Geothermal Energy (Week 9, 28 Oct) - Reservoir Geomechanics

민기복

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Question

- Shear sliding
- Tangential stress
- How do we measure in situ stress?

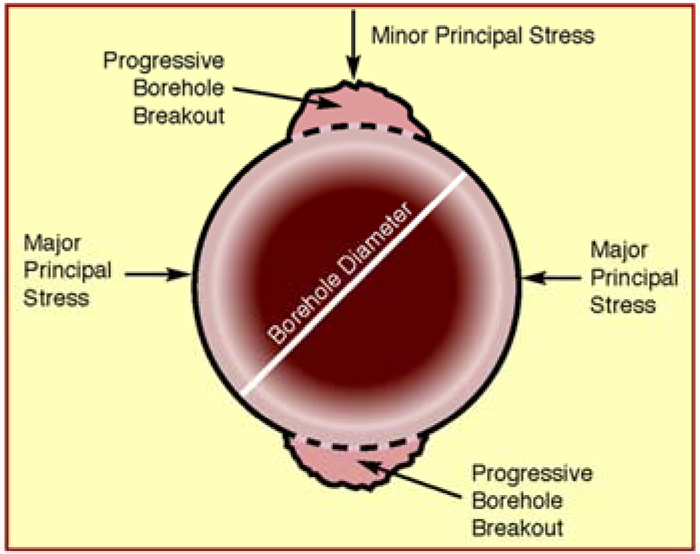
Term Paper
Progressive Report

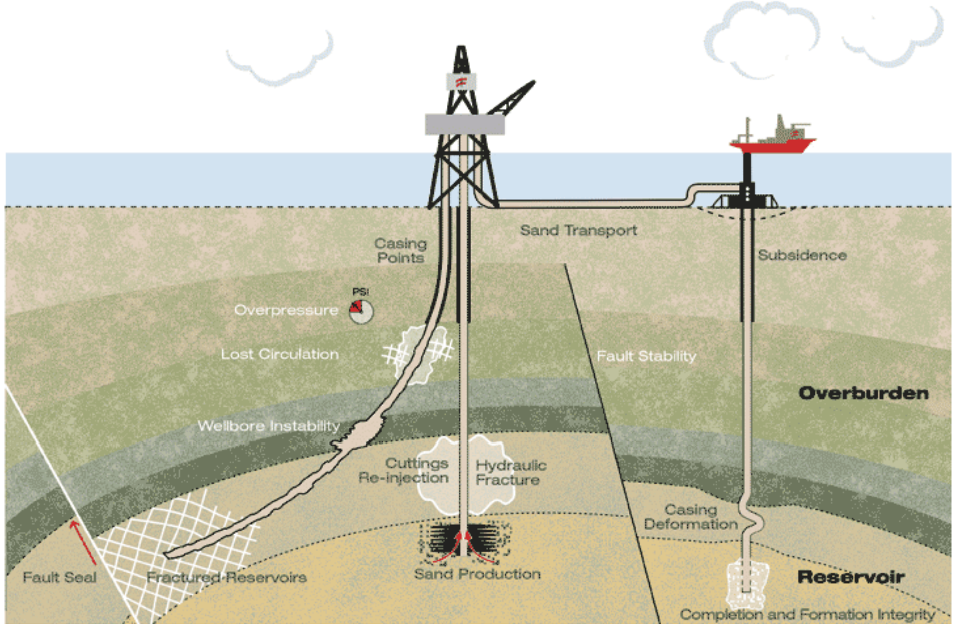
- Submission by 24:00 30 Oct (through email)
- Late submission by 24:00 1 Nov (20% penalty)
- Please use MS Word for writing report (due to track change function)
- Meeting with me (after class on 28 Oct)

Milestone	Length	Due date	Mark
Proposal	~1 page	25 Sept	10%
Progress Report	~5 pages	30 Oct	20%
Final Report	~20 pages	4 Dec	35%
Presentation	20 minutes (including questions)	7 & 9 Dec	35%

Reservoir Geomechanics
outline

- Fundamentals of rock mechanics
- Borehole stability – stability of geothermal wellbore
- Mechanics of Hydraulic fracturing
- Reservoir Geomechanics





http://www.swri.edu/3PUBS/BROCHURE/D20/geotech/geotech.HTM

http://www.helix-rds.com/EnergyServices/HelixRDS/Capabilities/Geomechanics/tabid/178/Default.aspx

Monday

- Borehole Stability (continued)
  - Mohr-Coulomb Failure Criteria
- Hydraulic Fracturing
  - Direction of fracturing
  - Condition for fracture initiation/propagation

Stresses distribution around borehole
General solution

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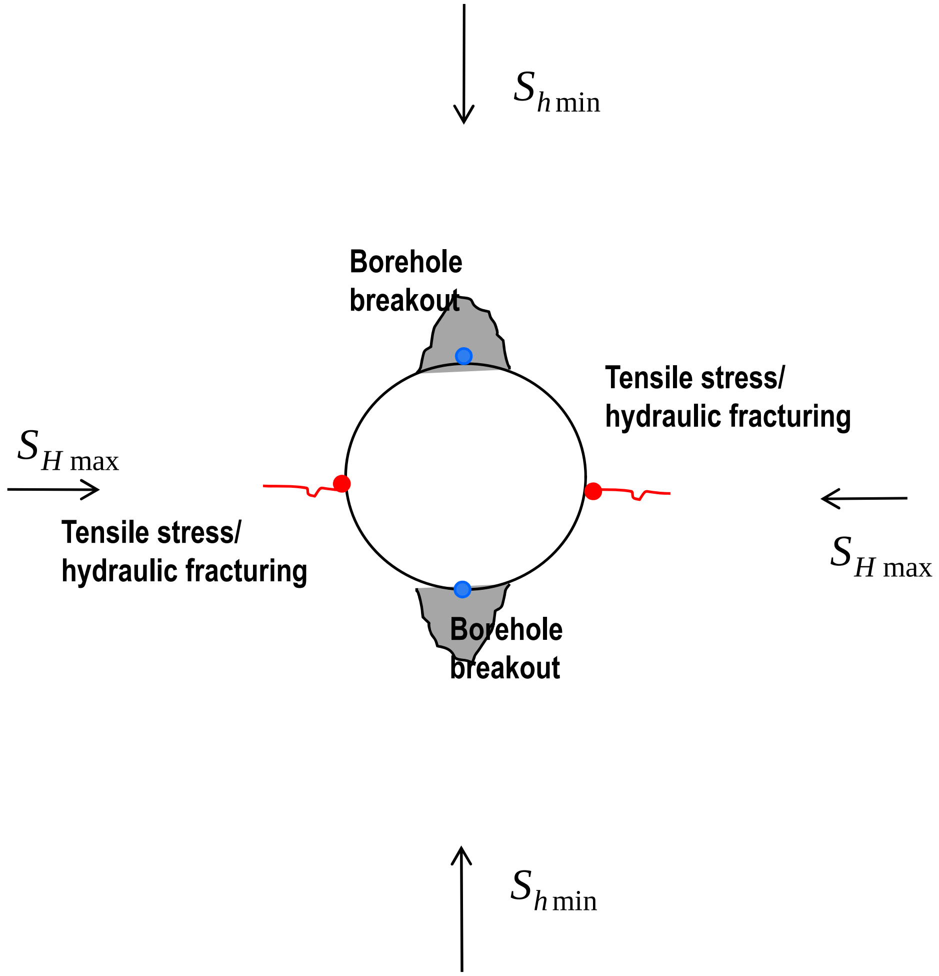
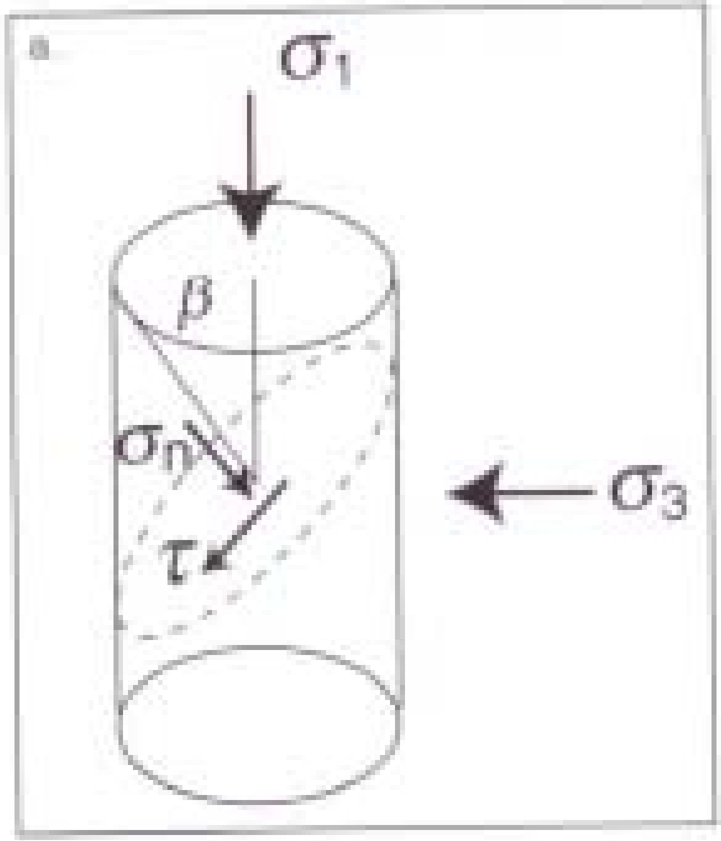


