Geothermal Energy
- Enhanced Geothermal Systems (Week13, 25 Nov)

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Introduction
Term Project

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- Each student will prepare a term paper and present it during student conference. Proceedings will be published.
- Both report and presentation should be in English.
- Choose a critical geomechanical issue for EGS.
- My expectation: term papers may be publishable in the future with additional work.
- Timeline

28 Oct	Submission of proposal (~1 p)	10%
8 Nov	Presentation of proposal /progress	20%
2 Dec	Presentation of final term paper	30%
2 Dec	Submission of final term paper (~15 p)	40%

Introduction
Term Project

- Topics of term project: It has to be a critical issue for the EGS
  - Renewability of geothermal energy: How renewable is EGS? And what is the role of geomechanical issues?
  - Predictability of enhanced permeability: is this really universal technology?
  - Reliable estimation of *in situ* stress: is there any hope for better estimation in the future?
  - Hazard of microseismicity: Can we estimate the magnitude of induced microseismicity? What are the critical parameters?
  - Cost of drilling: Is the breakthrough possible in this area dominated by empiricism?
  - Quantifying the uncertainty in EGS: How does the different technical issues combine together to increase the uncertainty?

Outline

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- Definition
- Status and History
- Case Study
  - Rosemanowes, UK
  - Soultz, France
  - Cooper Basin, Australia
- Achievement and Remaining issues

Enhanced Geothermal System
Definition

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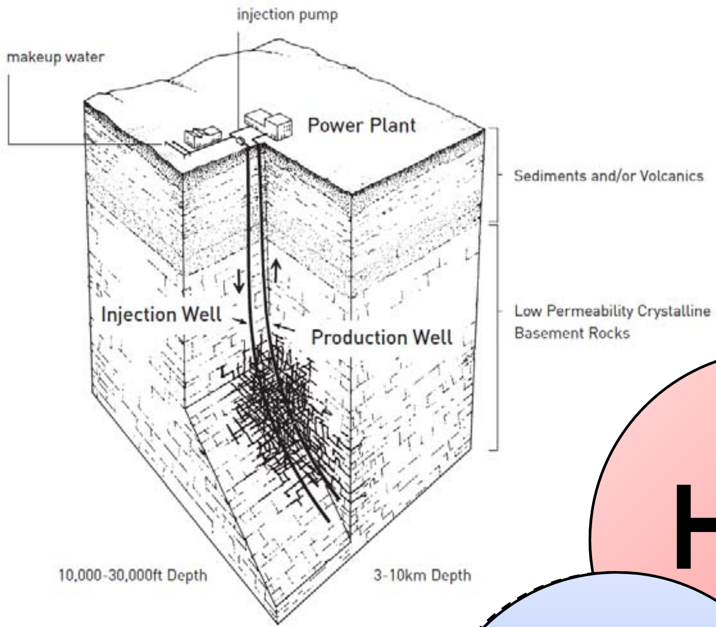

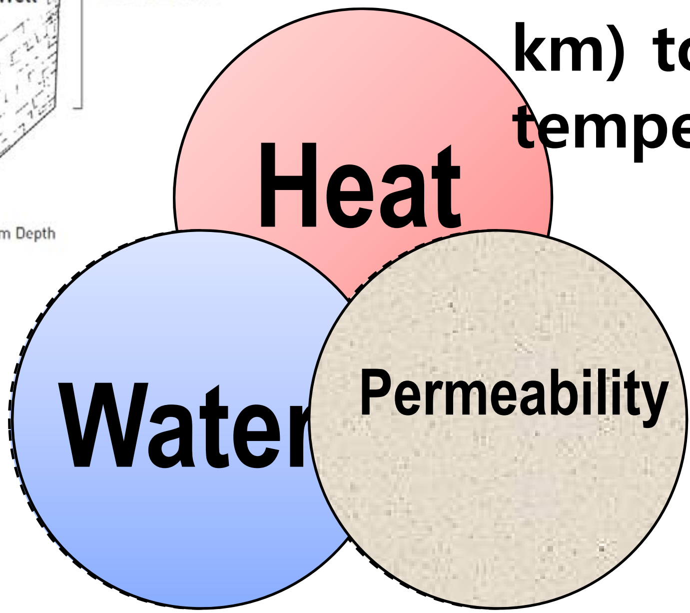

Drill a deeper borehole (3~7 km) to reach a target temperature

- Provide water through injection

Artificially generate geothermal reservoir by hydraulic stimulation

Enhanced Geothermal System
Definition

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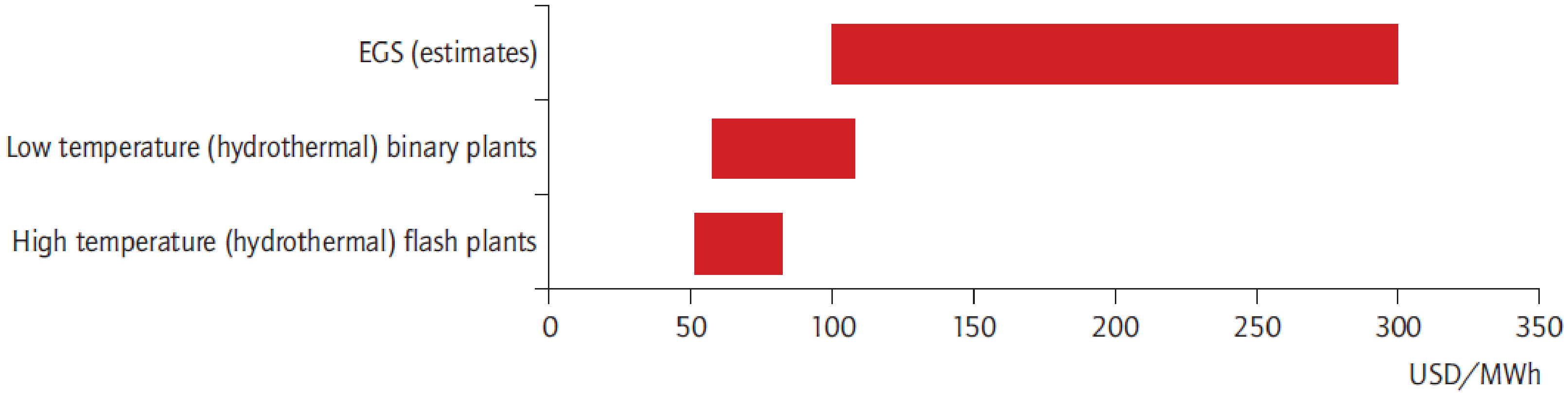
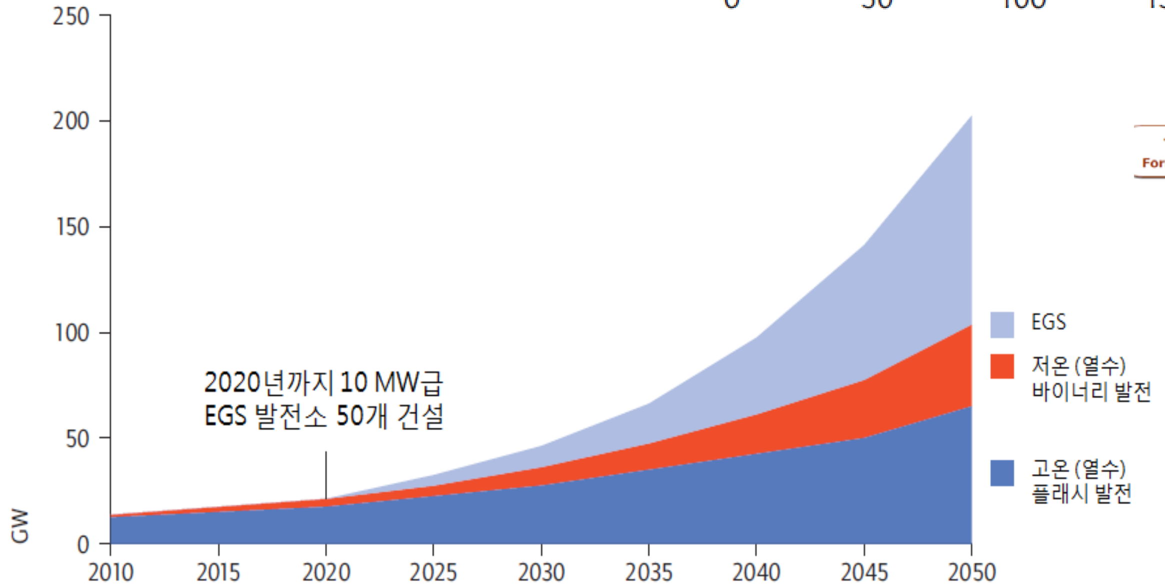
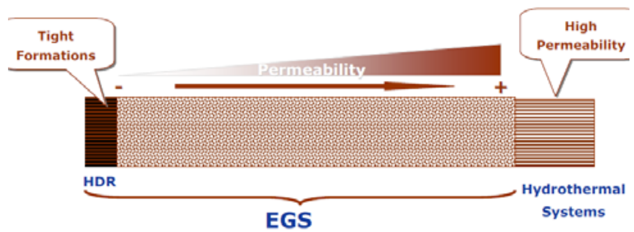
- EGS: Enhanced (or Engineered) Geothermal System
- Broader definition: A system designed for primary energy recovery using heat-mining technology, which is designed to extract and utilize the Earth's stored thermal energy (Tester et al., 2006)
- Narrower definition (also called HDR, Hot Dry Rock, or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

