# Geological Carbon Sequestration

## A Viable Option for Mitigating the Greenhouse Effect

**Dongxiao Zhang**
**College of Engineering, Peking University, Beijing**

**Pingping Shen**
**Research Institute of Petroleum Exploration and Development, PetroChina, Beijing**

- Part I: General discussion on geological carbon sequestration, in particular, as a measure for enhancing oil recovery (EOR)

- Part II: Pore-scale studies pertinent to some fundamental issues associated with geological carbon sequestration

# Carbon Emissions

- The Intergovernmental Panel on Climate Change (IPCC 1995) predicted that for the business as usual energy scenario:
  - Global emissions of $CO_2$ to the atmosphere will increase from the current level of **7.4 to ~26 GtC/year** by 2100
  - => doubling of CO2 conc. in the atm. by 2050

- Although the effects of increased $CO_2$ and other greenhouse gases levels are still under debate
  - Scientific consensus: A significant increase of atmosphere $CO_2$ concentrations could have serious environmental consequences

    => ***The Greenhouse Effect*** !
  - National and international concern is rising
- There is therefore a need for reduction in carbon emissions to reach atmospheric stabilization

# Carbon Sequestration is a MUST

- **Fossil fuels will remain the primary energy source well into this century**
- **Natural sinks are going down because of deforestation and change in agriculture patterns**

**Desired**

$$\textit{Net C} = (C/E) * (E/GDP) * GDP - \textit{Sinks}$$

**Present**

- **Energy efficiency improvements are not enough to offset the increased energy demand**
- **As developing countries' economies expand, worldwide energy consumption will continue its rapid growth**

# The Situation in China

**China's fossil fuel accounts for 92.6% of the total energy, consisting of:**

- **Coal 67.1%**
- **Oil 22.7%**
- **Natural gas 2.8%**

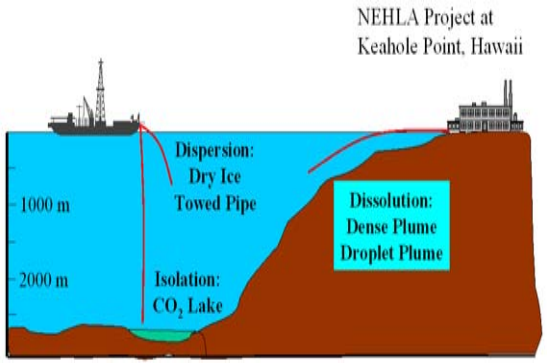
# The Situation in China

- China's $CO_2$ release: the 2nd place, accounting for 13% of the world's amount
- In 2020, China is predicted to be the first largest $CO_2$-emitting country

| Country | $CO_2$ emission (Millions of tons) |
|---|---|
| USA | 4881 |
| China | 2668 |
| Russia | 2103 |
| Japan | 1093 |
| Germany | 878 |
| India | 769 |
| Ukraine | 611 |
| Britain | 566 |
| Canada | 410 |
| Italy | 408 |
| France | 362 |
| Poland | 342 |
| Mexico | 333 |
| Kazakhstan | 298 |
| South Africa | 290 |

# Carbon Sequestration Approaches

- Ocean **(>1400 Gt Est. Capacity)**
  - Direct injection
  - Enhancement of natural processes
  - Largest capacity, but least understood
- Terrestrial **(>10 Gt Est. Capacity)**
  - Crops & land management
  - Soil improvement
  - C-species selection
- Geologic **(>1000 Gt Est. Capacity)**
  - Oil & gas reservoirs
  - Deep saline aquifers
  - Unmineable coal beds