- Required internal pressure to induce tensile stress;
  - ● $P_w > 3S_{h\min} - S_{H\max} + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$
- Required uniaxial compressive strength not to have borehole breakout
  - ● $\sigma_c > 3S_{h\max} - S_{h\min} - P_w + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$

Failure Criteria
Mohr-Coulomb Failure criteria



$$\tau = S_0 + \sigma_n \mu_i$$

- τ: Shear stress
- S_0=cohesion (or cohesive strength)
- σ_n: normal stress
- μ_i: coefficient of internal friction

Failure Criteria
Application to a borehole

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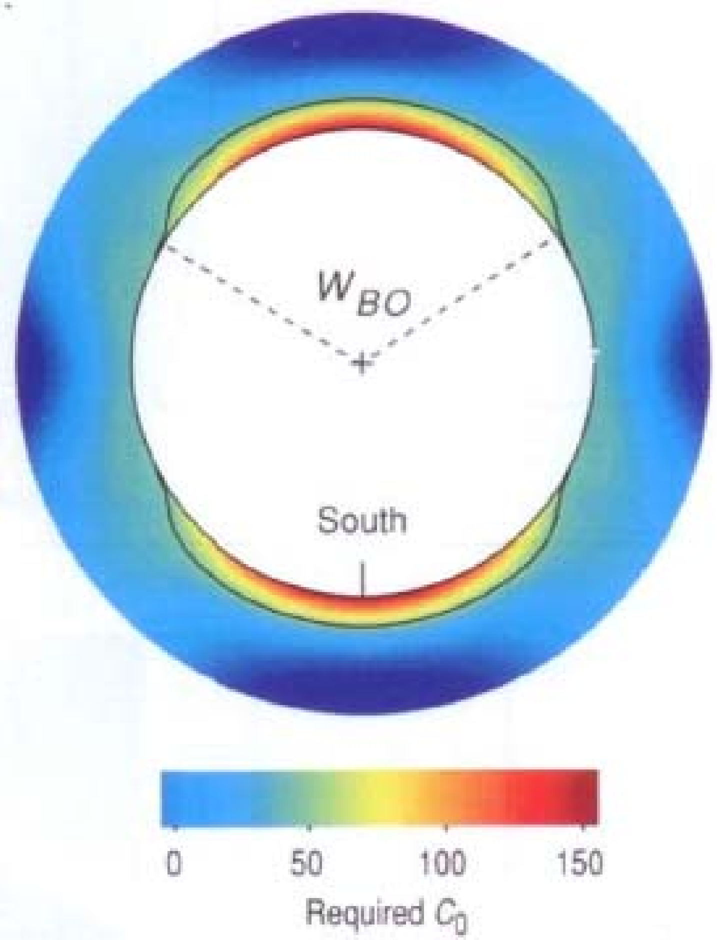
- S_{hmax}=90 MPa, S_{hmin}=51.5 MPa, S_v=88.2 MPa, UCS(C_0) = 45 MPa, μ_i=1.0
- Region of failure
- Color indicate the required UCS to avoid failure

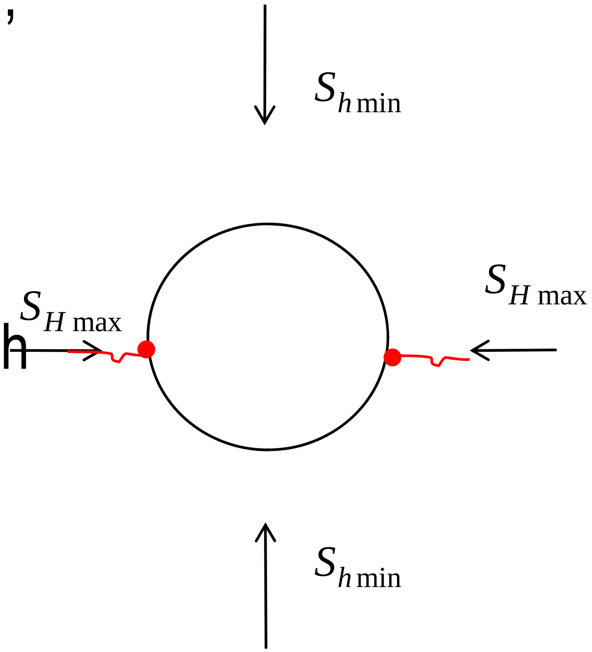


Hydraulic Fracturing
Breakdown Pressure

- At the borehole wall (r = R), maximum and minimum hoop stresses are (without considering temperature effect);

$$\sigma_{\theta,\min} = 3S_{h\min} - S_{H\max} - P_w + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$$

$$\sigma_{\theta,\min} = 3S_{h\min} - S_{H\max} - P_w$$



- Tensile failure occur when hoop stress reach the tensile strength

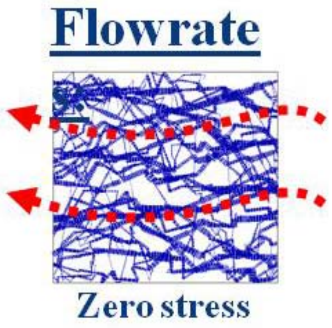
$$-T_0 = 3S_{h\min} - S_{H\max} - P_w$$

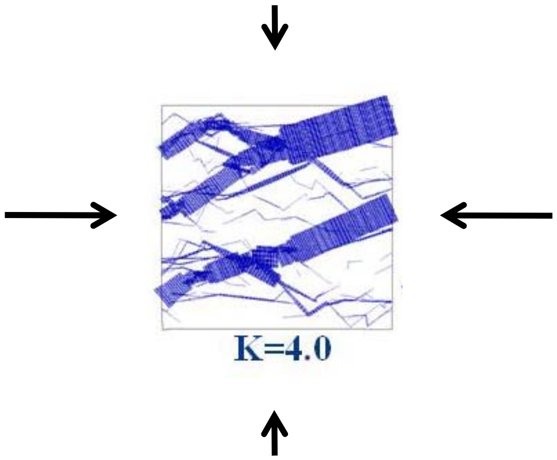
$$P_b = 3S_{h\min} - S_{H\max} + T_0$$

- p_b: breakdown pressure

Hydraulic stimulation

- The fractures created by hydraulic stimulation, which best connect across the reservoir, may not formed through tension. Instead, they are created by shearing on pre-existing joint sets (MIT, 2006).
- Shear failure of fracture occur inclined to the maximum principal stress





Effective Stress

- Pore Pressure

Effective Stress

- Principal assumptions:
  - Interconnected pore system uniformly saturated with fluid
  - Total volume of pore system is small compared to the volume of the rock as a whole
  - We consider;
    - Pressure in the pores
    - The total stress acting on the rock externaly
    - The stresses acting on individual grains (in terms of statistically averaged uniform values)

Effective Stress

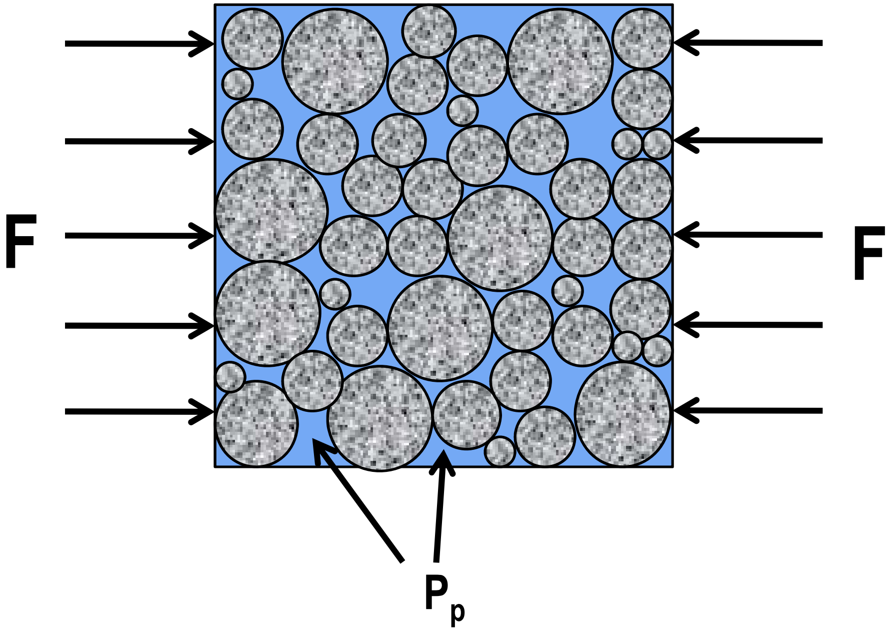
- Behavior of a oil will be controlled by the effective stress (Terzaghi, 1923).

