

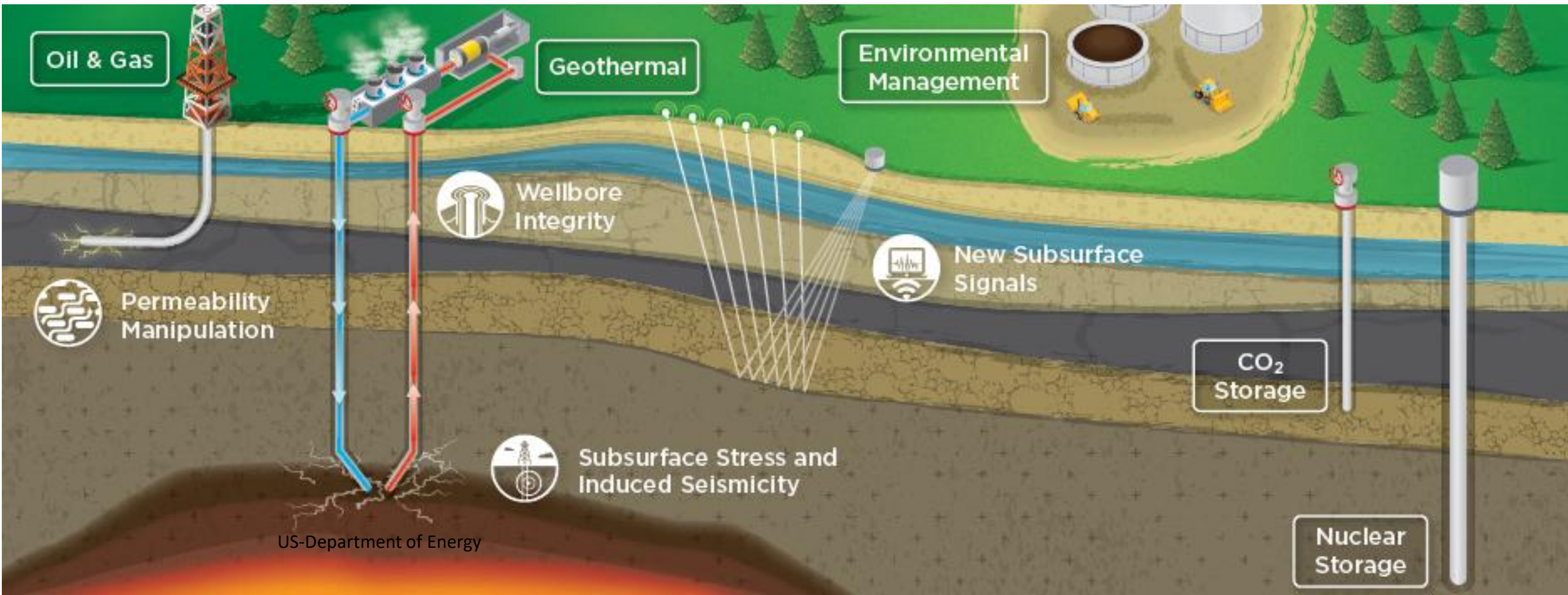
# Subsurface Energy Systems and Geologic CO<sub>2</sub> Storage

2025 Virtual Colloquium on Energy Transition, July 28-29, 2025

**USC Viterbi**  
School of Engineering

**Behnam Jafarpour, Professor**

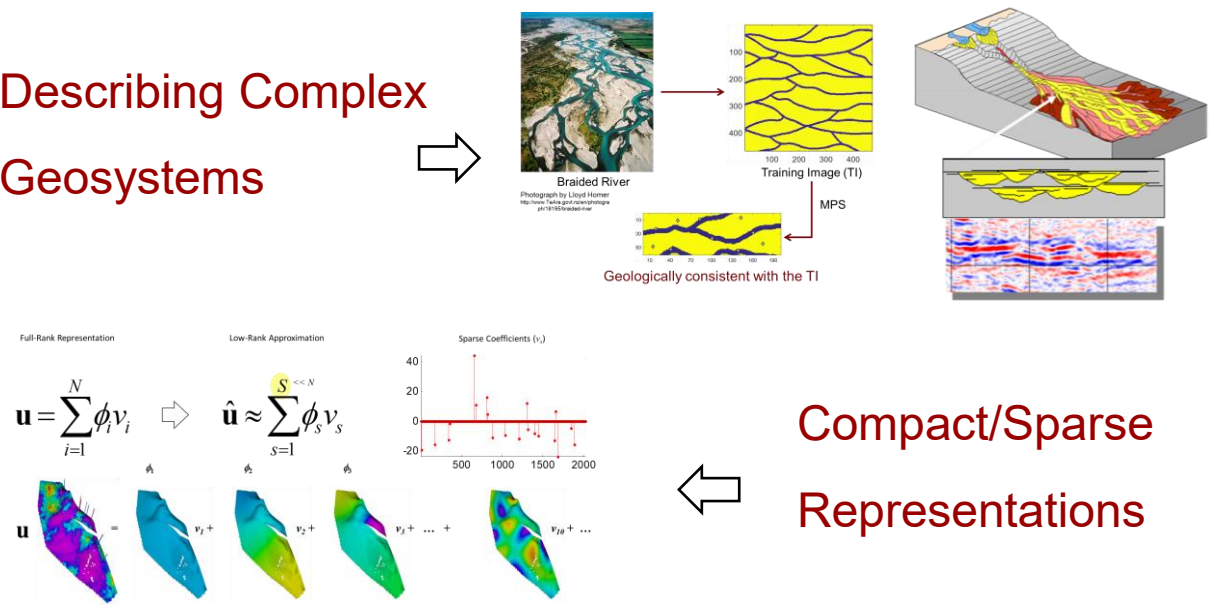
Chemical Engineering and Material Science, Electrical and Computer Engineering  
Civil and Environmental Engineering





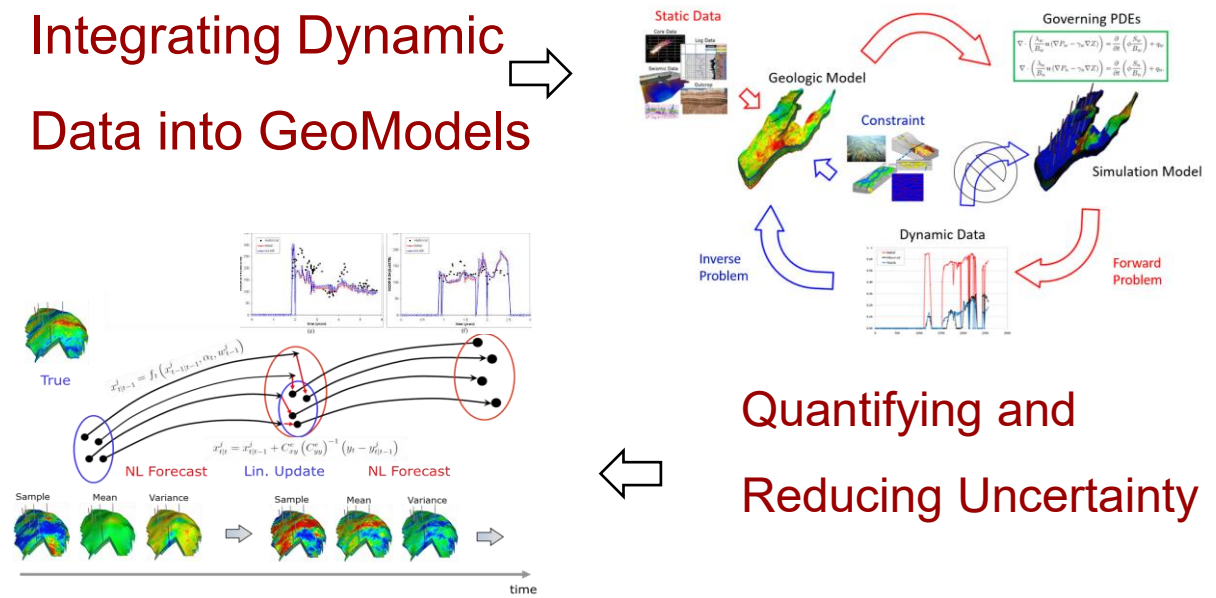
# (i) Description and Characterization of Complex Geosystems

## Describing Complex Geosystems



# (ii) Dynamic Model Updating and Uncertainty Quantification

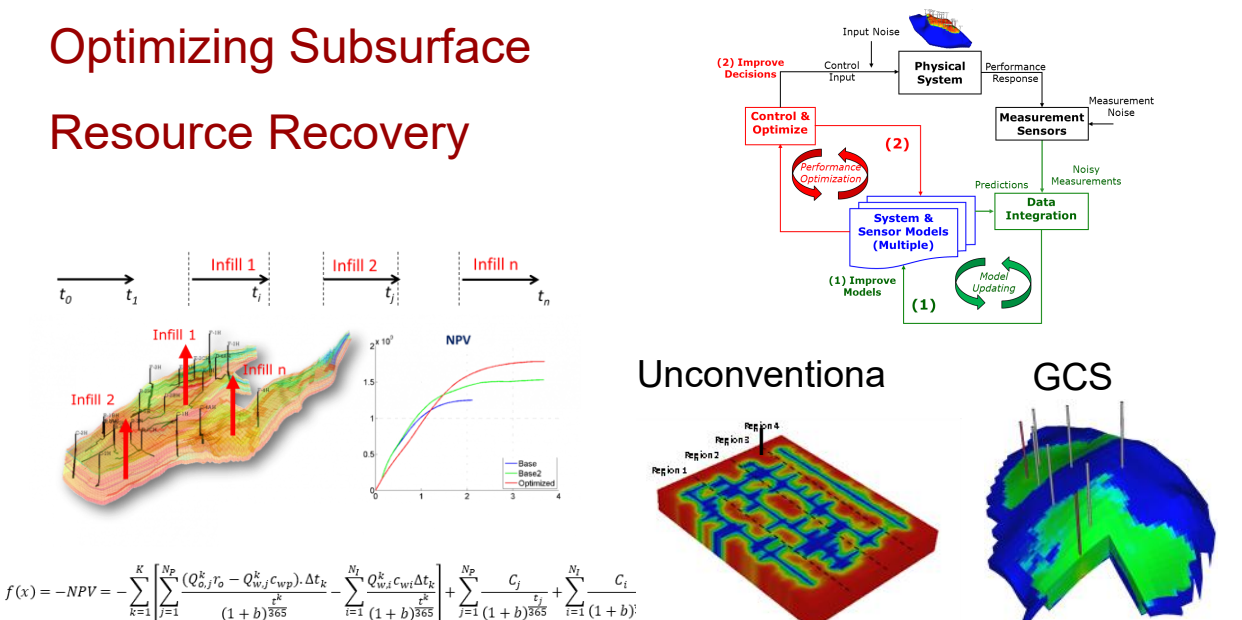
## Integrating Dynamic Data into GeoModels



## Quantifying and Reducing Uncertainty

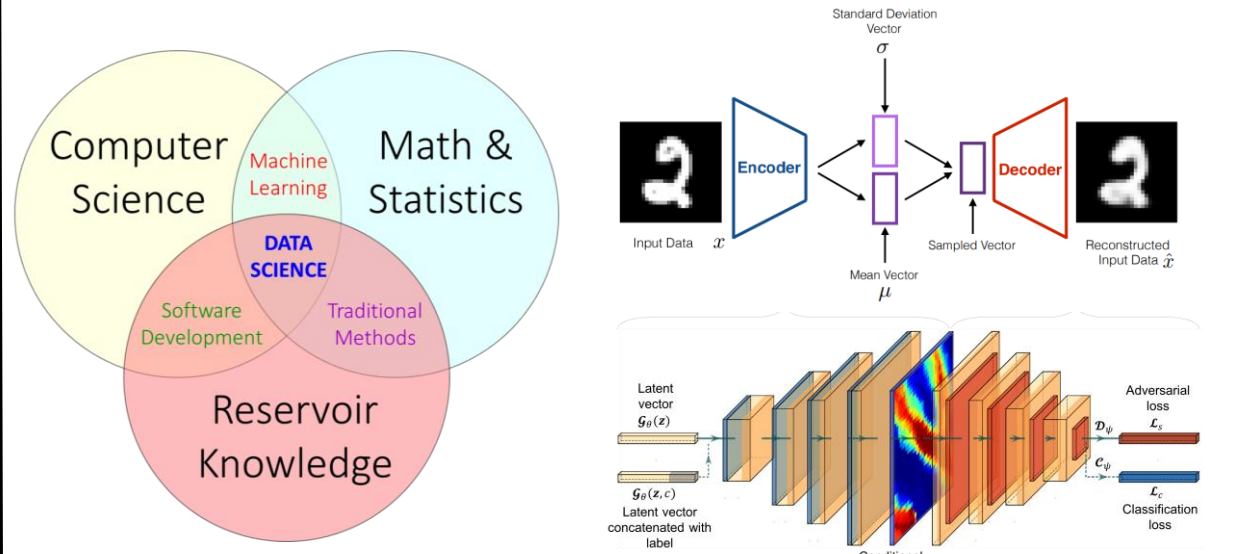
# (iii) Field Development Optimization

## Optimizing Subsurface Resource Recovery

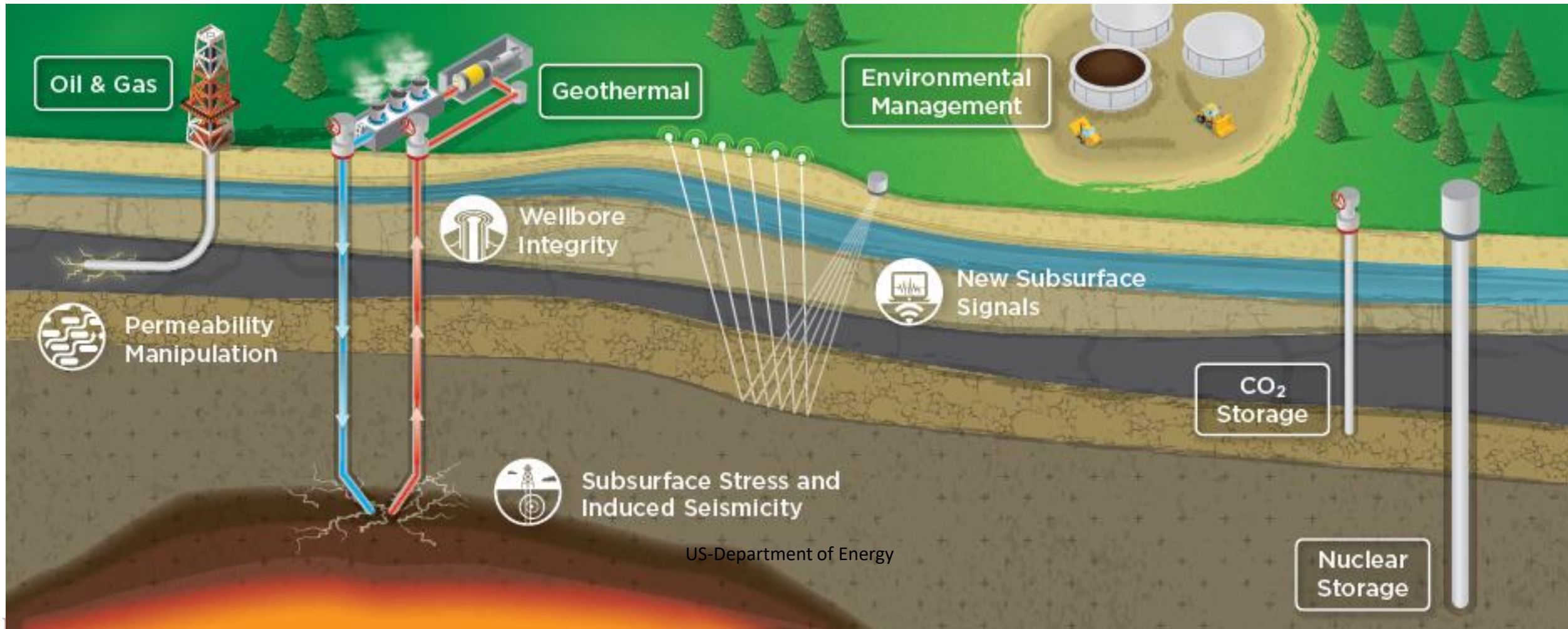


# (iv) Data Science for Prediction and Decision Support

## Machine Learning & Predictive Analytics



# The Subsurface Science, Technology and Engineering Research and Development (**SubTER**)



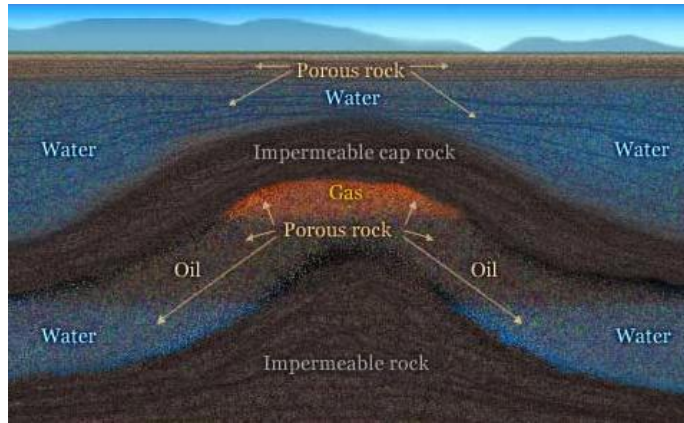
## US Department of Energy:

→ Energy sources originating from beneath the Earth's surface satisfy over 80% of total U.S. energy needs.

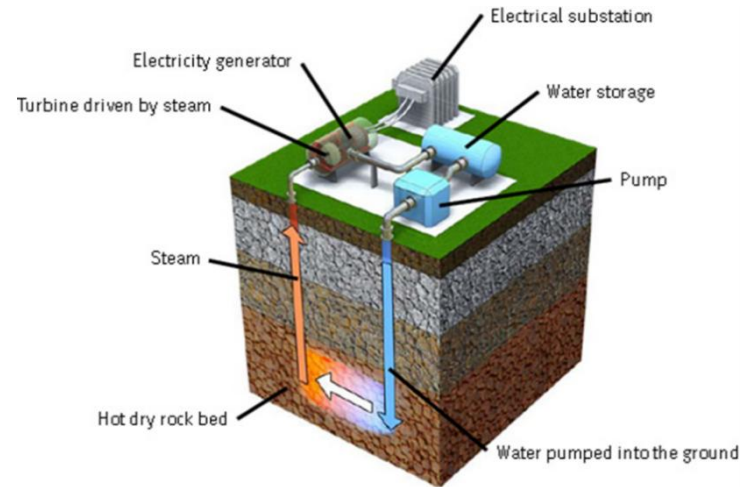
→ Finding and effectively utilizing these resources while mitigating impacts of their use constitute major technical and socio-political challenges and opportunities.

→ The DOE has an economic, safety, and energy security imperative to advance our understanding and effective use of the subsurface.