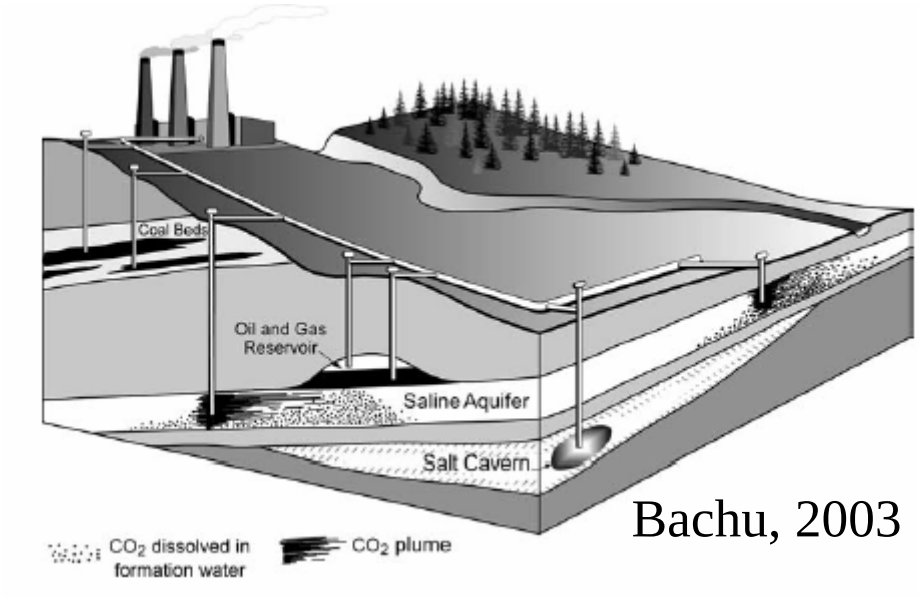


# Geological Sequestration Presents a Viable Option

- Past experience
  - Recent: Natural gas storage, groundwater remediation
  - Century-long: Oil/gas production, groundwater resources management
  - Geological time: Natural $CO_2$ reservoirs (e.g., Bravo Dome, NM)
- Economic benefits that offset the cost of sequestration
  - Enhanced oil recovery from oil reservoirs
  - Increased gas production from natural gas reservoirs
  - Enhanced methane production from coal beds
- Worldwide availability and in close proximity of geological media to $CO_2$ sources

# Geological Sequestration Mechanisms

- Hydrodynamic trapping
  - $CO_2$ trapped as supercritical fluid or gas under a low-permeability caprock
  - The most important mechanism, in the short term
- Solubility trapping
  - $CO_2$ dissolved in a liquid such as water and oil
  - Reduces the likelihood that $CO_2$ gas will quickly return to the atmosphere

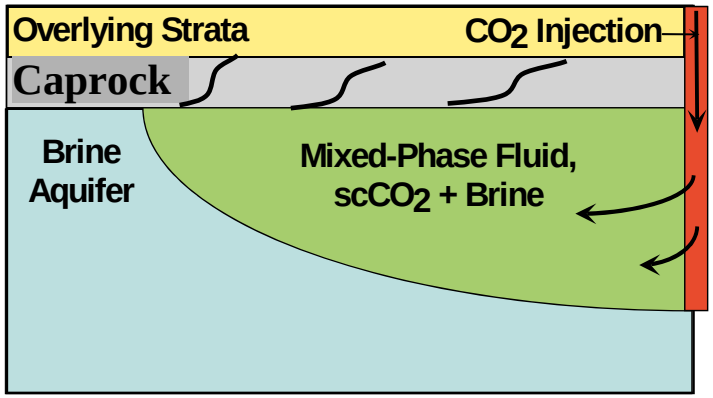


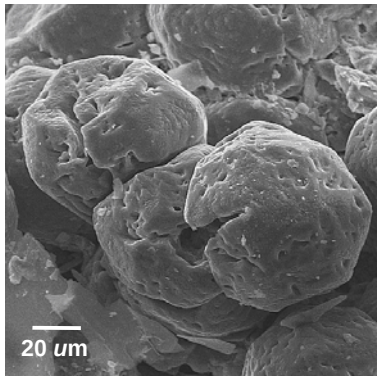

Bachu, 2003

- Mineral trapping
  - $CO_2$ can react with the minerals and organic matter in the formations
  - The most permanent solution: stable repositories
  - Slow process with poorly understood kinetics

