

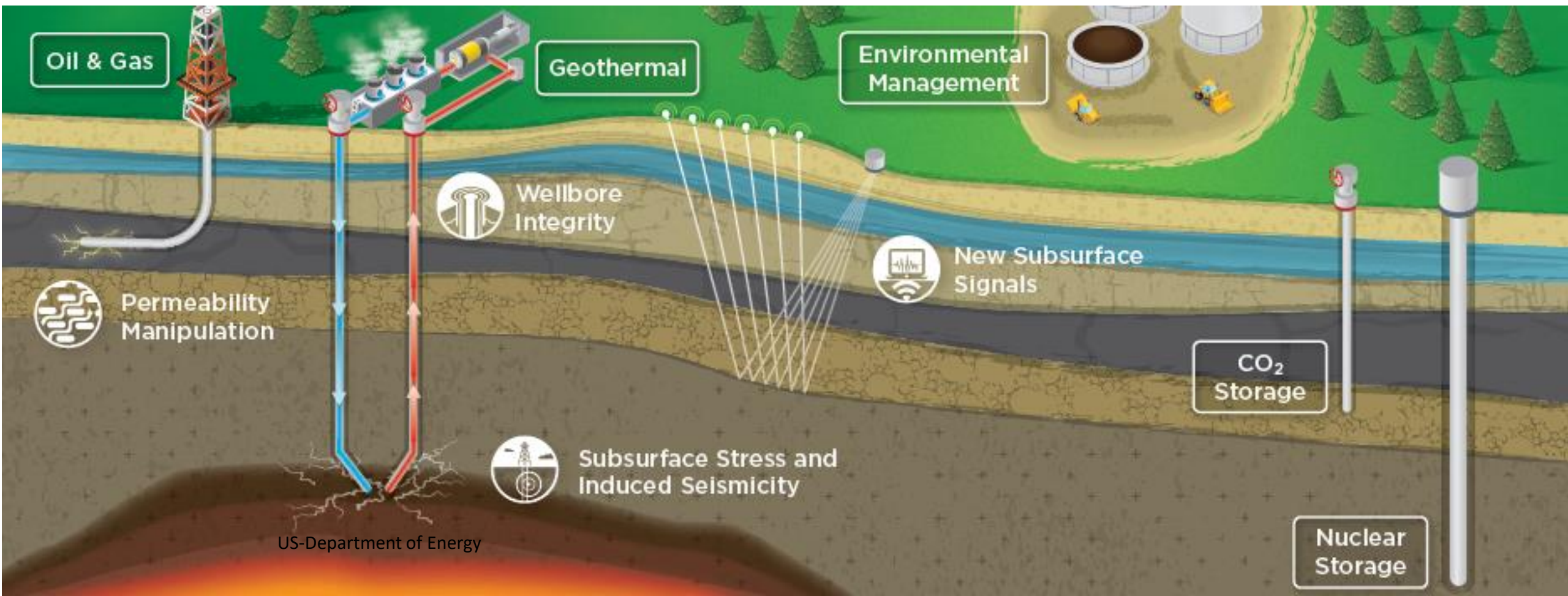
Subsurface Energy Systems and Geologic CO₂ Storage

2023 Virtual Colloquium on Energy Transition, July 24-25, 2023

USC Viterbi
School of Engineering

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





(ii) Description and Characterization of Complex Geosystems

Describing Complex Geosystems

Compact/Sparse Representations

(ii) Dynamic Model Updating and Uncertainty Quantification

Integrating Dynamic Data into GeoModels

Quantifying and Reducing Uncertainty

(iii) Field Development Optimization

Optimizing Subsurface Resource Recovery

Unconventional GCS

(iv) Data Science for Prediction and Decision Support

Machine Learning & Predictive Analytics

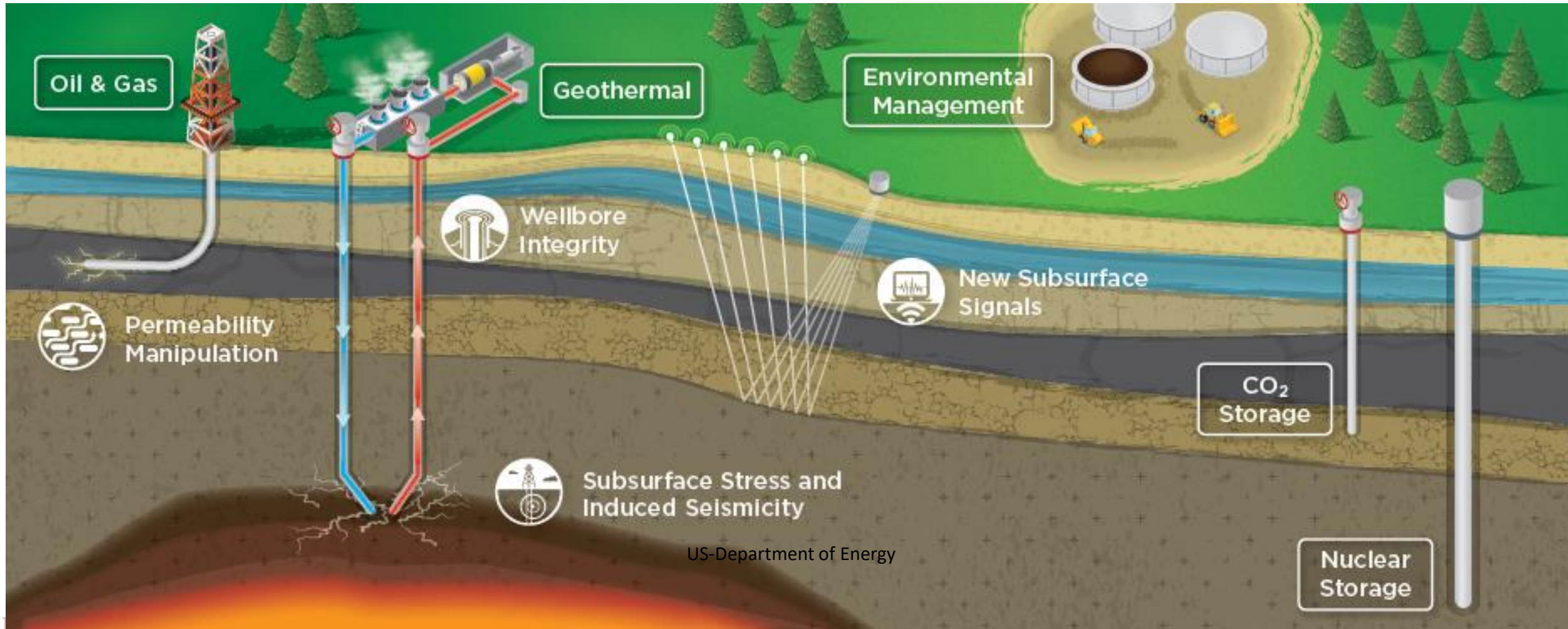
US Department of Energy:

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

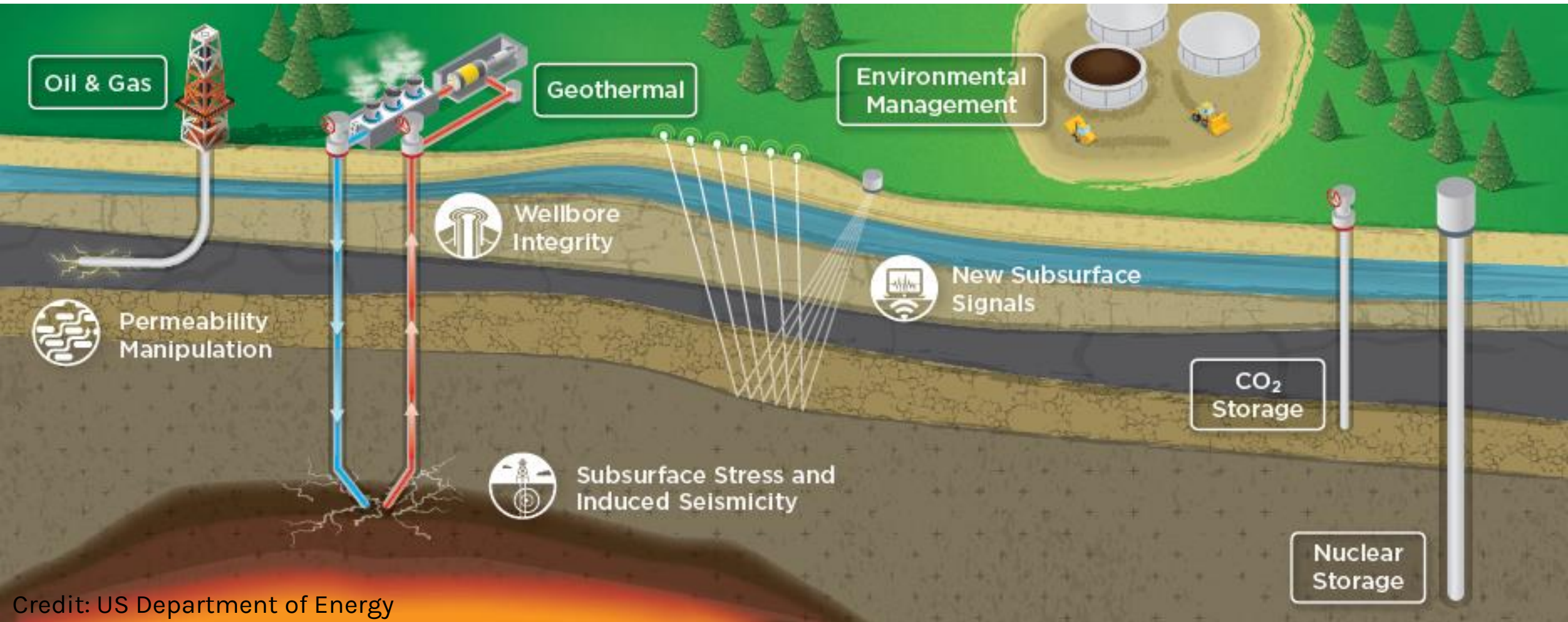
→ Finding and effectively utilizing these resources while mitigating impacts of their use constitute major technical and socio-political challenges and opportunities.

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

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



Understanding, Predicting, and Controlling Fluid Flow in Subsurface Environments



Credit: US Department of Energy

Collaborative Research in

- energy production/extraction
- subsurface storage
- environmental remediation

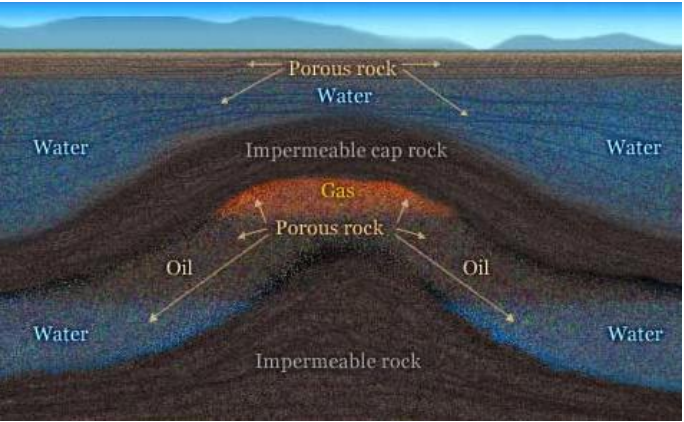
DOE Offices Involved

- [Fossil Energy](#)
- [Geothermal Technologies Office](#)
- [Nuclear Energy](#)
- [Environmental Management](#)
- [Science](#)

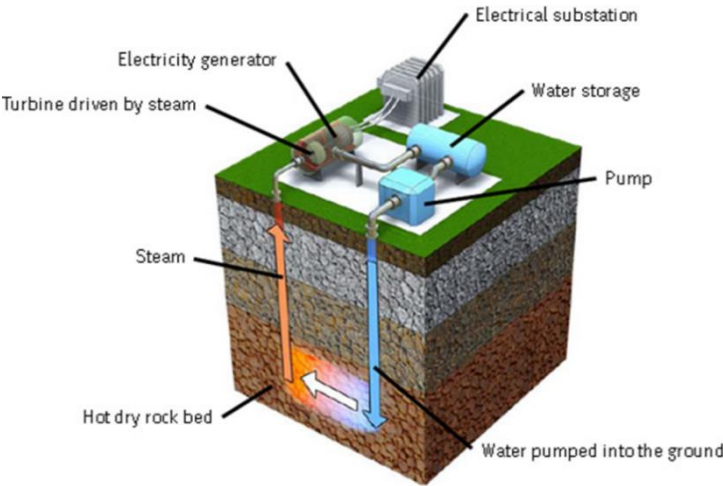
Benefits

- Double reservoir (recovery) efficiency with a smaller footprint
- More than double electricity from U.S. geothermal reservoirs
- Safely sequester CO₂ on large scale
- Establish feasibility of deep borehole disposal
- Protect public safety and the environment

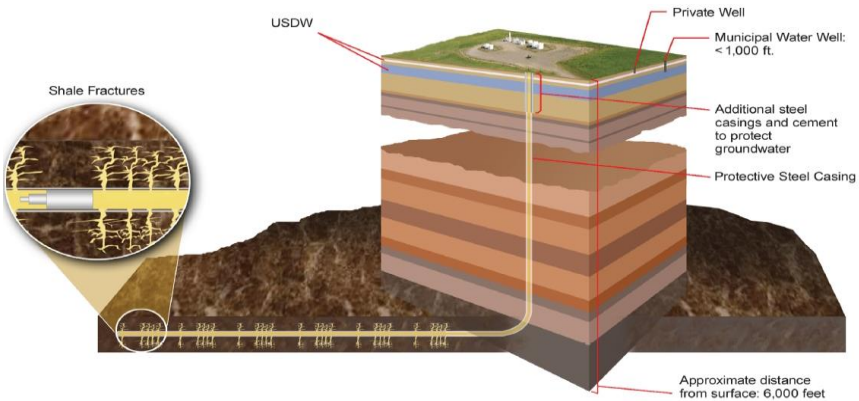
Conventional Resources



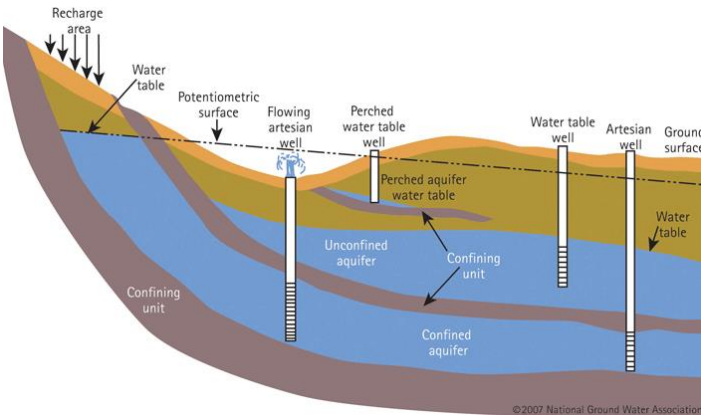
Geothermal Resources



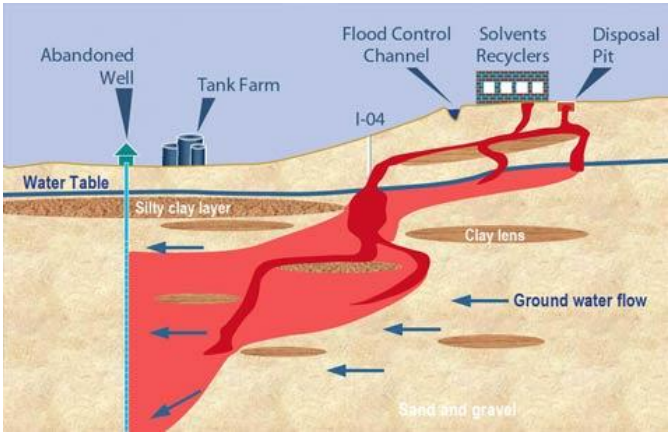
Unconventional Resources



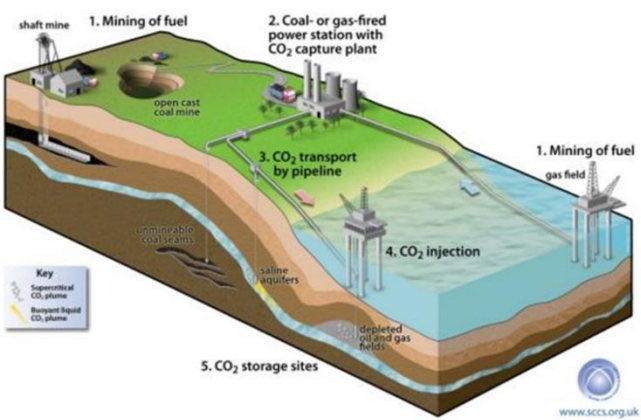
Groundwater Resources



Groundwater Remediation



Geologic CO₂ Storage

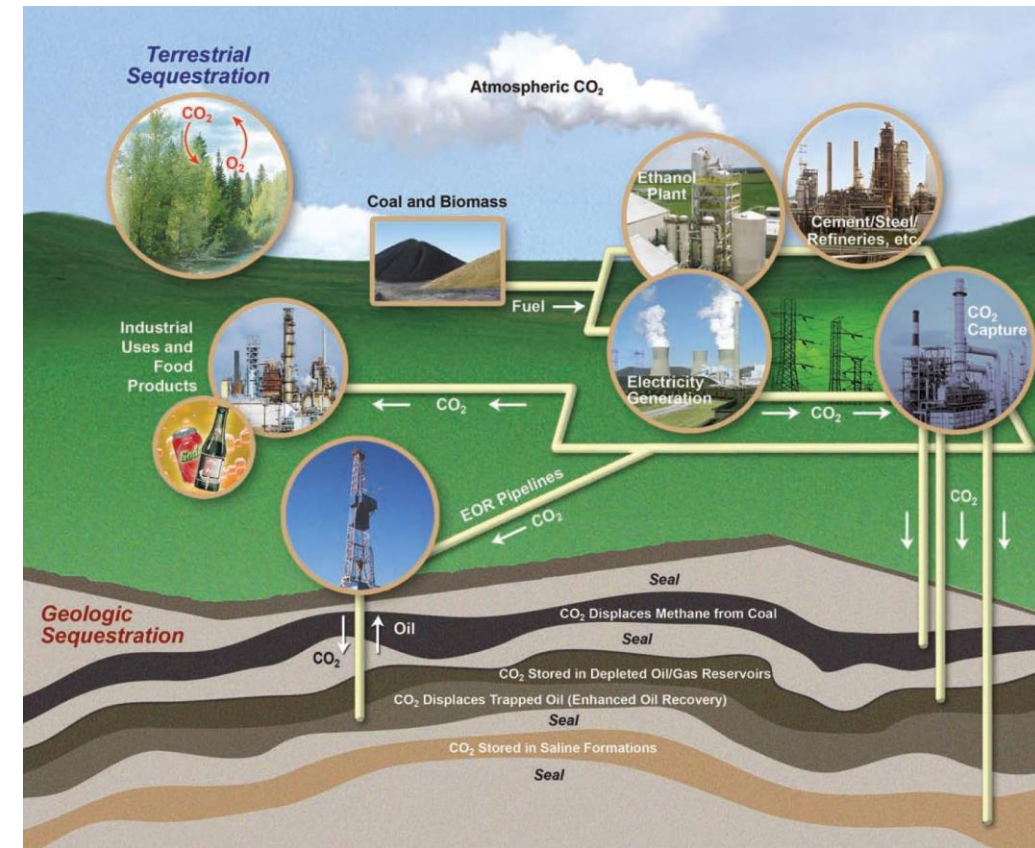


What is Geological Storage?

- Reducing CO₂ emission by injecting it into underground storage formations

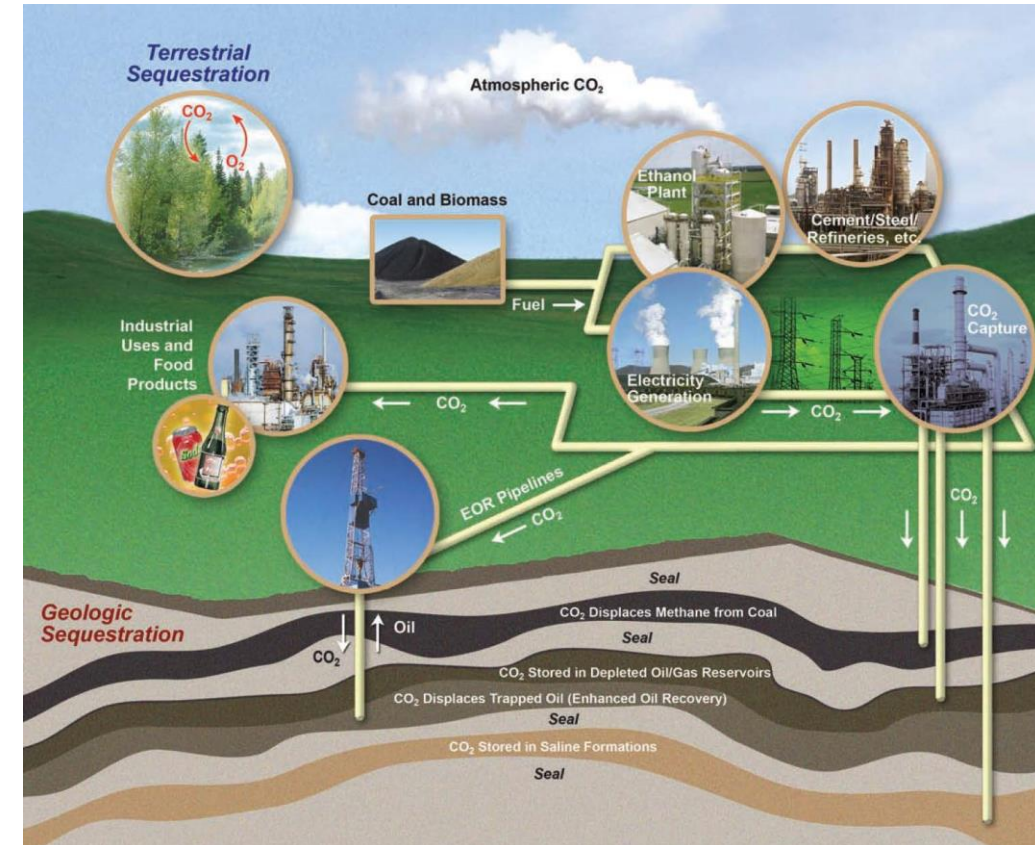
What is involved?