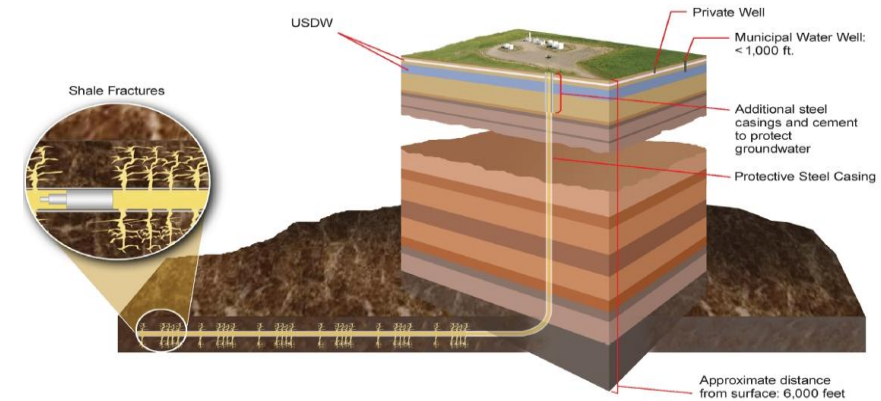
## Conventional Resources



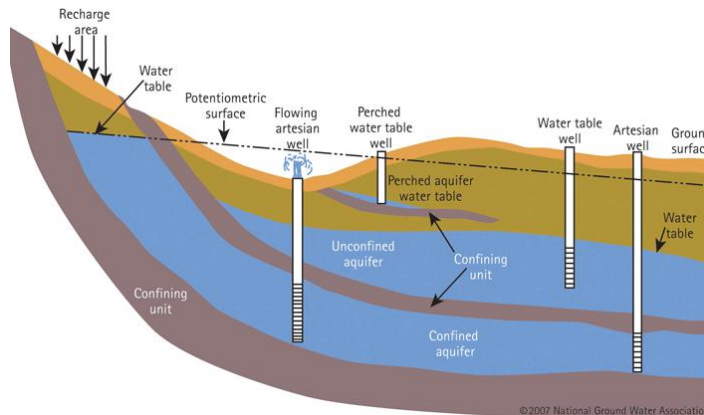
## Geothermal Resources



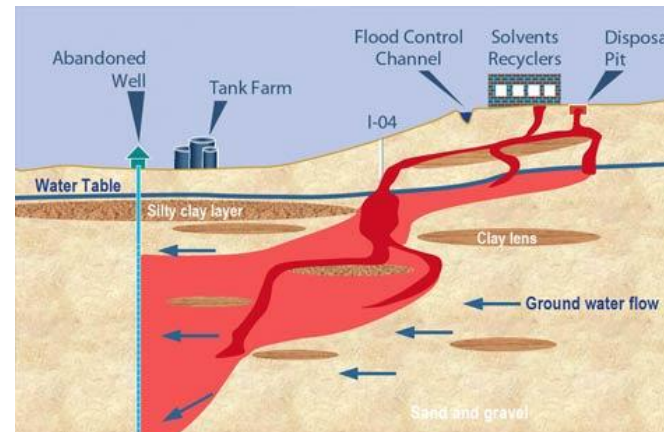
## Unconventional Resources



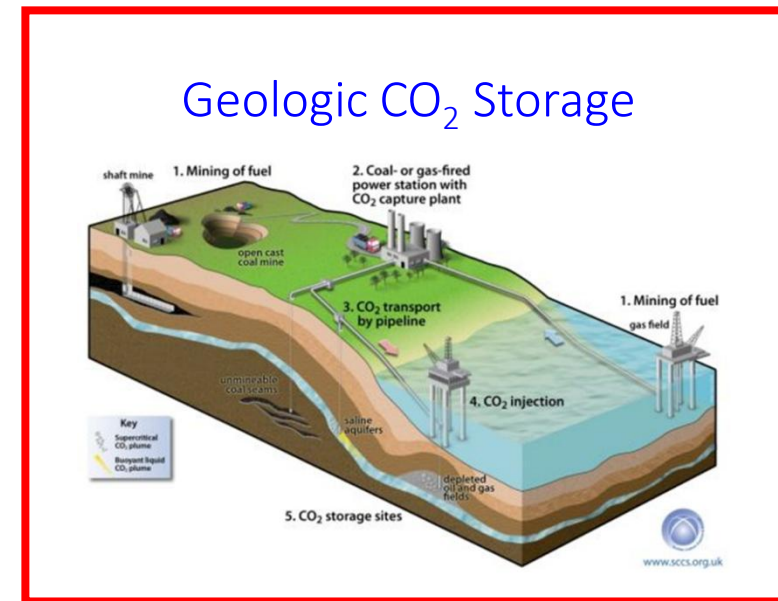
## Groundwater Resources



## Groundwater Remediation



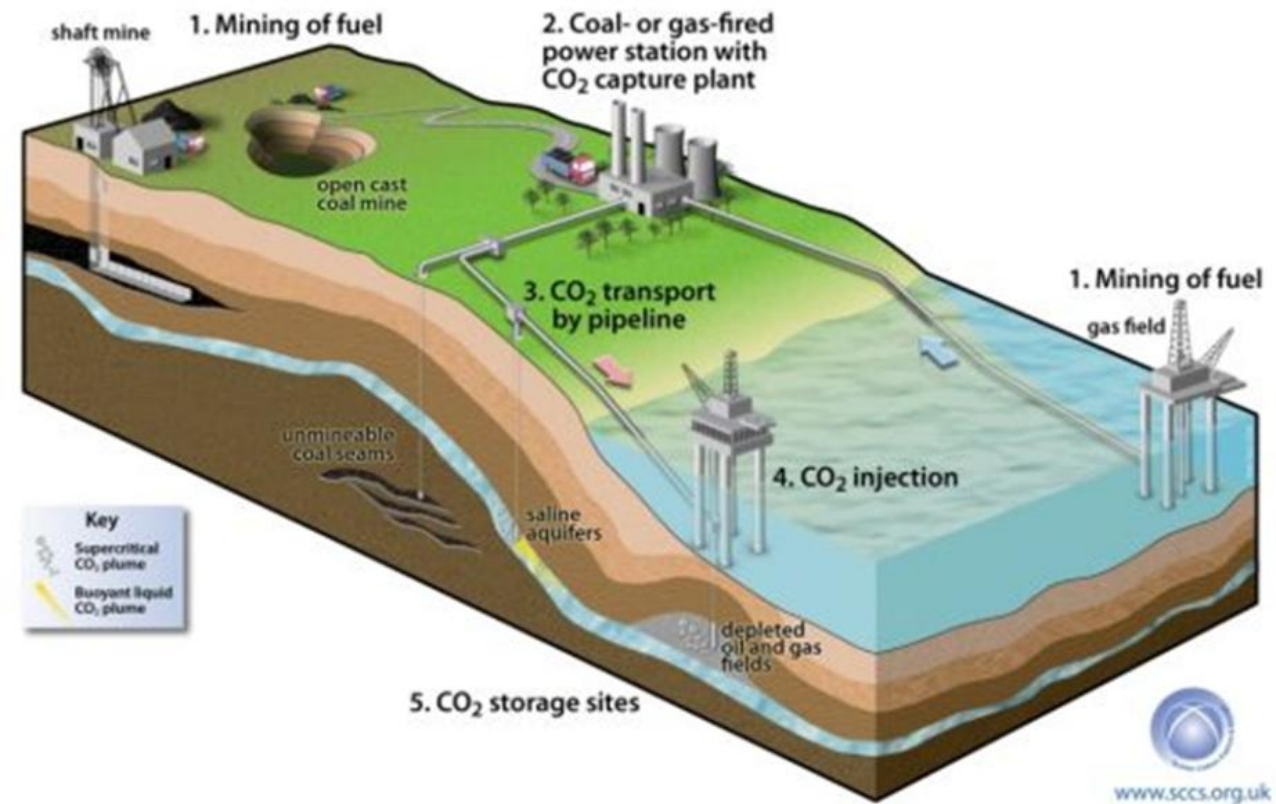
## Geologic CO<sub>2</sub> Storage



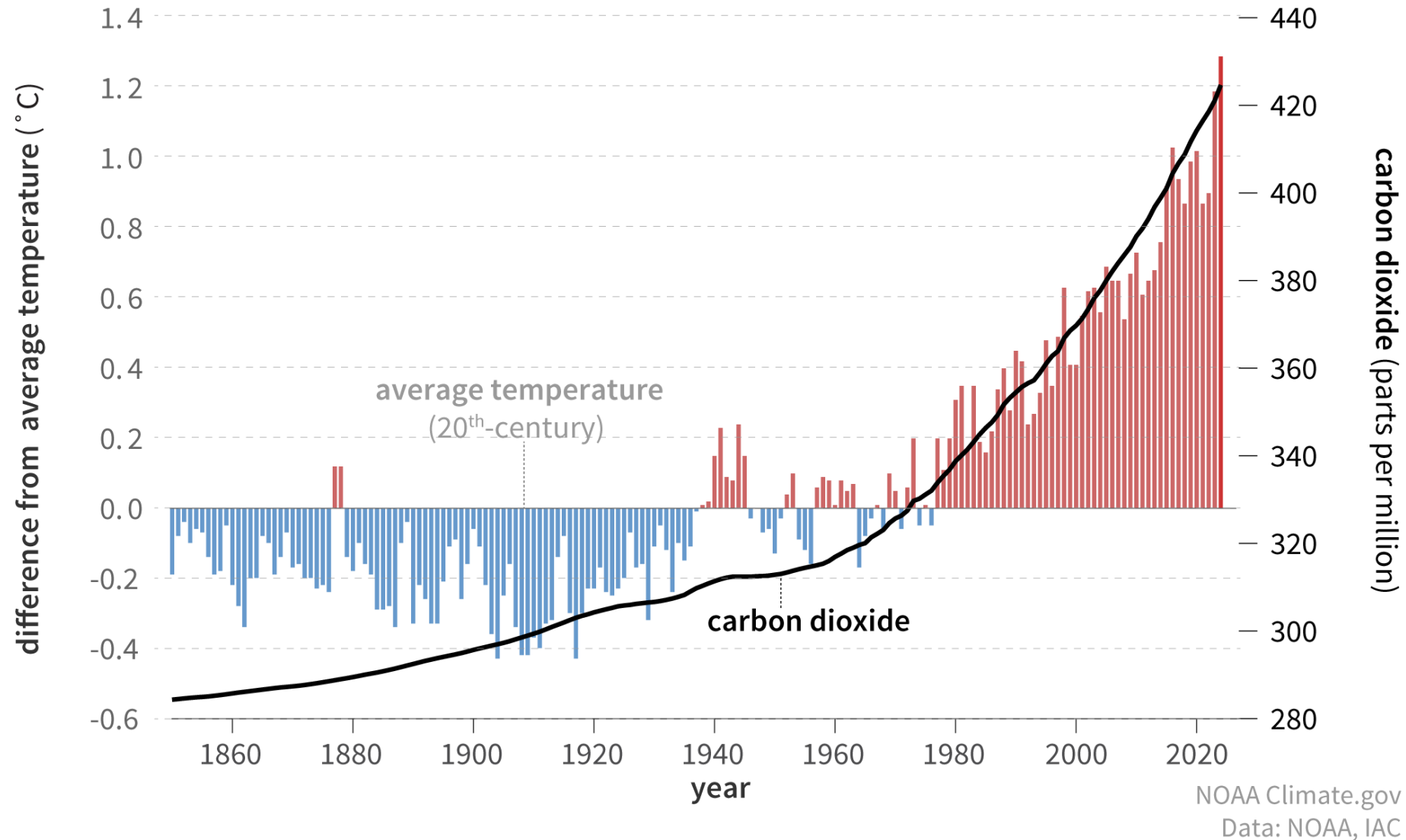


An important component in energy transition

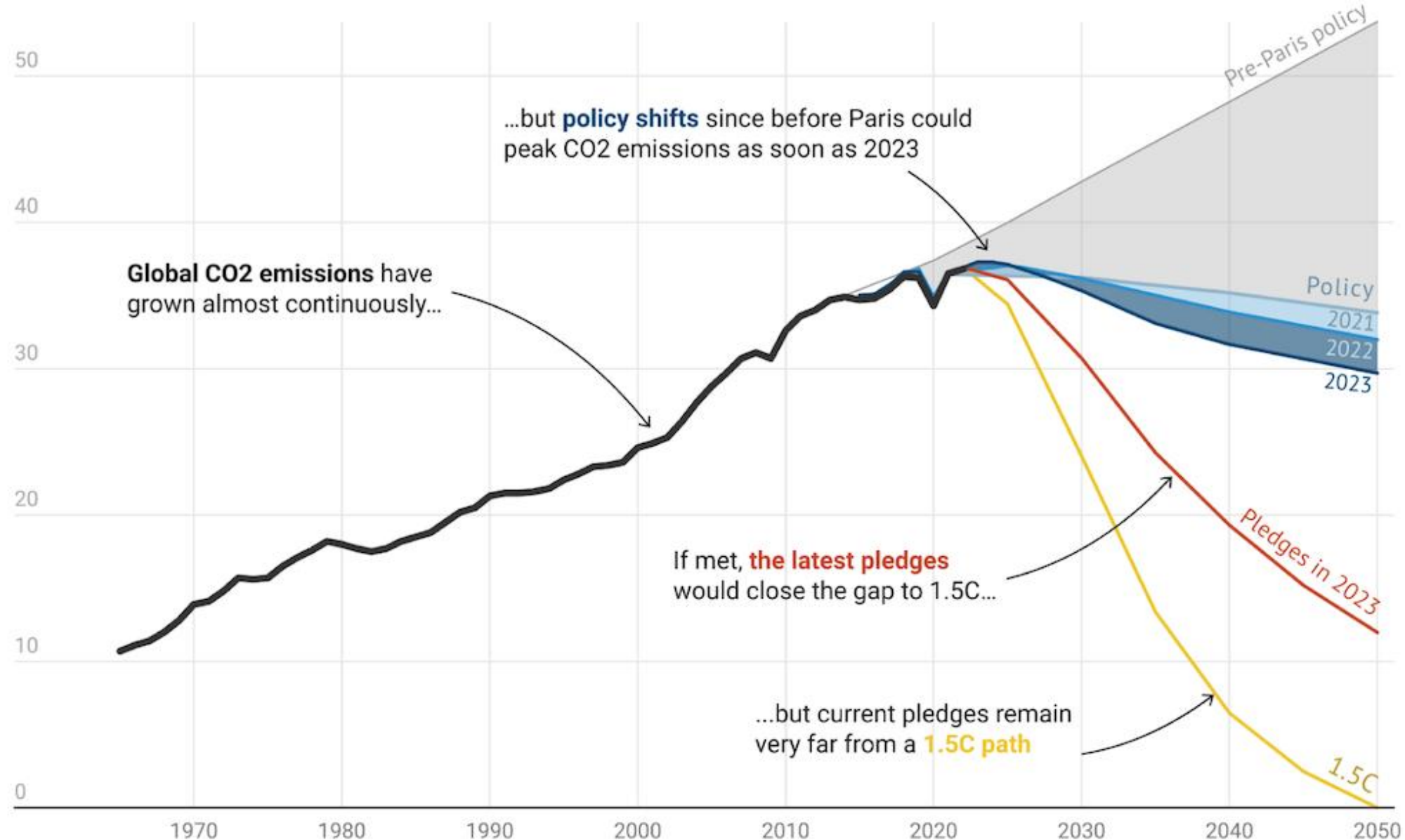
Reducing CO<sub>2</sub> emission by permanently storing it underground

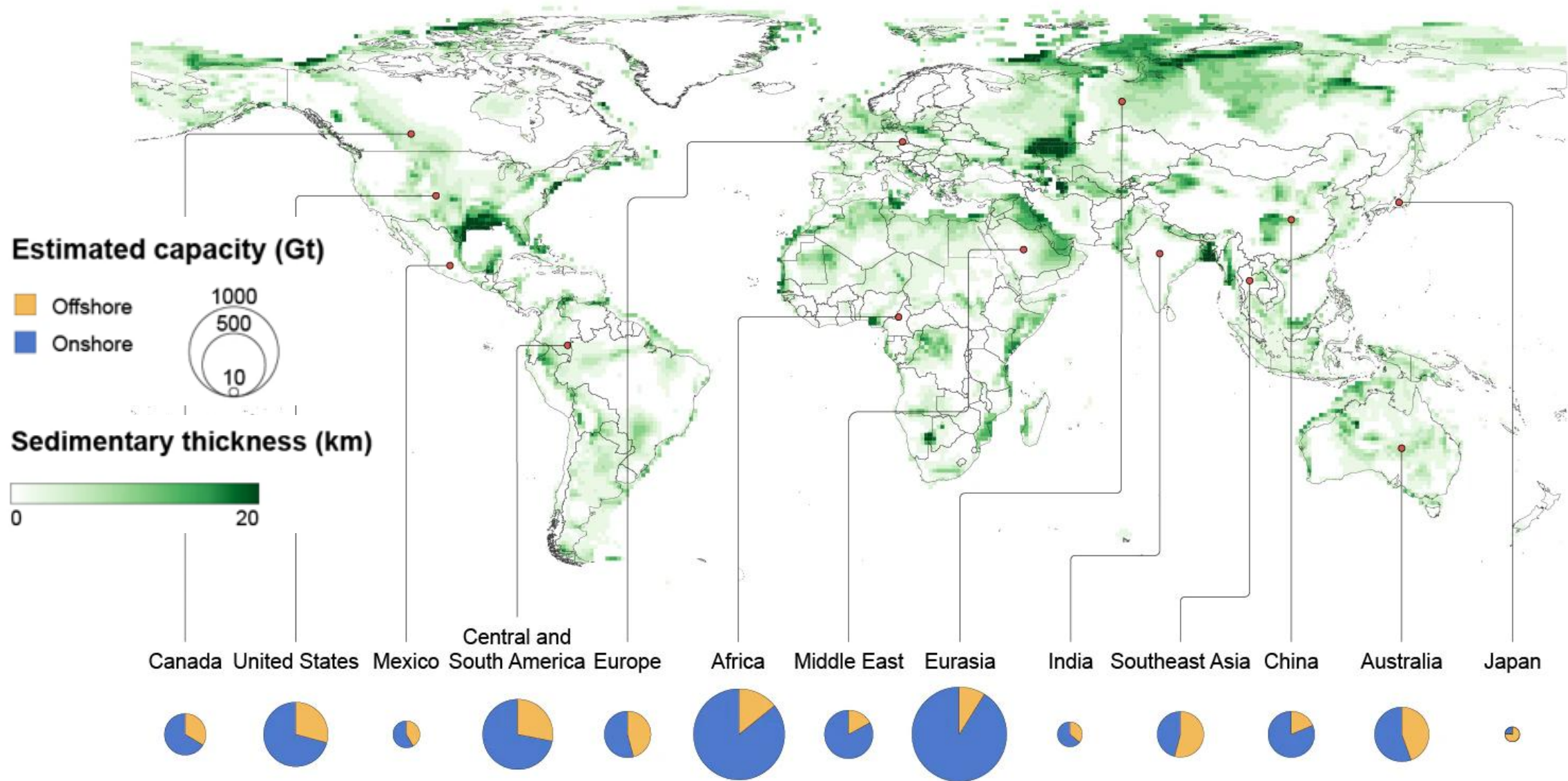


## Increases in atmospheric carbon dioxide and global temperature (1850-2024)



Paris Agreement: Limiting global warming to 1.5 degrees Celsius, compared to pre-industrial levels.





Global CO<sub>2</sub> emissions (2022) **36.8 Gt**

**379 years** of resources

**16 years** discovered

**2.5 days** commercial



Global Storage Resources

**13,954 Gt CO<sub>2</sub>**

**577 Gt (4.1%)** discovered

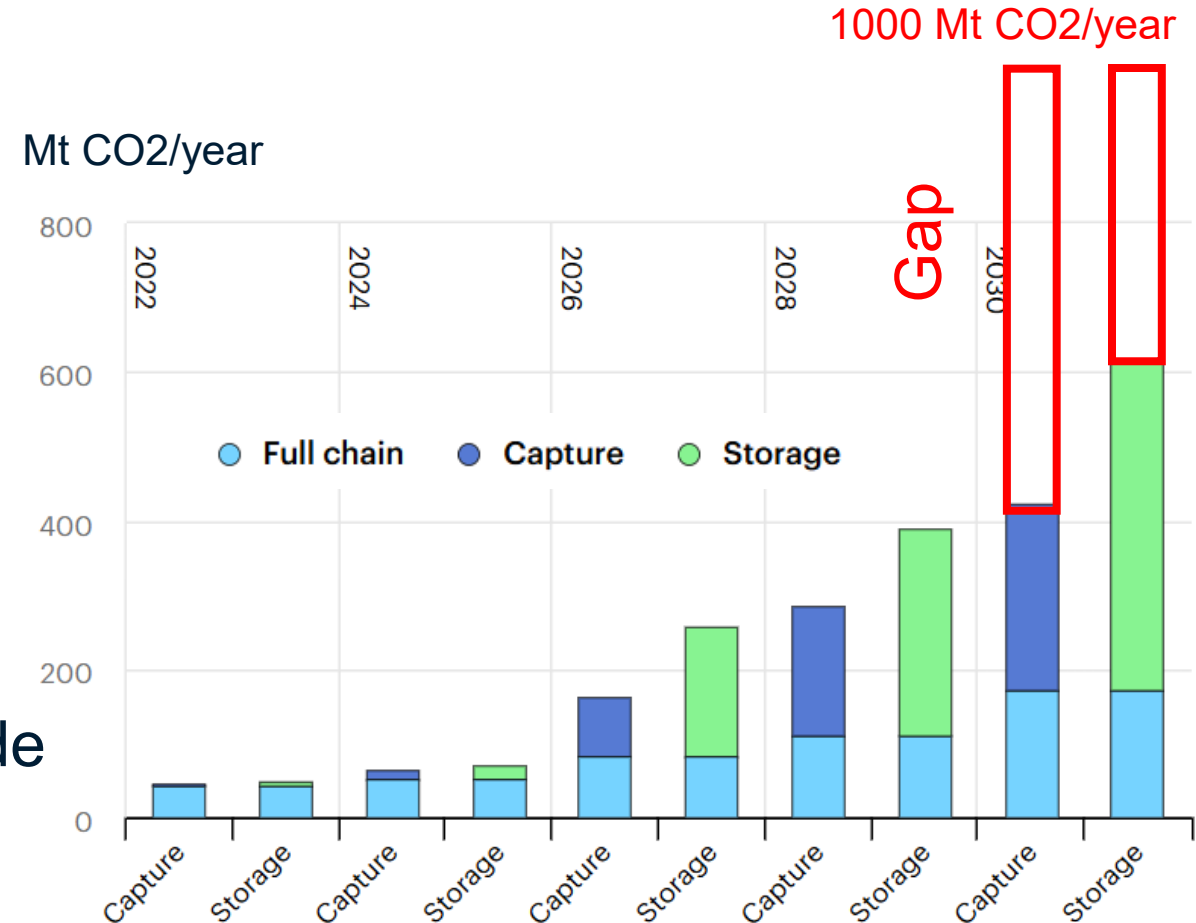
**253 Mt (0.002%)** commercial

**“Significant opportunity exists to explore, develop, and appraise storage resources globally”**

■ HIGHLY SUITABLE ■ SUITABLE ■ POSSIBLE ■ UNLIKELY

## CCUS Global Capacity:

- **Currently** ~ 50 Mt CO<sub>2</sub>/yr.
- **Future (by 2030):** ~ 615 Mt CO<sub>2</sub>/yr.
- **Required (by 2030):** ~ 1000 Mt CO<sub>2</sub>/yr
- **Required (by 2050):** ~ 6-10 Gt/yr
- **To date:** Over 300 Mt CO<sub>2</sub> stored worldwide
- **Global Storage Potential:** ~ 55,000 Gt



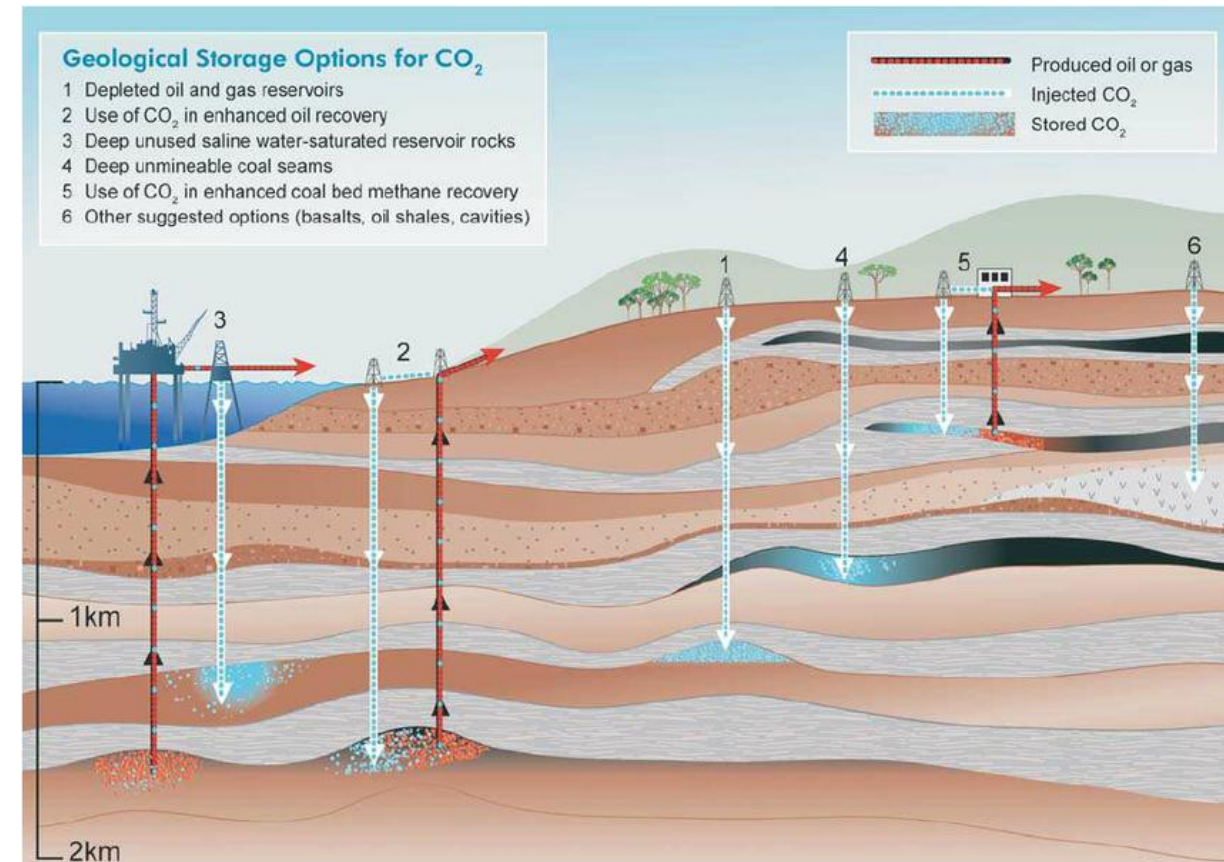
**Massive CCUS scale-up (over 100-fold) needed by 2050 to meet Net-Zero emissions target!**

## What is Geological Storage?

- Reducing CO<sub>2</sub> emission by injecting it into underground storage formations

## What is involved?

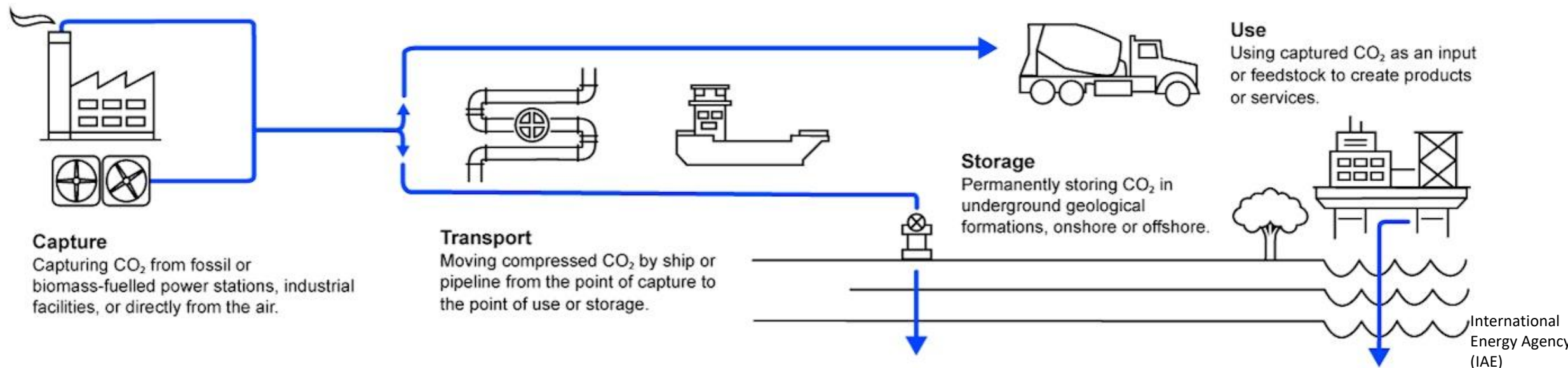
- Capturing, transporting, and storing CO<sub>2</sub>
- Injecting CO<sub>2</sub> into deep rock formations
- Monitoring to ensure permanent storage
- Risk mitigation and management



**Objective:** To reduce CO<sub>2</sub> emissions by injecting it underground (geologic formations)

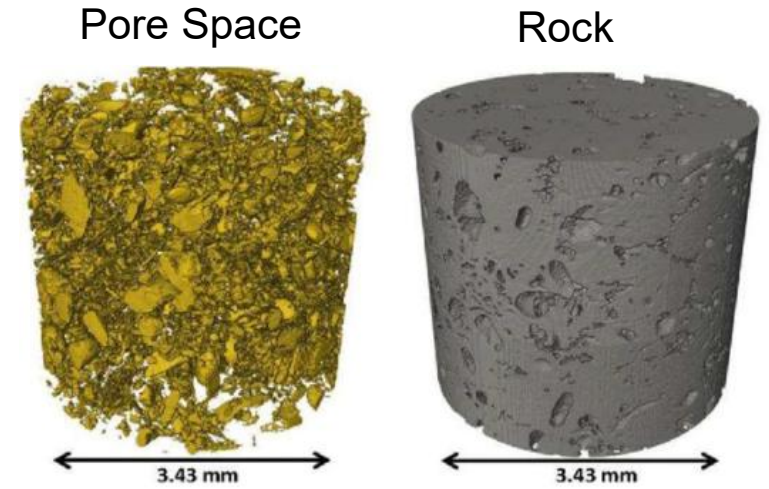
## CCUS Chain:

- **Capture** from large source points or directly from the air, **compress and transport** to injection/use sites, **inject/store** in deep geologic formations



## Storage in Rocks?

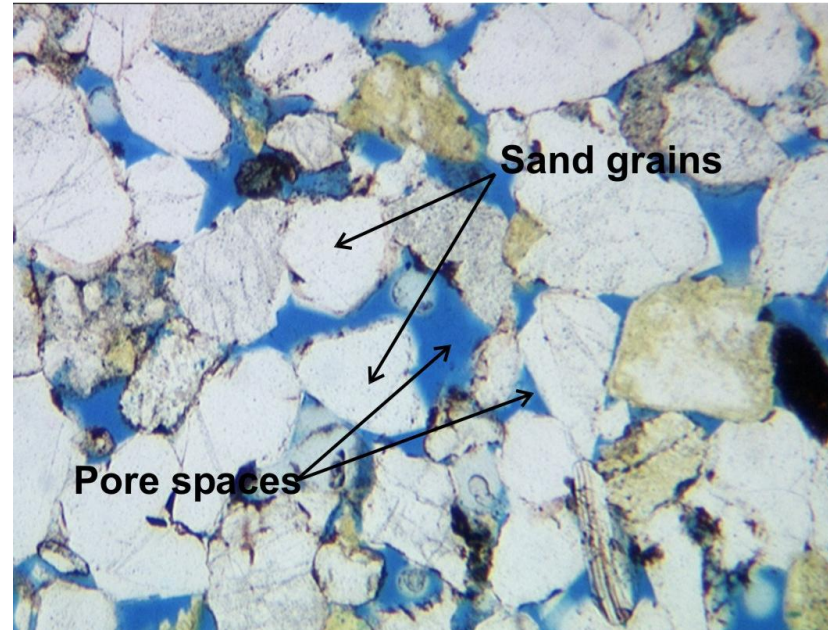
CO<sub>2</sub> is stored in **tiny pores** within rock formations. Large-scale storage possible due to available rock volumes.