# Geological Sequestration

- The science of geological sequestration is just starting
- R &D needs:
  - Accurate prediction of **coupled** hydrodynamic, geochemical, geomechanical, and geothermal **processes** involving $CO_2$-oil-water-rock
  - Performance assessment of **reservoir integrity** and long-term monitoring of leakage
  - Development of technologies for monitoring the migration and **fate of injected $CO_2$**
  - Evaluation of reservoir $CO_2$ **storage capacity** and property changes with long-term sequestration



# EOR Experiences

- In USA, about 190,000 barrels of oil per day are produced from more than 70 CO2 flooding operations.
- Most of these CO2 projects reside in the Permian Basin of West Texas and New Mexico, which produces 160,000 barrels of oil per day and accounts for almost 20% of the basin's total oil production.
- It is estimated that approximately 1/3 of CO2 injected in EOR activities will remain in the oil field permanently.
- CO2-EOR experiences indicate that CO2 flooding results in an average of 13% incremental oil recovery.

# EOR Potential with Gas Injection in CNPC

| Oilfield | | Reserve concerned($10^3$) | Recovery improved(%) | Recoverable reserve increased by($10^3$) |
|---|---|---|---|---|
| Liaohe | | 179,400 | 15.0 | 26,900 |
| Huabei | | 6,340 | 13.5 | 858 |
| Dagang | Miscible | 7,290 | 15.5 | 1,130 |
| | Immiscible | 2,580 | 9.7 | 250 |
| Jidong | | 6,620 | 15.3 | 1,010 |
| Xinjiang | | 80,900 | 27.8 | 22,500 |
| Tu-Ha | | 57,300 | 17.2 | 9,850 |
| Chang qing | Miscible | 6,080 | 17.9 | 1,090 |
| | Immiscible | 382,000 | 10.9 | 41,800 |
| Tarim | | 215,000 | 4.9 | 10,500 |
| Sum | | 943,510 | 15.9 | 115,888 |

# EOR Potential with Gas Injection in SinoPec

| Oilfield | | Reserve concerned($10^3$) | Recovery improved(%) | Recoverable reserve increased by($10^3$) |
|---|---|---|---|---|
| Zhong yuan | Miscible | 164,000 | 17.7 | 290,000 |
| | Immiscible | 102,000 | 8.0 | 8,180 |
| Jianghan | | 2,510 | 14.5 | 365 |
| Jiangsu | | 14,660 | 18.9 | 2,773 |
| Sum | | 283,170 | 12.8 | 40,318 |

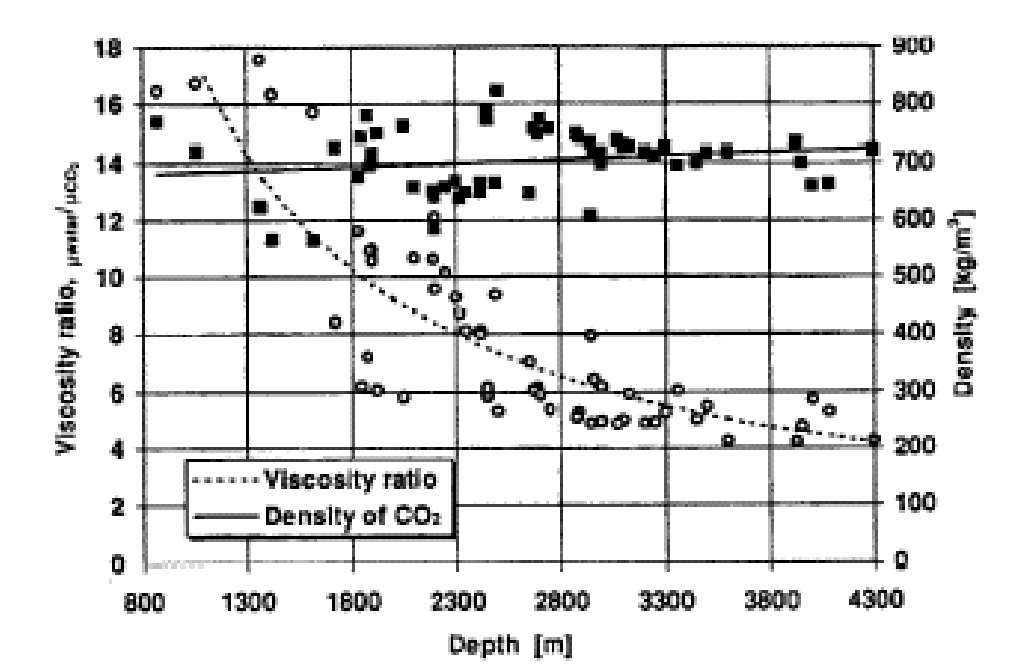
# CO2 flooding for Low-Permeable Reservoirs

