Enhanced Geothermal Systems (EGS)
- Its concepts and the state of the art

Week 1, 2 Sept 2013
Ki-Bok Min
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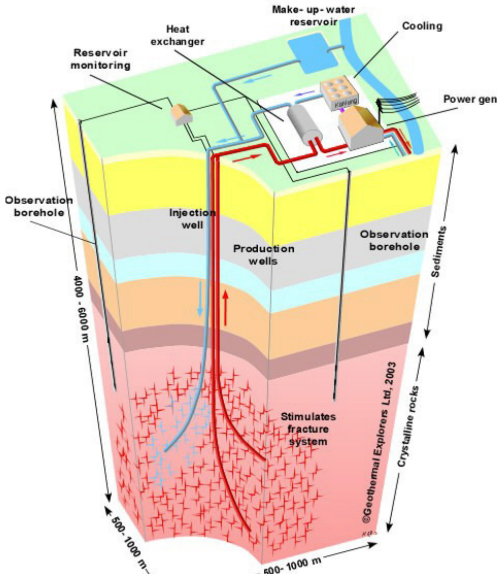
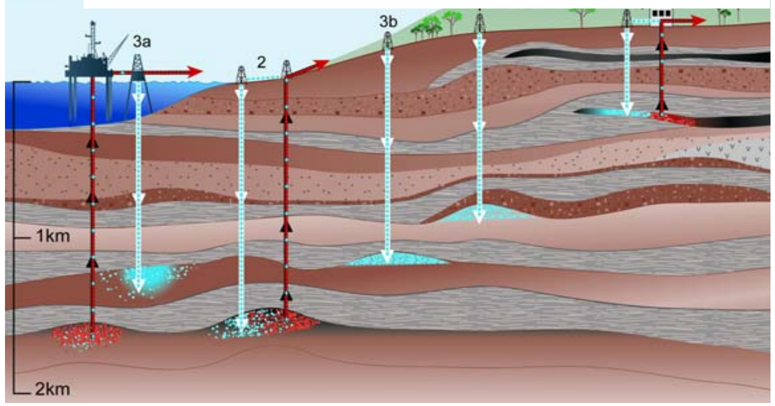
Introduction
Geothermal Energy and subsurface Engineering of environmental importance

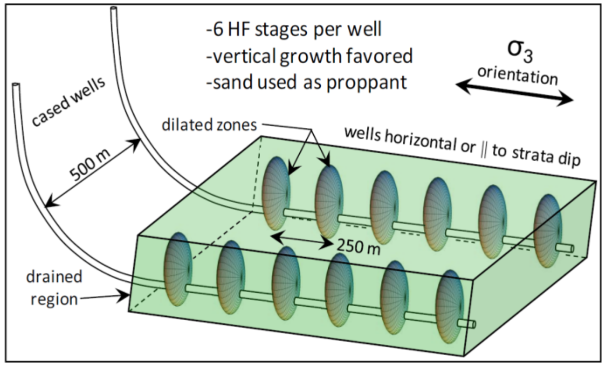


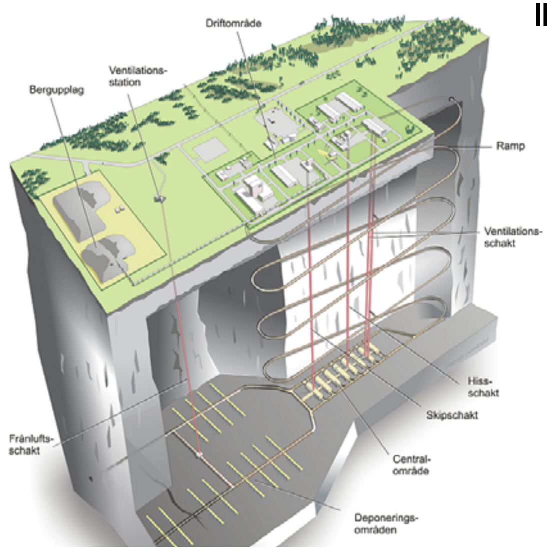
Geothermal Explorer, 2010

CO2 geosequestration



IPCC, 2005





SBK, 2010

Underground repository of nuclear waste

Outline

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- Introduction : Climate Change and Energy
- Enhanced Geothermal Systems
  - Definition
  - Status and History
  - Hydraulic Stimulation/Microseismicity
  - Achievement and Remaining issues
- Concluding remarks

Climate Change and Subsurface Eng
Introduction

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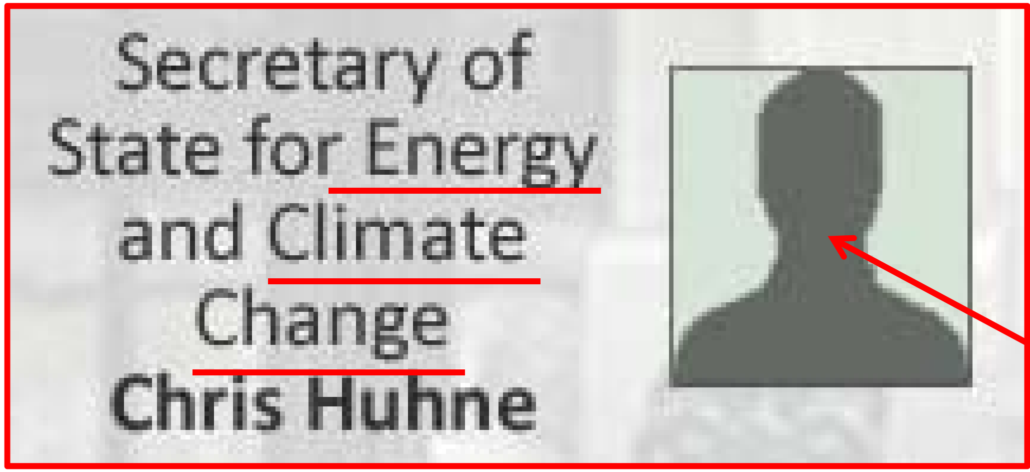
- Driving forces for Subsurface Engineering
  - Climate Change – Global Demand
  - National Energy Security
  - Alternatives for Conventional Fossil Fuel – Renewable Energy and Unconventional Resources (shale gas, oil sand, gas hydrates, …)
  - Infrastructure and natural hazard (Tunnel, Slope stability…)

Climate Change and Subsurface Eng
Government organization - UK



http://www.direct.gov.uk/en/prod_dg/groups/dg_digitalassets/@dg/documents/digitalasset/dg_187701.htm

Climate Change and Subsurface Eng
Government Organization - Australia

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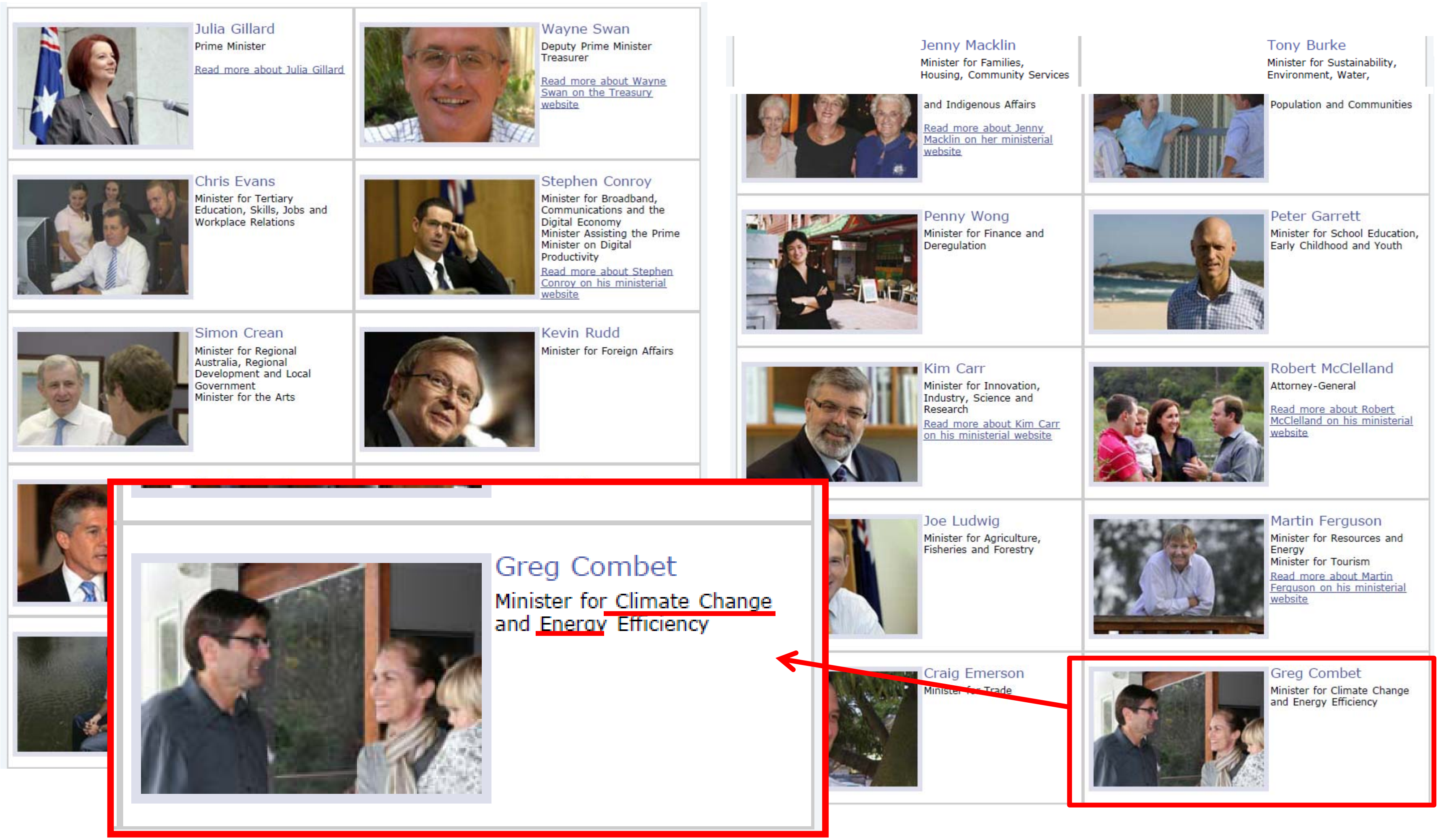

