Geomechanical Issues of CO2 Storage in Deep Saline Aquifers

二氧化碳咸水层封存的力学问题

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Outlines (提纲)

※ Background (背景)

※ THMC processes and geomechanical issues

(THMC耦合过程以及力学问题)

※ Analysis method for geomechanical issues

(力学问题的分析方法）

※ Conclusions and recommendations (结论与建议)

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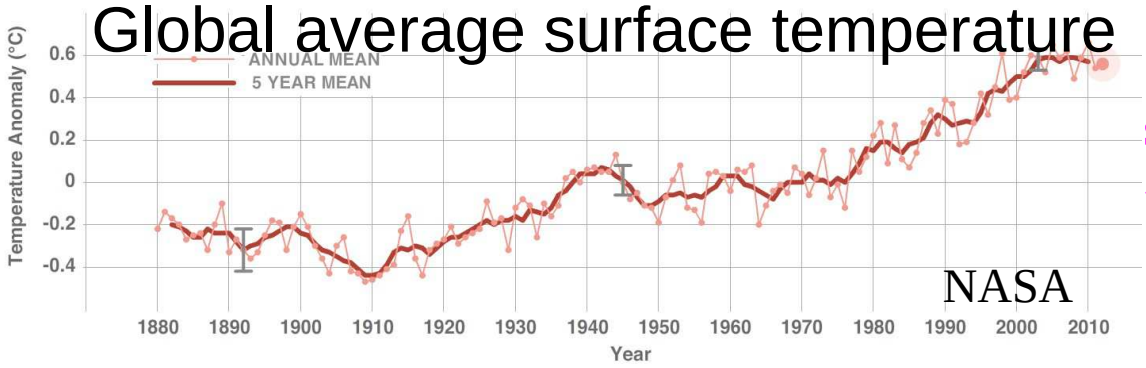
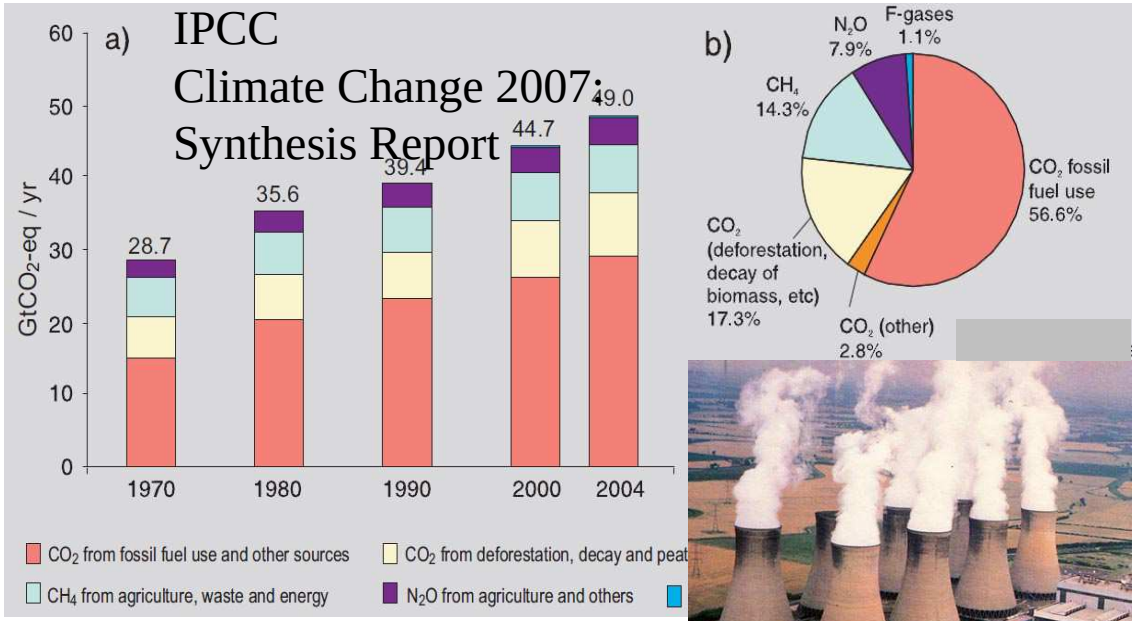
Background (背景)

Climate changes

Global average surface temperature





CO_2 emission

● **“Warming of the climate system is unequivocal ”!**
气候变暖是毋庸置疑的！

● **“It is likely that there has been significant anthropogenic warming over the past 50 years averaged over each continent (except Antarctica).”**
过去50年以来，各大陆(南极除外)平均可能出现了显著的人为变暖。

● **“Global GHG emissions due to human activities have grown, CO2 is the most important anthropogenic GHG.”**
人类活动导致大量温室气体排放，二氧化碳是最重要组成部分！

IPCC Climate Change 2007: Synthesis Report

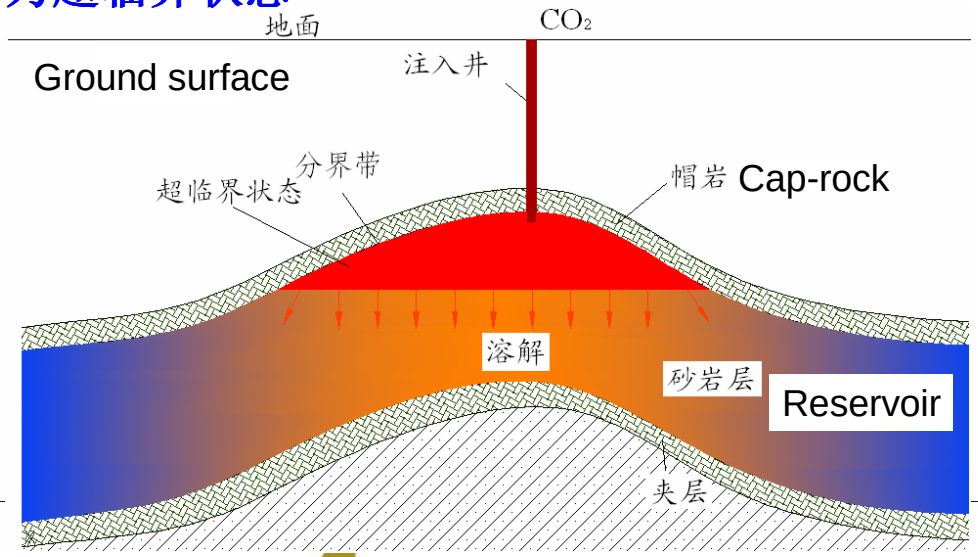
Background (背景)

Geological CO2 storage (GCS) 二氧化碳地质封存

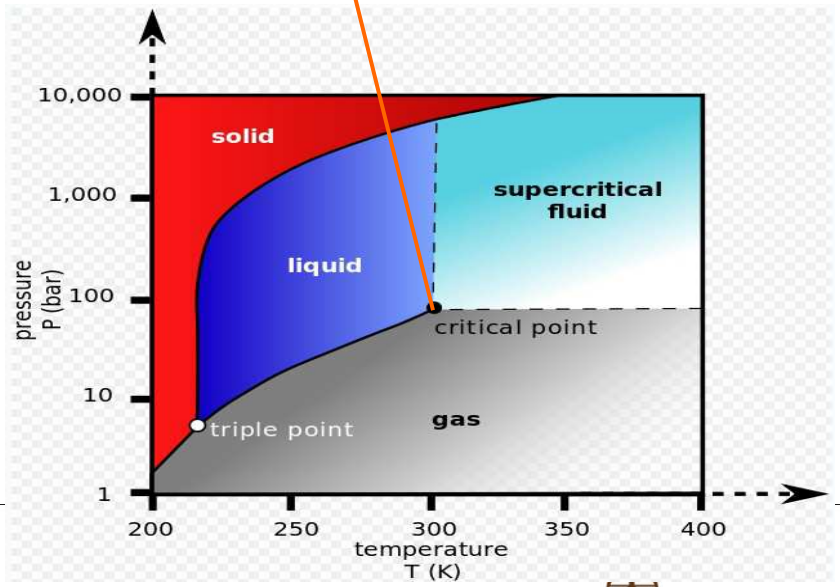
"Carbon dioxide (CO2) capture and storage (CCS) is a process consisting of the separation of CO2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere."

—— IPCC special report: Carbon Dioxide Capture and Storage

CO2 injected into deep formations at a depth below 800m : CO2 at super critical state.
二氧化碳被注入超过800m的深部地层：CO2为超临界状态

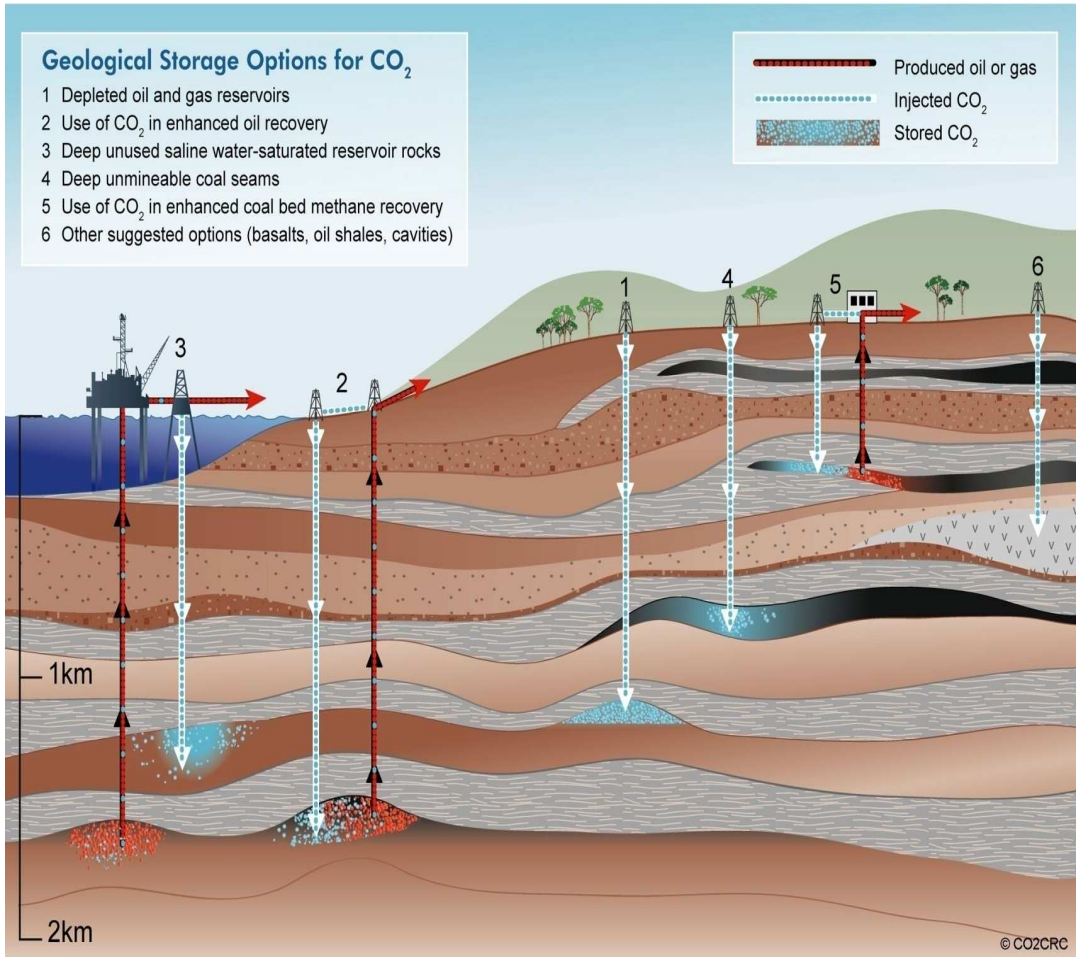


T— 31.04° C
P— 7.382MPa



Background (背景)

