Coupled Thermal-Hydrodynamic-Mechanical -Chemical (THMC) Processes in CO_2 Geological Storage

地质封存的热-流-力-化耦合过程

Xiaochun Li

(xcli@whrsm.ac.cn)

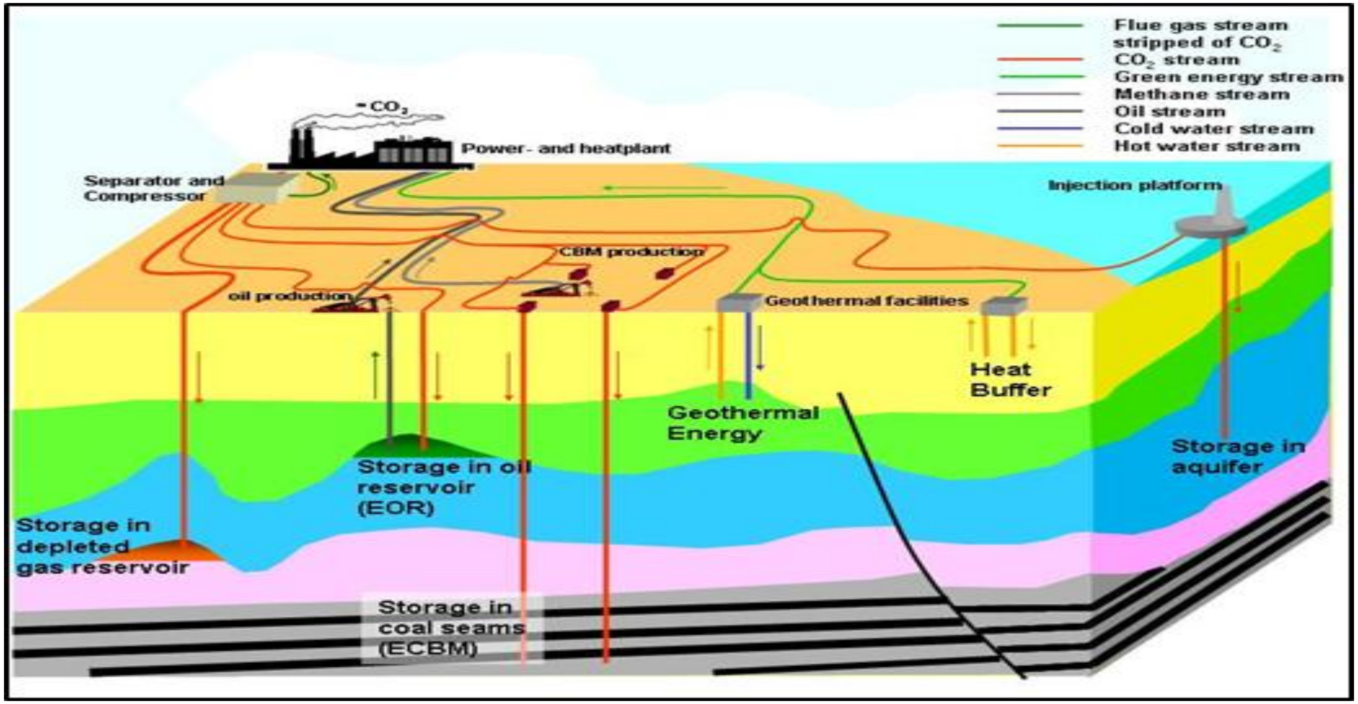
Institute of Rock and Soil mechanics
Chinese Academy of Sciences

Outlines

- Background
- Interactions between THMC processes
- Individual processes
- Coupled processes
- Conclusions and recommendations

Background

CO_2 Geological utilization and storage (CGUS)



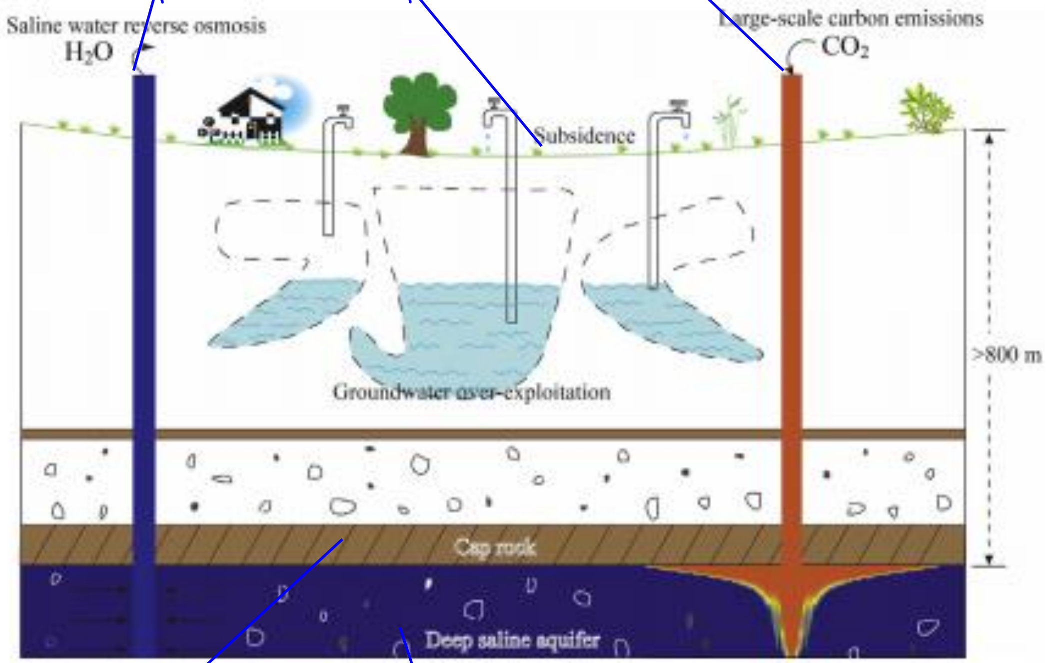
- EOR驱油
- ECBM驱煤层气
- EGR驱天然气
- ESGR驱页岩气
- EGS强化采热
- EUL溶浸采铀
- EWR驱水

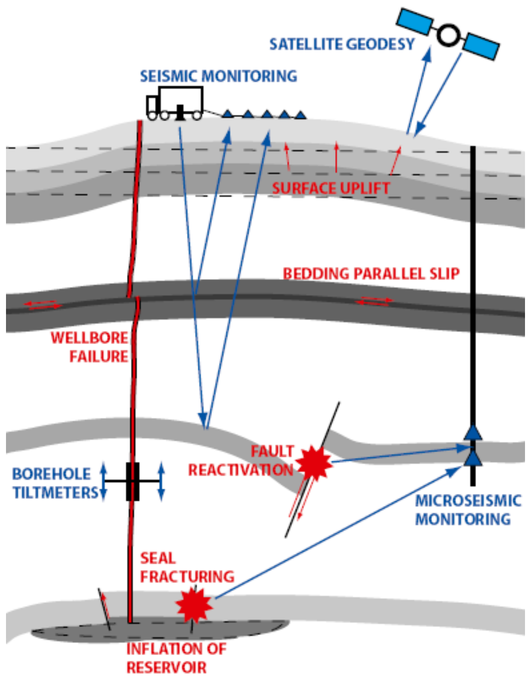
Common scientific issue？共同的基础科学问题

Background

Production   Safety   Injectivity

Mechanical Stability





Sealing   Storage capacity

- **Large scale:** tens of millions ton of CO_2 injected at single site, area of about 1000km^2 involved
- **Long term:** hundreds of years
- **Multi-physical coupling:** T-H-M-C coupling

Aims: Current understanding, theory framework

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Interaction among THMC processes

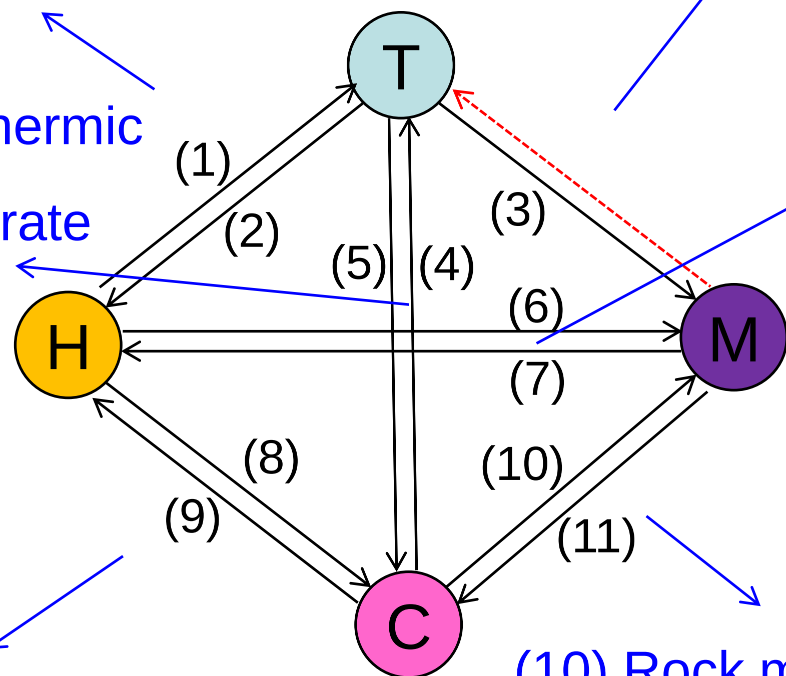
(1) Heat convection, enthalpy

(2) Density, viscosity

(3) Thermal stress, thermal damage

(4) Exothermic/endothermic

(5) Reaction rate, hydrate



(6) Effective stress

(7) Porosity & permeability

(8) Species convection transport

(9) Density, viscosity, porosity & permeability

(10) Rock mechanical properties, adsorption-induced swelling and softening

(11) Pressure solution

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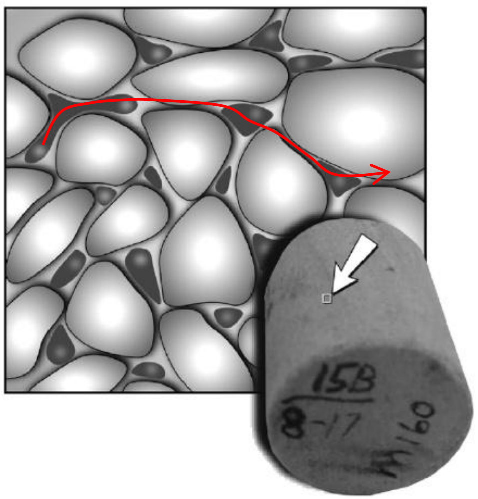
Individual process-Hydrodynamic process

Multiphase and multicomponent

CO_2, H_2O, NaCl

Aqueous, gaseous



Darcy's law for Multiphase flow

Mass conservation

$$\frac{d}{dt}\int_{V_n} M^{\kappa} dV = \int_{\Gamma_n} \mathbf{F}^{\kappa} \bullet \mathbf{n} d\Gamma + \int_{V_n} q^{\kappa} dV$$

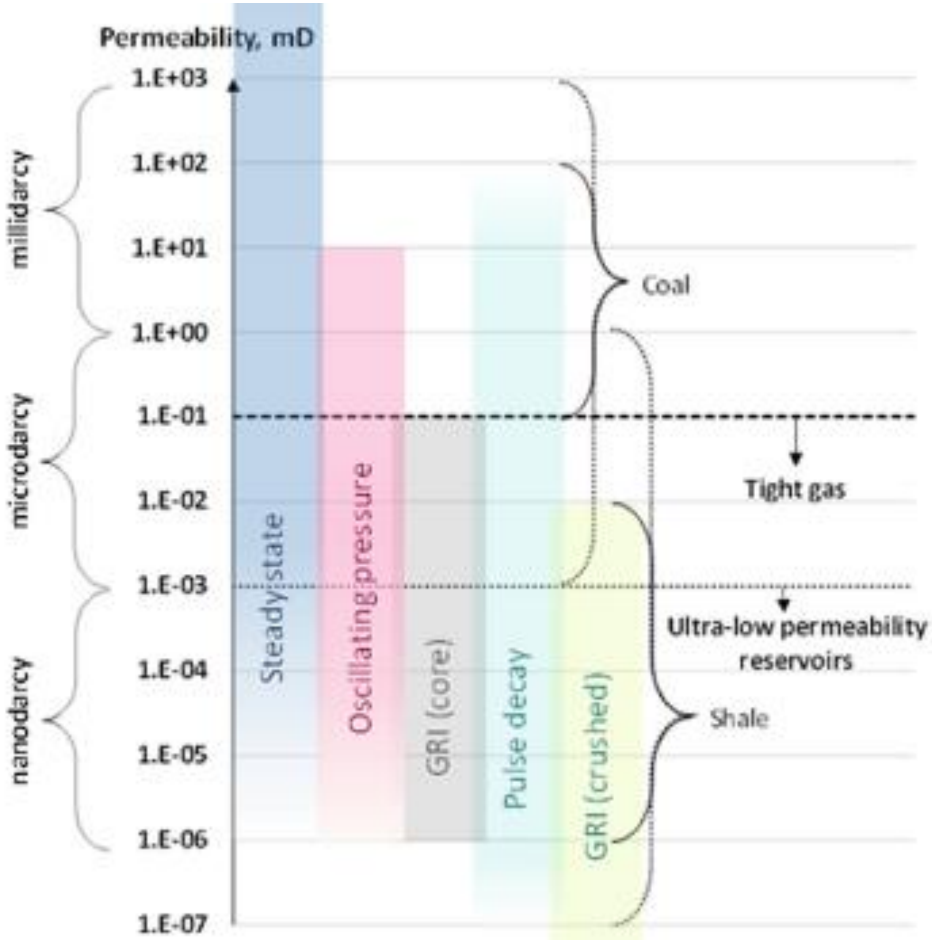
$$M^{\kappa} = \sum_{\beta=A,G} \phi S_{\beta} \rho_{\beta} X_{\beta}^{\kappa}, \quad \kappa = w, i, g$$

$$\mathbf{F}_{\beta}^{\kappa} = -k \frac{k_{r\beta}\rho_{\beta}}{\mu_{\beta}} X_{\beta}^{\kappa}(\nabla P_{\beta} - \rho_{\beta}\mathbf{g}) + \mathbf{J}_{\beta}^{\kappa}, \quad \kappa = w, i, g$$

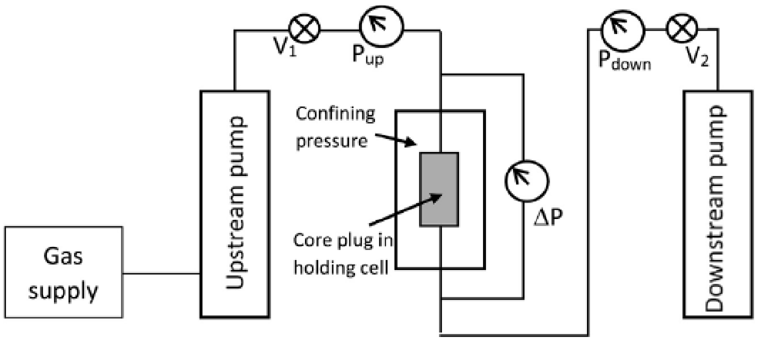
$$\sum_{\beta=A.G} S_{\beta} = 1 \qquad P_g - P_l = P_c$$