http://www.pm.gov.au/The_Ministry/Cabinet

Climate Change and Subsurface Eng
Government Organization - USA

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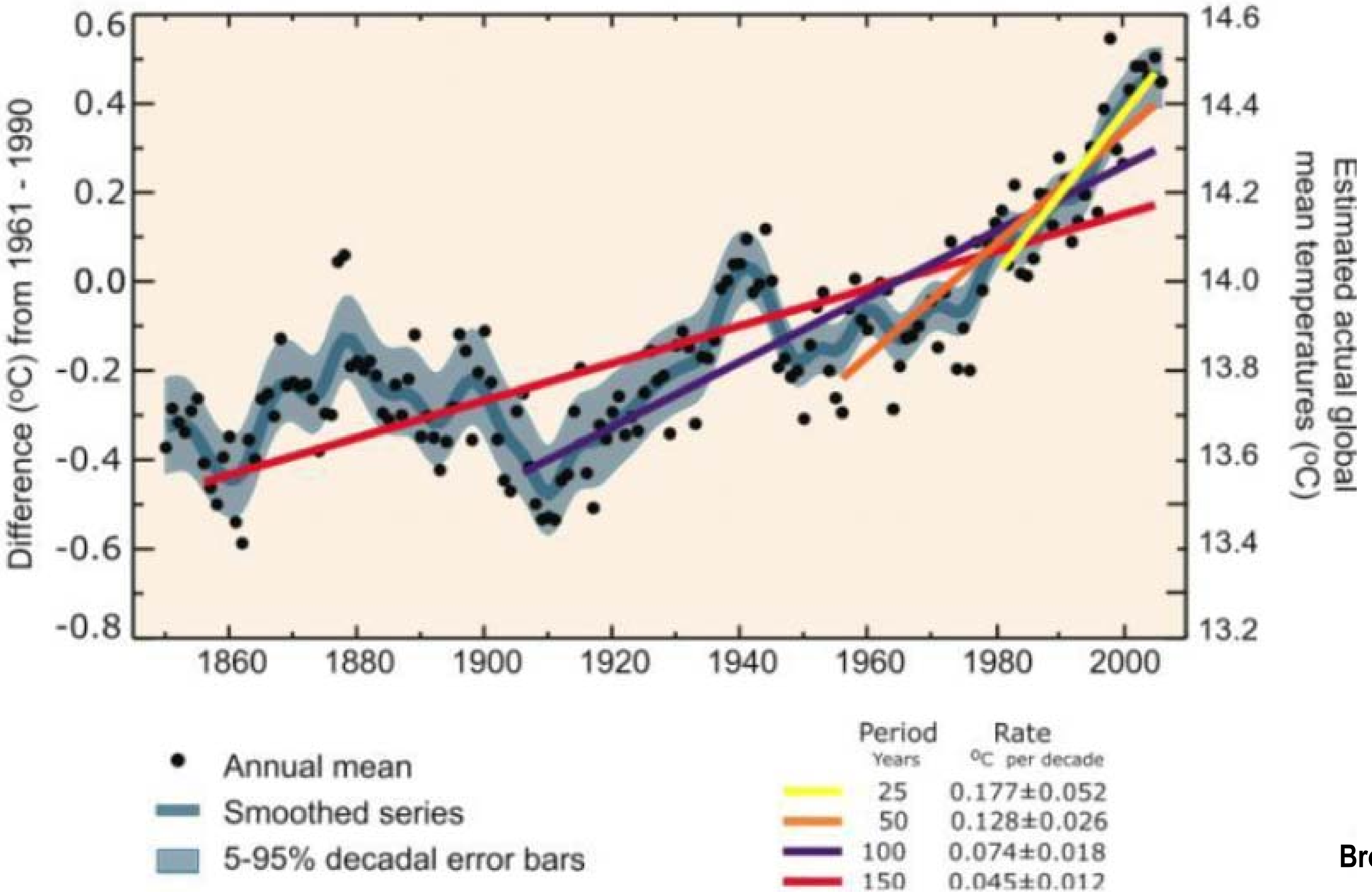
Dr Steven Chu
Secretary of Energy
Department of Energy

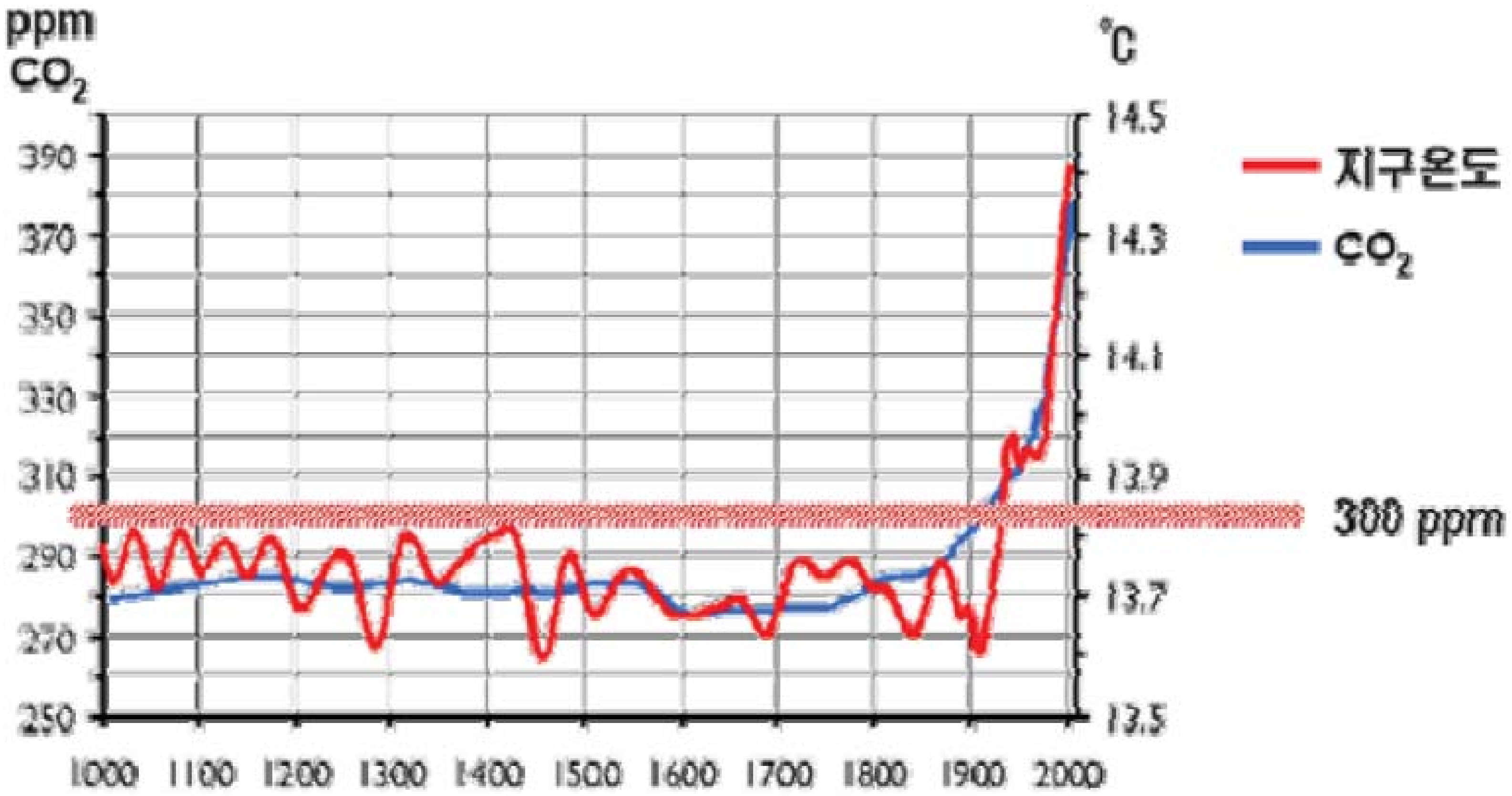
http://www.whitehouse.gov/administration/cabinet/

Climate Change and Subsurface Eng
Global Warming



Brook, 2008

Climate Change and Subsurface Eng
Global Warming and CO2 concentration



- Global Warming is a function of CO2 concentration.

이윤우, **2010**

Climate Change and Subsurface Eng
Technology needed for CO2 emission

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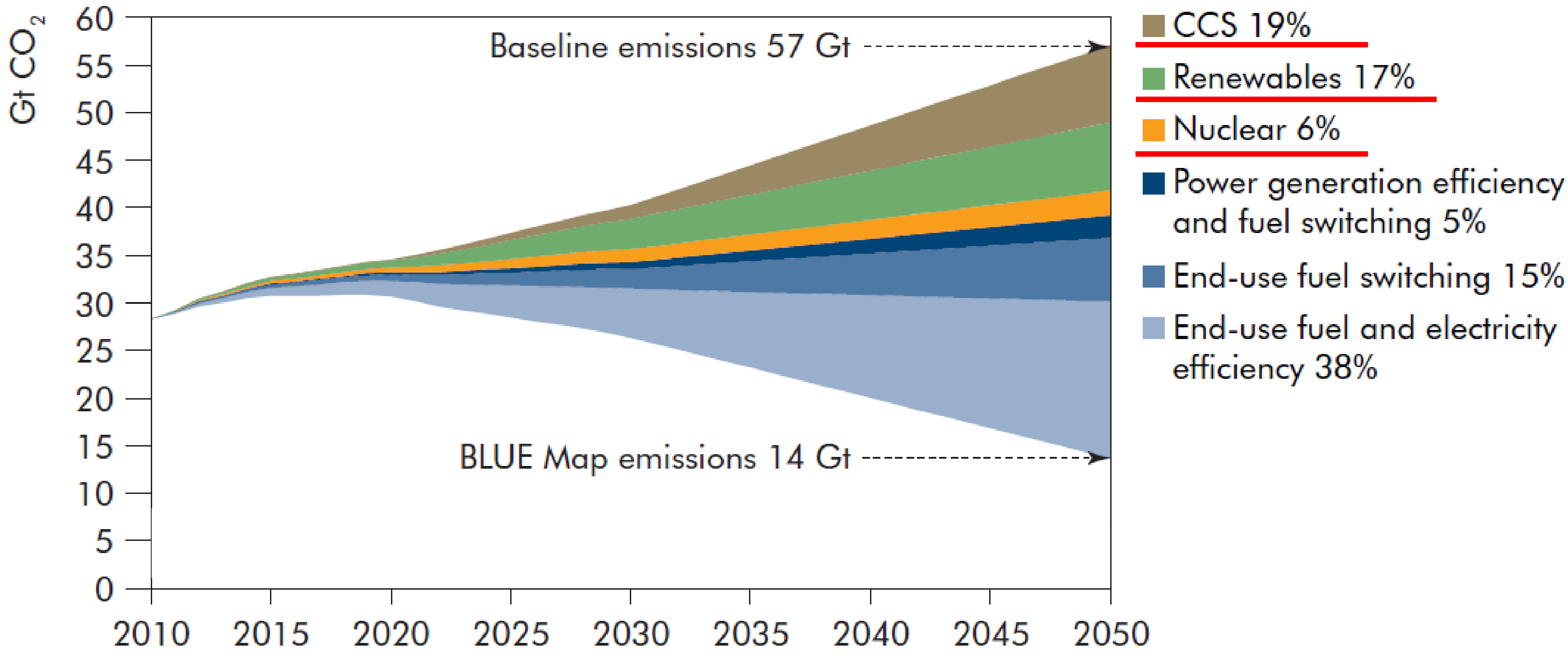
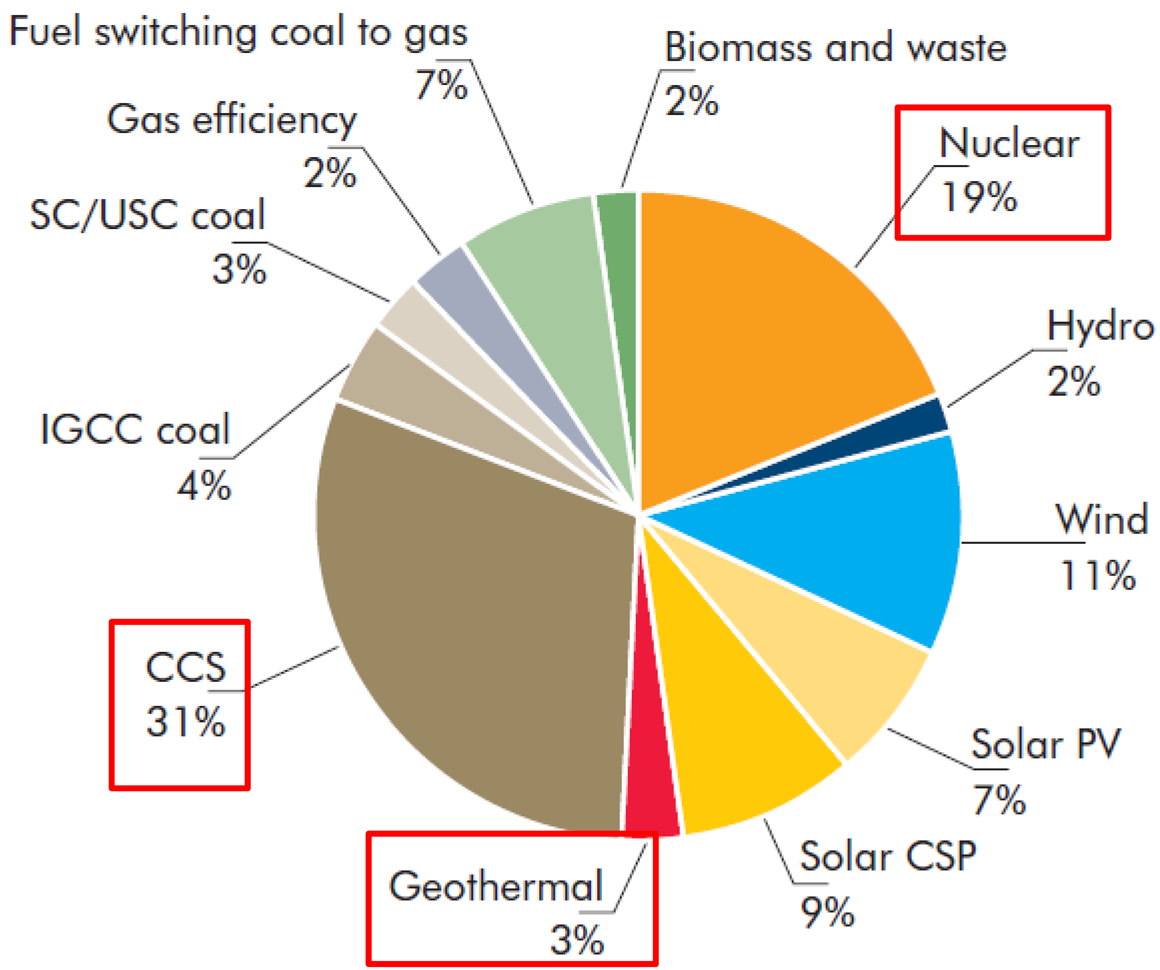