Enhanced Geothermal System
Vision

Production cost of geothermal electricity







IEA, Technology Roadmap, Geothermal Power and Heat, 2011

Enhanced Geothermal System
Principles

- www.geodynamics.com.au
- http://www.google.org/egs/
- http://www.youtube.com/watch?v=eB2rdudjIMY
  - A conversation with Dr Steven Chu, Dan Reicher, and Don O'Shei

Enhanced Geothermal System (EGS)
EGS and Shale gas production

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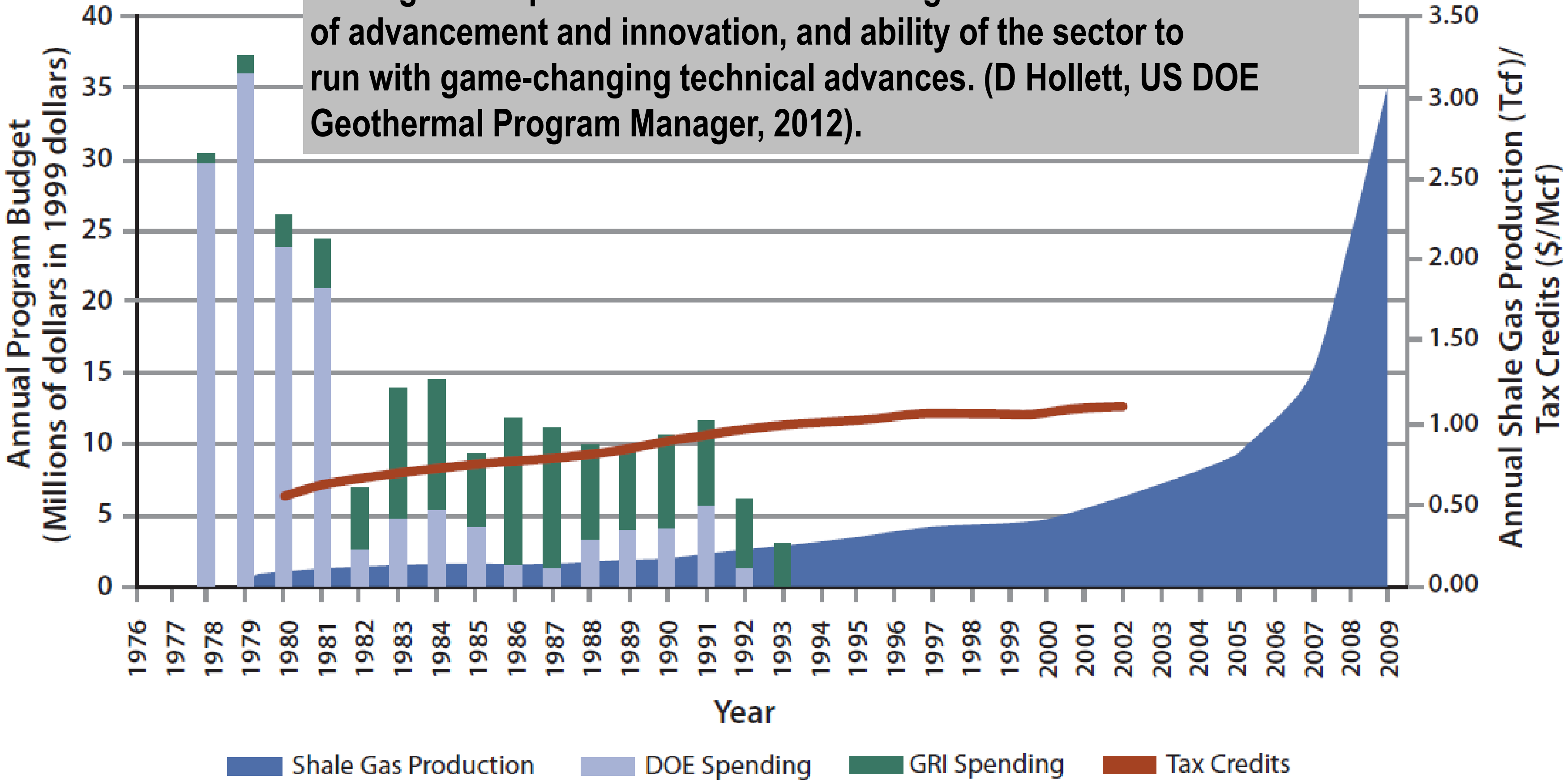
- Shale Gas R&D spending and production*

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

Enhanced Geothermal System
Various views

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A modest investment of $300-400 million over 15 years would demonstrate EGS technology at a commercial scale at several US field sites to reduce risks for private investment and enable the development of 100 GW.

JW Tester, Prof Cornell Univ, then MIT, 2007 – The future of geothermal energy

EGS is a clean, reliable base load energy…. Effectively unlimited supply of energy….you can bank on it.

Steve Chou, Nobel Laureate, LBNL, 2011 – Google.org

Geothermal will remain a globally marginal, although nationally and locally important, source of electricity. ~ 5% even if we were to develop the prospective potential of 138 GW.

Vaclav Smil, 2003 – energy at crossroads

…to treat geothermal heat the same way we currently treat fossil fuels: as a resource to be mined rather than collected sustainably. …Sadly for Britain, geothermal will only ever play a tiny part.

DJC MacKay, Prof Univ Cambridge, 2009 – Sustainable energy without hot air

Enhanced Geothermal System
History

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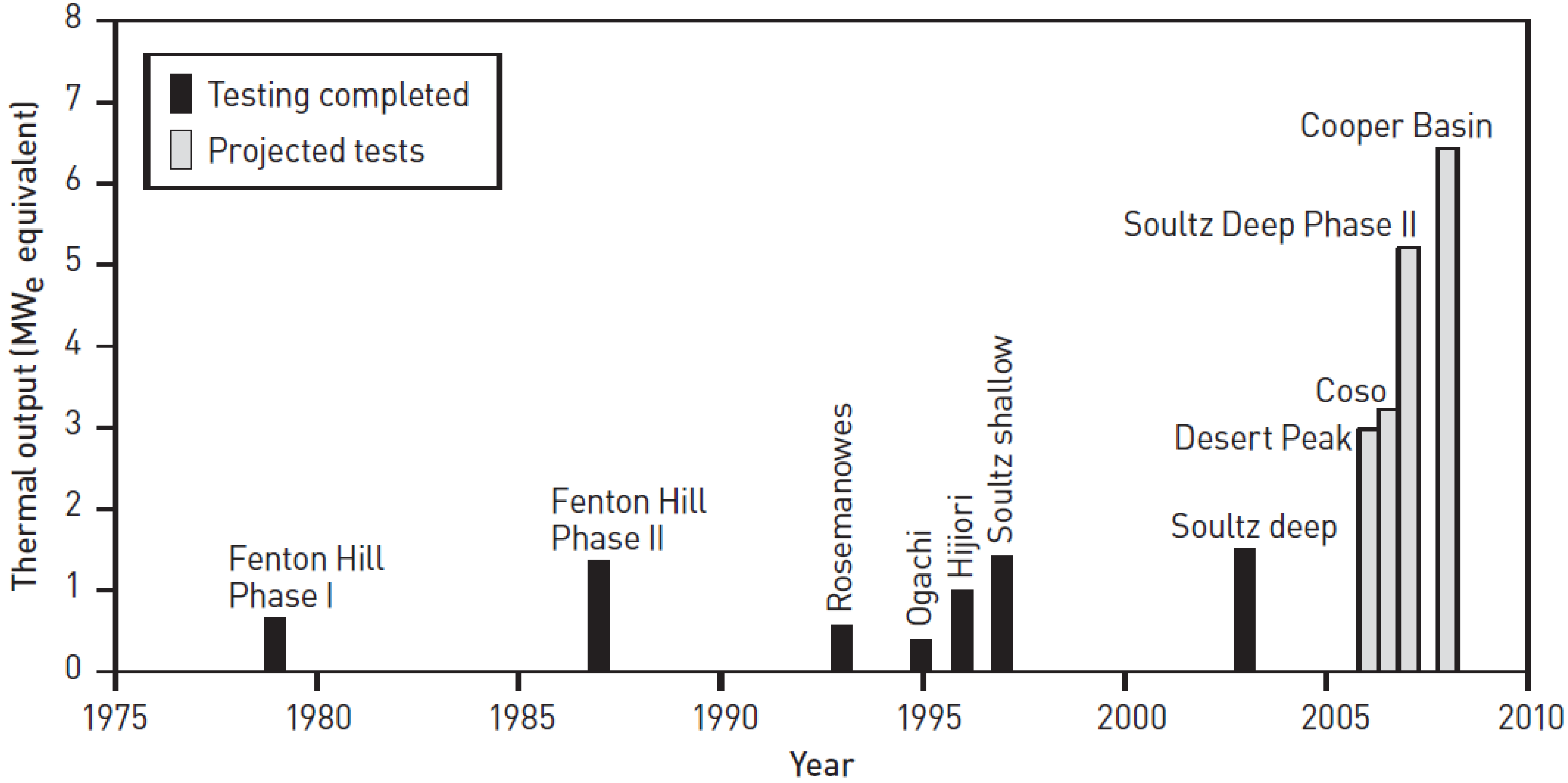

Figure 4.16 Evolution of estimated electrical power output per production well, with time from EGS projects. The Fenton Hill, Coso, and Desert Peak projects received, or are receiving, major funding from the U.S. DOE.