Single process-Hydrodynamic process

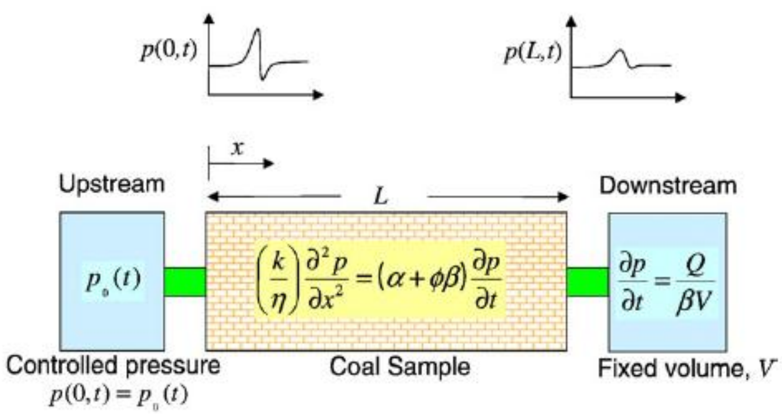
Key Parameter-permeability



Steady state method

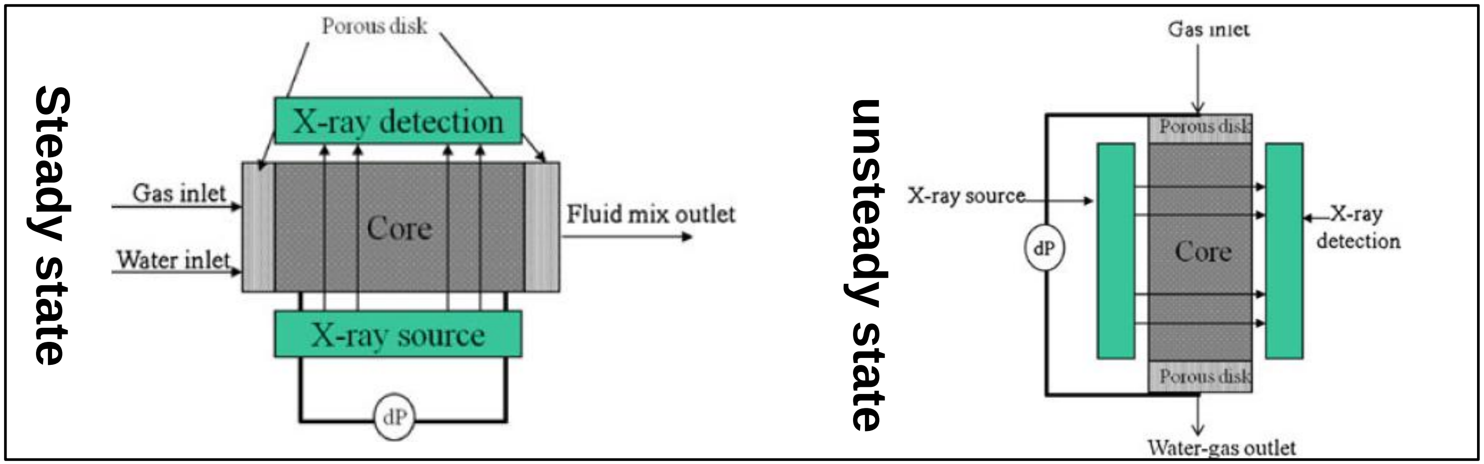


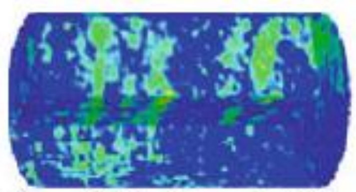
Pressure transient method



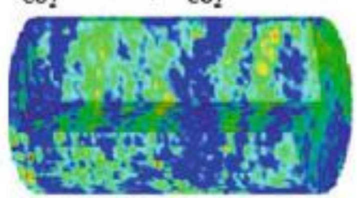
Single process-Hydrodynamic process

Key Parameter-relative permeability

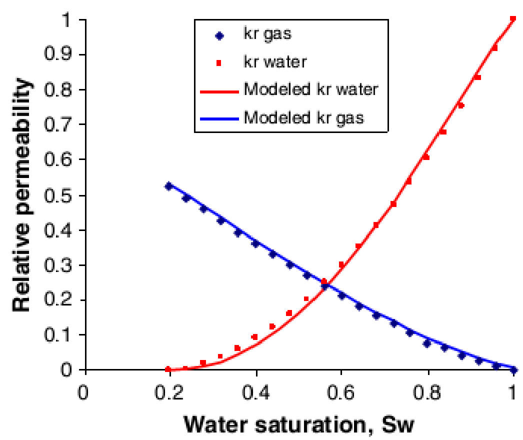


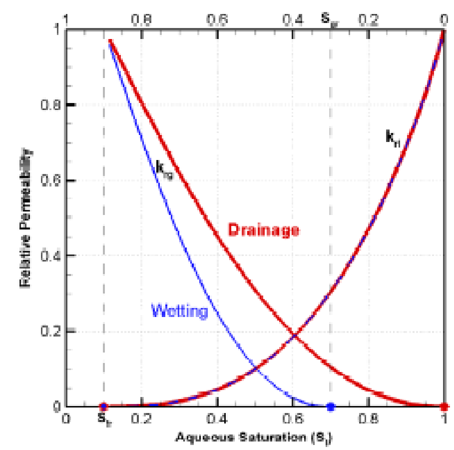


$f_{CO_2}=0.05$, $S_{CO_2}=0.132$



$f_{CO_2}=0.70$, $S_{CO_2}=0.278$

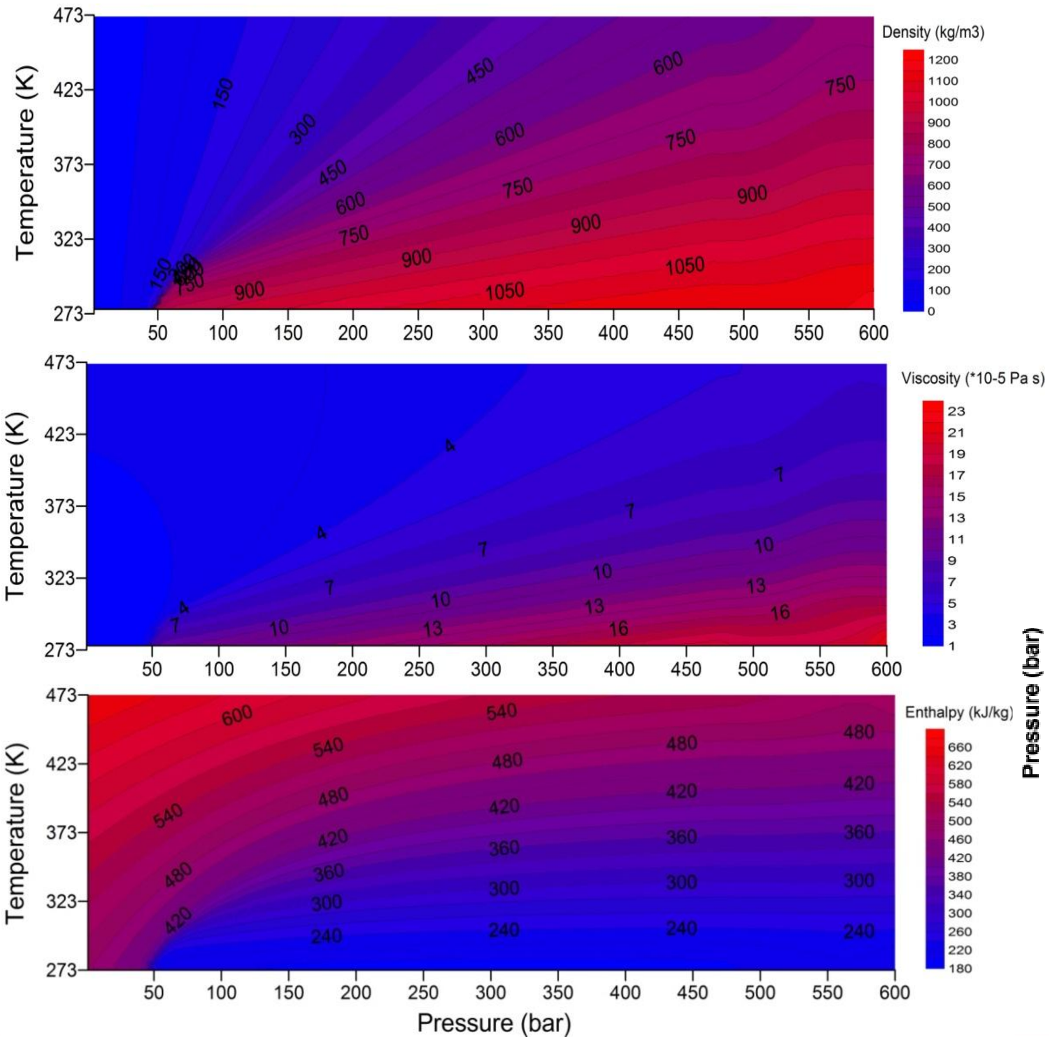




Single process-Hydrodynamic process

Fluid property

Pure CO_2

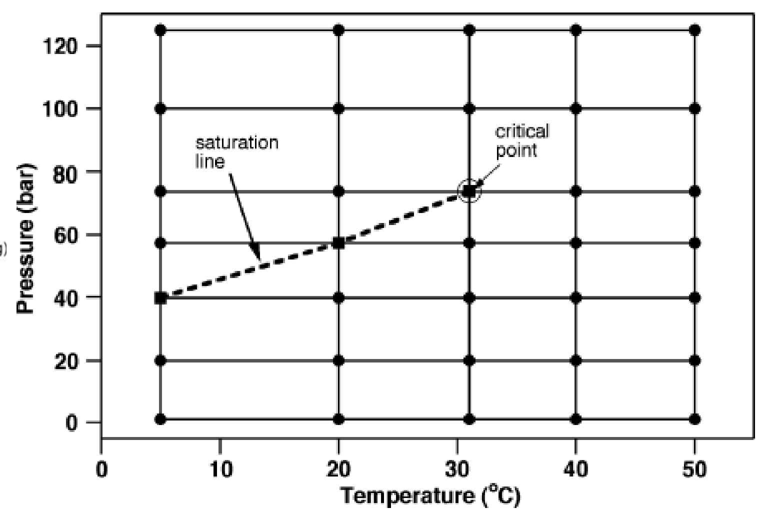


Pure H_2O

International Formulation Committee (1967)

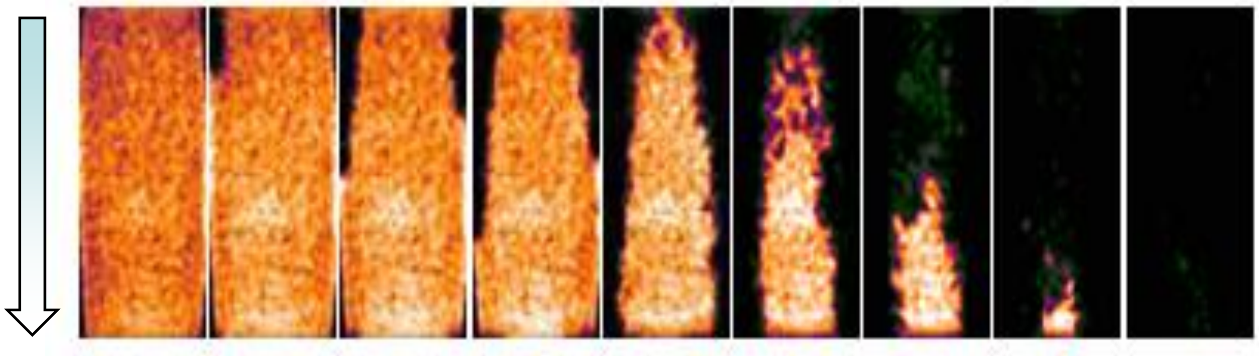
Mixtures

Density, viscosity, enthalpy

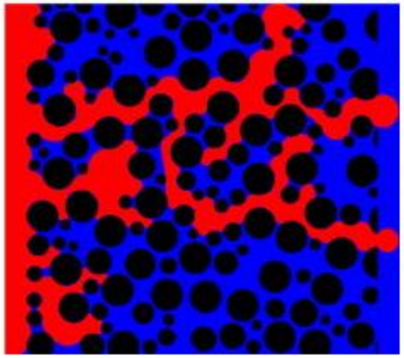


Coupled processes-Hydrodynamic process

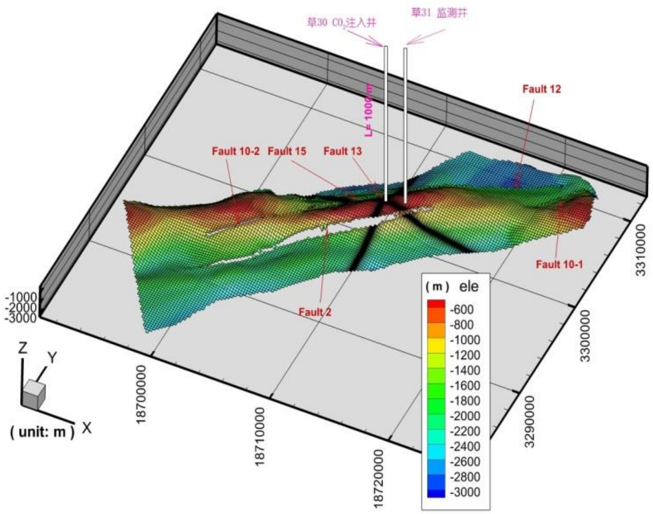
MRI images of CO2 displacement (Jiang LL, 2016)



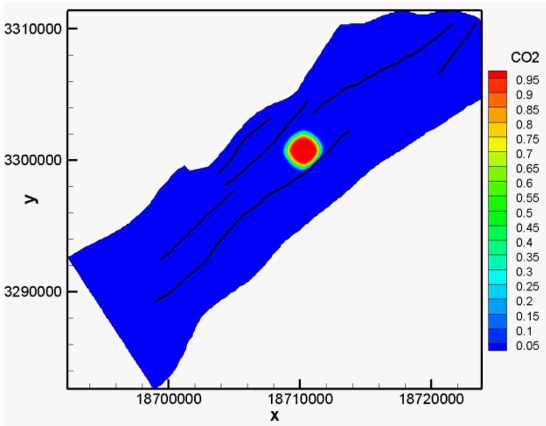
Pore-scale



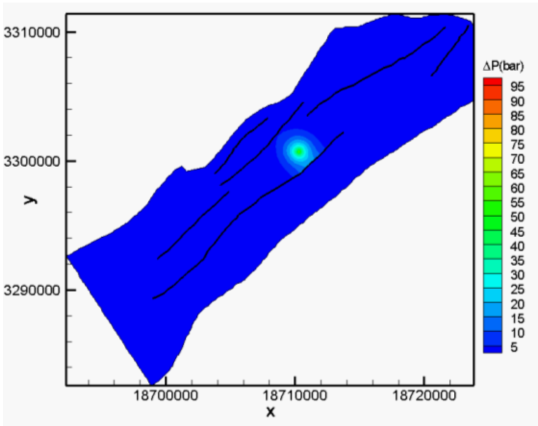
Numerical simulation of CO_2 injection (site-scale)