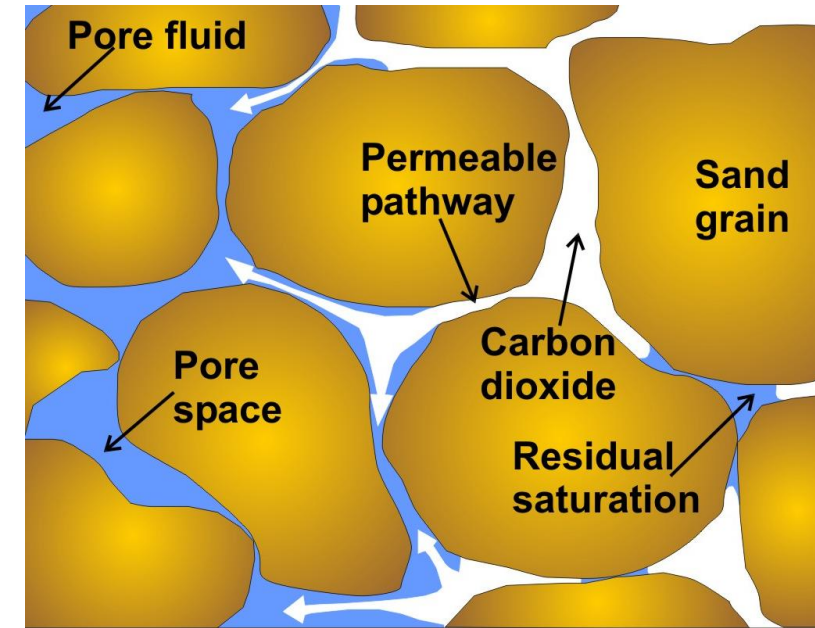
Sandstone Outcrop



Thin Sheet

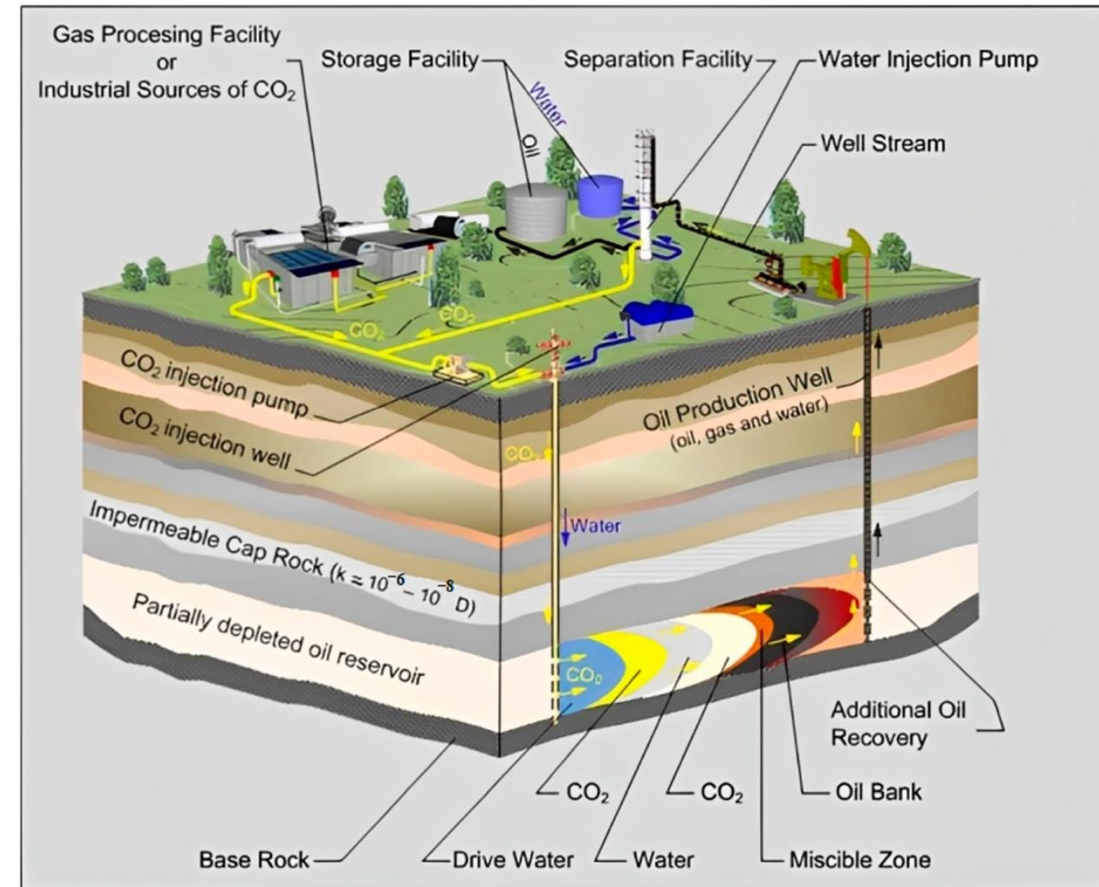


Illustration



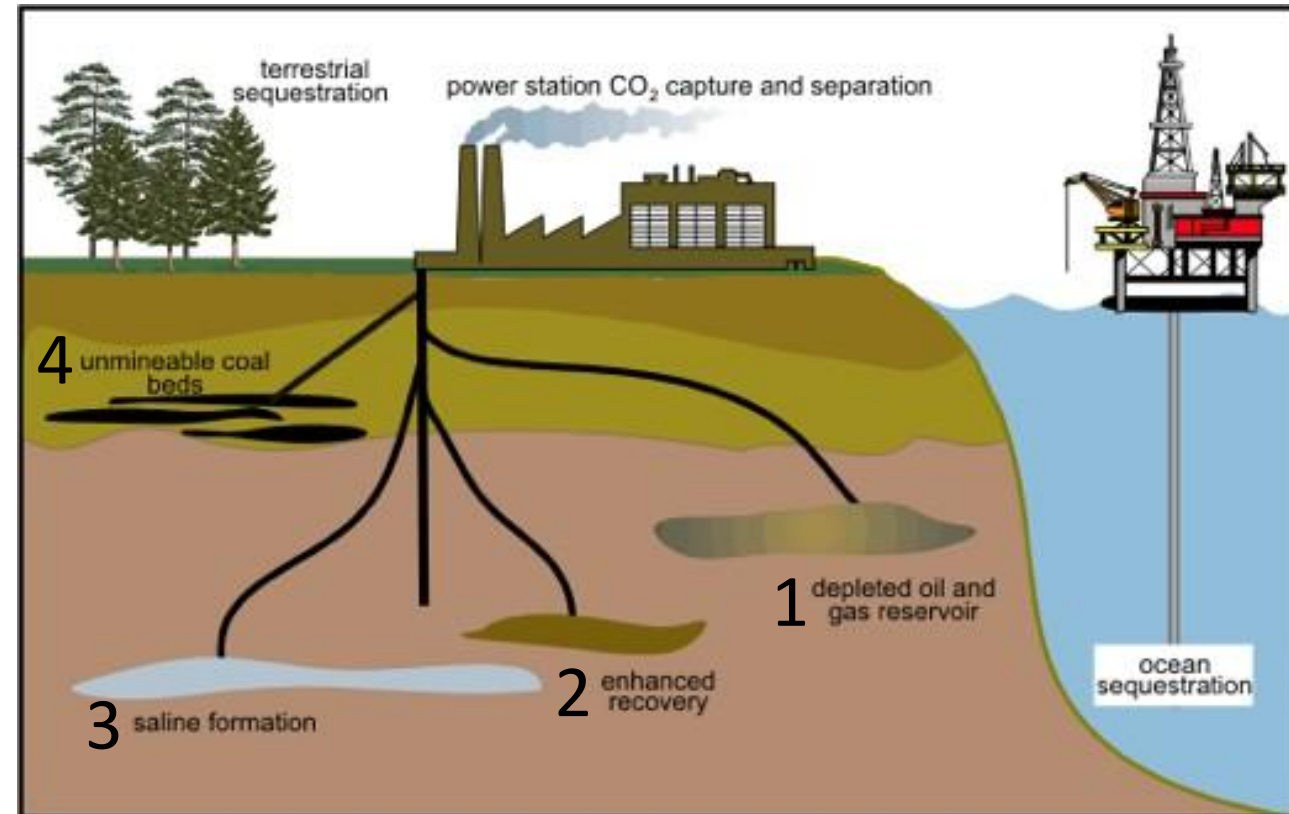
## What is needed:

- Large volumes of **good quality pore space** (high porosity and permeability) to ensure high injectivity and small pressure increases
- **Continuous monitoring for risk management** (risk related to CO<sub>2</sub> leakage and seismicity)
- Large **capital expense** (economics)
- **Regulations** to ensure safety and reliability of operations across all projects
- **Workforce** development and training



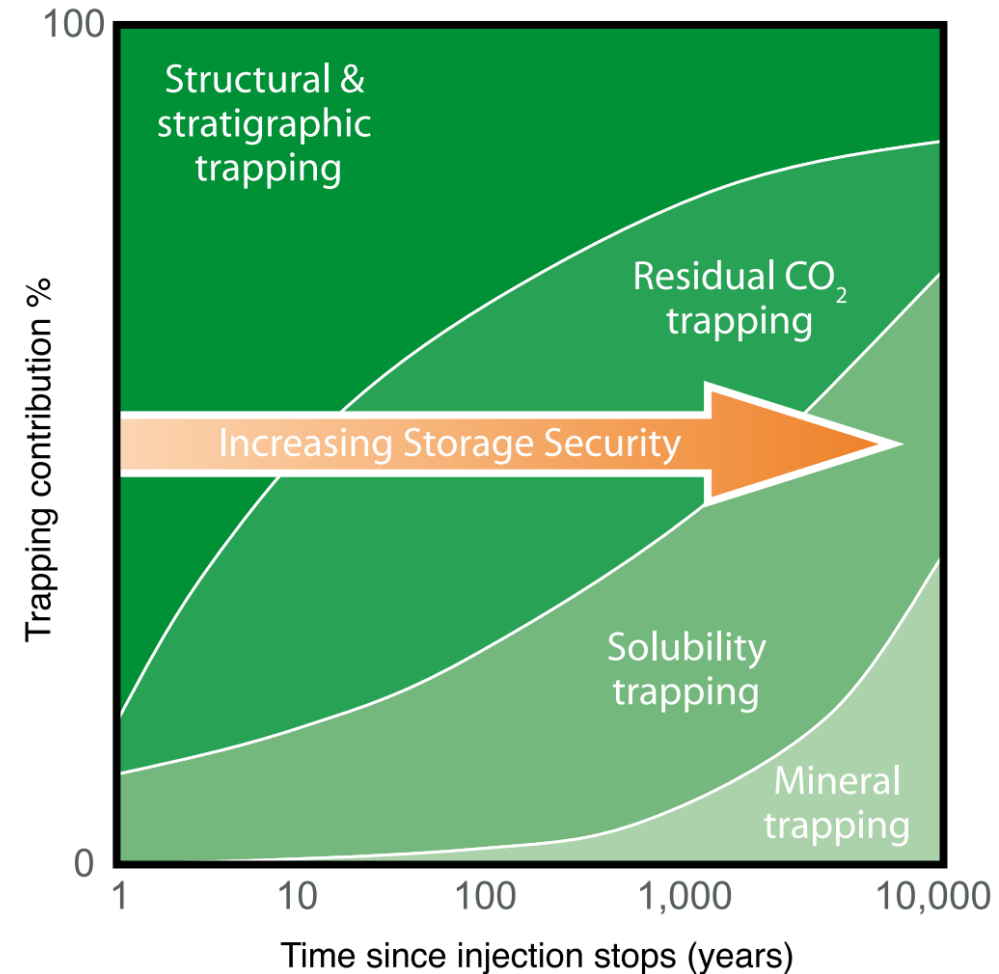
## Geologic CO<sub>2</sub> Storage Modes

1. Depleted oil and gas reservoirs
2. Enhanced oil and gas recovery
3. Deep saline formations:  
Offshore and onshore
4. Enhanced coal bed methane  
recovery



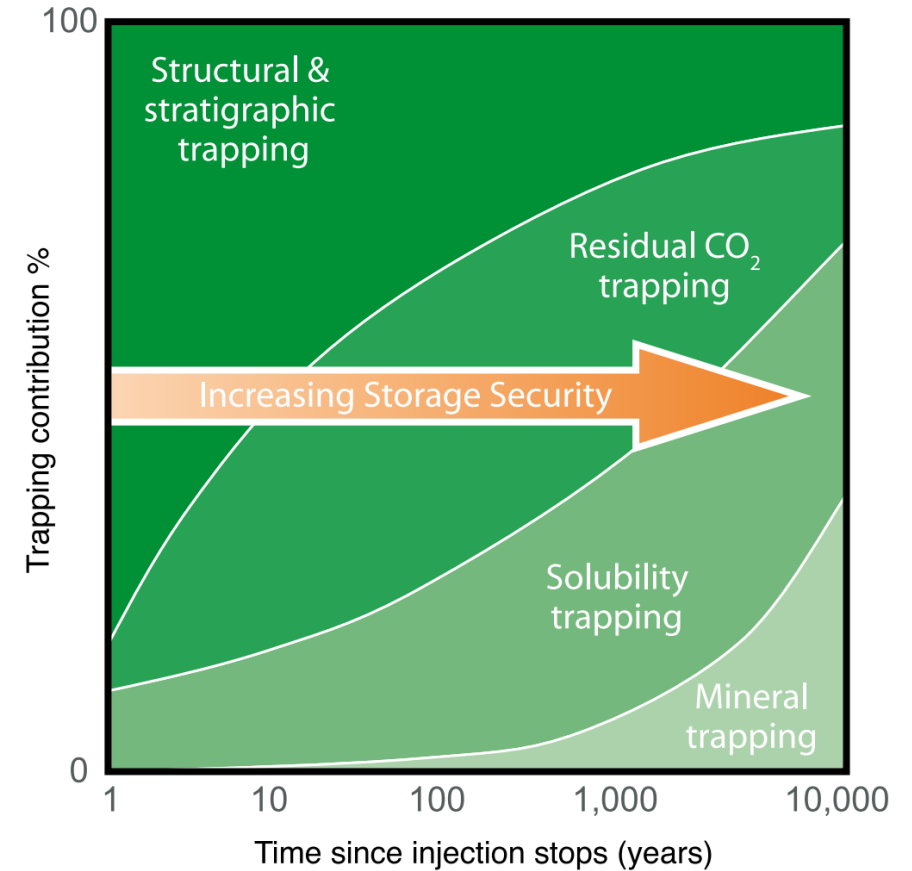
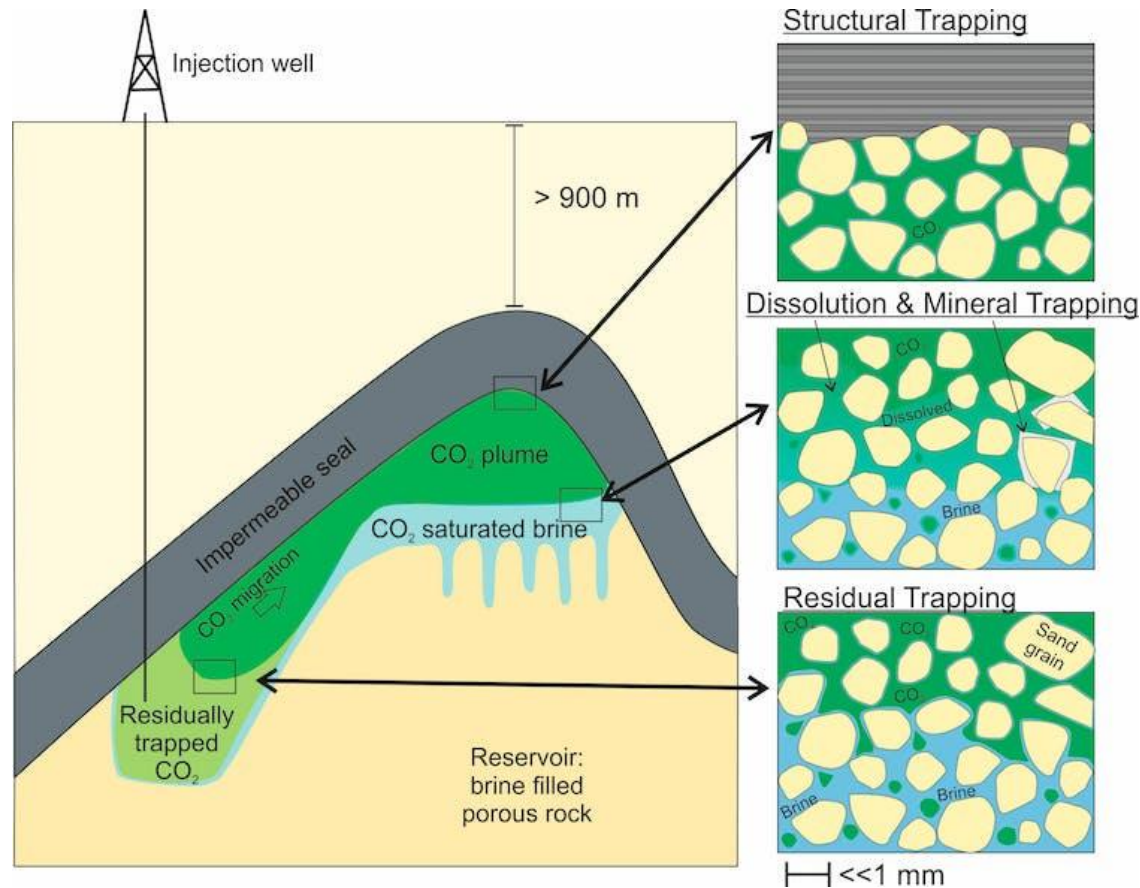
## CO<sub>2</sub> Trapping Mechanisms

- 1. Structural trapping:** formation sealing/caprock
- 2. Capillary/residual trapping:** CO<sub>2</sub> breaks up into small ganglia, immobilized by capillary forces in the pore space.
- 3. Solubility trapping:** CO<sub>2</sub> dissolved in brine water.
- 4. Mineral trapping:** carbonic acid react with rock minerals.



$$M_{\text{Storage}} = M_{\text{free CO}_2} + M_{\text{residual CO}_2} + M_{\text{dissolved CO}_2} + M_{\text{Mineral CO}_2}$$

## CO<sub>2</sub> Trapping Mechanisms



$$M_{\text{Storage}} = M_{\text{free CO}_2} + M_{\text{residual CO}_2} + M_{\text{dissolved CO}_2} + M_{\text{Mineral CO}_2}$$

## Risks

- Primary risks: CO<sub>2</sub> leakage and injection-induced seismicity
- Risk assessment: identifying and quantifying potential risks

## Monitoring

- Providing assurance and early warning for leakage and seismicity
- Technologies: downhole gauges, 4D seismic survey, InSAR

## Risk Management

- Site selection and injection scenario selection
- Managing geological uncertainty
- Modeling and prediction
- Mitigation strategies

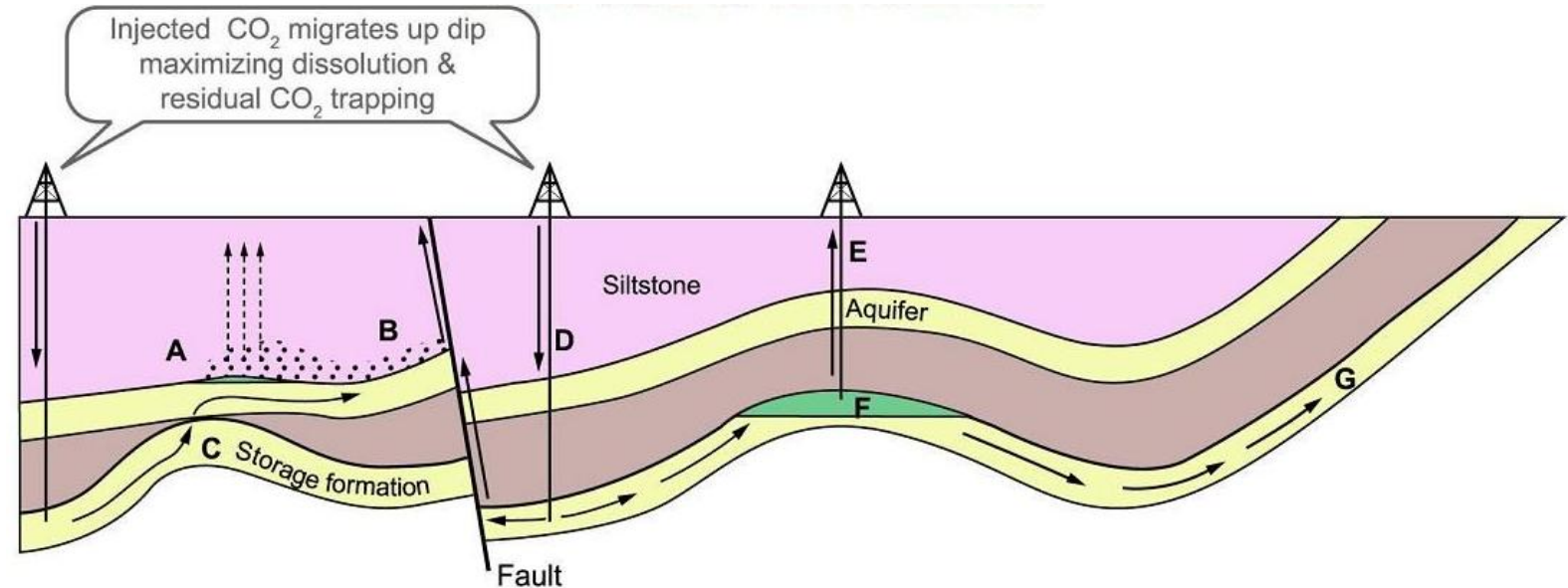
## (i) Potential Leakage of CO<sub>2</sub>

### CO<sub>2</sub> leakage into:

- Atmosphere
- Aquifers
- Shallow soil zones

### Leakage pathways:

- Injection-induced fracturing
- Abandoned wells
- Pre-existed faults and fractures



### Potential Escape Mechanisms

|  |   |   |  |   |   |  |
|--|---|---|--|---|---|--|
| <p><b>A.</b> CO<sub>2</sub> gas pressure exceeds capillary pressure &amp; passes through siltstone</p> | <p><b>B.</b> Free CO<sub>2</sub> leaks from A into upper aquifer up fault</p> | <p><b>C.</b> CO<sub>2</sub> escapes through 'gap' in cap rock into higher aquifer</p> | <p><b>D.</b> Injected CO<sub>2</sub> migrates up dip, increases reservoir pressure &amp; permeability of fault</p> | <p><b>E.</b> CO<sub>2</sub> escapes via poorly plugged old abandoned well</p> | <p><b>F.</b> Natural flow dissolves CO<sub>2</sub> at CO<sub>2</sub> / water interface &amp; transports it out of closure</p> | <p><b>G.</b> Dissolved CO<sub>2</sub> escapes to atmosphere or ocean</p> |
|--|---|---|--|---|---|--|

## (ii) Induced seismicity

**CO<sub>2</sub> Injection & Pressure Build-up**



**Stress-and-Strain Changes**



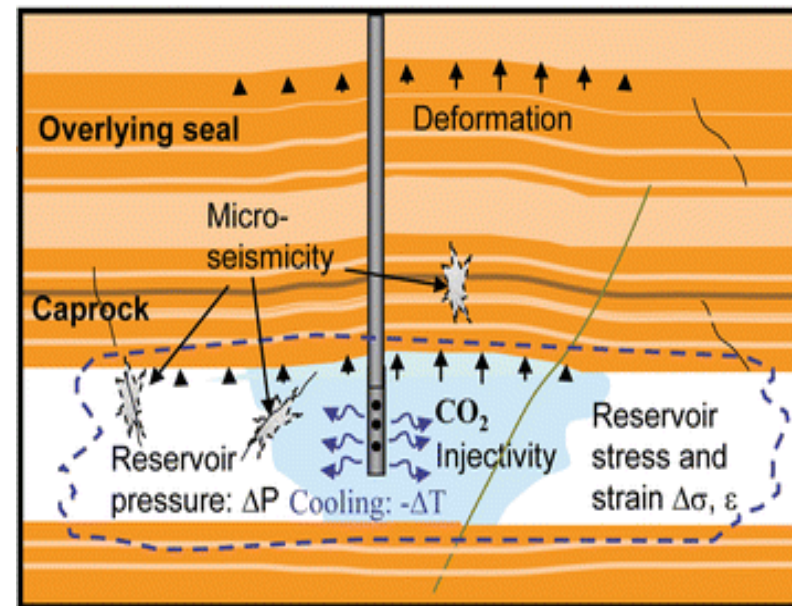
**Geomechanical risks:**

- Uplifting (surface displacement)
- Induced Seismicity (rock's plastic strain)
- Caprock Fracturing (CO<sub>2</sub> leakage)

- Injection of CO<sub>2</sub>

- Pressure Build-up

- Stress Field Changes



(Rutqvist, 2012)

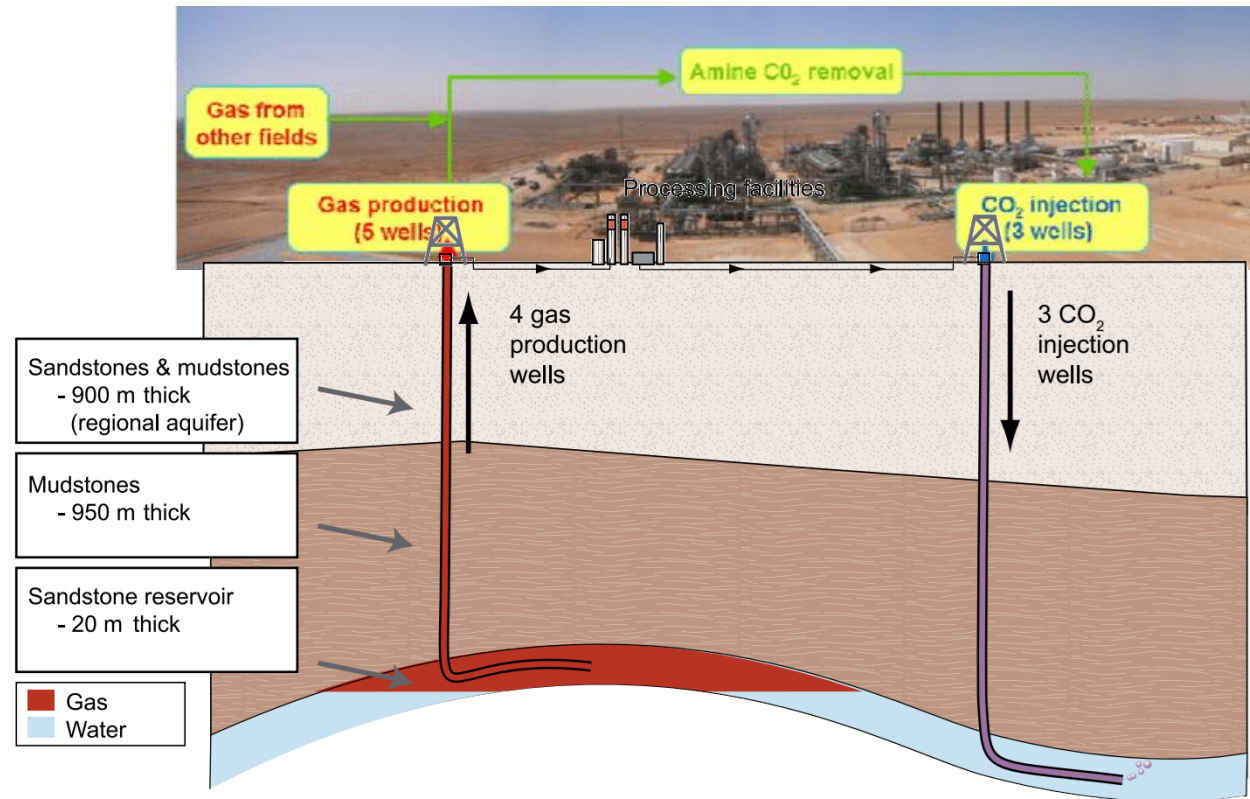
- Ground Uplifting

- Caprock Fracturing
- CO<sub>2</sub> Leakage

- Micro-seismicity

- Plastic Deformation
- Rock Fracturing

## In Salah Project

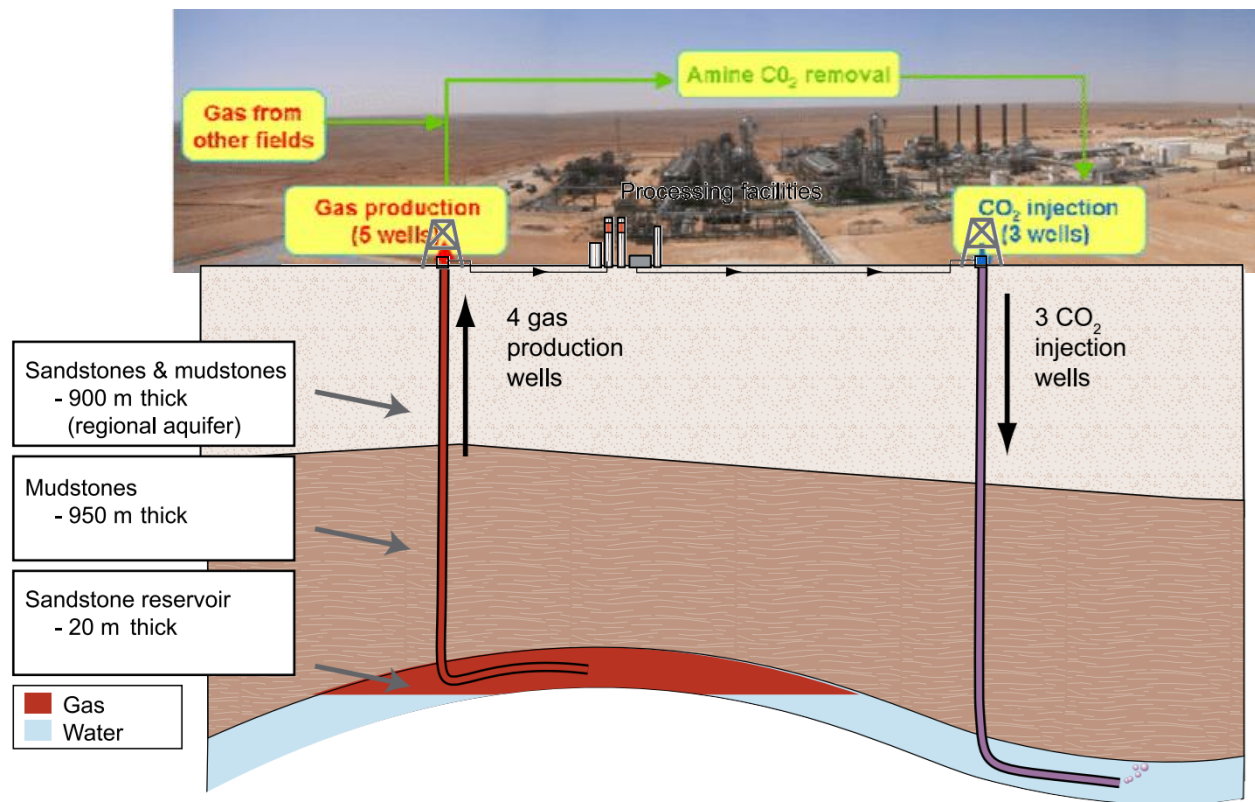


- A total of **3.8 mega-ton** of CO<sub>2</sub> were injected
- **9,506** injection induced seismic events detected
- Injection of CO<sub>2</sub> is **opening pre-existing fractures**
- Maximum of **25 millimeters uplift** after 2 years