Tester et al., 2006

Enhanced Geothermal System
Case studies

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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.*

Enhanced Geothermal System
Case studies - Temperature

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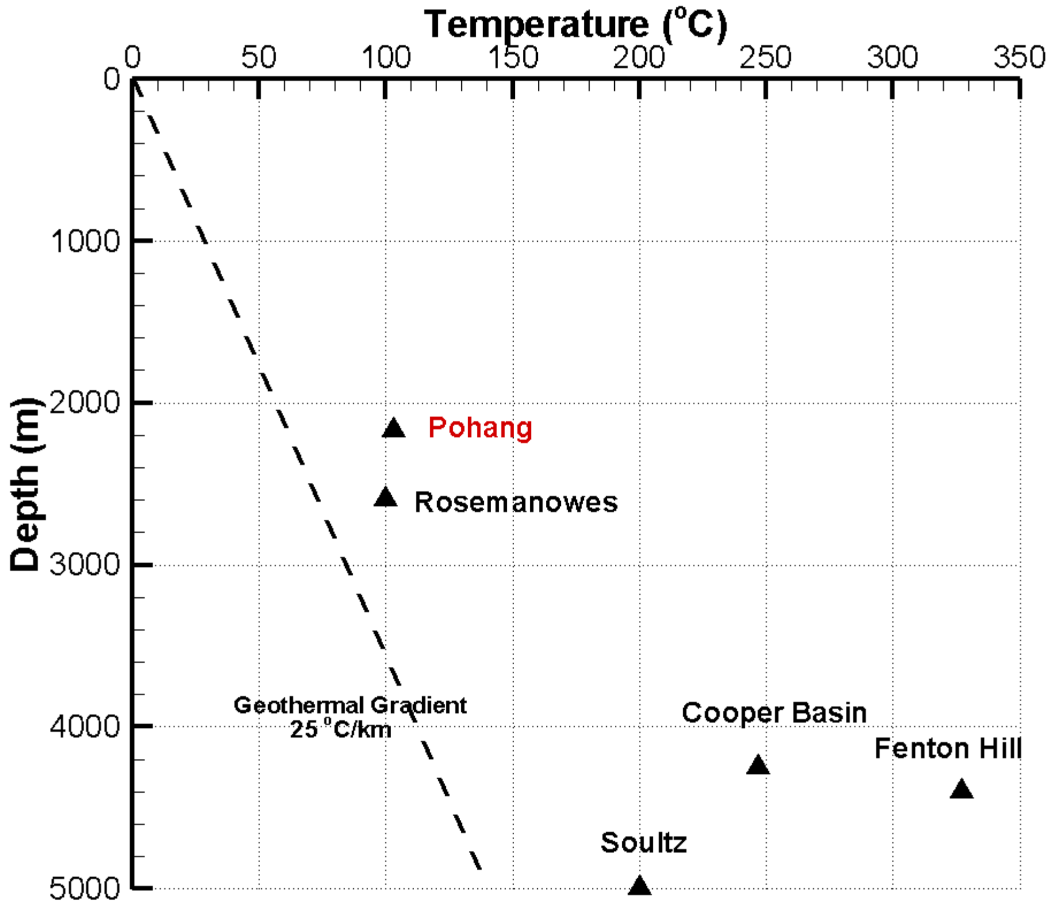
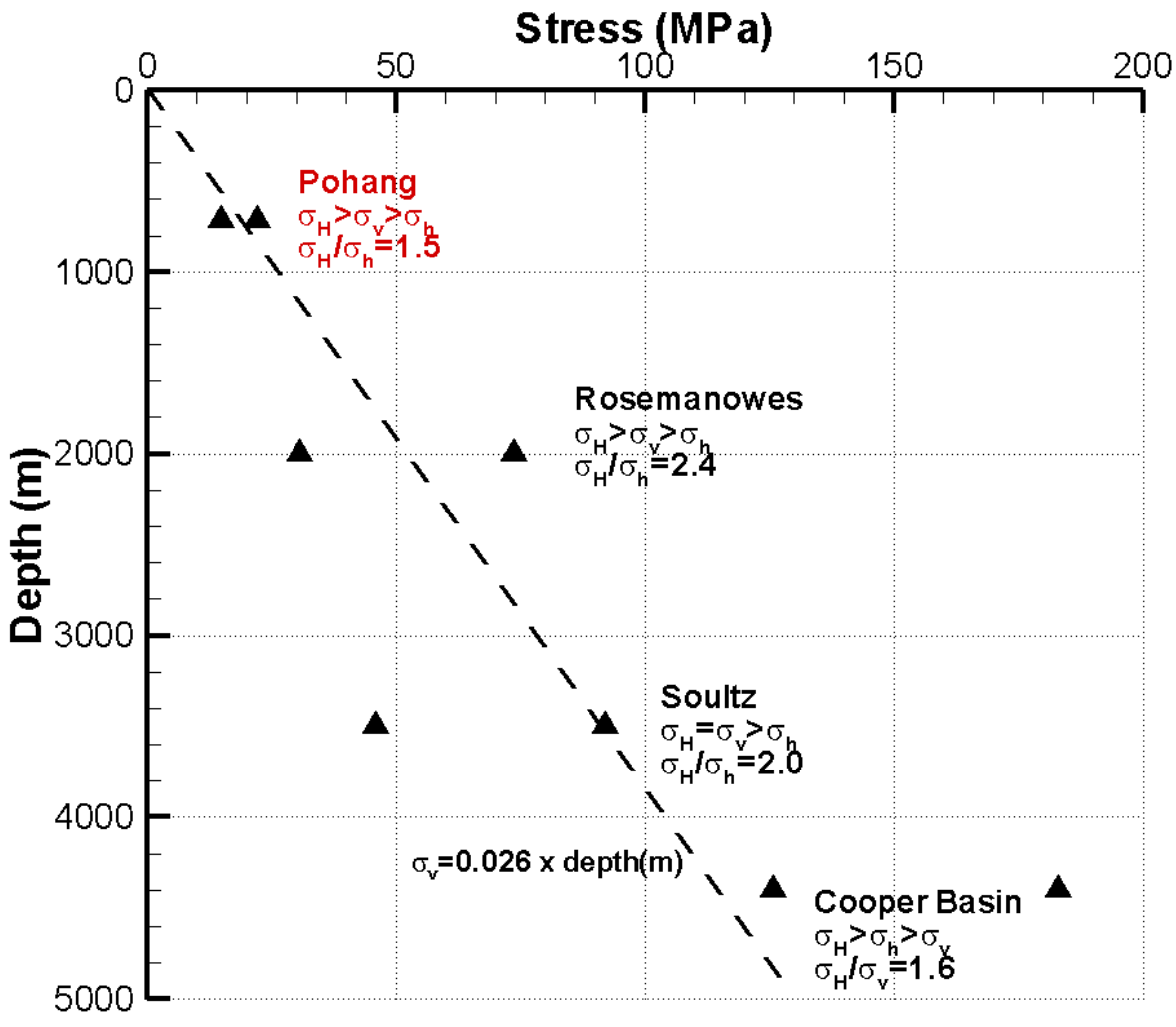


Fenton Hill, EE-2, (Brown and Duchane, 1999), Rosemanowes (Richards et al., 1994), Soultz (Genter et al., 2010), Cooper Basin (Wyborne, 2010)

Enhanced Geothermal System
Case studies – in situ stress



Rosemanowes Project
Overview

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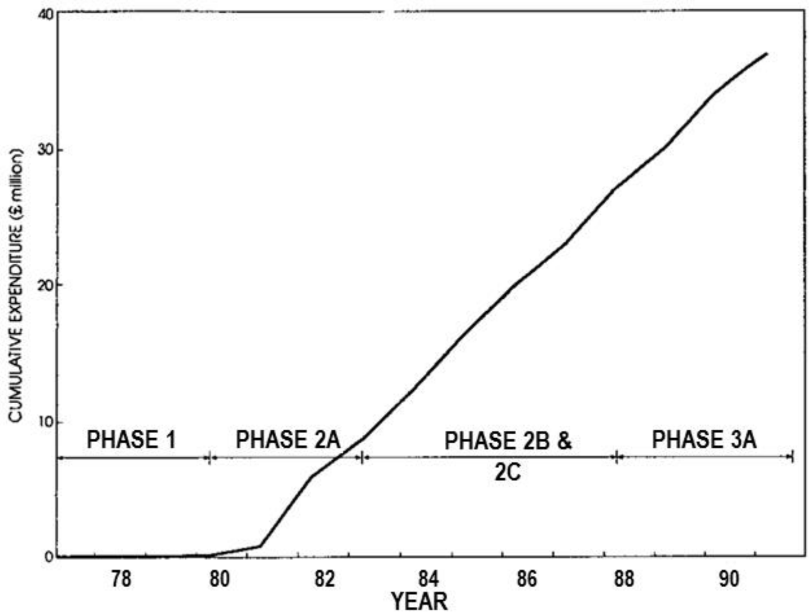
단계	기간	주요 연구
Phase 1	1977 – 1980	시추공 4개 (심도 300 m), 수리 및 발파에 의한 자극
Phase 2A	1980 – 1983	2 km 시추공 2개 (생산공 RH11, 주입공 RH12), 수리자극실시
Phase 2B	1983 – 1986	RH15 (생산공, 2.6 km), 점성유체 주입, RH12-RH15 저류층
Phase 2C	1986 – 1988	저류층 개선 기술 (manipulation)
Phase 3	1988 – 1991	Prototype HDR