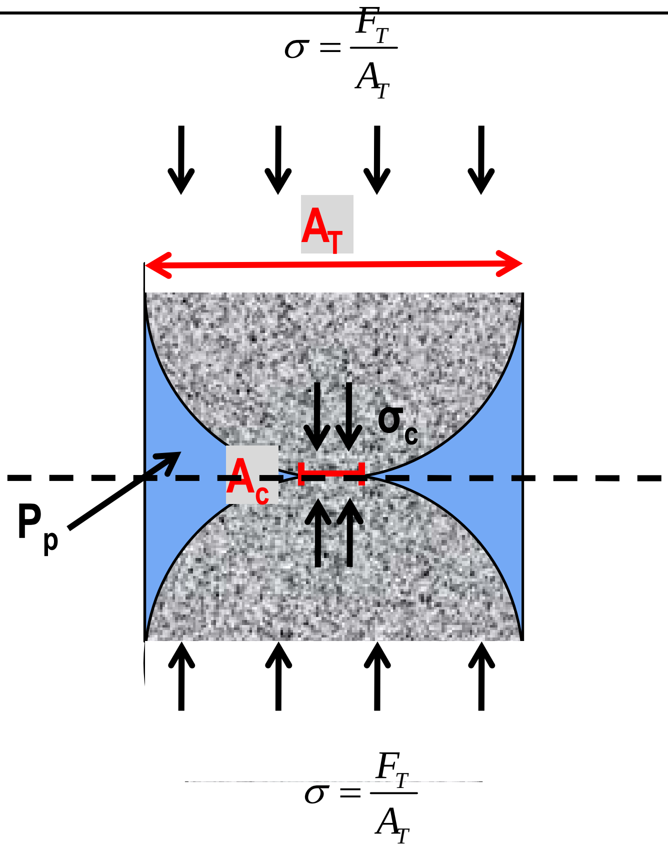
$$\sigma' = \sigma - p$$

$$\sigma'_x = \sigma_x - p \qquad \sigma'_y = \sigma_y - p \qquad \sigma'_z = \sigma_z - p$$

$$\tau'_{xy} = \tau_{xy} \qquad \tau'_{yz} = \tau_{yz} \qquad \tau'_{zx} = \tau_{zx}$$

Effective Stress





- Ac: contact area of grain
- AT: diameter (area) of grain
- σ_c: normal stress acting on the grain contact
- σ_g: normal stress acting on the grain contact = σ'
- p_p: pore pressure

Effective Stress

$$\sigma' = \sigma - p$$

- Exact effective stress law (more general)

$$\sigma' = \sigma - \alpha p$$

$$\alpha = 1 - \frac{K}{K_s}$$

- α: Biot coefficient (0< α <1)
- K: bulk modulus of rock
- Ks: bulk modulus of individual grain
- For nearly solid rock with no interconnected pores (such as quartzite): α= 0
- For highly porous rock (such as uncemented sands): α= 1

Effective Stress

- Physically, this means that the solid framework carries the part σ´ of the total external stress σ while the remaining part *α*p is carried by the fluid.
- Two important mechanism explained by the concept of effective stress
  - Deformation due to the change of pore pressure – subsidence and heaving of rock
  - Rock or fracture failure due to the increased pore pressure

Effective stress

deformation by effective stress

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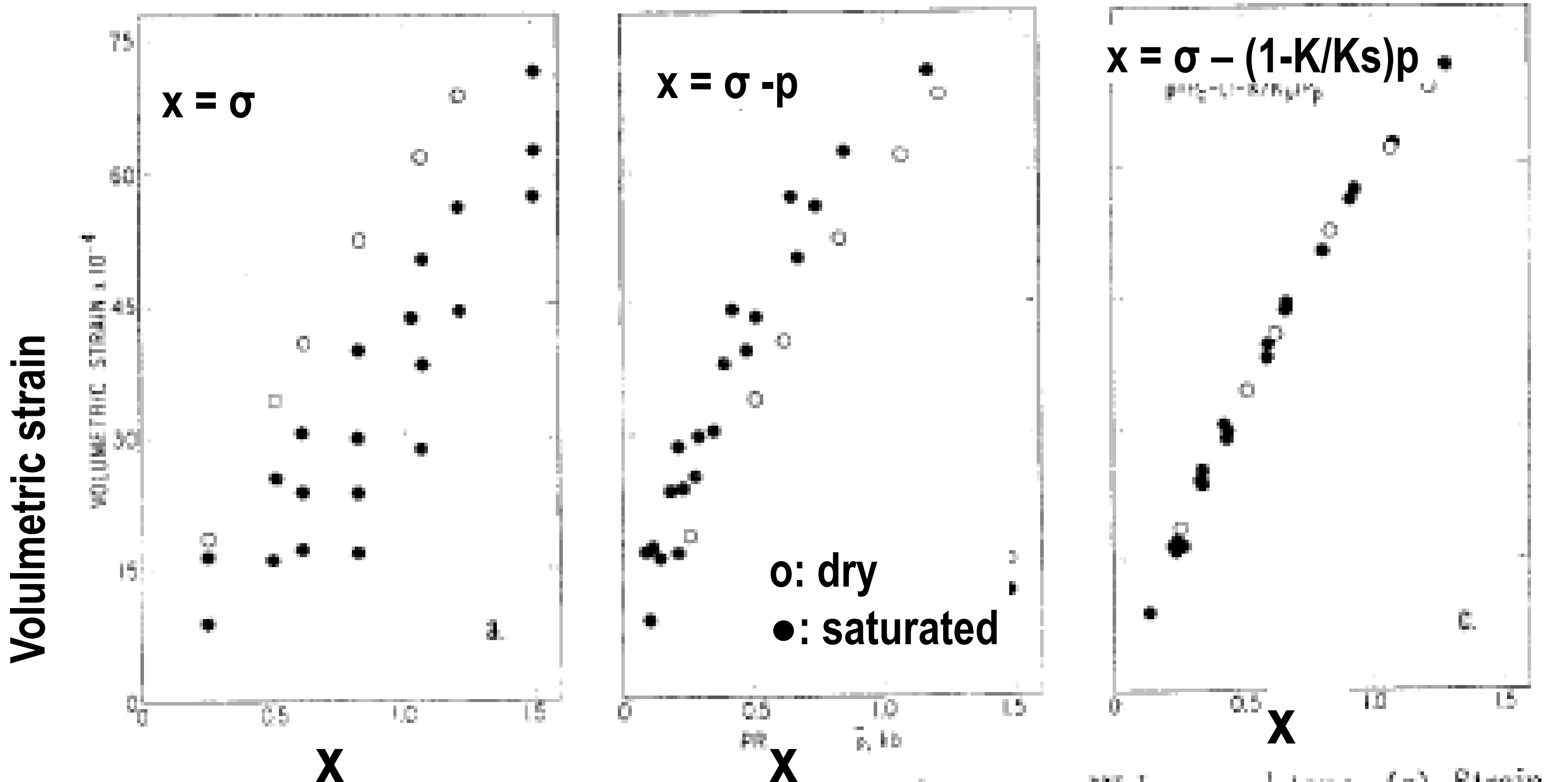

Fig. 2. Volumetric strain versus effective stress in porous Weber sandstone. (a) Strain versus confining pressure. (b) Strain versus the difference between confining and pore pressures. (c) Strain versus theoretical effective pressure. The open circles show the strain versus confining pressure in a dry confined sample.

- Volulmetric strain versus effective stress in porous Weber sandstone (Nur and Byerlee, 1971)