- **Depleted gas field in Algeria**
- 3-4000 ton/day; 17 mega-ton planned

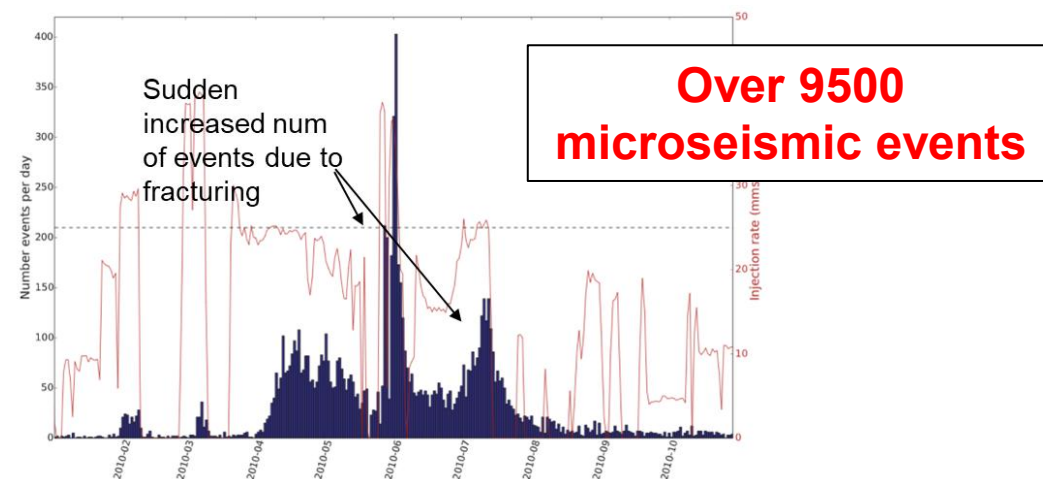
# Examples of CO<sub>2</sub> Storage Projects

## In Salah Project

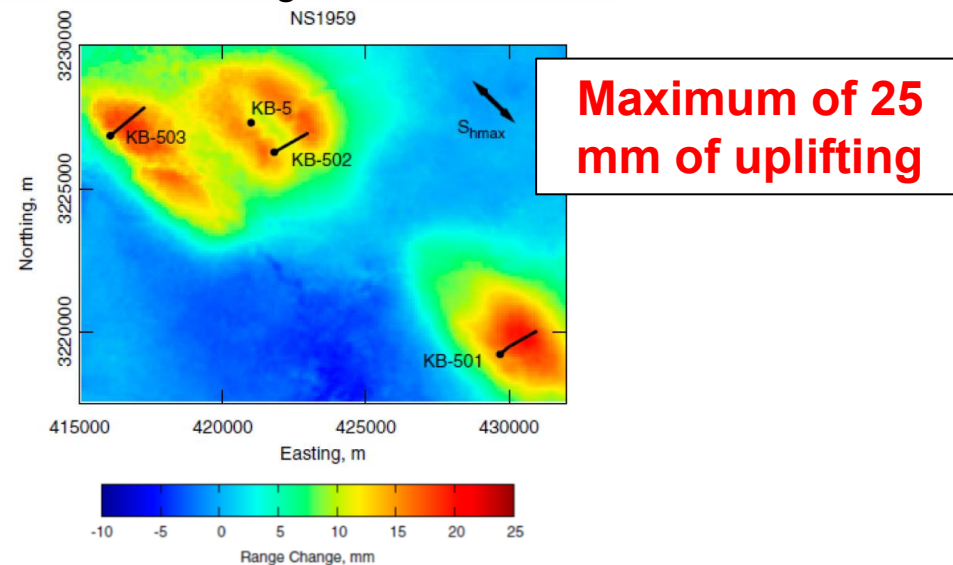


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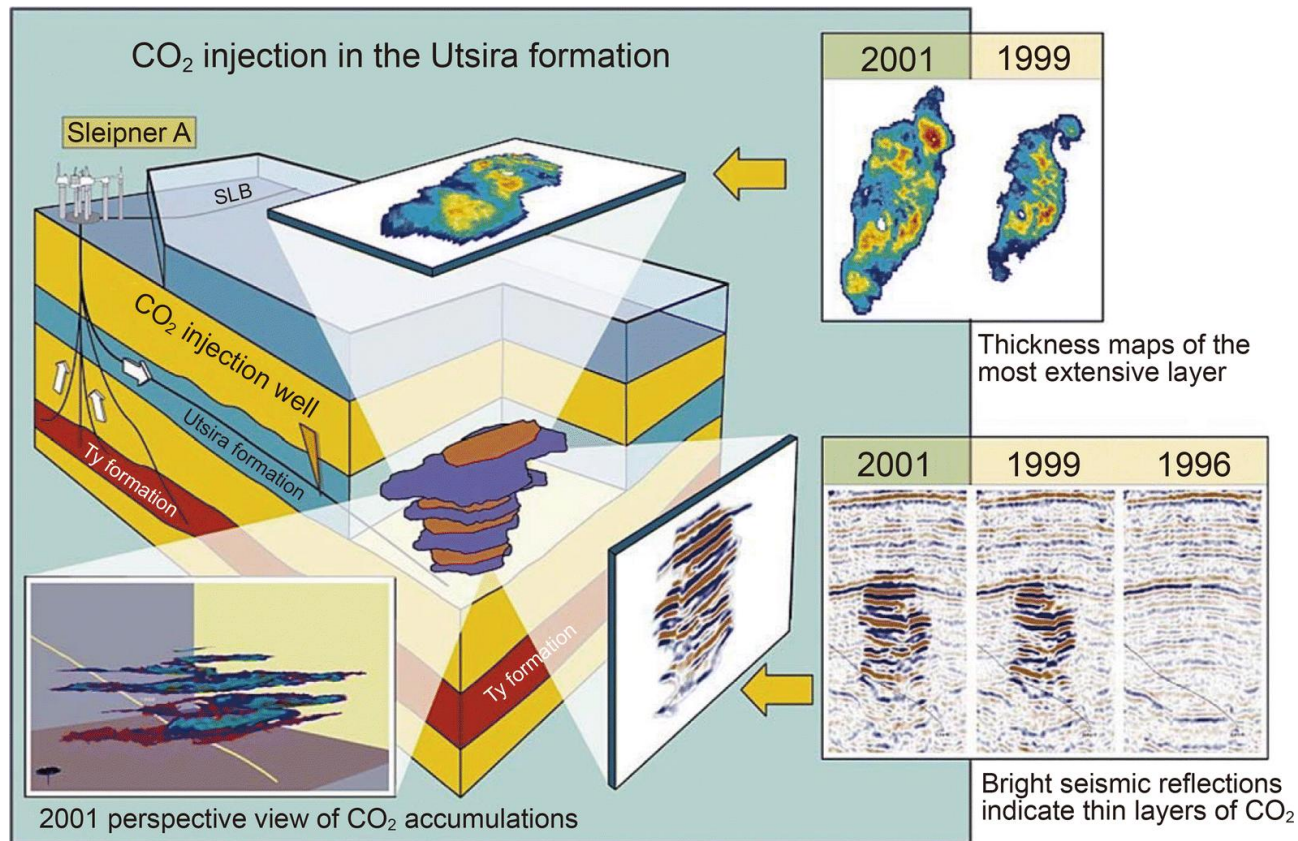
### Detected Microseismic events



### InSAR measured ground deformation



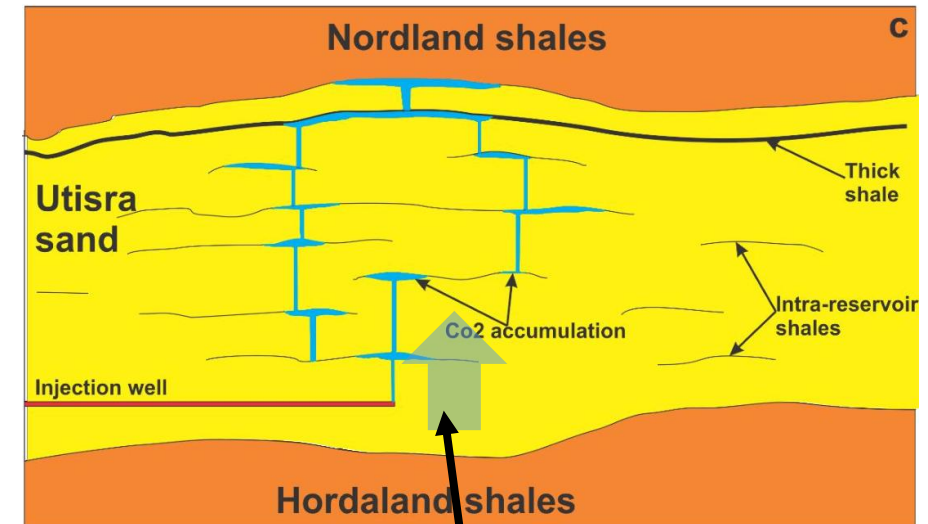
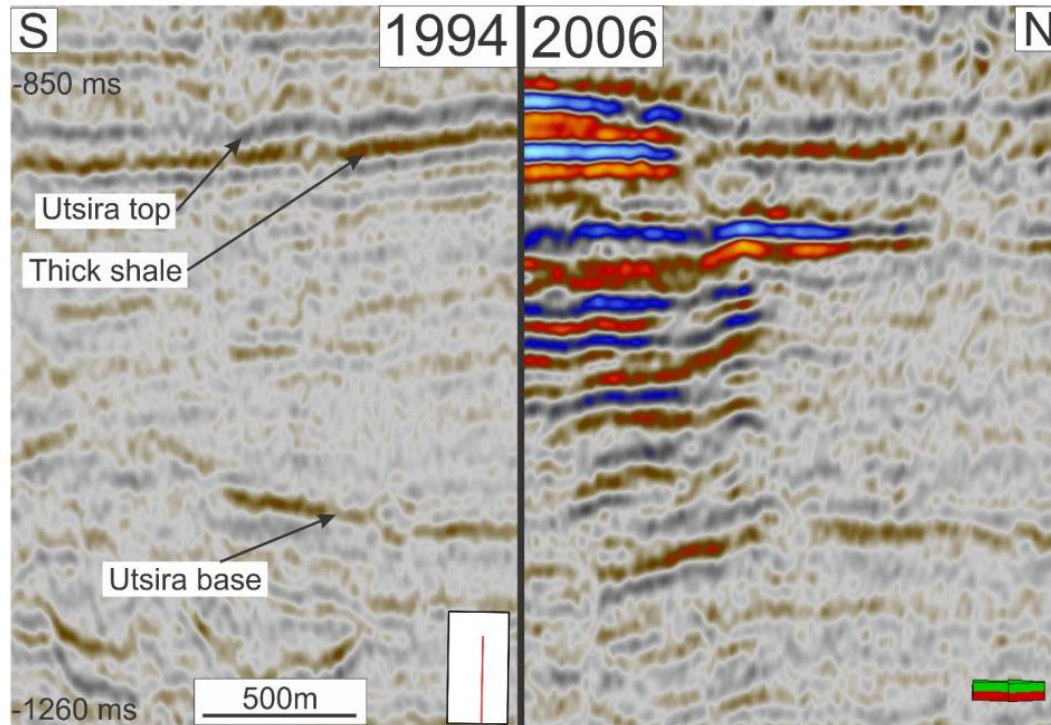
## Sleipner Project



- CO<sub>2</sub> plume (saturation) is monitored to ensure safe storage
- 4D seismic survey used for monitoring since 1999
- 4D seismic survey allows the tracking of CO<sub>2</sub> movement over time

- **Saline aquifer located in the North Sea, operated by Equinor**
- 3000 ton/day; 20 meta-ton planned

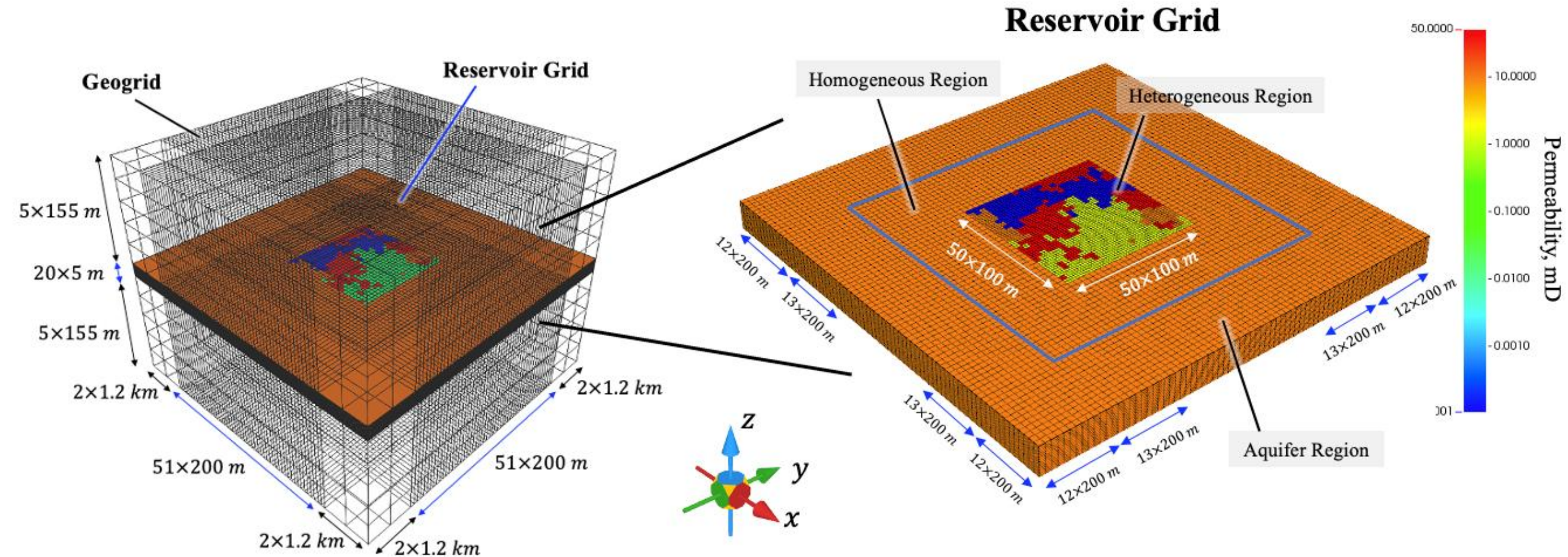
## Sleipner Project

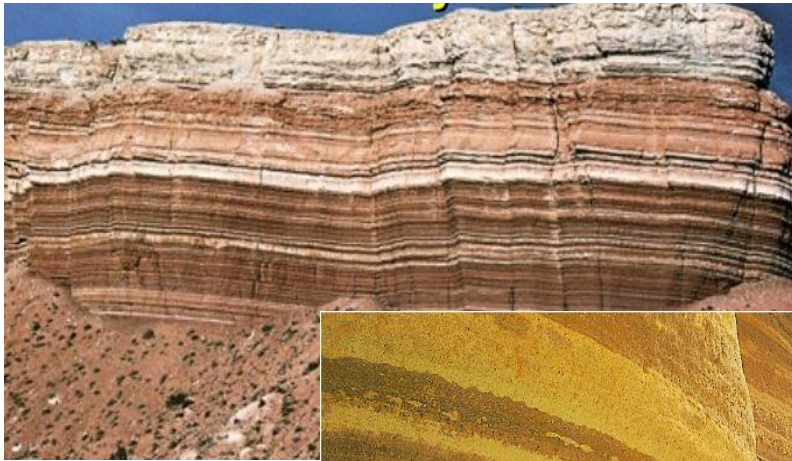


- CO<sub>2</sub> migrates upwards from the injection well
- And accumulates under shales

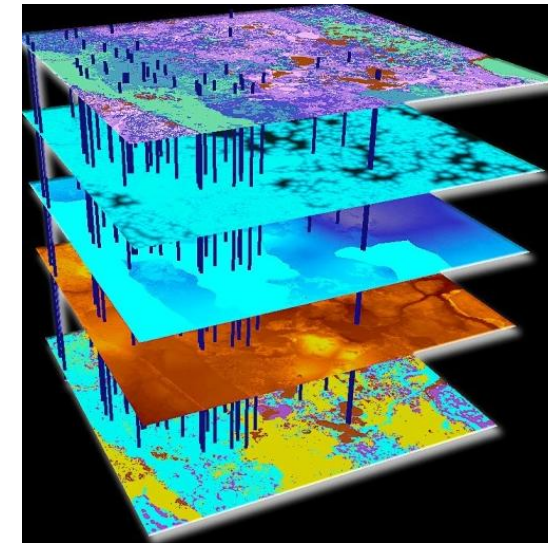
- 1994: Pre-injection seismic survey
- 2006: CO<sub>2</sub> accumulation affects reflectivity

To better understand and quantify the response of geologic formations to CO<sub>2</sub> injection (increase reservoir pressure / deformation / fracturing)

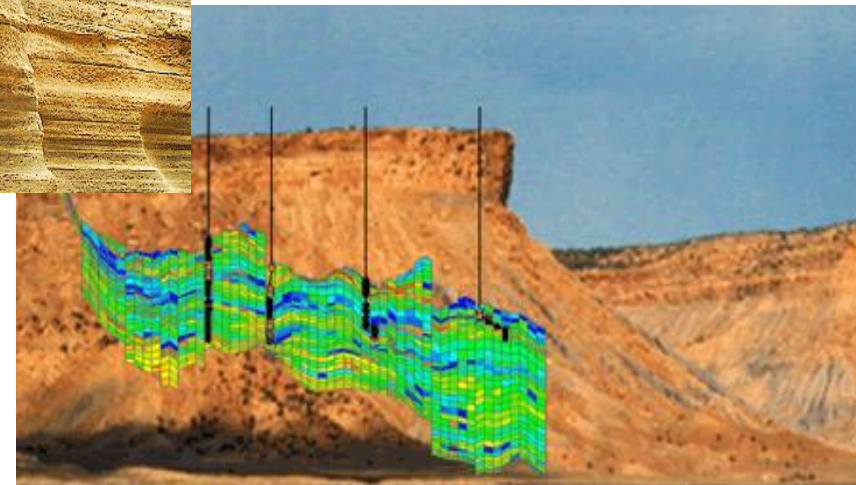




Computer Model



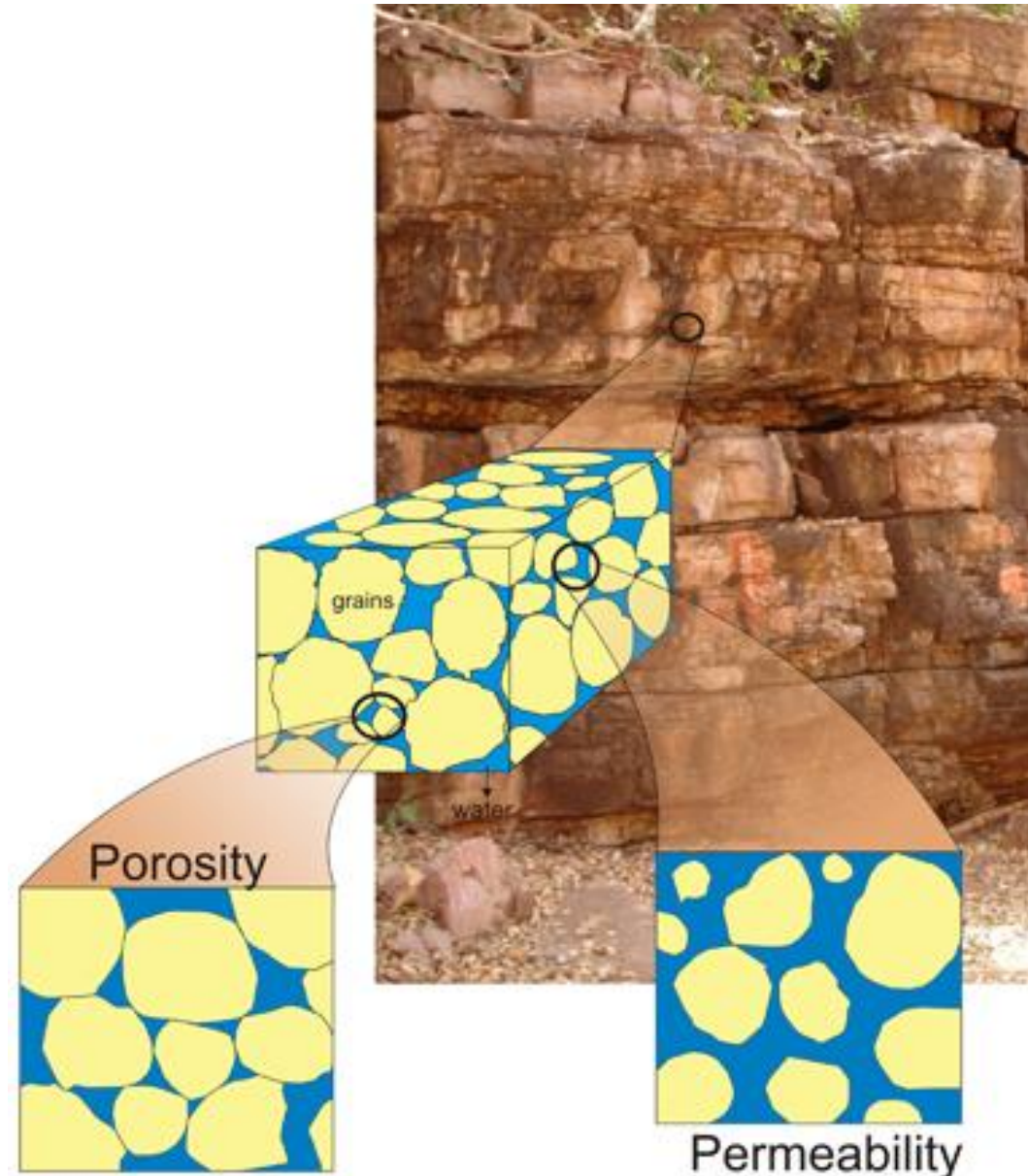
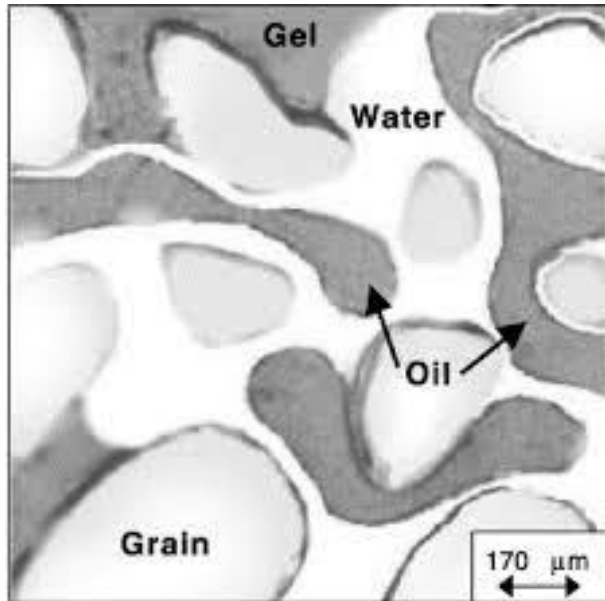
Sedimentary rock deposits with complex structures and fluid flow properties