MacDonald, P., A. Stedman, and G. Symons. "The UK Geothermal Hot Dry Rock R&D Programme." In *Seventeenth Workshop on Geothermal Reservoir Engineering, 5-11 (SGP-TR-141). Stanford, CA, USA, 1992.*

Rosemanowes Project
Overview

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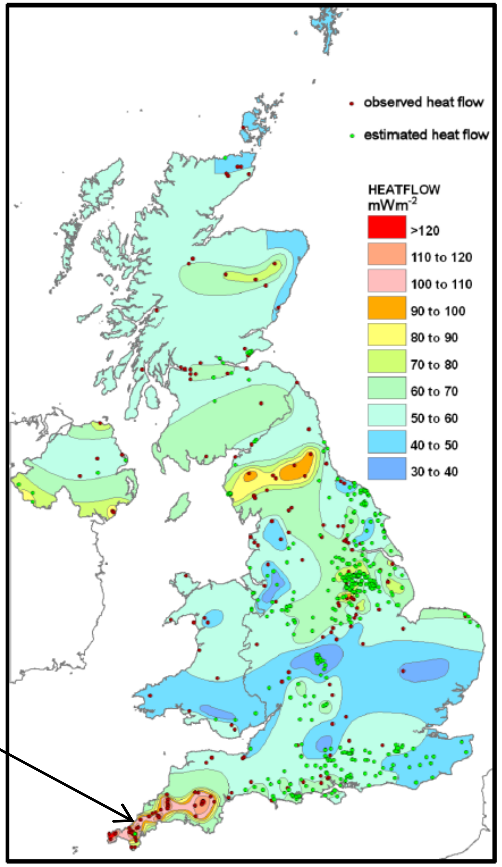
- 영국의 열유량 (Heat Flow) 현황

Rosemanowes



Busby J, 2012, Potential deep resources in UK, 2nd UK Deep geothermal symp

Heat flows are near average continental values – but there are anomalies

The distribution of the heat flow measurements is very uneven. Scotland, Wales and parts of eastern England are very poorly sampled.

- Heat flow values peak over the radiogenic granites with values up to 130 mW m^{-2}.
- Elsewhere, an average of 58 ± 16 mW m^{-2}.
- Average UK geothermal gradient is 26° C per km, but locally it can be in excess of 35° C per km.

Rosemanowes Project
Geology

- Carnmenellis Granite: 9 km 심도에 이르는 화강암 저반(granite batholith)
- 대규모 단층대 없음
- 퇴적층 없어 미소진동 모니터링에 용이

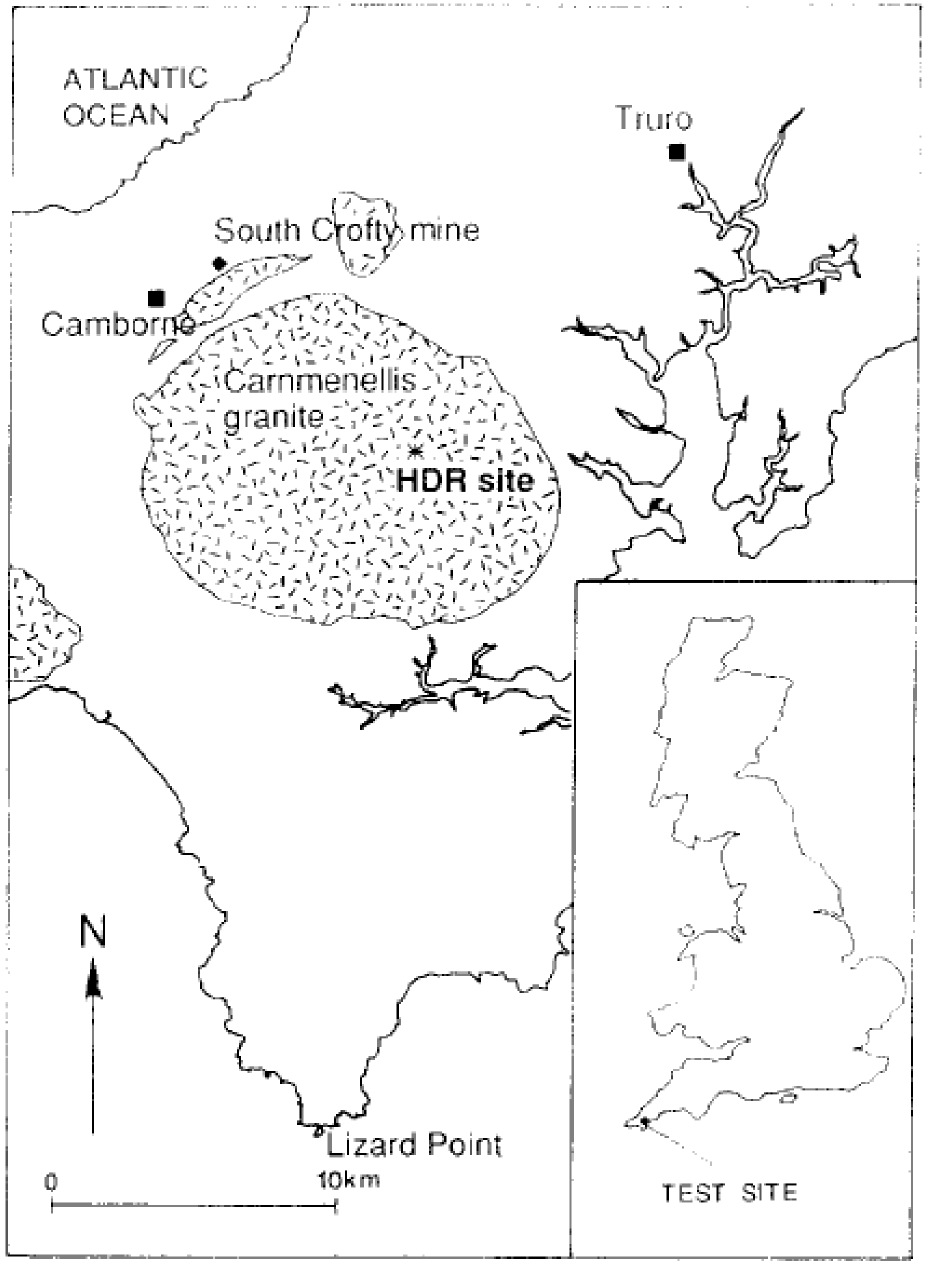


Fig. 3. Location of the Rosemanowes test site.

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.*

Rosemanowes Project
Fractures

Table 4. Joint spacings inferred from BHTV data in RH12 and RH15

Set	Well	*N*	Spacing (m)	
			Mean	Maximum
1 (cross-course)	RH12	55	1.5	12
1 (cross-course)	RH15	105	1.9	14
1 (cross-course)	Both	160	1.8	14
2 (lode)	RH12	61	3.9	18
2 (lode)	RH15	19	6.0	36
2 (lode)	Both	80	4.4	36