- Capturing, transporting, and storing CO₂
- Injecting CO₂ into deep rock formations
- Monitoring to ensure permanent storage
- Risk mitigation and management



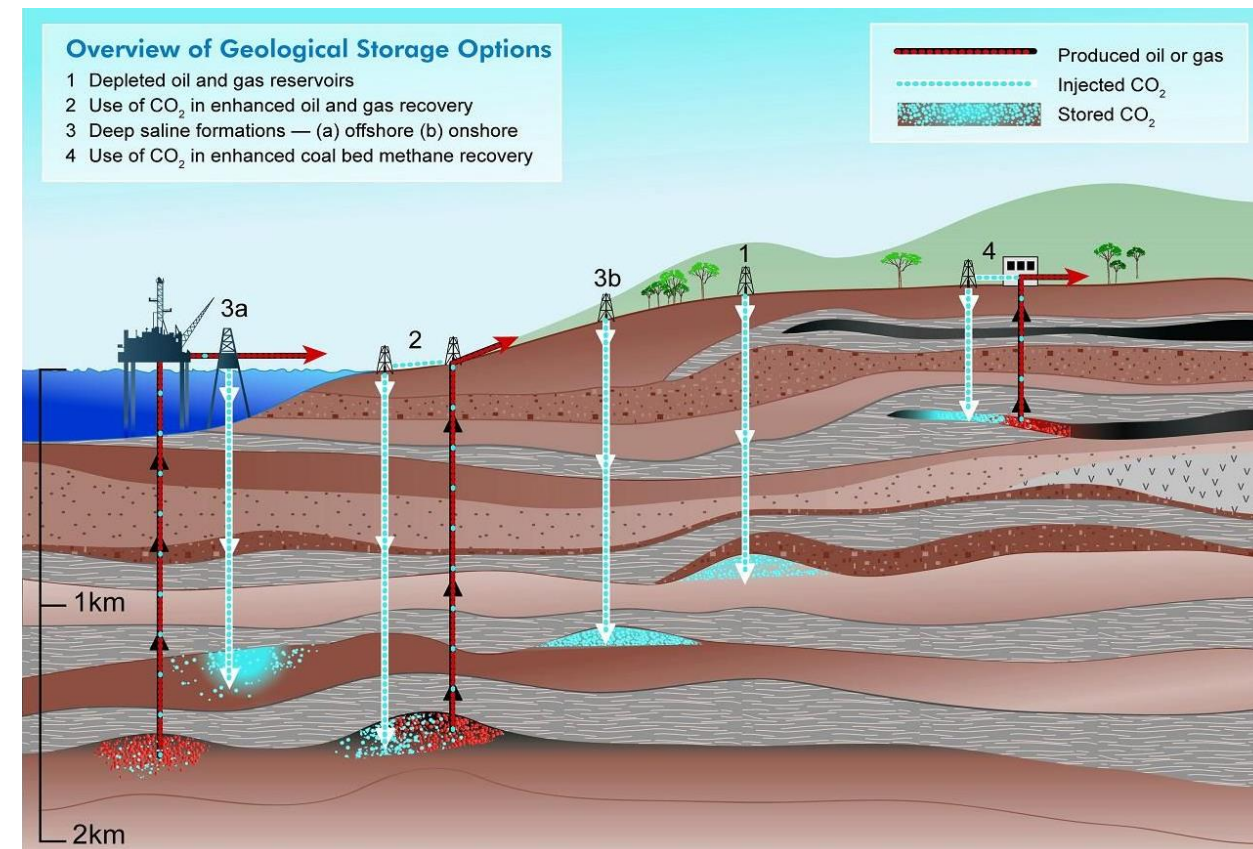
What it takes:

- Large-scale good quality pore space (high permeability) to ensure high injectivity and small pressure increases
- Continuous monitoring for risk assessment (risk related to CO₂ leakage and seismicity)
- Large capital expense (economics)
- Regulations to ensure safety and reliability of operations across all projects



Geologic CO₂ Storage Modes

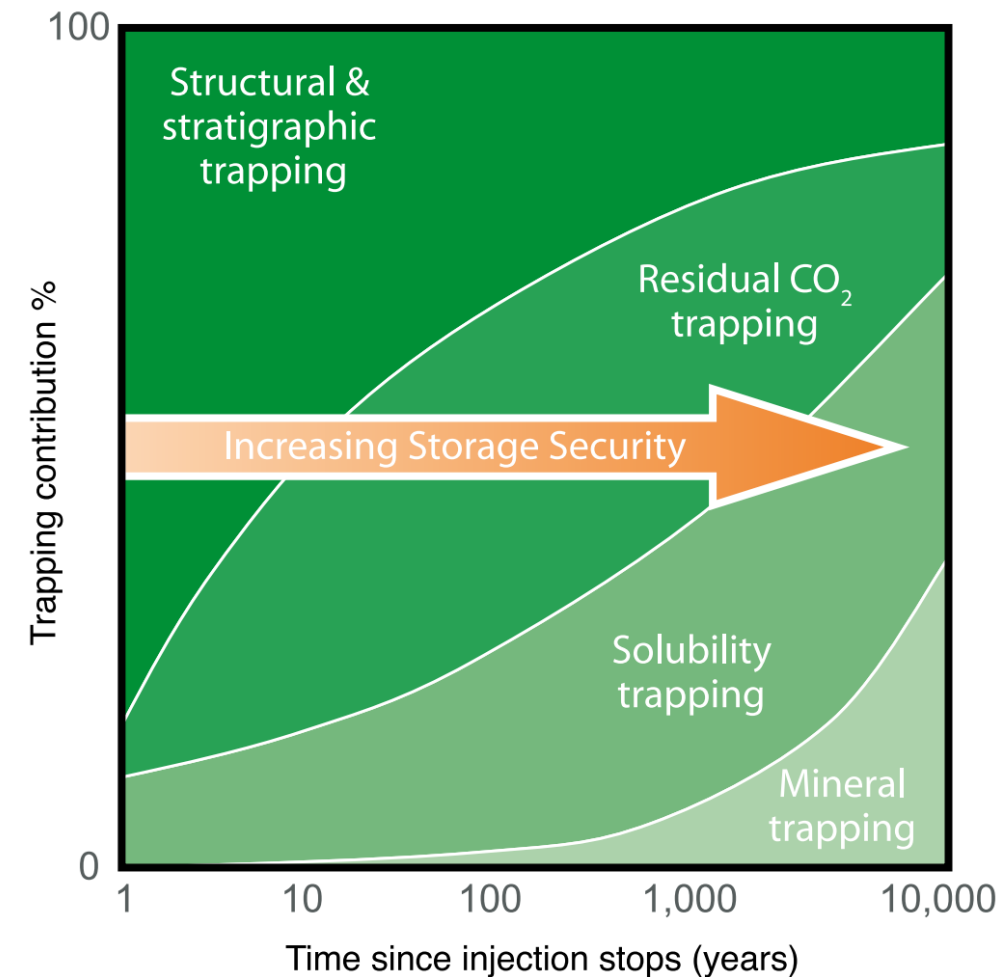
1. Depleted oil and gas reservoirs
2. Enhanced oil and gas recovery
3. Deep saline formations:
Offshore and onshore
4. Enhanced coal bed methane
recovery



IPCC, 2005

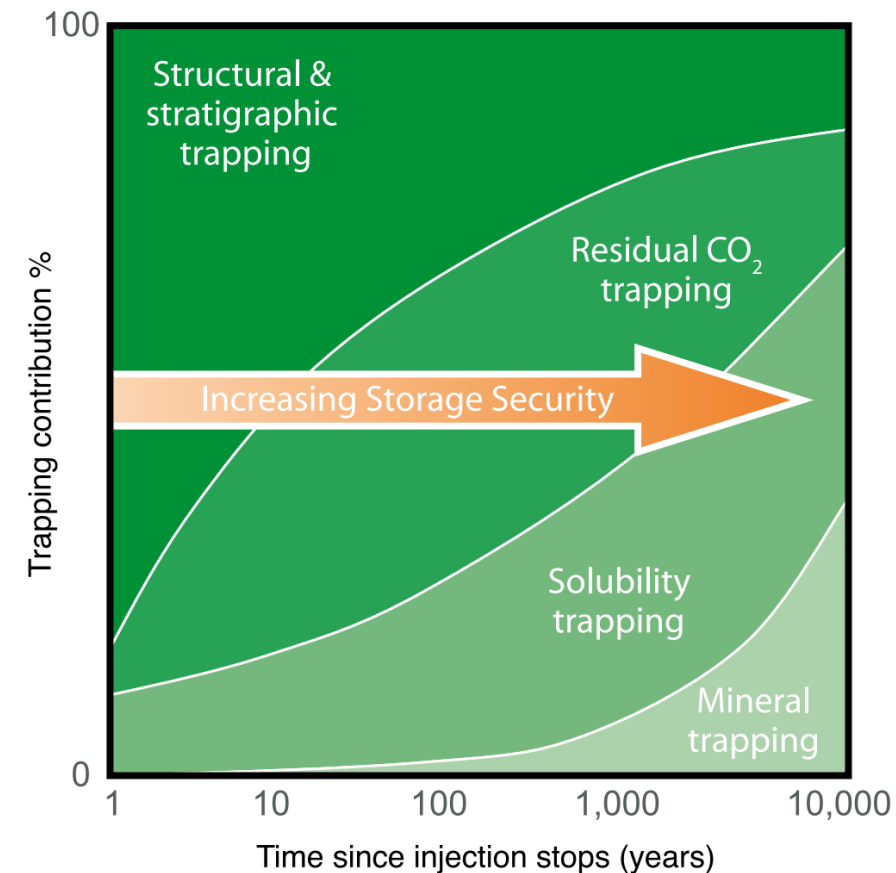
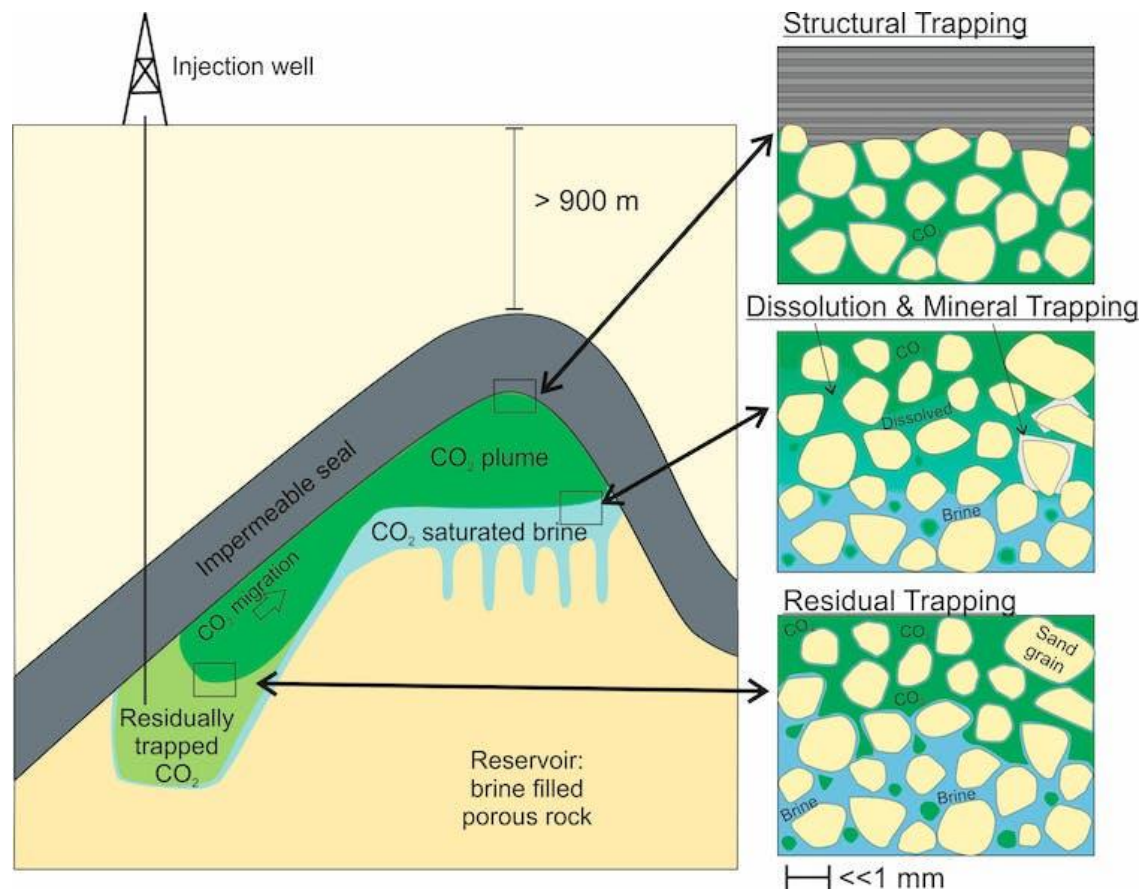
CO₂ Trapping Mechanisms

1. **Structural trapping:** formation sealing/caprock
2. **Capillary/residual trapping:** CO₂ breaks up into small ganglia, immobilized by capillary forces in the pore space.
3. **Solubility trapping:** CO₂ dissolved in brine water.
4. **Mineral trapping:** carbonic acid react with rock minerals.



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

CO₂ Trapping Mechanisms



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

Risk Assessment

- Primary risks: CO₂ 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

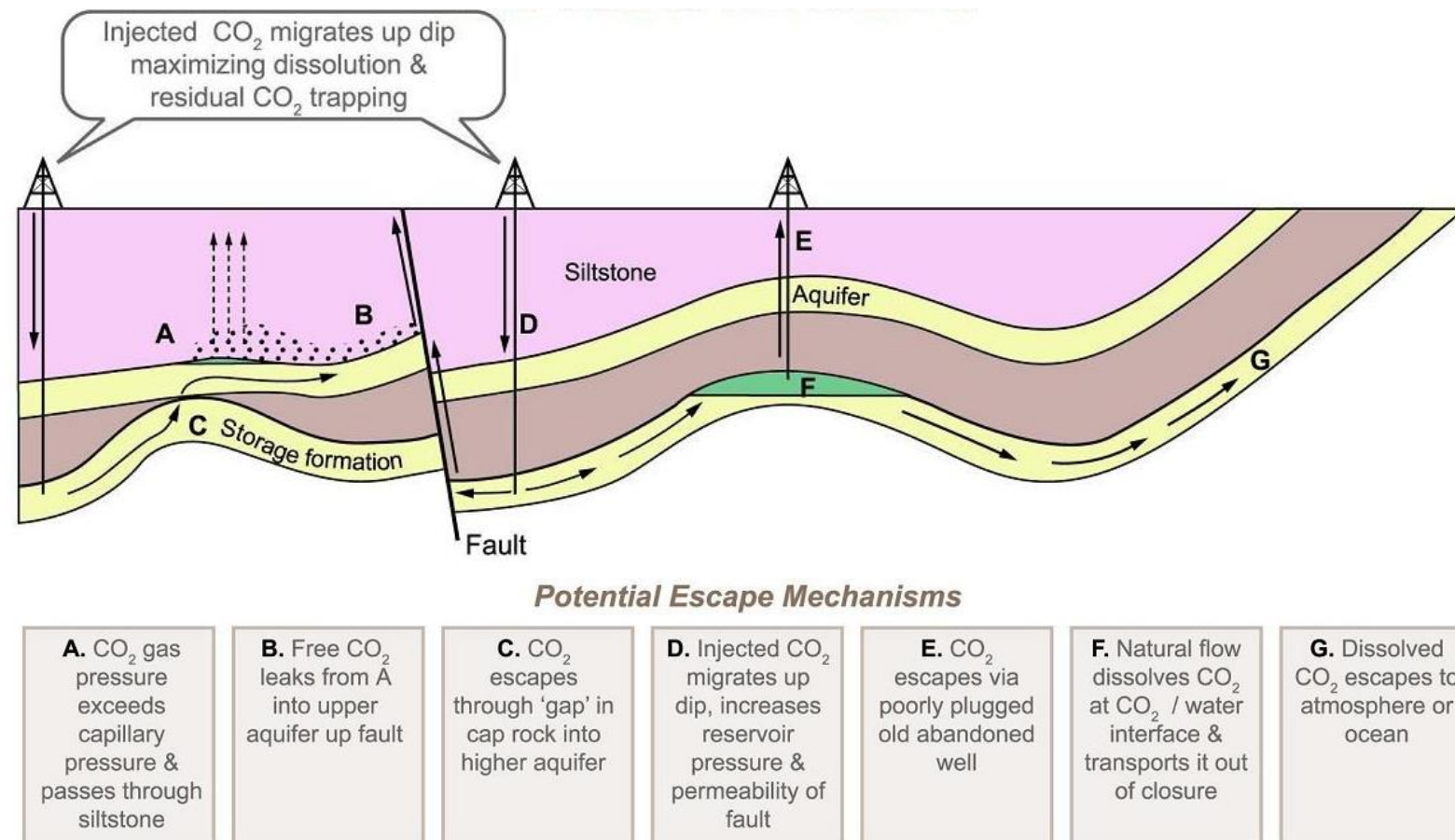
(i) Potential Leakage of CO₂

CO₂ leakage into:

- Atmosphere
- Aquifers
- Shallow soil zones

Leakage pathways:

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



(ii) Induced seismicity

CO₂ Injection & Pressure Build-up



Stress-and-Strain Changes



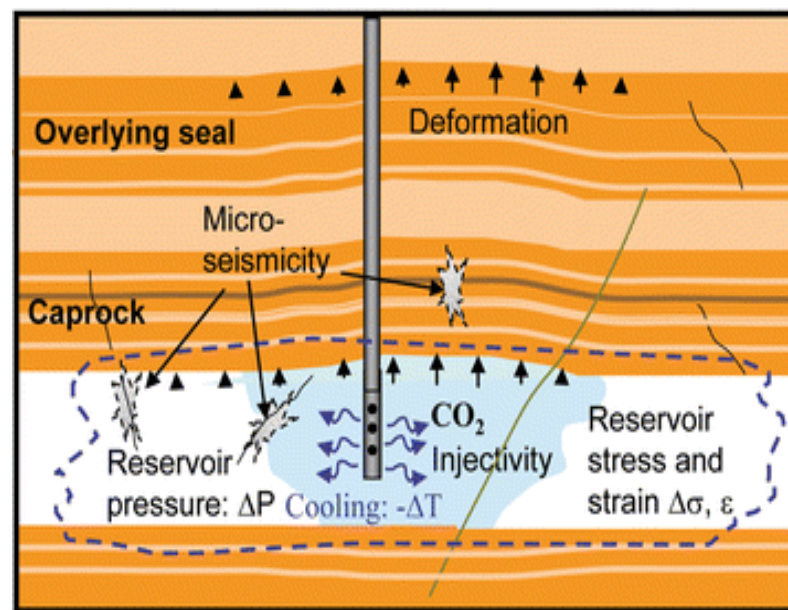
Geomechanical risks:

- Uplifting (surface displacement)
- Induced Seismicity (rock's plastic strain)
- Caprock Fracturing (CO₂ leakage)

- Injection of CO₂

- Pressure Build-up

- Stress Field Changes



- Ground Uplifting

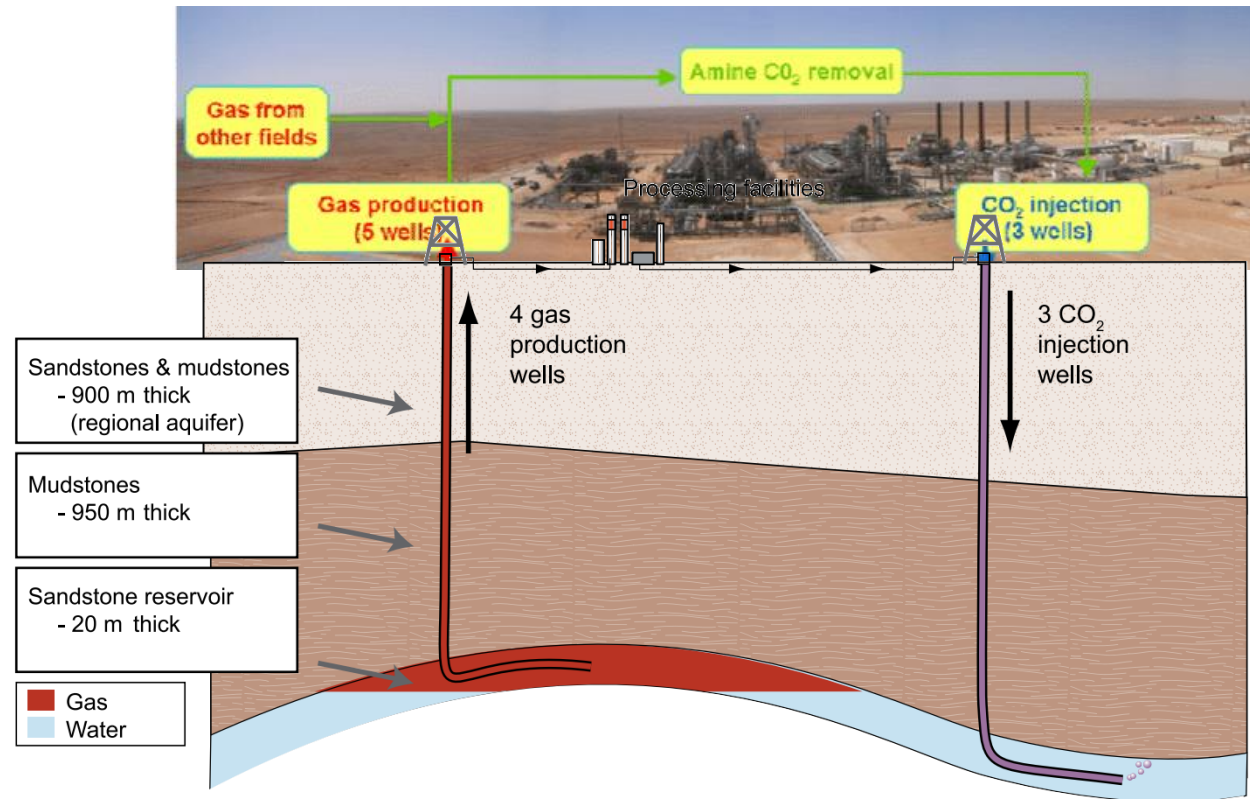
- Caprock Fracturing
- CO₂ Leakage

- Micro-seismicity

- Plastic Deformation
- Rock Fracturing

(Rutqvist, 2012)

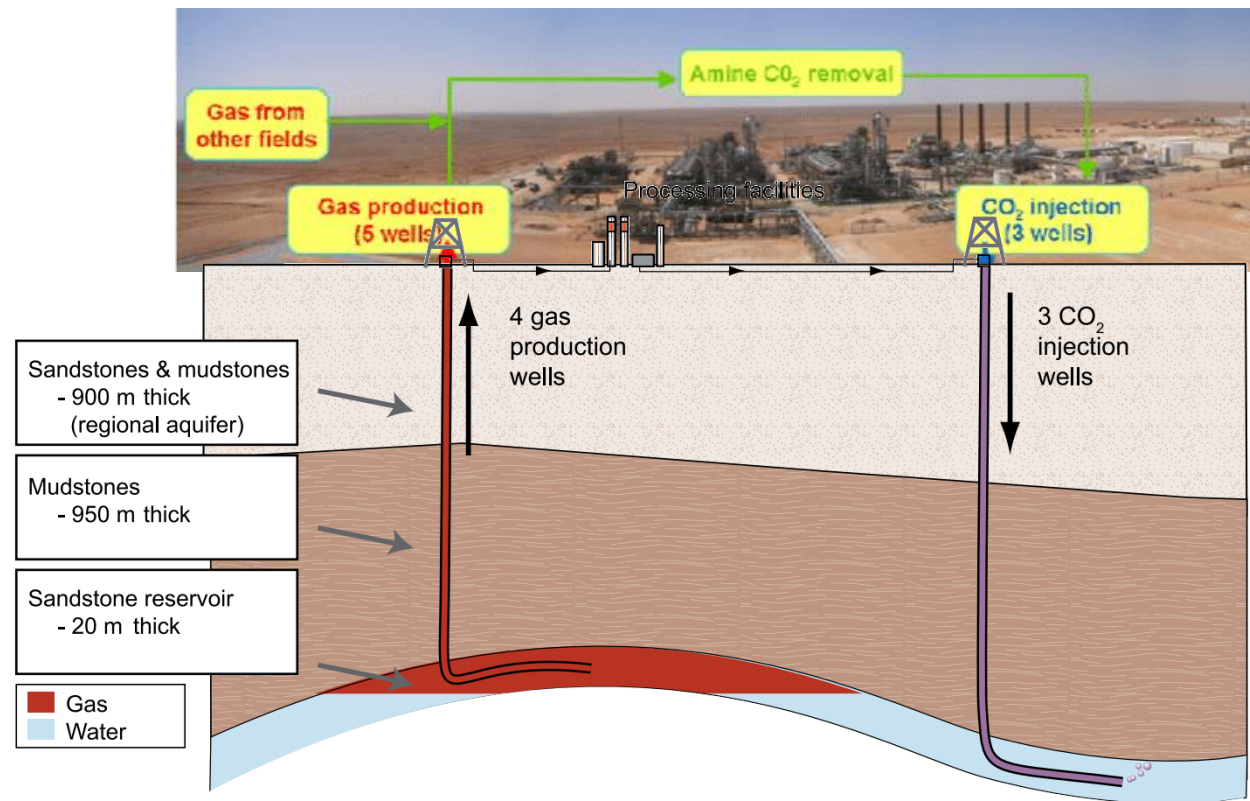
In Salah Project



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

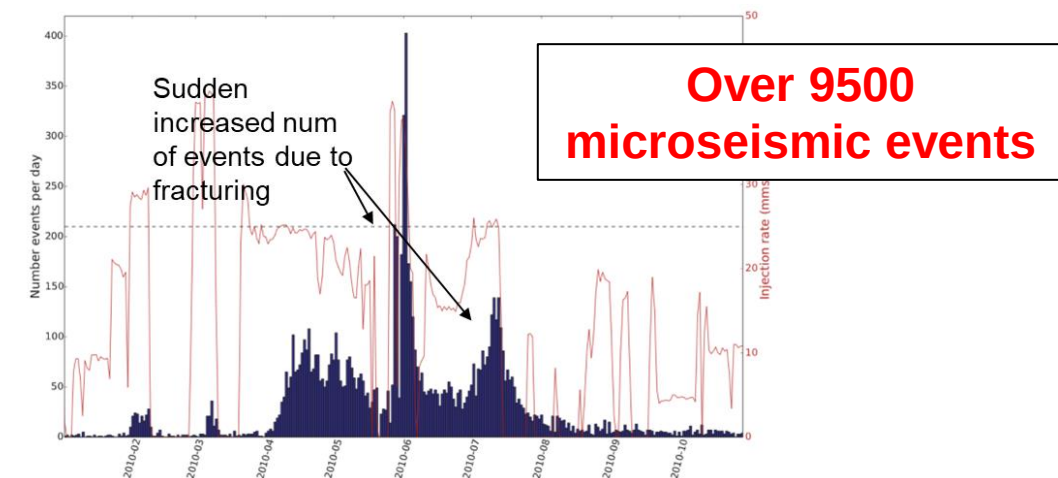
- A total of **3.8 mega-ton** of CO₂ were injected
- **9,506** injection induced seismic events detected
- Injection of CO₂ is **opening** pre-existing **fractures**
- Maximum of **25 millimeters uplift** after 2 years