- Subsurface Engineering plays a key role in reducing CO2 emissions – CCS, Renewables, Nuclear (waste disposal)

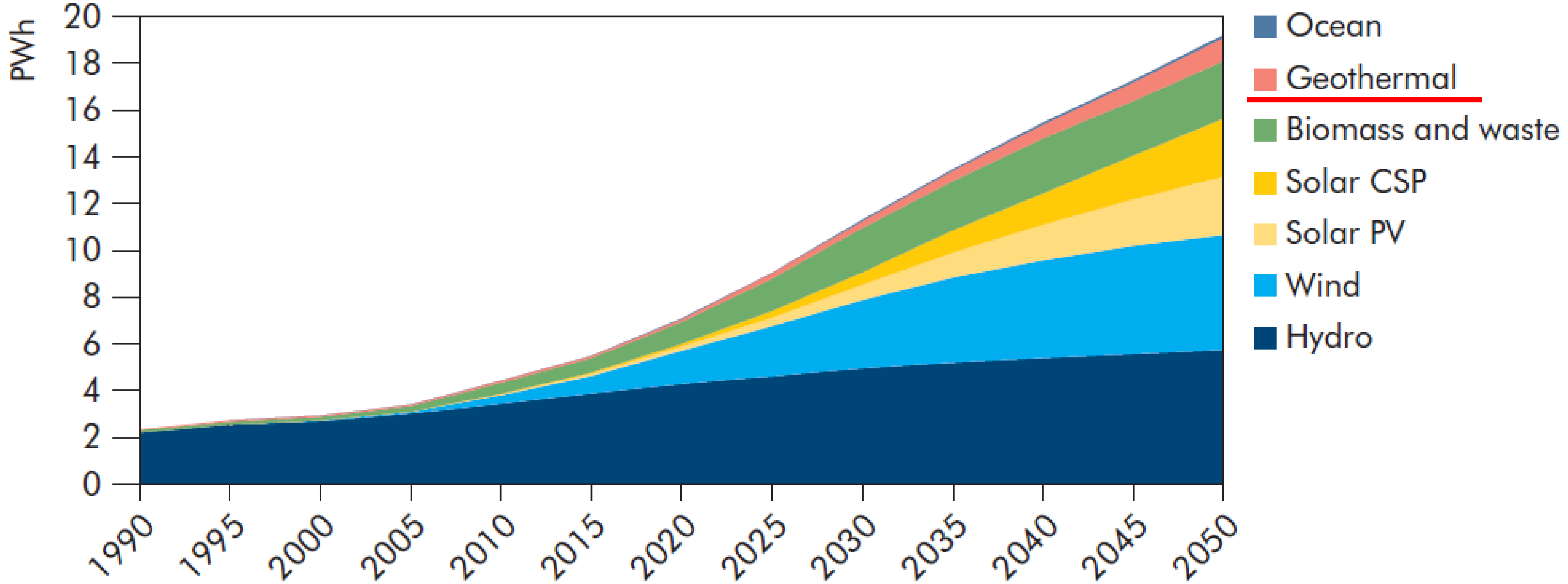
IEA, 2010, Energy Technology Perspective

Climate Change and Subsurface Eng
Contribution from different power sector technologies



IEA, 2010, Energy Technology Perspective

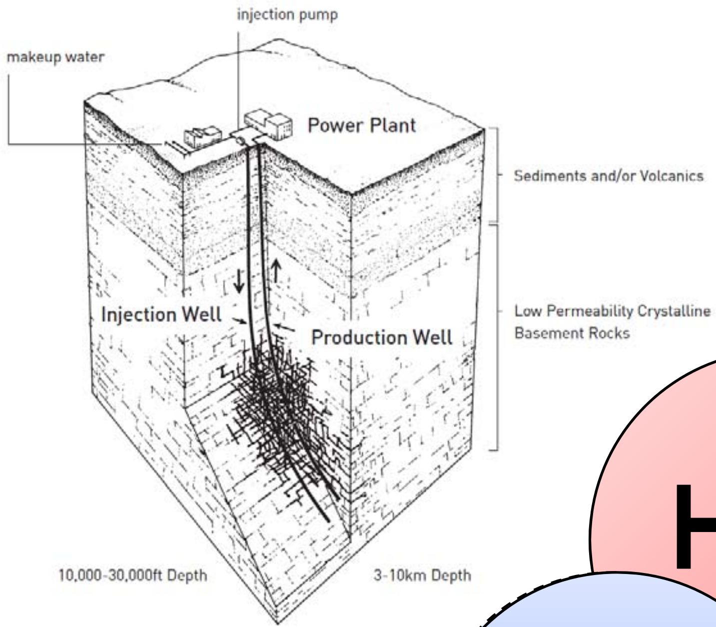
Climate Change and Subsurface Eng
Growth of renewable power generation

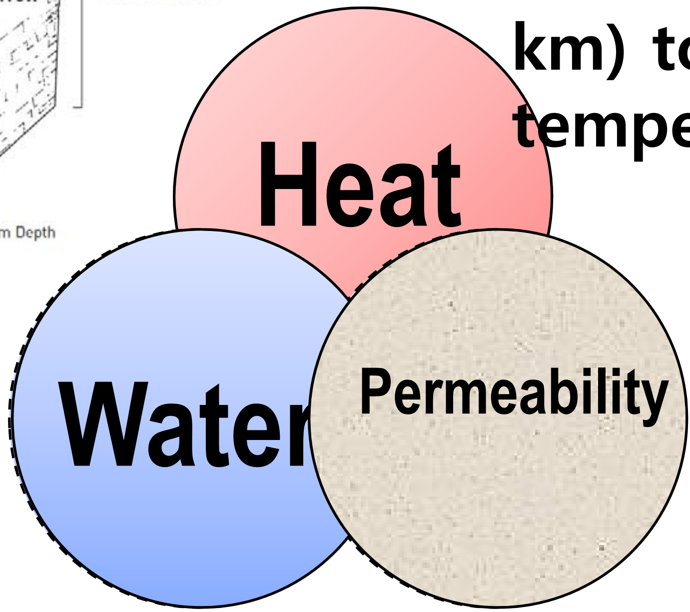


IEA, 2010, Energy Technology Perspective

Background and Motivation

Enhanced Geothermal Systems (인공저류층 지열시스템)





Drill a deeper borehole (3~7 km) to reach a target temperature

- Provide water through injection

Artificially generate geothermal reservoir by hydraulic stimulation

Enhanced Geothermal System
Definition

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- EGS: Enhanced (or Engineered) Geothermal System
- Broader definition: A system designed for primary energy recovery using heat-mining technology, which is designed to extract and utilize the Earth's stored thermal energy (Tester et al., 2006)
- Narrower definition (also called HDR, Hot Dry Rock, or HFR, Hot Fractured Rock): A geothermal system that requires hydraulic stimulation to improve the permeability.

실증현장 요약

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프로젝트	기간	시추공	온도	주체/지원	현황
영국 Rosemanowes	1977 – 1991	RH11 (2.0 km) RH12 (2.0 km) RH15 (2.6 km)	100 °C @2.6 km	주체: Camborne School of Mines (CSM) 지원:UK DOE	1991년 중단 후 재개노력중 (Eden Project)
프랑스 Soultz	1987 - 현재	EPS1 (2.2 km) GPK1 (3.6 km) GPK2 (5.1 km) GPK3 (5.1 km) GPK4 (5.3 km)	200 °C @5.0 km	주체: GEIE 지원: EU(~2009년) /독일/프랑스	2008년6월 첫 발전*, 현재 ~500kW
호주 Cooper Basin	2003 – 현재 (Habanero 1 시추 기준)	Habanero 1 (4.4 km) Habanero 2 (4.5 km) Habanero 3 (4.2 km) Savina 1 (3.7 km) Jolokia 1 (4.9 km) Habanero 4 (4.2 km)	247 °C @4.4 km 278 °C @4.9 km	민간: Geodynamics/Origin (7:3) 정부: 90m$ (전체의 1/3)	2012년 Habanero 4 Open flow test 완료 (35 kg/s)

*Genter, A., X. Goerke, J.-J. Graff, N. Cuenot, G. Krall, M. Schindler, and G. Ravier. "Current Status of the Egs Soultz Geothermal Project (France)." In *Proc World Geothermal Congress, Paper No.3124. Bali, Indonesia, 2010.*

Hydraulic stimulation

Two mechanisms – hydrofracturing/hydroshearing

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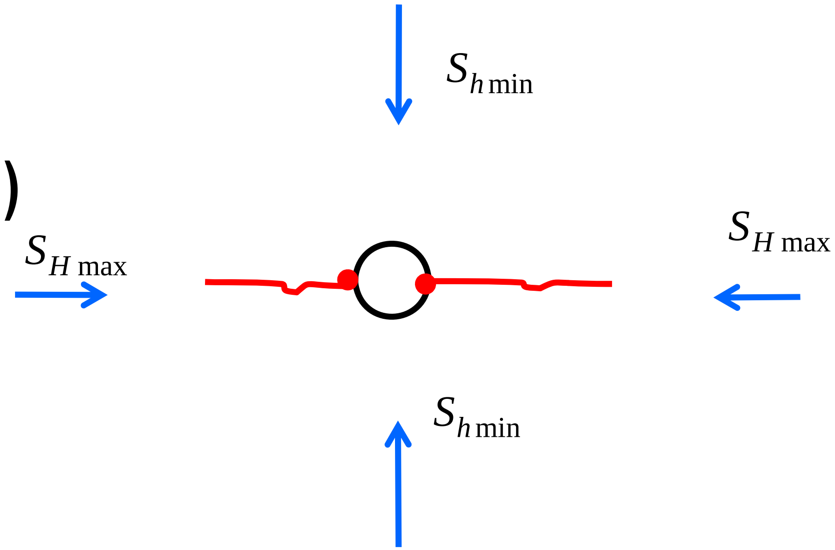
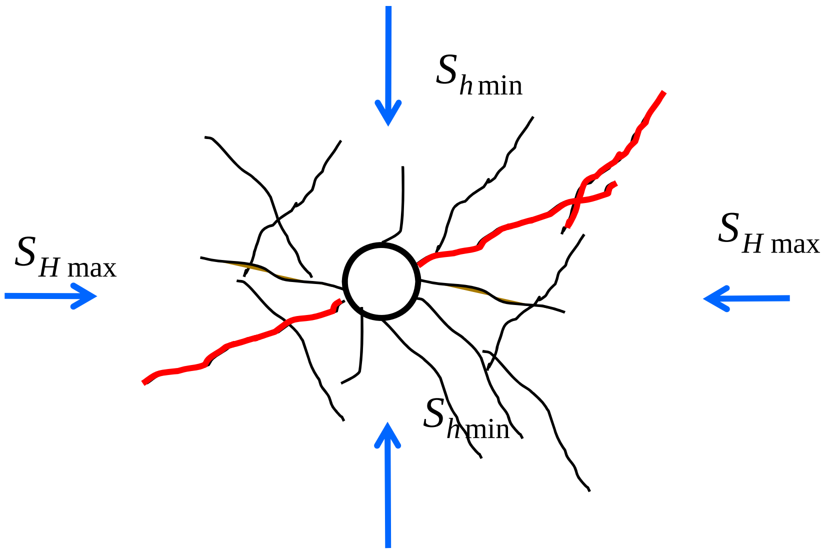
Hydrofracturing
수압파쇄 (인장파괴)