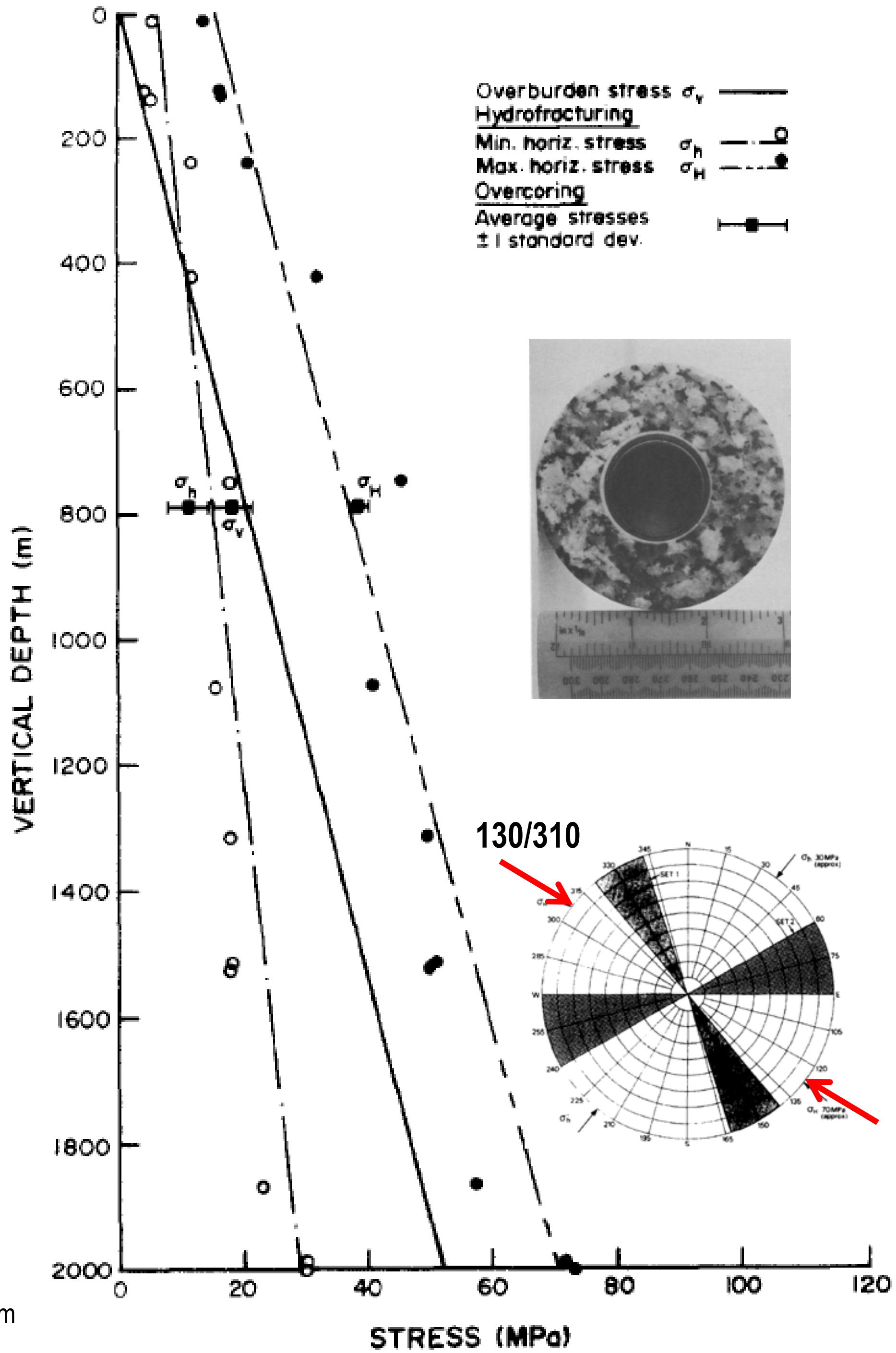
N = number of joints intercepted

- 보어홀 이미지를 통한 자료 취득
- 두 개의 수직적리군, 한 개의 수평절리군

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.*

Rosemanowes Project
In situ stress

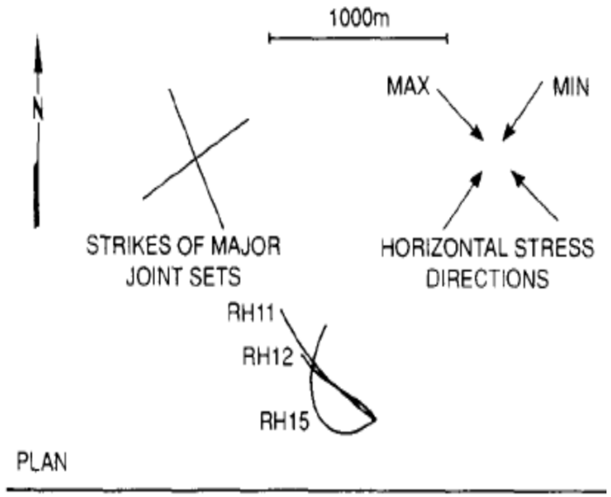
- 수압파쇄 (~2,000 m)
  - HDR 현장에서 실시. RH12
- 오버코링 (~790 m)
  - CSIRO Cell & USBM
  - ~10 km, south Crofty 광산
- 측정결과
  - Strike-slip faulting regime
  - S_H/S_h=2.4 → 큰 이방성
  - 수리전단에 유리한 조건

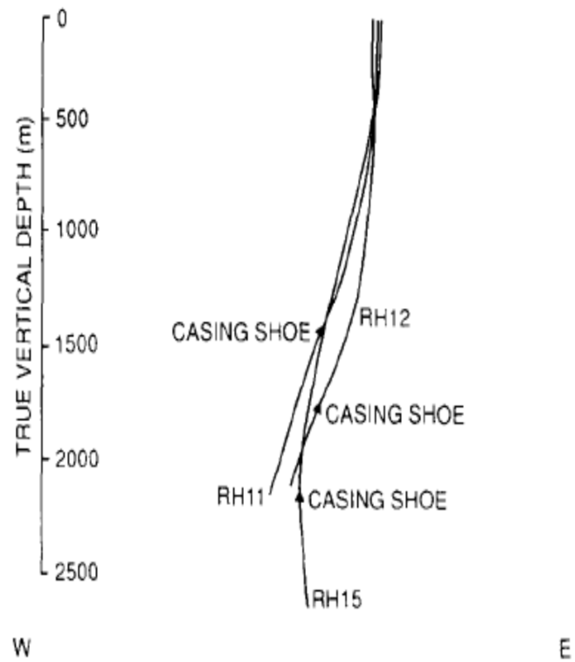


Pine, R. J., L. W. Tunbridge, and K. Kwakwa. "In-Situ Stress Measurement in the Carnmenellis Granite—I. Overcoring Tests at South Crofty Mine at a Depth of 790 m. *Int J Rock Mech Min Sci* 20(2) (1983): 51-62.
Pine, R. J., P. Ledingham, and C. M. Merrifield. "In-Situ Stress Measurement in the Carnmenellis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

Rosemanowes Project
Boreholes

- RH12 (D=311 mm), 경사 최대 32°





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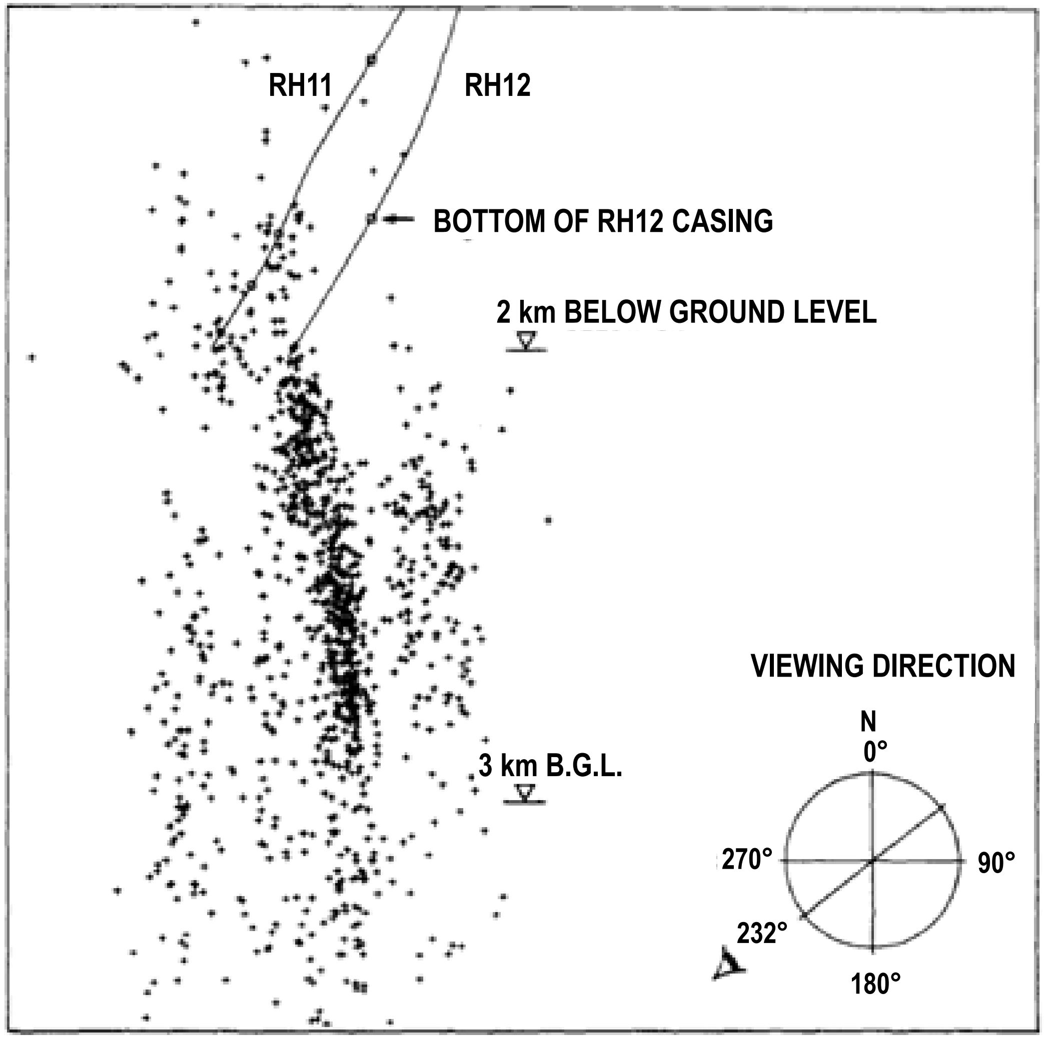
Rosemanowes Project
Hydraulic stimulation

- Phase 2A 시험 (1980-1983)
  - 임피던스: 1.5 MPa/(l/s)
  - 용수손실률 : 70-75%
  - 아래로의 인공저류층 형성
    (downward migration)
  - 추가 시추하기로 결정함.