Porosity

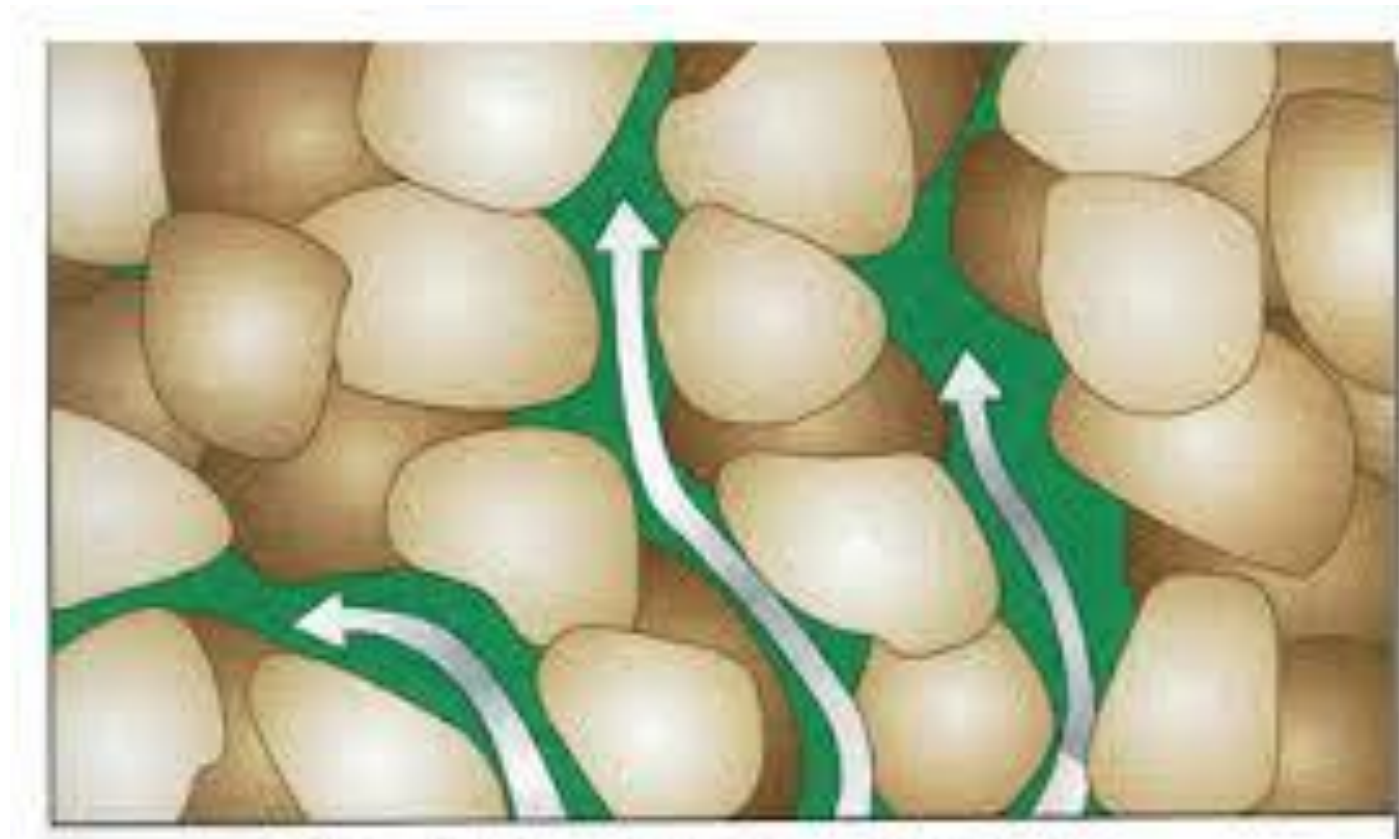
Permeability

Saturation



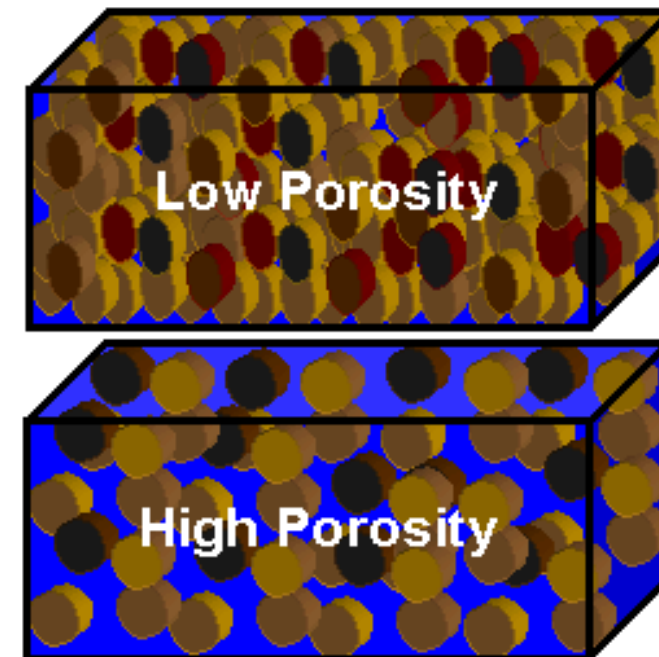
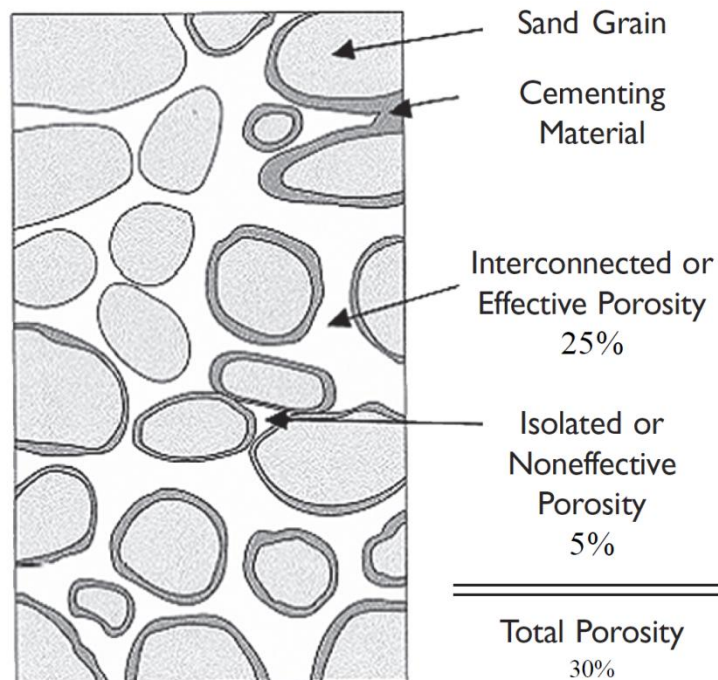
## Rock Permeability:

How conductive rock pore network is to fluid (oil/water/gas) flow.



# Rock Porosity:

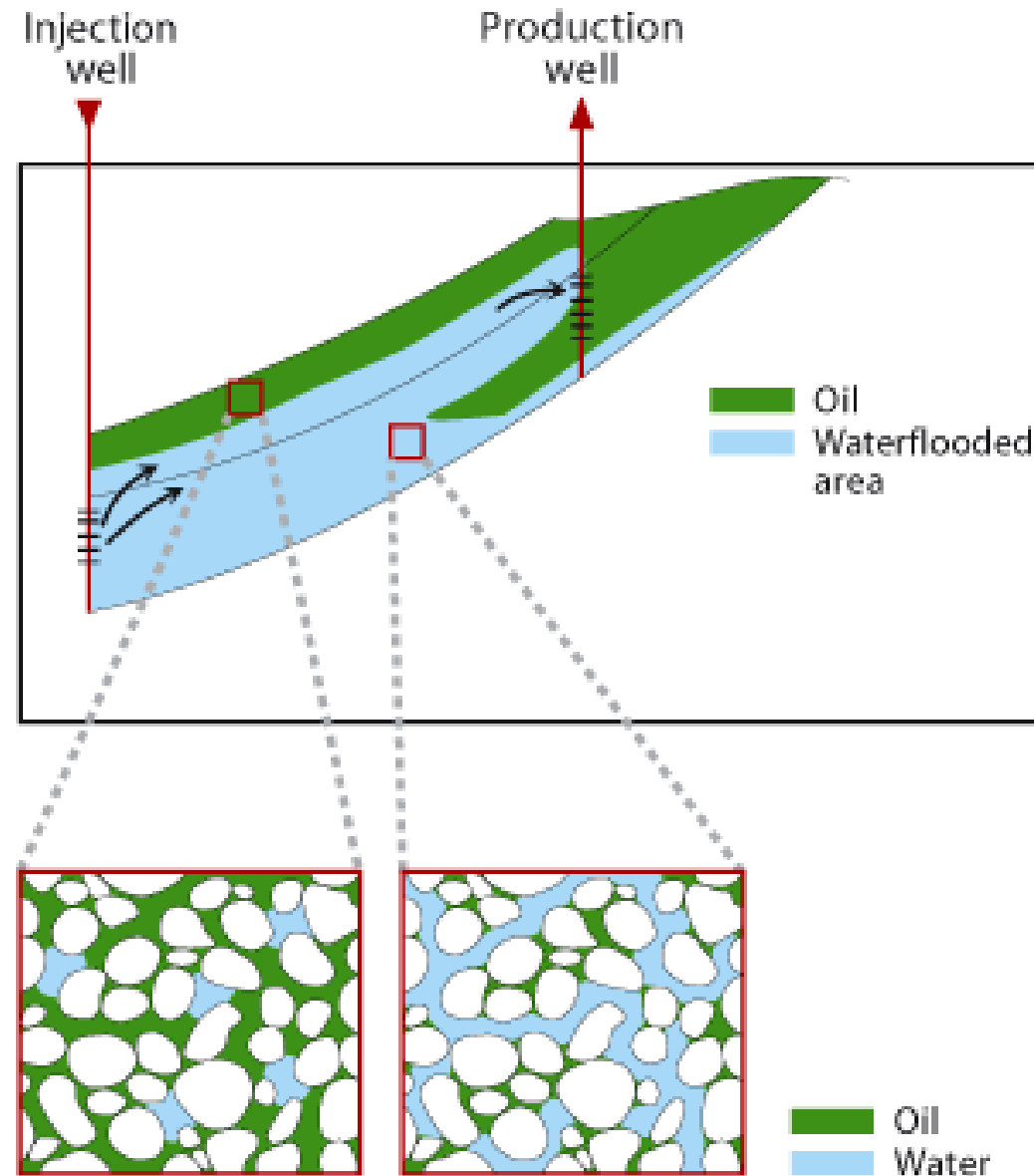
The ratio of pore volume to total rock volume (pore space is where the fluids reside)



# Phase Saturation

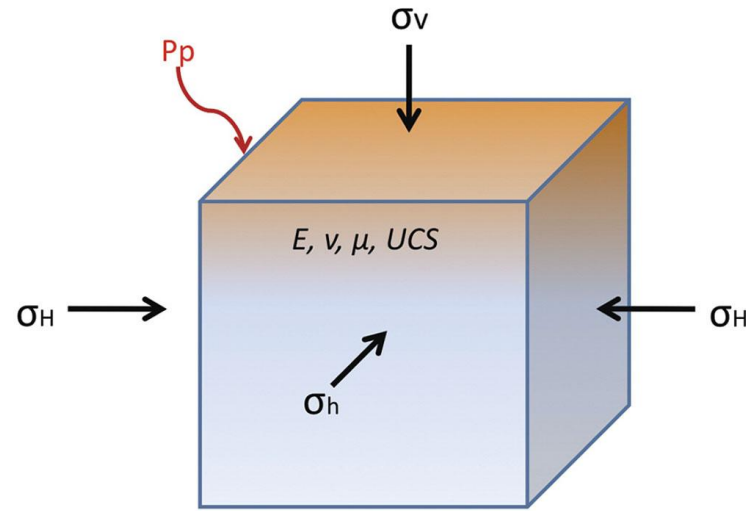
Fraction of pore volume that is occupied by fluid phase

$$V_{\text{phase}} / V_{\text{pore}}$$



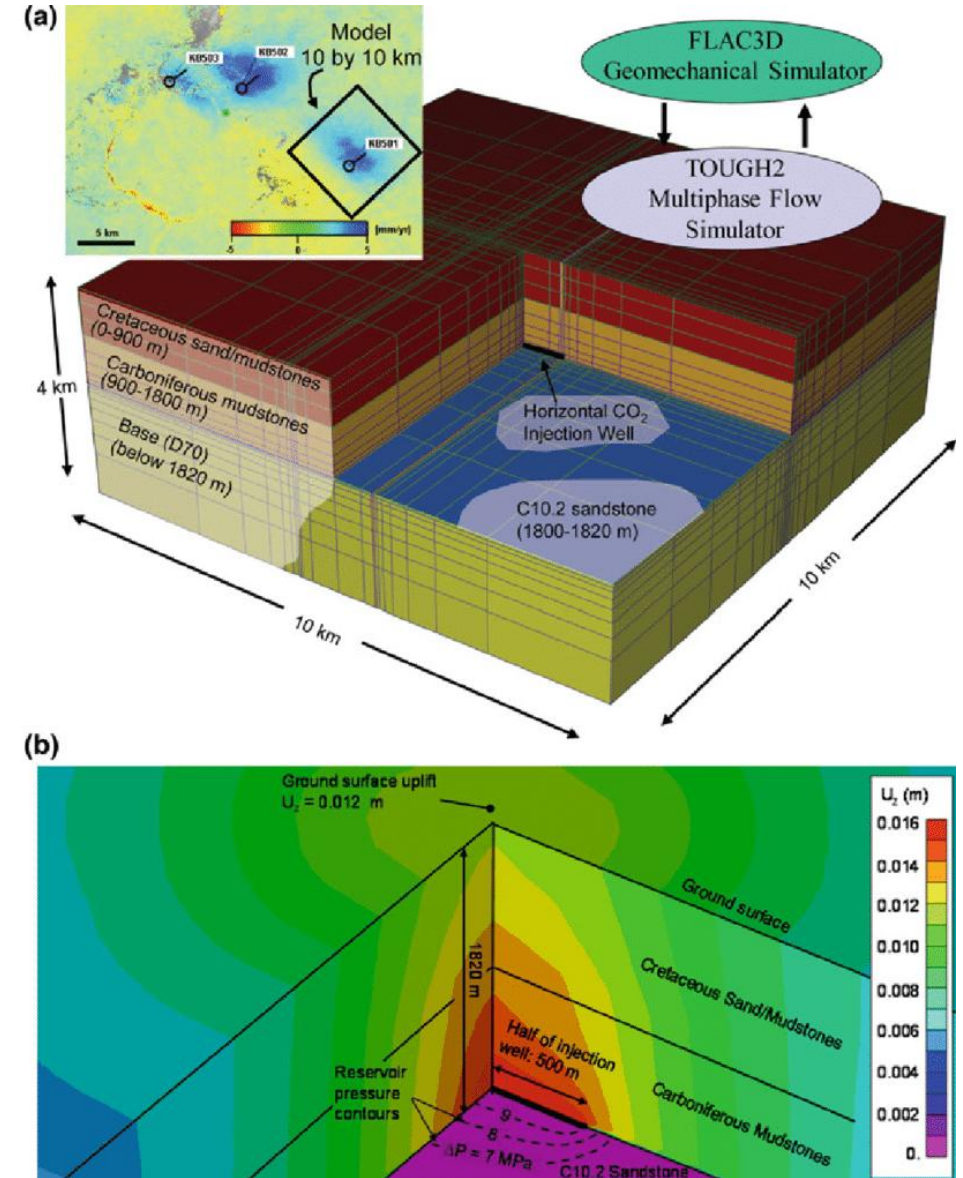
# Mechanical Rock Properties

Determine the mechanical response of geologic formations to CO<sub>2</sub> injection (state of pressure, stress, and strain / displacement)

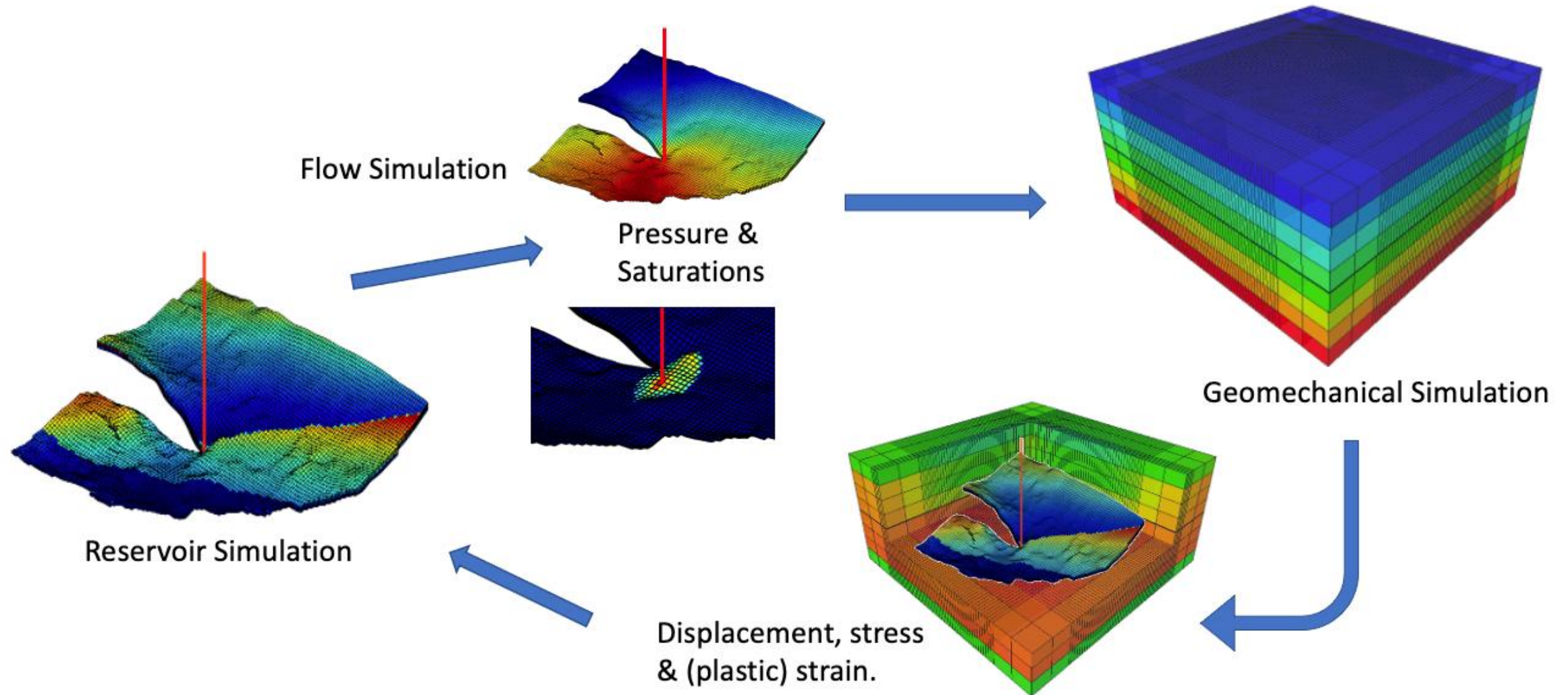


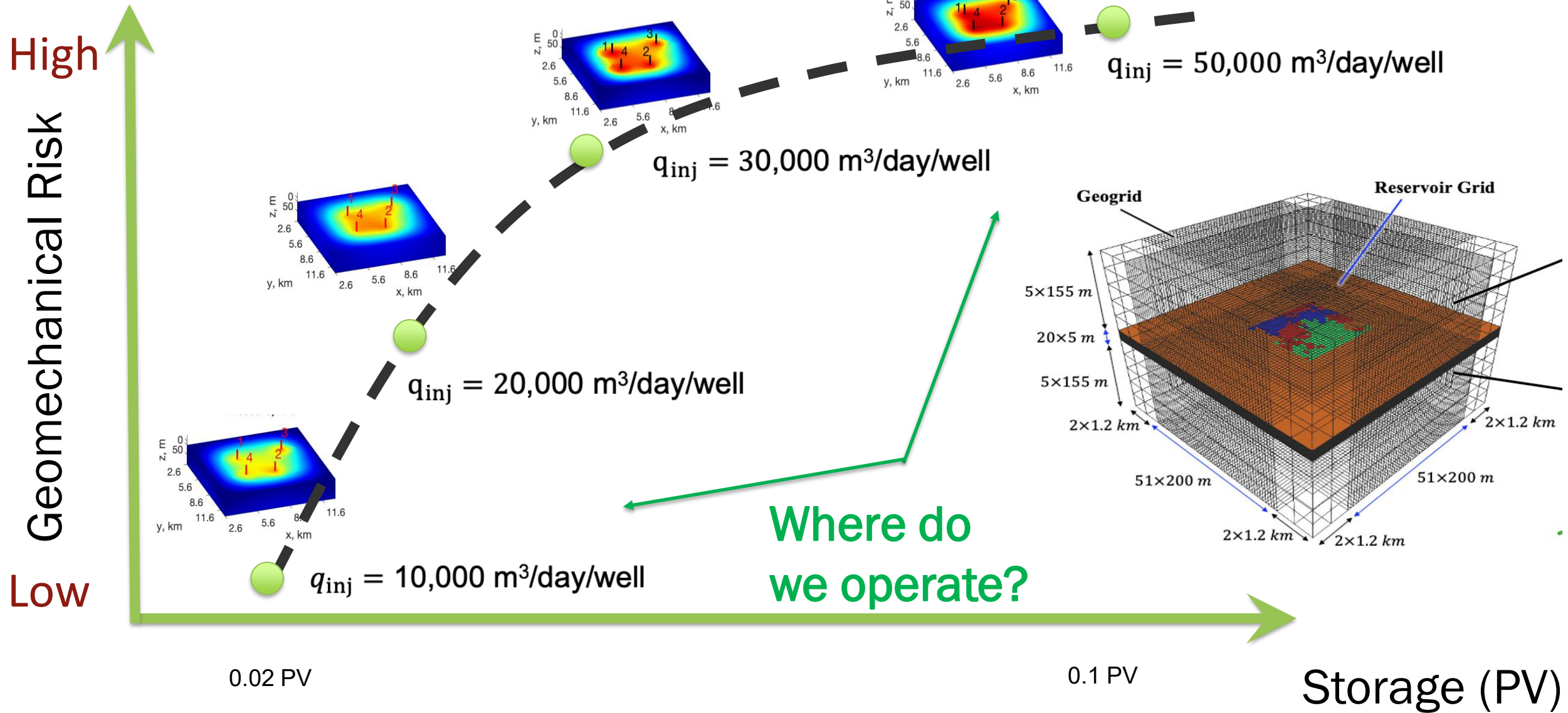
Property/rock mass

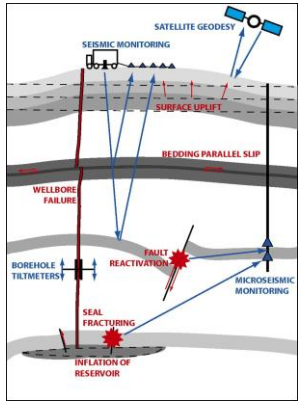
- Density, KN/m<sup>3</sup>
- $E$ , KPa
- Poisson's ratio,  $\nu$
- Cohesion, KPa
- Tensile strength, KPa
- Friction angle,  $\phi$
- Dilation angle,  $\varphi$