Hydroshearing
절리팽창 (전단파괴)

Hydraulic Fracturing
Breakdown Pressure

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– At the borehole wall (r = R), maximum and minimum hoop stresses are;

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

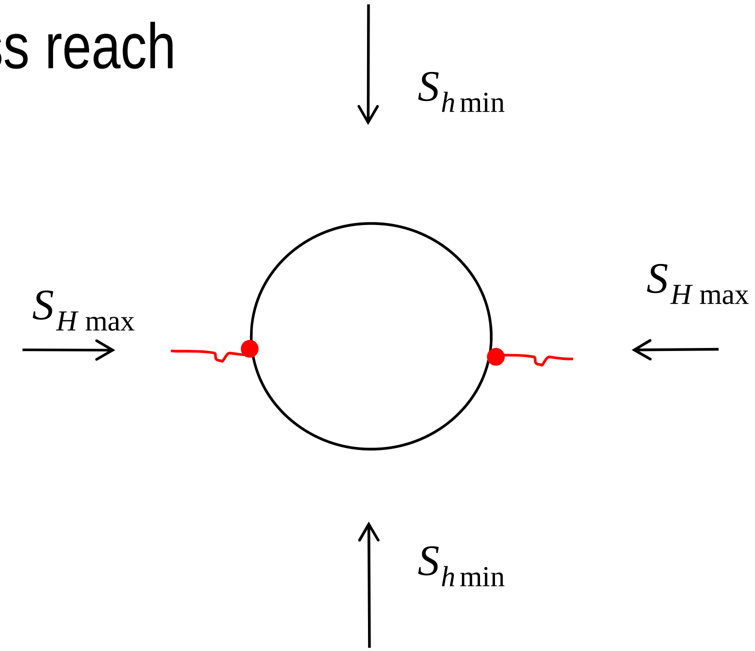
$$\sigma_{\theta,\min} = 3S_{h\min} - S_{H\max} - P_w$$

– 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



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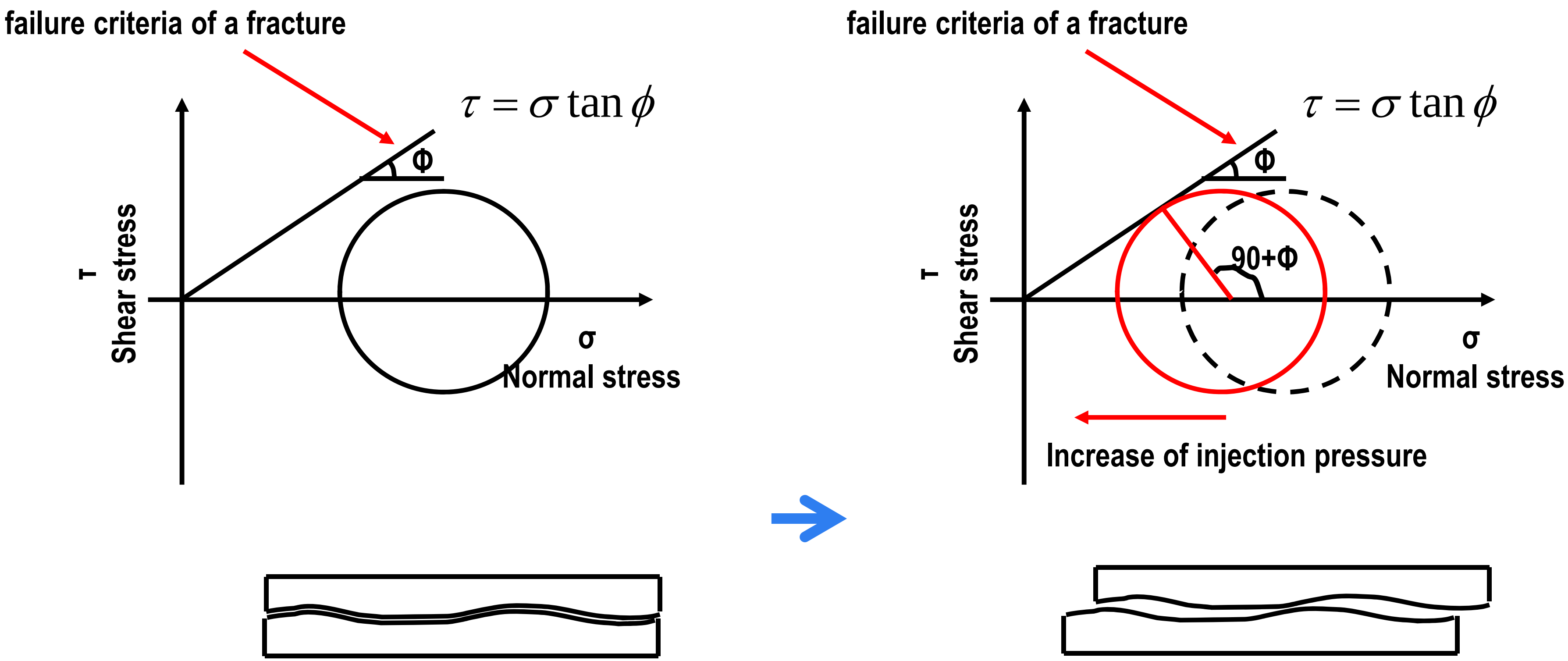
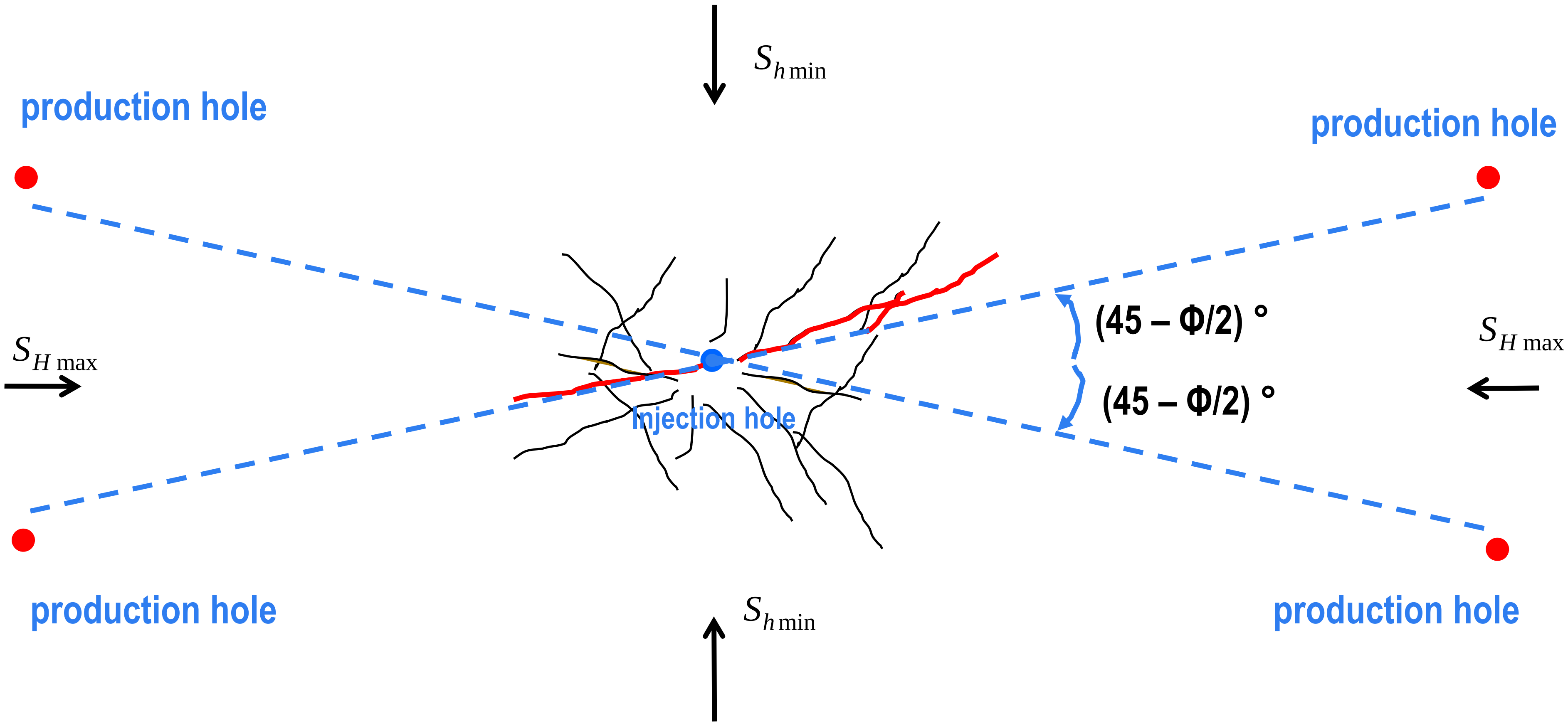
Hydraulic stimulation
Hydroshearing



- Hydraulic pressure in the fracture induces the sliding and dilation of fracture. Microseicmic event is followed

Hydraulic stimulation
Hydroshearing



Hydroshearing occur at (45 – Φ/2) ° from the maximum principal stress: ~ 30° (with 30 ° friction angle)

수리전단(hydroshearing)

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- 수리전단
  - 순수전단자극 (Pure Shear Stimulation, PSS)*
- 수압파쇄
  - 순수개구모드 (Pure Opening Mode, POM)
- 혼합메커니즘 (Mixed Mechanism Stimulation, MMS)
  - PPS + POM
- 순수수리전단의 조건
  - 1) 닫힌 자연균열의 저장성(storativity), 2) 자연균열의 초기 투과율(transmissivity), 3) 자연균열의 연결도 (percolation), 4) 자연균열의 최적 방향, 5) 자연균열의 팽창, 6) 적정하게 향상된 투과도

*McClure, M., and R. Horne. "Is Pure Shear Stimulation Always the Mechanisms of Stimulation in EGS?" Paper presented at the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford, California, US, 2013.