Pine, R. J., and A. S. Batchelor. "Downward Migration of Shearing in Jointed Rock During Hydraulic Injections." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 21, no. 5 (1984): 249-63.*

Rosemanowes Project
Hydraulic stimulation

- Phase 2B (1983-1986)
  - RH15 나선형 시추 (2.6 km) → 여전히 높은 손실률 → 점성유체 주입
  - RH12/RH15 시스템(최소 133 m): 임피던스 1.0 MPa/(l/s), 손실율 20%
- Phase 2C (1986-1988)
  - 다운홀 펌프 설치→ 임피던스 증가 (공벽주변 절리 닫힘), 회수율 향상 80-85%
  - 고정유량 (21.5 l/s) 장기거동 관찰
  - 온도 하강 1°C/month
  - 추적자 시험 (Na-fluorescein과 bromine)
  - 반복주입시험 (주기 1시간, 총 100시간)

Rosemanowes Project
Hydraulic Stimulation – temperature draw down

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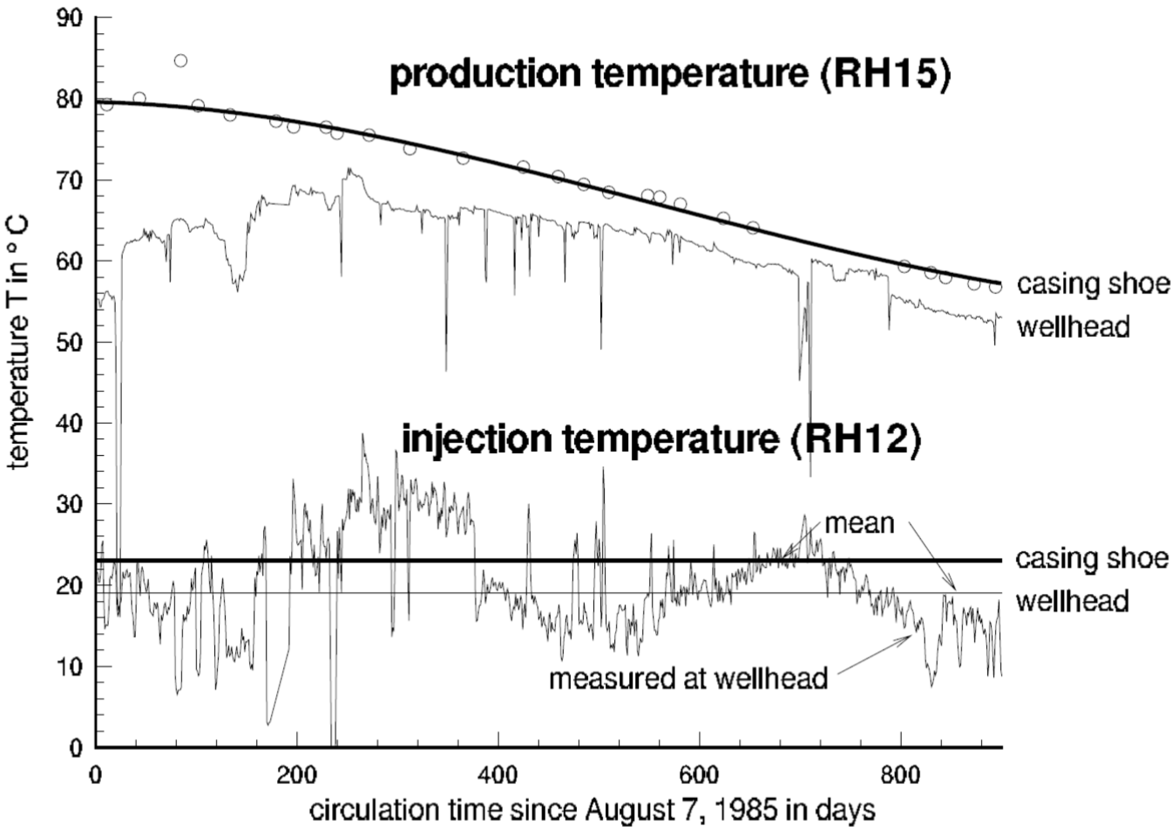

Rosemanowes Project
Conductive-convective heat transfer in a single fracture

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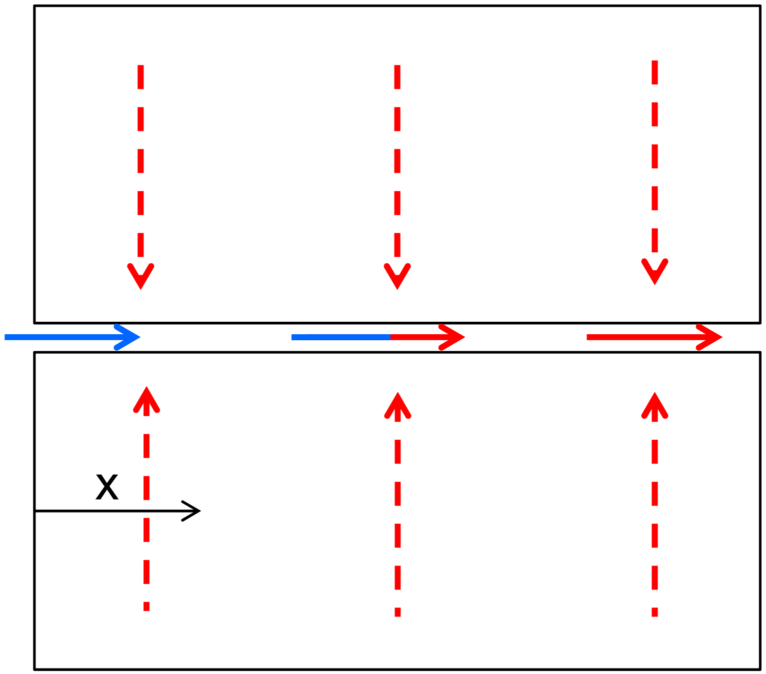
- Temperature variation due to conduction-convection in a single fracture with unit width (Bodvarsson, 1969)
  - Boundary assumed to be infinite with constant temperature
  - Conduction in the rock (only in y direction), convection in fracture



$$T_x = T_{rock} - \left(T_{rock} - T_{inj}\right) \cdot erfc\left[\left(\frac{k}{c_w m}\right) x / \sqrt{\alpha t}\right]$$

T_x : temperature at x

T_{rock} : temperature of rock

T_{inj} : injection temperature

k : thermal conductivity of rock

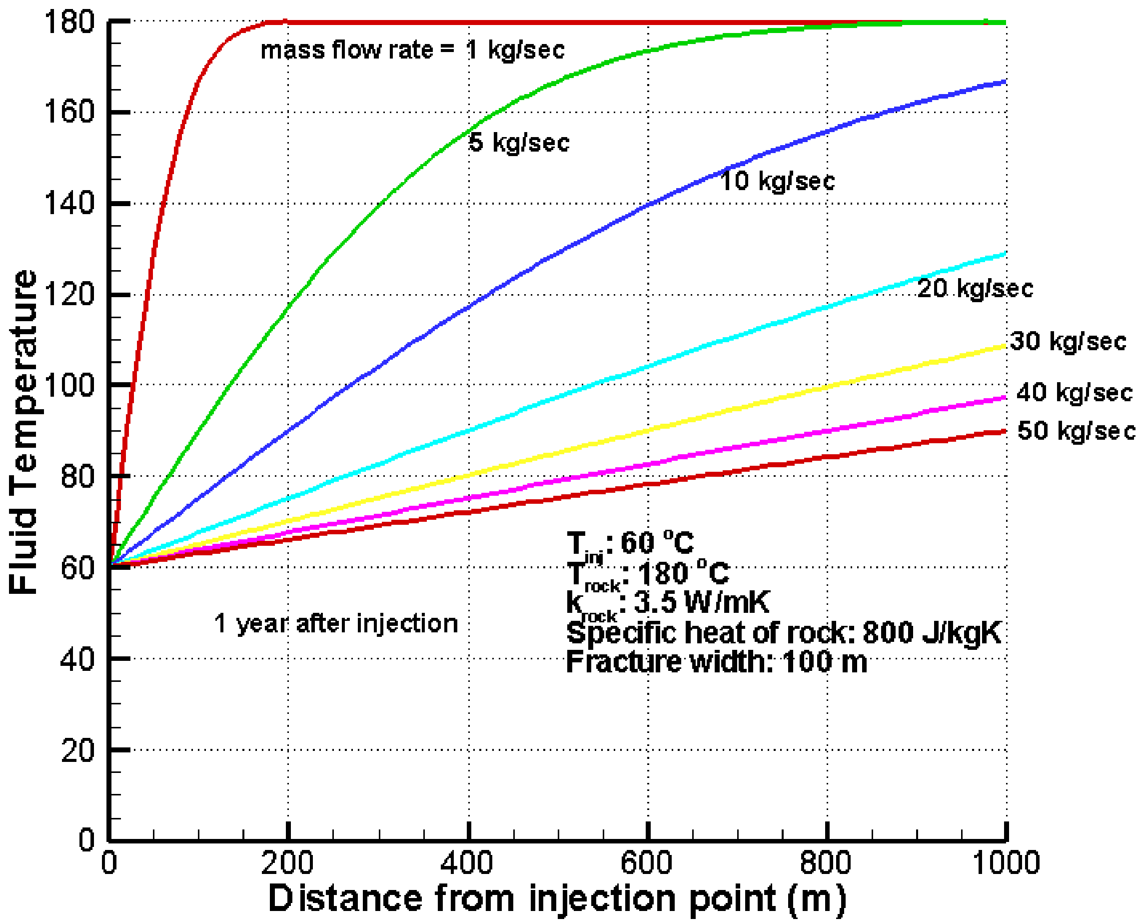
c_w : specific heat of water

m : mass flow rate (kg/sec)