In Salah Project

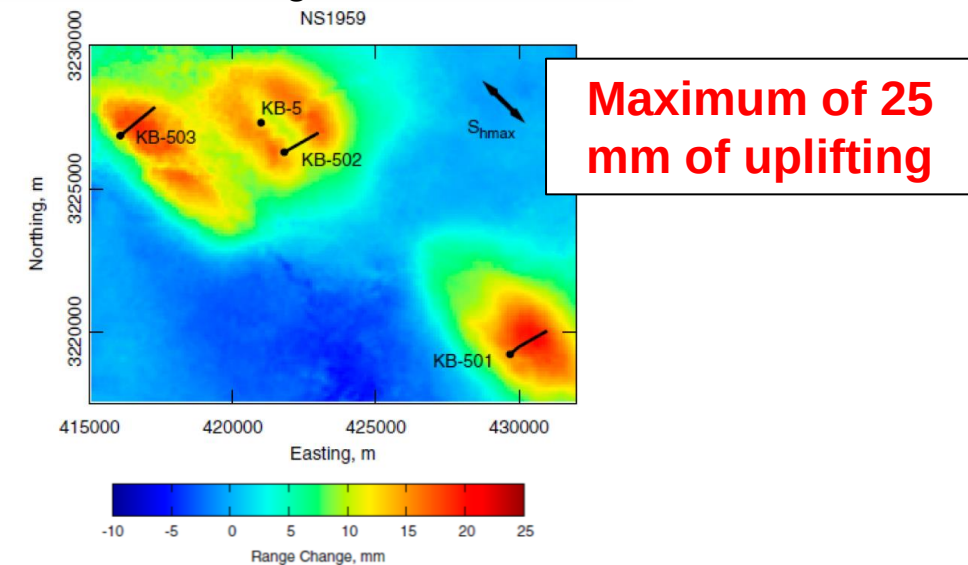


- **9,506** injection caused seismic events detected
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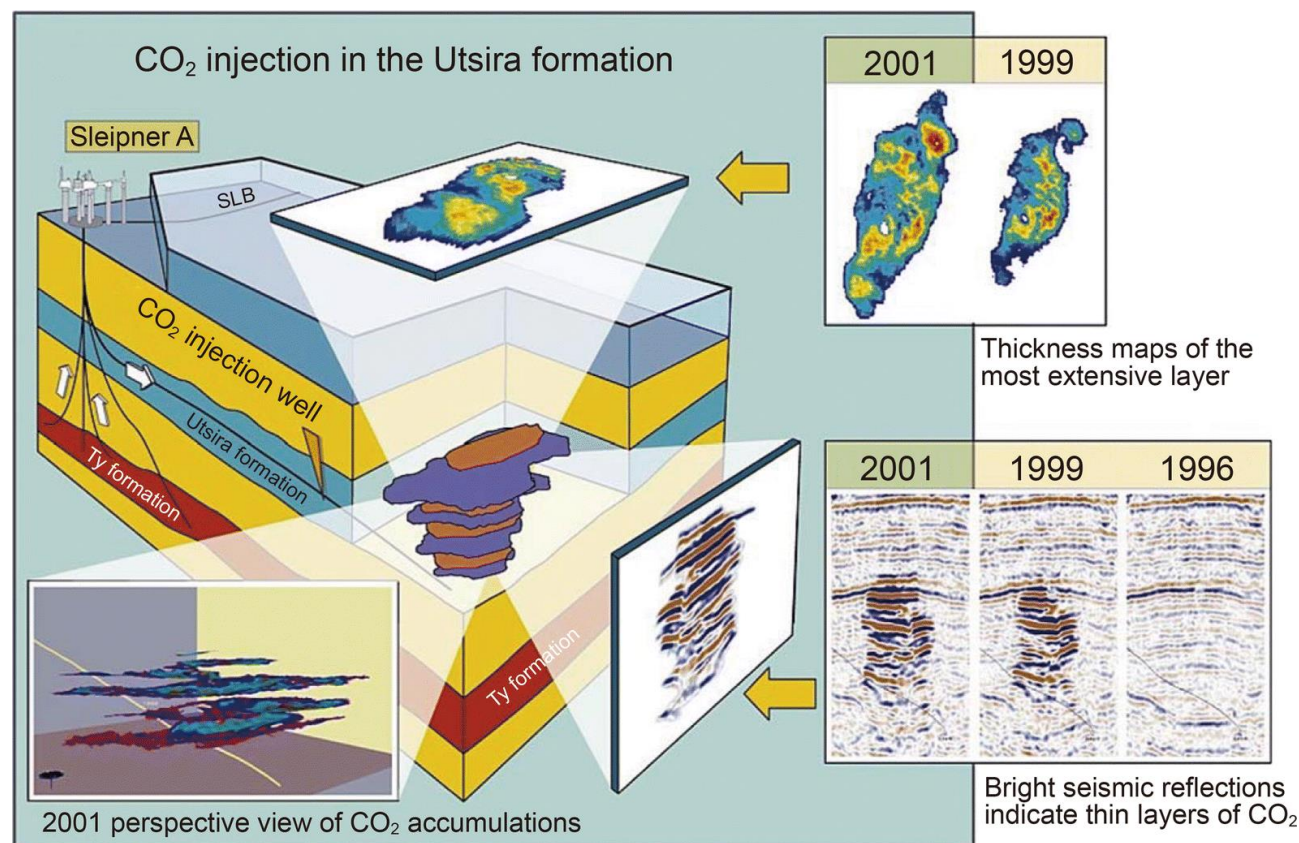
Detected Microseismic events



InSAR measured ground deformation



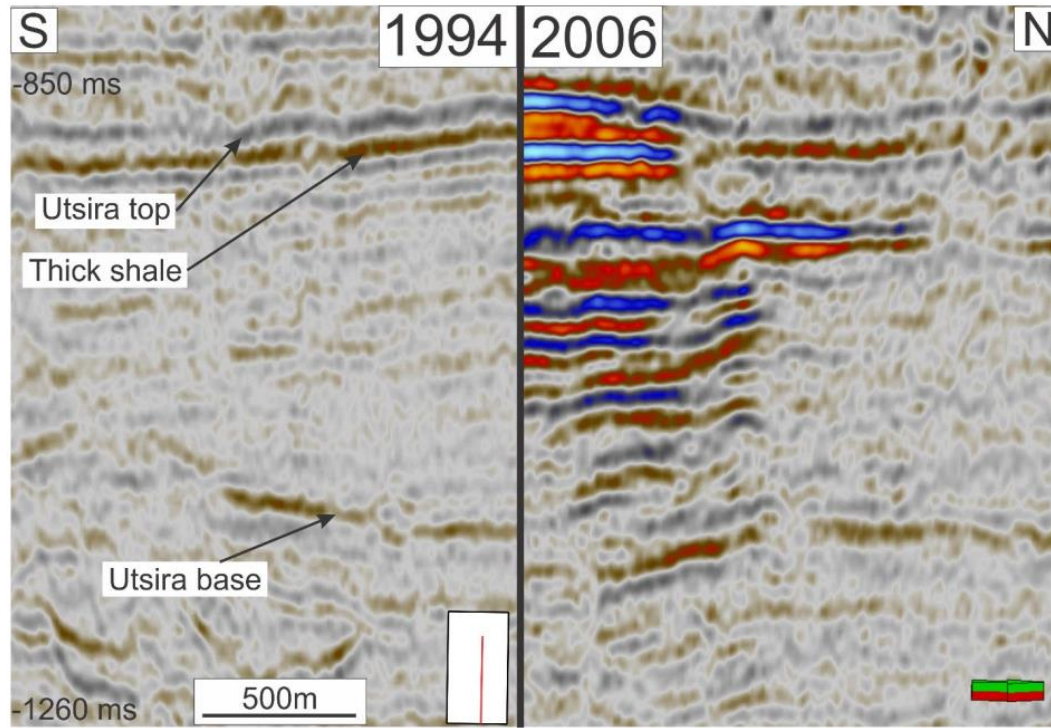
Sleipner Project



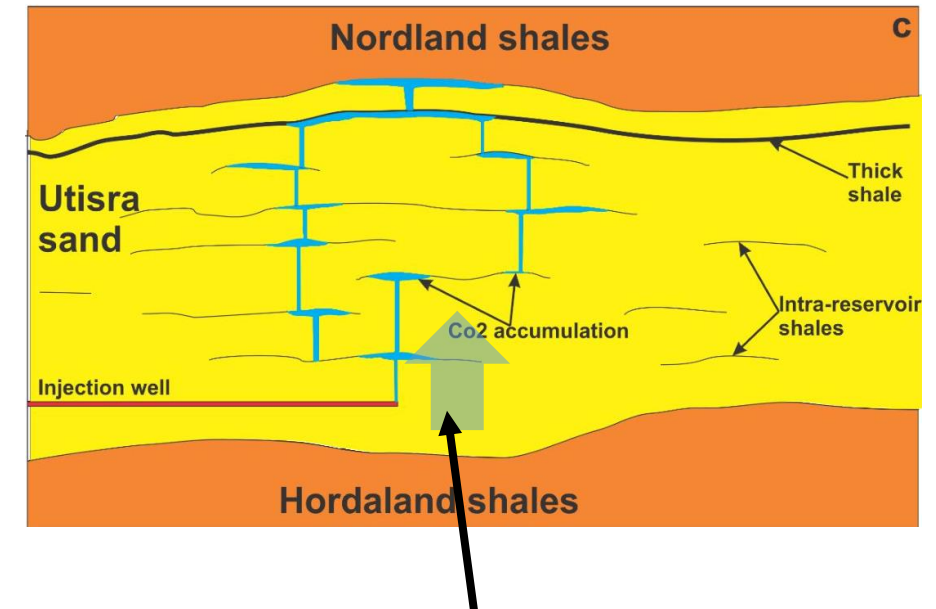
- CO₂ plume (saturation) is monitored to ensure safe storage
- 4D seismic survey used for monitoring since 1999
- 4D seismic survey allows the tracking of CO₂ movement over time

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

Sleipner Project

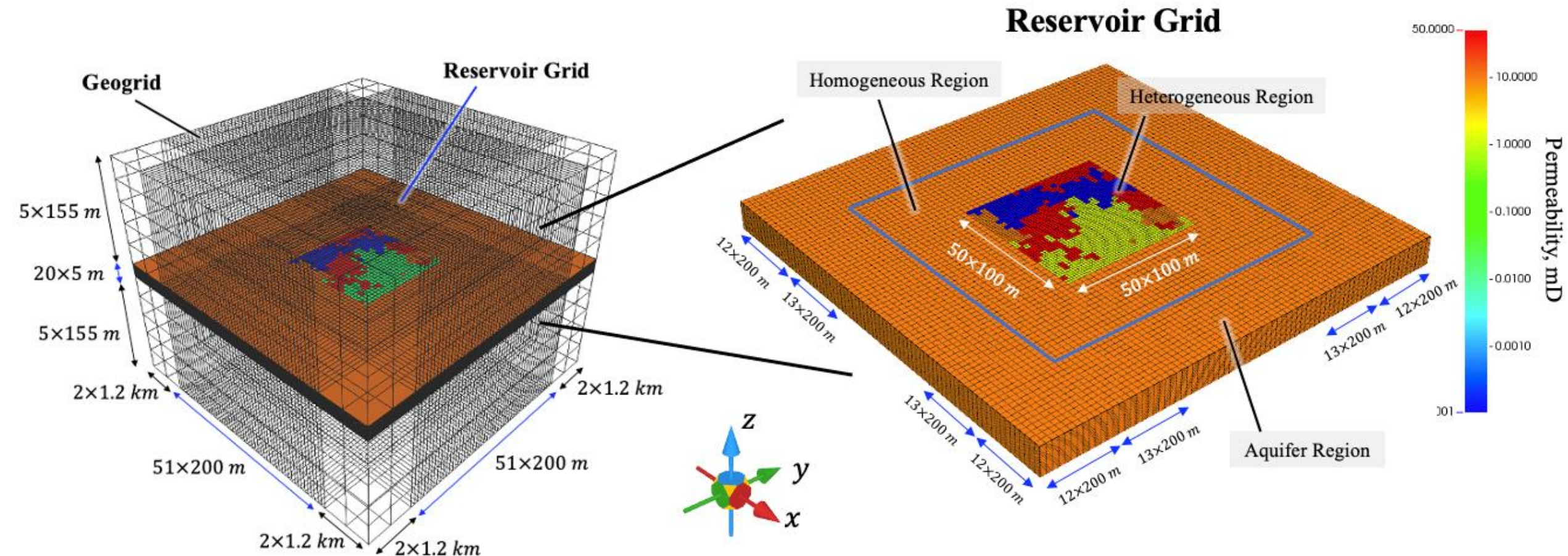


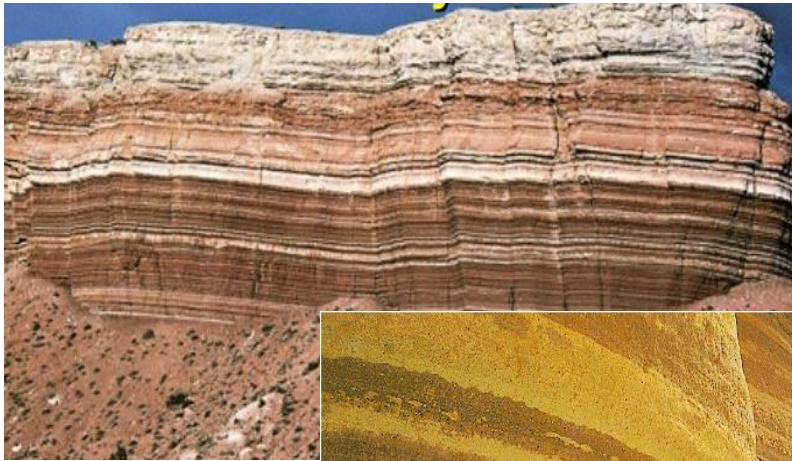
- 1994: Pre-injection seismic survey
- 2006: CO₂ accumulation affects reflectivity



- CO₂ migrates upwards from the injection well
- And accumulates under shales

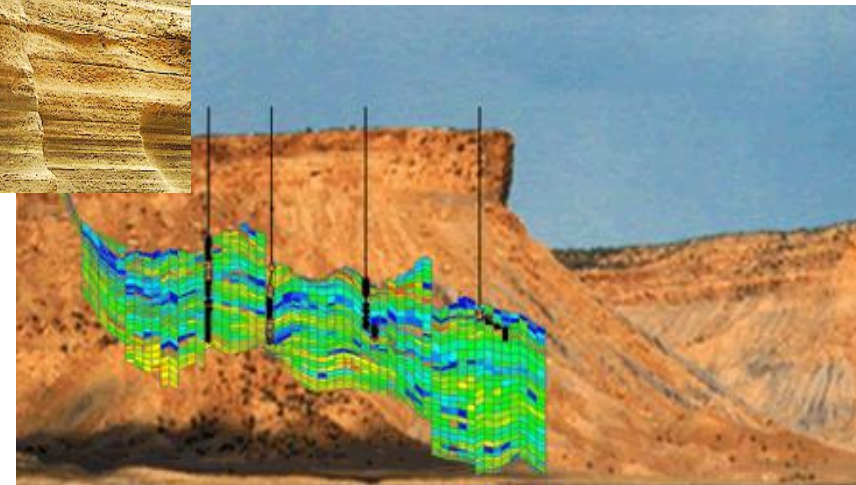
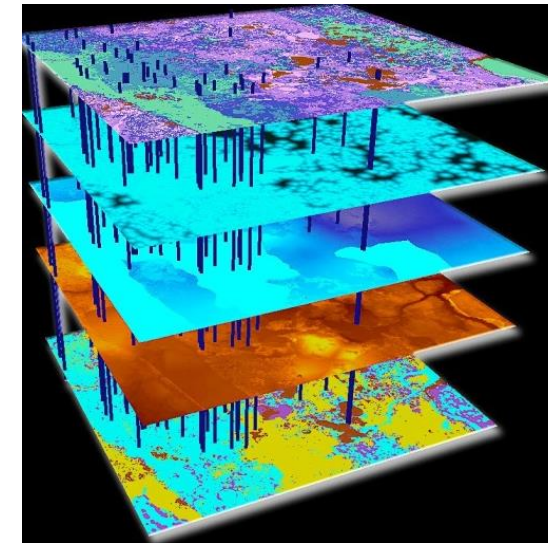
To better understand and quantify the response of geologic formations to CO₂ injection (increase reservoir pressure / deformation / fracturing)





Sedimentary rock deposits with complex structures and fluid flow properties

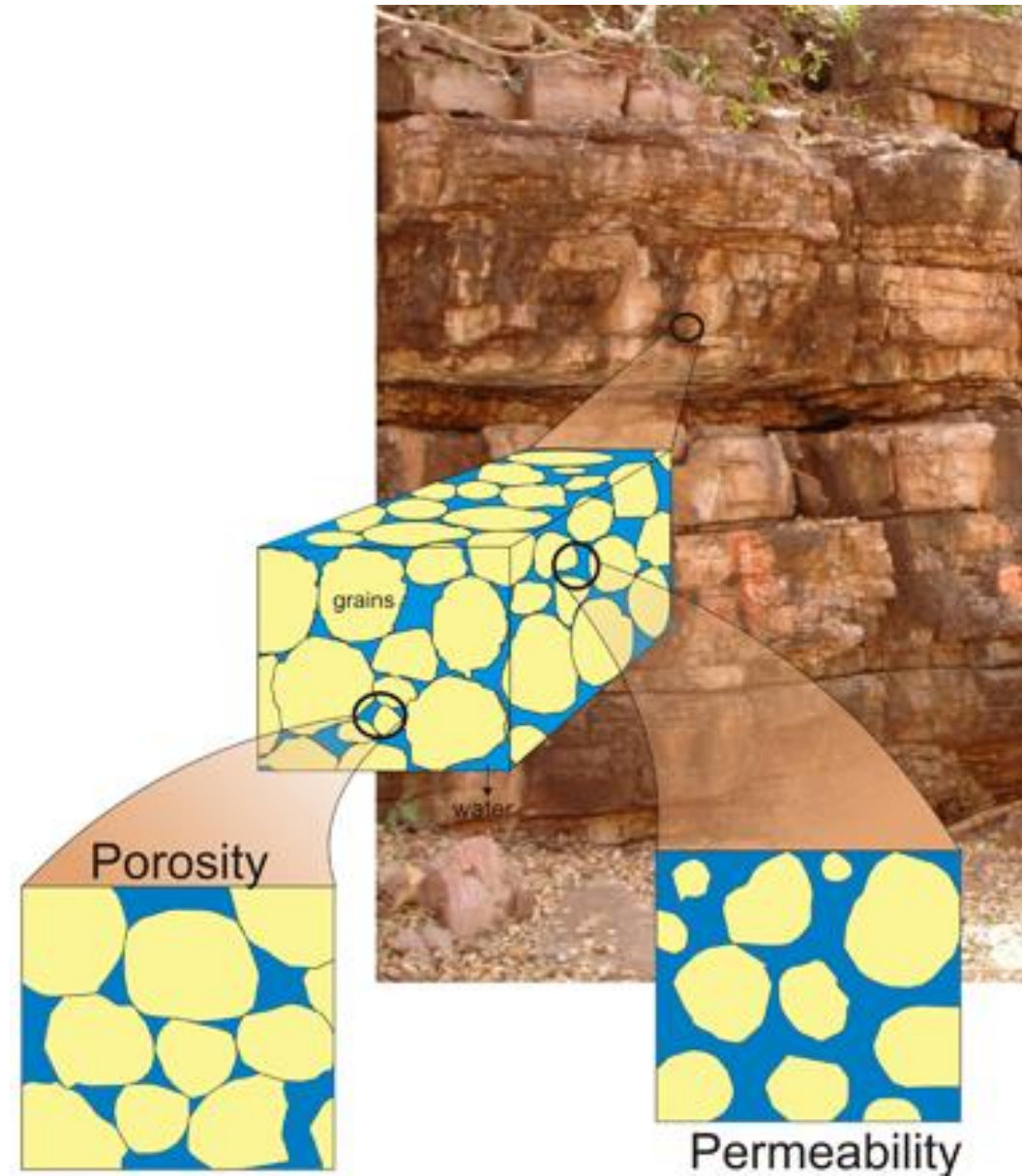
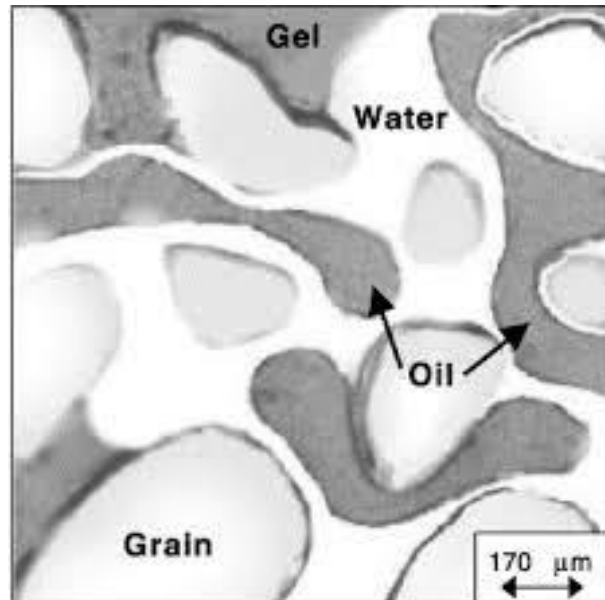
Computer Model



Porosity

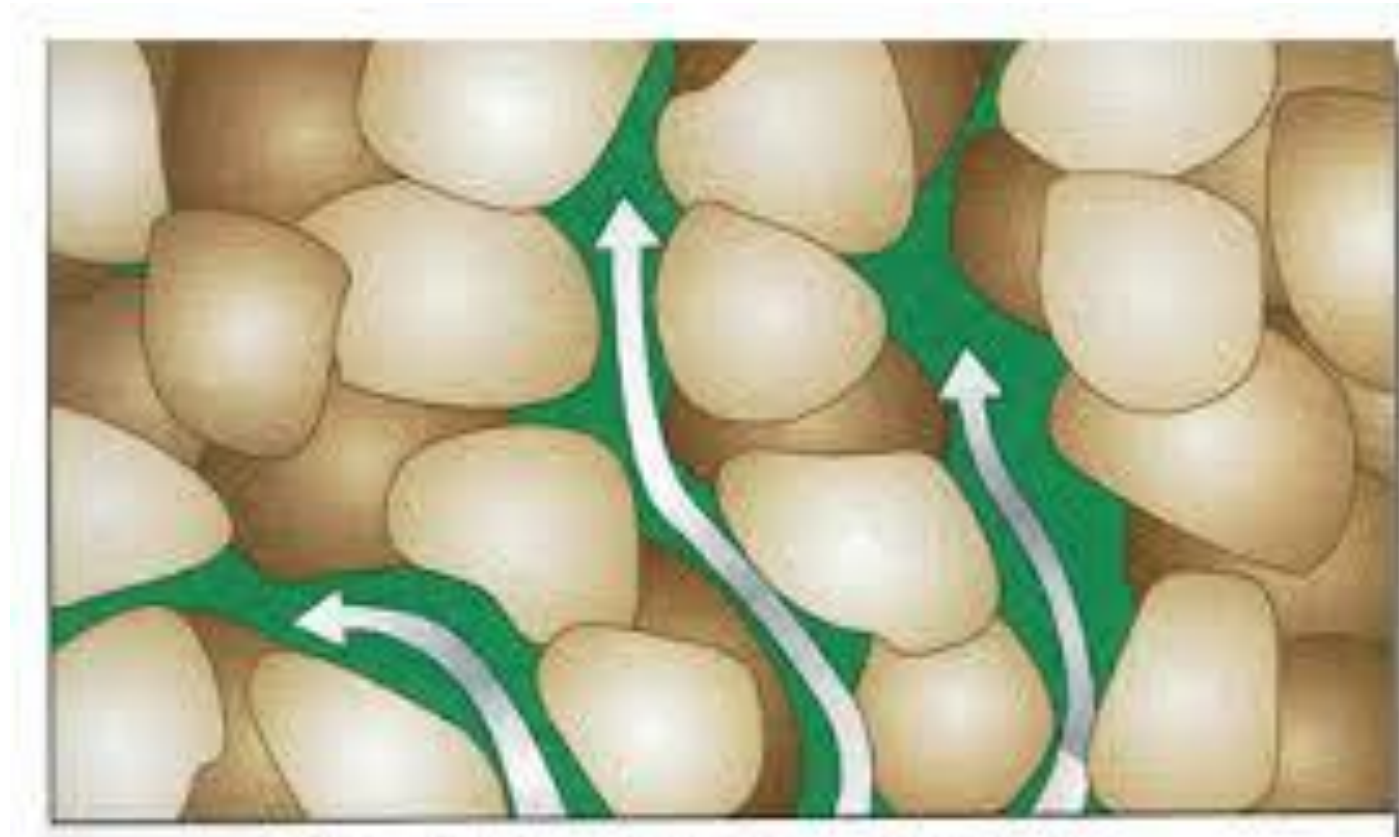
Permeability

Saturation



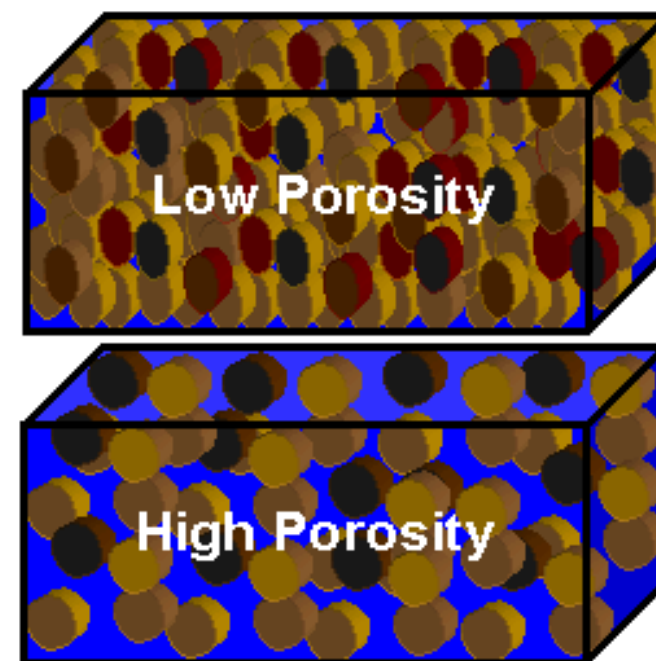
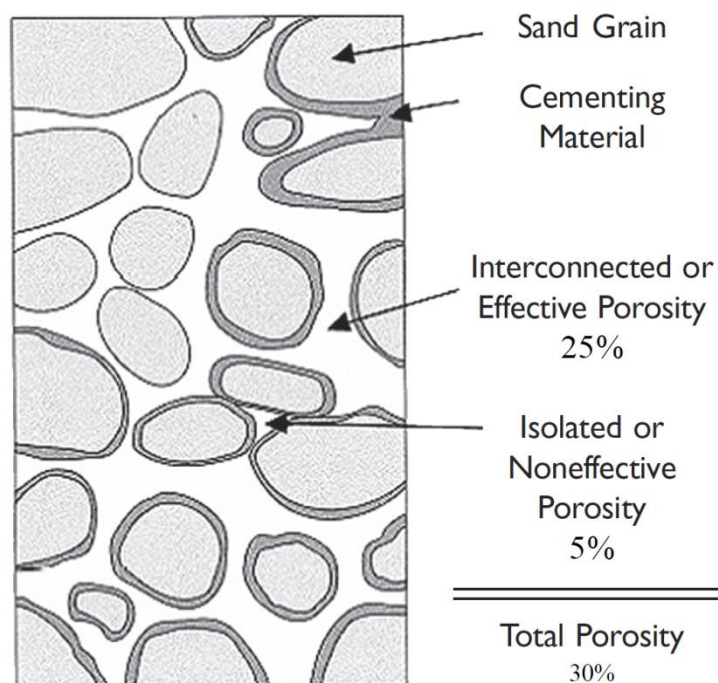
Rock Permeability:

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



Rock Porosity:

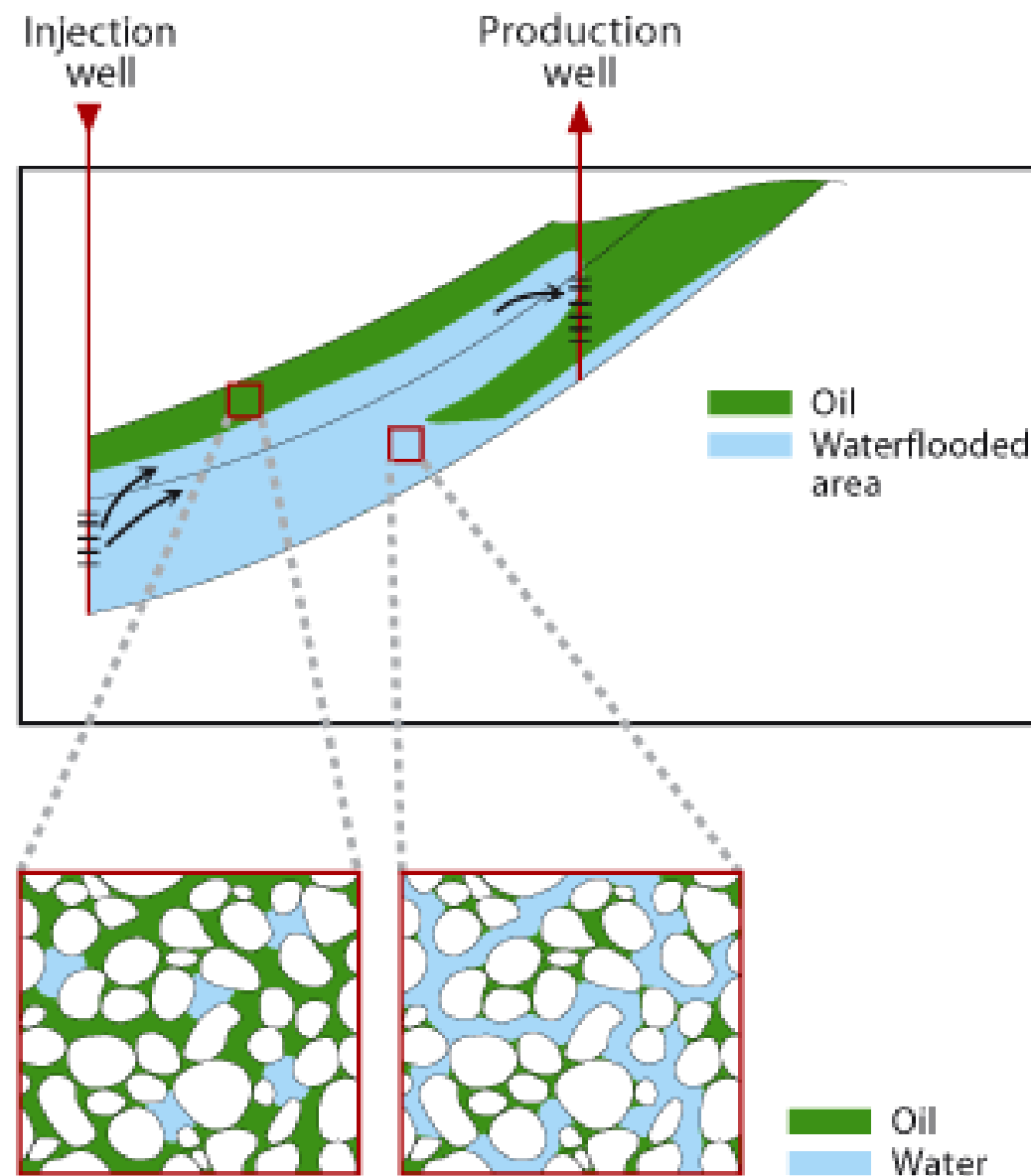
The ratio of pore volume to total rock volume (pore space is where the fluids reside)

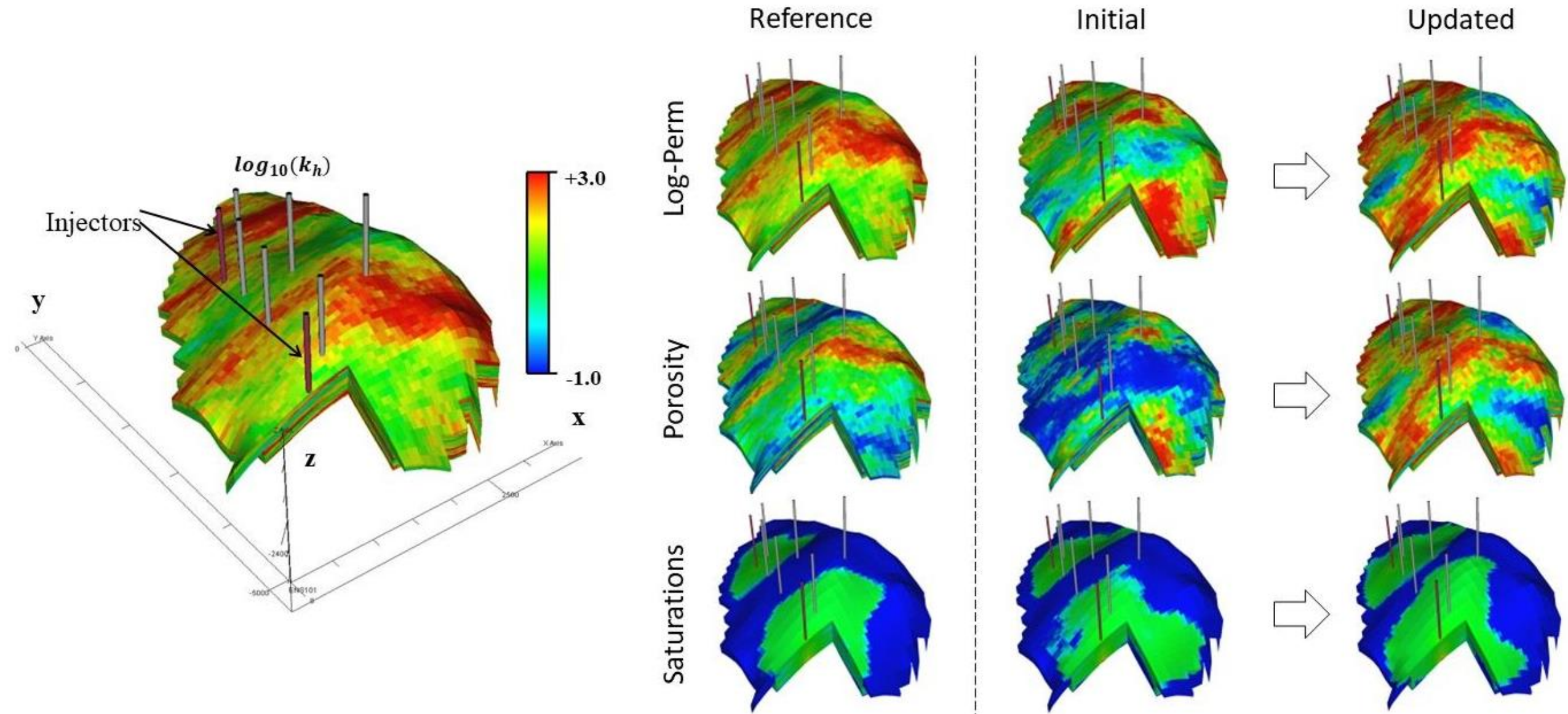


Phase Saturation

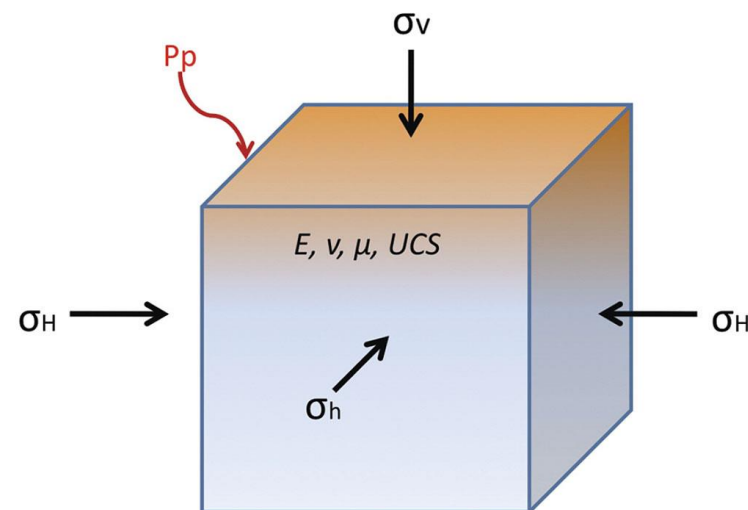
Fraction of pore volume that is occupied by fluid phase

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





Determine the mechanical response of geologic formations to CO₂ injection (state of pressure, stress, and strain / displacement)