수리전단과 수압파쇄

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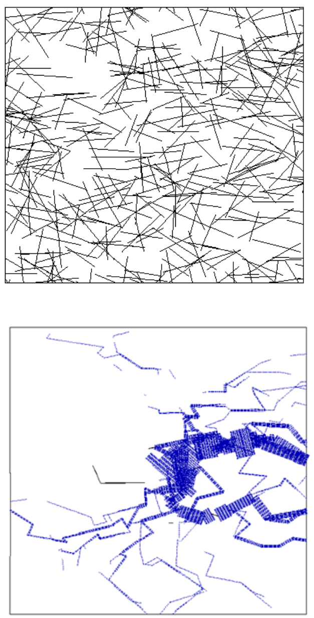
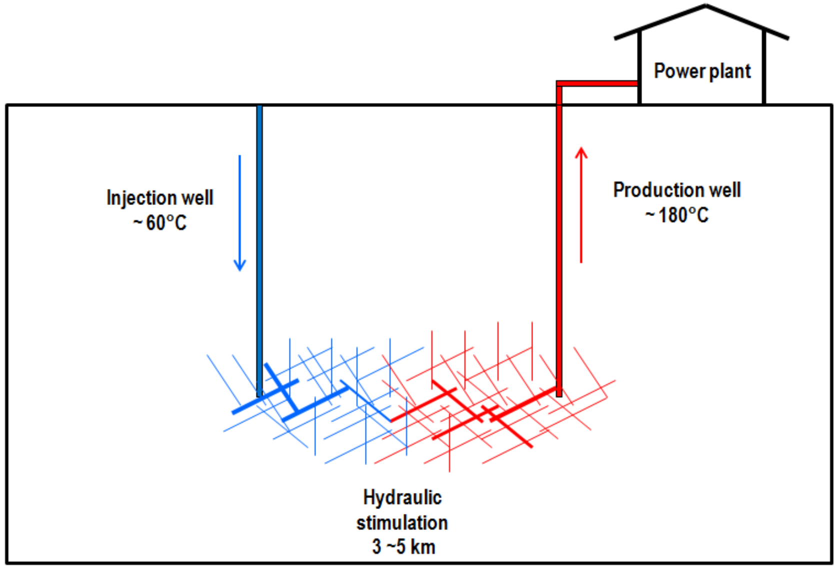
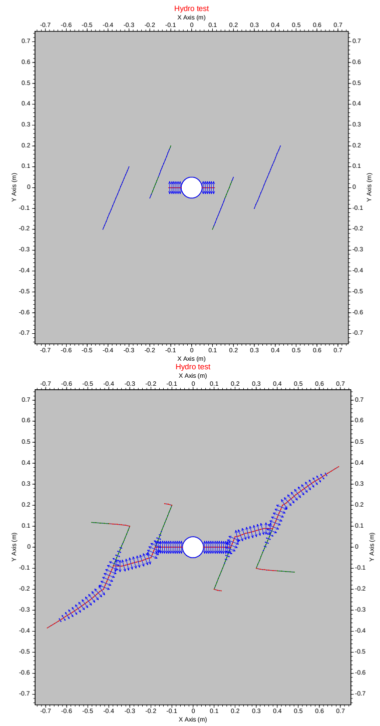
UDEC/3DEC





FRACOD



Dilation of existing fractures ← | → **Initiation of new fractures**

- 수리전단과 수압파쇄 메커니즘이 경쟁, 보완하며 인공저류층이 생성될 것이며 이에 대한 상세 연구 필요 (세일가스 수압파쇄도 마찬가지임)

수리자극
설계변수 검토*

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- Performance Parameters (성능 변수?)
  - 열적 성능 (Thermal Performance): 온도, 온도강하
  - 수리적 임피던스 (Hydraulic Impedance)/주입율
  - 유량 (flow rates)
  - 주입수 손실율/회수율 (Water Loss/recovery)

성능변수 결정

- Fundamental Parameters (기본 변수?)
  - 저류층 특성 – 지질, 저류층 크기, 초기응력, 절리 방향, 빈도, sweep efficiency
  - 엔지니어링 - 공간격, 시추궤적
- Operational Parameters (운영변수): 주입압력, 등
- Other Empirical Parameters (기타 경험 변수)

Richards, H. G., R. H. Parker, A. S. P. Green, R. H. Jones, J. D. M. Nicholls, D. A. C. Nicol, M. M. Randall, *et al. "The Performance and Characteristics of the Experimental Hot Dry Rock Geothermal Reservoir at Rosemanowes, Cornwall (1985-1988)." Geothermics 23, no. 2 (Apr 1994): 73-109.*

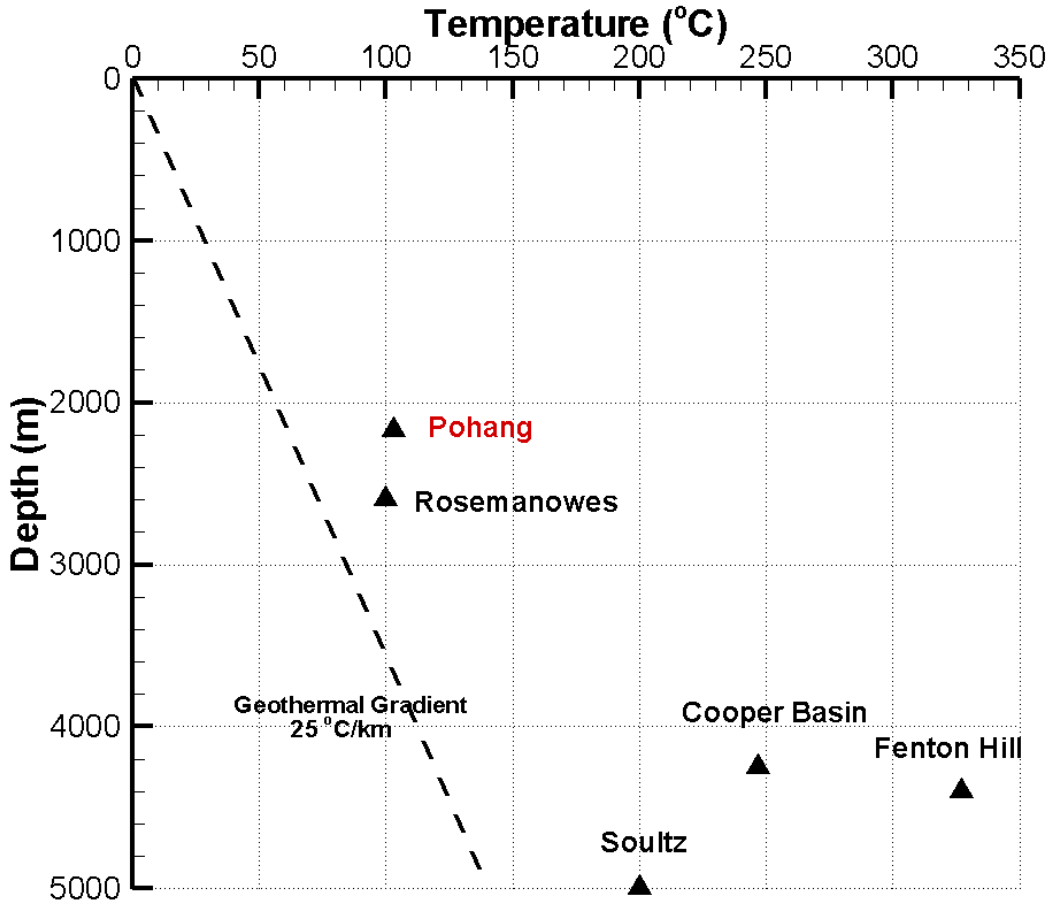
수리자극
설계변수 검토

- 열적 성능 (Thermal Performance)
  - 온도강하. E.g. 1°C/year (Rosemanowes)
- 수리적 임피던스 (MPa/(kg/s))

$$임피던스=\frac{주입압력(MPa)}{유량(kg/sec)} \qquad 주입률(injectivity)=\frac{유량(kg/sec)}{주입압력(MPa)}$$

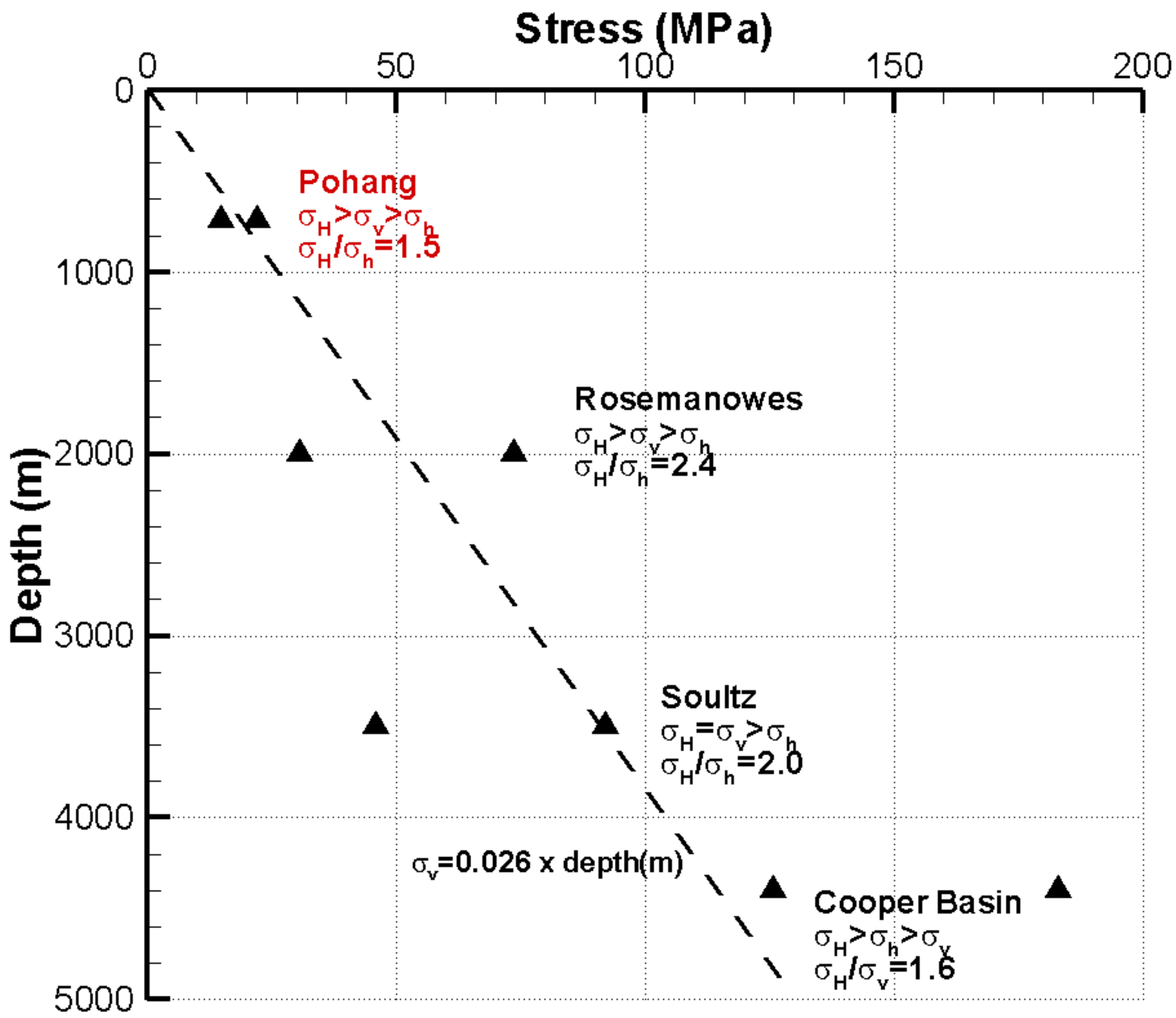
  - Rosemanowes 목표치: 0.1 MPa/(kg/s), 달성치 0.6
- 주입수 손실율/회수율 (Water Loss/recovery)
  - 회수율 = 생산량/주입량,
  - Rosemanowes, 목표치: 90%, 달성치: 70%

실증현장 요약
온도



Fenton Hill, EE-2, (Brown and Duchane, 1999), Rosemanowes (Richards et al., 1994), Soultz (Genter et al., 2010), Cooper Basin (Wyborne, 2010)