Effective stress
failure induced by pore pressure increase

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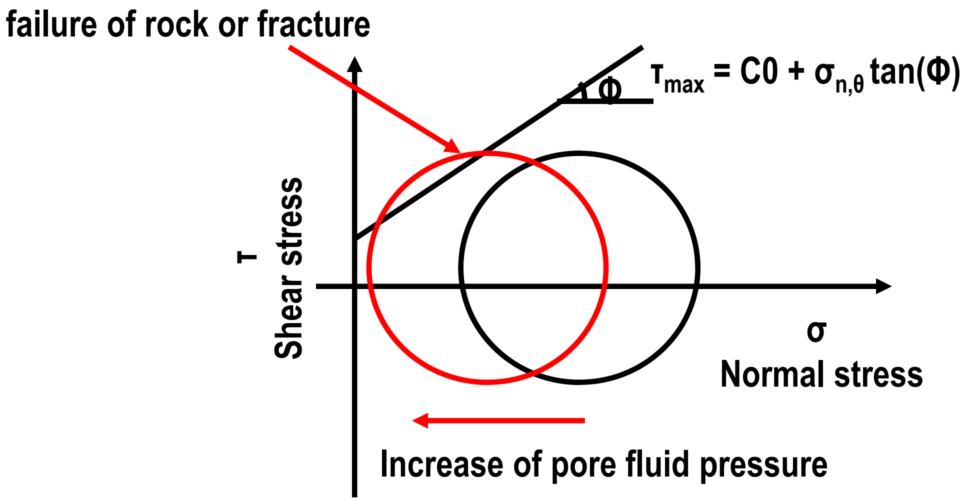
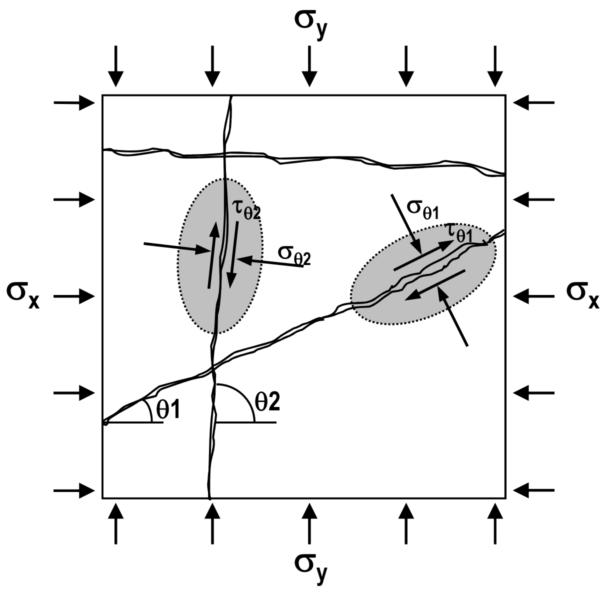
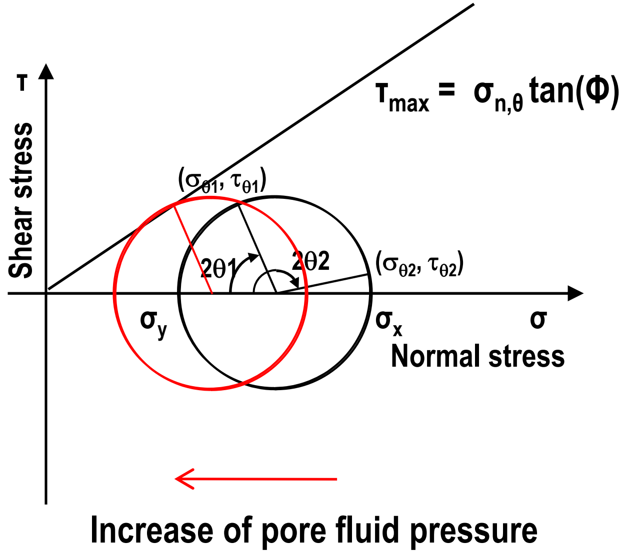


- Increase of pore pressure induce failure of intact rock

Effective stress
failure induced by pore pressure increase





- Cohesion (C0) of fracture is negligible and tends to have lower friction coefficient or friction angle ($\mu = 0.6 \sim 1$).

Effective stress
failure induced by pore pressure increase

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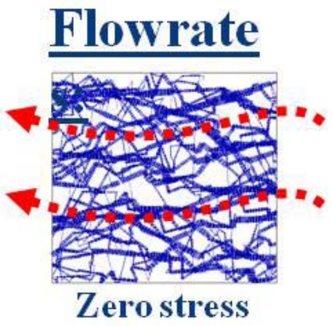

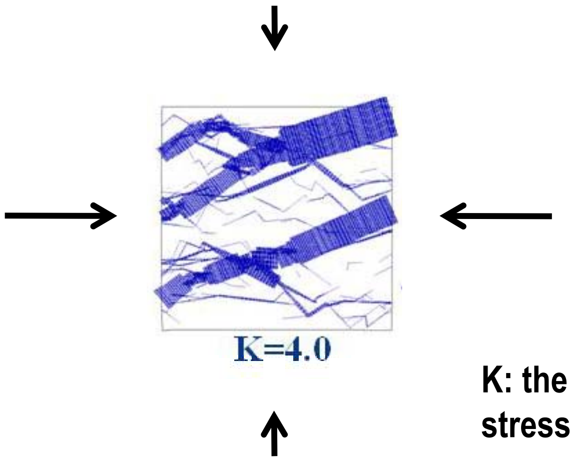

K: the ratio of horizontal stress to vertical stress

- Increase of anisotropy of stress (this is in fact similar effect to increasing pore pressure) → Shear sliding of fracture → Dilation of fracture → Change of fluid flow
- As a method of hydraulic stimulation, this mechanism is receiving more attention than the mechanism of hydrofracturing.

Min et al. (2004)

Reservoir Compaction and Subsidence

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- Reservoir compaction and associated surface subsidence – best-known example of geomechanical effect in reservoir scale

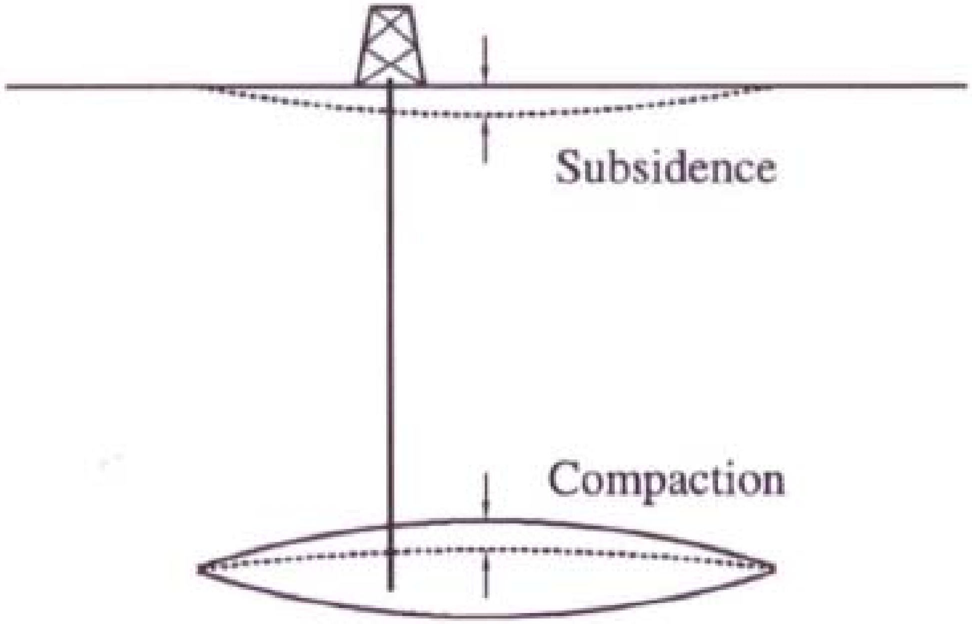

Fig. 12.1. Compaction and subsidence.

Fjaer et al., 2008

Reservoir Compaction and Subsidence

- Reservoir geomechanics is an important part of (geothermal) reservoir management.
- Geothermal fluid is extraction (or oil/gas is produced) from a reservoir → fluid pressure will decline → increase the effective stress → the reservoir will compact (shrink) → subsidence at the surface.
- Change of effective stress can also affect the fluid flow performance (via change of permeability/ porosity)
- Stress change triggers seismicity during reservoir depletion

Reservoir Compaction and Subsidence

- Most reservoir will experience a small degree of compaction.
- For a considerable degree of subsidence;
  - Reservoir pressure drop must be significant (pressure maintenance such as injection may counteract compaction)
  - The reservoir must be highly compressible → More important in soft rock.
  - The reservoir must have a considerable thickness
  - No shielding by the overburden rock
- Wilmington field in California: 9 m subsidence (Fjaer, 2008)

Reservoir Compaction and Subsidence
Uniaxial reservoir compaction

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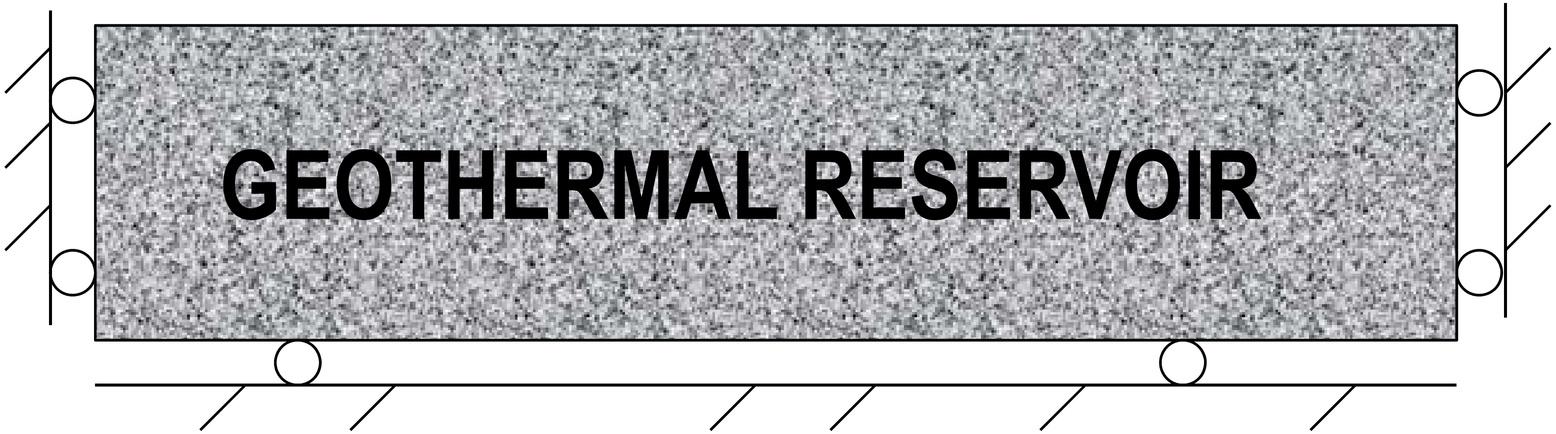
- In homogeneous and isotropic rock,