## Coupled Flow-Geomechanics Model



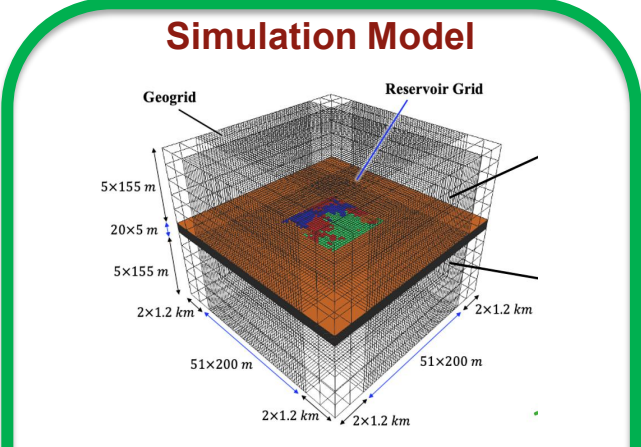




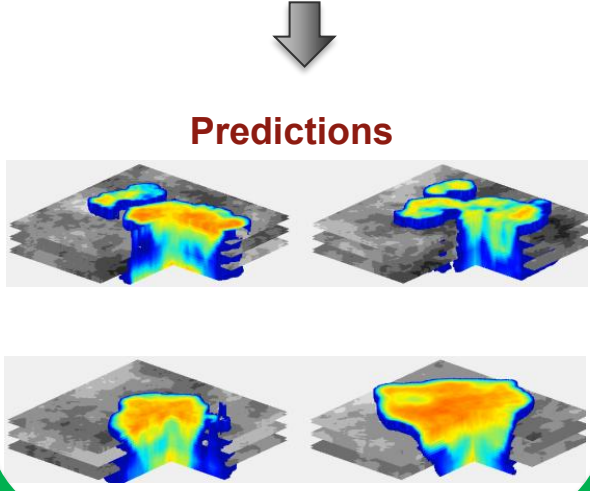
### Multimodal Monitoring

### Data Processing

## Geology and Geophysics

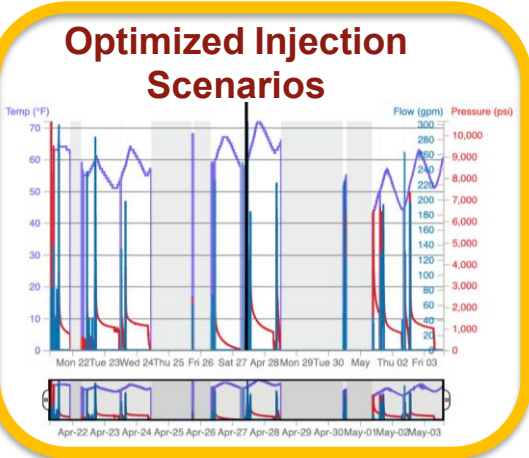


## Reservoir Engineering

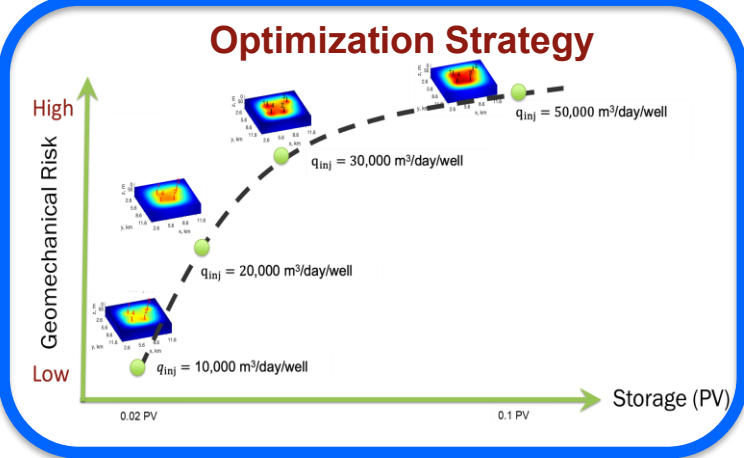


## Implement Controls

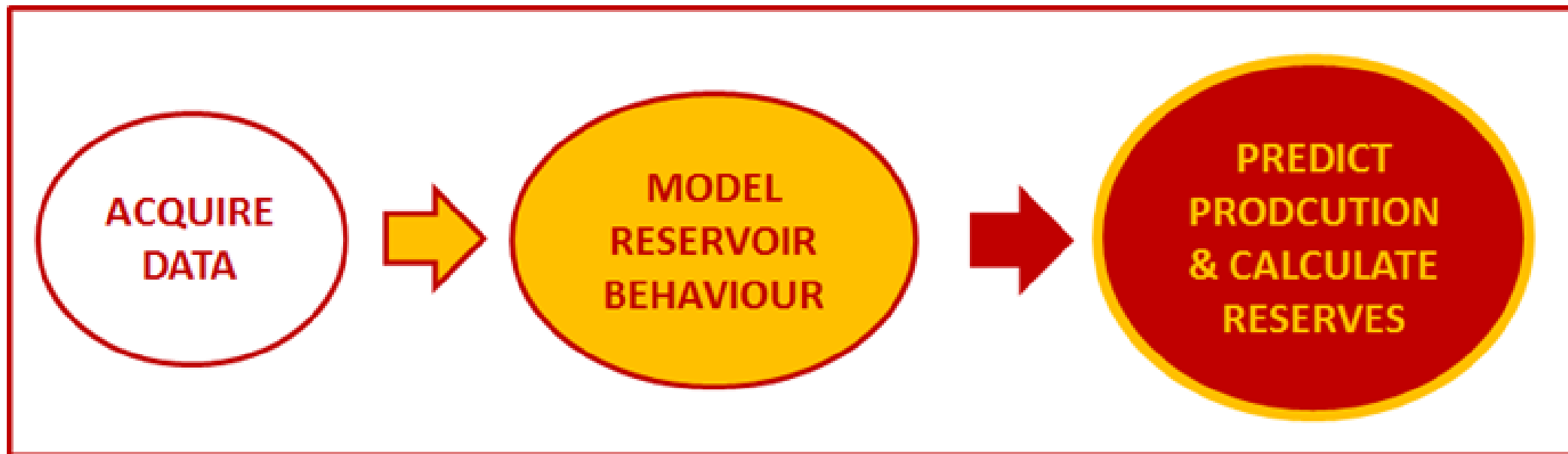
## Field Management



## Risk/Regulations



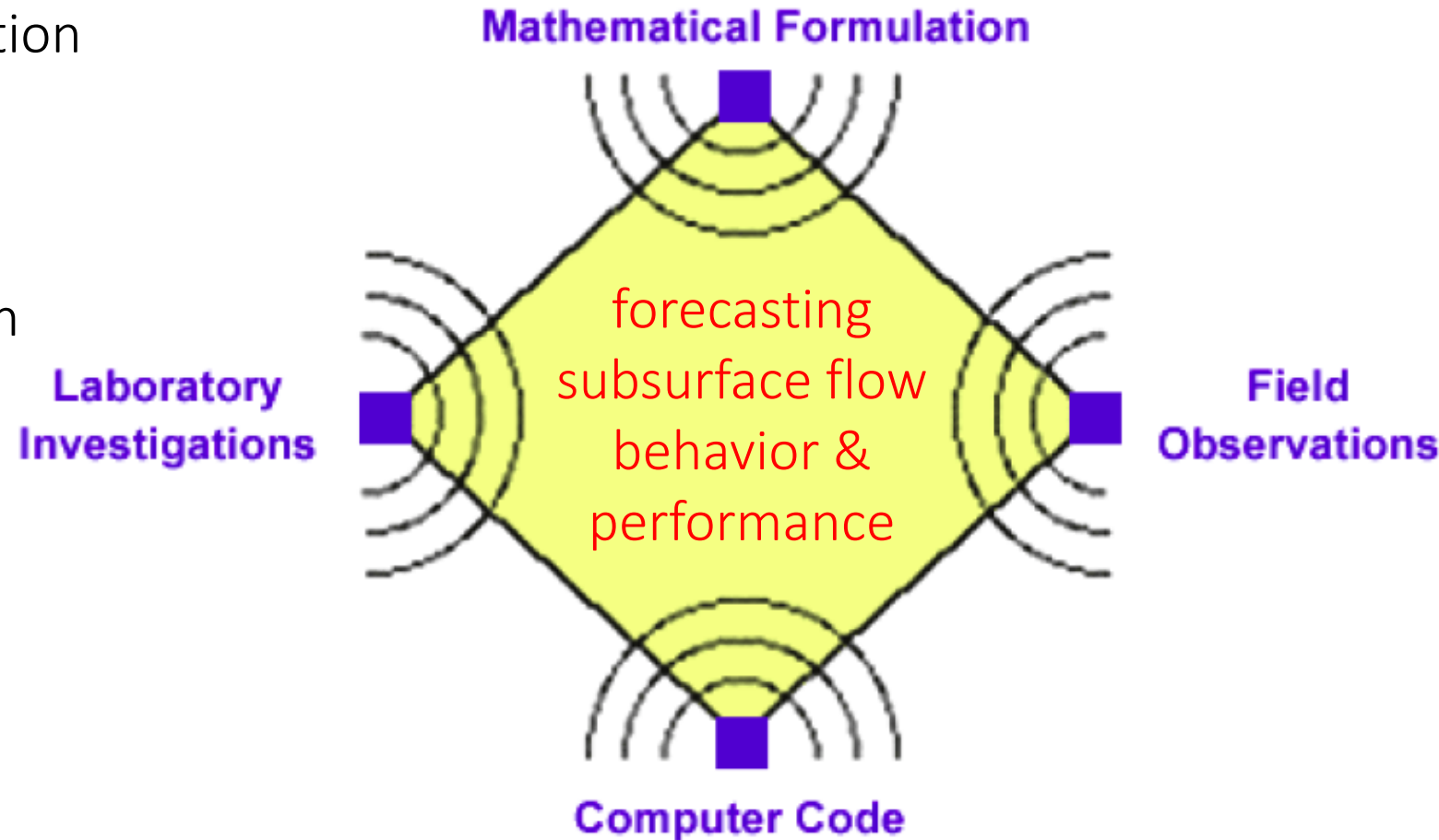
The ultimate goal of subsurface flow modeling is to **develop a predictive model that can facilitate and optimize decision making for field development, operation, and management.**

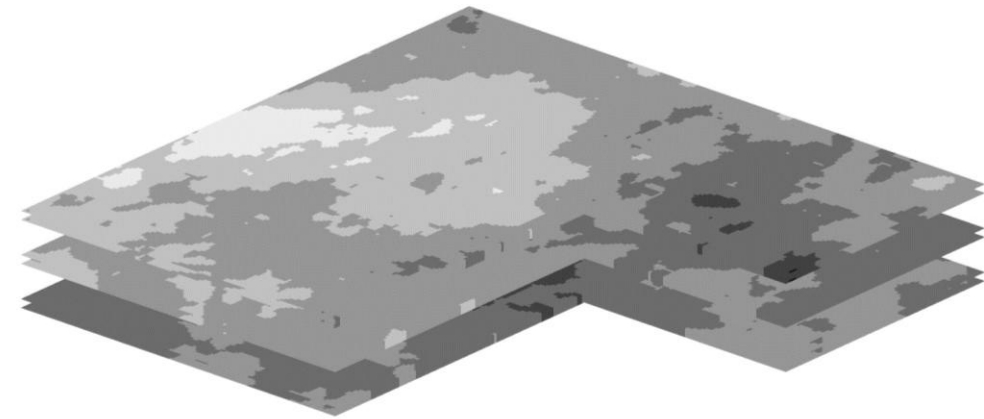
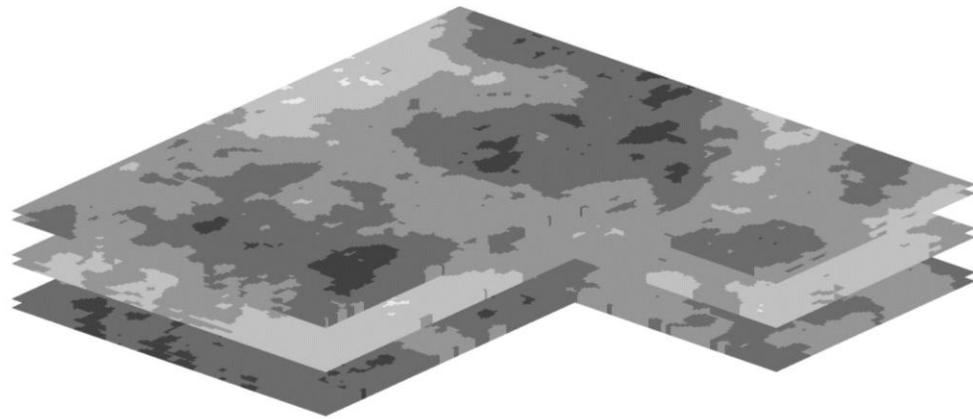
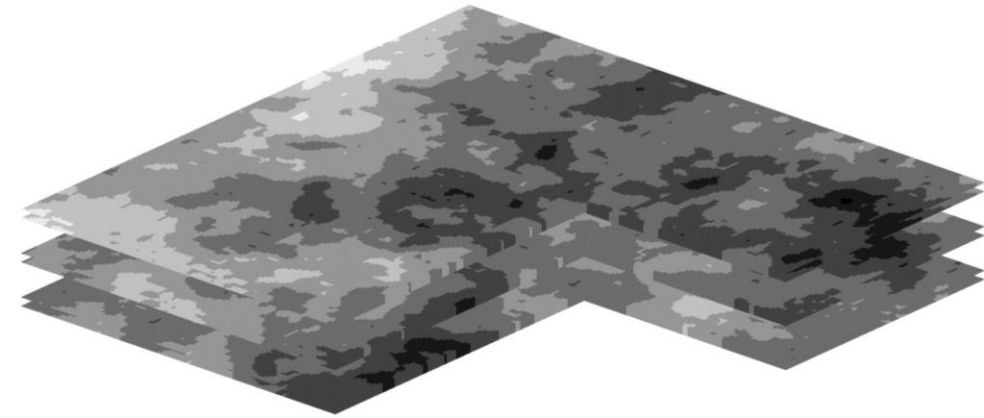
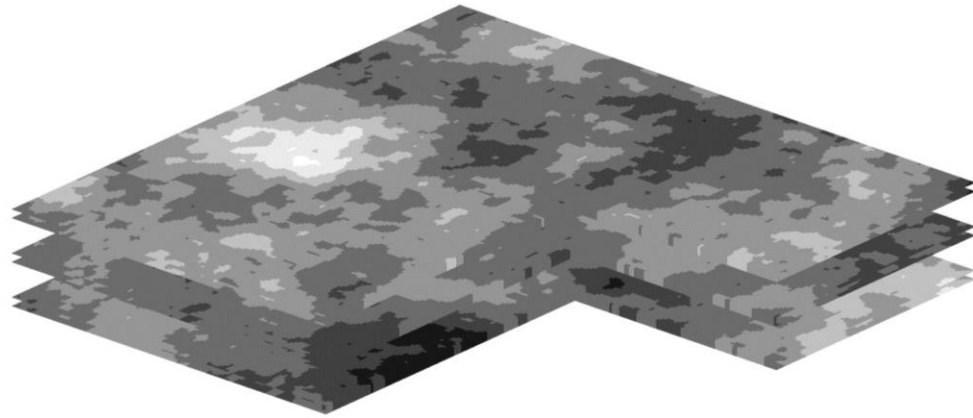


## Simulation Inputs

- Geologic Modeling and Interpretation
- Rock & Fluid Properties
- Rock-Fluid & Fluid-Fluid Interaction
- Model Geometry and Complexity
- Fluid Flow Equations
- Boundary and Initial Conditions
- Solution of Governing Equations

## Main Elements





**Engineers:** develop energy/storage resources with the **goal** of

- Maximizing efficiency
- Minimizing cost and risks
- Minimizing environmental impacts

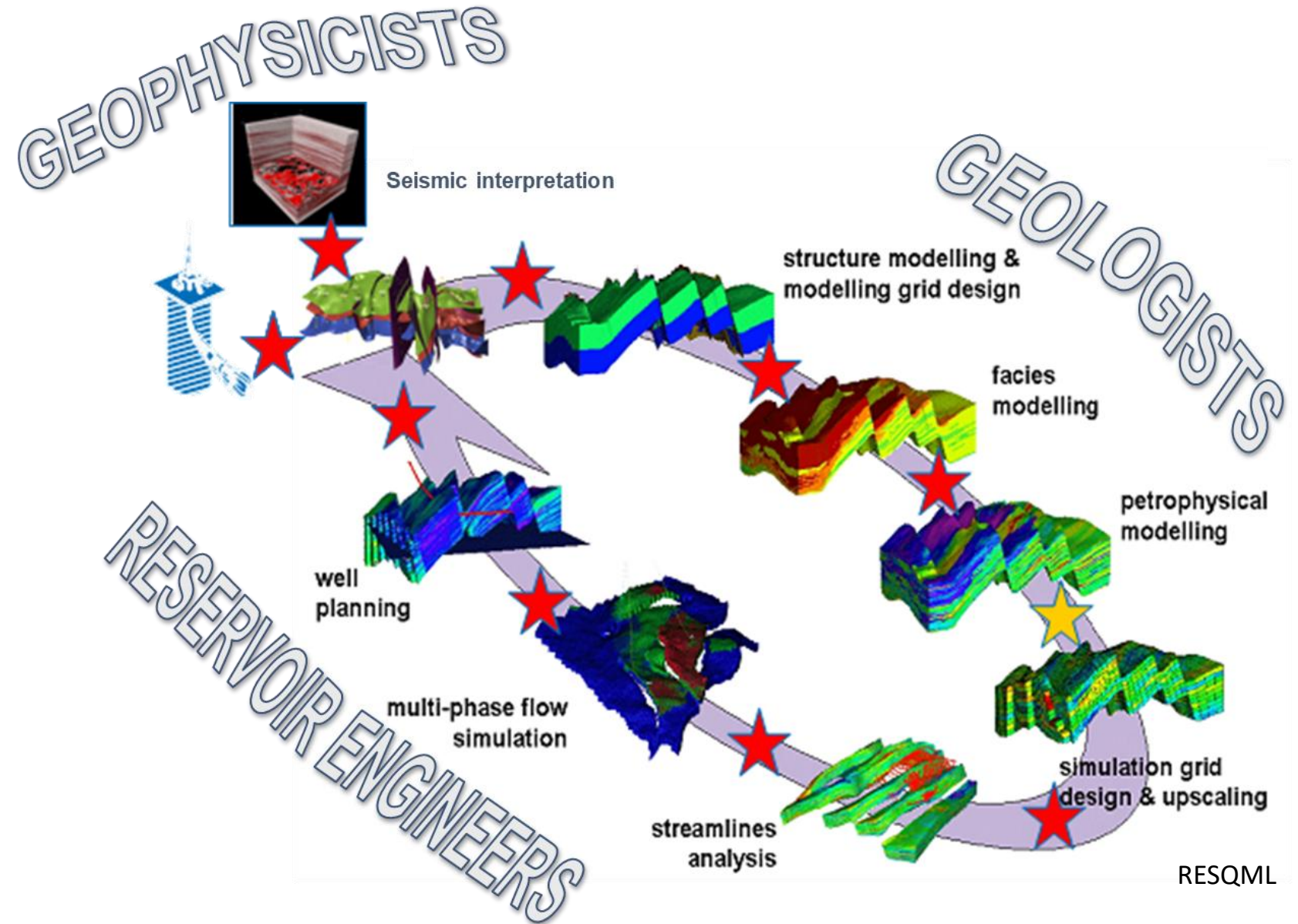
**Geologists/Geophysicists** find and characterize suitable geologic formations by analyzing subsurface structures with geological and geophysical methods.

## Interdisciplinary:

- Geophysics
- Geology
- Reservoir Engineering
- ...

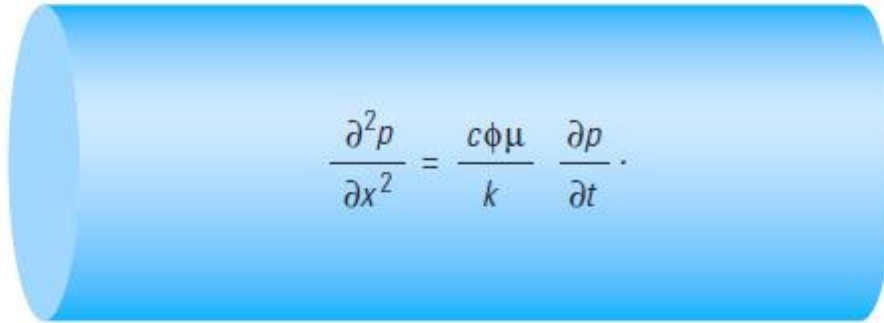
## Integrated:

- Team-based
- Closed-loop/Feedback
- Iterative



1951

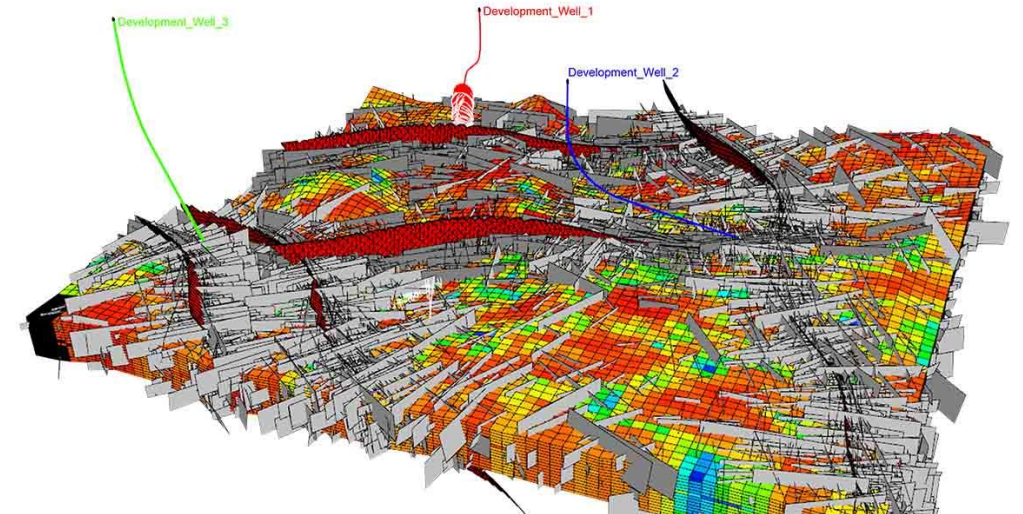
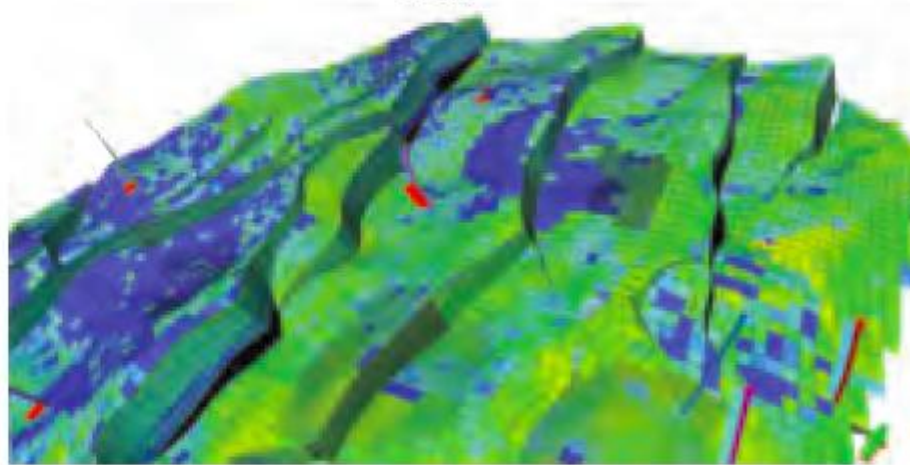
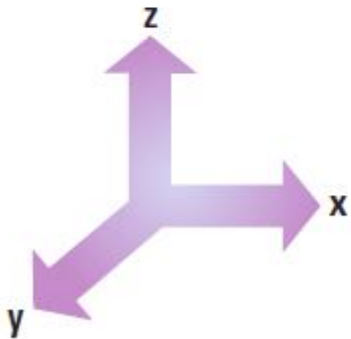
1D flow of a compressible fluid



More complex geology  
&  
More complex processes!

2011

3D flow of  $n$  components in a complex reservoir



$$\frac{V}{\Delta t} \delta \left( \phi \sum_p^{Np,c} \rho_p S_p \chi_{cp} \right) + q_c^W - \sum_k^{Faces} T_k \left\{ \sum_p^{Np,c} \left[ \rho_p \frac{k_{rp}}{\mu_p} \chi_{cp} (\Delta p - \Delta P_{Cp} - \rho_p g \Delta h) \right] \right\} = R_c.$$

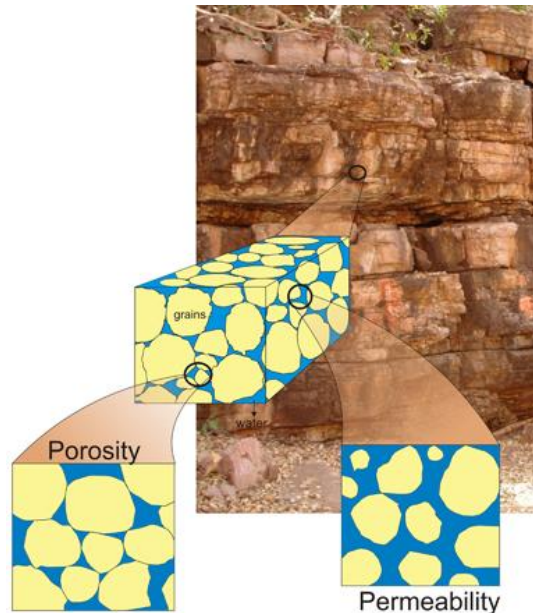
SCHLUMBERGER

Ultimate objective → forecasting reservoir performance

- *Fact-finding* → answering questions about a system or process that is already in place.
- *Development Design and Optimization* → developing a number of plausible scenarios for a process (e.g., waterflooding) and studying the system response in an attempt to determine the optimum scenario.

# Modeling Fluid Flow in Porous Media

- **Physics:** governed by **conservation principles** → Balance Equations (PDEs)
- **Key parameters:** fluid and **rock properties** & their interactions
- **Solution of governing PDEs:** over **complex large-scale geologic domains**
- **Prediction accuracy:** depends on **quality of input parameters**

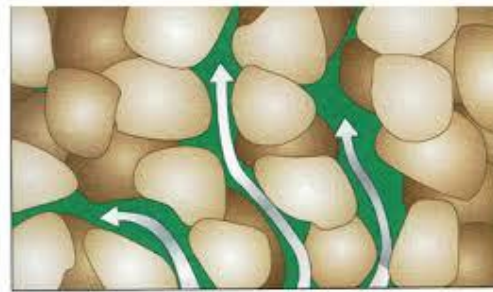


$$\nabla \cdot \left( \frac{\lambda_w}{B_w} \mathbf{u} (\nabla P_w - \gamma_w \nabla Z) \right) = \frac{\partial}{\partial t} \left( \phi \frac{S_w}{B_w} \right) + q_w$$

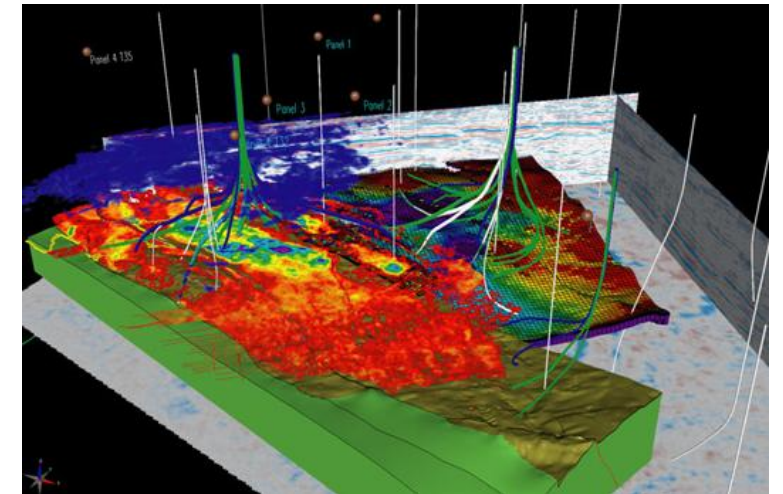
$$\nabla \cdot \left( \frac{\lambda_n}{B_n} \mathbf{u} (\nabla P_n - \gamma_n \nabla Z) \right) = \frac{\partial}{\partial t} \left( \phi \frac{S_n}{B_n} \right) + q_n$$

$$P_n - P_w = P_c(S_w)$$

$$S_n + S_w = 1$$



$$\frac{V}{\Delta t} \delta \left( \phi \sum_p^{No,c} \rho_p S_p \chi_{cp} \right) + q_c^W - \sum_k^{Faces} \Gamma_k \left\{ \sum_p^{No,c} \left[ \rho_p \frac{k_{rp}}{\mu_p} \chi_{cp} (\Delta p - \Delta P_{c,p} - \rho_p g \Delta h) \right] \right\} = R_c.$$



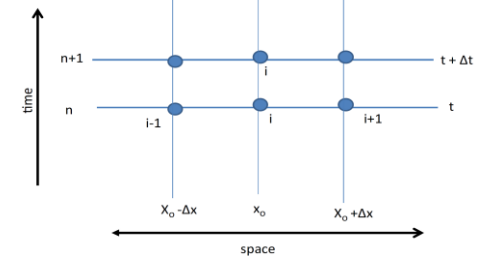
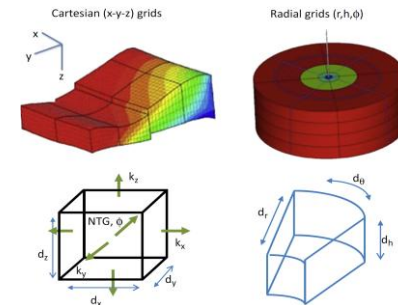
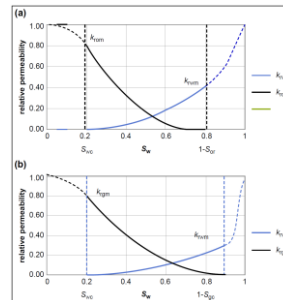
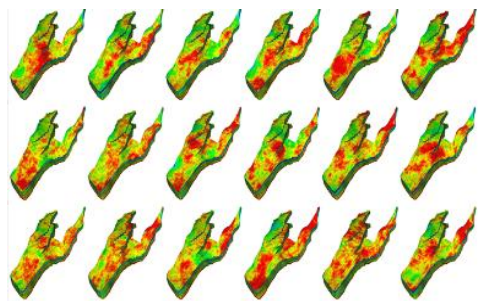
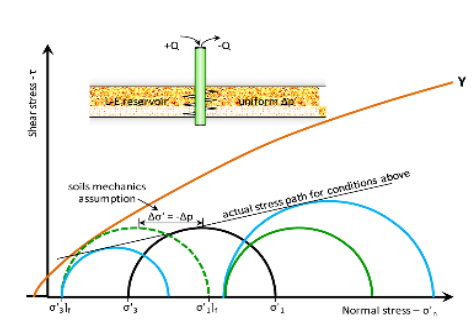
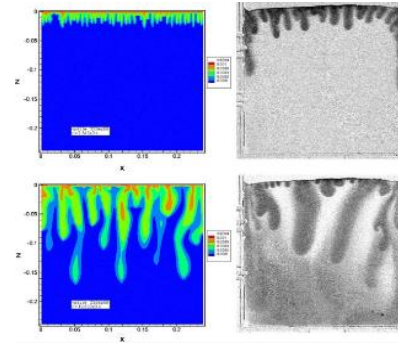
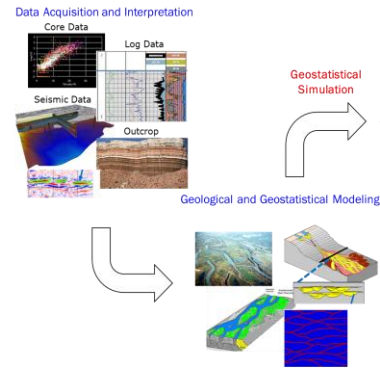
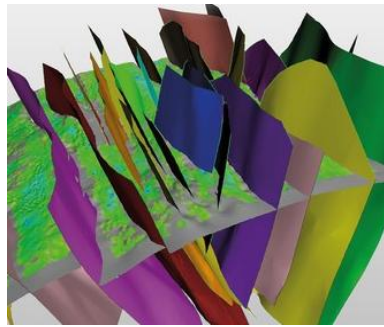
# Modeling Uncertainty

## ❖ Reservoir Description

- Geologic uncertainty
- Petrophysical properties
- PVT and SCAL Data
- Initial/Boundary conditions
- ...