Incremental pressure

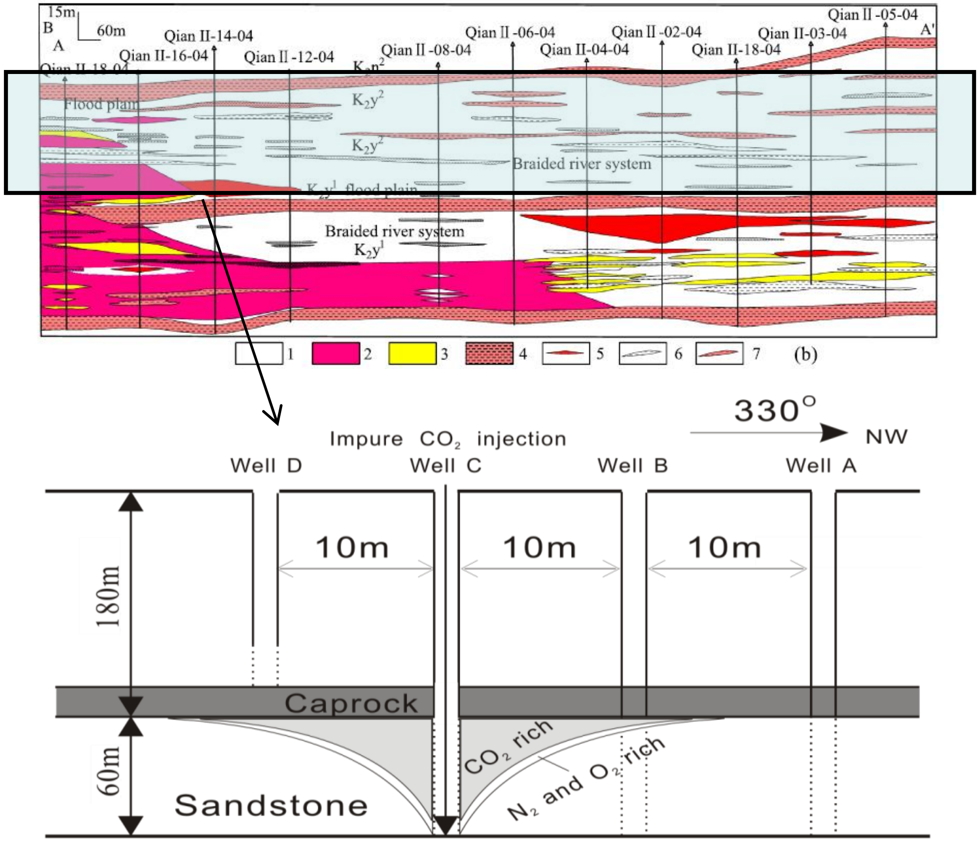


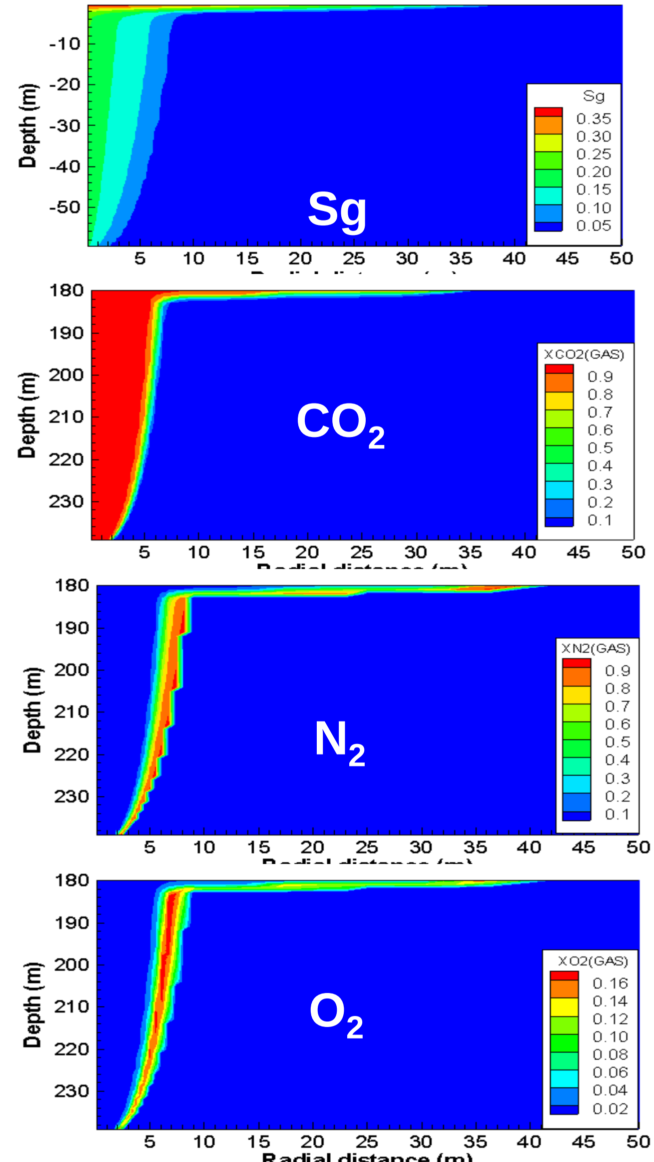
CO_2 mass fraction



Coupled processes-Hydrodynamic process

Impure CO_2 injection at Tongliao



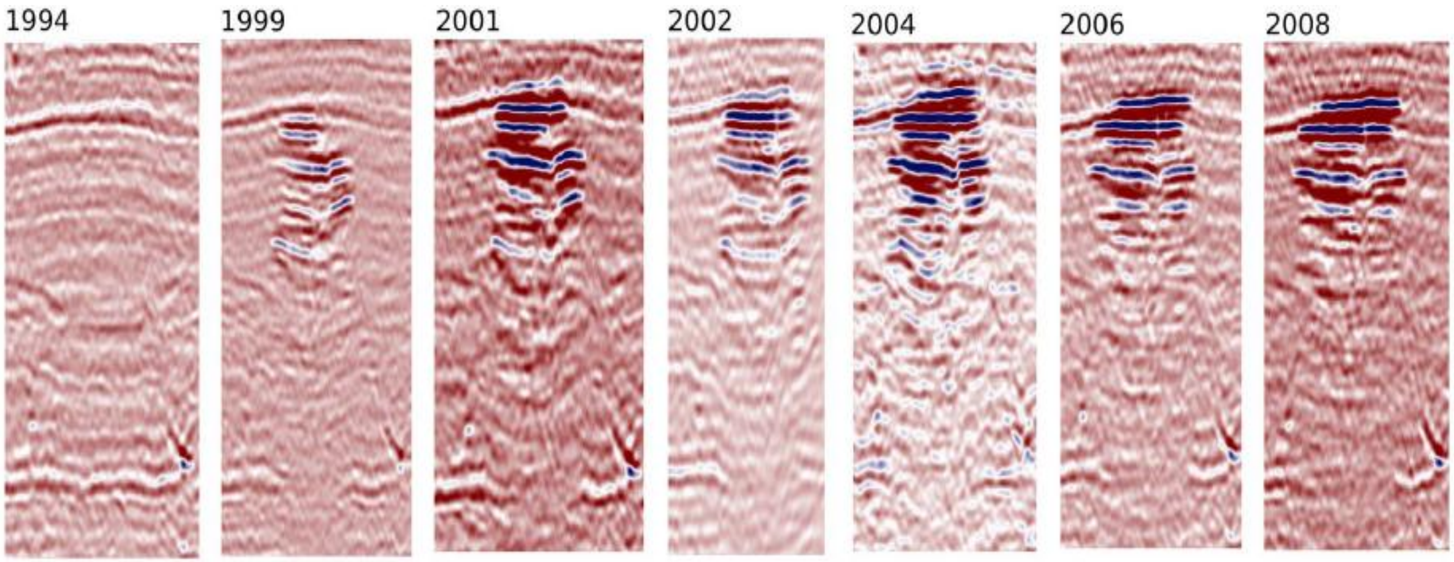


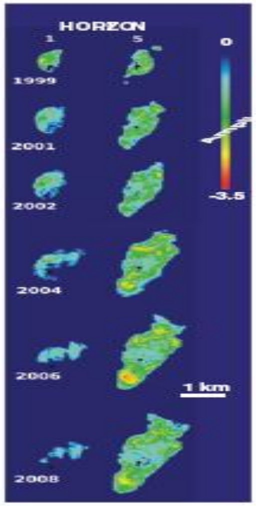
Lei, et al. 2016

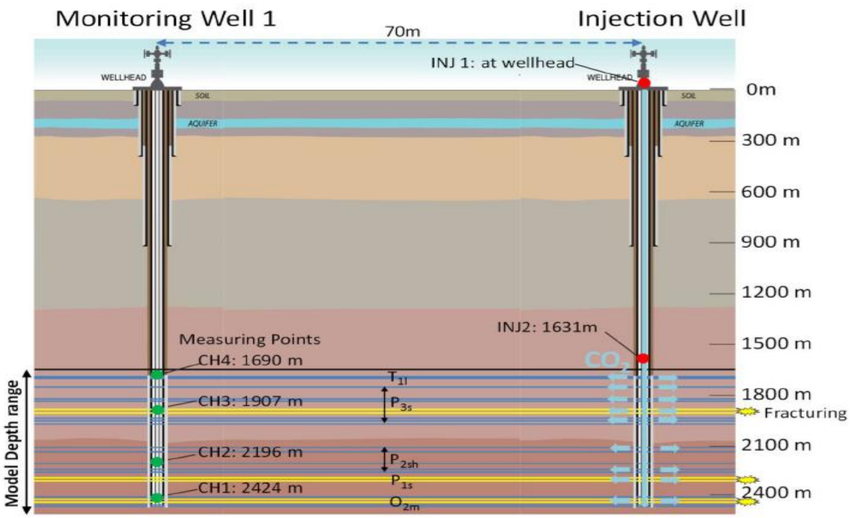
Coupled processes-Hydrodynamic process

Monitoring of CO_2 migration

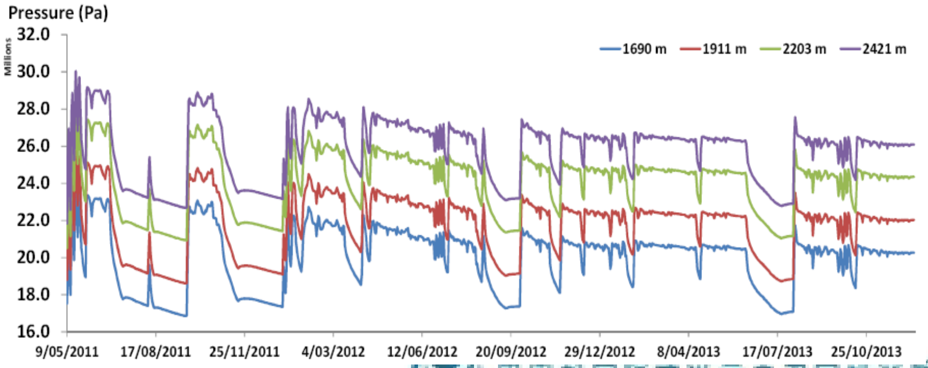
Sleipner Field Boait, et al. 2012







Shenghua CCS site Li, et al. 2016



Single process-Thermal process

Energy conservation

Must be coupled with H !

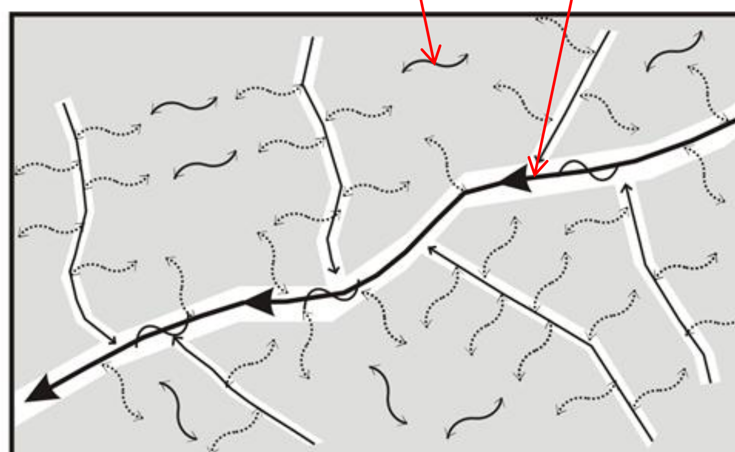
$$\frac{d}{dt}\int_{V_n} M^{\kappa} dV = \int_{\Gamma_n} \mathbf{F}^{\kappa} \bullet \mathbf{n}\, d\Gamma + \int_{V_n} q^{\kappa} dV$$

$$M^{\kappa+1} = (1-\phi)\rho_R C_R T + \sum_{\beta=A,G} \phi S_{\beta} \rho_{\beta} u_{\beta}$$

conduction

convection

$$\mathbf{F}_{\beta}^{\kappa+1} = -\lambda \nabla T + \sum_{\beta} h_{\beta} F_{\beta}$$



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State Key Laboratory of Geomechanics and Geotechnical Engineering

Single process-Mechanical process

Motion equation

$$\left.\begin{aligned}
-G\nabla^2 w_x - \frac{G}{1-2\upsilon}\frac{\partial}{\partial x}\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_y}{\partial y}+\frac{\partial w_z}{\partial z}\right)+\frac{\partial P}{\partial x}+3\beta_T K\frac{\partial T}{\partial x}=0\\
-G\nabla^2 w_y - \frac{G}{1-2\upsilon}\frac{\partial}{\partial y}\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_y}{\partial y}+\frac{\partial w_z}{\partial z}\right)+\frac{\partial P}{\partial y}+3\beta_T K\frac{\partial T}{\partial y}=0\\
-G\nabla^2 w_z - \frac{G}{1-2\upsilon}\frac{\partial}{\partial z}\left(\frac{\partial w_x}{\partial x}+\frac{\partial w_y}{\partial y}+\frac{\partial w_z}{\partial z}\right)+\frac{\partial P}{\partial z}+3\beta_T K\frac{\partial T}{\partial z}=\gamma_{sat}
\end{aligned}\right\}$$

Must be coupled with H and T !

