator |

# Milestones (4)

| Task/ Sub-task | Milestone Title | Planned Completion Date | Verification method |
|---|---|---|---|
| 5.2 | Large-Scale Reservoir Simulation: Driving Force Modeling and Sensitivity Analysis of Storage Capacity and Trapping Efficiency | 6/30/16 | Quarterly progress report describing the initial results from modeling and sensitivity analysis |
| 5.3 | Assessment and Enhancement of Storage and Trapping Efficiency in Heterogeneous Fractured Reservoirs | 12/31/16 | Quarterly progress report describing the geologic model and the injection scenarios |

# Milestones (5)

| Task/ Sub-task | Milestone Title | Planned Completion Date | Verification method |
|---|---|---|---|
| 6.1, 6.2 | Site-Specific Model Development and Modeling $CO_2$ Migration and Trapping for the Base Case at In Salah | 3/31/17 | Quarterly progress report describing the In Salah geologic model and initial results |
| 6.3 | Sensitivity Analysis of Fracture-Matrix Interaction Scenarios and Comparison with Monitoring Data for In Salah Site | 9/30/17 | Quarterly progress report describing initial results of sensitivity analysis and comparison to monitoring data |

# Risk Matrix

- Inability to develop new fracture-matrix transfer model for $CO_2$

  *Risk is considered low, due the experience of Prof. Geiger's research group in developing such models*

- Availability of In Salah data

  *Risk is considered low, as most data are already available to members of the project team through other projects*

# Proposed Schedule (1)

| Fiscal Year | BP 1 | | | | BP 2 | | | | BP 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quarter | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Task 1: Project Management, Planning and Reporting | | | | | | | | | | | | |
| Subtask 1.1: Updated Project Management Plan | MS | | | | | | | | | | | |
| Subtask 1.2: Kickoff Meeting | 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 | | | | | | |

# Proposed Schedule (2)

| Fiscal Year | BP 1 | | | | BP 2 | | | | BP 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quarter | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 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 | | |
| Subtask 6.3: Sensitivity analysis | | | | | | | | | | | | MS |

# Summary

Overall goal is to develop new modeling capabilities for simulation of $CO_2$ and brine migration in fractured reservoirs by developing more accurate descriptions of flow interactions between fractures and the rock matrix.