## ❖ Reservoir Dynamics

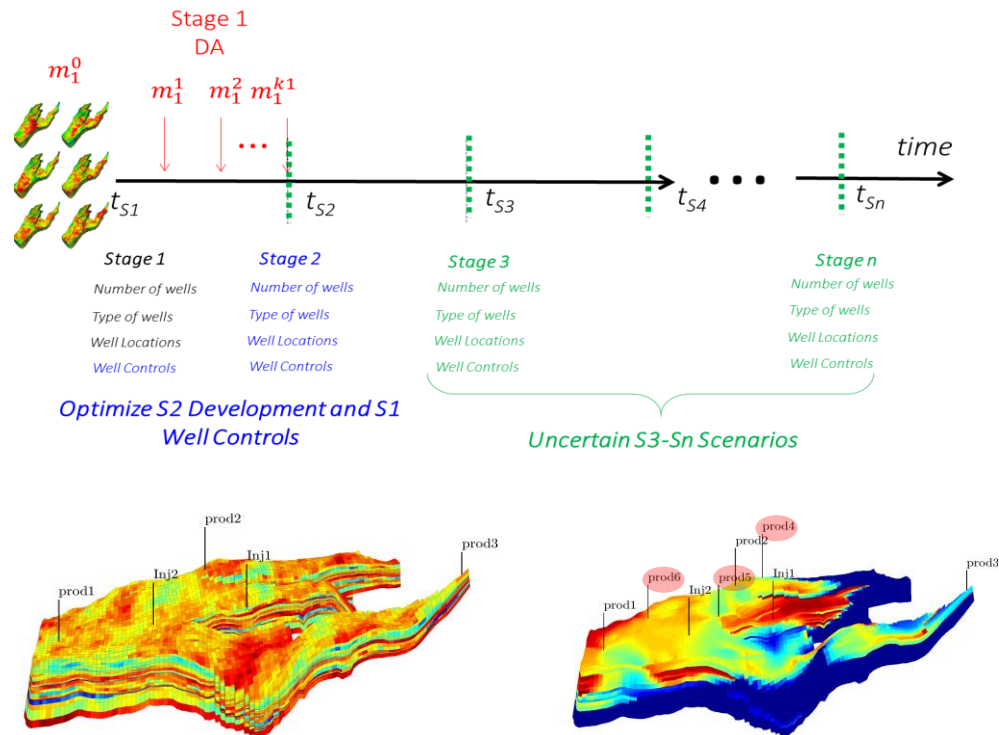
- Limited understanding
- Missed/simplified physics
- Solution Errors
- ...



# Other Uncertainties

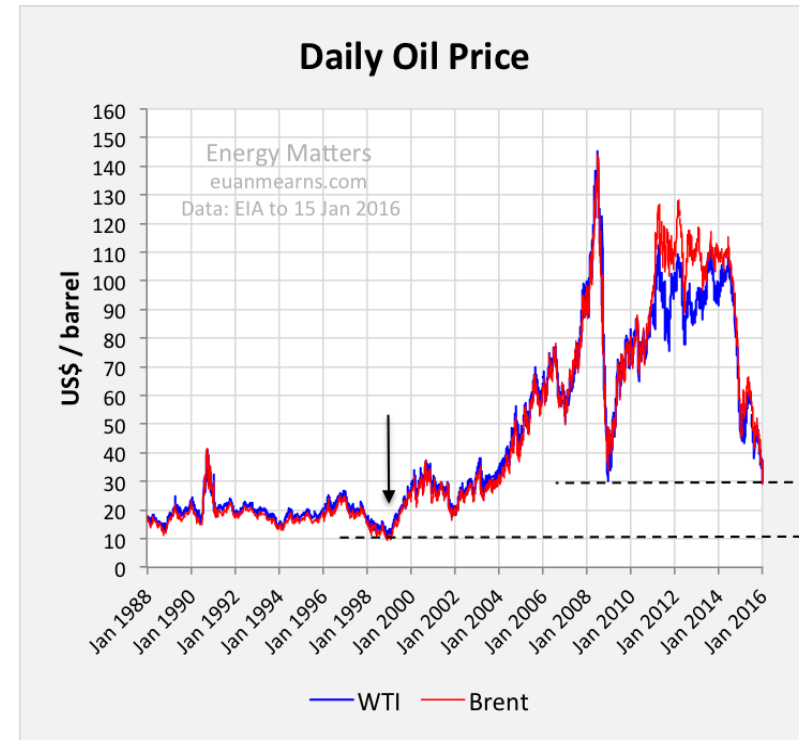
## ❖ Uncertainty in future development

- future wells (type/number)
- drilling sequence
- ...

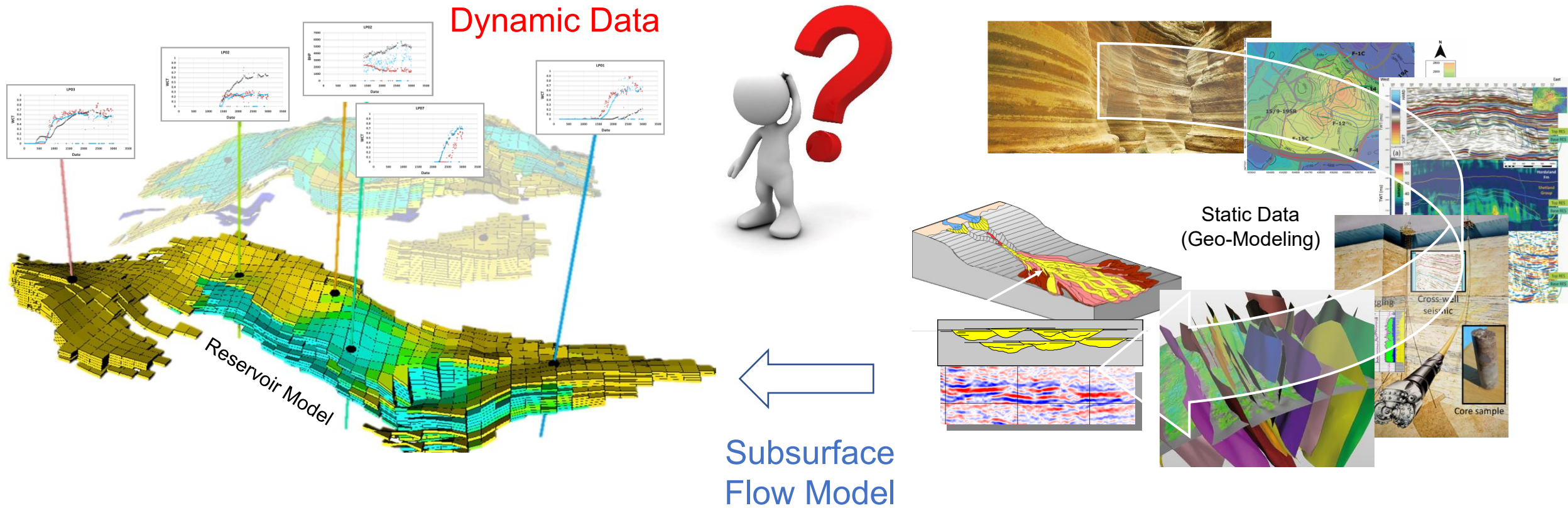


## ❖ Economic uncertainty

- OPEX
- tax benefits
- complying with regulation



## Continuously monitoring and model updating (using new data)

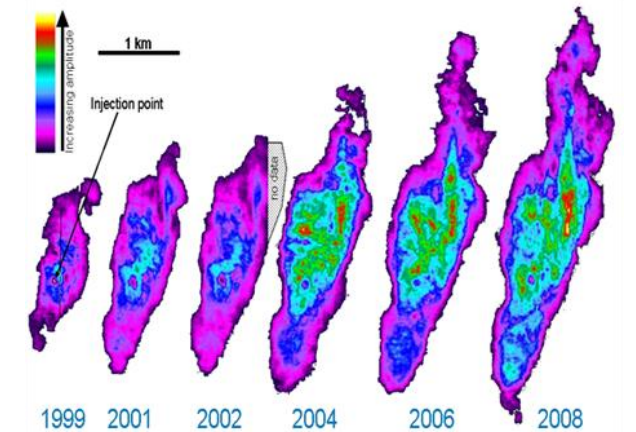
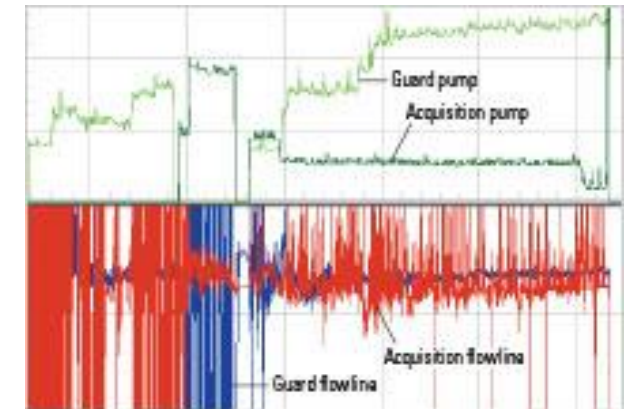
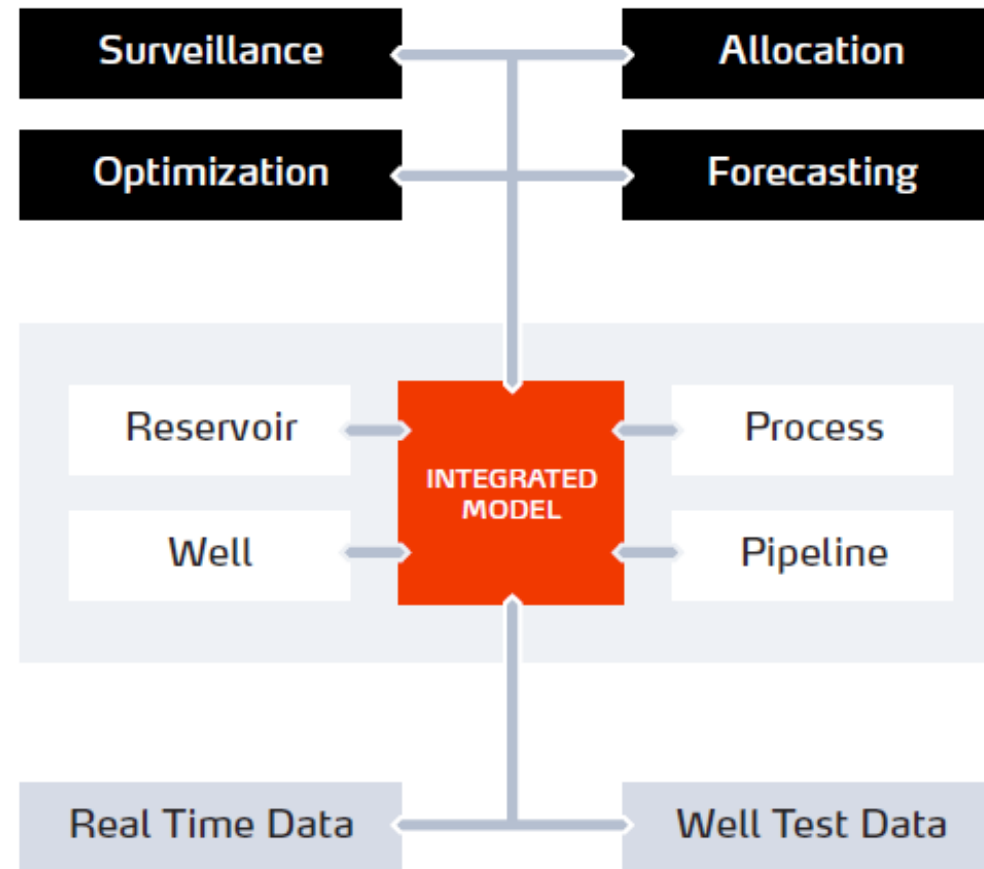


1) Monitoring injection/production quantities

3) Monitoring reservoir condition

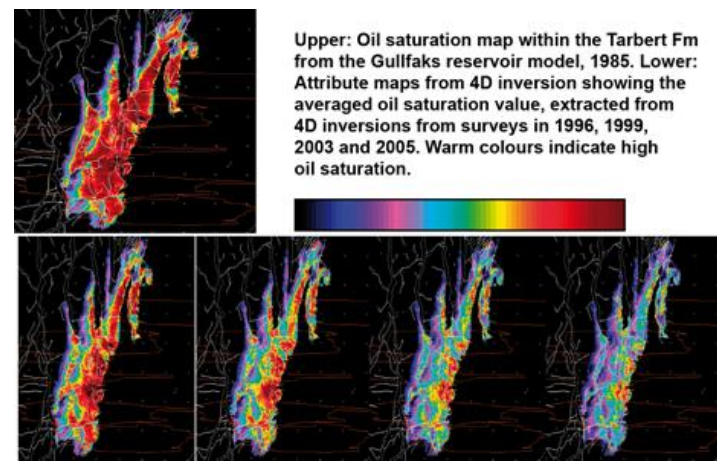
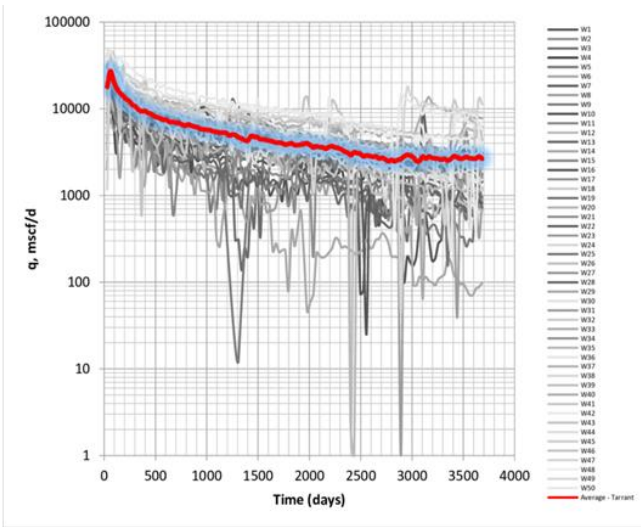
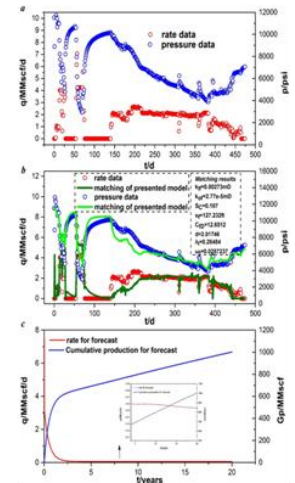
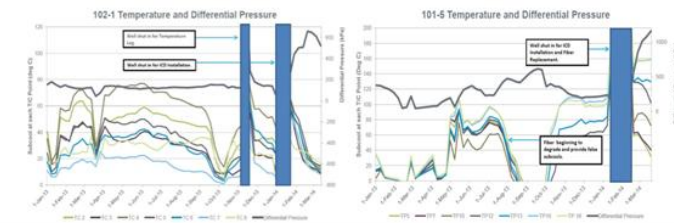
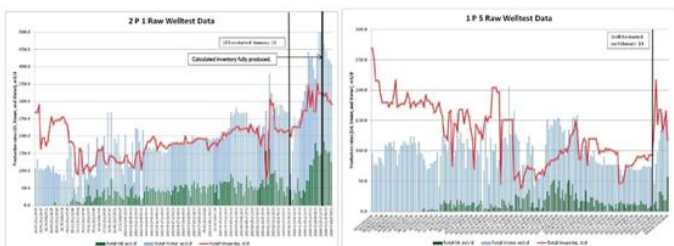
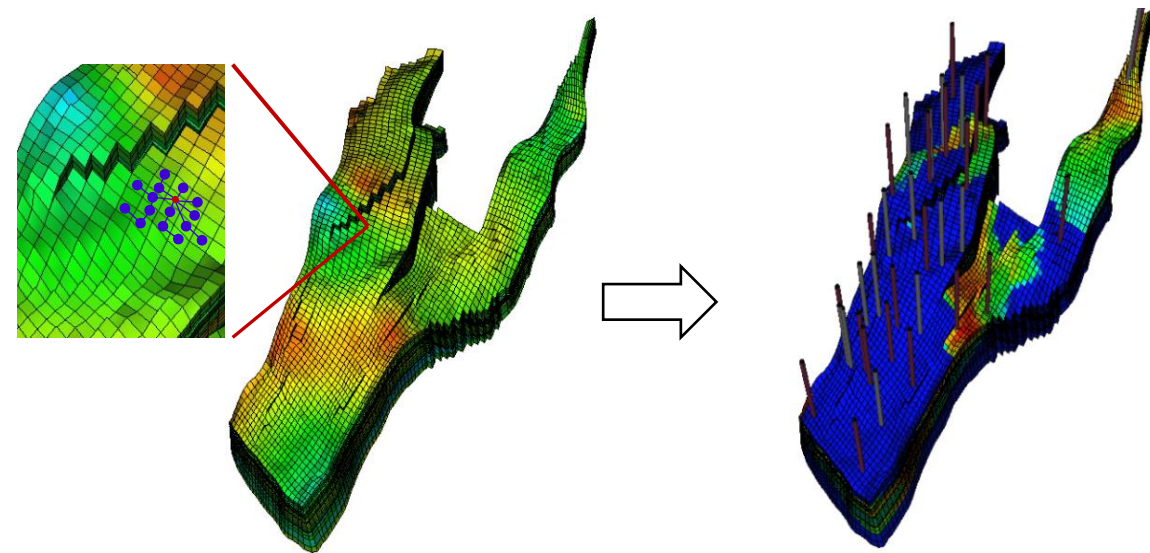
2) Monitoring well condition

4) Monitoring field performance



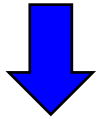
# Monitoring Data Integration

Integrating dynamic monitoring and performance data into flow simulation models to improve prediction accuracy

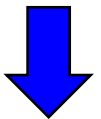


Upper: Oil saturation map within the Tarbert Fm from the Gullfaks reservoir model, 1985. Lower: Attribute maps from 4D inversion showing the averaged oil saturation value, extracted from 4D inversions from surveys in 1996, 1999, 2003 and 2005. Warm colours indicate high oil saturation.