Property/rock mass

Density, KN/m³

E , KPa

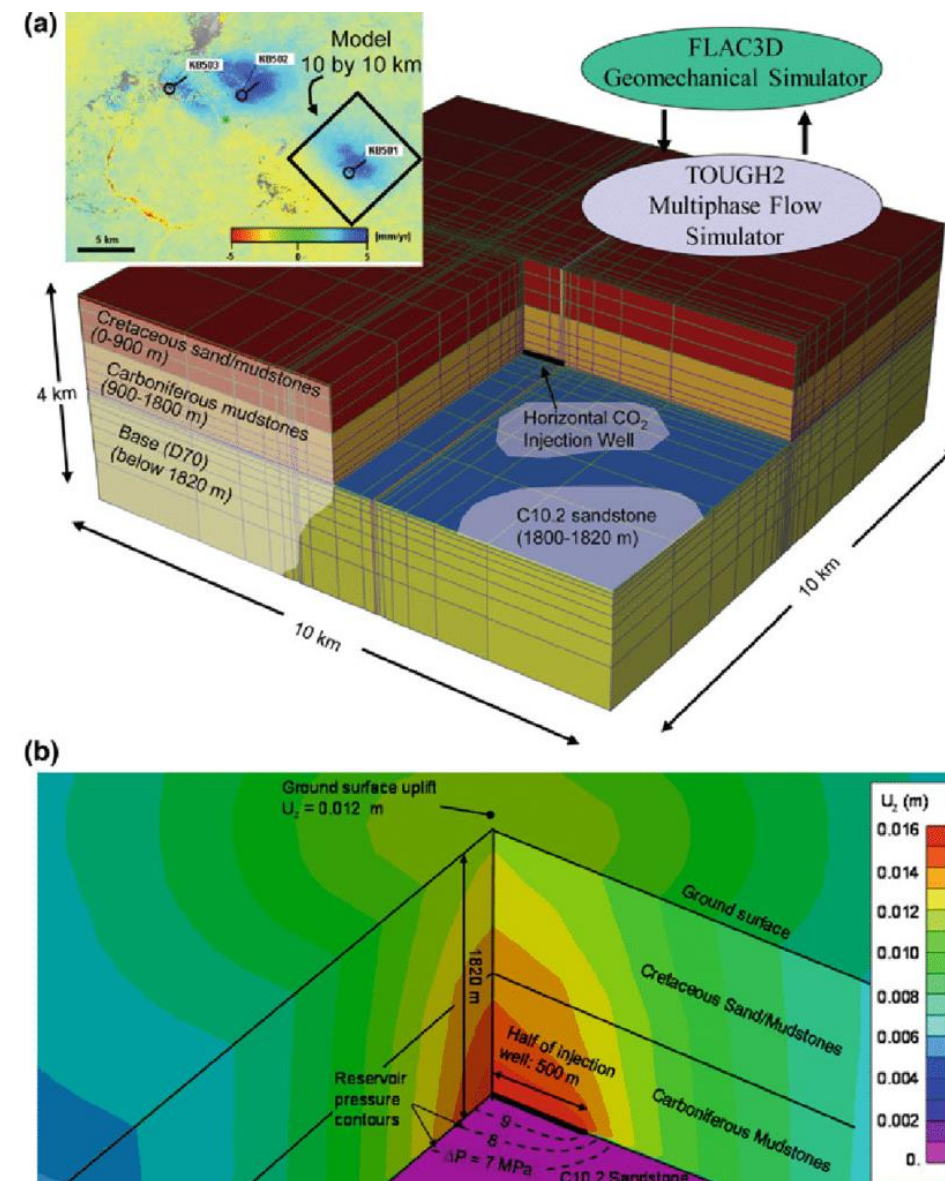
Poisson's ratio, ν

Cohesion, KPa

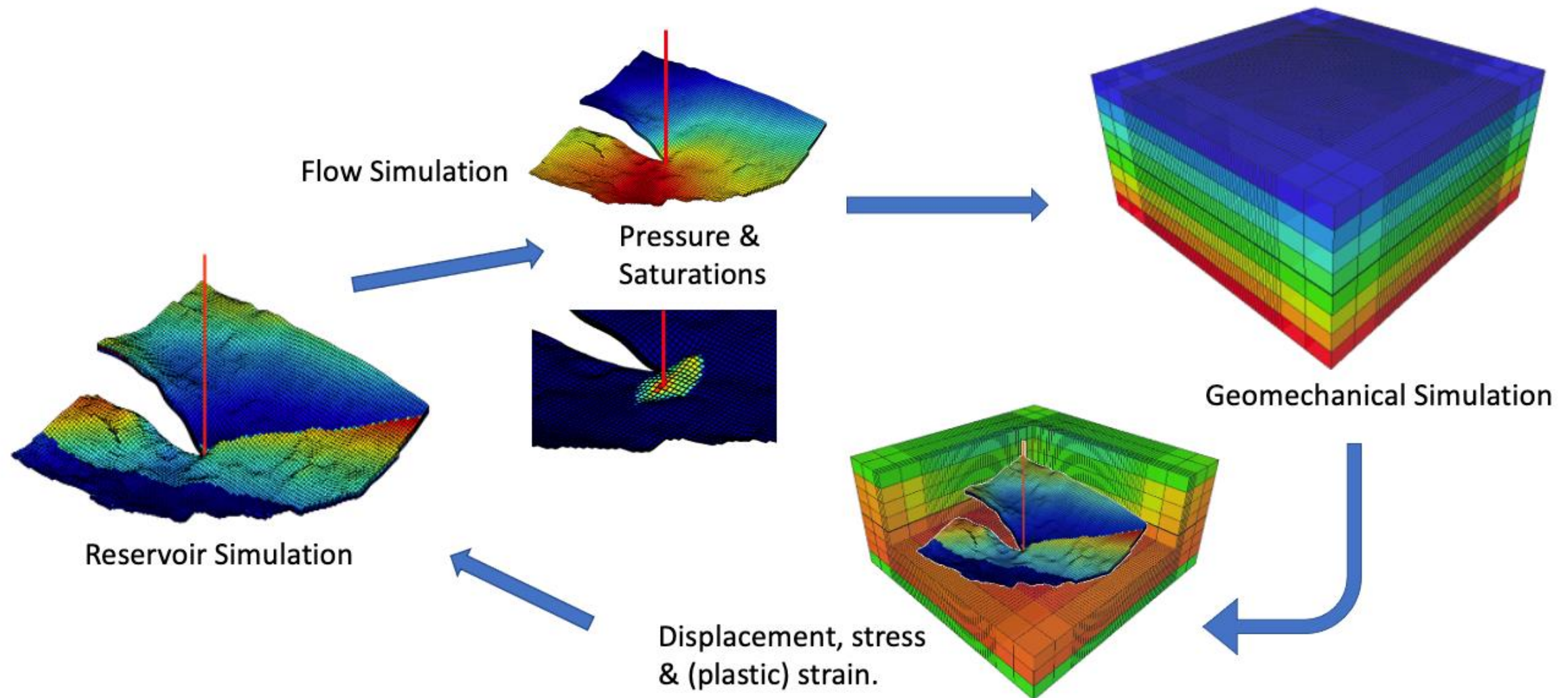
Tensile strength, KPa

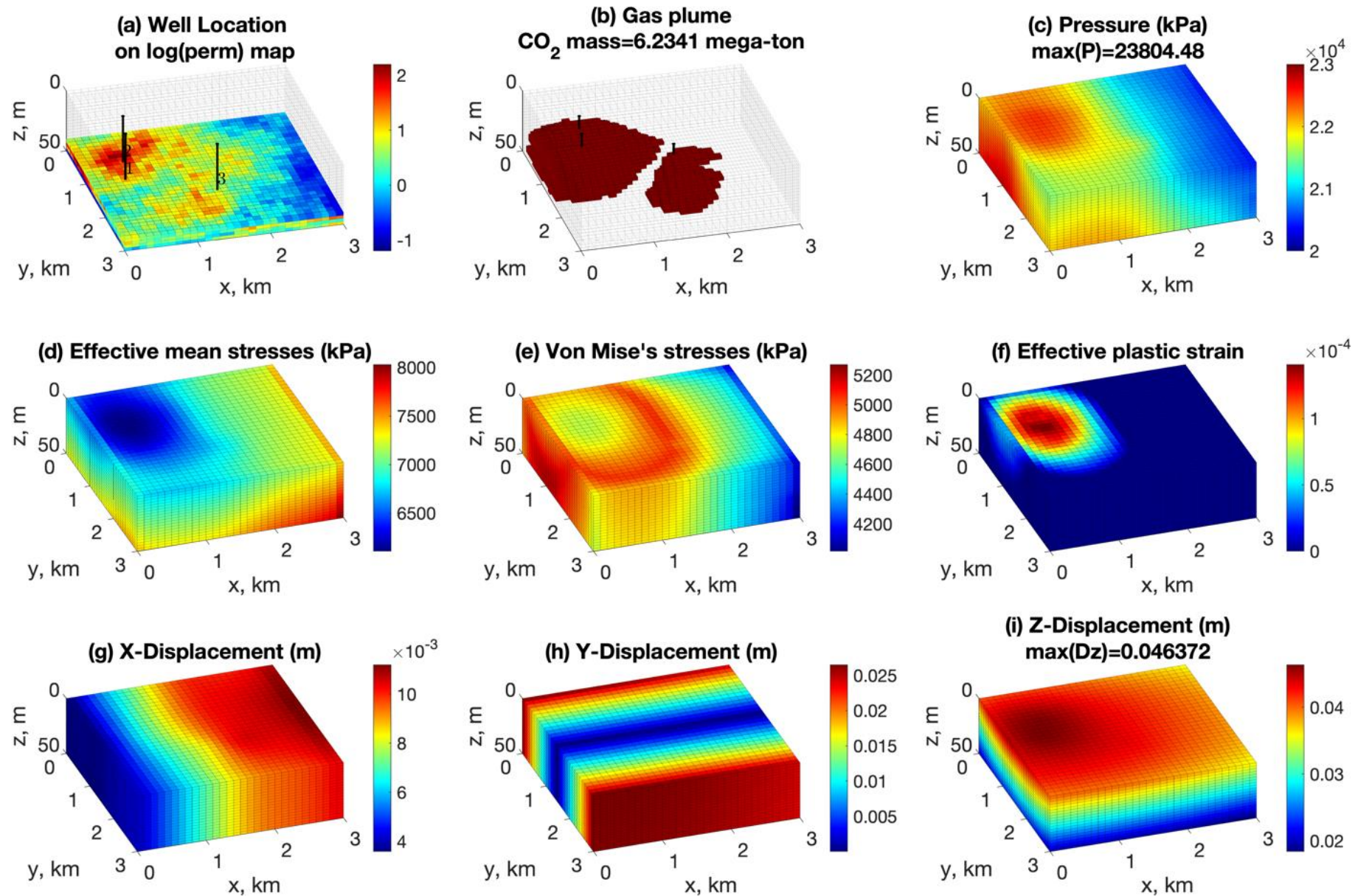
Friction angle, ϕ

Dilation angle, φ

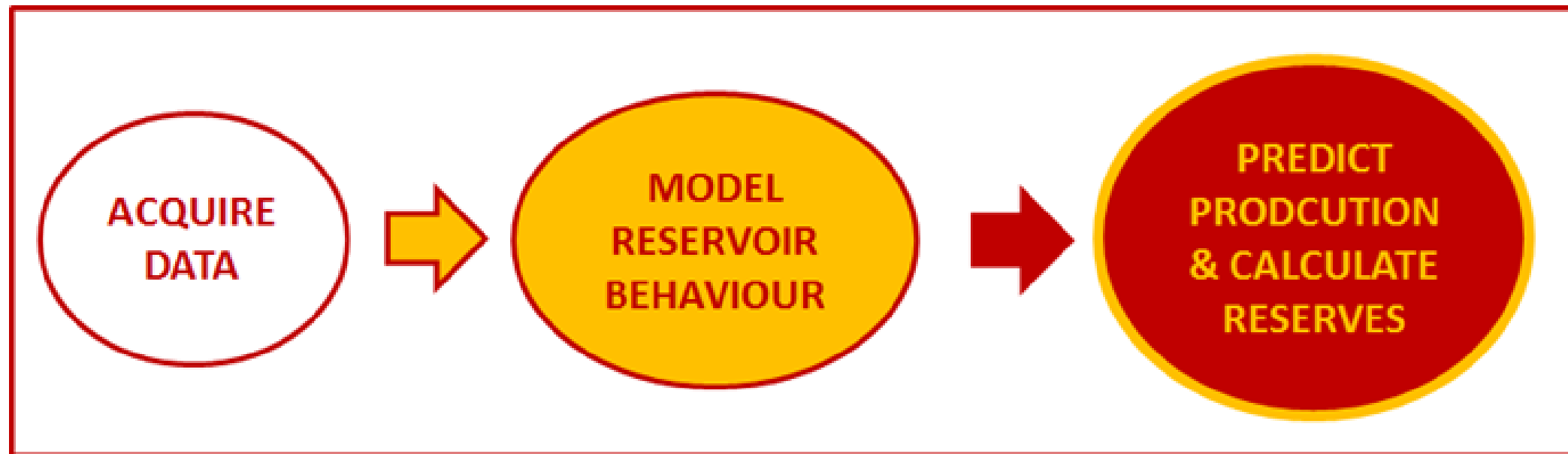


Coupled Flow-Geomechanics Model





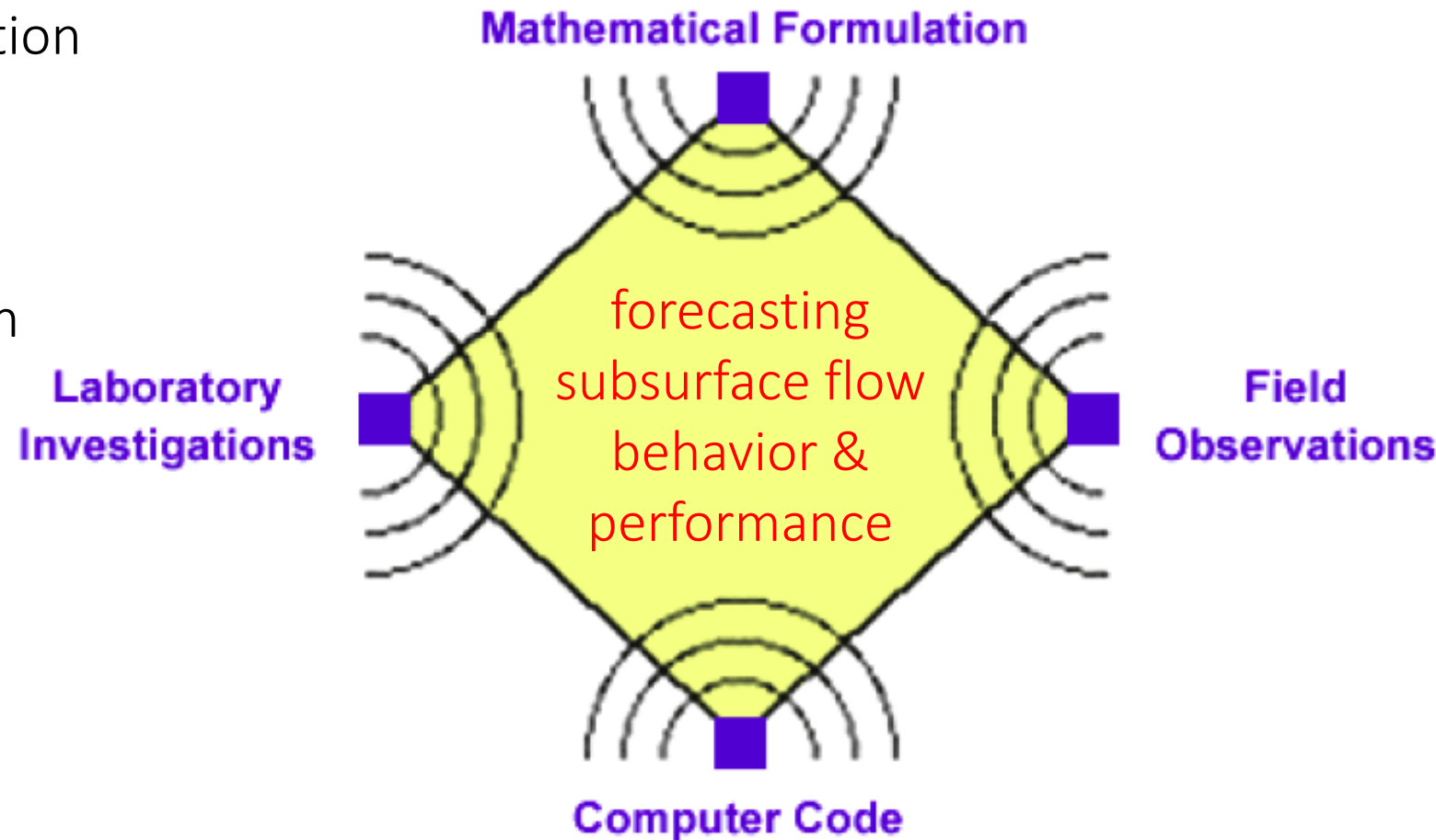
The ultimate goal of subsurface flow modeling is to **develop a predictive model that can facilitate and optimize decision making for field development, operation, and management.**



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

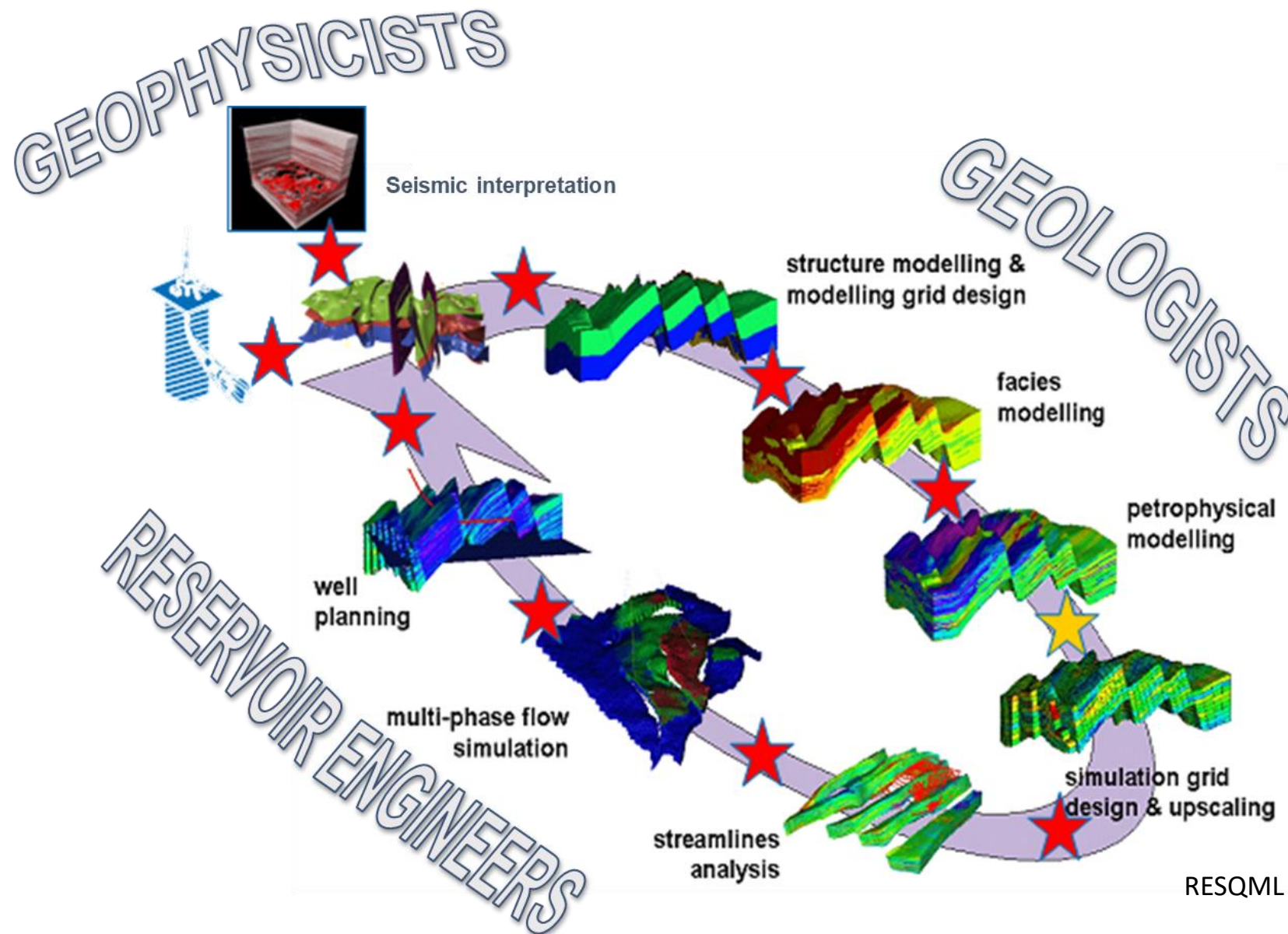
Geologists/Geophysicists find and characterize suitable geologic formations by analyzing subsurface structures with geological and geophysical methods.

Interdisciplinary:

- Geophysics
- Geology
- Reservoir Engineering
- ...

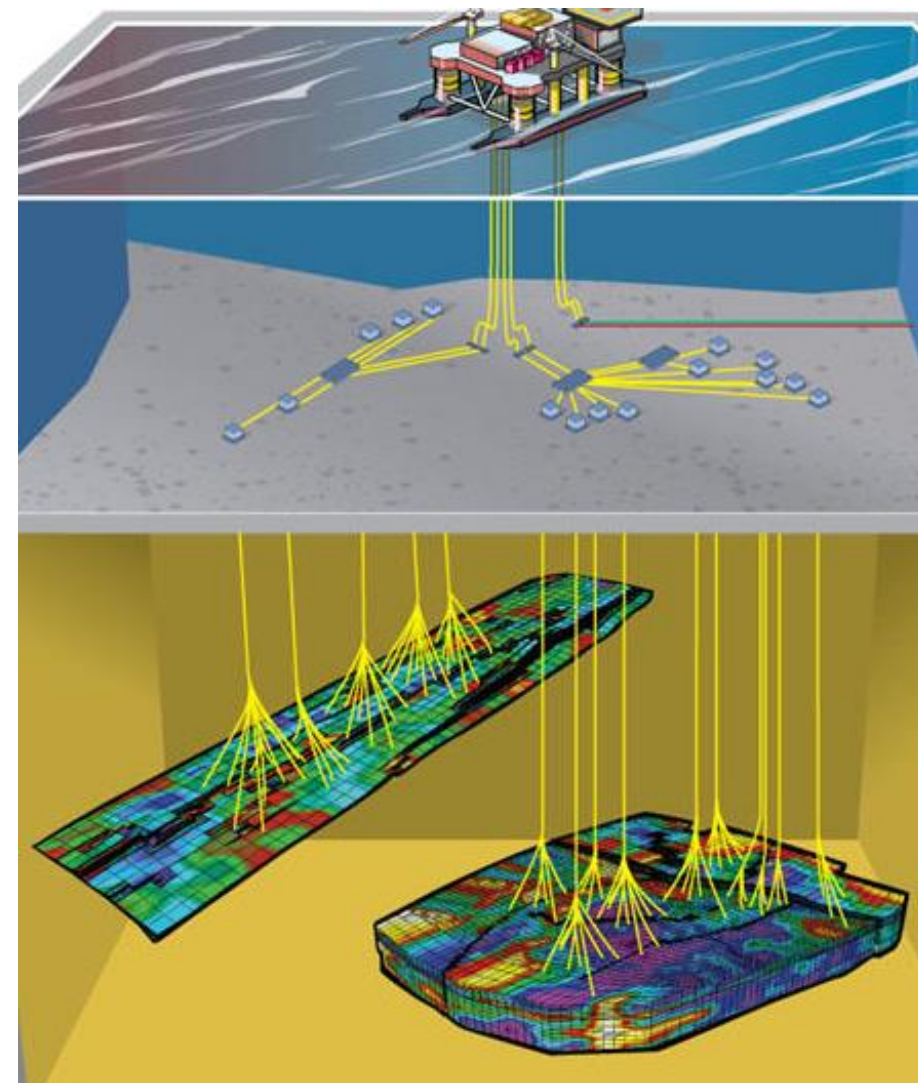
Integrated:

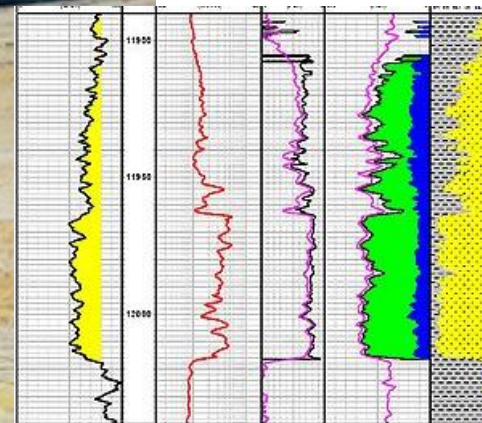
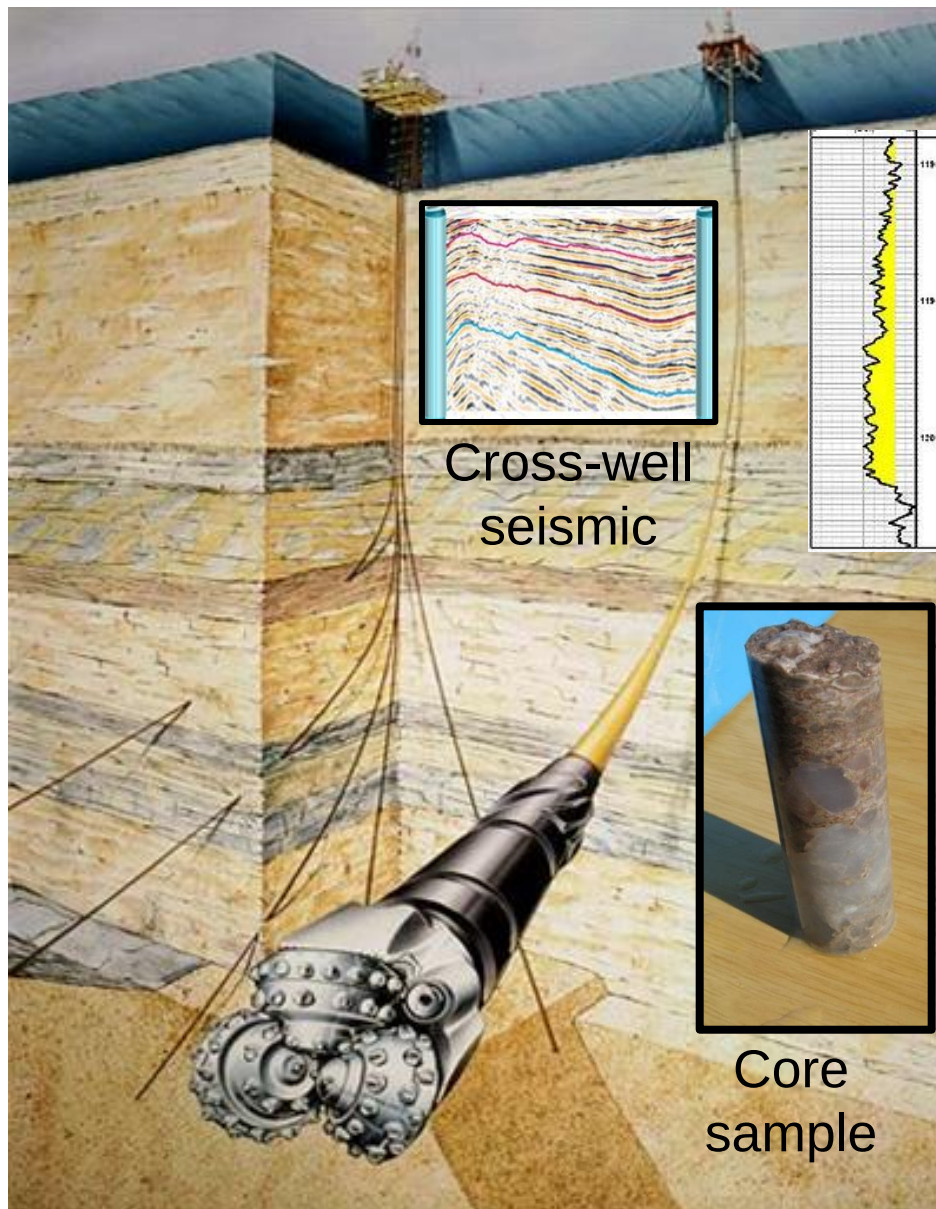
- Team-based
- Closed-loop/Feedback
- Iterative



Reservoir characterization and **fluid flow simulation** are needed to describe and quantify subsurface processes (storage, pressure increase, etc.).

Intensive data acquisition and site surveys for describing reservoir properties (and constructing a model).



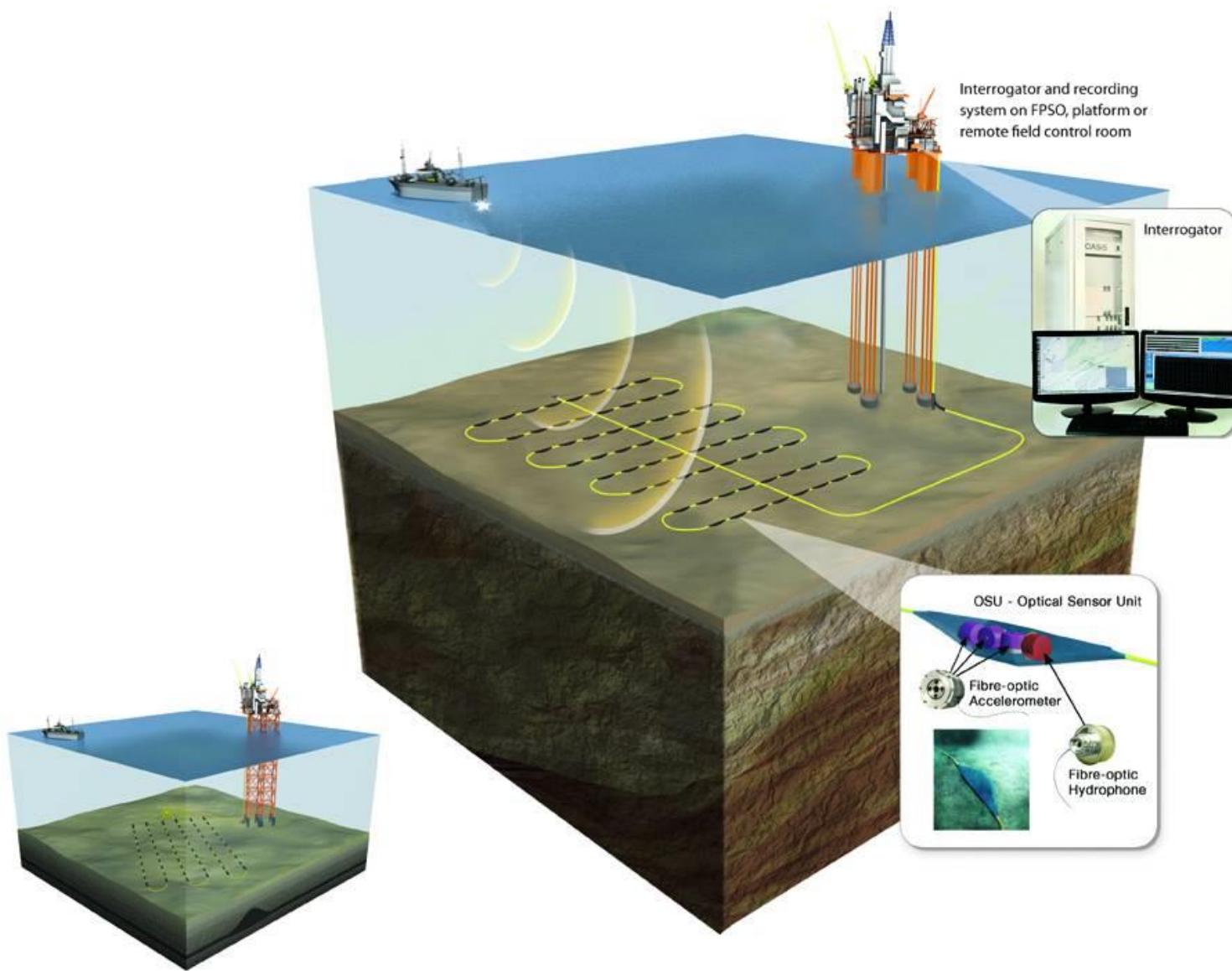


Well logging

Inconvenient access

Very costly

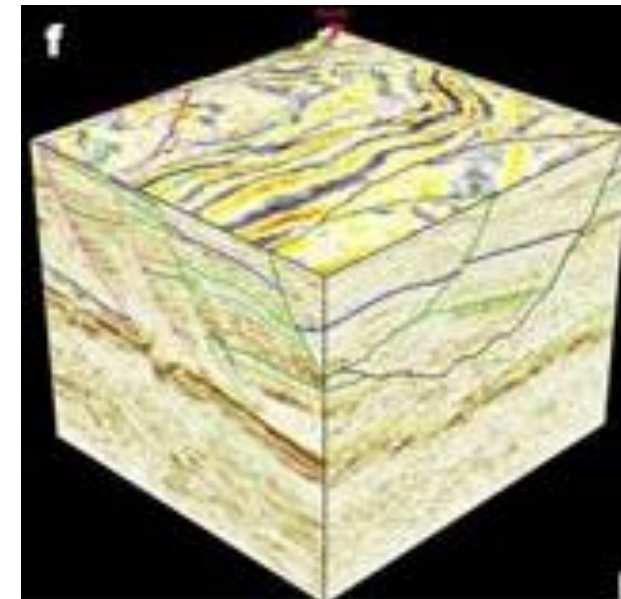
Local data resolution



Seismic surveys

Low resolution

Global coverage



Defining reservoir architecture

Large scale:

reservoir geometry

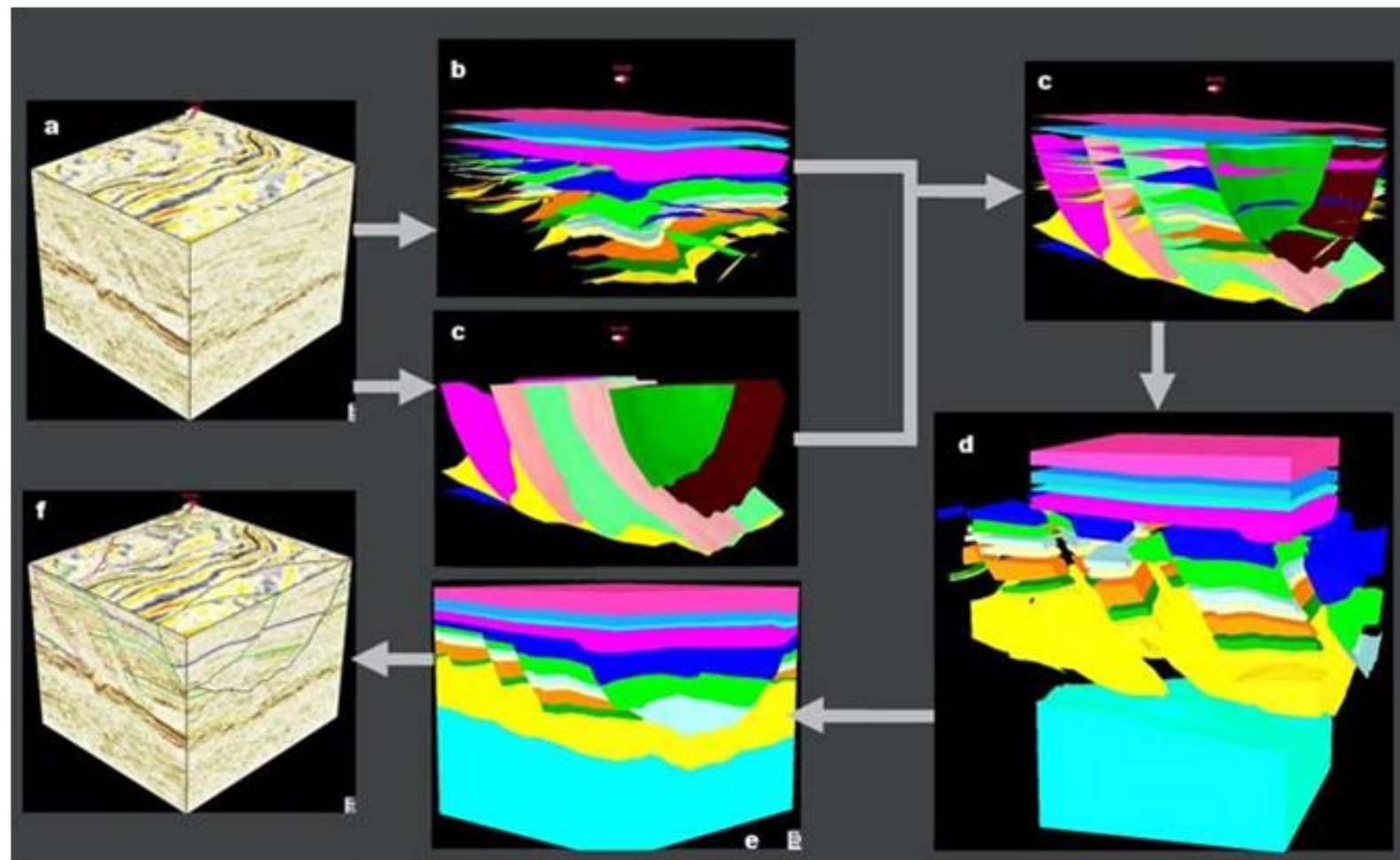
structural features (e.g. faults),

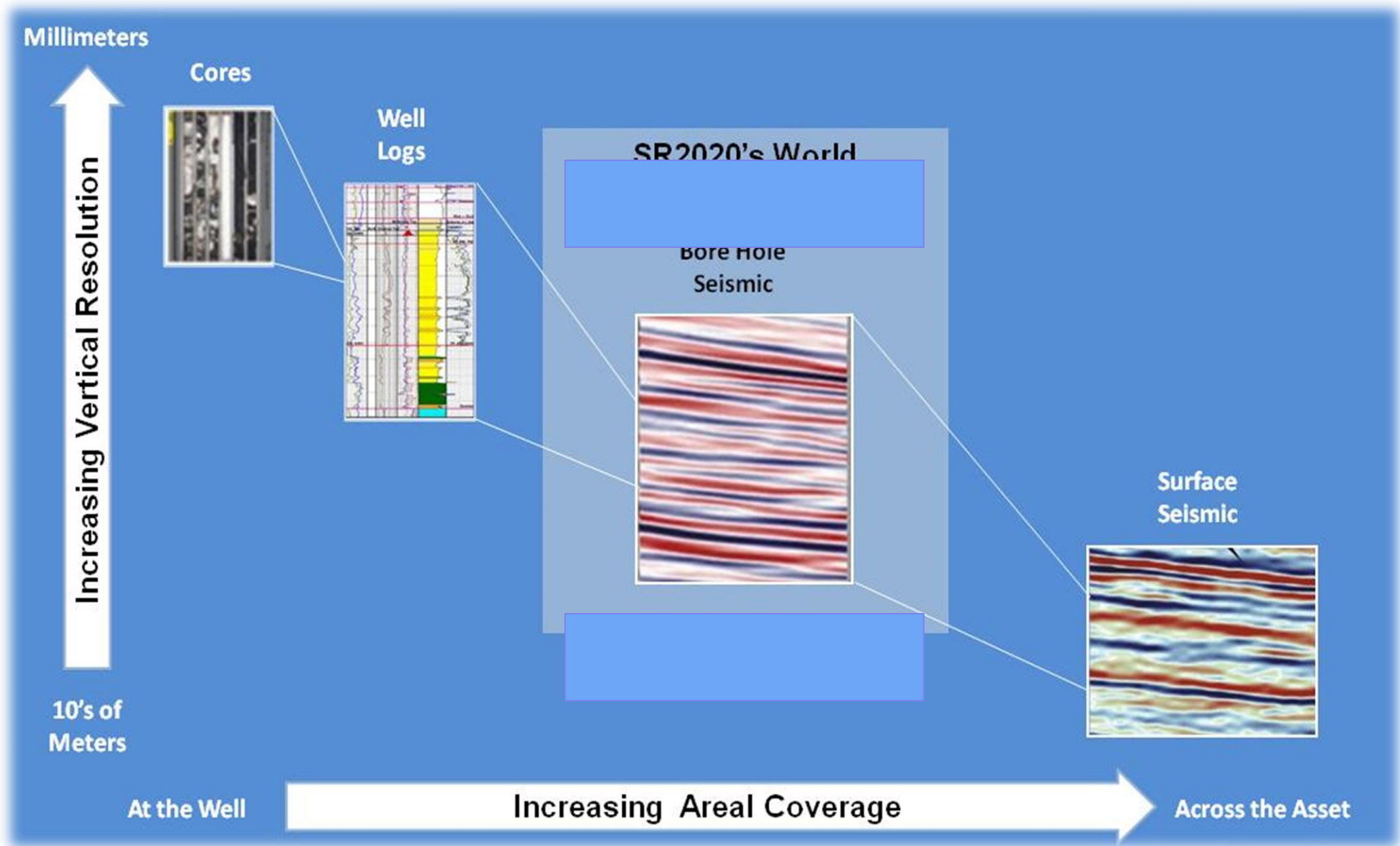
Small scale:

detailed structural elements

stratigraphical features,

fluid contacts, etc.