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} \frac{1}{E} & -\frac{\nu}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & \frac{1}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & -\frac{\nu}{E} & \frac{1}{E} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G} \end{pmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix}$$

Reservoir Compaction and Subsidence
Uniaxial reservoir compaction

- Compaction coefficient or unaxial compressibility, Cm;

$$\frac{\Delta h}{h} = -C_m \alpha \Delta p = -\frac{1}{E}\frac{(1+\nu)(1-2\nu)}{1-\nu}\alpha\Delta p$$



Reservoir Compaction and Subsidence
Uniaxial reservoir compaction/realistic case

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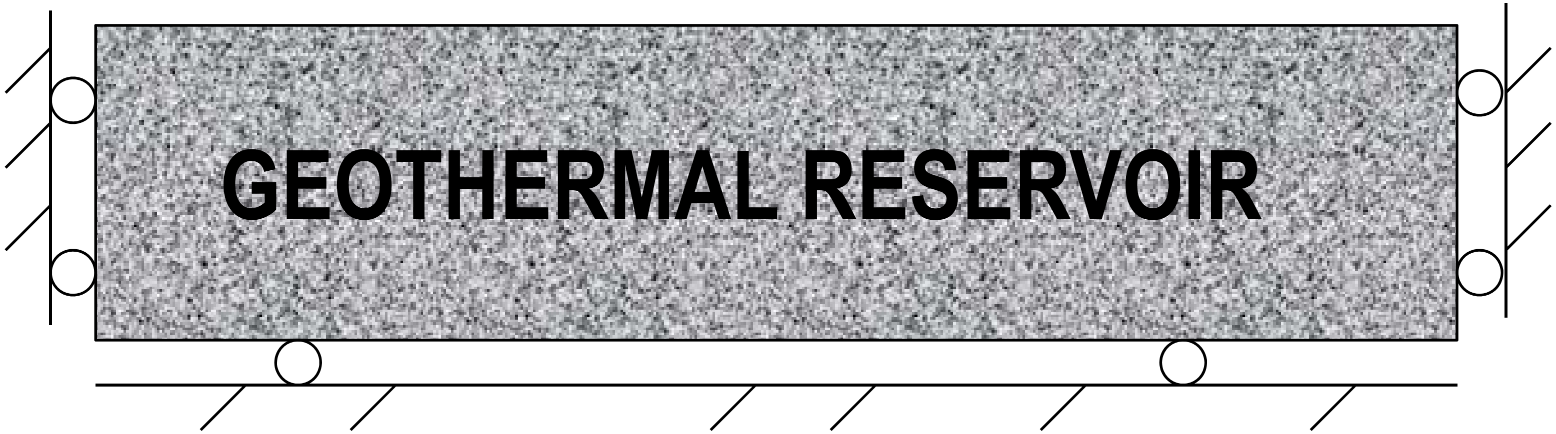
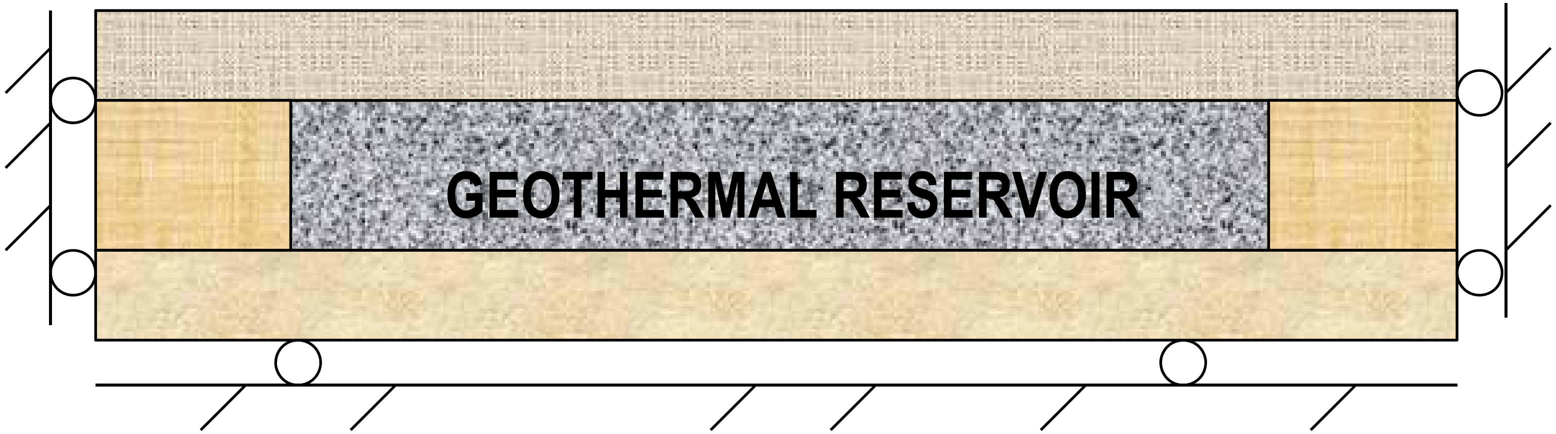
- Simplification



- Reality



Reservoir Compaction and Subsidence

Uniaxial reservoir compaction/realistic case

- Normally we don’t have uniform distribution of;
  - Pressure/mechanical properties
  - And the reservoir geometry is complex
- We would need more sophisticated model, which usually is numerical simulation.

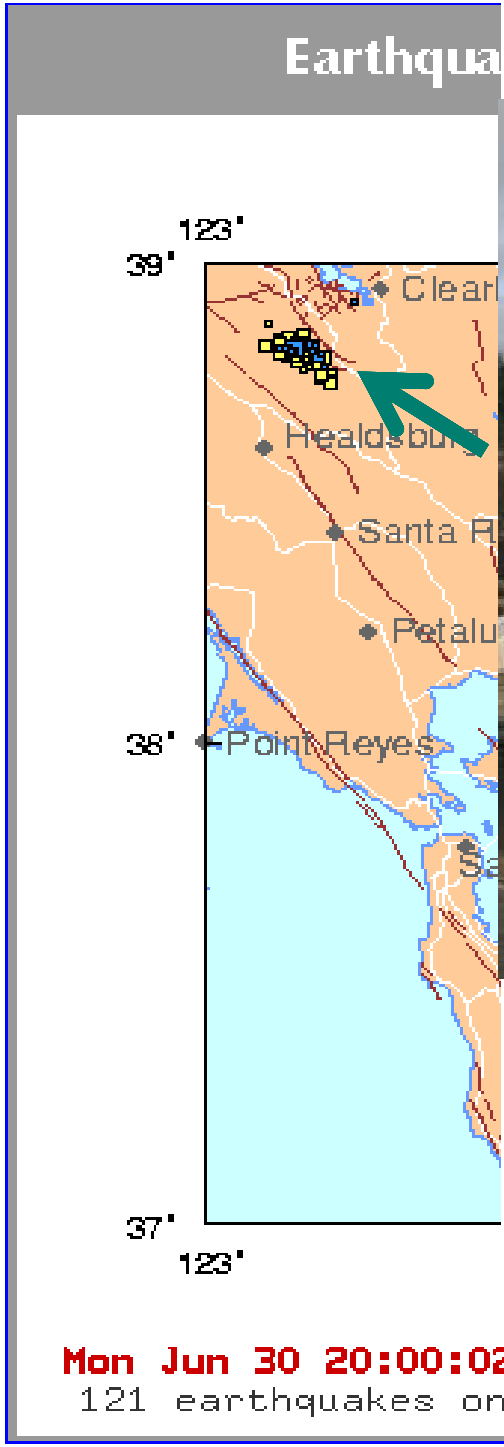
Reservoir Geomechanics

An example from Geysers Field in California

A study on Geysers Geothermal Steam Field, California, USA

With the courtesy of Dr Jonny Rutqvist, Lawrence Berkeley National Laboratory, USA

The Geysers Geothermal Field



- The largest geothermal electricity generating operation in the world (850 MW)
- Also one of the most seismically active regions in northern California

The Geysers Geothermal Field

- A vapor dominated geothermal reservoir system, which is hydraulically confined by low permeability rock units