- **China has a proved OOIP of low-permeable oilfields as 6.32 billion tons, 28.1% of the total proven OOIP**
- **Gas injection can increase low-permeable formation production energy, leading to improved recovery.**

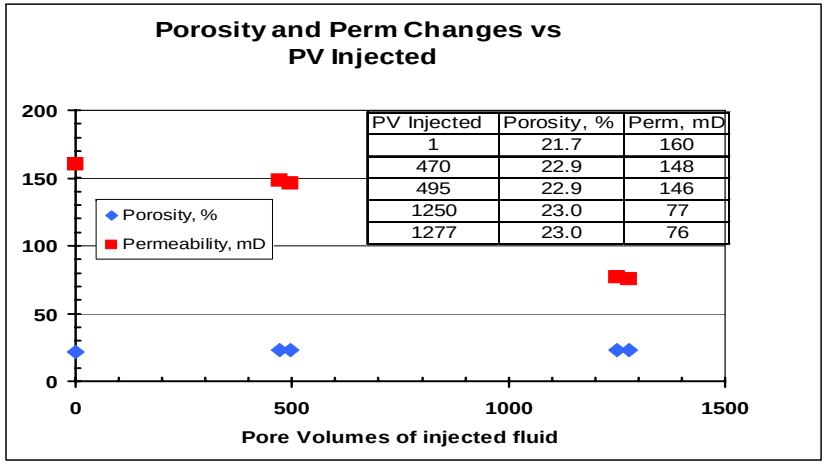
# Difference Between EOR and Seq.

- EOR minimizes the amount of $CO_2$ used while the goal of seq. is to store as much $CO_2$ as possible
- EOR is a short term process (of several years) while seq. is at the scale of 100s to 1000s years
- Long term performance assessment required for sequestration --- EOR has an industrial experience of 40 years (still a short time frame for seq.)
- Higher-confidence predictive and monitoring tools are needed for sequestration

- Part II: Pore-scale studies pertinent to some fundamental issues associated with geological carbon sequestration