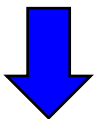
Monitor Measure



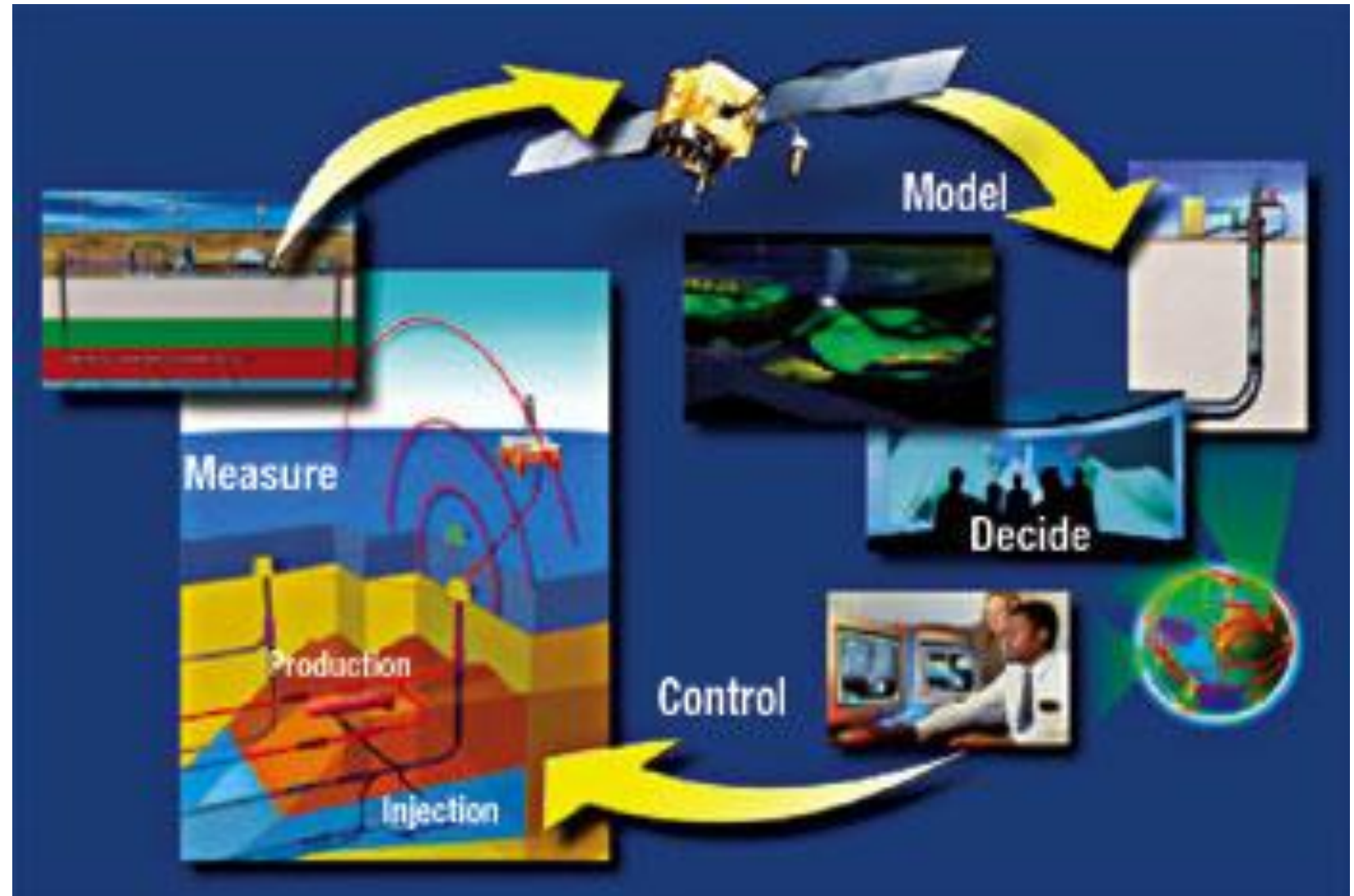
Update & Predict



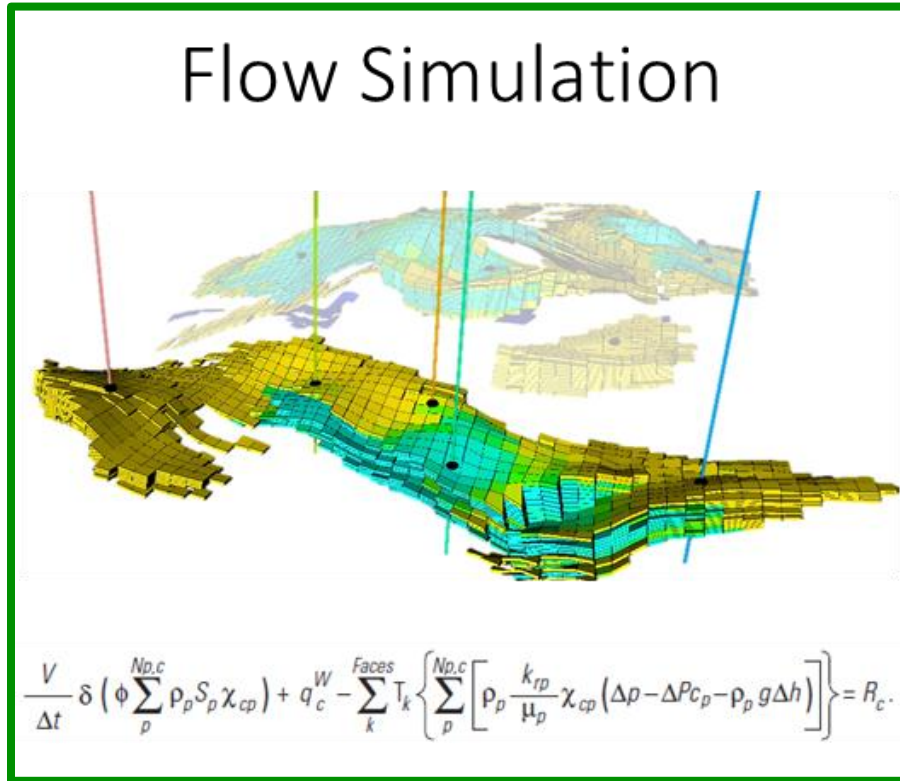
Decide



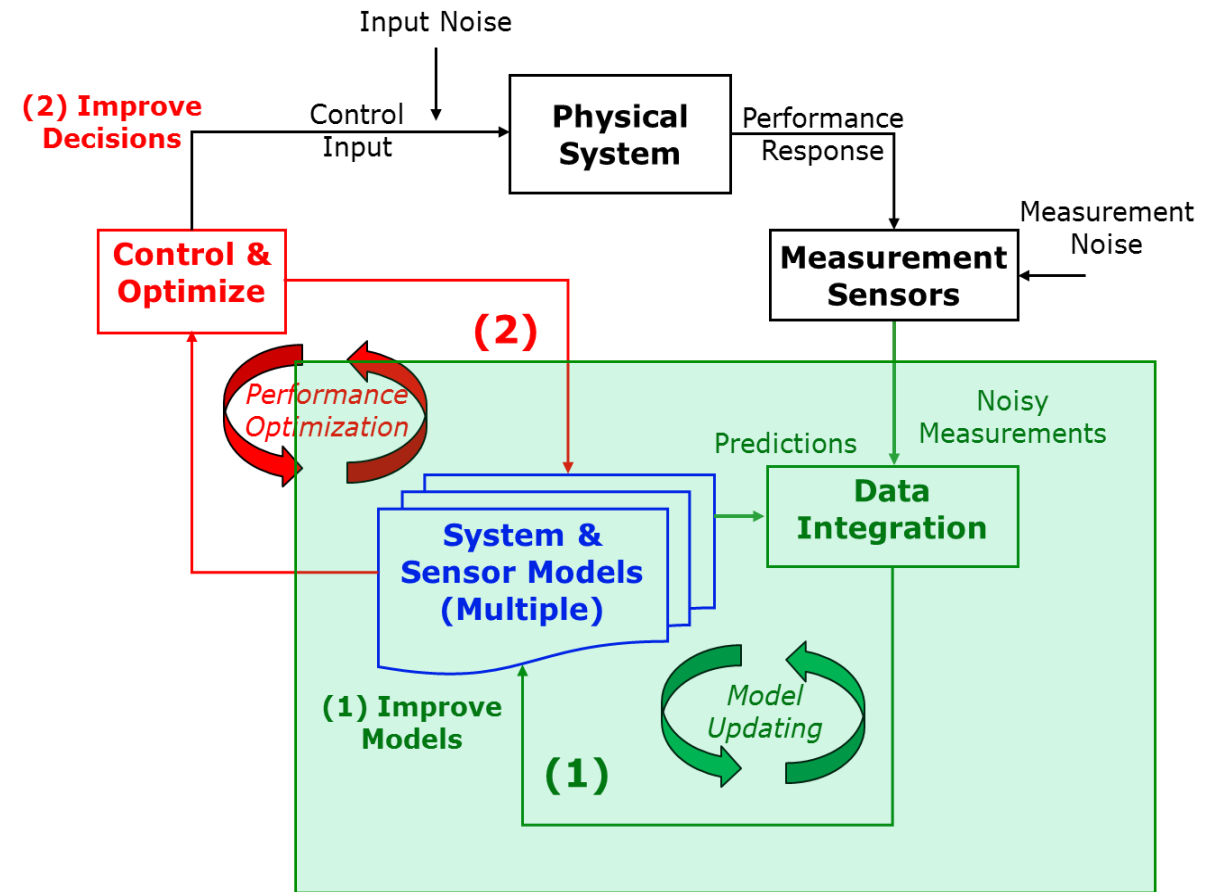
Control/Optimize



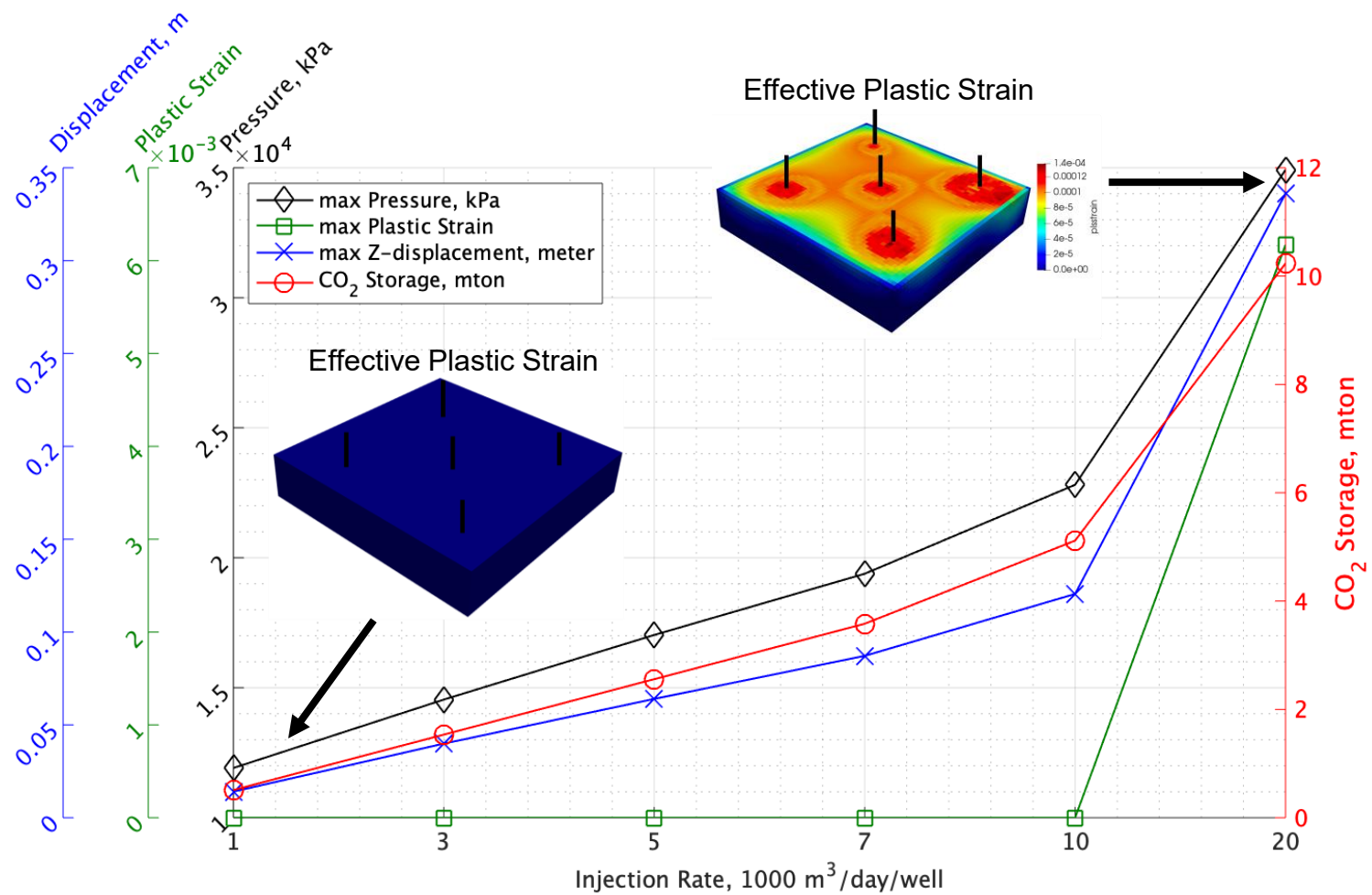
## Simulation models as prediction tools for performance optimization



Need Reliable Predictions!



## Minimizing Pressure Increase while Maximizing Storage Capacity

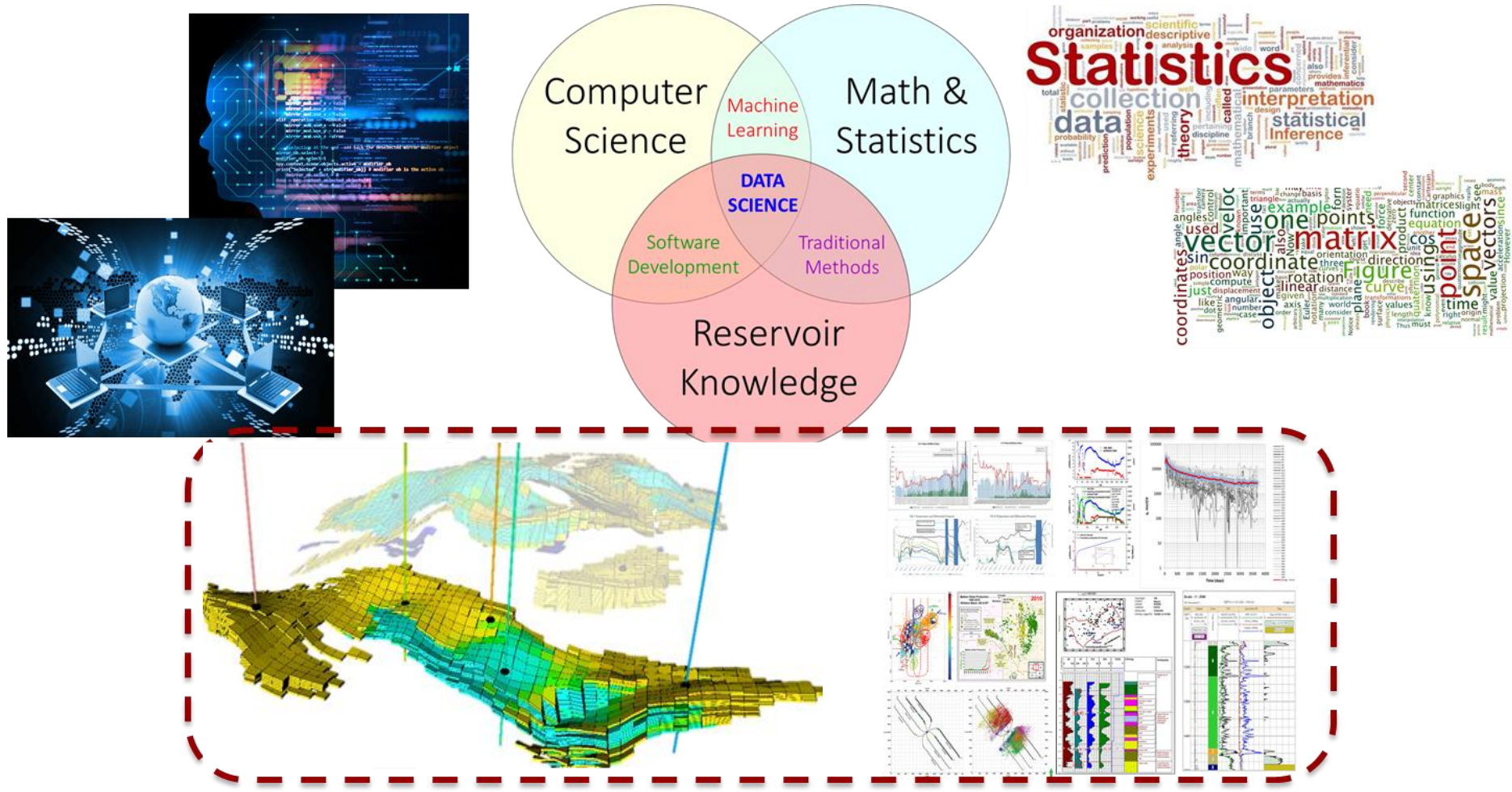


Goal { max Storage  
min Risks & Leakage

by adjusting

Variables { Well Locations  
Injection Rates

## Empowering the Development of Subsurface Storage Reservoirs





# CO<sub>2</sub> Storage Modeling, Analytics & Risk Reduction Technologies (CO<sub>2</sub>-SMART)



[co2smart.usc.edu](http://co2smart.usc.edu)

**NATIONAL SCIENCE FOUNDATION**

**INDUSTRY-UNIVERSITY COOPERATIVE RESEARCH CENTER**



**USC Viterbi**  
School of Engineering



**IUCRC**



**PennState**  
College of Earth  
and Mineral Sciences

## PARTNERSHIP



### Government

NSF catalyzes partnership; other agencies join as Members or co-fund the Center



### Universities

Provide **research infrastructure**, human capital, and **technical expertise**.



### Industry

Members provide funds for research and **insight into needs** of the economic sector.

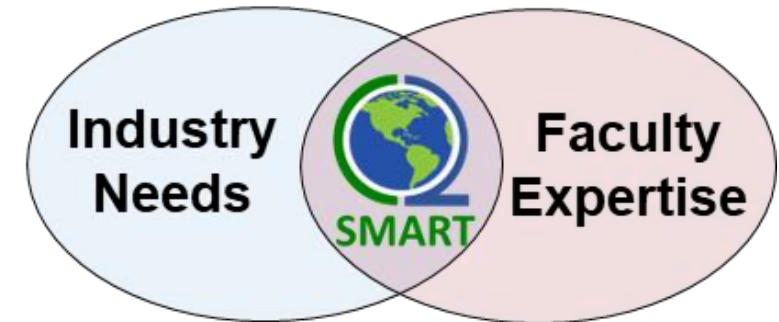


### IUCRCs Focus:

bridge the gap between academic research and commercial deployment.

## Stakeholders

**Universities**  
**Industry**  
**Government**  
**Foundations**

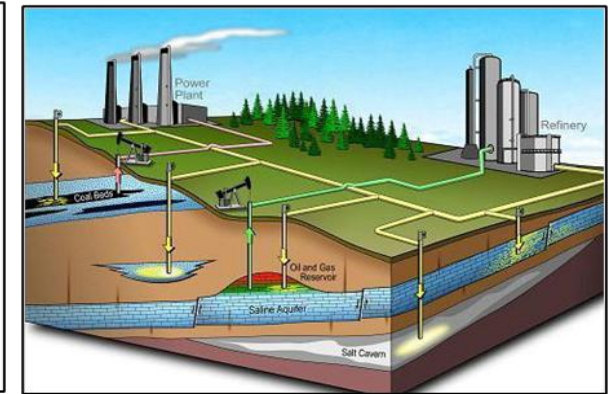
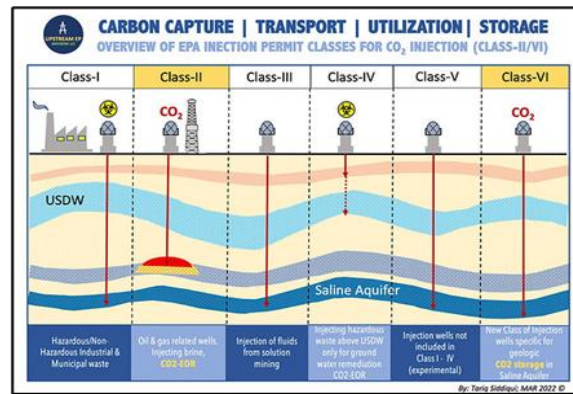
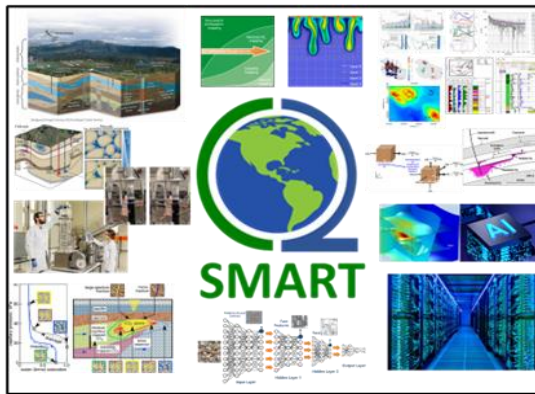


To deliver scientific and technological solutions for safe, scalable, and cost-effective deployment of geologic carbon storage

- Drives science and innovation for safe and & CO<sub>2</sub> storage
- Accelerate deployment via real-time monitoring and de-risking
- Build a skilled, industry-ready workforce
- Foster collaboration and technology transfer

- **Economics:** High capital investment and operating costs (business model)  
Incentives (carbon pricing, credits, etc.), and technologies to improve economics, ...
- **De-Risking:** Policy and Regulation, Permitting, Liabilities  
Clear/efficient permitting process, guidelines for monitoring/verification, mitigation plans, ...
- **Scale-up:** Infrastructure for commercial-scale deployment  
CCS clusters (hubs) to share capture, transport, and storage infrastructure, ...
- **Public Support:** Perception vs reality (safety concerns, leakage, seismicity)  
Public outreach and communication, community support, ...
- **Workforce Development:** Competency in CCS (industry/regulatory agencies)  
Demand for skilled workforce to meet the anticipated growth in GCS projects, ...

Science-based information to help address key challenges and accelerate safe and cost-effective GCS deployment at scale.



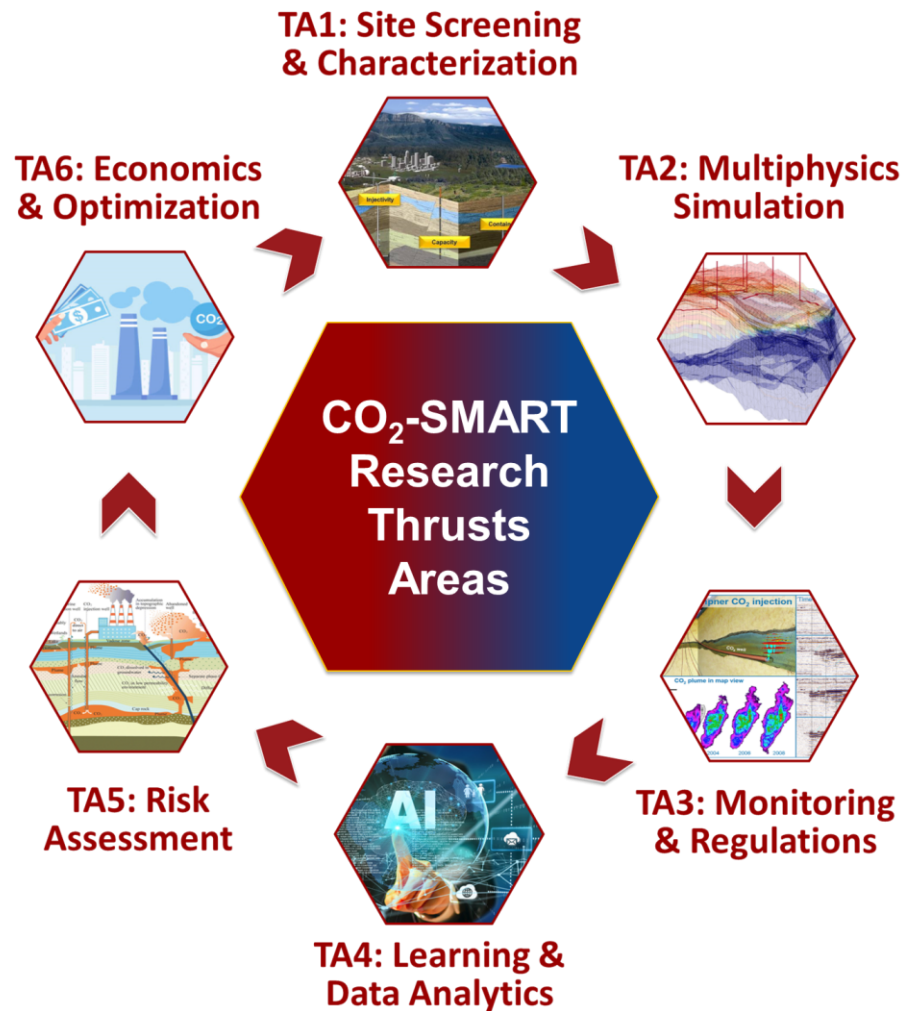
Advance GCS Science & Technology

Inform GCS Policies and Regulations

Develop Workforce & Educate the Public

Enable Safe & Cost-Effective Deployment

**Industry-University-Government Collaboration is Critical**



## USC Engineering+



## PSU Geoscience+

**Behnam Jafarpour**  
Professor (Center Director)  
*Subsurface Energy Systems*



**Roger Ghanem**  
Professor  
*Risk & Uncertainty*



**Birendra Jha**  
Assistant Professor  
*Multiphysics Simulation*



**Yan Liu**  
Professor  
*Machine Learning*



**Felipe de Barros**  
Associate Professor  
*Subsurface Flow*



**Iraj Ershaghi**  
Professor  
*Well Testing*



**Donald Paul**  
Professor  
*Industry Lead*



**Maurena Nacheff-Benedict**  
Executive Director  
*Corporate/Foundation Relations*



**Sanjay Srinivasan**  
Professor (PSU Site Director)  
*Geostatistical Characterization*



**Tieyuan Zhu**  
Associate Professor  
*Geophysical Monitoring*



**Anne Menefee**  
Assistant Professor  
*Geochemistry & Rock Minerals*



**Eugene Morgan**  
Associate Professor/Industry Liaison  
*Subsurface Data Assimilation*



**Seth Blumsack**  
Professor  
*Energy Policy & Economics*



**Hannah Wiseman**  
Professor  
*Energy Law & Regulations*



**Parisa Shokouhi**  
Professor  
*Lab Geophysics Monitoring*



**Derek Elsworth**  
Professor  
*Permeability & Injectivity*

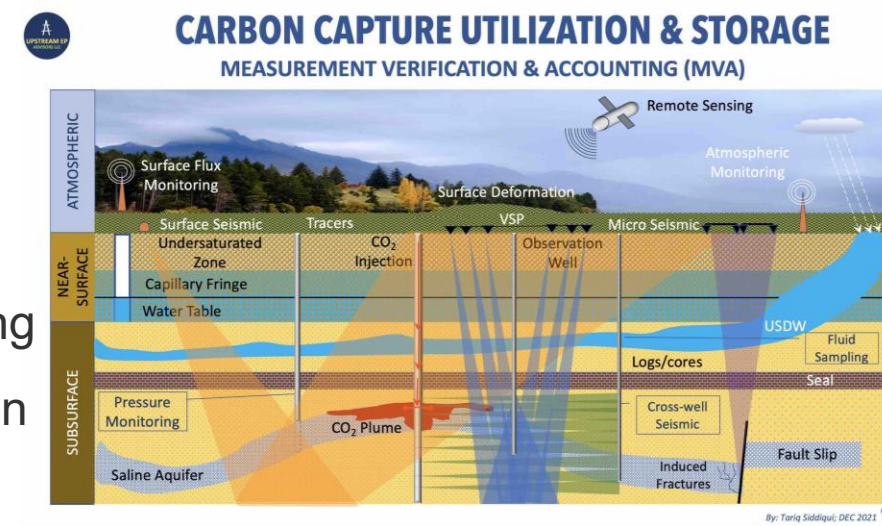
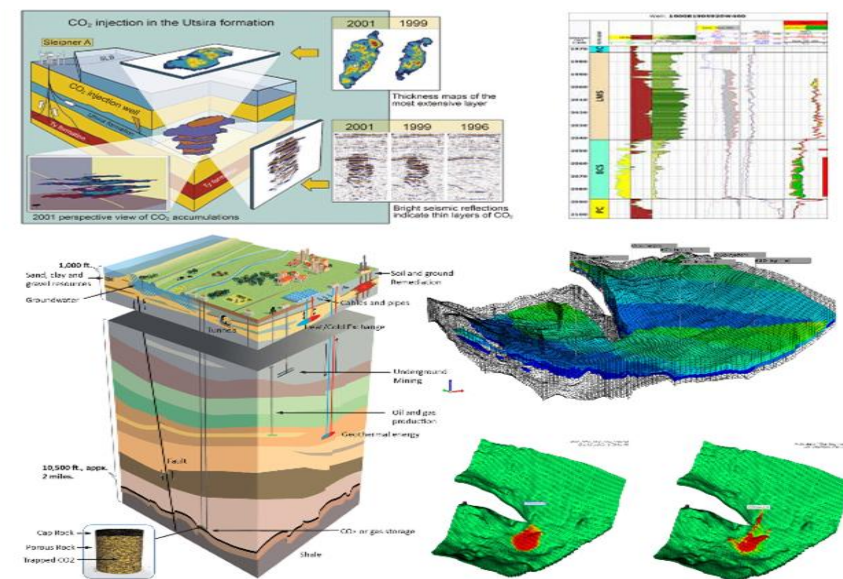


## Technical Challenges:

- Significant uncertainty in subsurface description/knowledge
- Complex physics concerning long-term behavior of injected CO<sub>2</sub>
- Risk assessment and mitigation (leakage, seismicity)
- Challenging economics (cost-driven, fewer surveys, sparse data)
- Regulatory requirements (permitting, monitoring, liability issues)

## R&D Focus:

- Building on **experience within subsurface community**
- Addressing **scientific gaps** to tackle industry challenges
- **De-risking** strategies (pre-emptive risk management)
- **Monitoring**: real-time, low-cost, design/optimization, data processing
- **Efficiency and agility**: AI, automation, anomaly detection, mitigation



- Hydrocarbons supply > 80% of energy needs power/ transportation
- As we transition our fossil-based energy resources to renewable sources, we need to reduce CO<sub>2</sub> emissions
- Geologic CO<sub>2</sub> storage can help mitigate the impact of fossil fuels
- Developing subsurface energy and storage systems rely on advanced technologies that are rooted in Science, Technology, Engineering, Mathematics

Important frontiers of research:

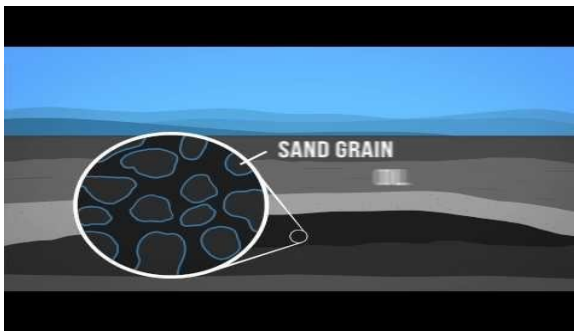
- **Technology for subsurface monitoring & characterization**
- **Technology of maximizing Storage efficiency**
- **Technology to enable environmental safety**

Understanding subsurface energy/environmental systems and their underlying processes requires skills in  
**Science, Technology, Engineering, Mathematics**

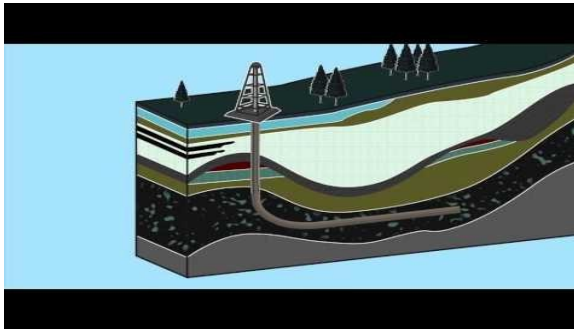
## Fossil Fuels



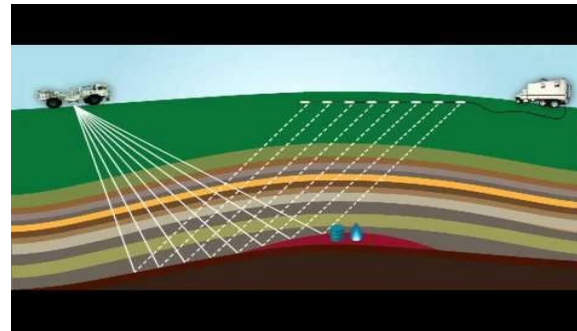
## Conventional



## Unconventional



## Seismic Exploration



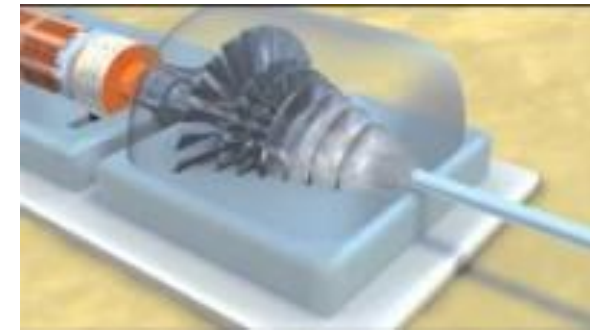
## Reservoir Simulation



## Petroleum Engineers



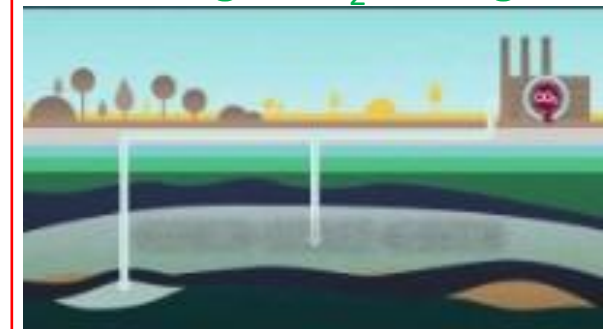
## Geothermal Energy



## Groundwater



## Geologic CO<sub>2</sub> Storage





<https://www.youtube.com/watch?v=GgISLuWP5cM>

# Subsurface Energy Systems and Geologic CO<sub>2</sub> Storage

2025 Virtual Colloquium on Energy Transition, July 28-29, 2025

**USC Viterbi**  
School of Engineering

**Behnam Jafarpour, Professor**

Chemical Engineering and Material Science, Electrical and Computer Engineering  
Civil and Environmental Engineering