Stress-strain

$$\left.\begin{aligned}
\sigma_x^{'} &= 2G\left(\frac{\upsilon}{1-2\upsilon}\varepsilon_v+\varepsilon_x\right)+3\beta_T K\Delta T\\
\sigma_y^{'} &= 2G\left(\frac{\upsilon}{1-2\upsilon}\varepsilon_v+\varepsilon_y\right)+3\beta_T K\Delta T\\
\sigma_z^{'} &= 2G\left(\frac{\upsilon}{1-2\upsilon}\varepsilon_v+\varepsilon_z\right)+3\beta_T K\Delta T\\
\tau_{yz}^{'} &= G\gamma_{yz},\tau_{zx}^{'}=G\gamma_{zx},\tau_{xy}^{'}=G\gamma_{xy}
\end{aligned}\right\}$$

Strain-displacement

$$\left.\begin{aligned}
\varepsilon_x &= -\frac{\partial w_x}{\partial x},\gamma_{yz}=-\left(\frac{\partial w_y}{\partial z}+\frac{\partial w_z}{\partial y}\right)\\
\varepsilon_y &= -\frac{\partial w_y}{\partial y},\gamma_{zx}=-\left(\frac{\partial w_z}{\partial x}+\frac{\partial w_x}{\partial z}\right)\\
\varepsilon_z &= -\frac{\partial w_z}{\partial z},\gamma_{xy}=-\left(\frac{\partial w_x}{\partial y}+\frac{\partial w_y}{\partial x}\right)
\end{aligned}\right\}$$

中国科学院武汉岩土力学研究所
Institute of Rock and Soil Mechanics, Chinese Academy of Sciences

Single process-Chemical process

Mass conservation

$$\frac{d}{dt}\int_{V_n} M^{\kappa} dV = \int_{\Gamma_n} \mathbf{F}^{\kappa} \bullet \mathbf{n} d\Gamma + \int_{V_n} q^{\kappa} dV$$

$$M_l^{\kappa} = \phi S_l C_l^{\kappa}$$

Solute transport

- Mechanical dispersion
- Molecular diffusion

convection **dispersion**

$$F_l^{\kappa} = F_l \, C_l^{\kappa} - (\tau \phi S_l D_l^{\kappa}) \nabla C_l^{\kappa}$$

Chemical reaction

$$T_j = c_j + \sum_{k=1}^{N_x} v_{kj} c_k + \sum_{m=1}^{N_p} v_{mj} c_m + \sum_{n=1}^{N_q} v_{nj} (c_n^0 - r_n \Delta t_r) = T_j^0$$

Basis species

Aqueous complexes

Mineral at equilibrium and kinetic constraint

- **Gas solution**
- **Aqueous complexation**
- **Redox**
- **Ion exchange**
- **Adsorption**
- **Mineral dissolution /precipitation**

Single process-Chemical process

Chemical reaction-gas solution

$$\mu_i^{NA} = \mu_i^{AQ}$$

Cubic model for fugacity

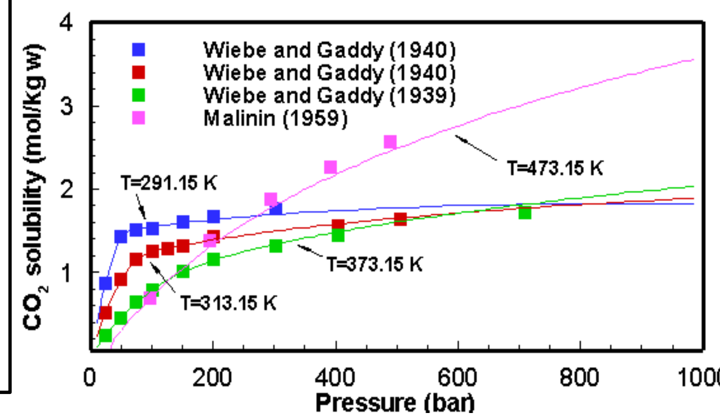
$$\mu_i^{NA}(T,P,y_i) = \mu_i^{NA(0)}(T) + RT\ln f_i(T,P,y_i) = \mu_i^{NA(0)}(T) + RT\ln y_i P + RT\ln \varphi_i(T,P,y_i)$$

$$P = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)+b(V-b)}$$

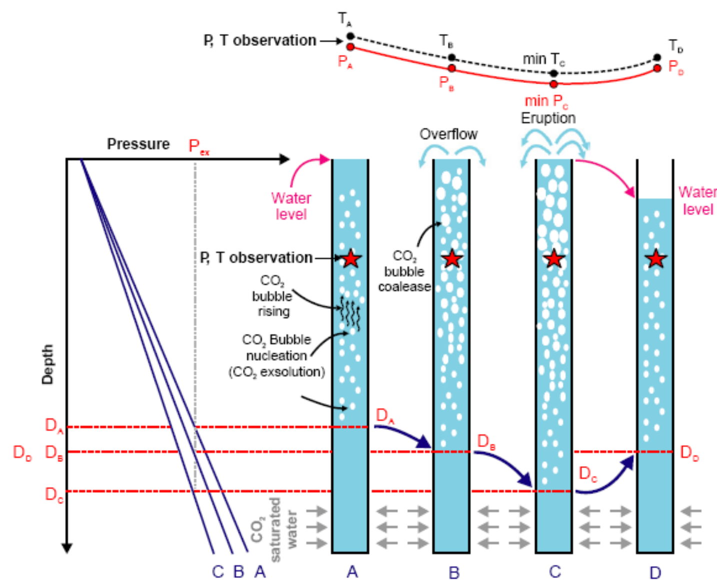
Pitzer model for water activity

$$\mu_i^{AQ}(T,P,m_{sol}) = \mu_i^{AQ(0)}(T,P) + RT\ln a_i(T,P,m_{sol}) = \mu_i^{AQ(0)}(T,P) + RT\ln(Nw \times x_i) + RT\ln \gamma_i(T,P,m_{sol})$$

$$\ln \gamma_i = \sum_c 2m_c\lambda_{i-c} + \sum_a 2m_a\lambda_{i-a} + \sum_c\sum_a m_a m_c \zeta_{i-a-c}$$



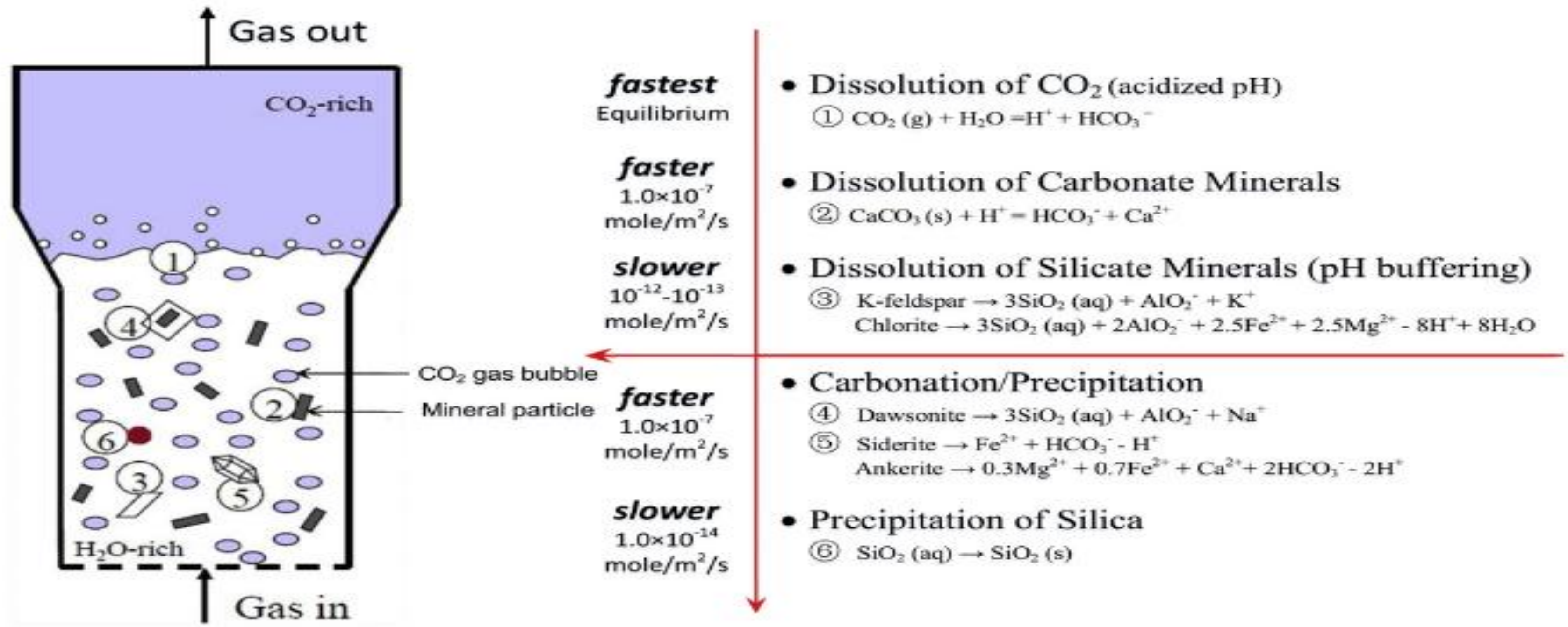
CO2 eruption from Crystal Geyser, UT



Han WS et al., 2013

Single process-Chemical process

Chemical reaction-water/rock reaction



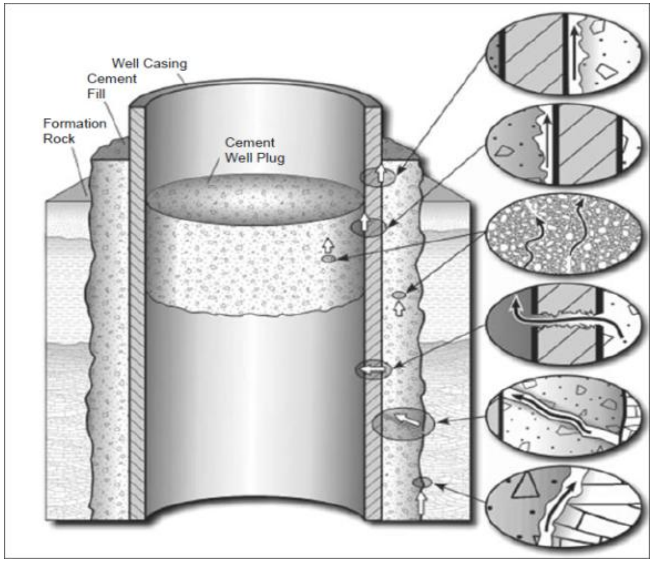
Reaction rate for kinetic minerals

$$r_m = \pm k(T)_m \left| 1 - \left(\frac{Q_m}{K_m}\right)^{\theta} \right|^{\eta}$$

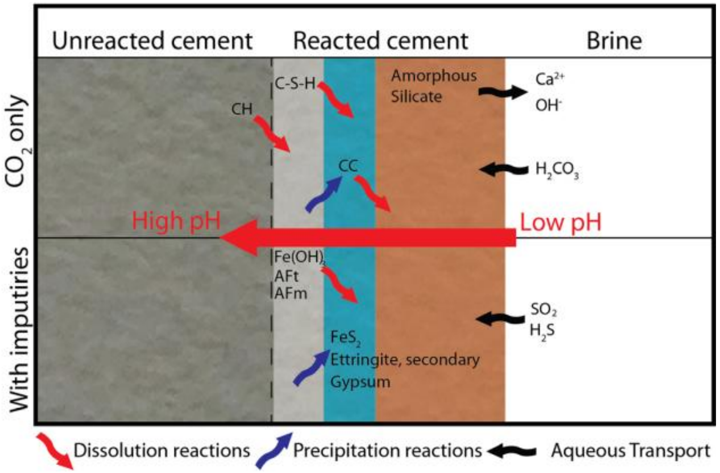
$$k(T) = k_{25}^{nu} \exp\left[\frac{-E_a^{nu}}{R}\left(\frac{1}{T} - \frac{1}{298.15}\right)\right] + k_{25}^{H} \exp\left[\frac{-E_a^{H}}{R}\left(\frac{1}{T} - \frac{1}{298.15}\right)\right] a_H^{n_H} + k_{25}^{OH} \exp\left[\frac{-E_a^{OH}}{R}\left(\frac{1}{T} - \frac{1}{298.15}\right)\right] a_{OH}^{n_{OH}}$$

Coupled processes-Chemical process

CO_2-water-rock reaction-batch experiment



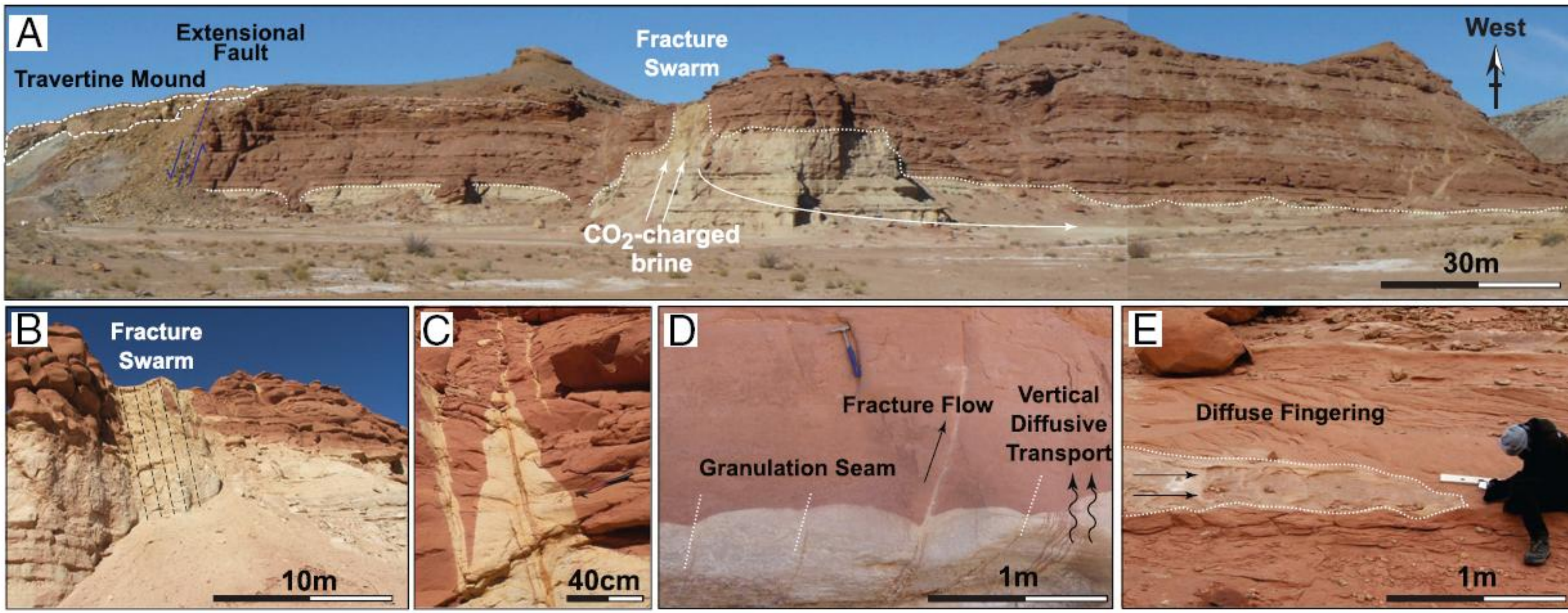
CO2-water-rock reaction near the wellbore