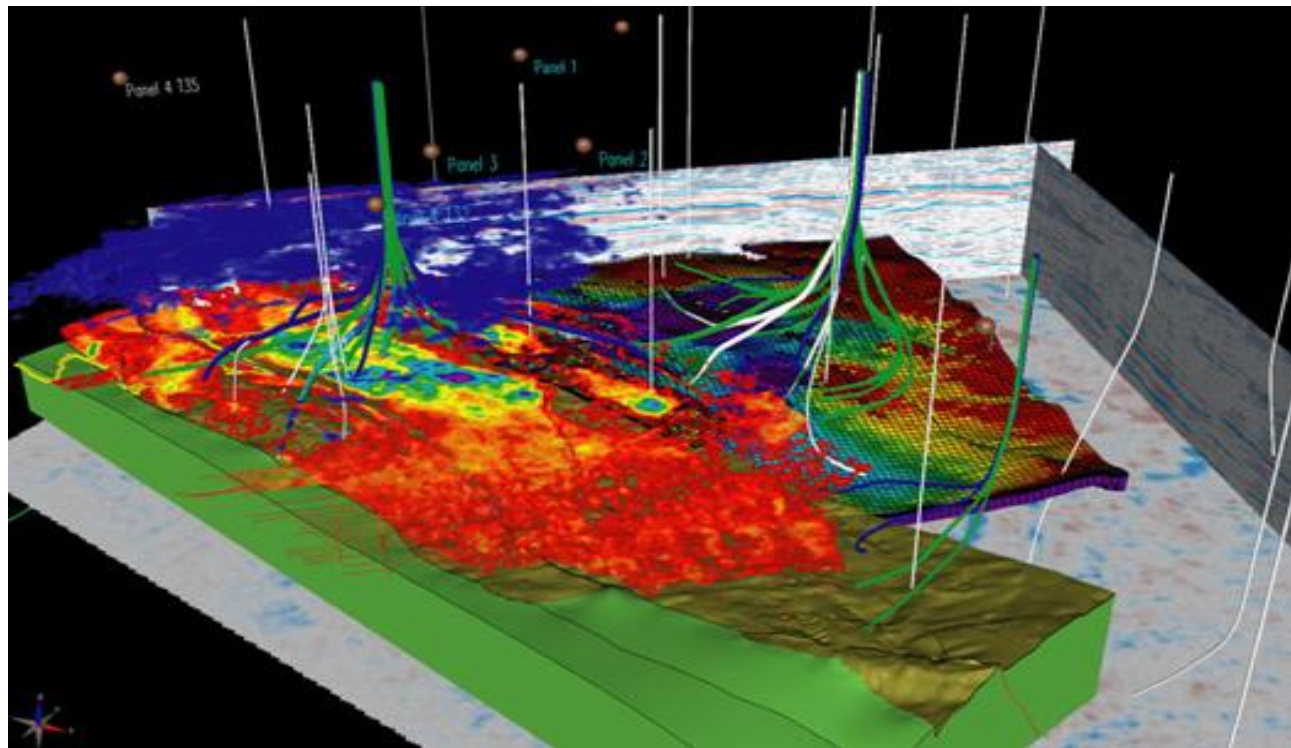
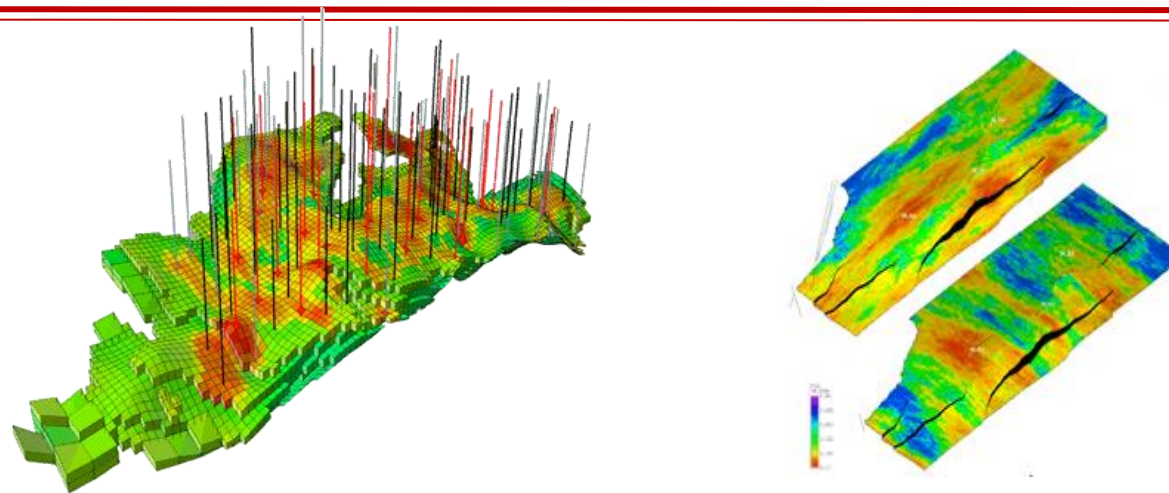
Integration of various
sources of data



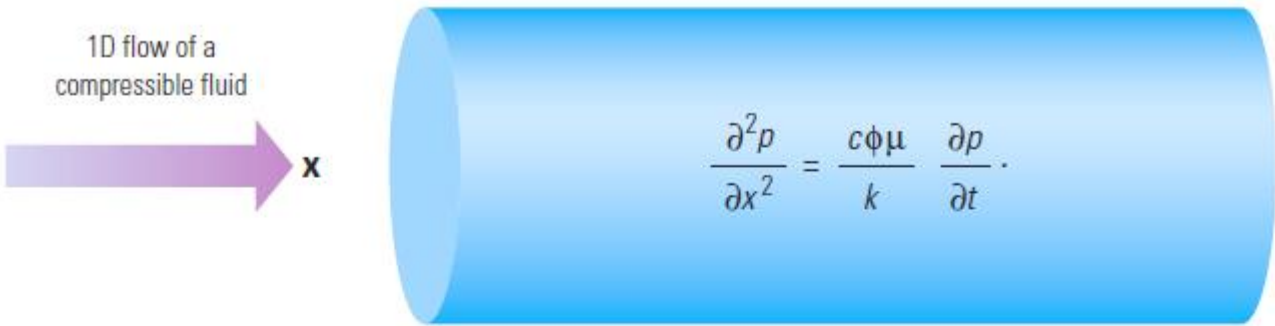
Descriptive static model(s)



Predict dynamic
behavior/response

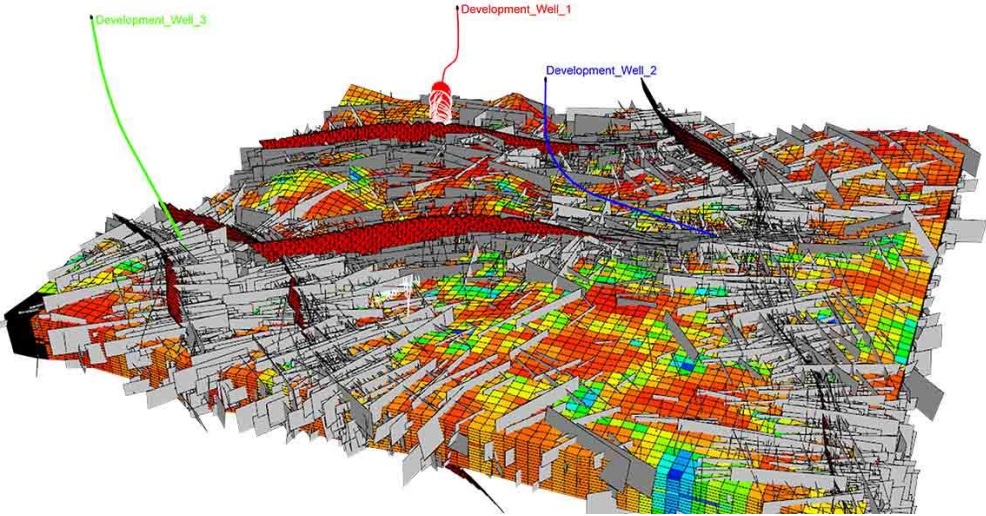
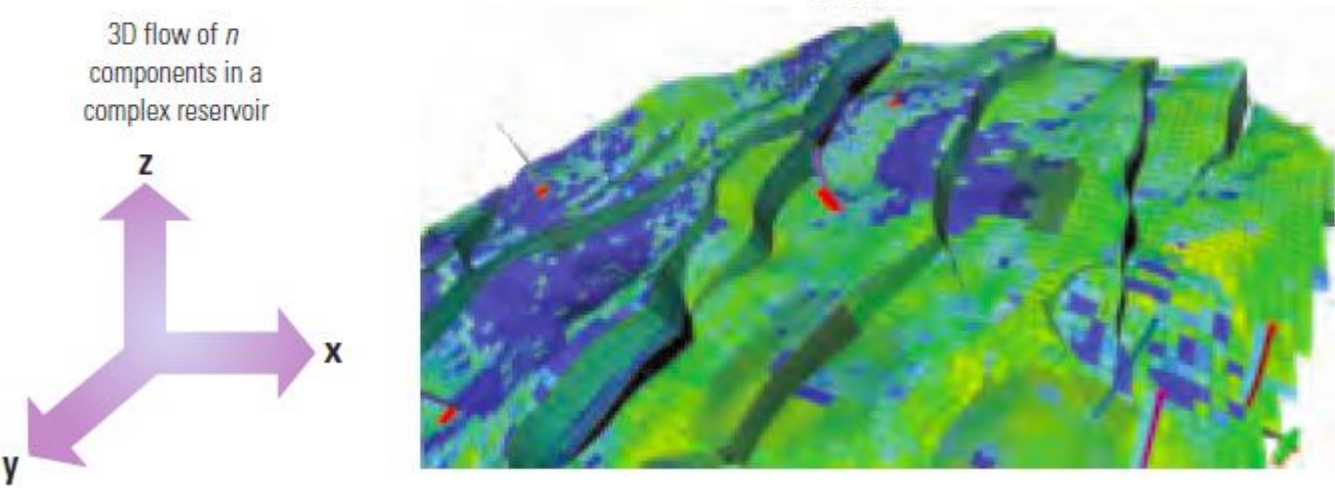


1951



More complex geology
&
More complex processes!

2011

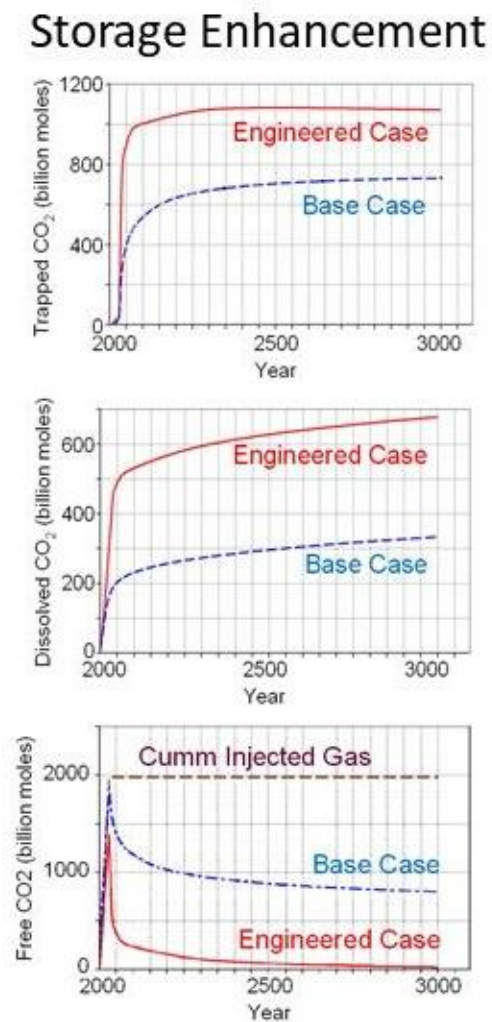
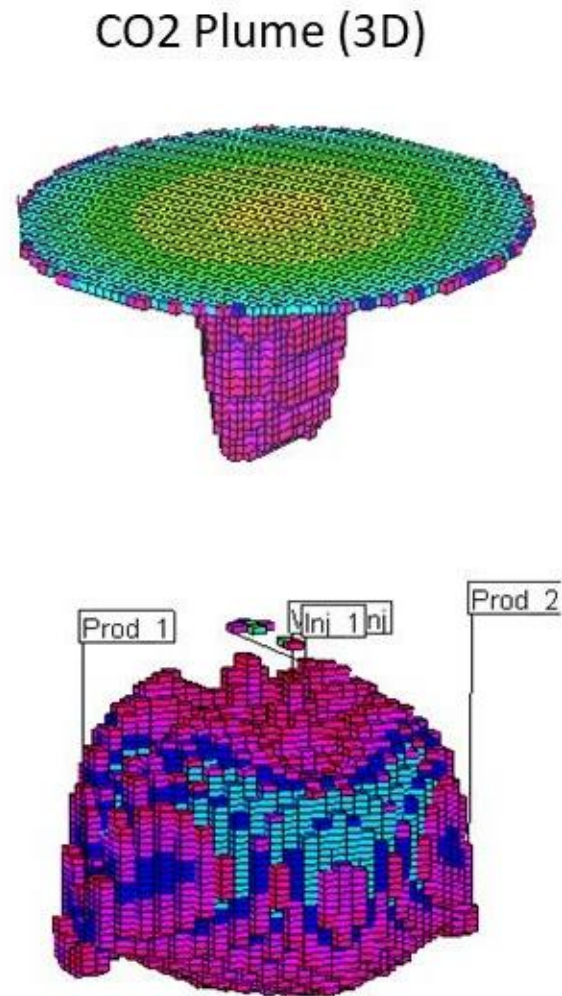
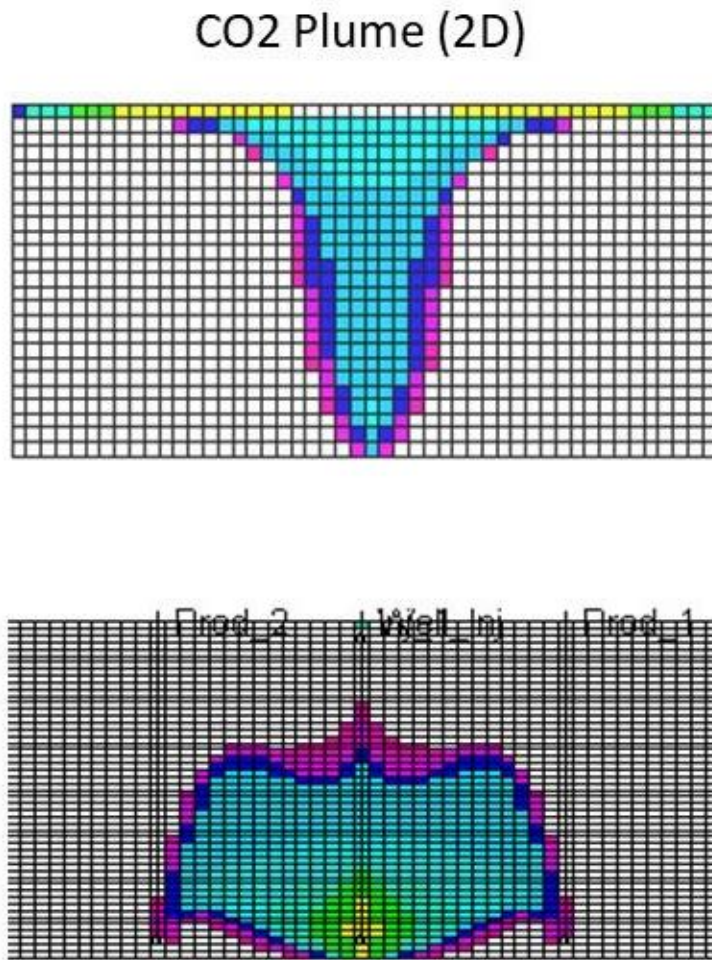
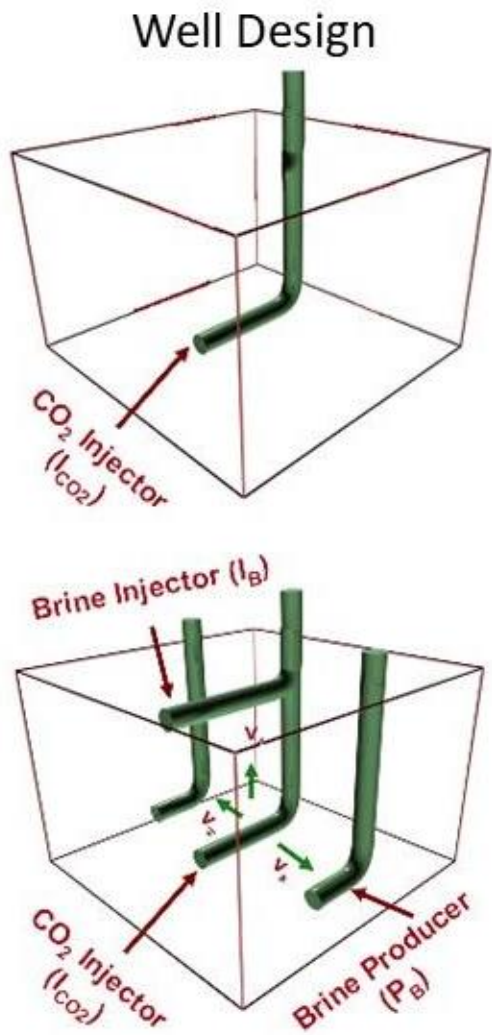


$$\frac{V}{\Delta t} \delta \left(\phi \sum_p^{Np,c} \rho_p S_p \chi_{cp} \right) + q_c^W - \sum_k^{Faces} T_k \left\{ \sum_p^{Np,c} \left[\rho_p \frac{k_{rp}}{\mu_p} \chi_{cp} \left(\Delta p - \Delta P_{cp} - \rho_p g \Delta h \right) \right] \right\} = R_c$$

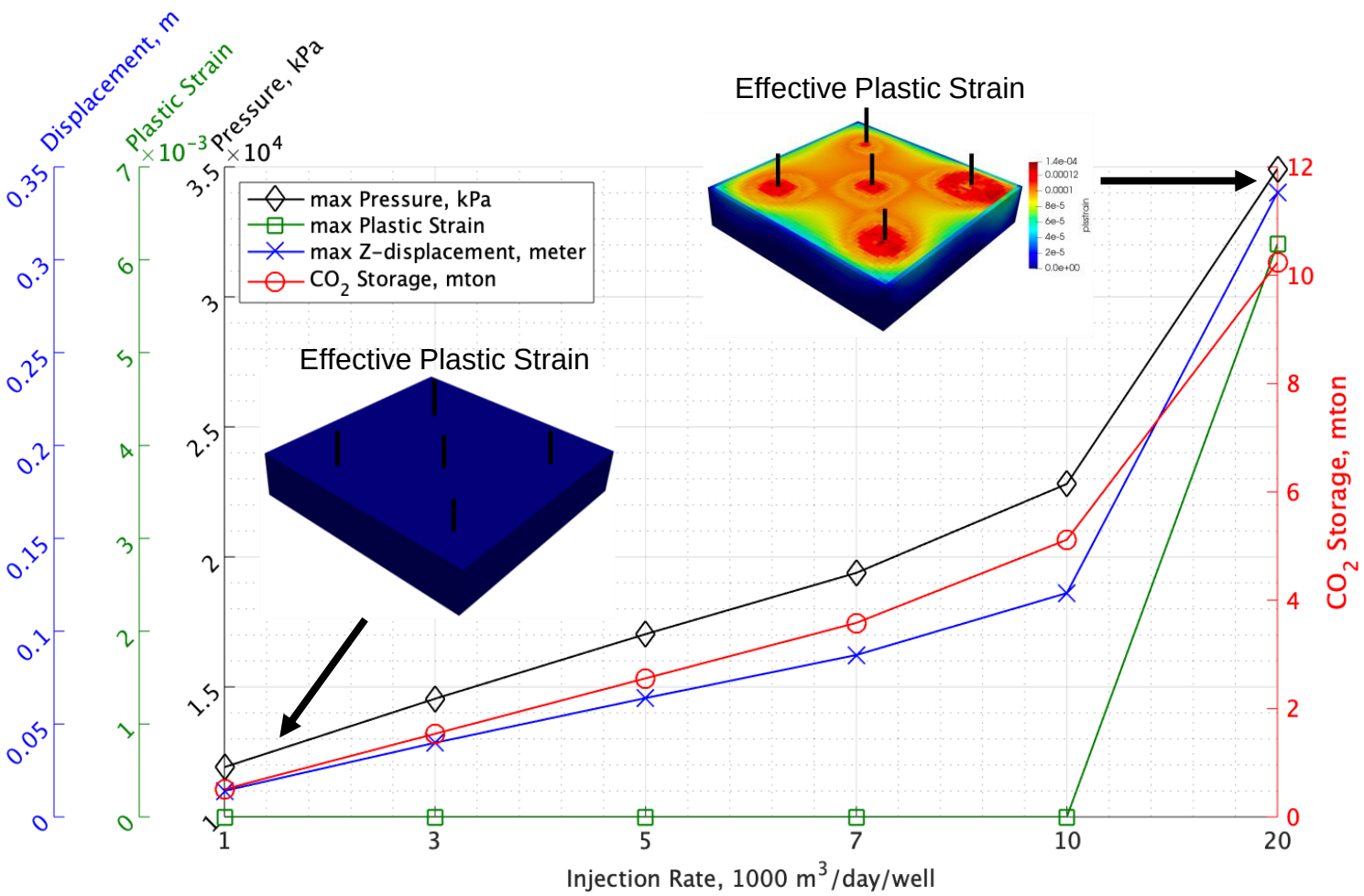
SCHLUMBERGER

Ultimate objective → forecast 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.