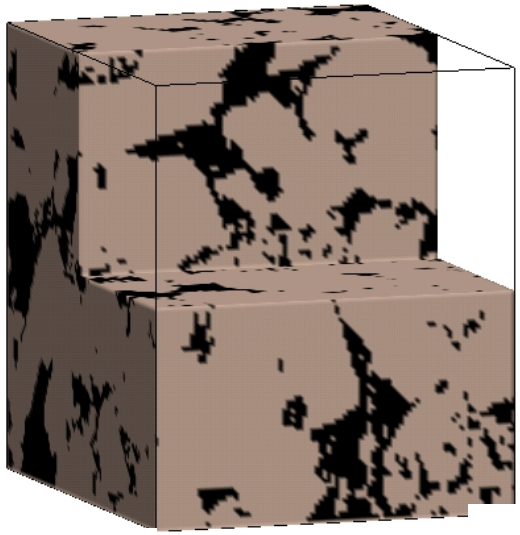

Lindeberg and van der Meer, 1996

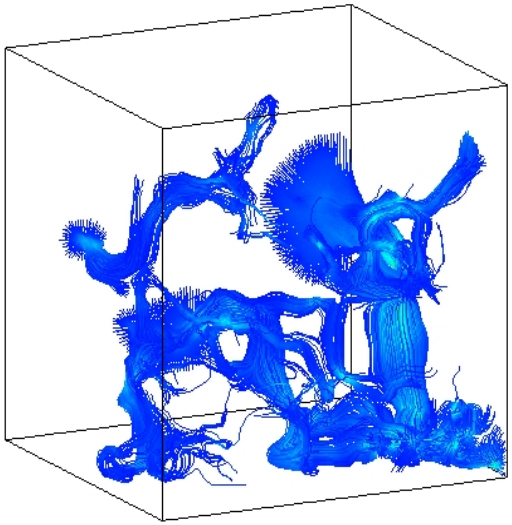


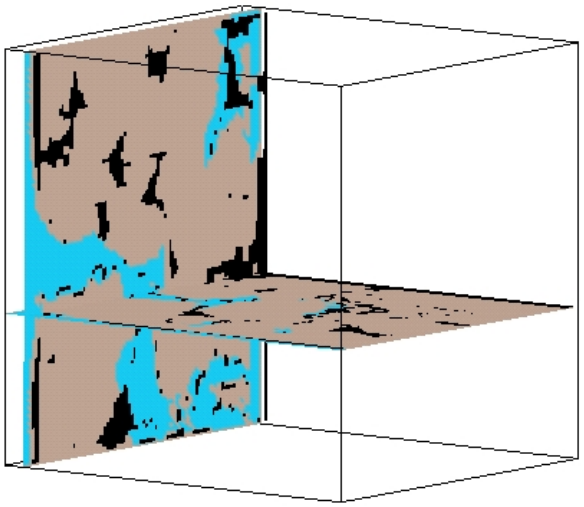

| PV Injected | Porosity, % | Perm, mD |
|---|---|---|
| 1 | 21.7 | 160 |
| 470 | 22.9 | 148 |
| 495 | 22.9 | 146 |
| 1250 | 23.0 | 77 |
| 1277 | 23.0 | 76 |

- Important phenomena for geol. carbon seq.
  - **Viscous fingering**
  - **Gravity segregation**
  - **Mineral dissolution/precipitation**