Zhang, et al. 2013

Coupled processes-Chemical process

Long term CO_2-water-rock reaction



Kampman, et al. 2014

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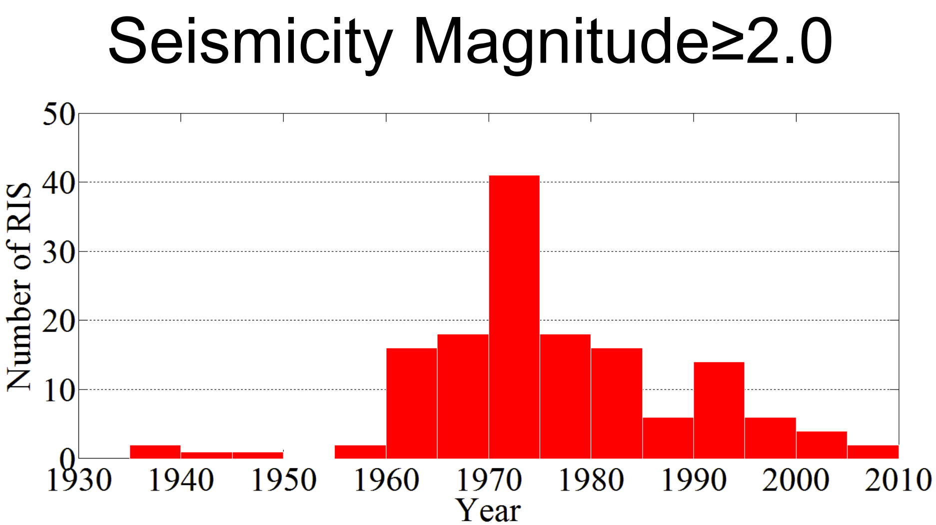
Coupled processes-Focus

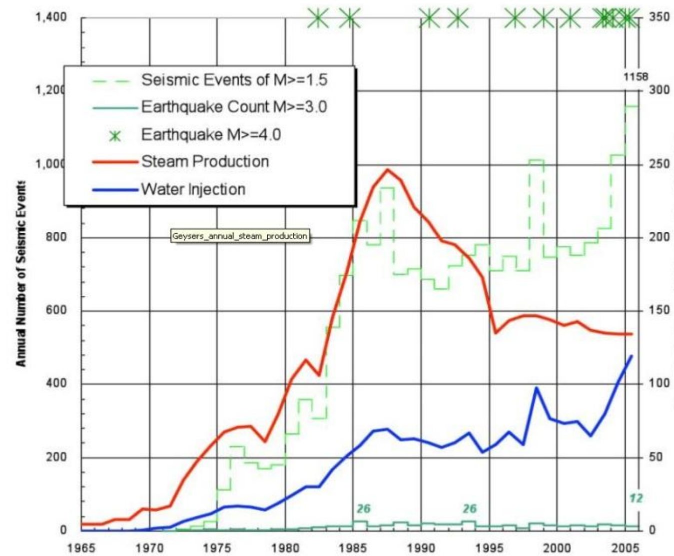
Number of process	Coupling
1	T、H、C、M
2	TH、HM、HC、MC、TM、TC
3	THC、THM、HMC、TCM
4	THMC

Coupled processes-HM processes

Induced-seismicities can be mitigated by regulations, site selection, evaluation, monitoring and control



Reservoir-induced seismicities in the world

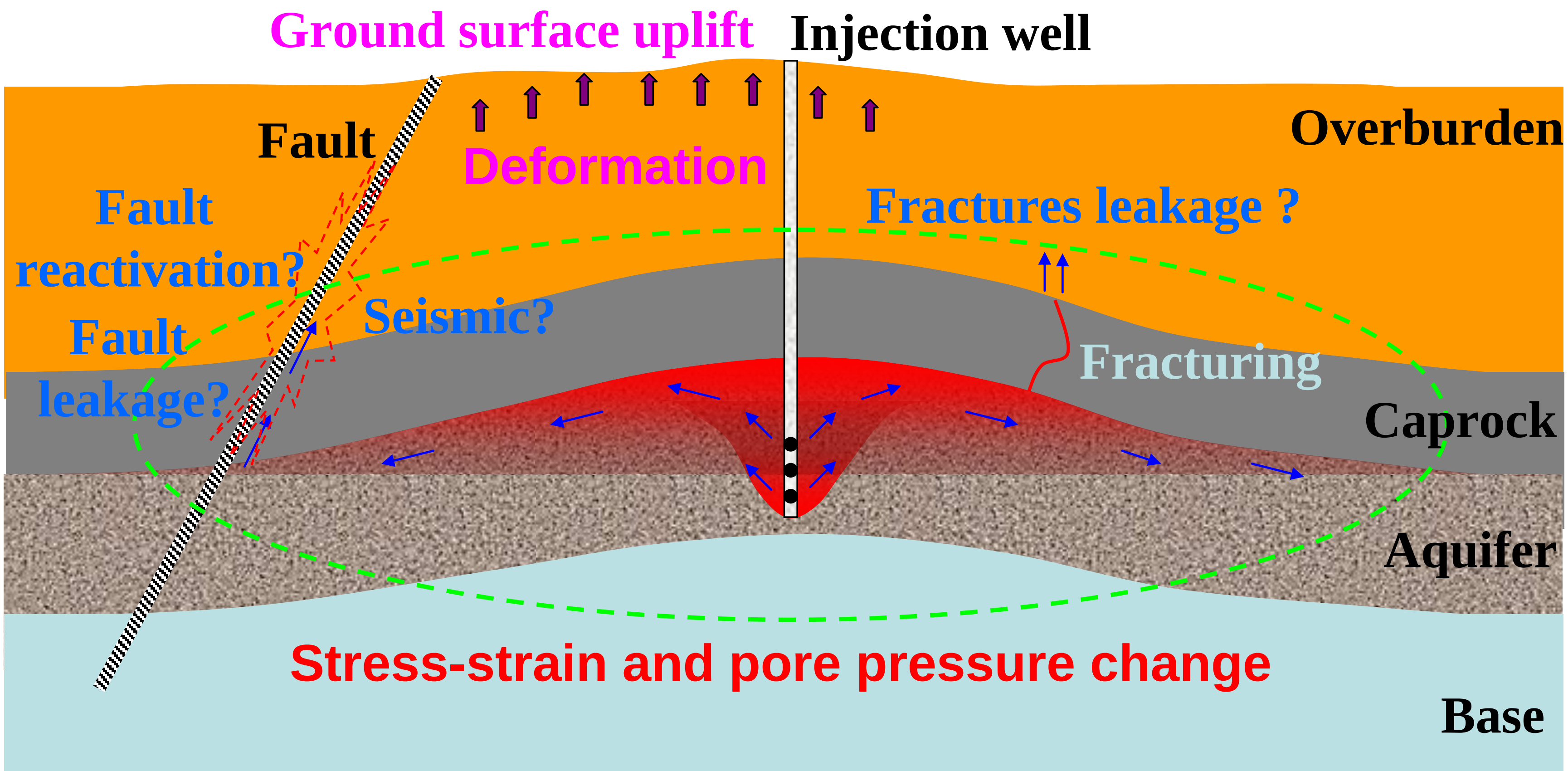


The Geysers Geothermal Field, California, USA

M≥1.5 events recorded since 1965 (maximum M4.6)

Coupled processes-HM processes

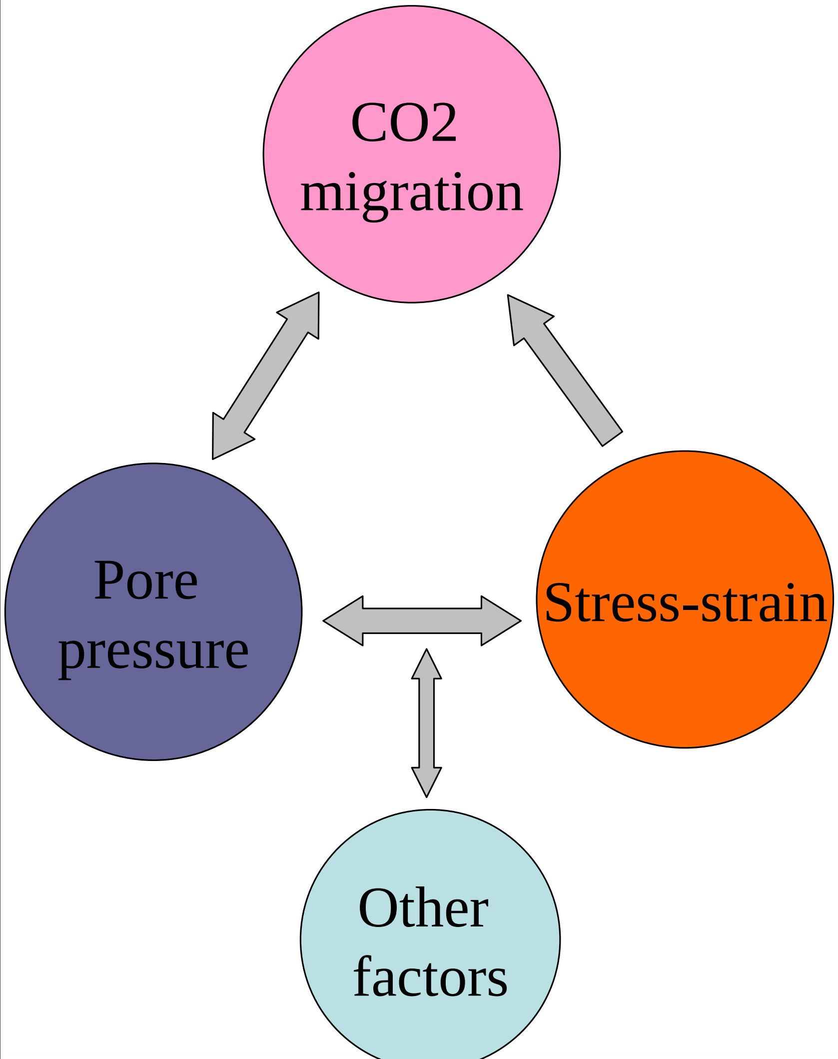
- stress-strain and pore pressure change
- fault stability
- mechanical integrity of the cap-rock
- ground surface uplift



Pressure buildup induced by CO2 injection is the driving force !

Coupled processes-HM processes

The changes of the stress-strain and pore pressure



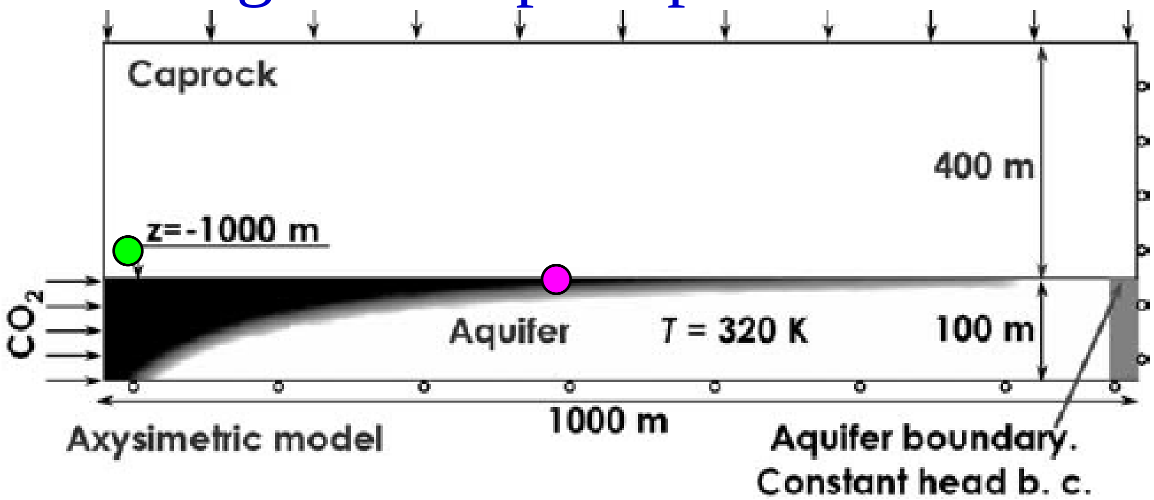
CO_2 injection
→ Pore pressure increase
→ Effective stress decrease
→ Pore volume expansion
→ Facilitating the evolution of the pore pressure
→ Promoting CO2 migration

Importance:

- Preconditions for analyzing other issues
- Basic understandings for the changes of cap-rock and reservoir

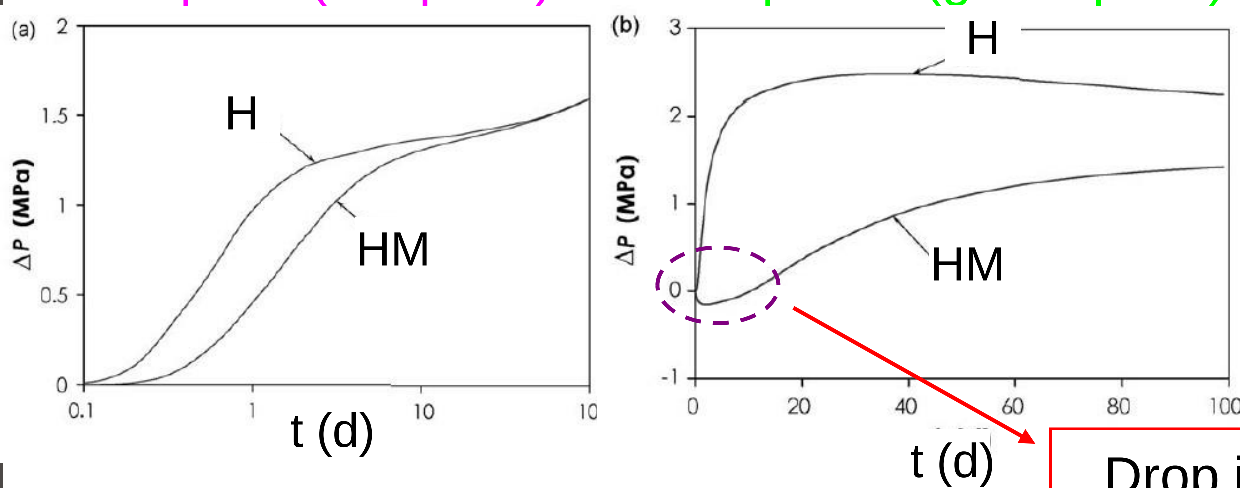
Coupled processes-HM processes

The change of the pore pressure



- Prominent effect of mechanics to pore pressure.
- Notable difference between the aquifer and cap-rock.