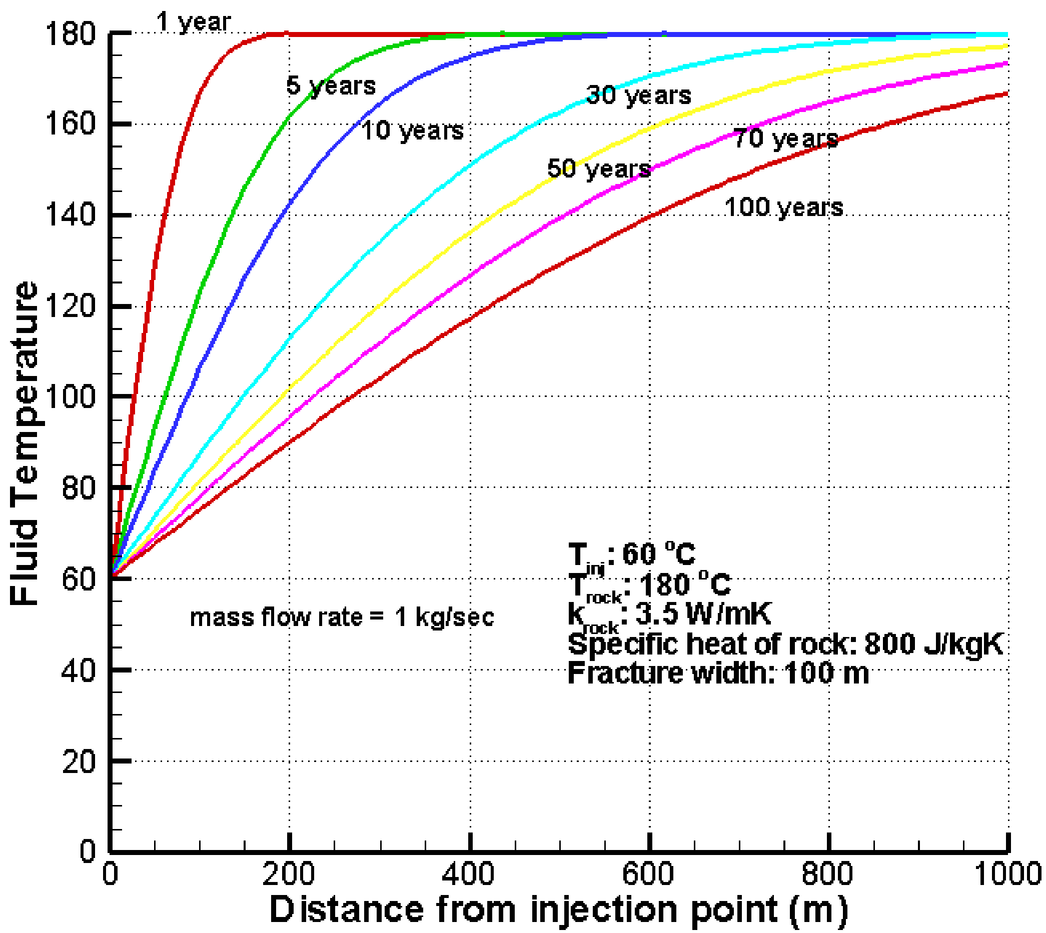
α : thermal diffusivity of rock

t : time after injection(sec)

Rosemanowes Project
Conductive-convective heat transfer in a single fracture



Rosemanowes Project
Conductive-convective heat transfer in a single fracture



Rosemanowes Project
Hydraulic Stimulation

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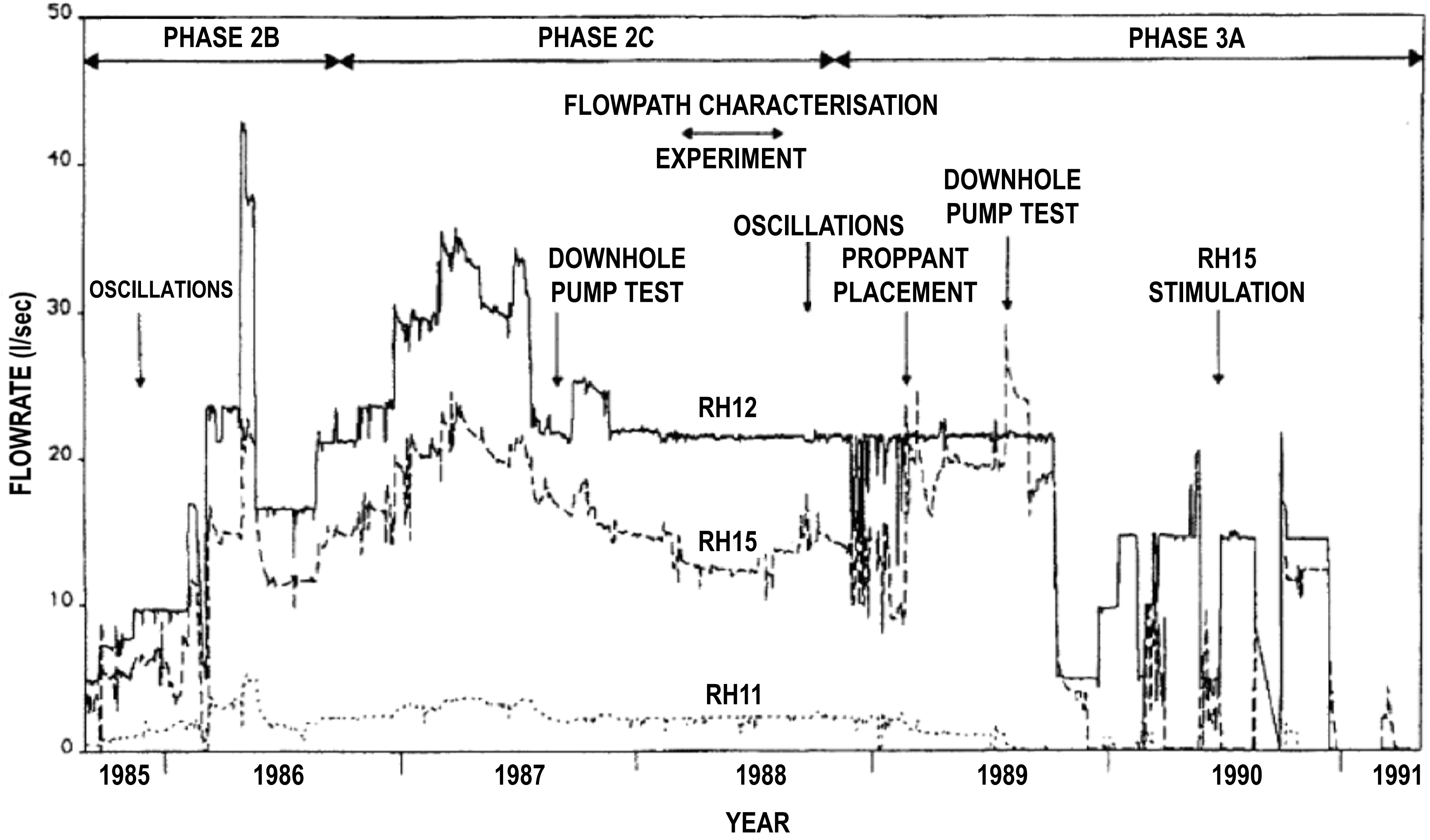
- Phase 3 (1988-1991)
  - 상업발전을 위한 Prototype 확립
  - 프로판트 주입시험: 모래 55톤, 젤 (700cp) 530m3, 85 l/s, 24 Mpa → 임피던스는 줄고(~0.5), 회수율 증가하였으나 열적성능은 감소
  - 저류량 구간 생산시험 (Low Flow Zone Production Test, LFZPT): 숏서킷을 막기위한 인위적 공벽 막기 시험...→ 인위적 지열저류층 향상은 쉽지 않다.
  - 6 km 지열저류층 개발 계획 제시 (multi-cell 개념)
  - 이 지역의 지온경사가 높지 않고, 인공저류층 형성기술은 미성숙되어 성공하더라도 너무 비싸므로 현 단계에는 유럽 과제에 집중하는 것이 낫다는 이유로 1991년 영국 정부 지원 중단 결정*.

*Harrisson, R., and G.D. Symons. "HDR Economics: A Review of the Uk Geothermal Hot Dry Rock R&D Programme." *Geothermal Resources Council Transactions* 15 (1991): 333-37.

Rosemanowes Project
Hydraulic Stimulation



Parker, R. "The Rosemanowes HDR Project 1983-1991." *Geothermics* 28, no. 4-5 (Aug-Oct 1999): 603-15.

Rosemanowes Project
Lessons

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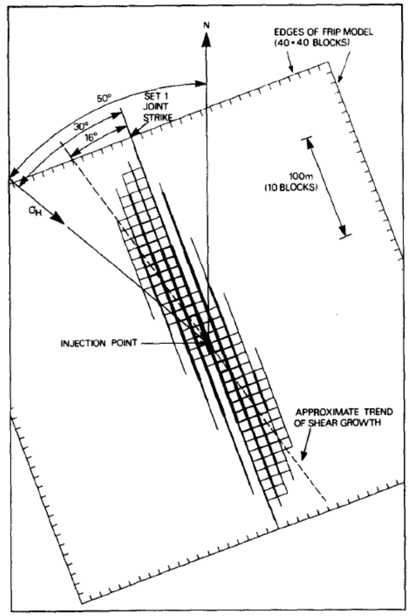
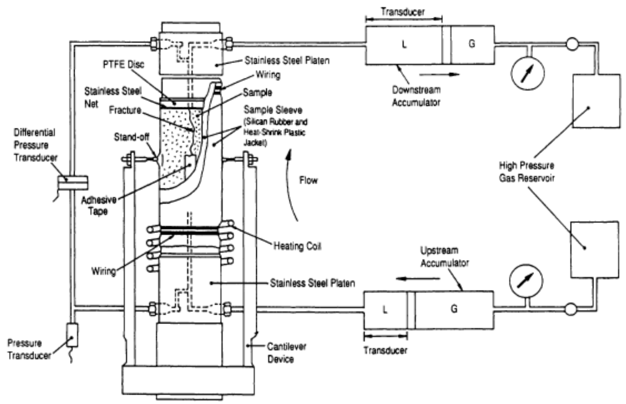
- 지열저류층 수리자극시 전단파괴의 중요성
- 균열암반의 수리역학적 수치해석 프로그램 개발
  - UDEC의 시초
- 균열암반의 열-수리-역학적 거동
  - Zhao and Brown (1992)
- 다운홀펌프, 프로판트, 점성유체시도 등





Zhao, J., and E. T. Brown. "Hydro-Thermo-Mechanical Properties of Joints in the Carnmenellis Granite." *Quarterly Journal of Engineering Geology* 25, no. 4 (1992): 279-90.
Pine, R. J., and A. S. Batchelor. "Downward Migration of Shearing in Jointed Rock During Hydraulic Injections." *Int J Rock Mech and Min Sci 21, no. 5 (1984): 249-63.*

Rosemanowes Project
Lessons

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- The unfavourable orientation of the openholes of RH11 and RH12 arose through lack of knowledge of the jointing pattern and *in situ* stress regime at depth, before the wells were drilled. The intention had been to drill the wells such that the azimuth of the openholes was half way between what were thought to be the two major jointing directions (Batchelor, 1985). With hindsight, it appears that the wells should have been drilled with their azimuths parallel to the minimum *in situ* horizontal stress direction. The fact that this was not done has severely compromised the experimental programme that followed.