# Lattice Boltzmann Simulations

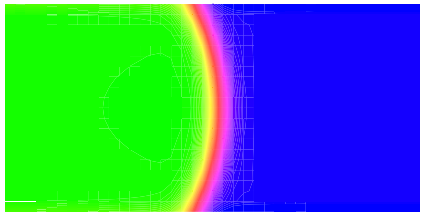




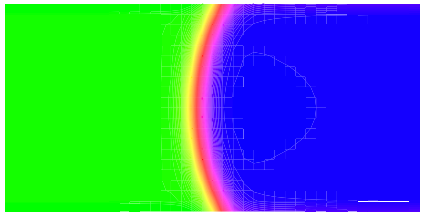


Zhang et al., GRL, 2000

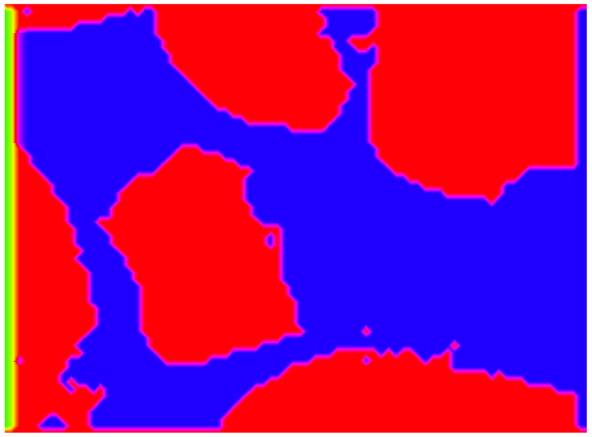
# Two-phase flow: effect of wettability

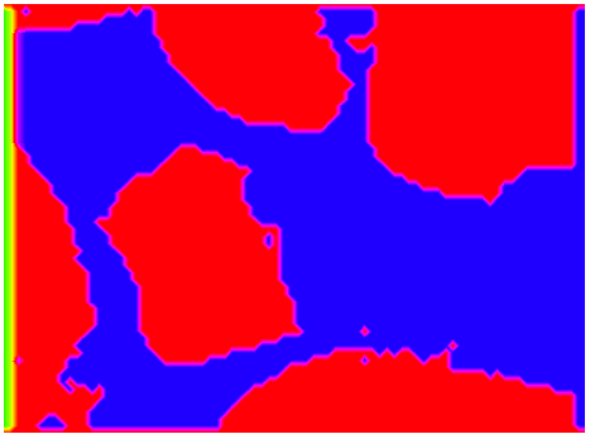


$\theta_1 = 105^\circ$



$\theta_1 = 75^\circ$