Aquifer (red point)　　Cap-rock (green point)

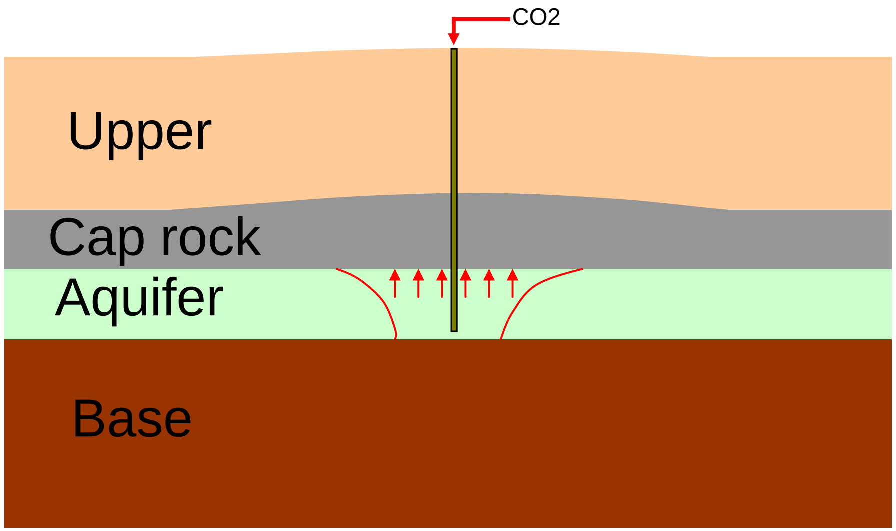


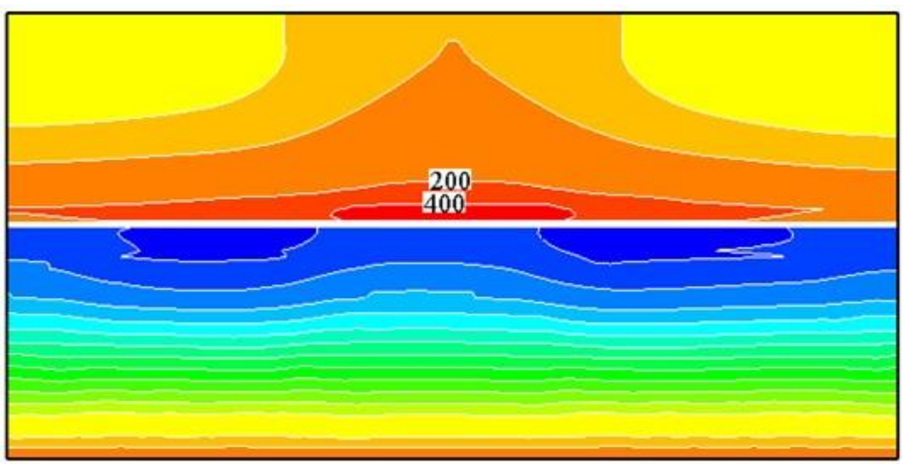
Drop in the initial fluid pressure

Vilarrasa et al. 2010

Coupled processes-HM processes

Ground surface deformation





Pore pressure increase

↓

Volumetric expansion in the injection zones | extrusion force from the bended cap-rock

↓

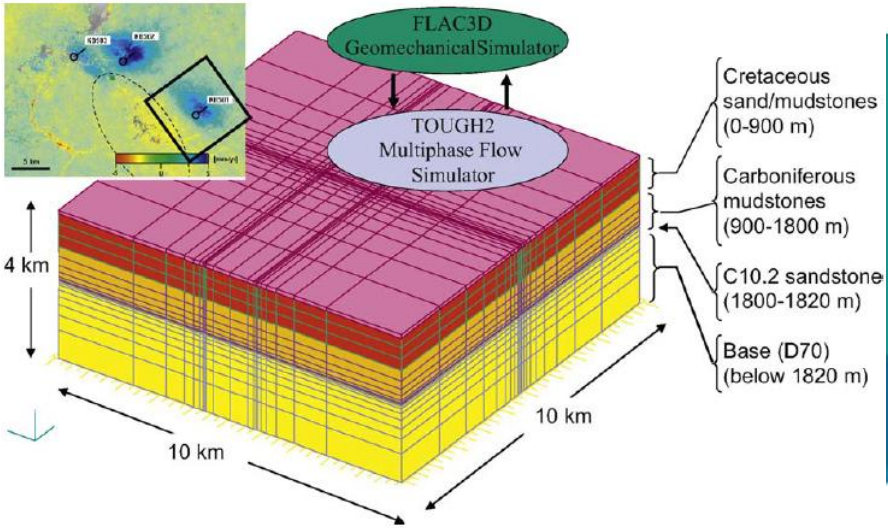
squeezing the overlying rock mass

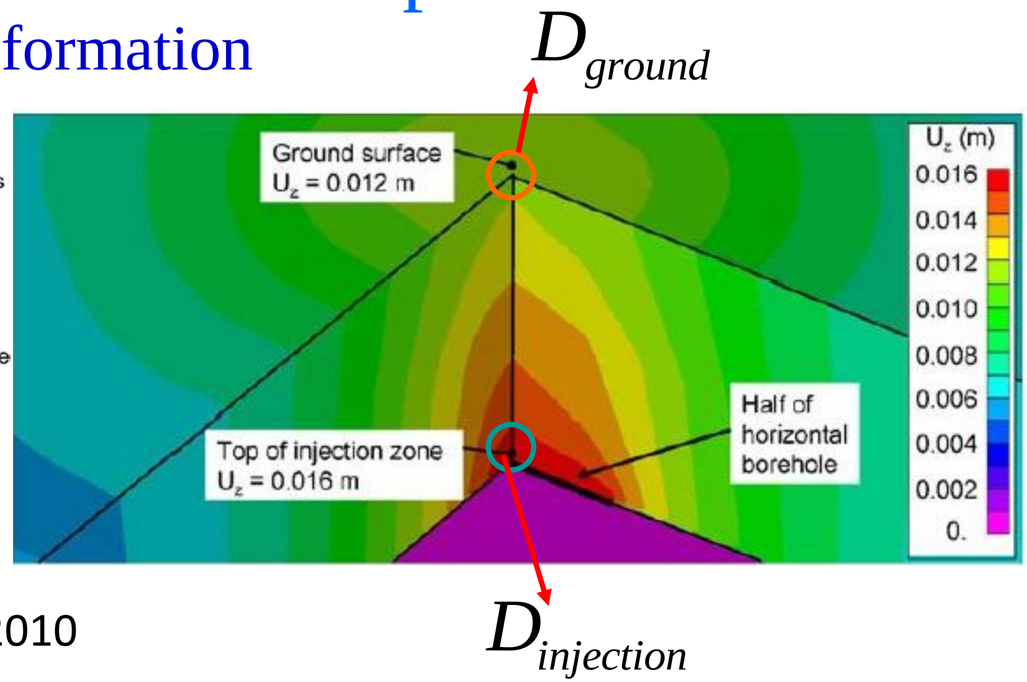
↓

ground surface deformation

Coupled processes-HM processes

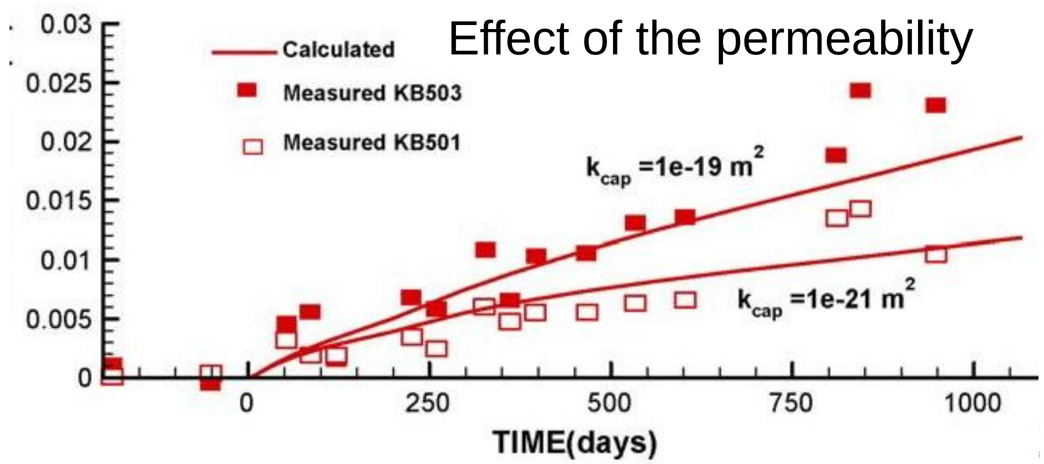
Ground surface deformation





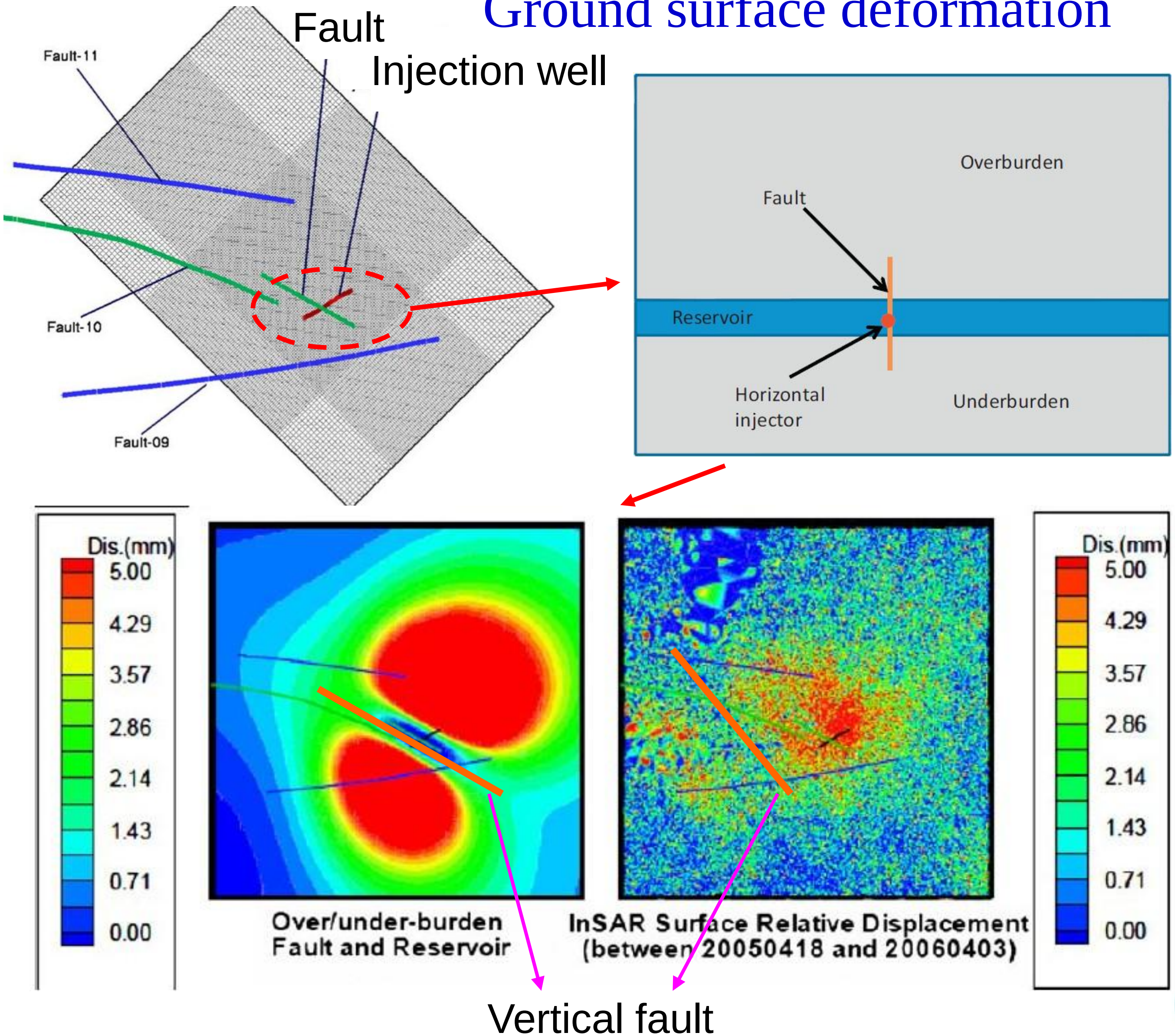
Rutqvist et. al. 2010

- $D_{ground} < D_{injection}$
- The permeability of the cap-rock has and effect to the surface uplift.
- Temperature and stiffness have a slight effect.



Coupled processes-HM processes

Ground surface deformation

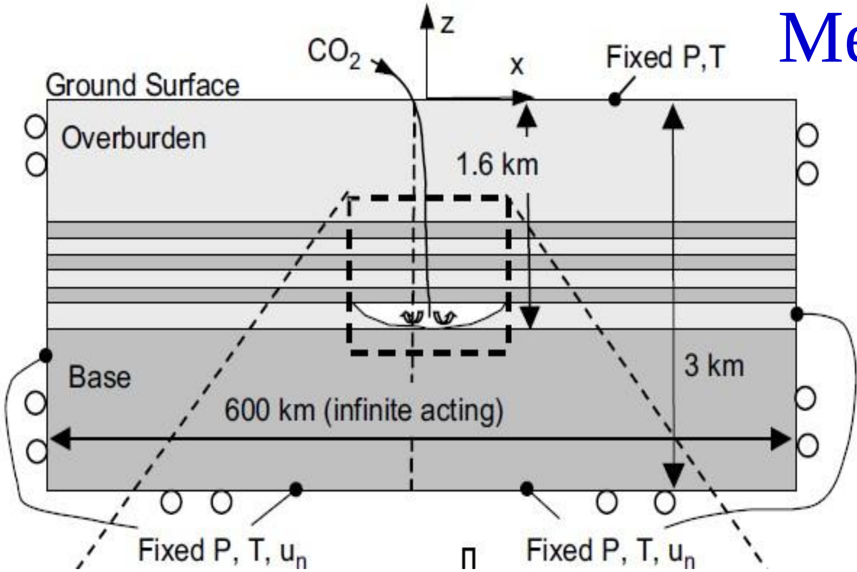


- Direct response of the subsurface mechanical issues
- Coinciding with the monitoring results

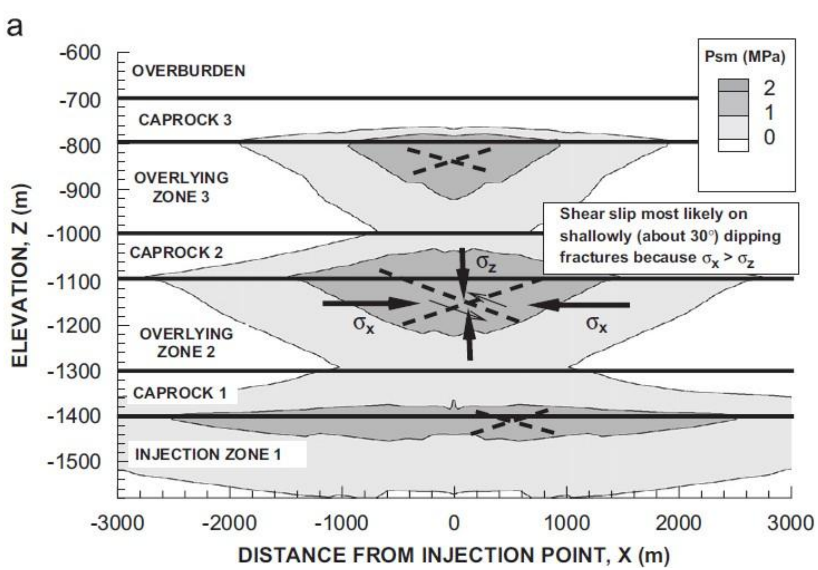
In Salah project
Left:
numerical simulation
Right:
field monitoring