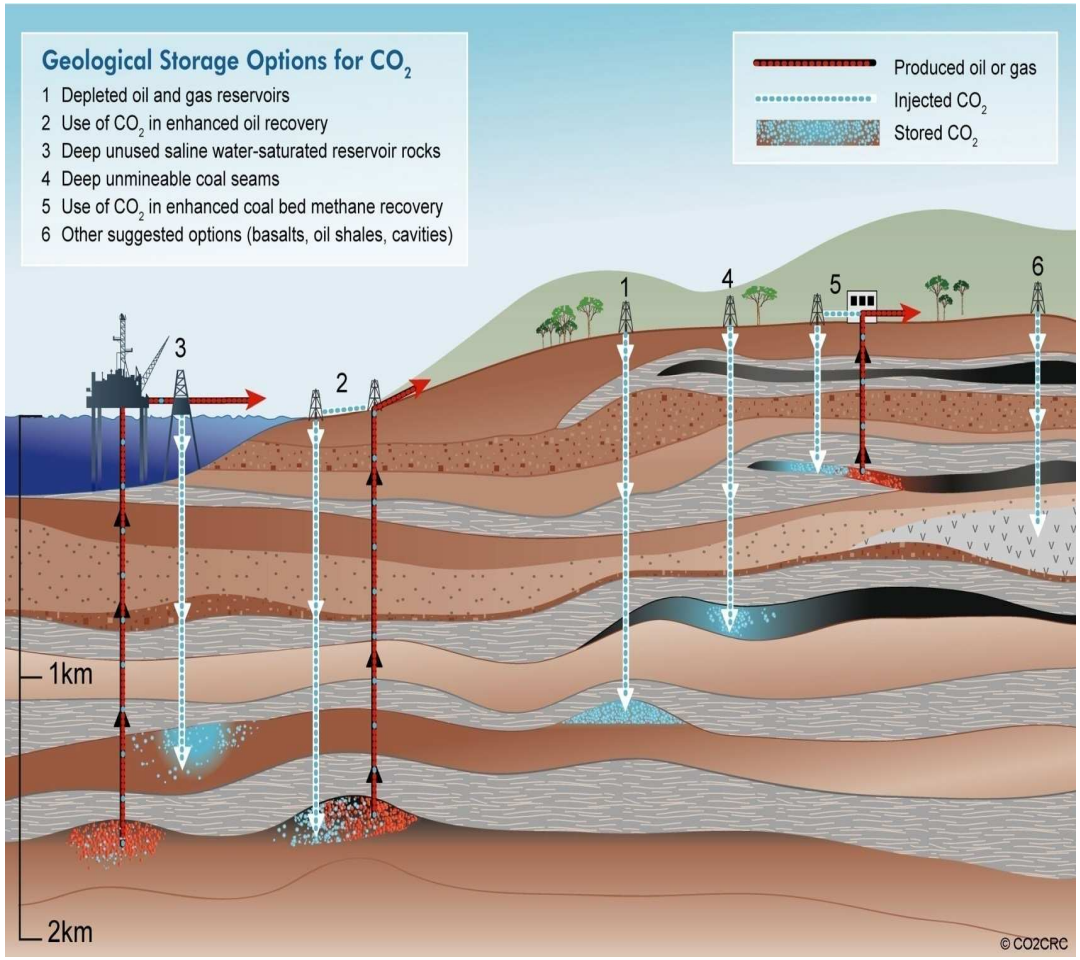
Geological CO2 storage (GCS) 二氧化碳地质封存



- **Deep saline aquifers**
  深部咸水层封存
- **Depleted oil and gas reservoirs**
  枯竭油气田封存
- **Deep unmineable coal seams**
  不可开采煤层封存
- **Enhanced oil recovery**
  二氧化碳驱油（EOR）
- **Enhanced coal bed methane recovery**
  二氧化碳驱替煤层气（ECBM）

Background (背景)

Geological CO2 storage (GCS) 二氧化碳地质封存



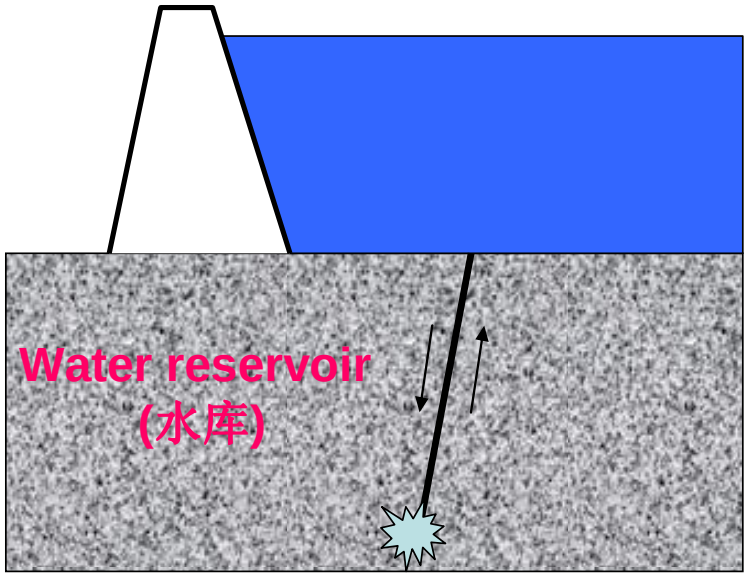
Features (特点)：

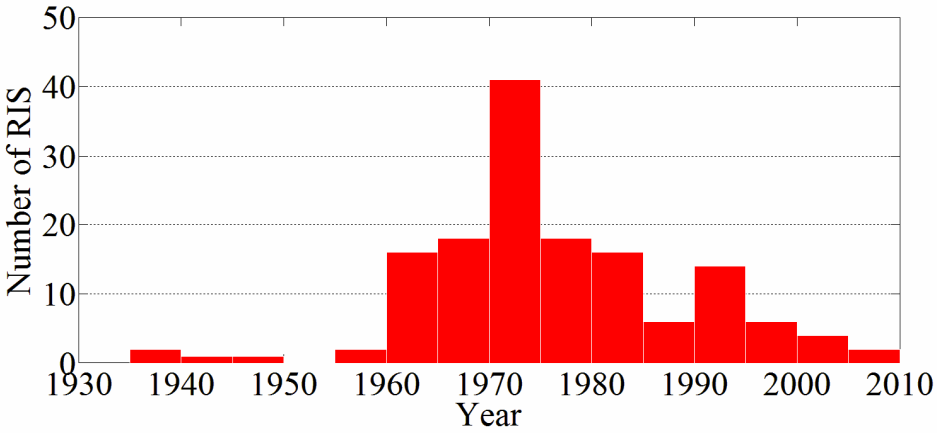
- **Large scale （大规模）**
  (millions of CO2 injected through one well)
- **Long term （长期）**
  (hundreds of years)
- **Multi physical fields coupling （多物理场耦合）**
  (H-T-M-C coupling process)

Background (背景)

Importance of the geomechanical issues

Fluid injection inducing seismicities （流体注入诱发地震）





Reservoir-induced seismicities in the world

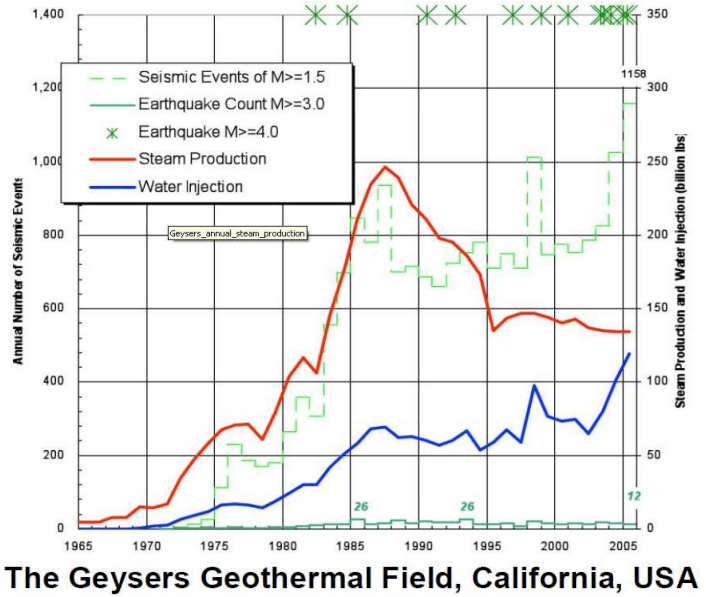
Induced-seismicities really exist, but can be mitigable through some supervision measures.

诱发地震确实存在，但是可以通过一定的措施得到缓解。

Background (背景)

Importance of the geomechanical issues

Fluid injection inducing seismicities （流体注入诱发地震）



The Geysers Geothermal Field, California, USA

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

CO2 injection is similar with water injection, the geomechanical issues have received increasing attentions.

（注入CO2与注水类似，因此，CO2地质封存的力学问题越来越受到重视。）

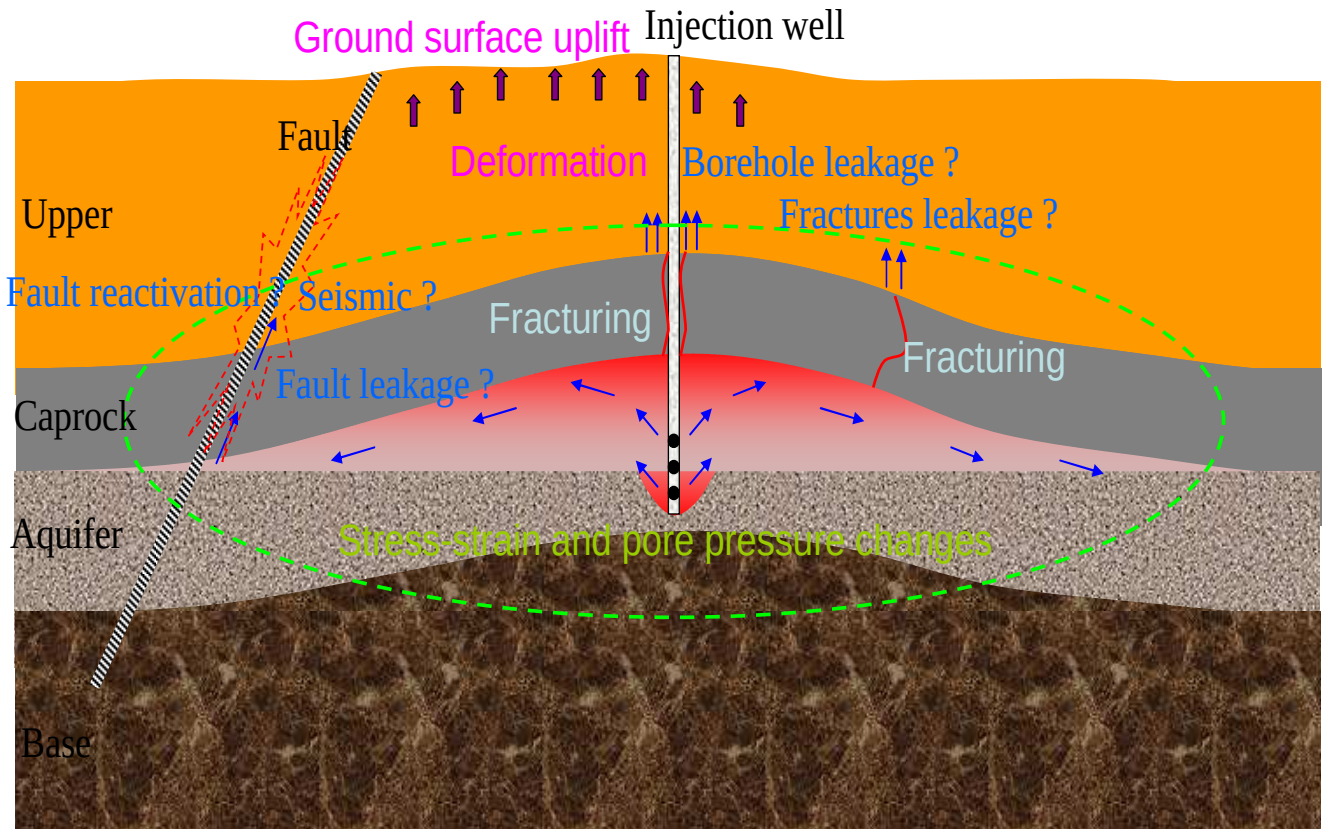
- Baseline geomechanical characterization
- Steps and outcomes for geomechanical modeling