Minimizing Pressure Increase while Maximizing Storage Capacity

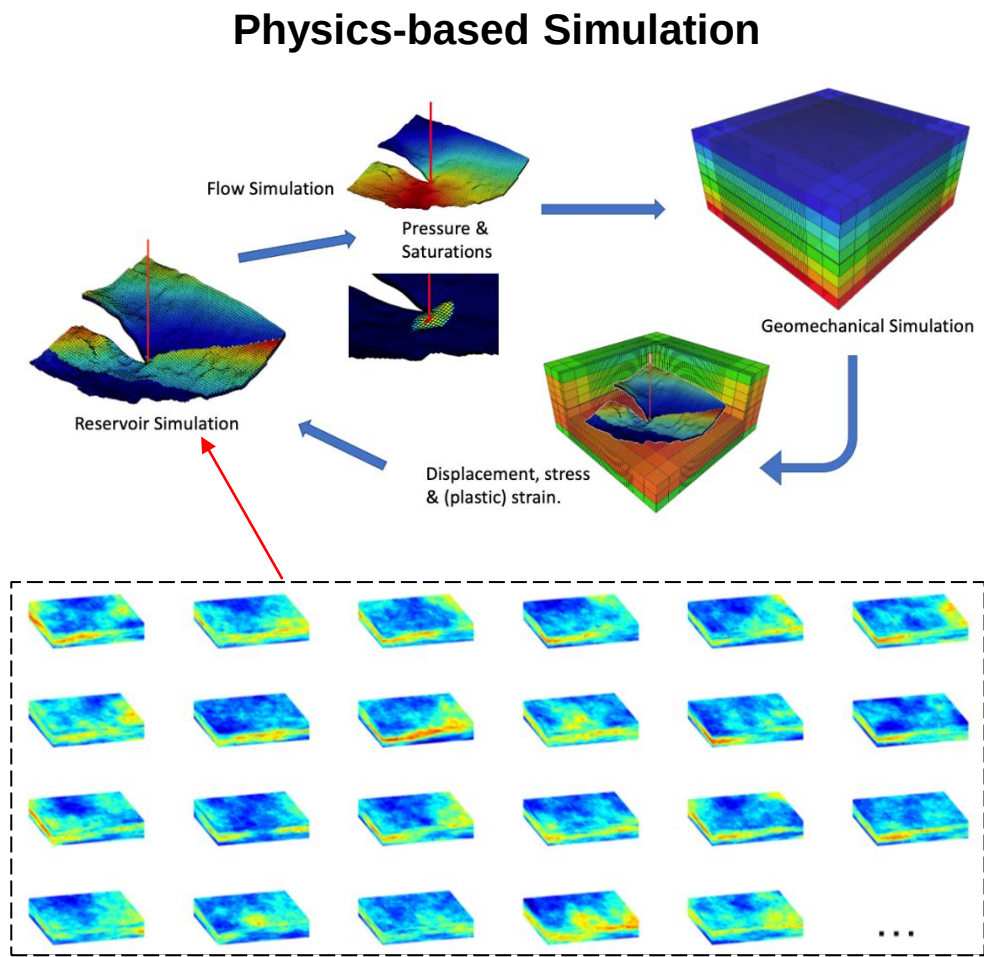


Goal { max Storage
min Risks & Leakage

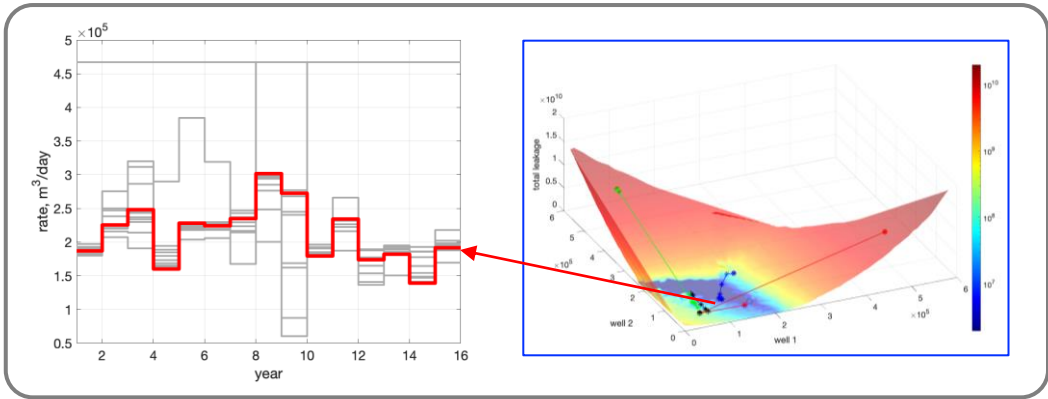
by adjusting

Variables { Well Locations
Injection Rates

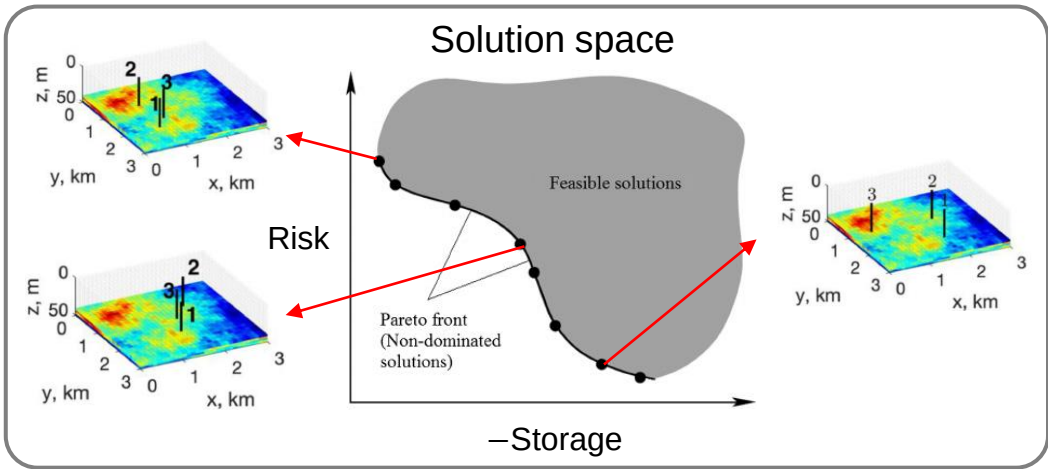
Optimization Workflow



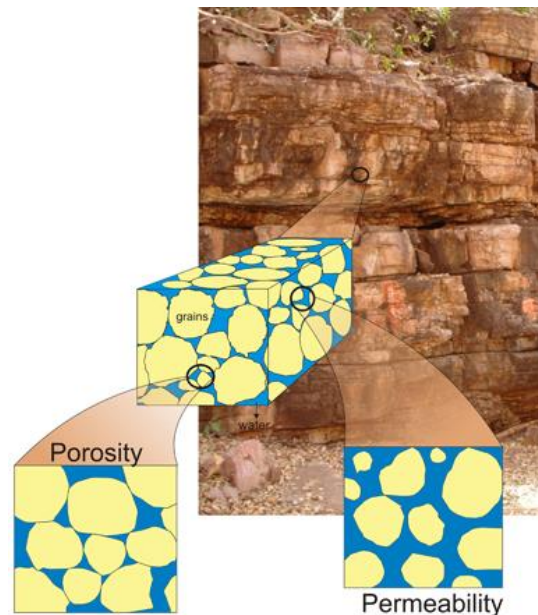
Control Optimization



Well Placement Optimization



- **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

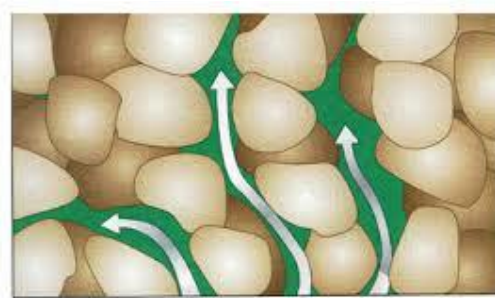


$$\nabla \cdot \left(\frac{\lambda_w}{B_w} \mathbf{u} (\nabla P_w - \gamma_w \nabla Z) \right) = \frac{\partial}{\partial t} \left(\phi \frac{S_w}{B_w} \right) + q_w$$

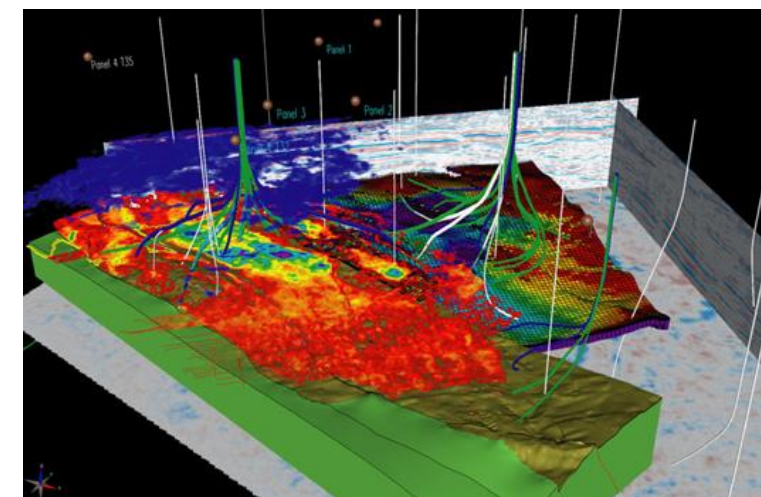
$$\nabla \cdot \left(\frac{\lambda_n}{B_n} \mathbf{u} (\nabla P_n - \gamma_n \nabla Z) \right) = \frac{\partial}{\partial t} \left(\phi \frac{S_n}{B_n} \right) + q_n$$

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

$$S_n + S_w = 1$$

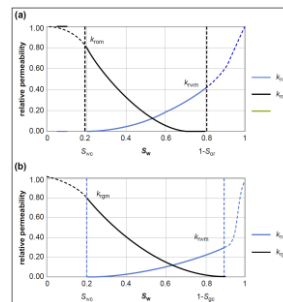
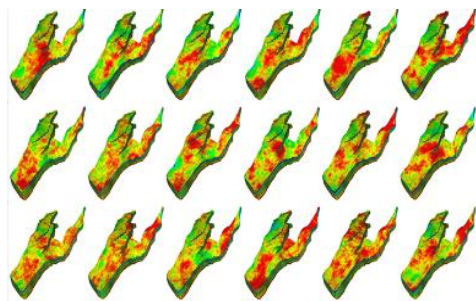
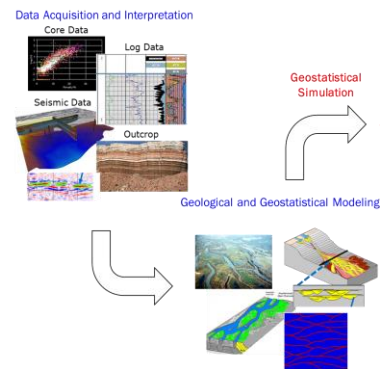
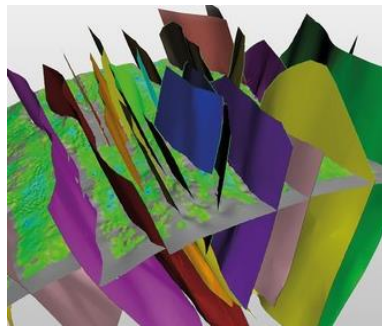


$$\frac{V}{\Delta t} \delta \left(\phi \sum_p^{Np,c} \rho_p S_p \chi_{cp} \right) + q_c^W - \sum_k^{Faces} T_k \left\{ \sum_p^{Np,c} \left[\rho_p \frac{k_{rp}}{\mu_p} \chi_{cp} (\Delta p - \Delta P_{cp} - \rho_p g \Delta h) \right] \right\} = R_c.$$



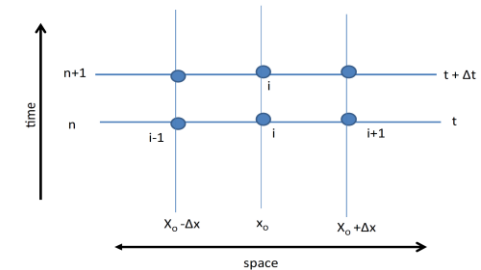
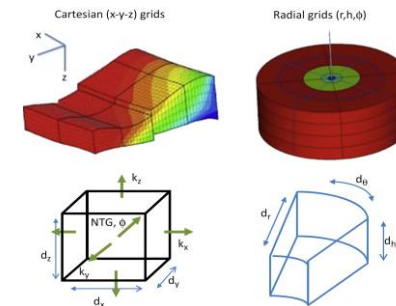
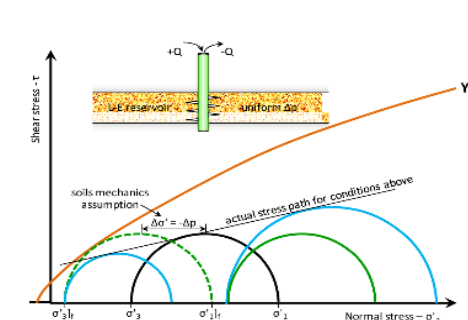
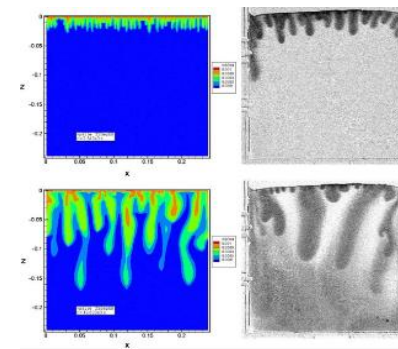
❖ Reservoir Description

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



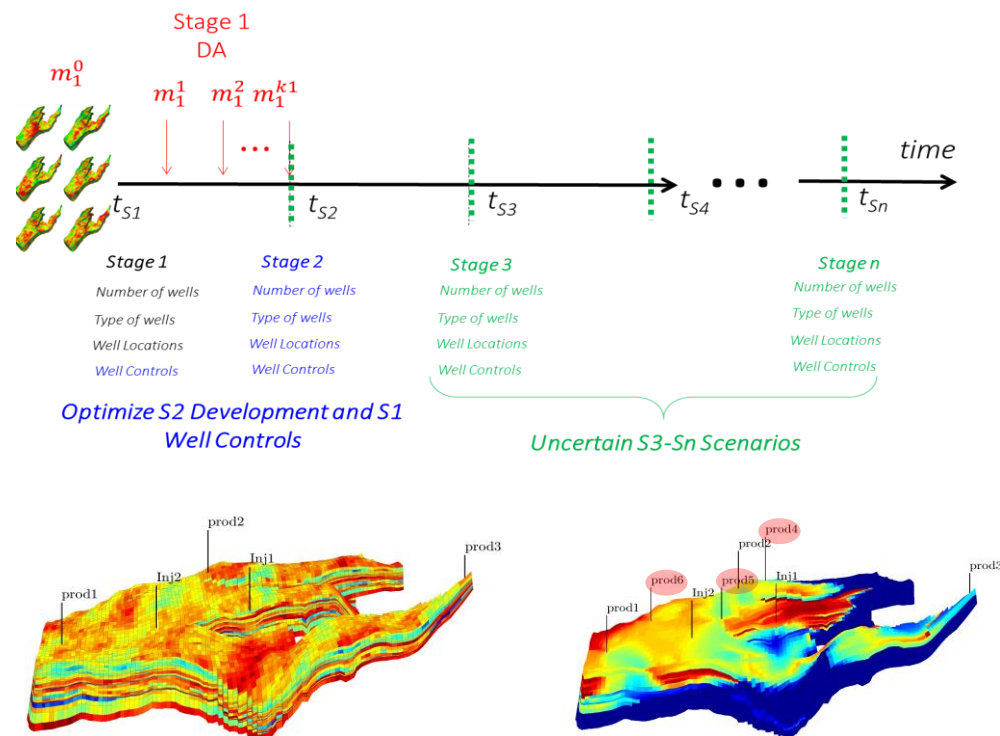
❖ Reservoir Dynamics

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



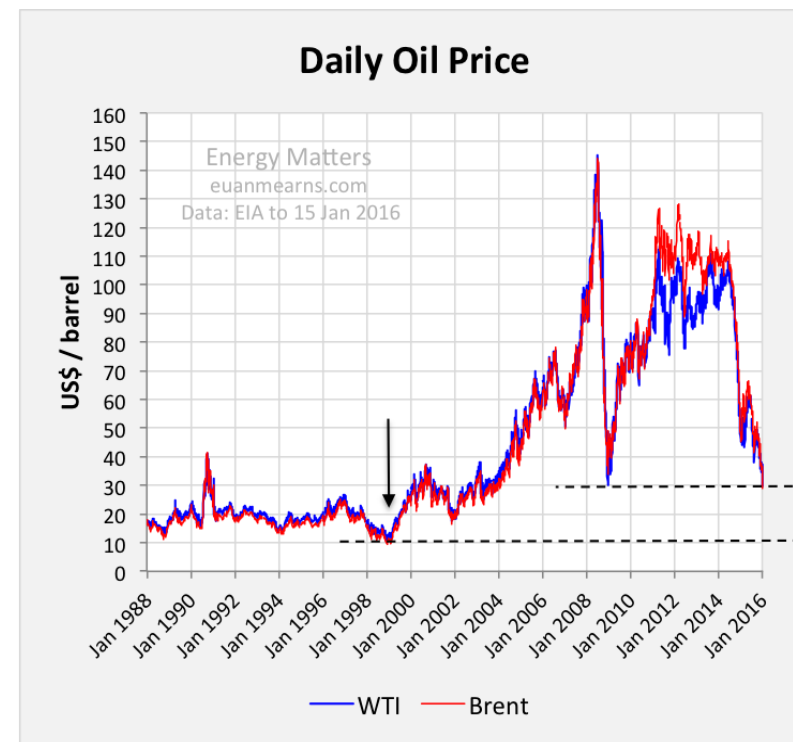
❖ Uncertainty in future development

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

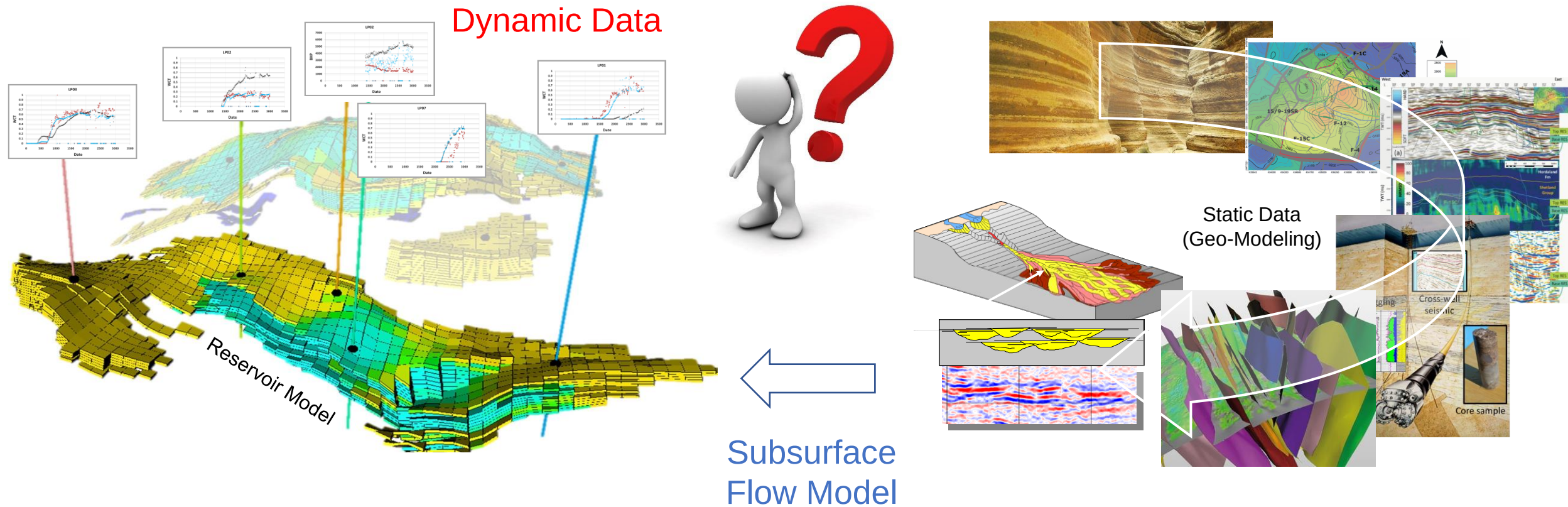


❖ Economic uncertainty

- OPEX
- tax benefits
- complying with regulation



Continuously updating subsurface flow models using monitoring data

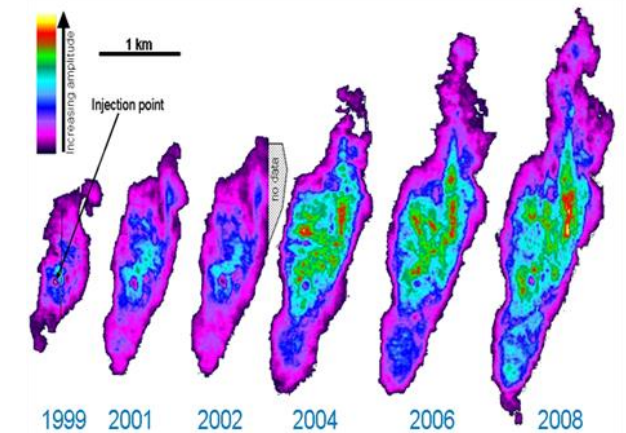
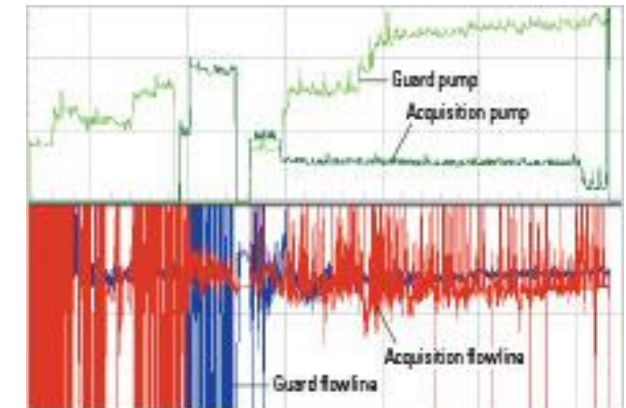
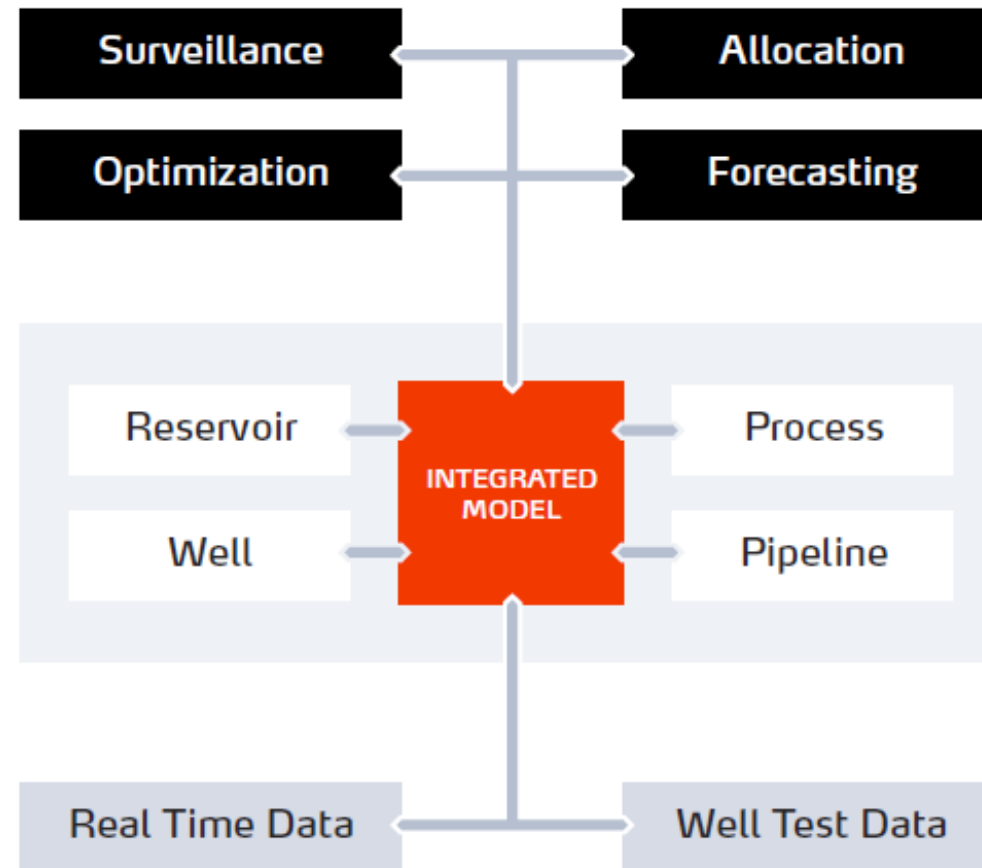