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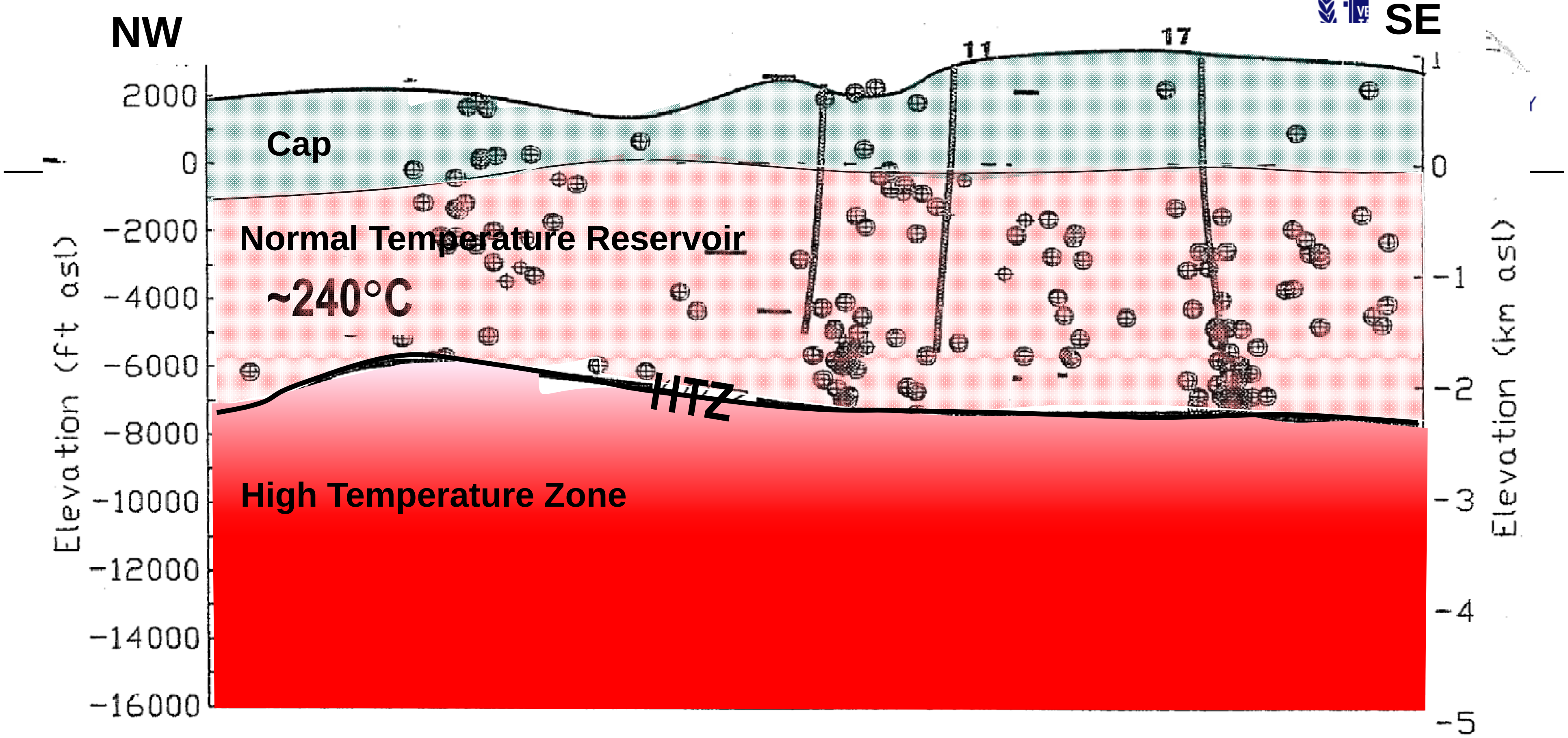
- High rate of steam withdrawal resulted in reservoir pressure decline until the mid 1990s, when increasing water injection stabilized the steam reservoir pressure
- If The Geysers were produced without simultaneously injecting water, reservoir pressures and flow rates from production wells would decline fairly rapidly
- However, the water injection has also resulted in an increased level of seismicity at The Geysers, which has raised concerns in the local communities
- For public acceptance, a good understanding of the causes and mechanisms of induced seisimicity at The Geysers is important

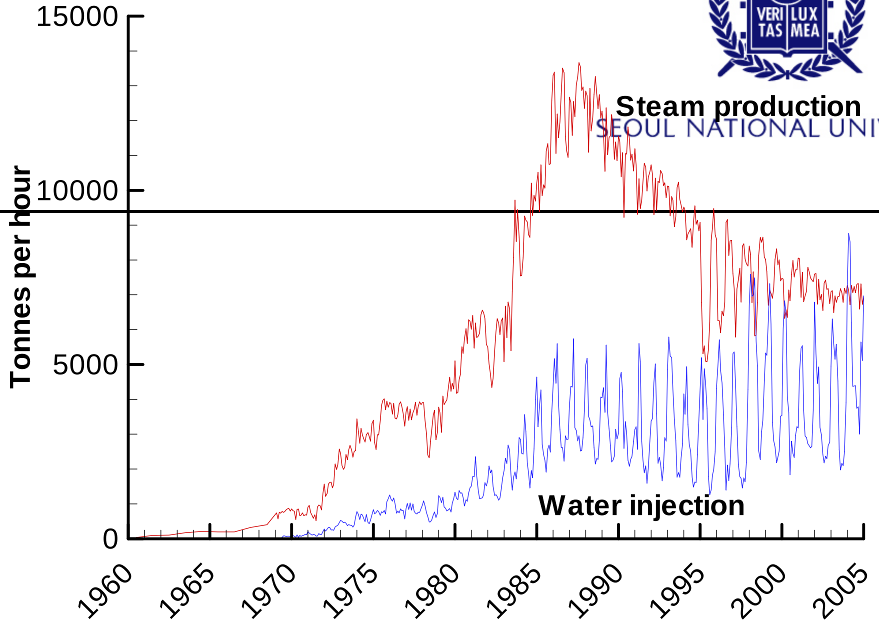
Micro-Earthquakes at The Geysers

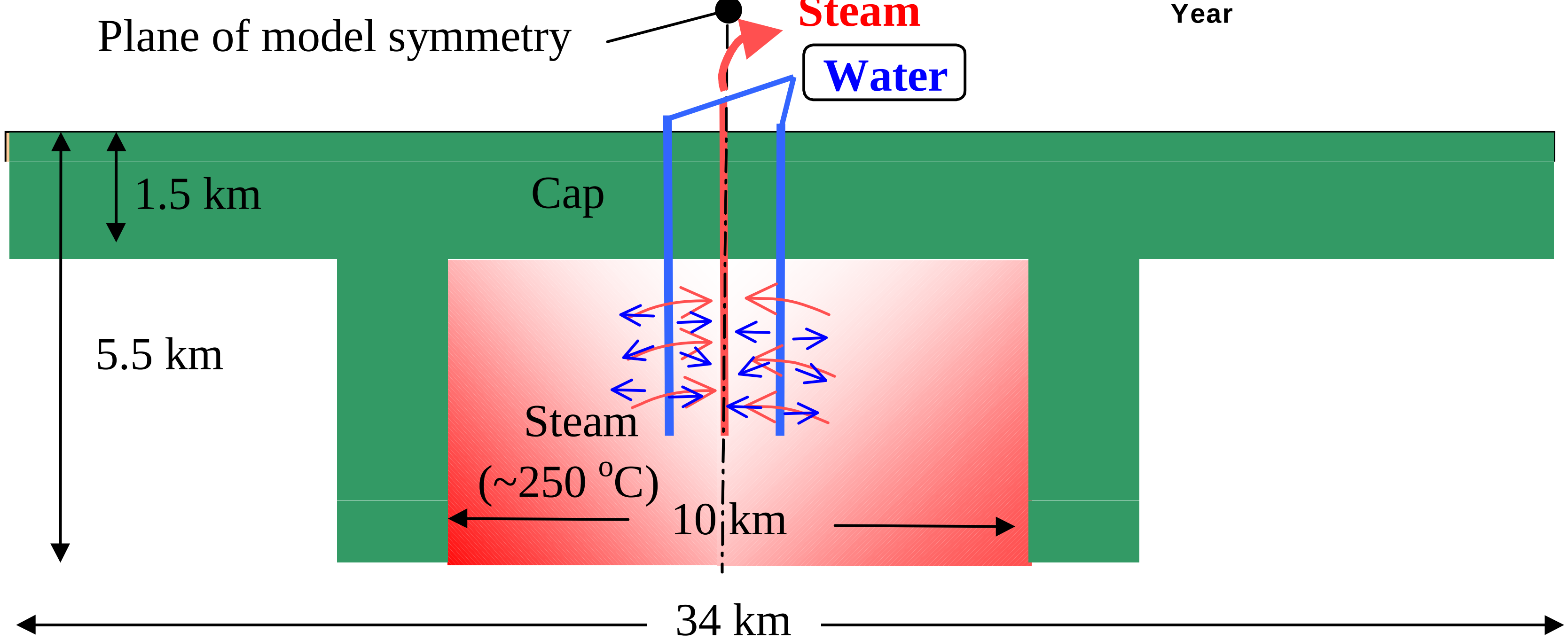


NW-SE cross-section through The Geysers geothermal field showing 2002 MEQ hypocenters, injection wells, power plants, and top of the High Temperature Zone (HTZ) (Stark, 2003).