Directive 2009/9/31 EC of the European parliament and of the council of 23 April 2009

CSA Z741: Geological Storage of Carbon Dioxide

Background (背景)

Geomechanical issues



- stress-strain and pore pressure change
  应力-孔压变化规律
- ground surface uplift
  地表变形隆起
- mechanical integrity of the cap-rock
  盖层力学完整性
- fault stability
  断层稳定性

Intention: a brief introduction to geomechanical issues and the analysis Method. (简要介绍CO2地质封存的力学问题及其分析方法)

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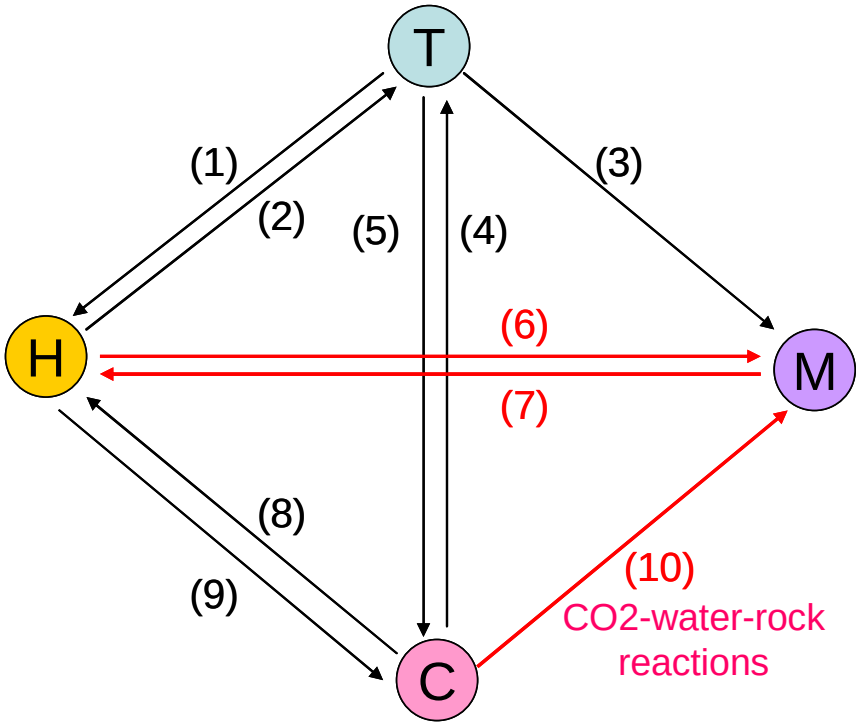
THMC processes and geomechanical issues

HTMC processes in GCS



T— *thermal (热)*

H— *hydraulic (水)*

M— *mechanical (力)*

C— *chemical (化)*

(1) Density, viscosity (密度,粘度)

(2) Advective heat transport (对流传热)

(3) Thermal expansion (热膨胀)

(4) Exothermic/endothermic process (放热/吸热过程)

(5) Reaction rates (反应速率)

(6) Stress and strain (应力应变)

(7) Porosity, permeability (孔隙度,渗透率)

(8) Density, viscosity, porosity & permeability (密度,粘度,孔隙度,渗透率)

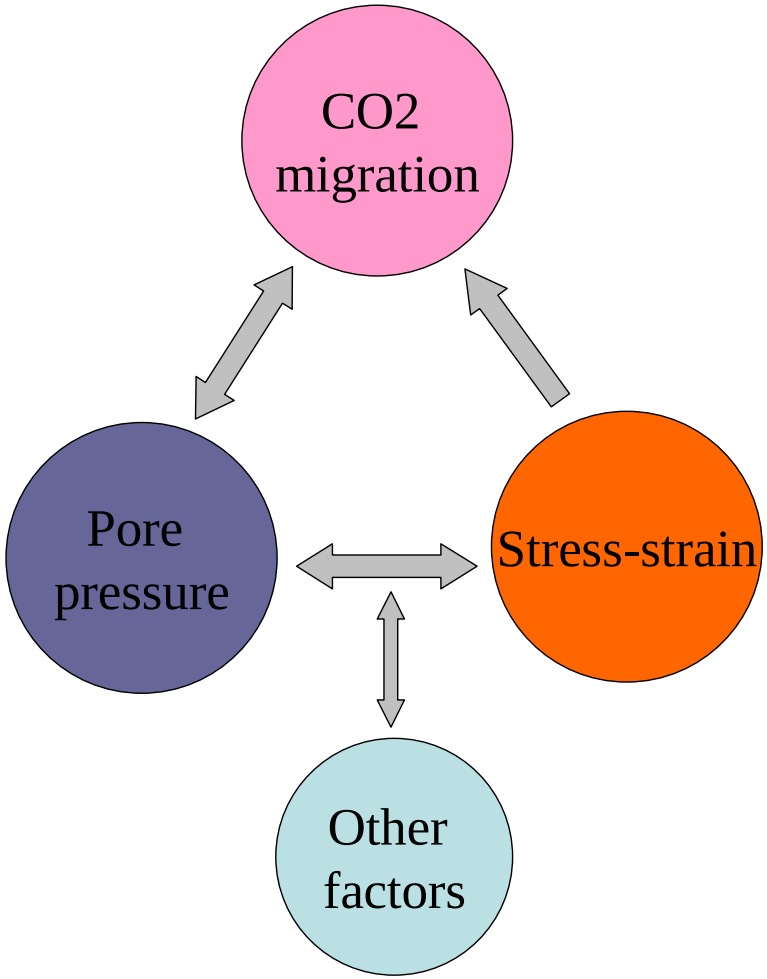
(9)Advective solute transport (溶质运输)

(10)Rock properties (岩体性质)

- ***GCS is a complex* multi physics problem.**
- ***From GCS perspective,* H→M, M →H *&* C→M *are most relevant.***

THMC processes and geomechanical issues

Stress and pore pressure change (应力与孔压变化)



CO2 injection (二氧化碳注入)

→ Pore pressure increase
(孔压增加)

Principle of effective stress

→ Effective stress decrease
(有效应力降低)

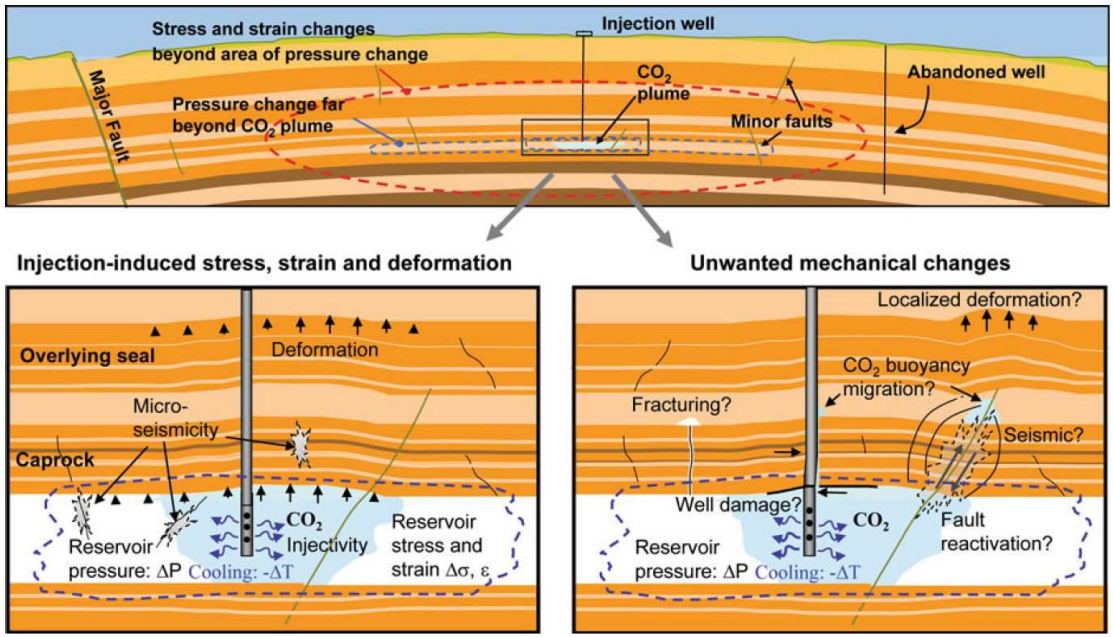
→ Pore volume expansion
(孔隙体积膨胀)

→ Facilitating the evolution of the pore pressure
(促进孔压的演化)

→ Promoting CO2 migration
(利于二氧化碳的运移)

THMC processes and geomechanical issues

Stress and pore pressure change (应力与孔压变化)



Rutqvist et. al. 2013

● Any change in reservoir pore pressure will induce some stress and strain changes in and around the injection zone.
(储层的压力任意变化将引起注入区域一定范围的应力变化)

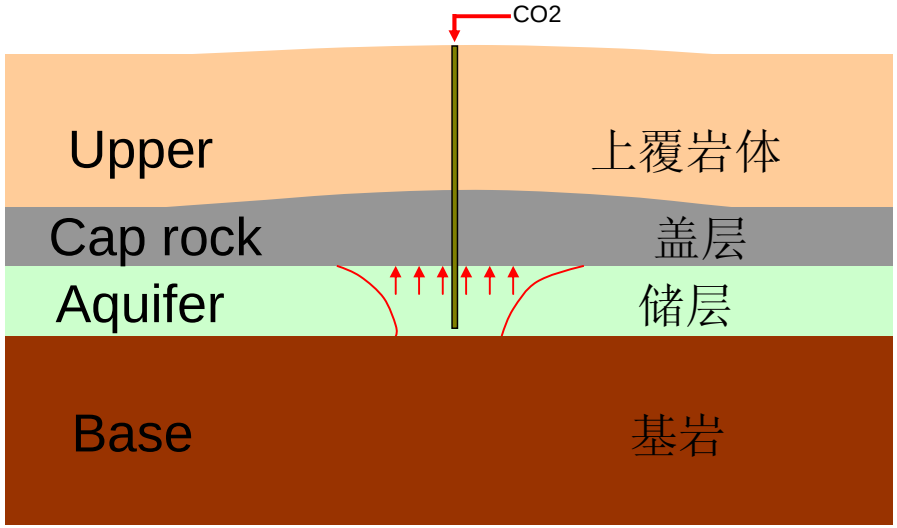
●Resulting in ground surface uplift, cap-rock fracturing or fault reactivation.
(应力变化达到一定的程度可能导致地表位移隆起、盖层开裂或者断层活化)