# Wormhole Formation

- Experimental result due to CO2 flooding for over one hundred of days

# *Lattice Boltzmann Simulations*

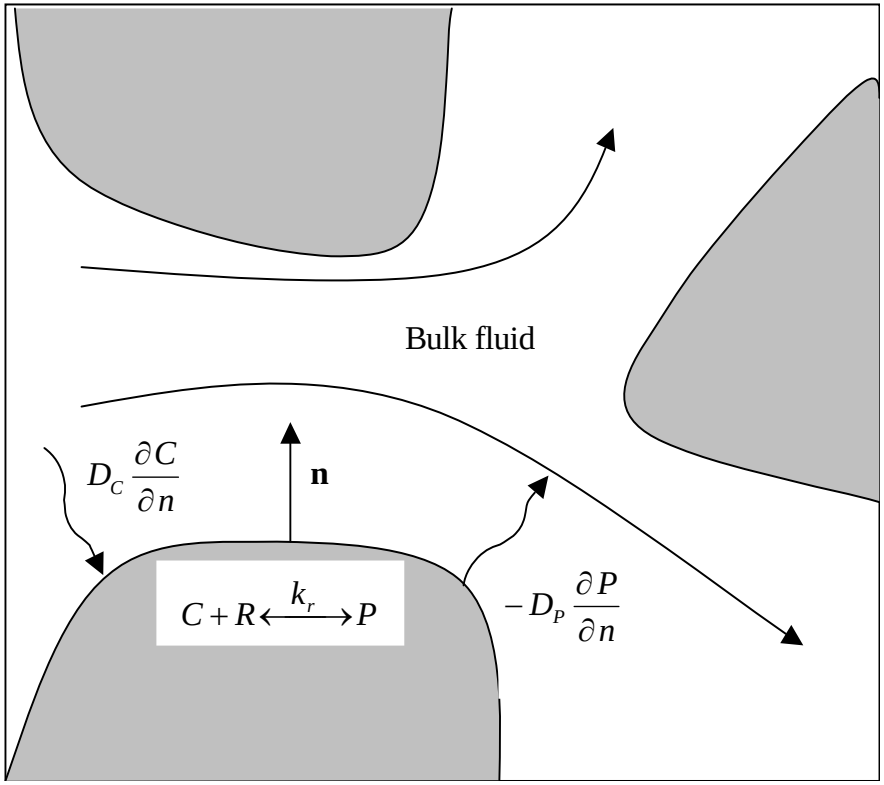
- **Coupled processes:**

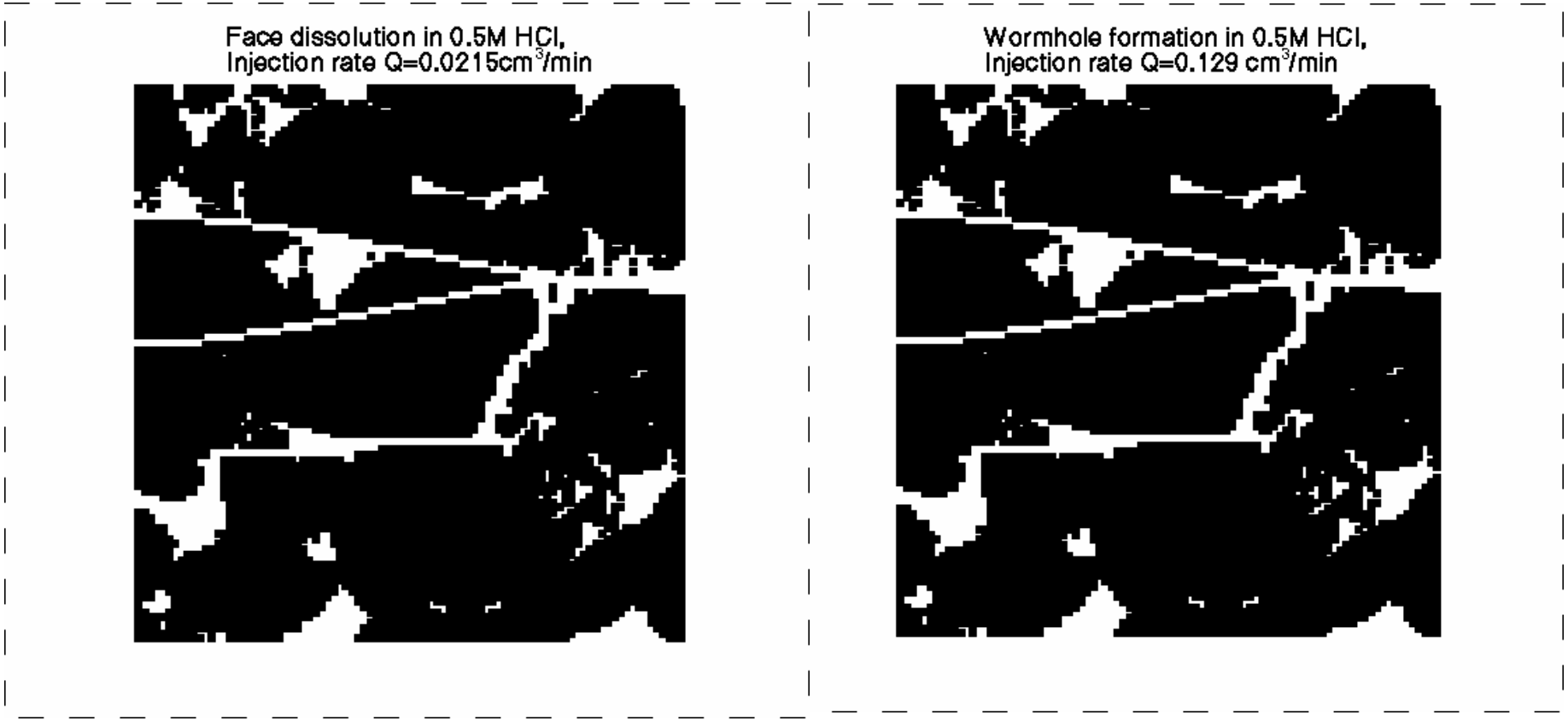
  Convection,

  Diffusion,

  Reaction

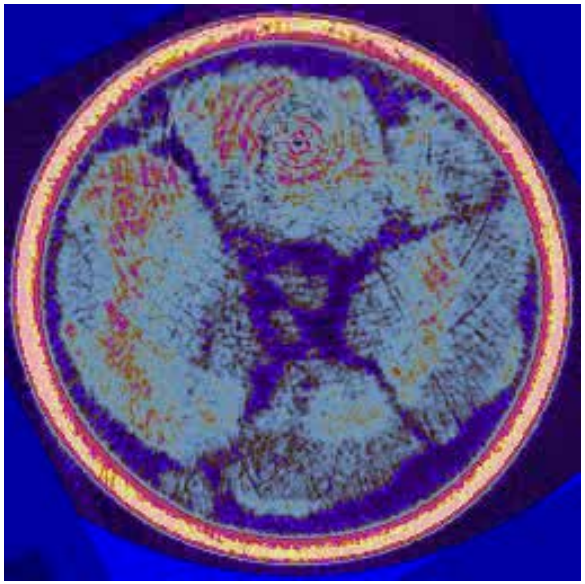
- **Resulting in dynamic evolution of pore geometries**