- **Injection-induced seismicity is typically clustered around injection wells, extending downward in plume-like forms (several km).**
- **Time lag between seasonal injection cycles and seismicity (<2 months).**

COUPLED RESERVOIR AND GEOMECHANICAL MODELING





ANALYSIS OF 44 YEARS PRODUCTION/INJECTION

The simulation broadly models the pressure and temperature decline, and settlement that has been observed at the Geysers (e.g., Williams, 1992, Mossop and Segall, 1997, 1999):

- **Reservoir steam pressure and temperature declines a few MPa and a few degrees, respectively**
- **Settlement of about 0.5 to 1 meter caused by poro-elastic contraction, with a small contribution from thermo-elastic contraction**

Rock mass bulk modulus = 3 GPa (Consistent with Mossop and Segall, 1997, 1999)

Thermal expansion coefficient = 3×10^{-5} °C^{-1} (Corresponds to values determined on core samples of reservoir rock at high temperature (Mossop and Segall, 1999)

⇒ Calculated thermal-elastic and poro-elastic responses are reasonable ⇒ use the model to evaluate potential for induced seismicity using a shear failure analysis

SURFACE DEFORMATIONS FROM SATELLITE (1992-1999)

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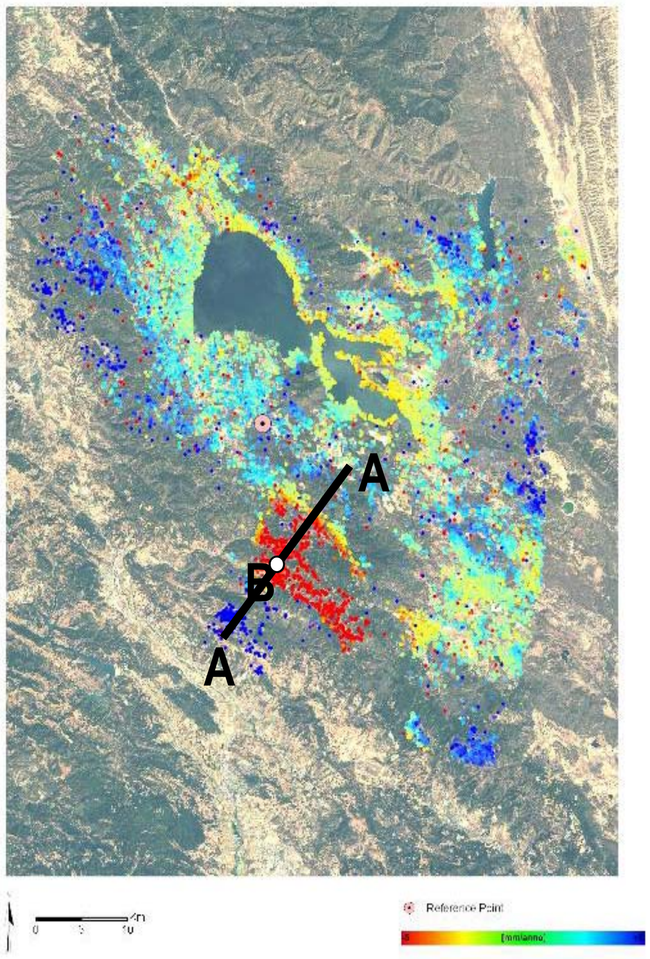
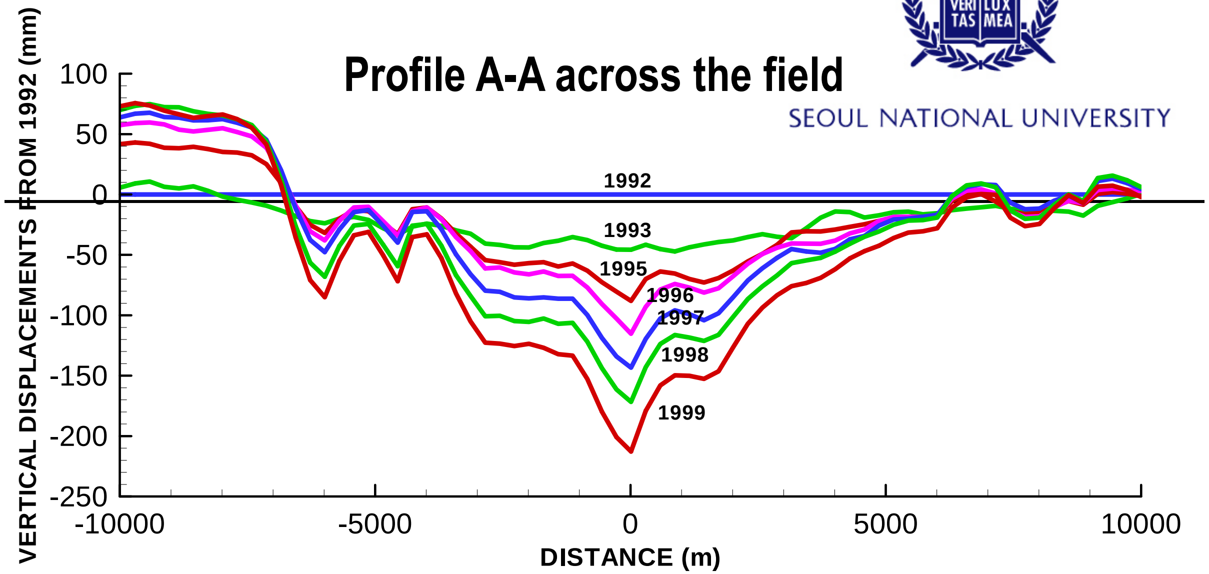
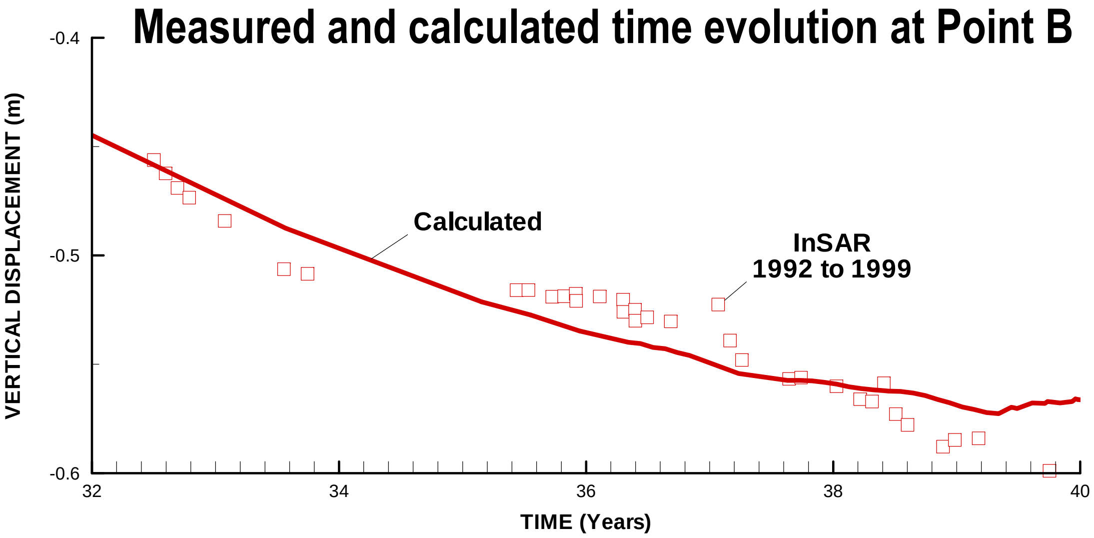


Yearly average deformation -5 (red) to +5 (blue) mm/year

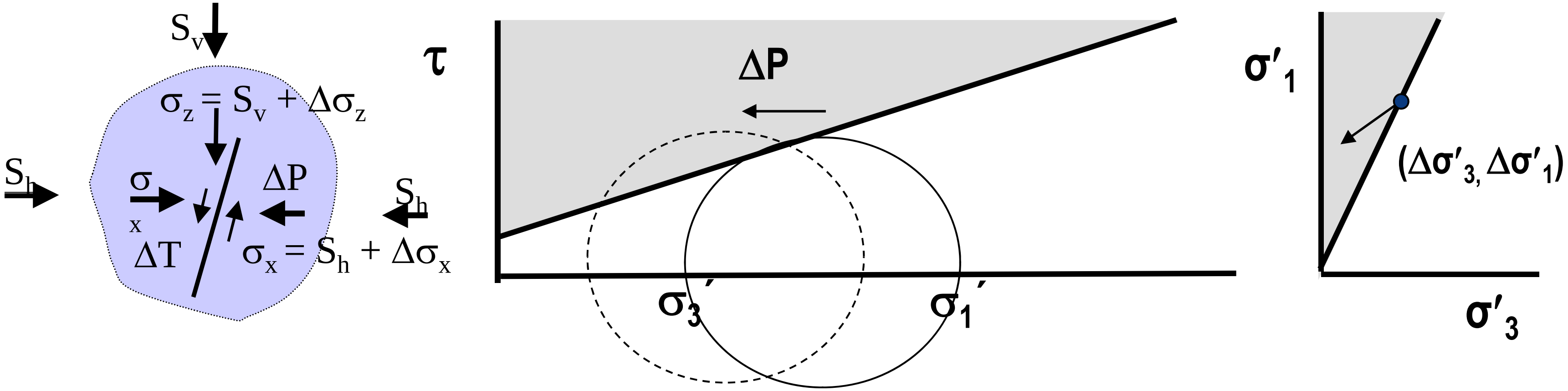

Profile A-A across the field


Measured and calculated time evolution at Point B

SHEAR-FAILURE ANALYSIS

- Previous studies indicate that shear stress in the region is probably near the rock-mass frictional strengths and that a small perturbation of the stress field could trigger seismicity (e.g. Lookner et al., 1982, Oppenheimer, 1986)

Fractures on the verge of shear-failure : $\sigma_1' = \sigma_{1c}' = 3\sigma_3'$