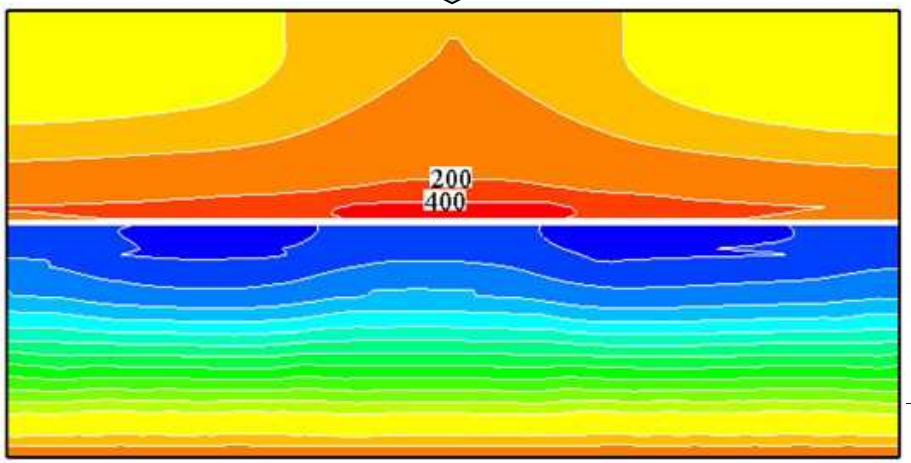
Importance:

- *Preconditions for analysing other issues (分析其它力学问题的前提条件)*
- *Basic understandings for the changes of cap-rock and reservoir (从原理上理解盖层和储层的应力变化规律)*

THMC processes and geomechanical issues

Ground surface uplift (地表隆起)





Pore pressure increase
(孔压增大)

Volumetric expansion in the injection zones
(孔隙体积膨胀)

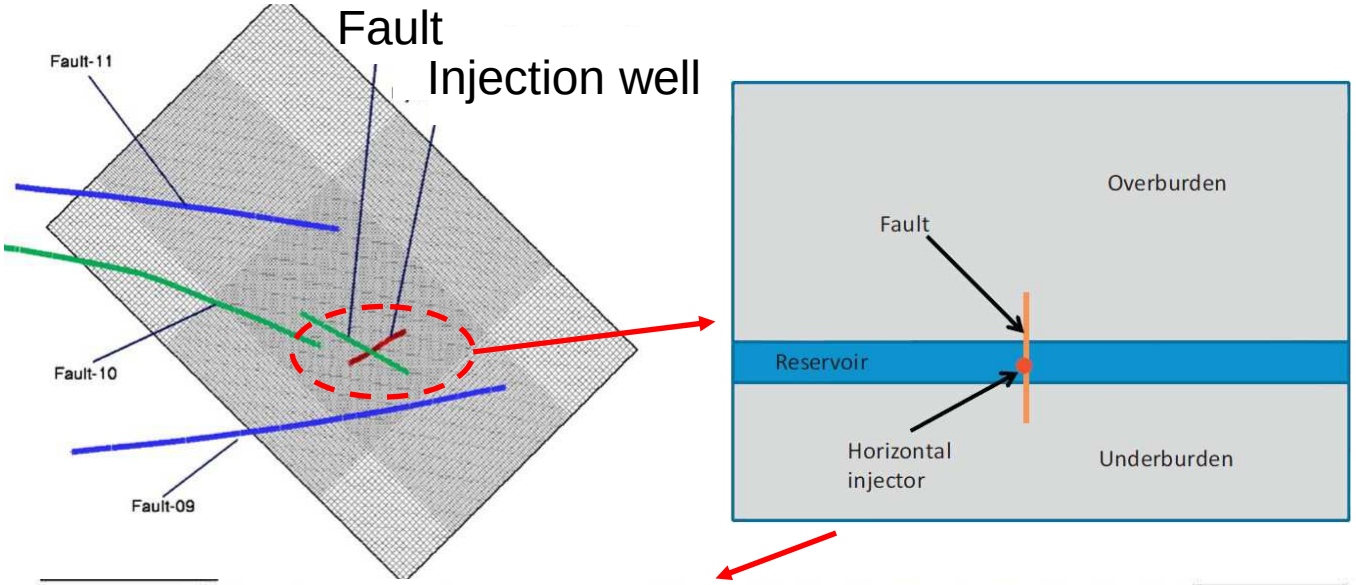
extrusion force from the bended cap-rock
(盖层弯曲挤压)

squeezing the overlying rock mass
(挤压上覆岩体)

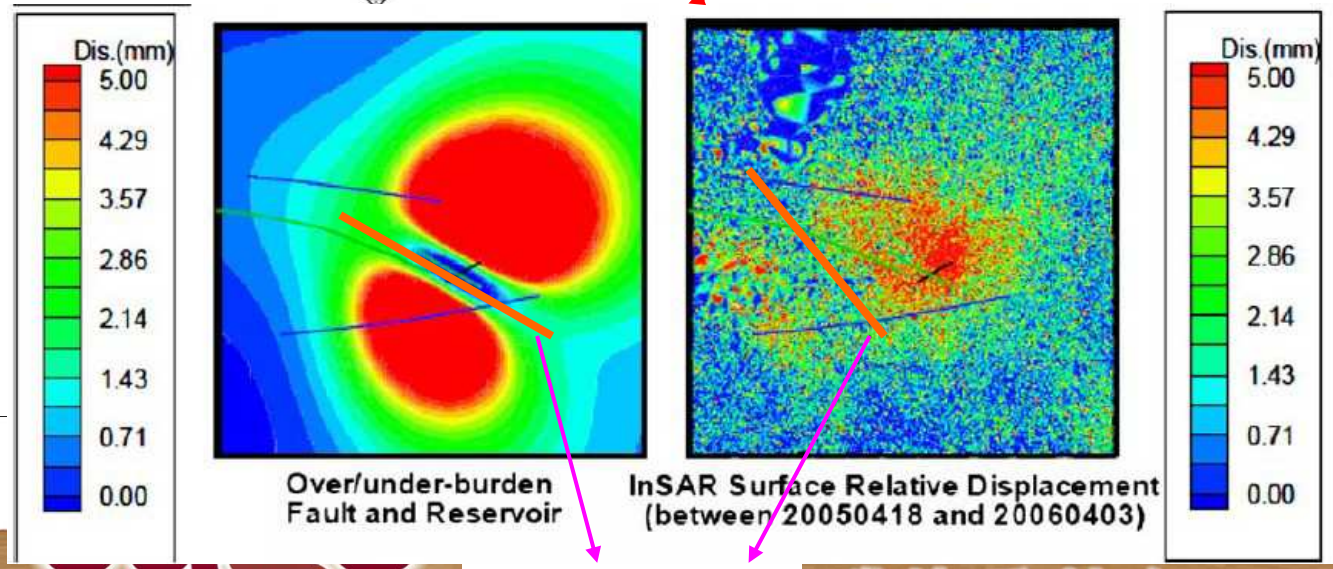
ground surface deformation
(地表变形隆起)

THMC processes and geomechanical issues

Ground surface uplift (地表隆起)



●Direct response of the subsurface mechanical issues (地下力学问题的直接反映)



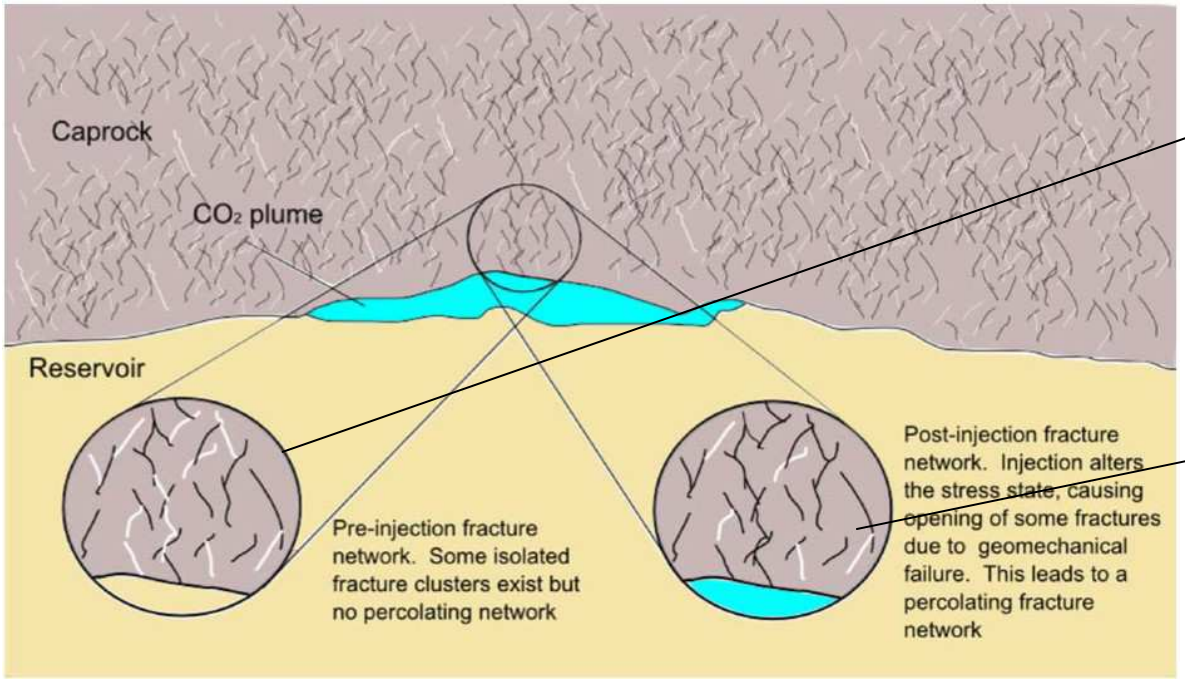
In Salah project
Left:
numerical simulation
Right:
field monitoring

Morris et. al. 2011

Vertical fault

THMC processes and geomechanical issues

Mechanical integrity of the cap-rock (盖层力学完整性)



- Pre-injection fractures reactivation
  (注入前已有裂隙的活化)
- CO2-injection inducing new fractures
  (CO2注入产生新的裂隙)

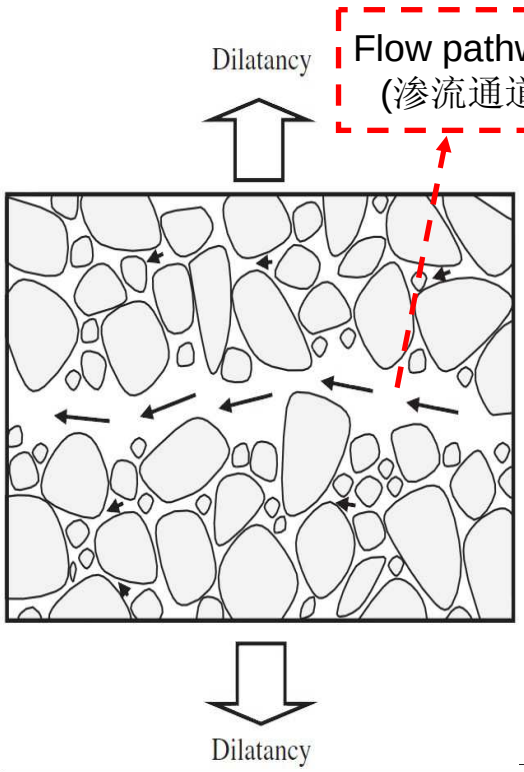
Connecting fractures supply a potential leakage path for CO2 escaping through the cap-rock. The mechanical integrity is considered to be damaged if the pre-fractures are activated or new fractures are induced.
(连通的裂缝为CO2的逃逸提供了一条潜在的通道，因此，一旦已有裂缝活化或者产生了新的裂缝，即认为盖层的力学完整性受到一定的影响。)

THMC processes and geomechanical issues

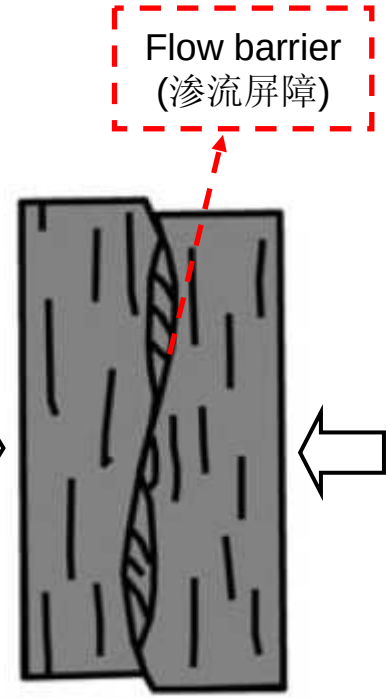
Mechanical integrity of the cap-rock (盖层力学完整性)

Pre-injection fractures activation or induced fractures are not the sufficient condition for CO2 leakage.