Coupled processes-HM processes

Mechanical integrity *Elastic model*



- Two-dimensional plane-strain model
- Partial coupling method
- H-M



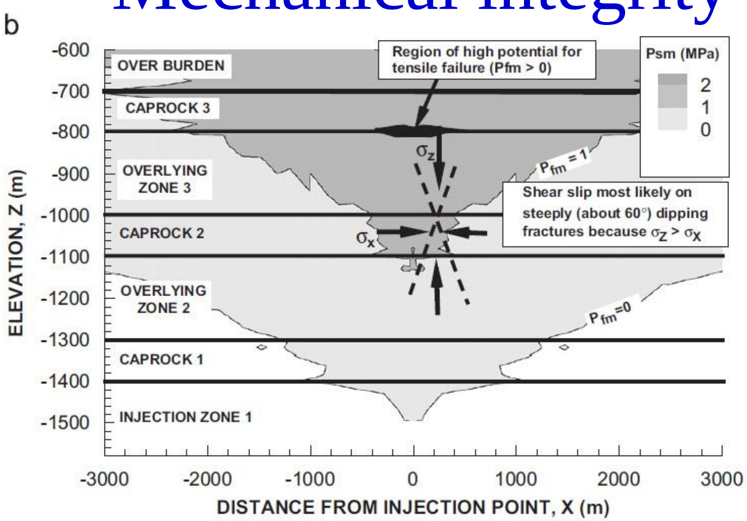
Compressive stress regime $\sigma_x = 1.5\sigma_z$

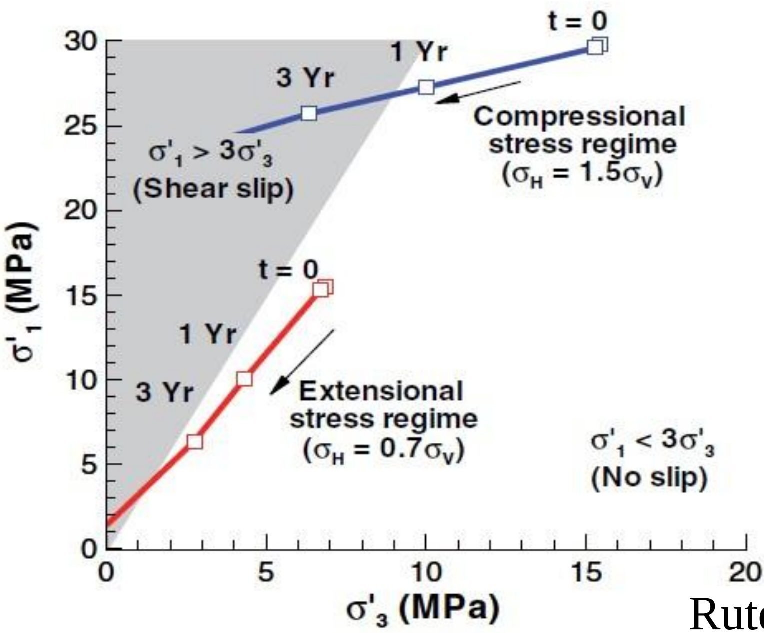
- Shear failure is likely to be initiated in shallowly dipping at the interface between the reservoir and cap-rock.
- Low possibility for tensile failure.

Rutqvist et al. 2007

Coupled processes-HM processes

Mechanical integrity





Elastic model

Extensional stress regime $\sigma_x = 0.7\sigma_z$

● High potential for shear failure occurs throughout the CO_2-storage system and in preferentially steeply dipping fractures.

● High potential for tensile failure occurs in the bottom of the cap-rock

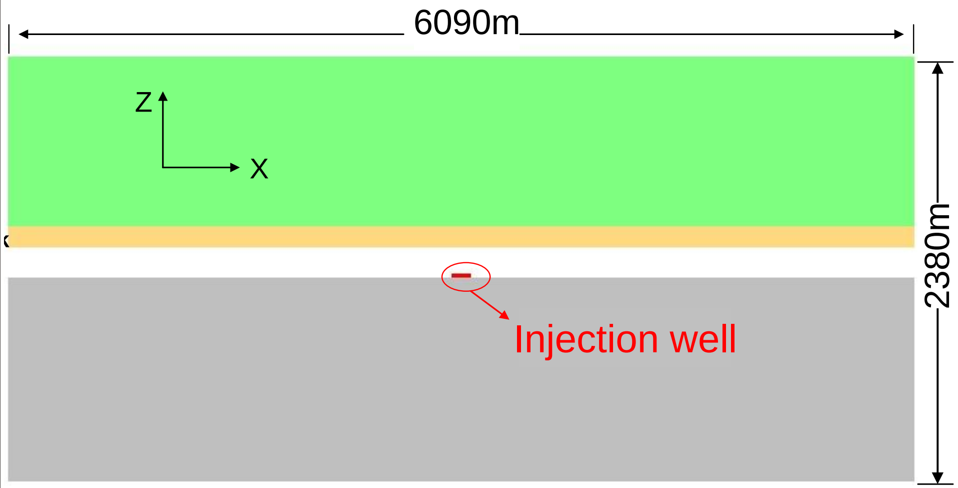
● In compressional stress regime, shear failure is much more likely to occur.

● Compressional stress regime is not favorable for mechanical integrity.

Rutqvist et al. 2007

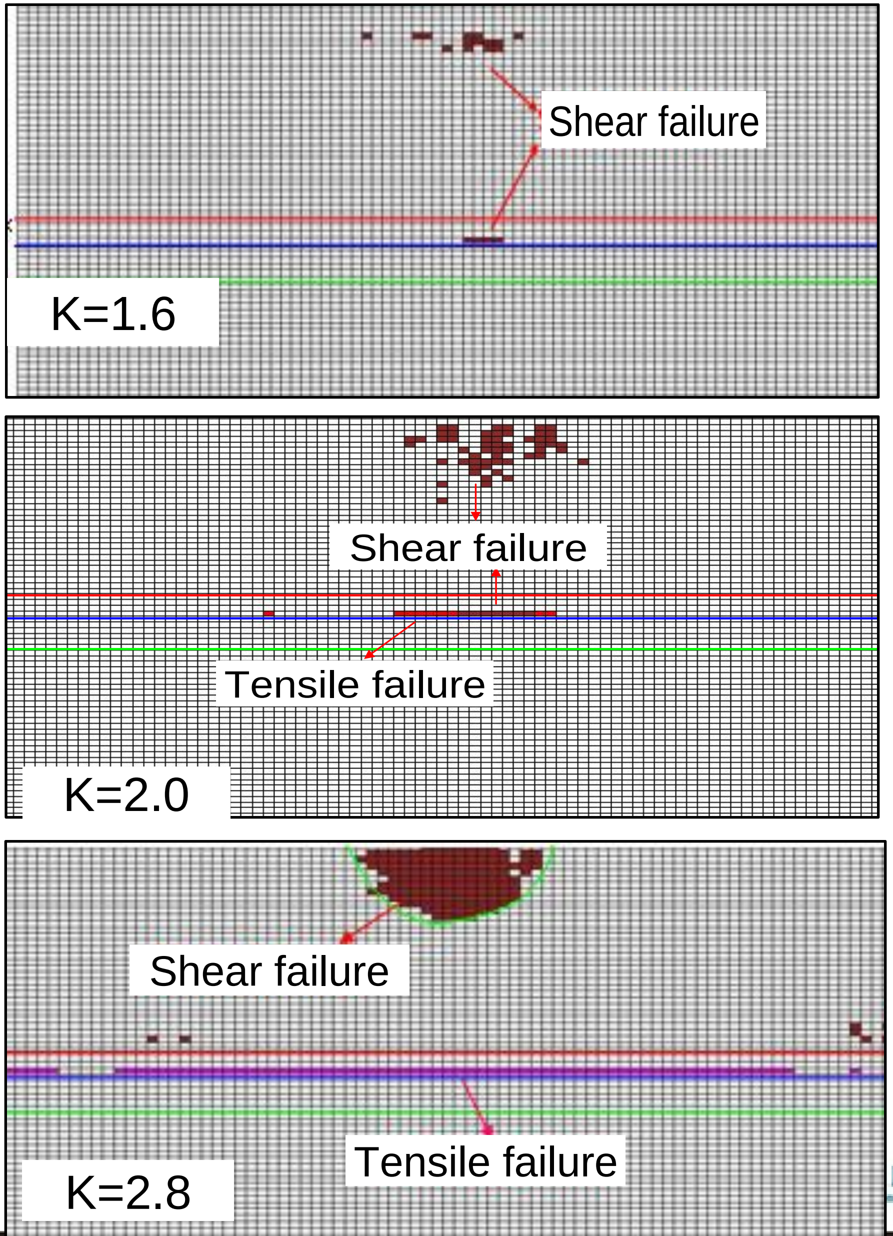
Coupled processes-HM processes

Mechanical integrity



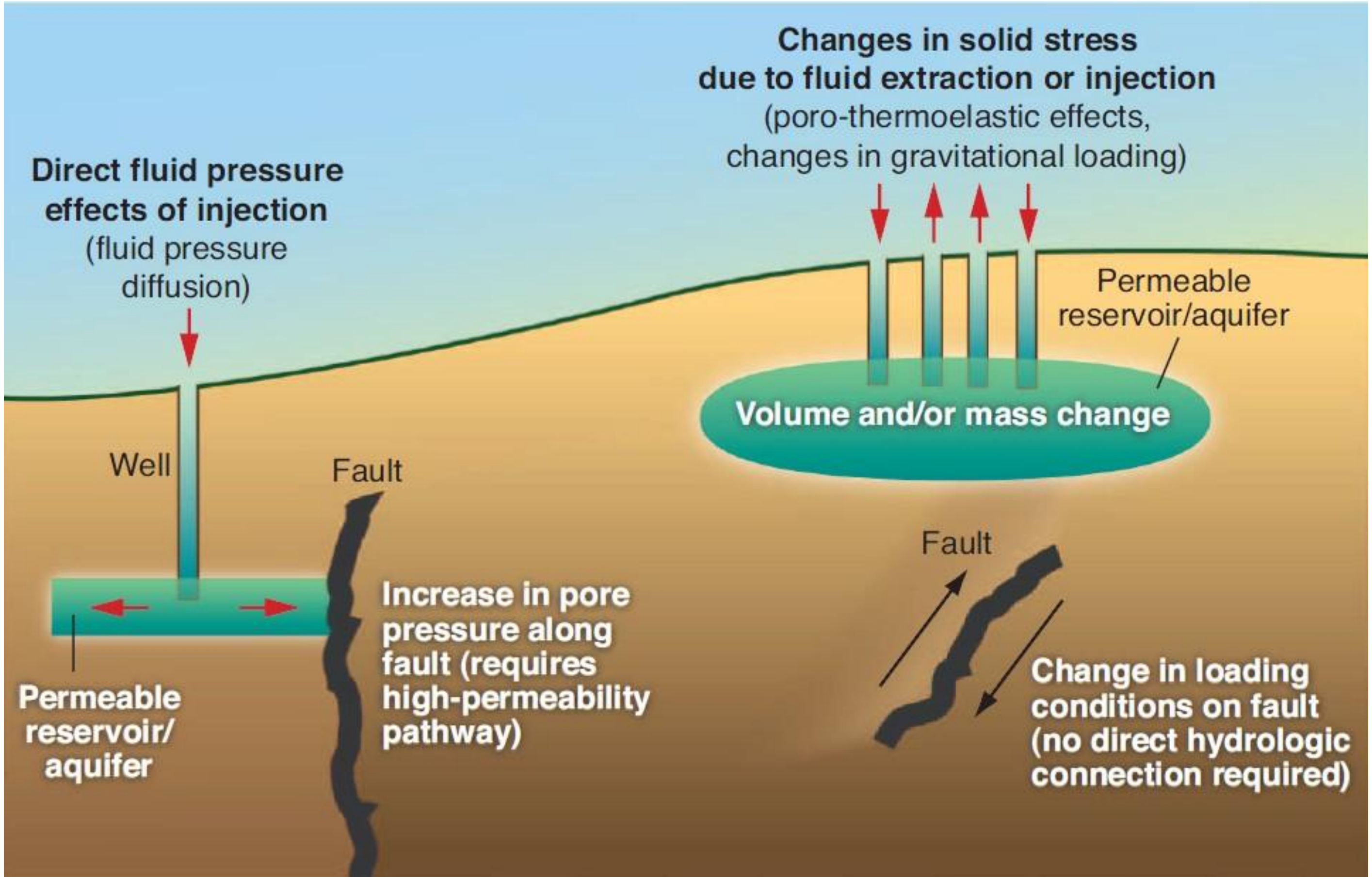
Wei Yuan et. al. 2013

- Elastic-plastic constitutive model
- Criterion: the elements of the cap rock tensile yield
- Method: strength reduction method
- As the reduction factor increase, the failure area enlarge.



Coupled processes-HM processes

Mechanisms for inducing earthquakes

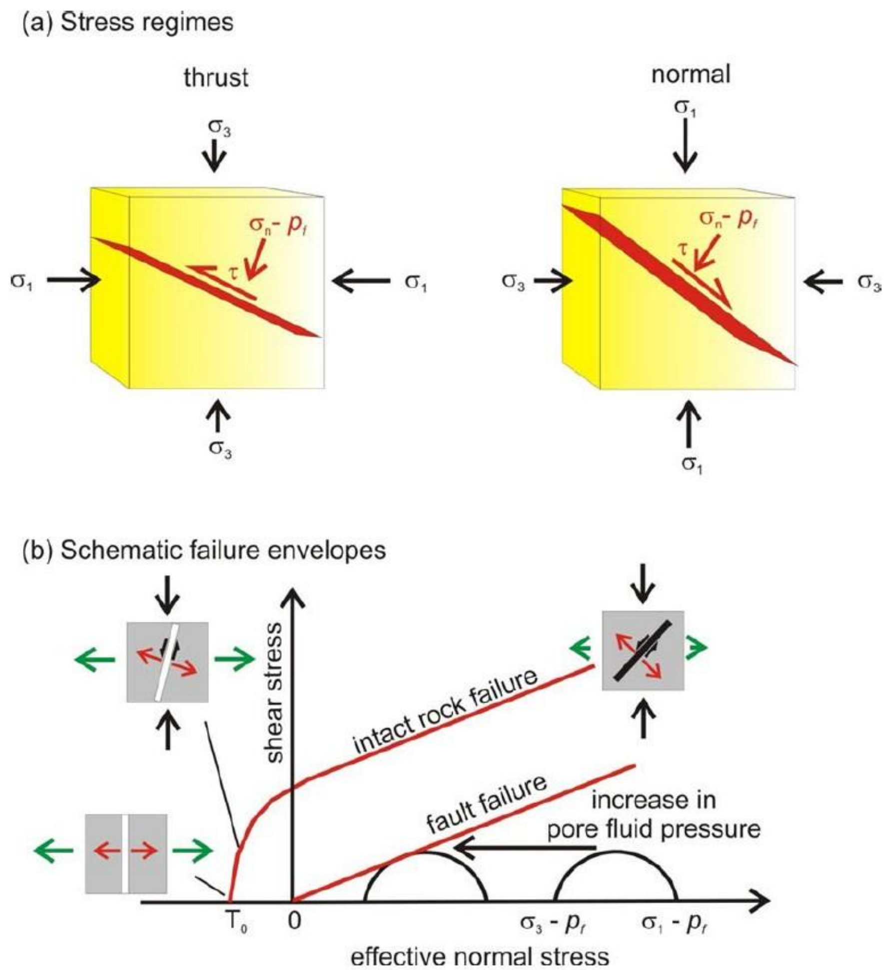


William L. Ellsworth 2013

- The effective stress acting on fault decrease by increasing pore pressure.
- The loading condition on fault has changed.