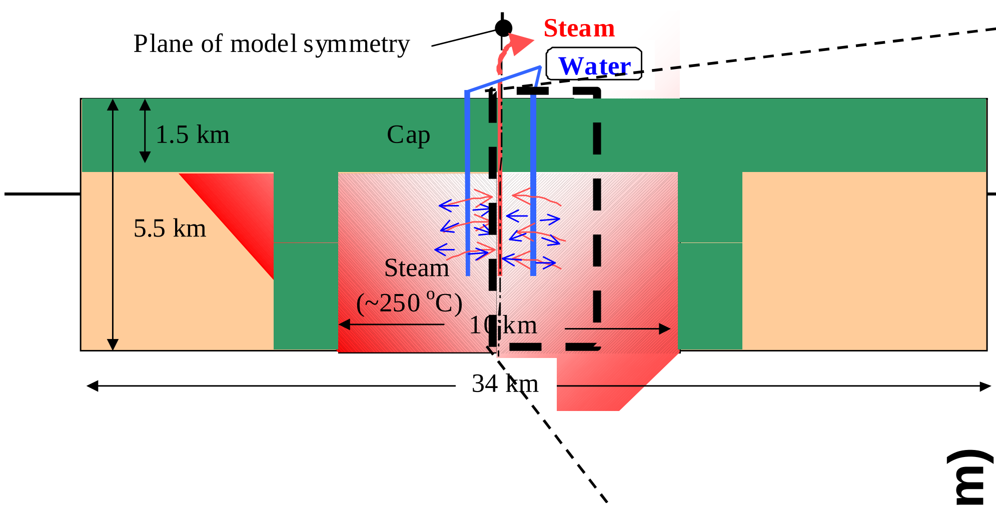


⇒ we analyze changes in the effective principal stress state at the site and evaluate whether the stress state moves toward failure or away from failure:

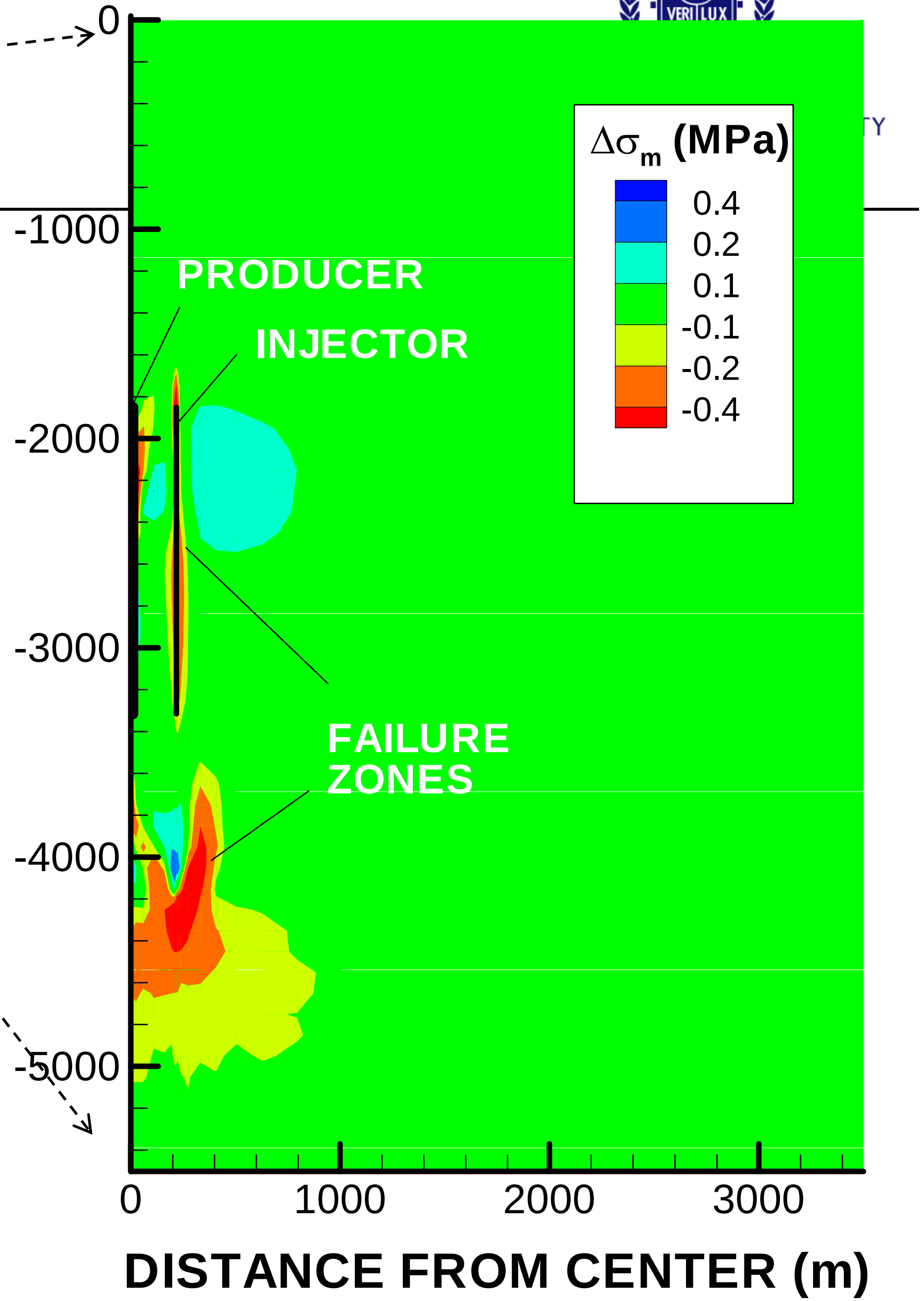
$\Delta\sigma'_1 \geq 3\times\Delta\sigma'_3 \Rightarrow$ stress state moves toward failure

$\Delta\sigma'_1 < 3\times\Delta\sigma'_3 \Rightarrow$ stress state moves away from failure

POTENTIAL FOR INDUCED SEISMICITY (STRESS STATE)



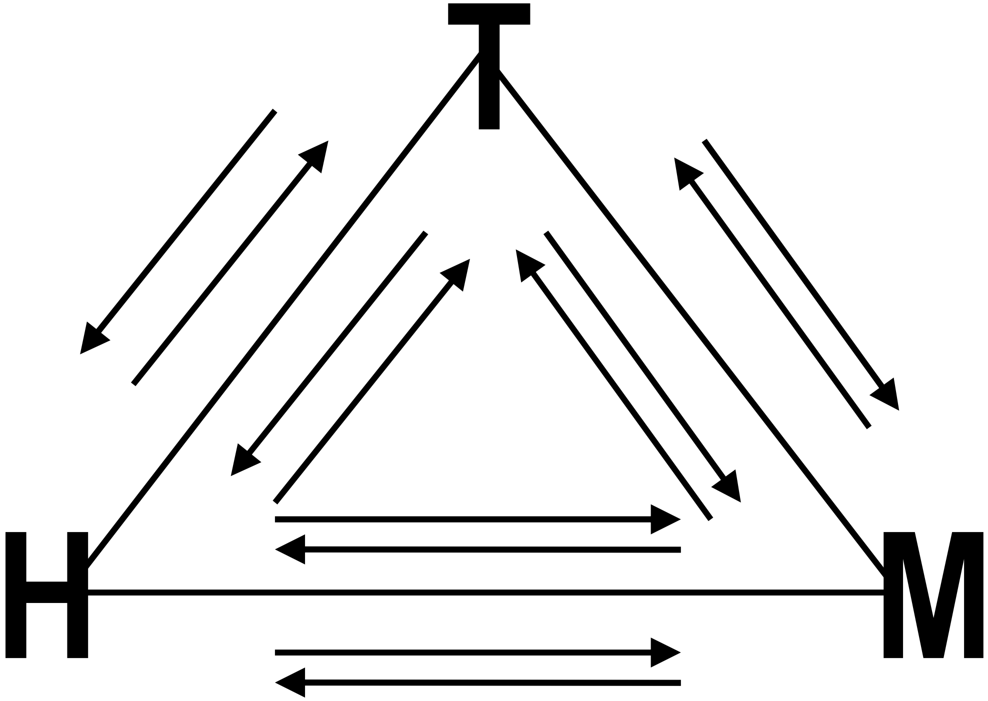
- **Near well bore induced seismicity caused by cooling shrinkage due to coldwater injection.**
- **Explains induced seismicity occurring several km below injection as being caused by the combined effect of cooling shrinkage and fluid pressurization by the downward migration of coldwater within the fractured steam reservoir**



Summary of Coupled process

- Thermal process (T)
- Hydraulical process (H)
- Mechanical process (M)
- TH
- TM
- HM

Summary of Coupled process



Today

- Reservoir Geomechanics
  - Effective stress
    - Deformation due to effective stress
    - Failure induced by effective stress
  - Coupled Process

References

- Zoback MD, 2007, Reservoir Geomechanics, Cambridge University Press
- Fjaer E et al., 2008, Petroleum-related Rock Mechanics, 2nd Ed., Elsevier
- Min KB, Rutqvist J, Tsang CF, Jing L. Jing, 2004, Stress-dependent permeability of fractured rock masses: a numerical study, *International Journal of Rock Mechanics & Mining Sciences*; 41(7):1191-1210