(已有裂缝活化或者新裂缝的产生并非CO2泄露的充分条件.)



- Low normal stress (低的法向应力)
- shear dilation (剪胀)
- high porosity and permeability (高的孔隙度和渗透率)

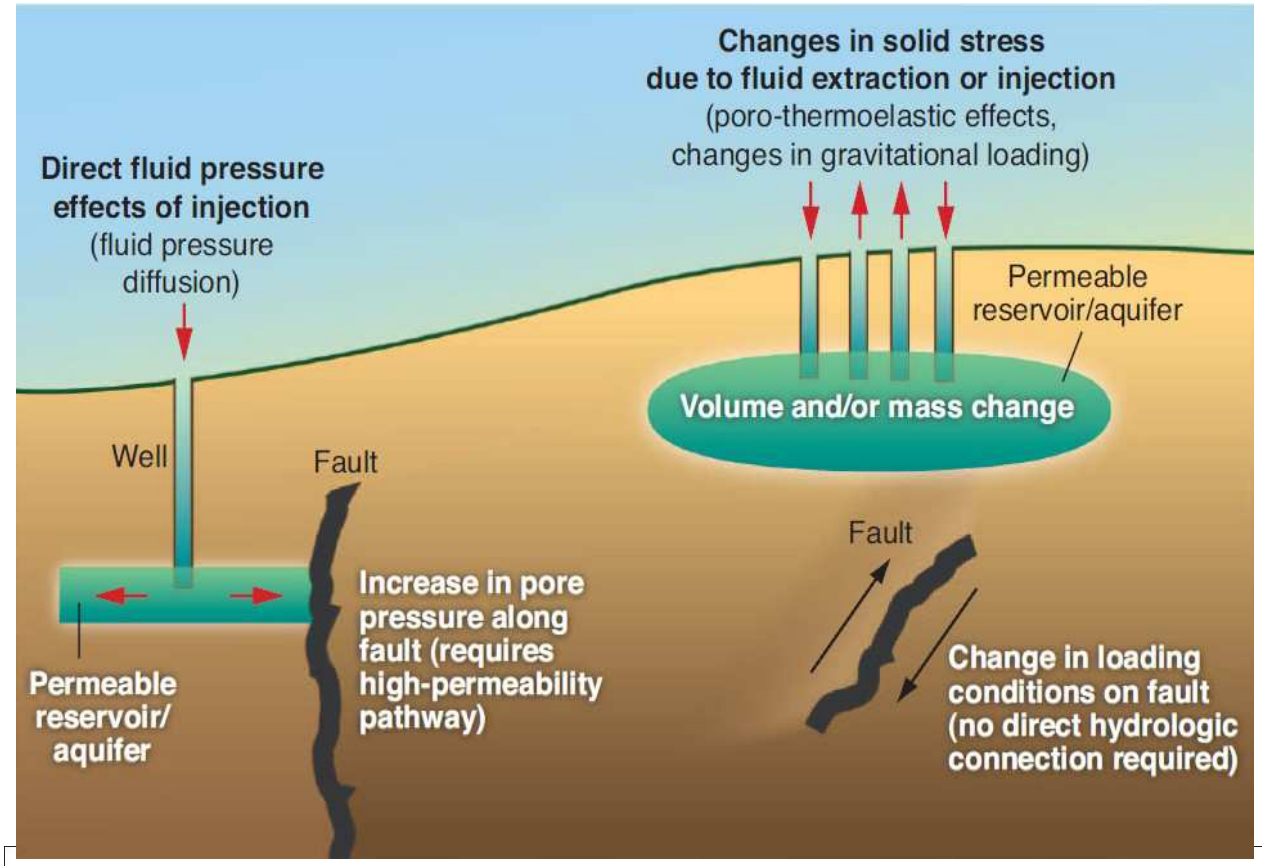


- High normal stress (高的法向应力)
- shear contraction (剪缩)
- Low porosity and permeability (低的孔隙度和渗透率)

THMC processes and geomechanical issues

Fault stability (断层稳定性)

Mechanisms for inducing fault reactivation
(断层活化的机制)

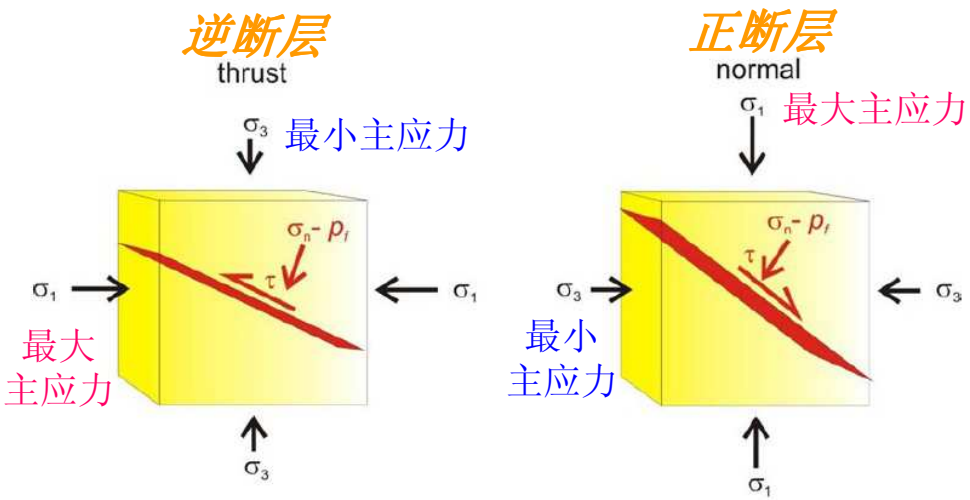


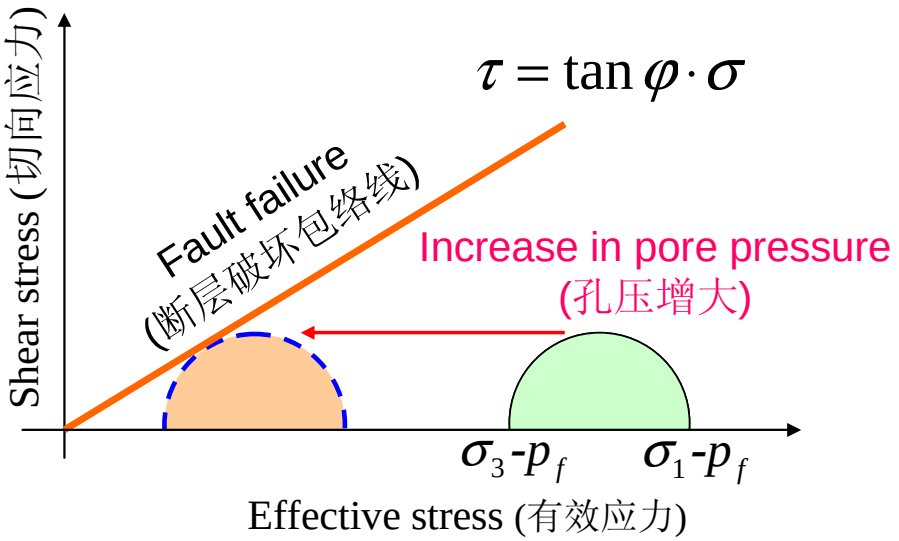
- The effective stress acting on fault decrease by increasing pore pressure.
  (断层孔压增大导致有效应力降低)

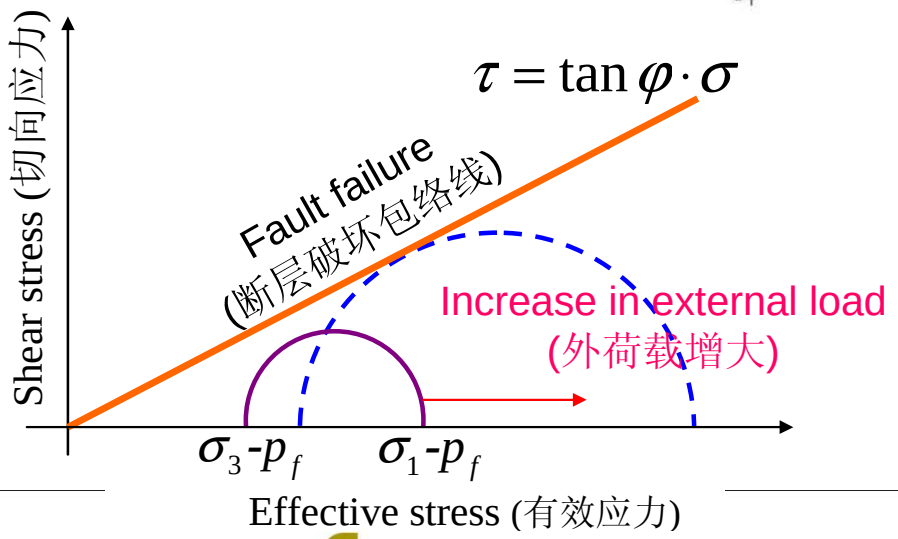
- The loading condition on fault has changed.
  (改变外荷载条件)

THMC processes and geomechanical issues

Fault stability (断层稳定性)







- Mohr-Coulomb criterion
  (摩尔库伦准则)
- Without consideration of the cohesive strength
  (不考虑粘结力)

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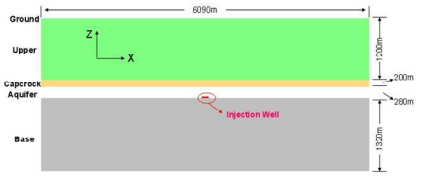
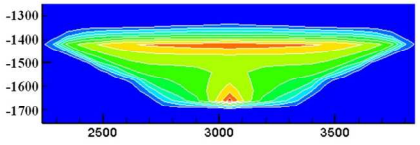
Analysis method for geomechanical issues

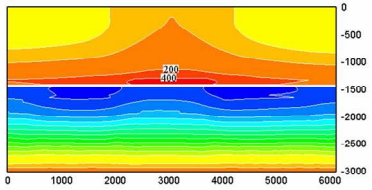
Numerical simulation (数值模拟)



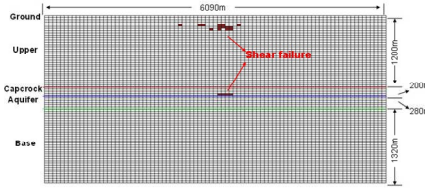
Stratum Partition Map of Vertical Section



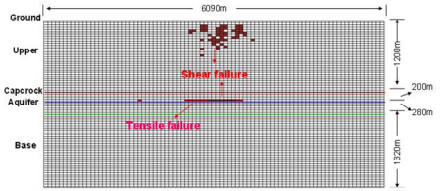
Distribution Map of CO_2 saturation ($t=2.5\times10^8$s)



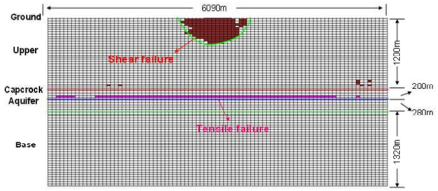
Distribution Map of Displacement along Direction Z ($t=2.5\times10^8$s)