Kang, Zhang, & Chen, PRE, 2002

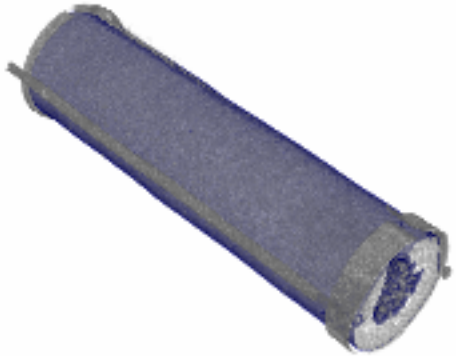
# Hybrid Multiscale Method



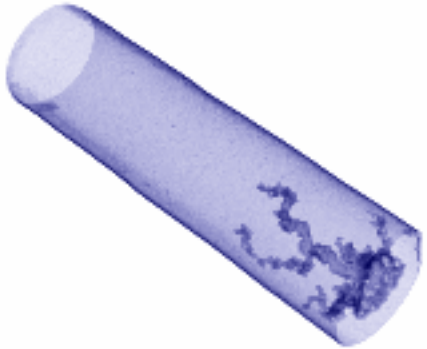
Neutron Tomography

- Innovative experiments: Needed for pinpointing the causes of the fundamental mechanisms
- A **hybrid** approach combining the **pore-scale and continuum methods**: Needed for simulating the formation of wormholes

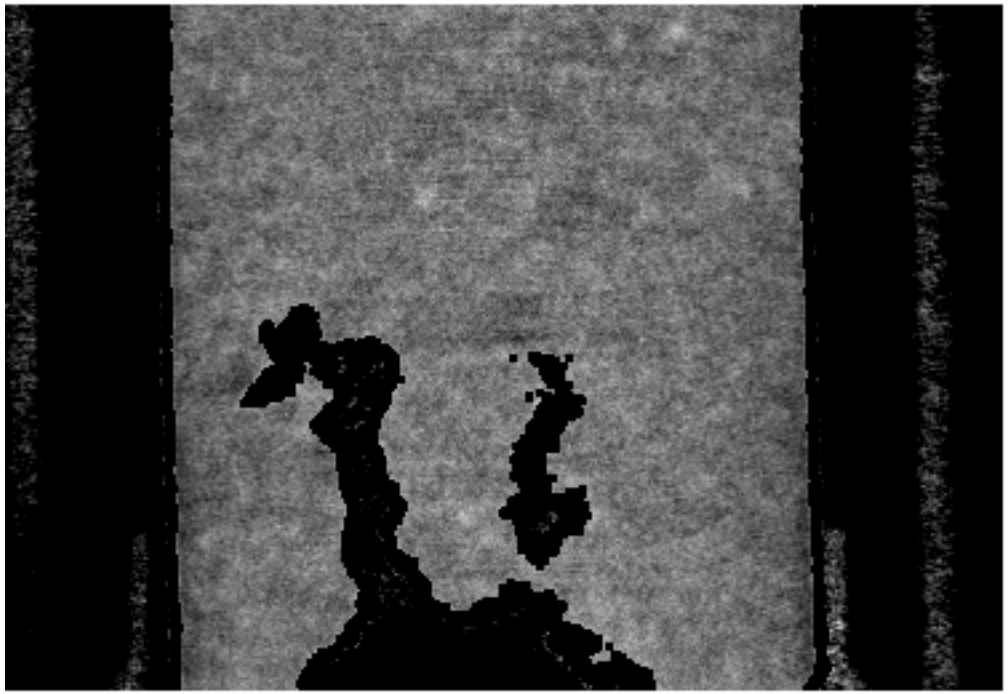
# Neutron Tomography of Limestone After Stage 1 Flooding



Outer Surface of Core



3-D Wormhole View



2-D Slice

# Conclusions (1)

- Geological sequestration presents an **immediate, low-cost** option for carbon management.
- Carbon sequestration is an important measure for sustaining fossil fuel based economy.
- In spite of past experiences, many fundamental R&D issues are outstanding:
  - Predictive models: Development, validation, and verification
  - Monitoring and verification technologies
  - Performance and risk assessment
  - Public awareness and acceptance

# Conclusions (2)

- CO2 injection into oil reservoirs is a viable option to reduce greenhouse gas emissions as well as to improve oil recovery.
- China has many oilfields, including low-permeable oilfields found in recent years, which are suitable for CO2 sequestration while improving oil recovery.
- Field pilot test studies of CO2 flooding are under planning.
- International cooperation is crucial.

*Putting carbon back*
*where it came from !!!*