1) Monitoring injection/production quantities

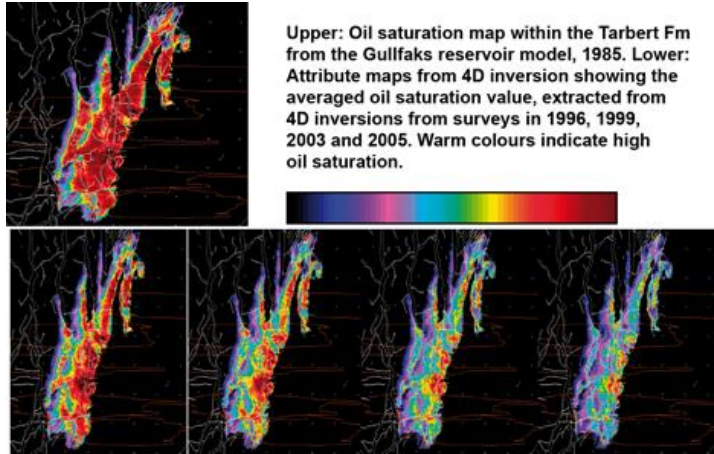
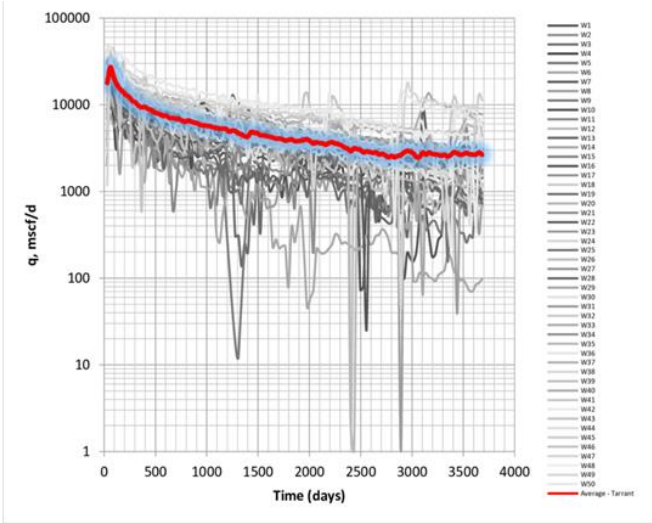
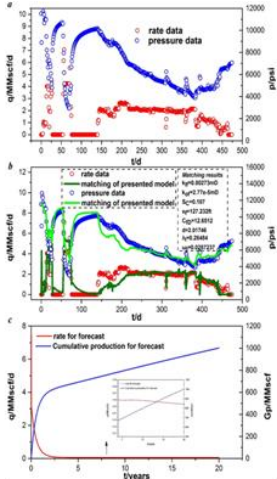
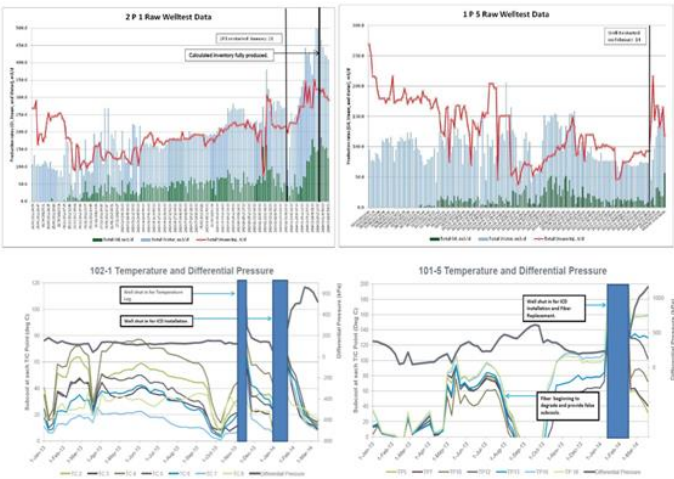
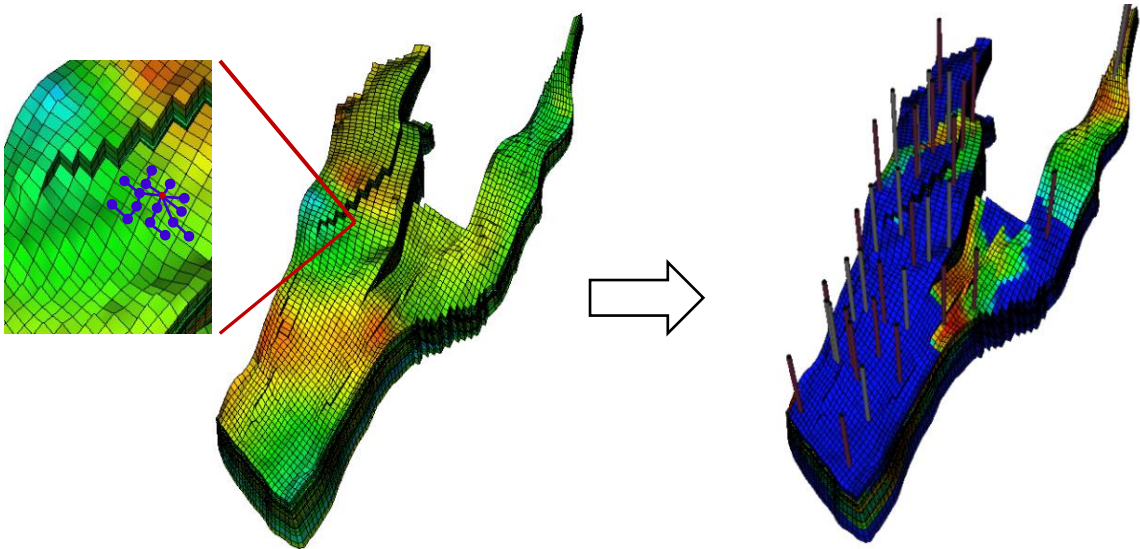
3) Monitoring reservoir condition

2) Monitoring well condition

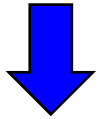
4) Monitoring field performance



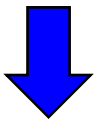
Integrating dynamic monitoring and performance data into flow simulation models to improve prediction accuracy



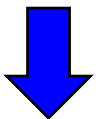
Monitor Measure



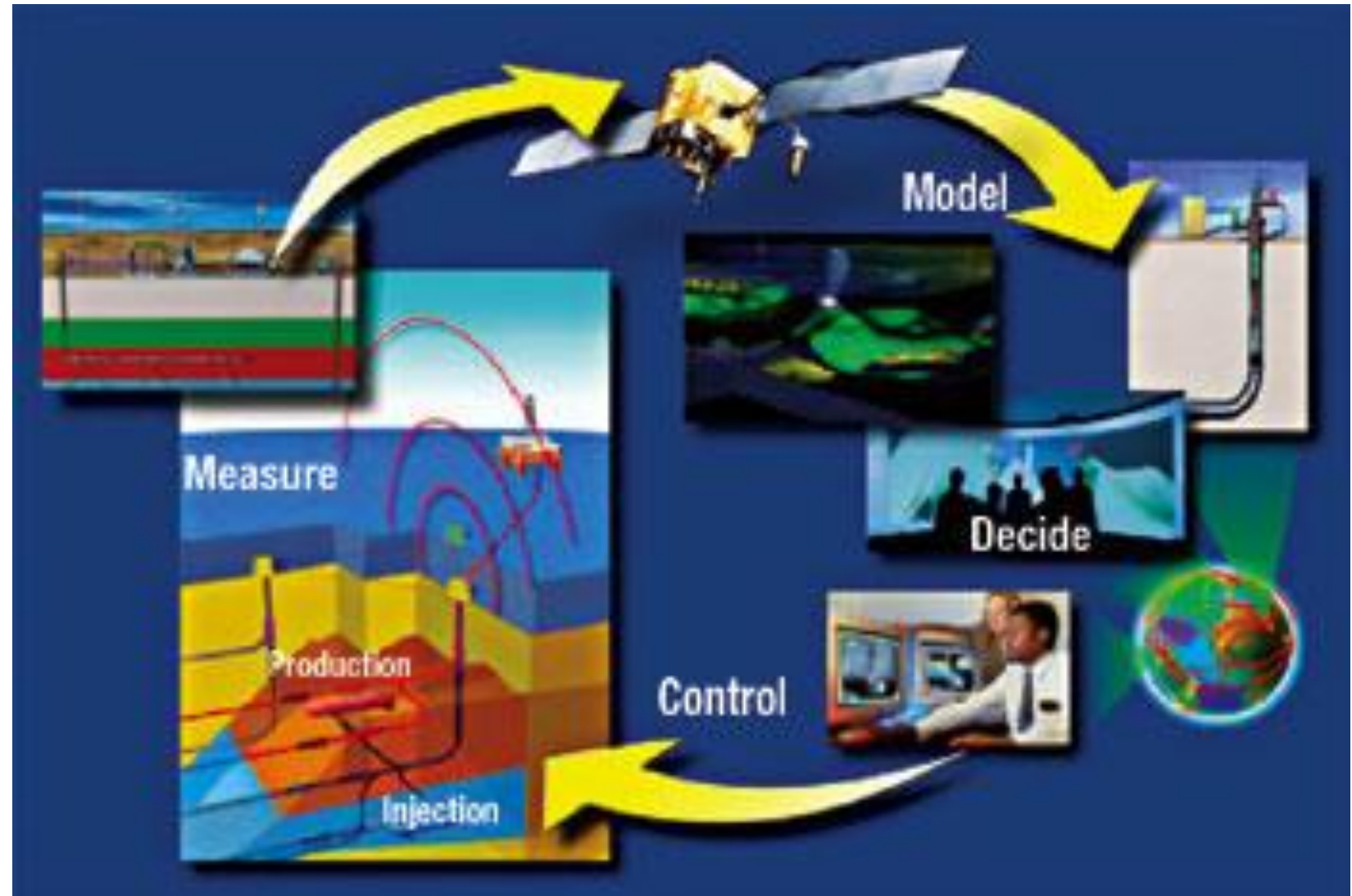
Update & Predict



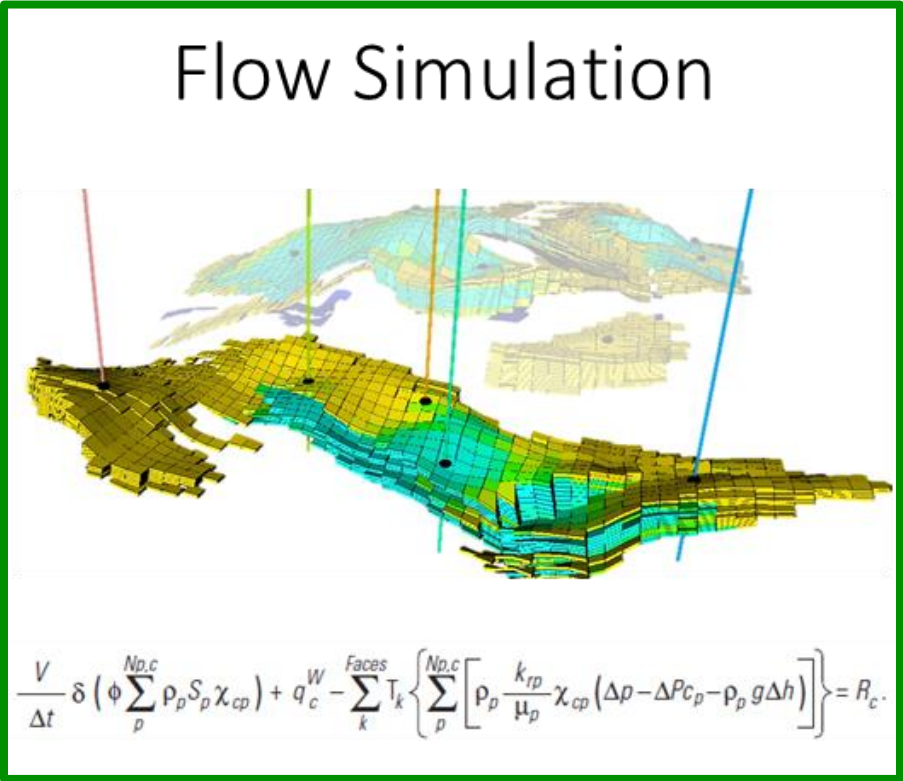
Decide



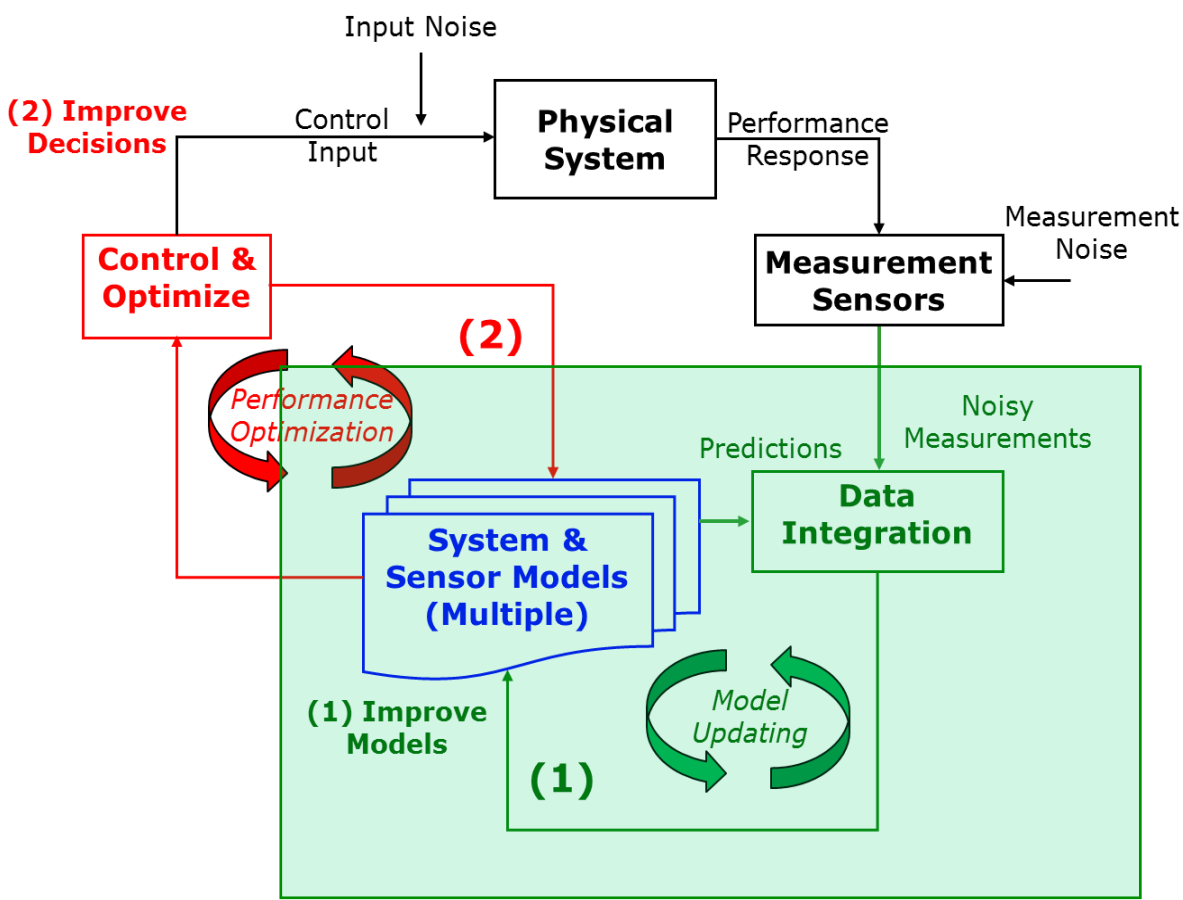
Control/Optimize



Simulation models as prediction tools for performance optimization



Need Reliable Predictions!



Systems approach to field development optimization (main research areas):

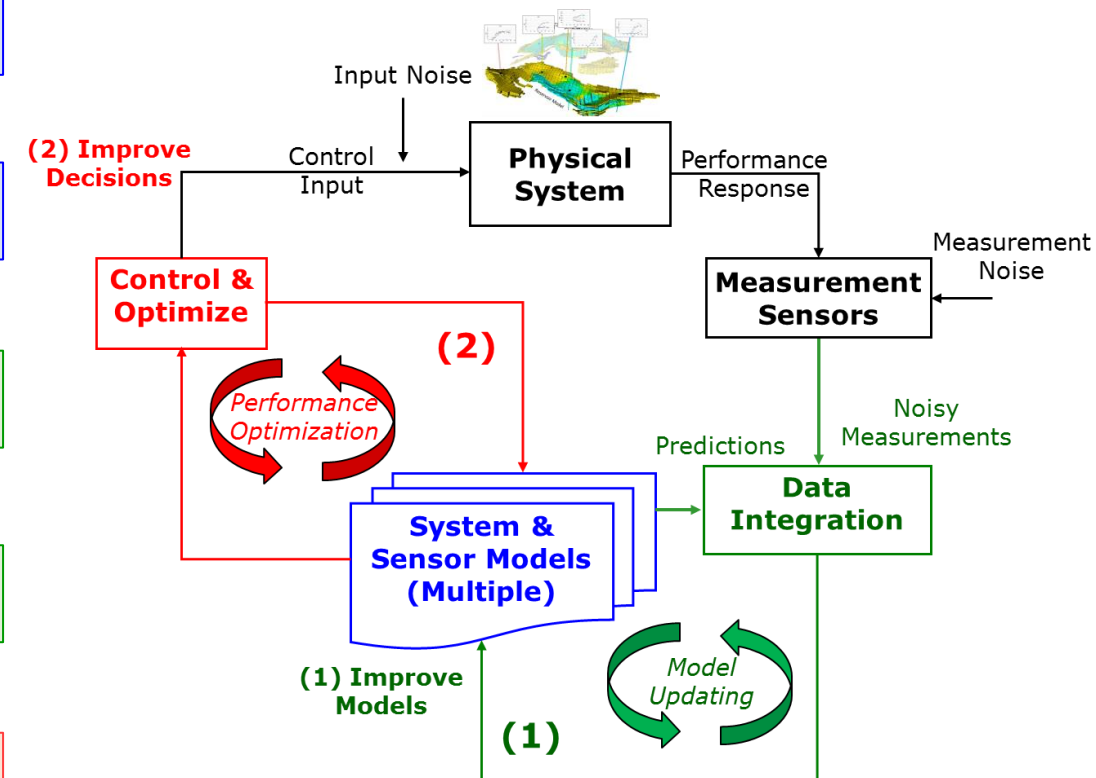
1) Subsurface Description and Modeling

2) Well Performance Prediction

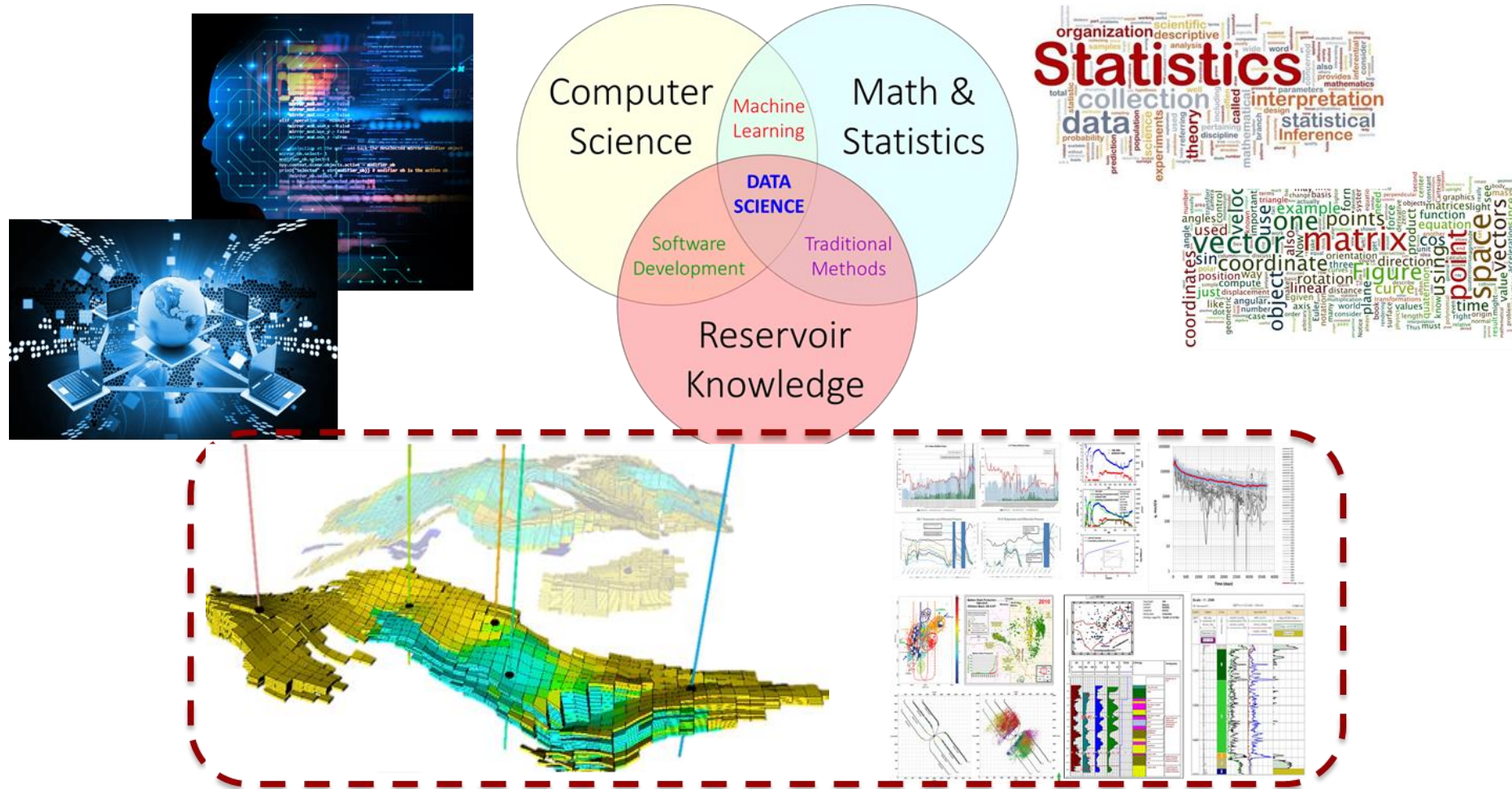
3) Continuous Monitoring and Model Updating

4) Uncertainty Quantification and Reduction

5) Performance Optimization under Risk



Empowering the Development of Subsurface Storage Reservoirs



- Hydrocarbons supply > 80% of energy needs power/ transportation
- As we transition our fossil-based energy resources to renewable sources, we have to minimize the CO₂ emissions
- Geologic CO₂ 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:

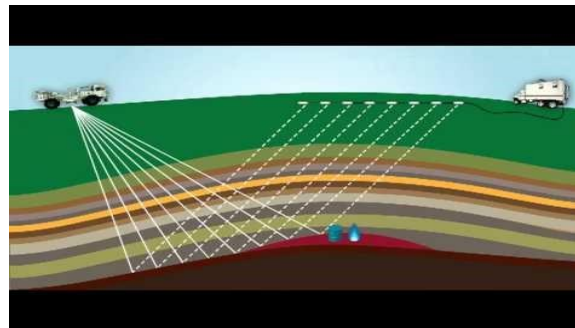
- Technology for subsurface monitoring & characterization
- Technology of maximizing Storage efficiency
- Technology to enable environmental safety

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

Fossil Fuels



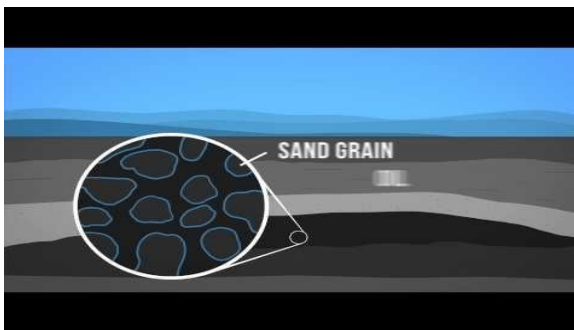
Seismic Exploration



Geothermal Energy



Conventional



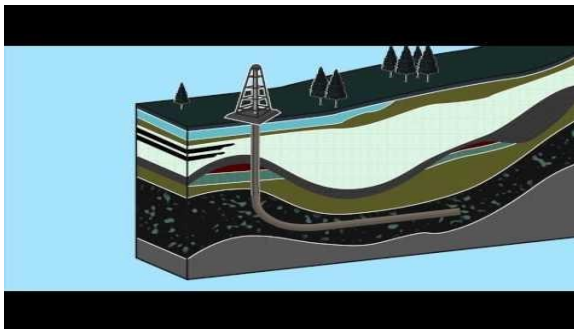
Reservoir Simulation



Groundwater



Unconventional



Petroleum Engineers



Geologic CO₂ Storage





<https://www.youtube.com/watch?v=GglSLuWP5cM>

Subsurface Energy Systems and Geologic CO₂ Storage

2023 Virtual Colloquium on Energy Transition, July 24-25, 2023

USC Viterbi
School of Engineering

Behnam Jafarpour, Professor

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