Distribution Map of Plastic Zone (K=1.6)



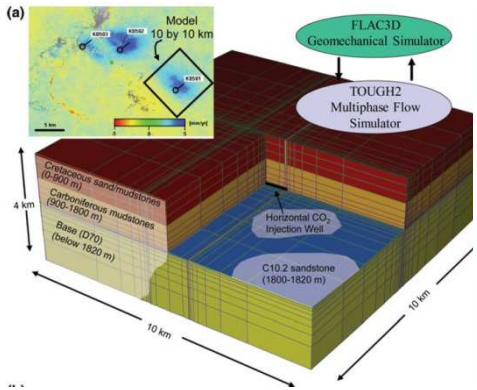
Distribution Map of Plastic Zone (K=2.0)

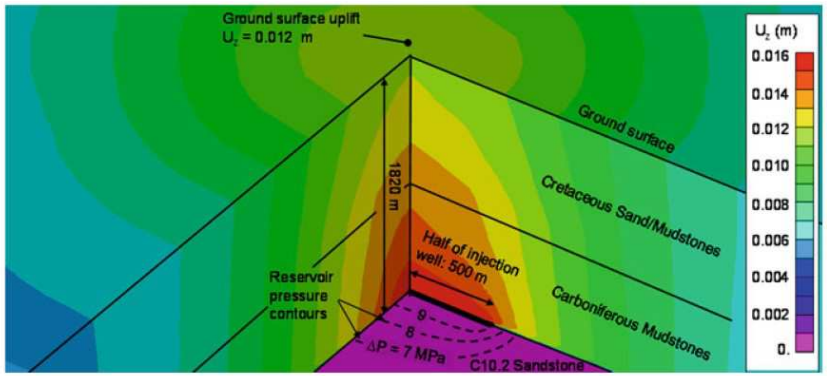


Distribution Map of Plastic Zone (K=2.8)

Yuan Wei et al. 2013

- Complicated situations
  - — irregular geometry (不规则几何模型)
  - — multiphysics problem (多场耦合问题)
  - — long time span (时间跨度大)





Rutqvist et al. 2008

- Numerical modeling method is the most widely used method in simulating the geomechanical issues in GCS.
(数值模拟在CO2地质封存的力学问题中应用最为广泛.)

Analysis method for geomechanical issues

Governing equations for HTMC processes
(HTMC耦合过程的控制方程)

$$\frac{\partial}{\partial t}[\theta_s \cdot (1-\phi)] + \nabla q_s = 0$$

$$\frac{\partial}{\partial t}(\theta_l^w S_l \phi + \theta_g^w S_g \phi) + \nabla (q_l^w + q_g^w) = f^w$$

$$\phi \frac{D_s(\theta_l^a S_l + \theta_g^a S_g)}{Dt} + (\theta_l^a S_l + \theta_g^a S_g)\frac{D_s \phi}{Dt} + [(\theta_l^a S_l + \theta_g^a S_g)\phi]\nabla \frac{d\vec{u}}{dt} + \nabla (q_l^a + q_g^a) = f^a$$

Mass balance (质量守恒)

$$\frac{\partial}{\partial t}[E_s \rho_s (1-\phi) + E_l \rho_l S_l \phi + E_g \rho_g S_g \phi] + \nabla (q_c + q_{Es} + q_{El} + q_{Eg}) = f^Q$$

Energy conservation (能量守恒)

$$\nabla [\sigma'' + \alpha p I - K \beta_T (\Delta T) I] + \rho g \vec{k} = 0$$

Momentum equation (动量方程)

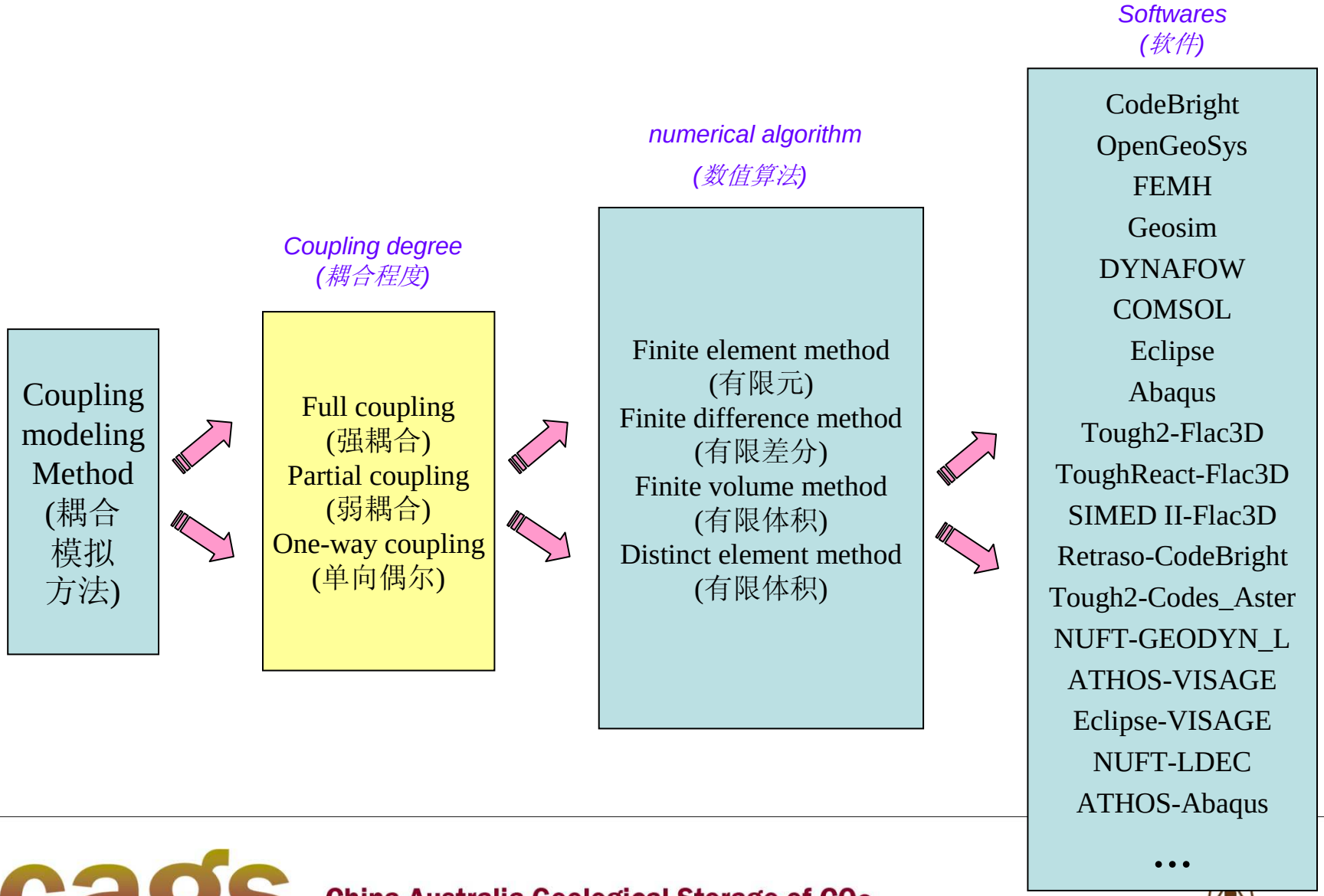
$$\nabla^T (D_i \nabla C_i) + \phi \frac{\partial C_i}{\partial t} + v_w \nabla C_i = R_i \qquad i = 1, \ldots, N$$

$$\frac{\partial C_j}{\partial t} = R_j \qquad j = 1, \ldots, M$$

$$R_j = A_j k_j (1 - \frac{Q_j}{K_{eq,j}})$$

Reactive solute transport (反应流通)

Analysis method for geomechanical issues



Analysis method for geomechanical issues

Full coupling (强耦合)

Matrix form for governing equations

$$\begin{bmatrix} \mathbf{M} & -\mathbf{C}_{sw} & -\mathbf{C}_{sT} & 0 & 0 & 0 \\ 0 & \mathbf{H}_{ww} & 0 & 0 & 0 & 0 \\ 0 & 0 & \mathbf{H}_{TT} & 0 & 0 & 0 \\ 0 & 0 & 0 & \mathbf{H}_{CC1} & 0 & 0 \\ 0 & 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & \mathbf{H}_{CCN} \end{bmatrix} \begin{Bmatrix} \mathbf{u} \\ \mathbf{p} \\ \mathbf{T} \\ \mathbf{C}_1 \\ \vdots \\ \mathbf{C}_N \end{Bmatrix}$$

displacement

pressure

temperature

composition

$$+ \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ \mathbf{C}_{ws} & \mathbf{R}_{ww} & \mathbf{C}_{wT} & 0 & 0 & 0 \\ 0 & \mathbf{C}_{Tw} & \mathbf{R}_{TT} & 0 & 0 & 0 \\ 0 & 0 & 0 & \mathbf{R}_{CC} & 0 & 0 \\ 0 & 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & \mathbf{R}_{CC} \end{bmatrix} \begin{Bmatrix} \mathbf{u}_t \\ \mathbf{p}_t \\ \mathbf{T}_t \\ \mathbf{C}_{1t} \\ \vdots \\ \mathbf{C}_{Nt} \end{Bmatrix} = \begin{Bmatrix} \mathbf{f}^u \\ \mathbf{f}^w \\ \mathbf{f}^T \\ \mathbf{f}^{C1} \\ \vdots \\ \mathbf{f}^{CN} \end{Bmatrix}$$

$[u, p, T, C_1, ..., C_N]^T$ —— unknown variables

$[u_t, p_t, T_t, C_{1t}, ..., C_{Nt}]^T$ —— time derivatives

$[f^u, f^w, f^T, f^{c1}, ..., f^{cN}]^T$

—— the nodal loads, the flow source, the heat source, and the solute source.

Definition

Simultaneous solution of all of the partial differential equations. (所有的偏微分方程同时求解)

Features

- The highest level coupling method (耦合程度最高)
- Heavy computational requirements (计算量大)
- Relatively simple physical and mathematical models (相对简单的模型)

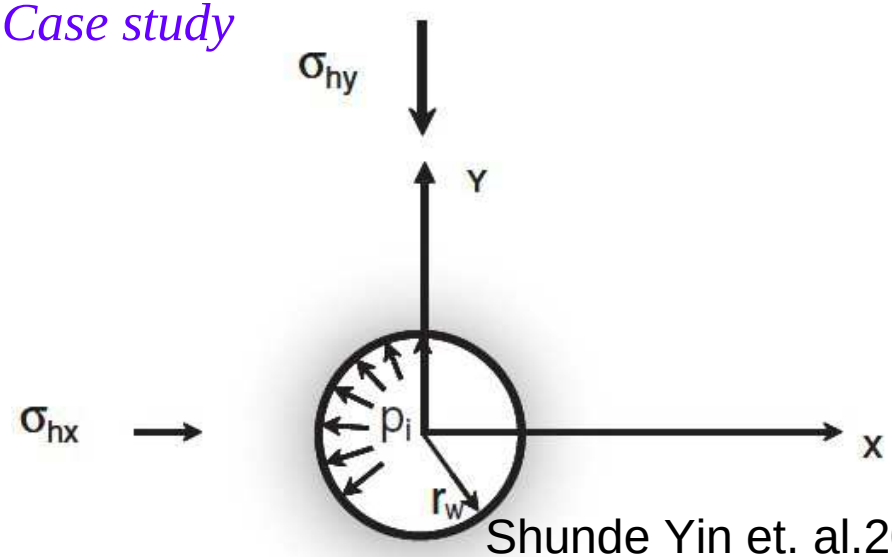
Codes

CodeBright; OpenGeoSys; FEMH; Geosim; DYNAFOW;COMSOL; Eclipse; Abaqus

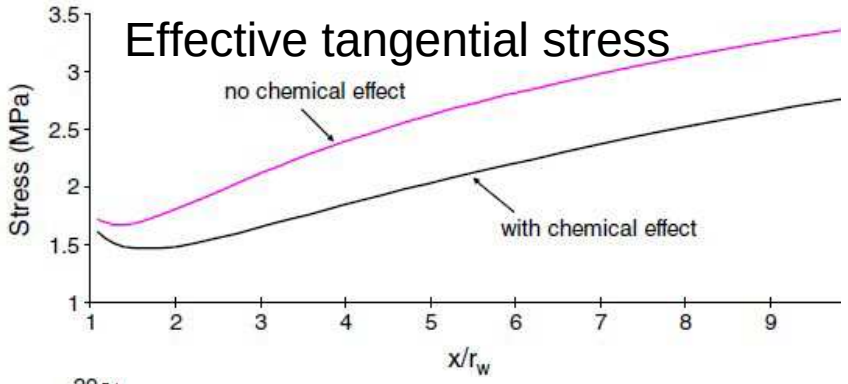
Analysis method for geomechanical issues