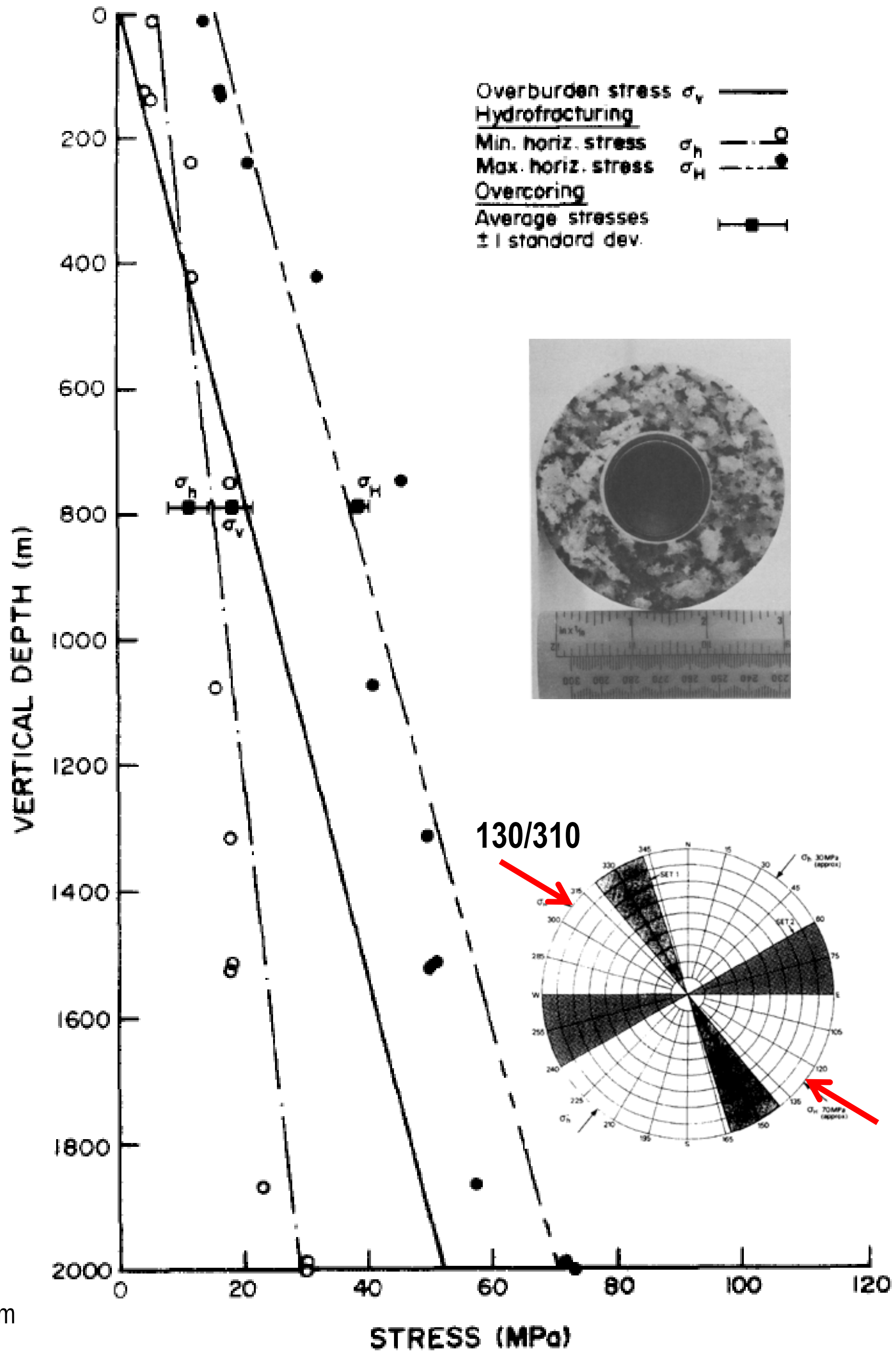
실증 사례 종합
초기응력



Stress (MPa)
0
50
100
150
200
0
1000
2000
3000
4000
5000
Depth (m)
Pohang
σH>σv>σh
σH/σh=1.5
Rosemanowes
σH>σv>σh
σH/σh=2.4
Soultz
σH=σv>σh
σH/σh=2.0
σv=0.026 x depth(m)
Cooper Basin
σH>σh>σv
σH/σv=1.6

Rosemanowes Project
초기응력

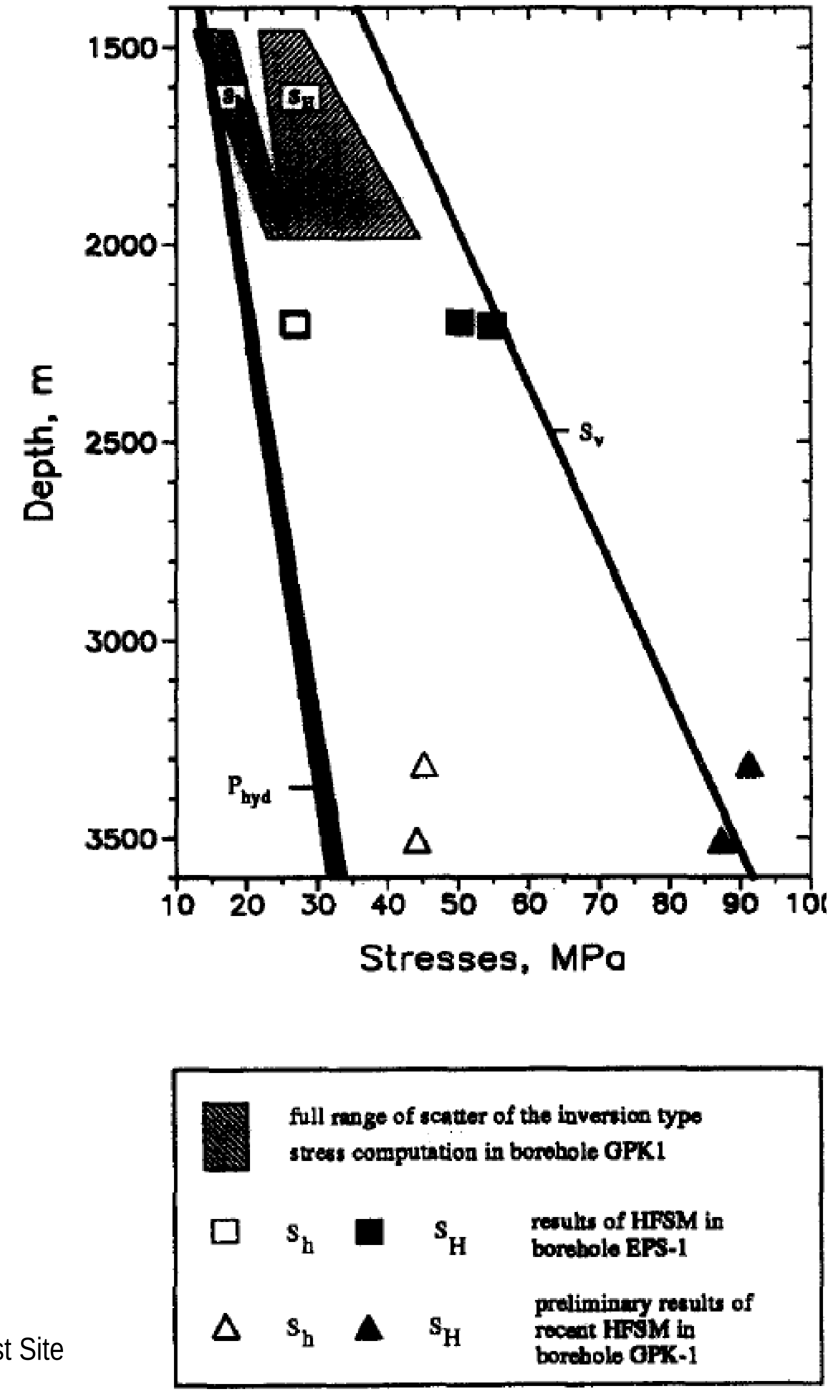
- 수압파쇄 (~2,000 m)
  - HDR 현장에서 실시. RH12
- 오버코링 (~790 m)
  - CSIRO Cell & USBM
  - ~10 km, south Crofty 광산
- 측정결과
  - Strike-slip faulting regime
  - S_H/S_h=2.4 → 큰 이방성
  - 수리전단에 유리한 조건



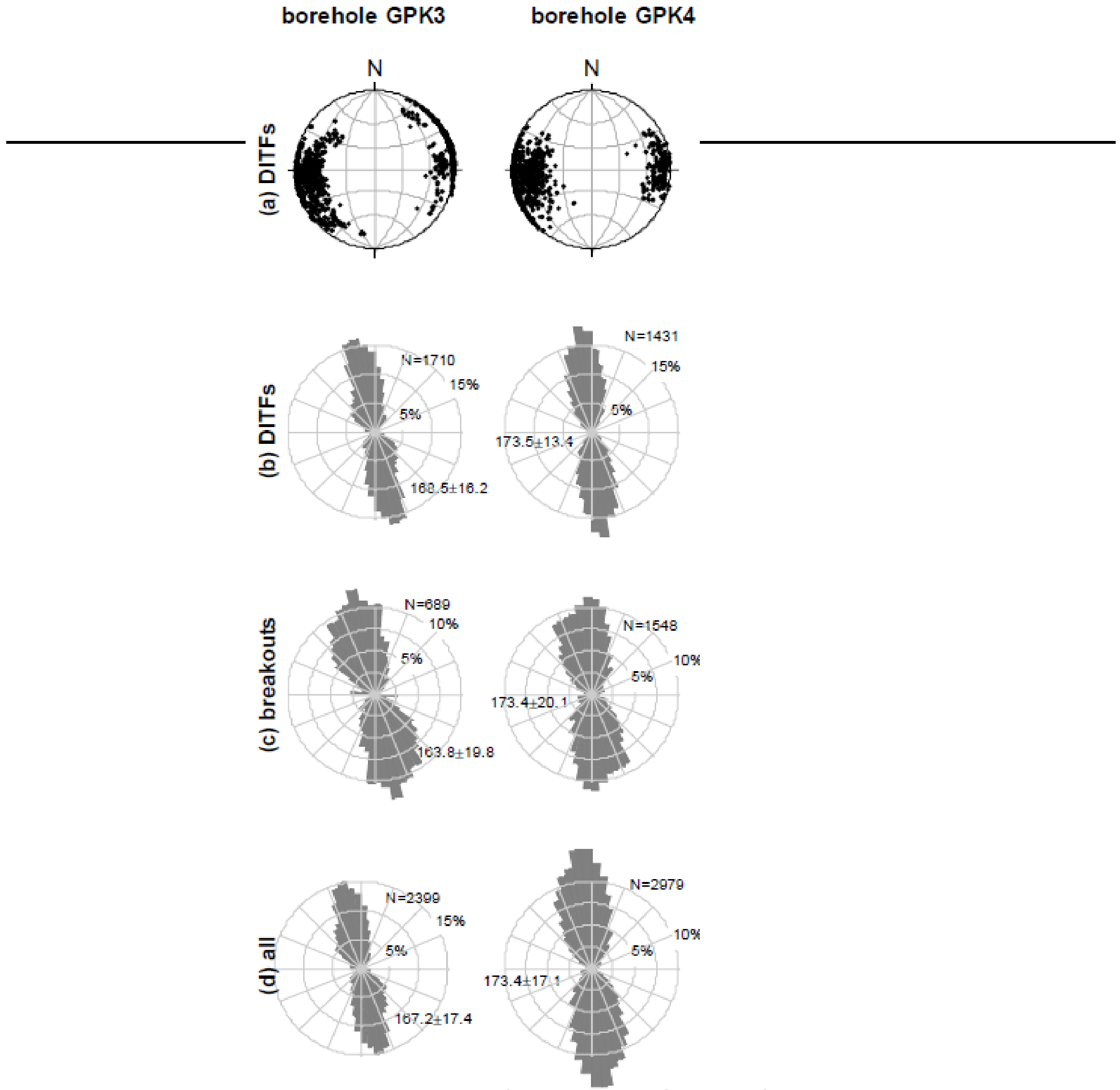
Pine, R. J., L. W. Tunbridge, and K. Kwakwa. "In-Situ Stress Measurement in the Carnmenellis Granite—I. Overcoring Tests at South Crofty Mine at a Depth of 790 m. *Int J Rock Mech Min Sci* 20(2) (1983): 51-62.
Pine, R. J., P. Ledingham, and C. M. Merrifield. "In-Situ Stress Measurement in the Carnmenellis Granite—Ii. Hydrofracture Tests at Rosemanowes Quarry to Depths of 2000 m *Int J Rock Mech Min Sci* 20, no. 2 (1983): 63-72.