Coupled processes-HM processes

Fault stability- *Constitutive model and failure criterion*



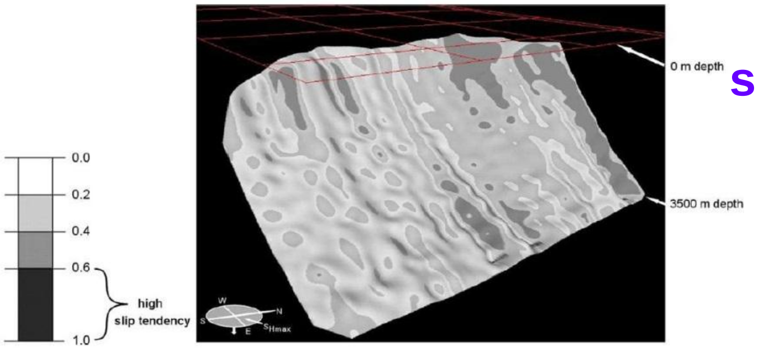
Elastic-perfectly plastic theory

- Mohr-Coulomb criterion
- Zero cohesive strength.
- The coefficients of the static friction: $0.6 \le \mu \le 0.85$

IEA Environmental Projects Ltd. (IEAGHG) 2013

Coupled processes-HM processes

Stability evaluation of the fault



Slip tendency on fault surface

The slip tendency **is defined as the ratio of the shear stress to the normal effective stress**

$$T_s = \frac{\tau}{\sigma_n - p_f}$$

Streit et al.2004

σ_n — Normal effective stress

τ — Shear effective stress

p_f — Pore pressure

Evaluating the seismic magnitude

Quantification of the overall size of an earthquake is generally based on the seismic moment M_0 defined for a ruptured patch on a fault by the following:

$$M_o = \mu A d$$

$$M = \left(\log_{10} M_o / 1.5\right) - 6.1$$

M— Seismic magnitude

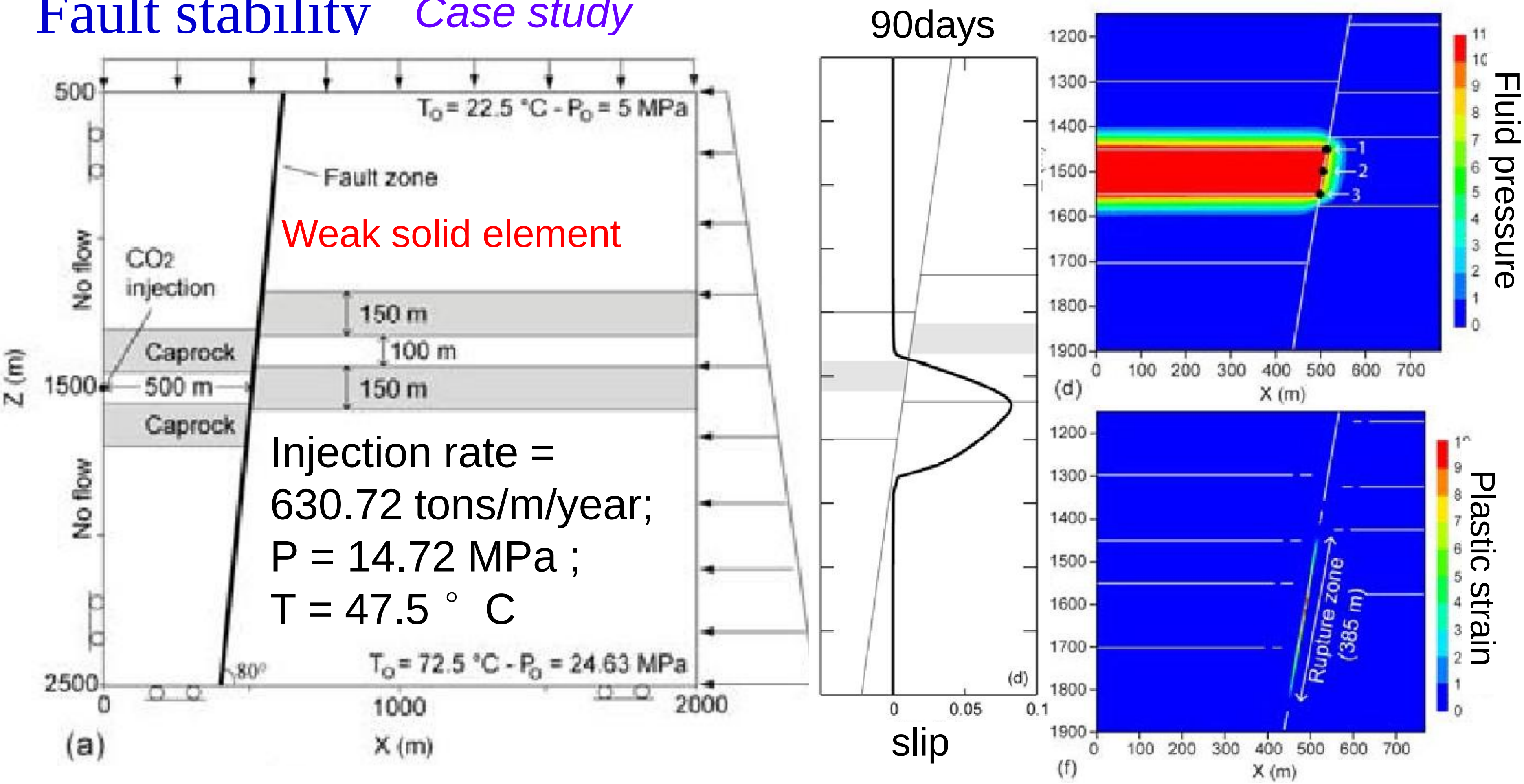
μ — Shear module

A — Reactive area

d — Slip distance

Coupled processes-HM processes

Fault stability *Case study*



Injection rate = 630.72 tons/m/year;
P = 14.72 MPa ;
T = 47.5 ° C

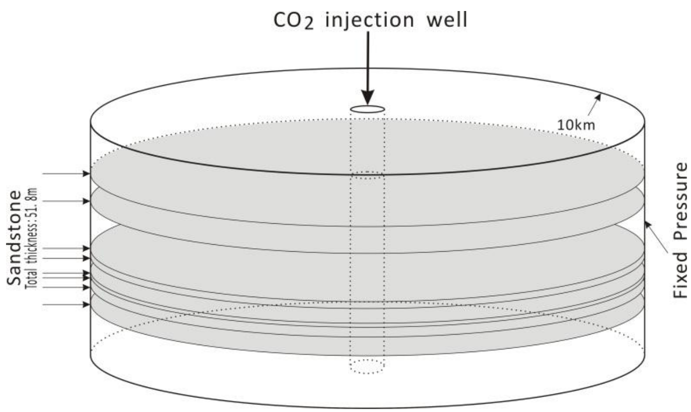
Intention: earthquake magnitude resulting from CO2 injection

$$M_0 = 4\times10^9 \times 1000 \times 385 \times 0.08 = 1.23\times10^{14}\ Nm$$

$$M = (\log_{10} M_o / 1.5) - 6.1 = 3.29$$

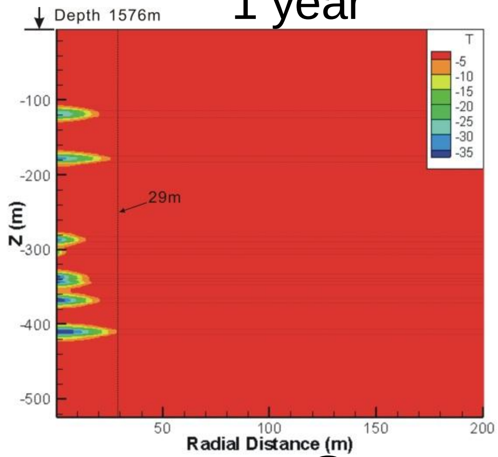
Coupled processes-TH processes

Shenhua CCS site

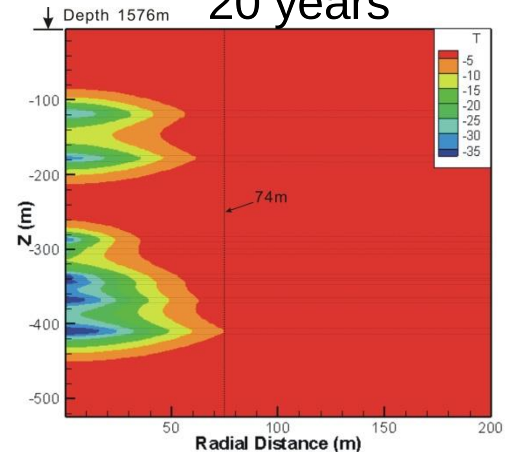


temperature

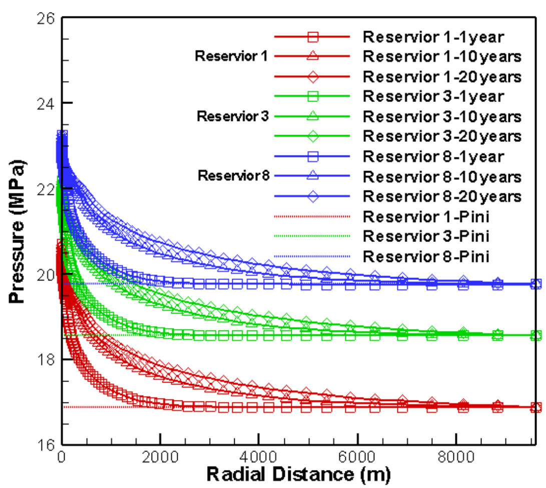
1 year



20 years

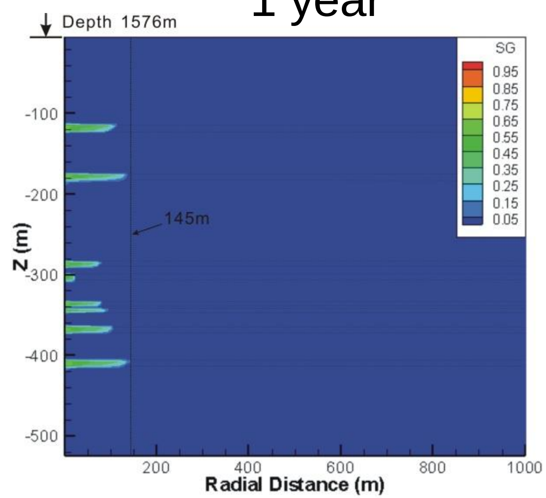


Pressure

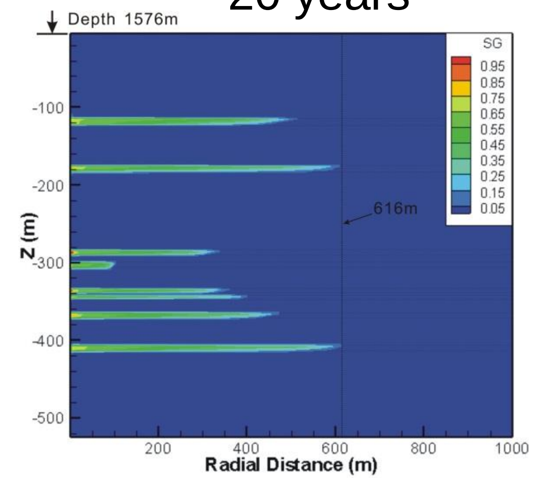


Gas saturation

1 year



20 years



Summary

质量守恒：单元含有的=进来的-出去的+内生的

能量守恒：单元含有的=进来的-出去的+内生的

运动规律：运动量=驱动力×常数

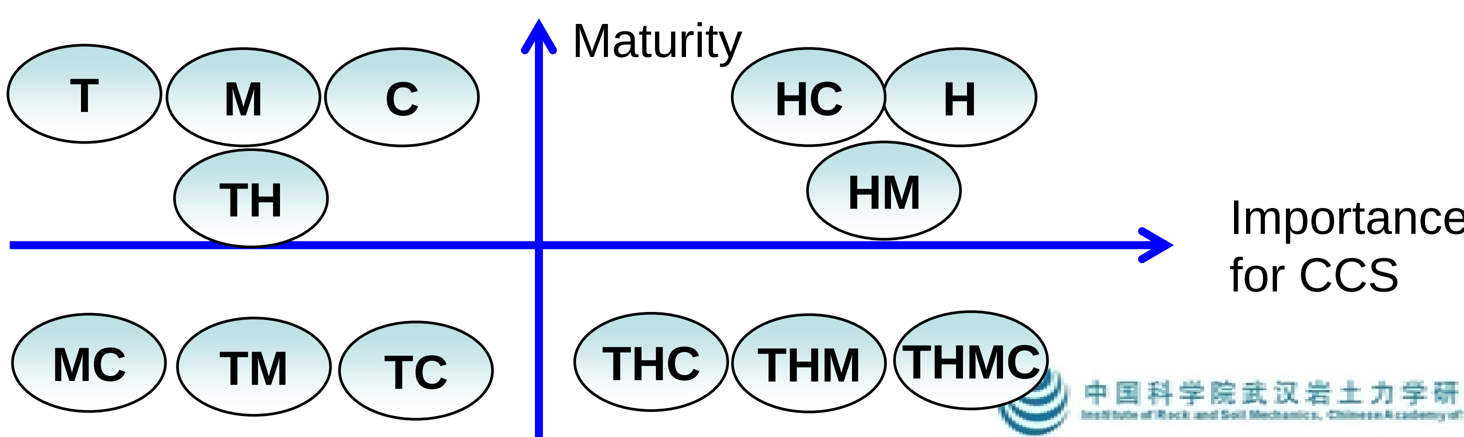
- T：热流=温度梯度×热传导系数
- H：流速=压力梯度×导流系数
- M：应力=应变×弹性系数
- C：反应速度=f（平衡浓度差）

耦合途径：

- 通过物质、能量的交换
- 通过对材料特性、结构、相态的改变

Summary

1. The key indicators of CGUS project performance are capacity, injectivity, sealing, stability and productivity
2. Prediction is based on detailed geological model and on knowledge and analysis of THMC processes
3. Short-term processes in EOR and DSF/EWR have be well understood and reasonably simulated
4. Their long-term processes and the other CGUS options need to be studies
5. Fully coupled analyses is not always necessary. Identifying the dominated processes is critical



Thank you !