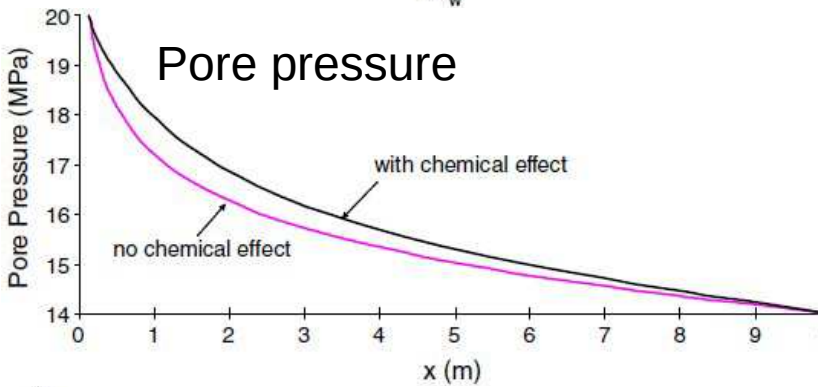
Full coupling (强耦合)

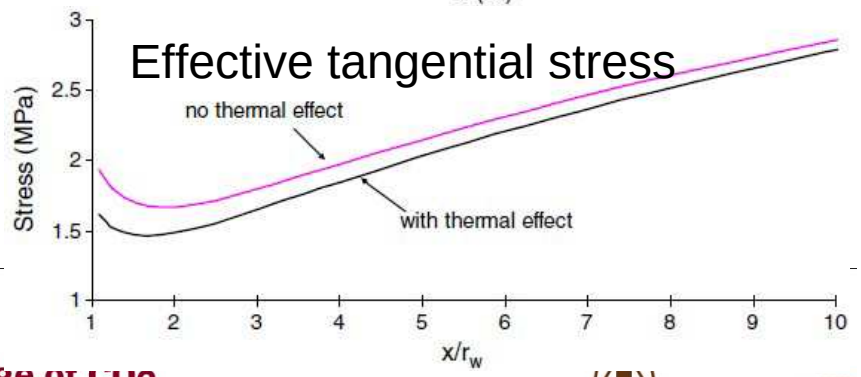
Case study



Shunde Yin et. al.2012





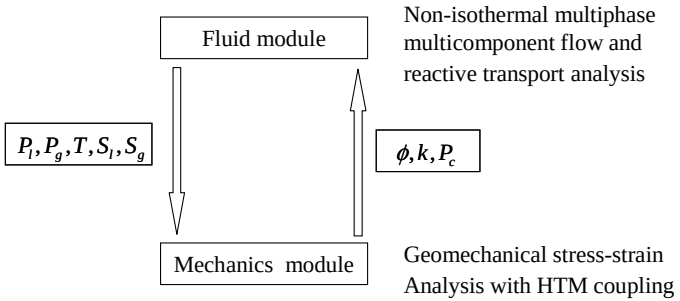


- Two-dimensional model (二维模型)
- Elastic constitutive model (弹性本构)
- CO2 saturated water injected into a carbonate aquifer
  (饱和CO2水溶液注入碳酸盐储层)

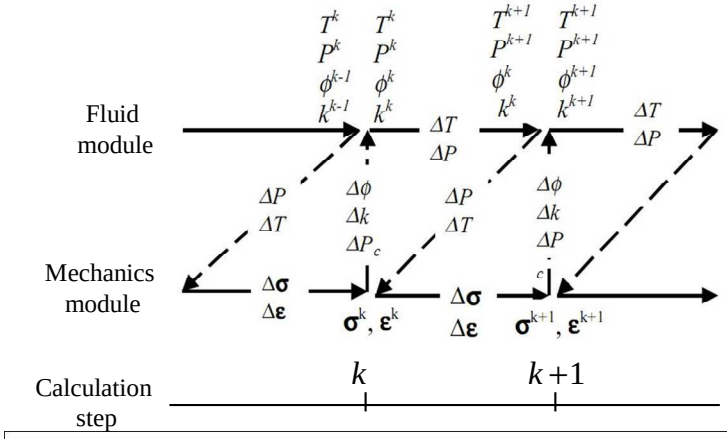
Analysis method for geomechanical issues

Partial coupling (弱耦合)

Coupling processes



P_l = *liquid pressure*
P_g = *gas pressure*
P_c = *capillary pressure*
k = *permeability*
ϕ = *porosity*
T = *temperature*



Definition

Each module is implemented separately, the parameters of computation modules are corrected at the end of each calculation step. (各个模块独自计算，在每一步计算末尾修正其参数)

Features

- Complicated constitutive model and irregular geometry (较复杂的本构模型和几何模型)
- A more wide and complicated application (fault stability, fractures network et al.) (广泛的应用)
- Separate softwares linked through data communication (不同的软件相互交换数据)

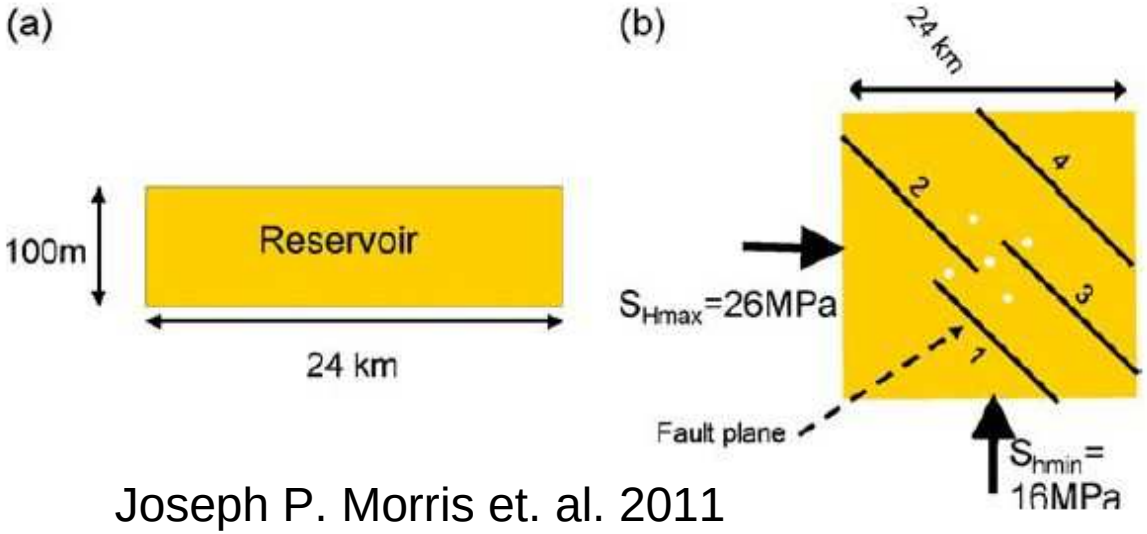
Codes

Tough2-Flac3D; ToughReact-Flac3D; SIMED II-Flac3D; Retraso-CodeBright;Tough2-Codes_Aster; ATHOS-VISAGE; NUFT-GEODYN_L;

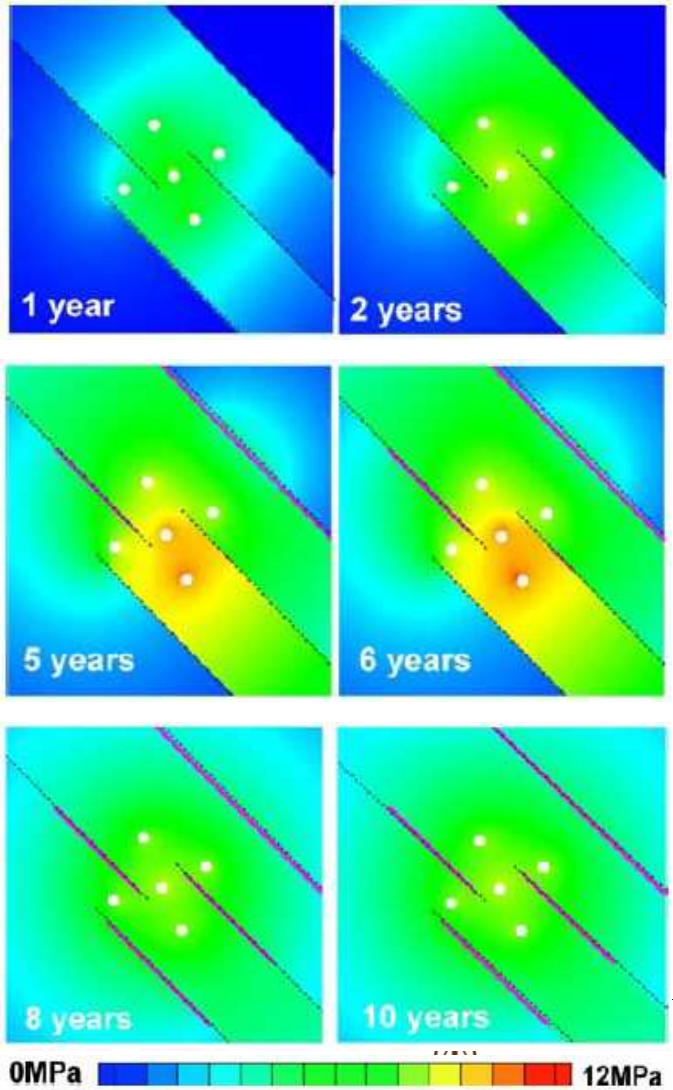
Analysis method for geomechanical issues

Partial coupling (弱耦合)

Case study



Joseph P. Morris et. al. 2011

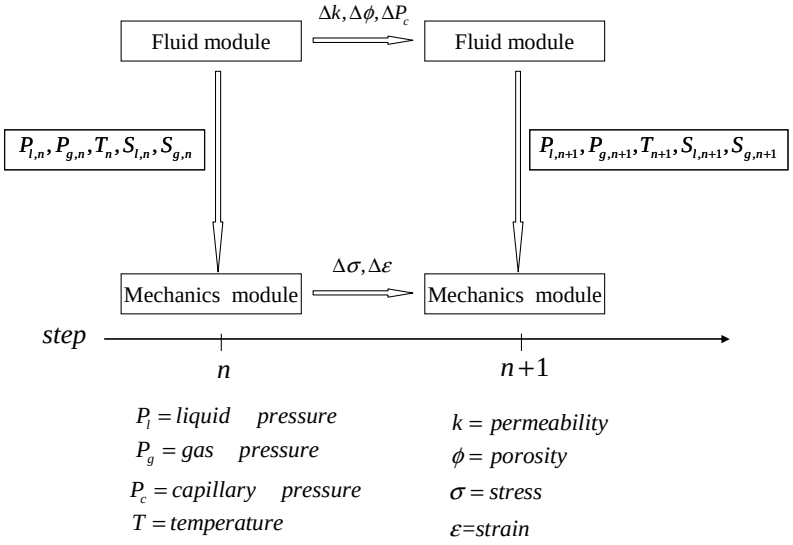


- Three-dimensional model; large scale
  (三维模型；大尺度)
- Elastic-plastic constitutive model (弹塑性本构)
- Several faults (多条断层)