Soultz
초기응력

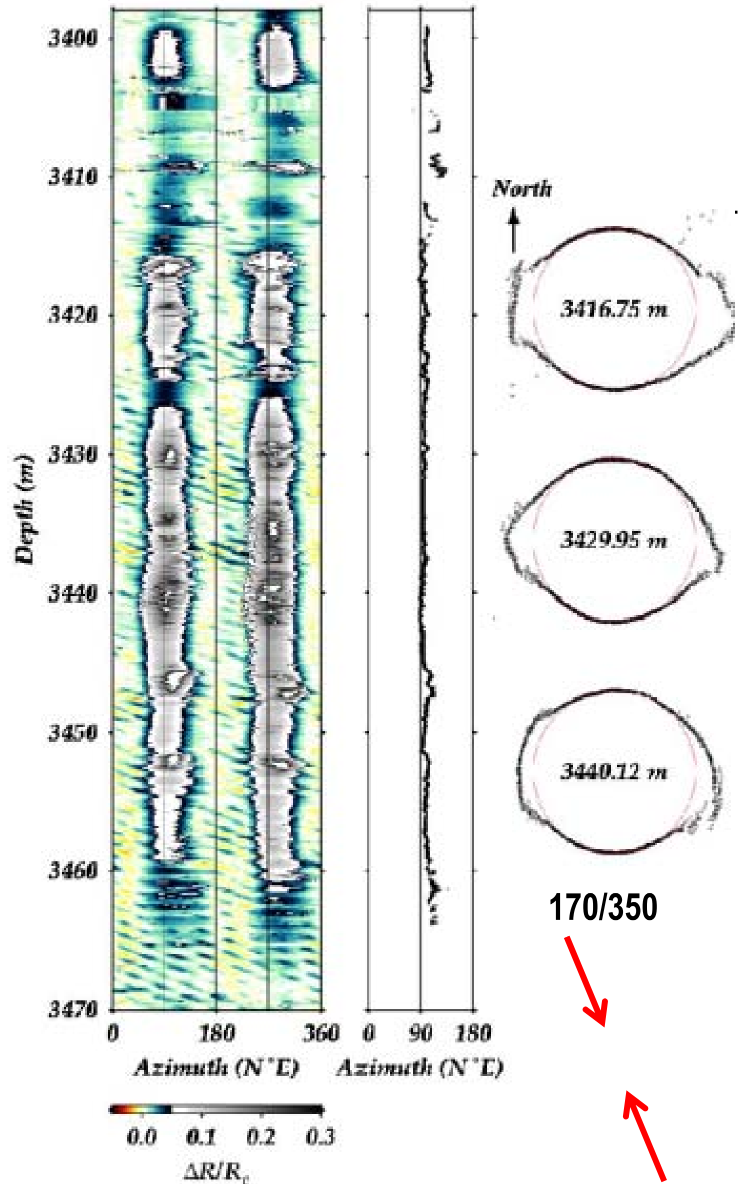
- 수압파쇄 (~3,500 m)
  - HDR 현장에서 실시. EPS-1 (150°C @2.2 km), GPK-1(175°C @3.5 km)
  - 알루미늄 패커 이용
  - 정단층 응력장 (수직응력이 중간)
  - S_H/S_h=2.0 → 큰 이방성
  - 수리전단에 유리한 조건
- 공벽관찰
- Focal mechanism
- S_H: N170°±15° (Cornet et al., 2007)



Klee, G., and F. Rummel. "Hydrofrac Stress Data for the European Hdr Research Project Test Site Soultz-Sous-Forets. *Int J Rock Mech Min* 30(7) (1993): 973-76.



Borehole breakout & DITF at GPK3 & 4 @all depth. (Valley and Evans, 2007)



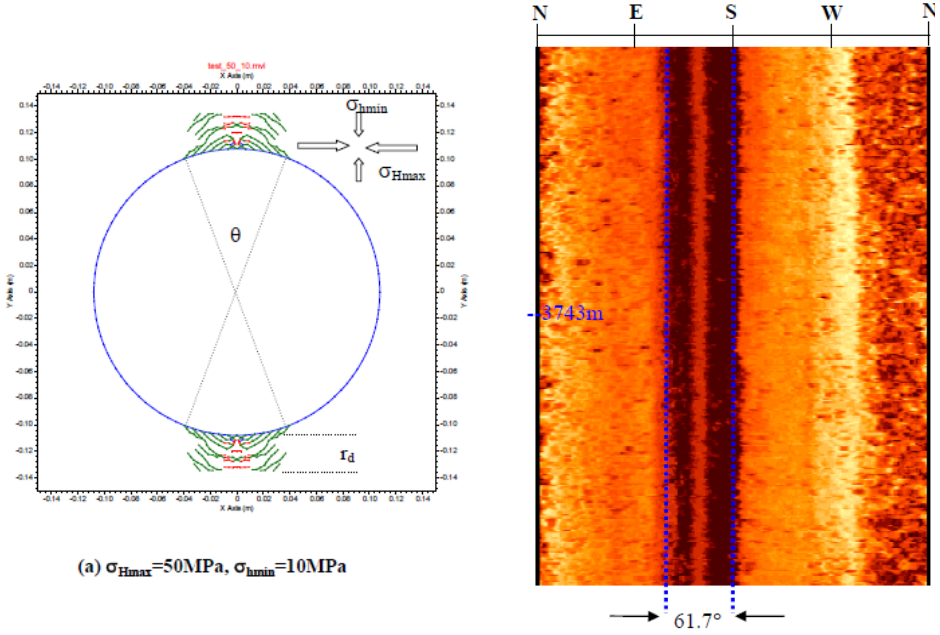
Borehole breakout at GPK1 @3450 m. Observed one year after drilling (Cornet et al., 2007)

Valley, B., and K.F. Evans. "Stress Heterogeneity in Teh Granite of the Soultz Egs Reservoir Inferred from Analysis of Wellbore Failure." In *Proc World Geothermal Congress 2010, Paper No.3144. Bali, Indonesia*

Cornet, F. H., Th Bérard, and S. Bourouis. How Close to Failure Is a Granite Rock Mass at a 5 km Depth?. *Int J Rock Mech Min 44(1) (2007): 47-66.*

Cooper Basin Project
In situ Stress

- 공벽 관찰 (~4,250 m)
- 인근 응력자료 (석유생산공)
  - S_H: East-West
  - 역단층 응력장 (수직응력이 최소)
  - S_H:S_h:S_v=1.6:1.1:1.0 → 수평균열 발달

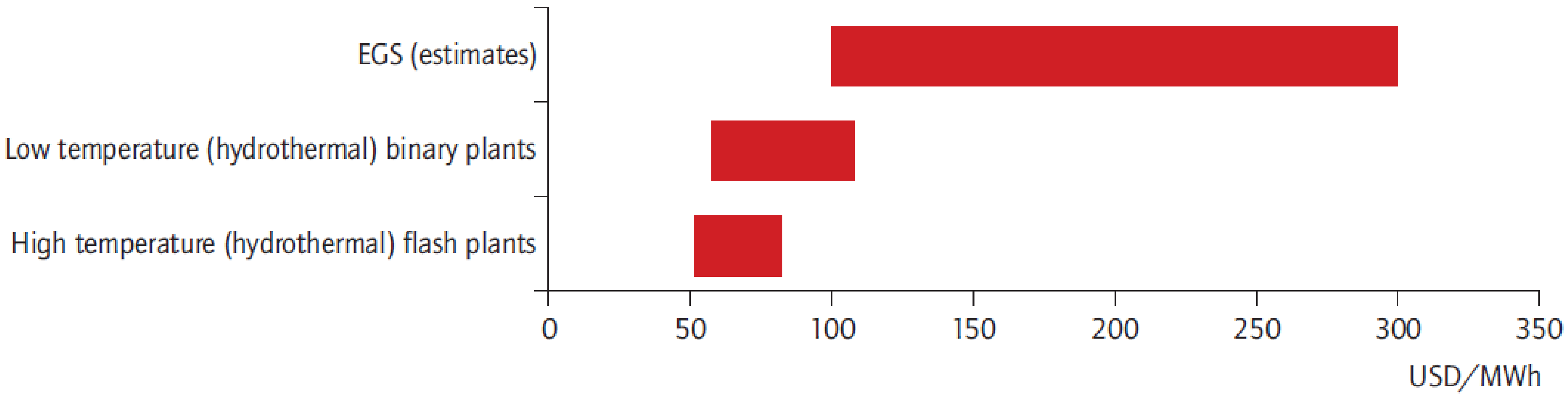


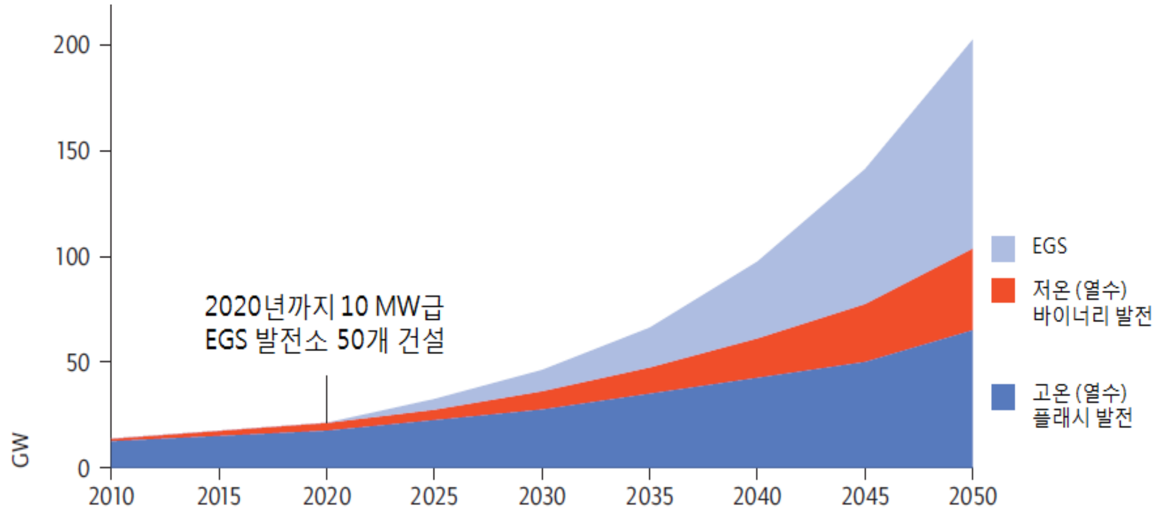
Observed and modeled borehole breakout (Shen, 2008)

Chen, D. "Concepts of a Basic Egs Model for the Cooper Basin, Australia." In *Proc World Geothermal Congress 2010, Paper No.3141. Bali, Indonesia, 2010.*
Shen, B. "Borehole Breakouts and in Situ Stresses." In *SHIRMS 2008, edited by Y. Potvin, J. Carter, A. Dyskin and R. Jeffrey, 407-18, 2008.*

Enhanced Geothermal System
Vision

Production cost of geothermal electricity





IEA, Technology Roadmap, Geothermal Power and Heat, 2011

Enhanced Geothermal System
The things that we know

- Achievements
  - High flow rates with long path lengths are needed
  - Stimulation is through shearing of pre-existing fractures
  - Monitoring of acoustic emission is our best tool for understanding the system
  - Rock-fluid interactions may have a long-term effect on reservoir operation

Enhanced Geothermal System
The things that we know

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- Achievements
  - Pumping the production well for high flow rates without increasing overall reservoir pressure → reduce the risk of short circuiting
  - Drilling technology being improved
  - Circulation for extended time periods without temperature drop is possible
  - Models are available for characterizing fractures and for managing the reservoir
  - Induced seismicity concerns

Enhanced Geothermal System
Remaining issues

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- Cost of drilling
  - > 50% of whole cost,
- Efficient hydraulic stimulation
  - No proven method, key parameters?
- Induced seismicity
  - Lack of understanding, Public acceptance
- Reservoir characterization
  - Site investigation, innovative exploration, transparent earth???
- Renewability of geothermal energy
  - Life time or power plant, thermal drawdown
- Long term behavior of reservoir
  - Geochemical reaction, corrosion