Analysis method for geomechanical issues

One-way coupling (单向耦合)

Coupling processes



Definition

The fluid flow problem is solved first followed by the use of updated pore pressure as the external load in order to solve the geomechanical problem.
(先求解流体模块，然后把孔压作为荷载输入到力学模块计算)

Features

- Minimal coupling degree (耦合程度最低)
- No feedback of the mechanical results to the fluid module (没考虑力学过程对渗流的影响)
- The highest calculating efficiency and the lowest accuracy (效率最高，准确性最低)
- Only pays attention to the mechanical response (仅关注力学响应)

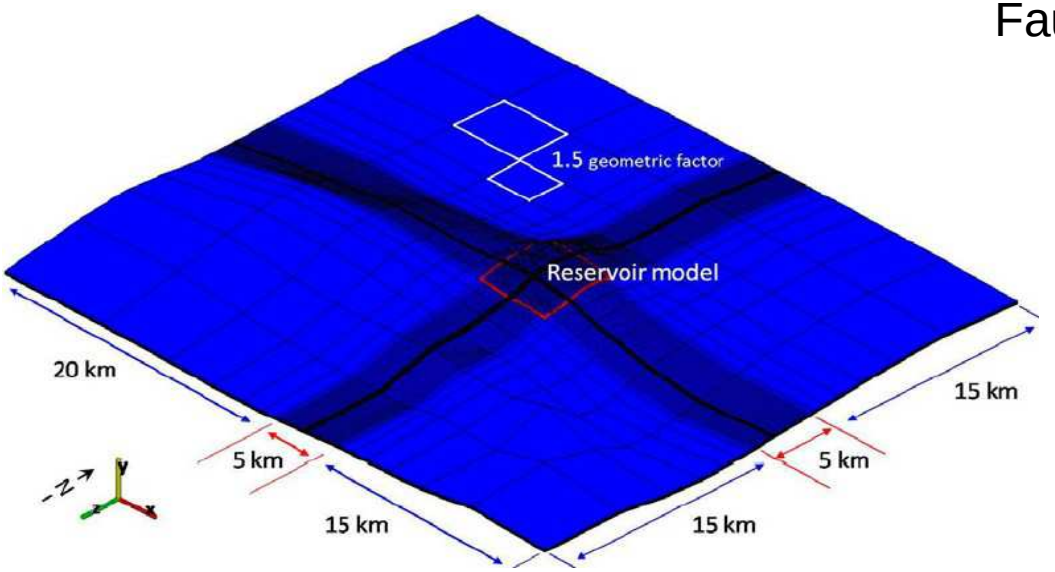
Codes

Eclipse-VISAGE; NUFT-LDEC; ATHOS-Abaqus

Analysis method for geomechanical issues

One-way coupling (单向耦合)

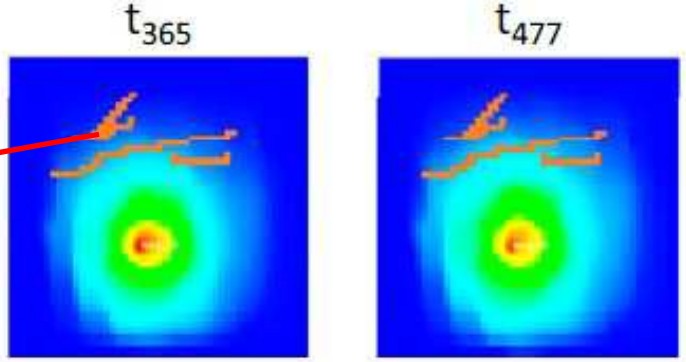
Case study



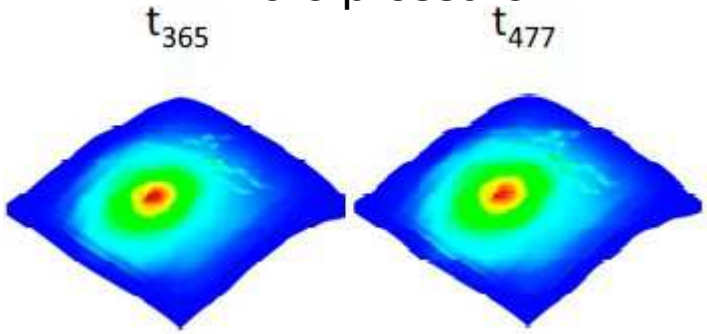
Amélie Ouellet et. al. 2011

- Three-dimensional model; large scale
  (三维模型；大尺度)
- Elastic-plastic constitutive model (弹塑性本构)
- Several faults (多条断层)

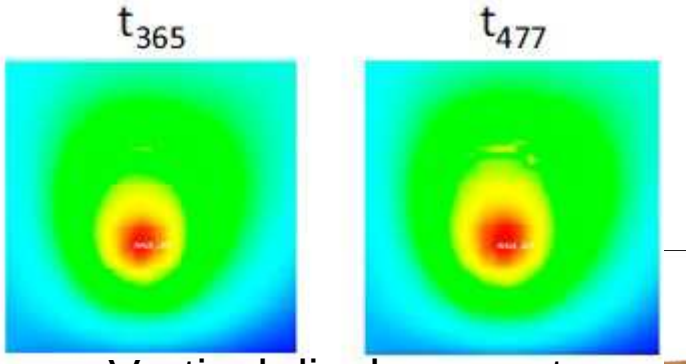
Faults



Pore pressure



volumetric strain



Vertical displacement

Outlines (提纲)

※ Background (背景)

※ THMC processes and geomechanical issues

(THMC耦合过程以及力学问题)

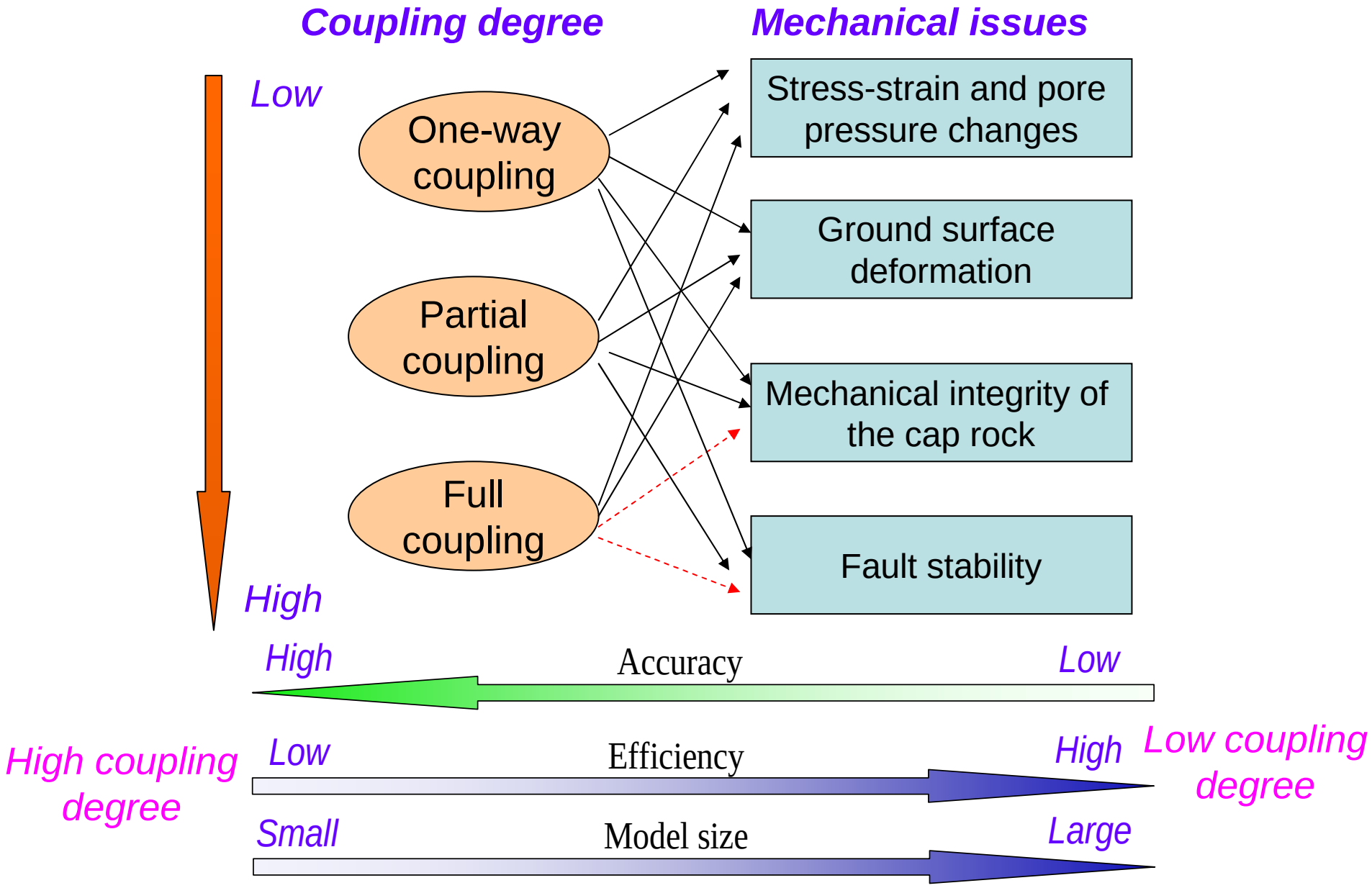
※ Analysis method for geomechanical issues

(力学问题的分析方法)

※ Conclusions and recommendations (结论与建议)

Conclusions and recommendations

Conclusions (结论)



Conclusions and recommendations

Conclusions (结论)

(1) Isotropic elastic and elastic-plastic models are widely used for numerical modeling in CO2 storage systems. Discontinuous model are relative seldom used.(各向同性的弹性和弹塑性模型应用较为广泛，而非连续介质模型的应用较少。)

(2) The intact elastic model and plastic model are the most widely used methods for simulating the integrity of the cap-rock. However, these researches are only qualitative analysis of the integrity of the cap-rock. (弹性模型和弹塑性模型广泛应用于盖层的完整性研究中，但是仅是定性分析盖层的完整性。)

(3) Fault stability assessment is based on Mohr-Coulomb criterion. The earthquake process are relative seldom simulated.(断层稳定性的评价主要是基于摩尔库伦准则，对地震过程的模拟相对较少。)

Conclusions and recommendations

Recommendations (建议)

(1) Almost all geologic formations are considered to be isotropic materials, which can not describe the sedimentary rocks accurately. A constitutive model depicting the GCS process should be studied in the future. (各向同性模型不能准确描述沉积岩体的特性，因此，需要探索一种适合描述CO2地质封存过程的本构模型。)

(2) Simulations should be developed to investigate the propagation of multiple cracks coupled with HTMC in order to assess the integrity of the cap-rock.(考虑HTMC过程的多裂纹扩展模拟方法值得探索)

(3) Although a geomechanical analysis of CO2 storage systems has been performed to acquire a basic understanding, a perfect evaluation system and procedure for the stability analysis of an entire site is lacking. Such an evaluation system should be developed and used for site selection in the future. (当前对CO2地质封存的力学问题已取得一定的认识，但是，对场地稳定性评价系统和步骤的研究较少。)

Thank you !

谢谢！