Enhanced Geothermal System
Microseismicity

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- Addressing induced seismicity (Huenges, 2010)
  - Estimate local potential for natural seismic hazard and induced seismicity
  - Technological innovation: controlling water injection rate, controlling fracturing depth, …
  - Information and education
  - Monitoring Concept
  - Implement emergency action plan

Enhanced Geothermal System (EGS)
EGS and Shale gas production

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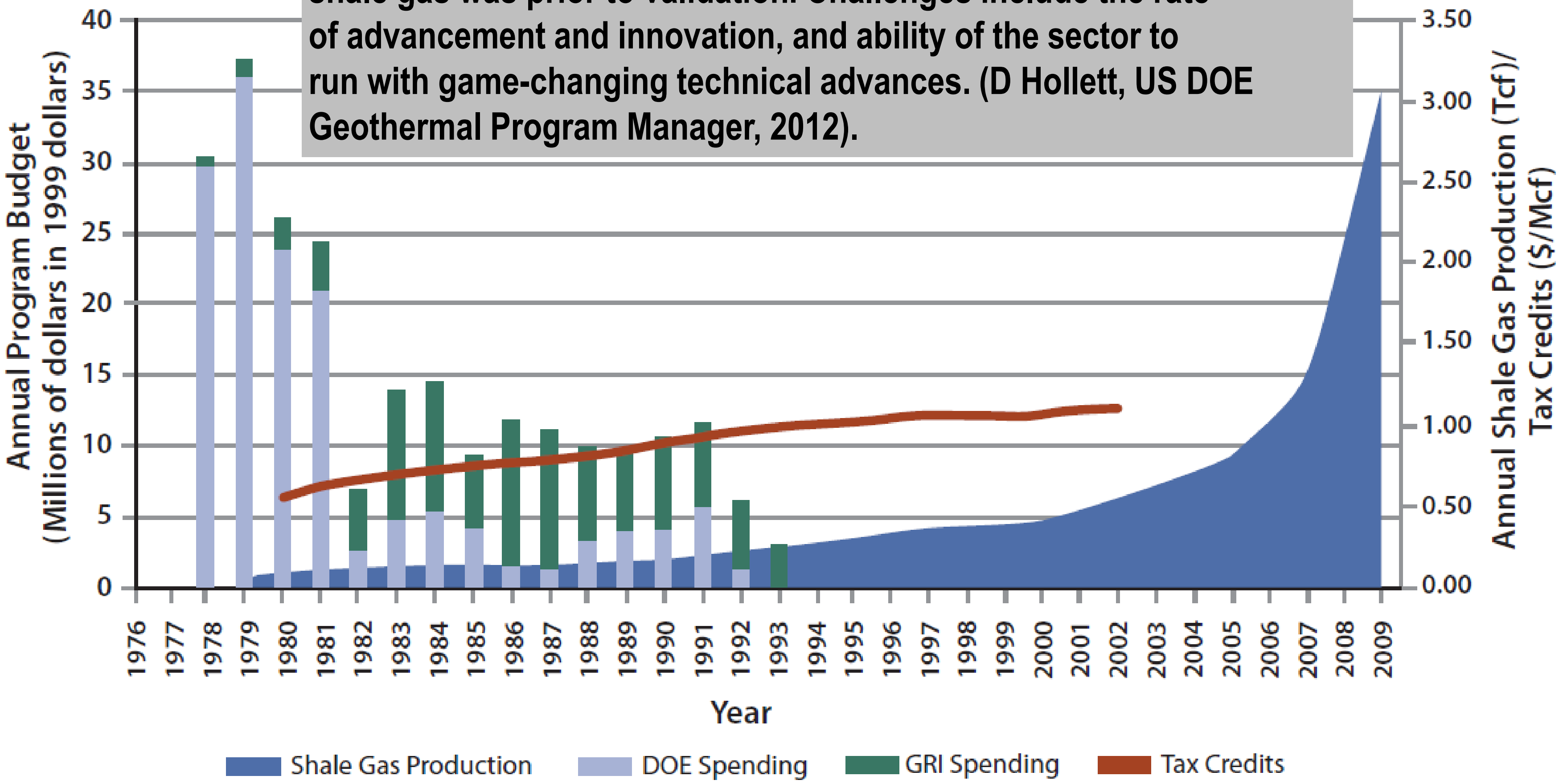
- Shale Gas R&D spending and production*

EGS is arguably in the same techno-commercial space that shale gas was prior to validation. Challenges include the rate of advancement and innovation, and ability of the sector to run with game-changing technical advances. (D Hollett, US DOE Geothermal Program Manager, 2012).

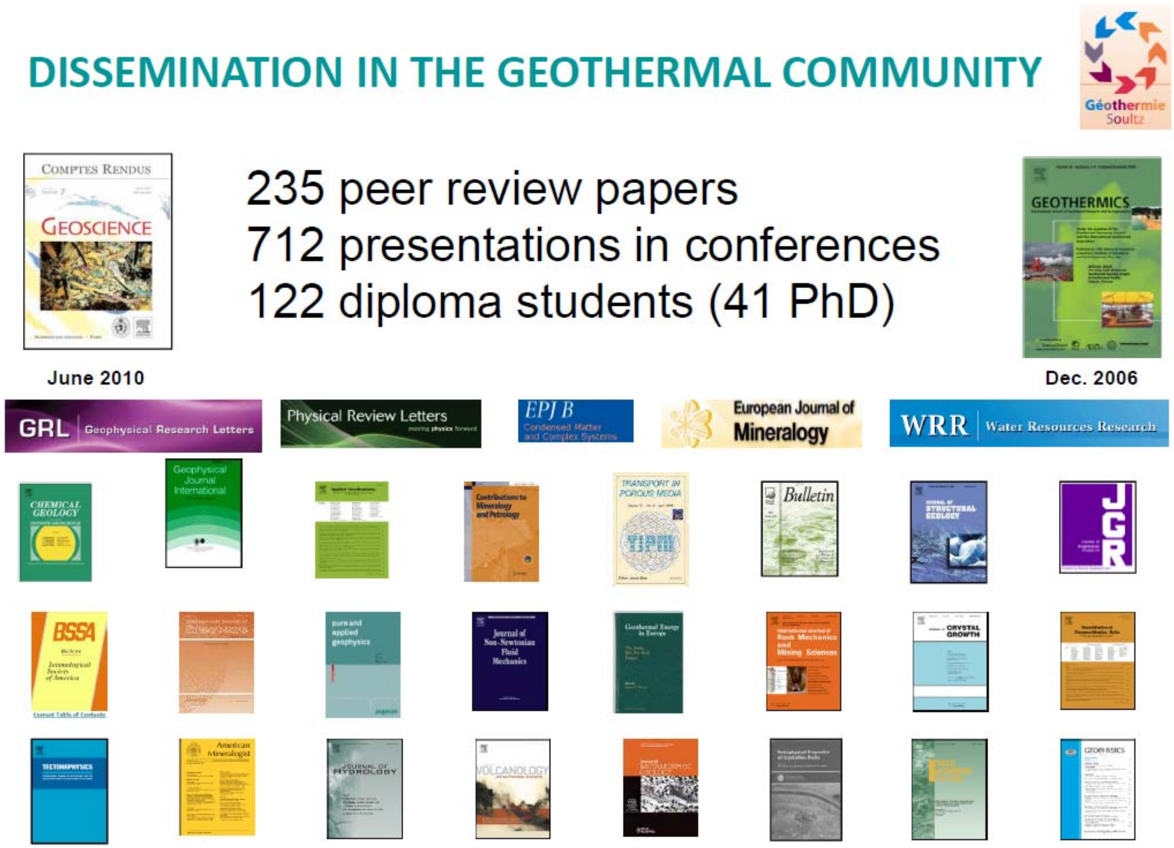


*Future of Natural Gas (MIT Report, 2009)

**GRI: Gas Research Institute

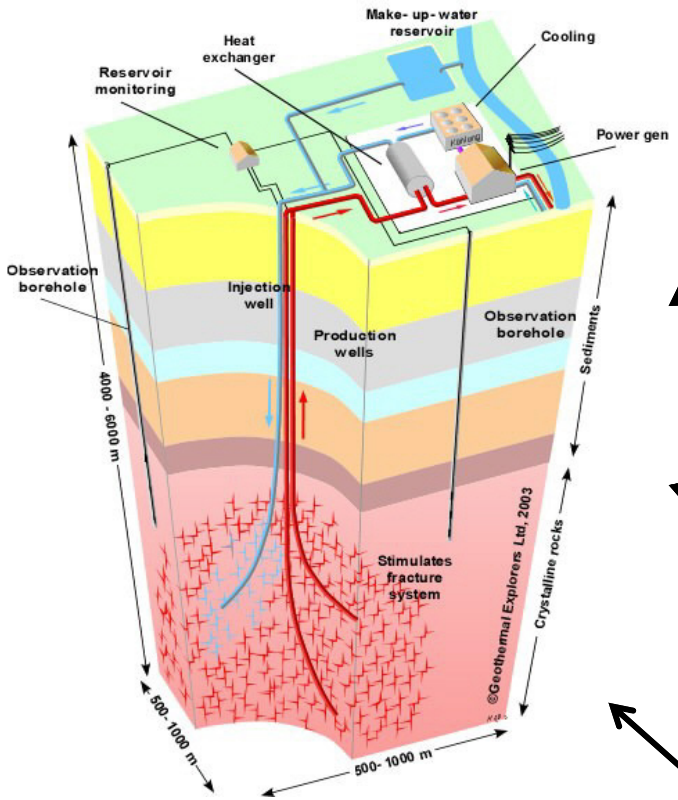
Case Study
Soultz Project, France – impact

- Scientific results from Soultz project



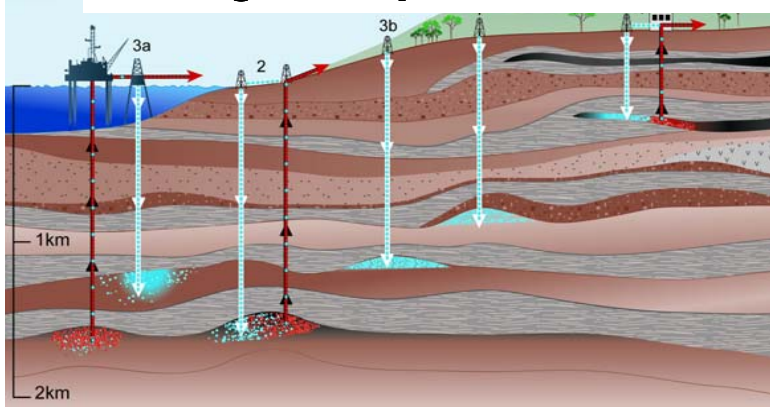
Genter, 2012

Summary
Geothermal Energy and subsurface Engineering of environmental importance

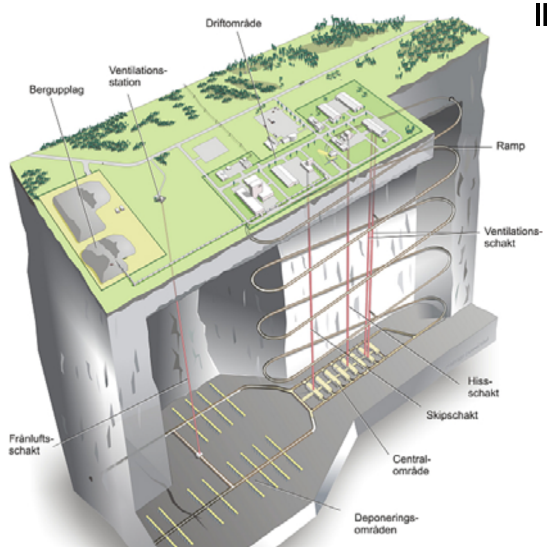


Geothermal Explorer, 2010

CO2 geosequestration



IPCC, 2005



SBK, 2010

Petroleum and mineral resources

Underground repository of nuclear waste

Think Big!

And

Go Deep!