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.*

Rosemanowes Project
Lessons

- Location of injection and production well
  - In situ stress & fracture distributions
- Effect of viscosity as injecting fluid
- Thorough theoretical studies on design parameters
  - Performance parameters, reservoir parameters, operation parameters
- In situ stress model

Soultz Project
Overview

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- 시작: 1987년 (첫 발전: 2008년 6월)
- 설치용량: 1.5 MW (현재 ~ 500 kW생산)
- 총예산: 80 m euro(EC), 25 m euro (French Gov), 25 m euro (German Gov)
- Temperature: 157 ℃, 25 ℓ/sec at 5,000 m depth

Soultz Project
Overview

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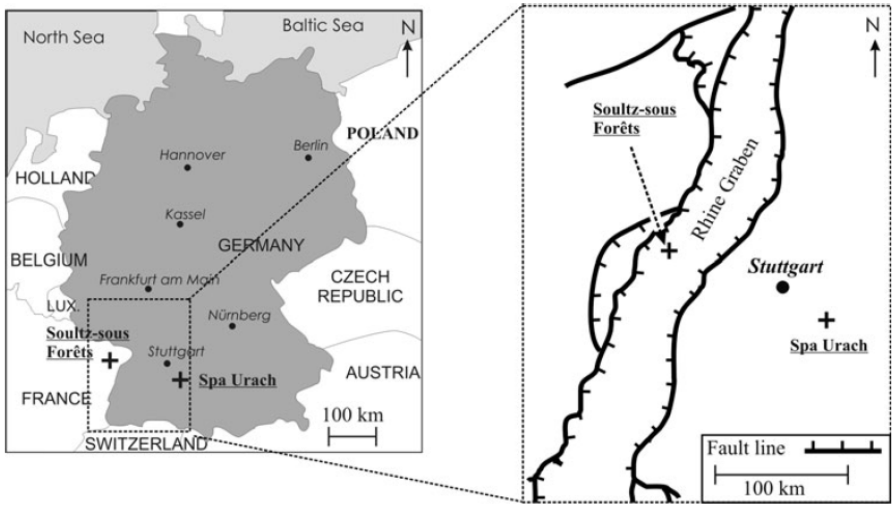
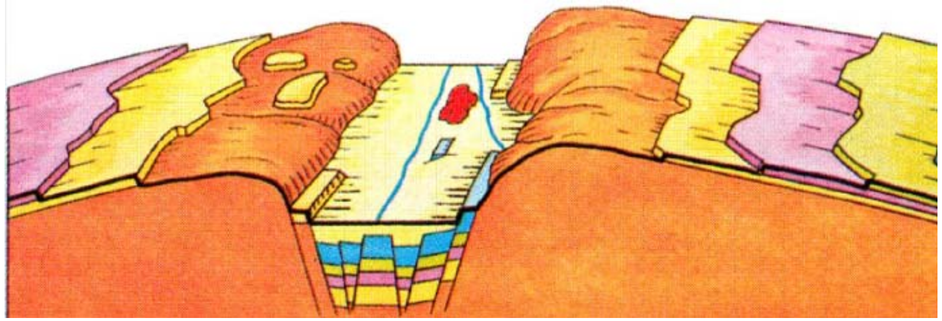


- High quality geothermal resources in Rhine Graben
- Graben(지구대): a downthrown, linear, crustal blocks bordered lengthways by normal faults.



Courtesy of Hettkamp

Soultz Project
Overview

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The main project steps

Géothermie Soultz

1987 – 1991
Exploration phase

- Drilling GPK1 at - 2000 m
- Coring EPS1 at - 2227 m

1991 – 1998
Creation of the 2 wells system GPK1/GPK2 at - 3600 m

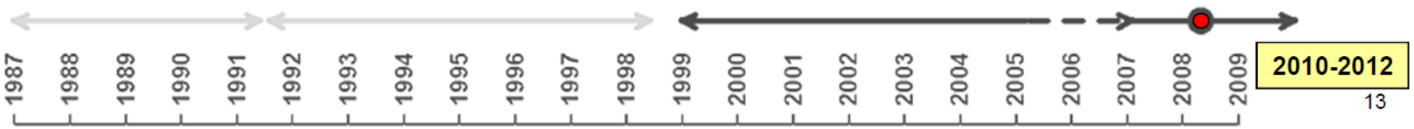
- Deepening of GPK1 at - 3600 m and stimulation
- Drilling of GPK2 at - 3880 m and stimulation
- Circulation test between the 2 wells (4 months)

1999 – 2007
Creation of the 3 wells system GPK2/GPK3/GPK4 at - 5000 m

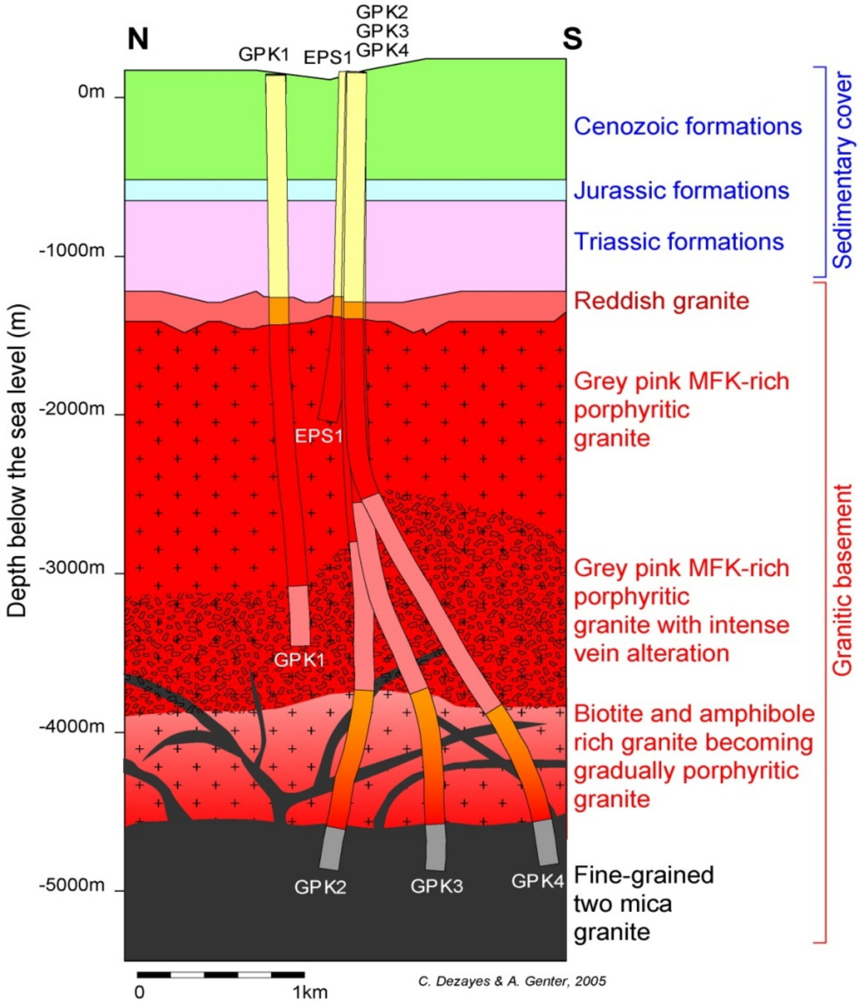
- Deepening of GPK2 at - 5080 m and stimulation
- Drilling of GPK3 at - 5100 m and stimulation
- Drilling of GPK4 at - 5270 m and stimulation
- Circulation test between the 3 wells (5 months)
- Complementary stimulations (chemical)

2007 – 2009
Construction of the first production unit ORC - 1.5 MWe

- **Installation of surface equipment (turbine and generator, heat exchangers, cooling systems …)**
- **Installation of the LSP in GPK2 at - 350 m**
- **Inauguration of the power plant 13.06.2008**
- **Installation of the ESP in GPK4 at - 500m**

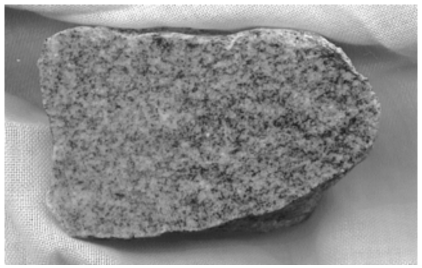


Soultz Project
Geology



7 cm

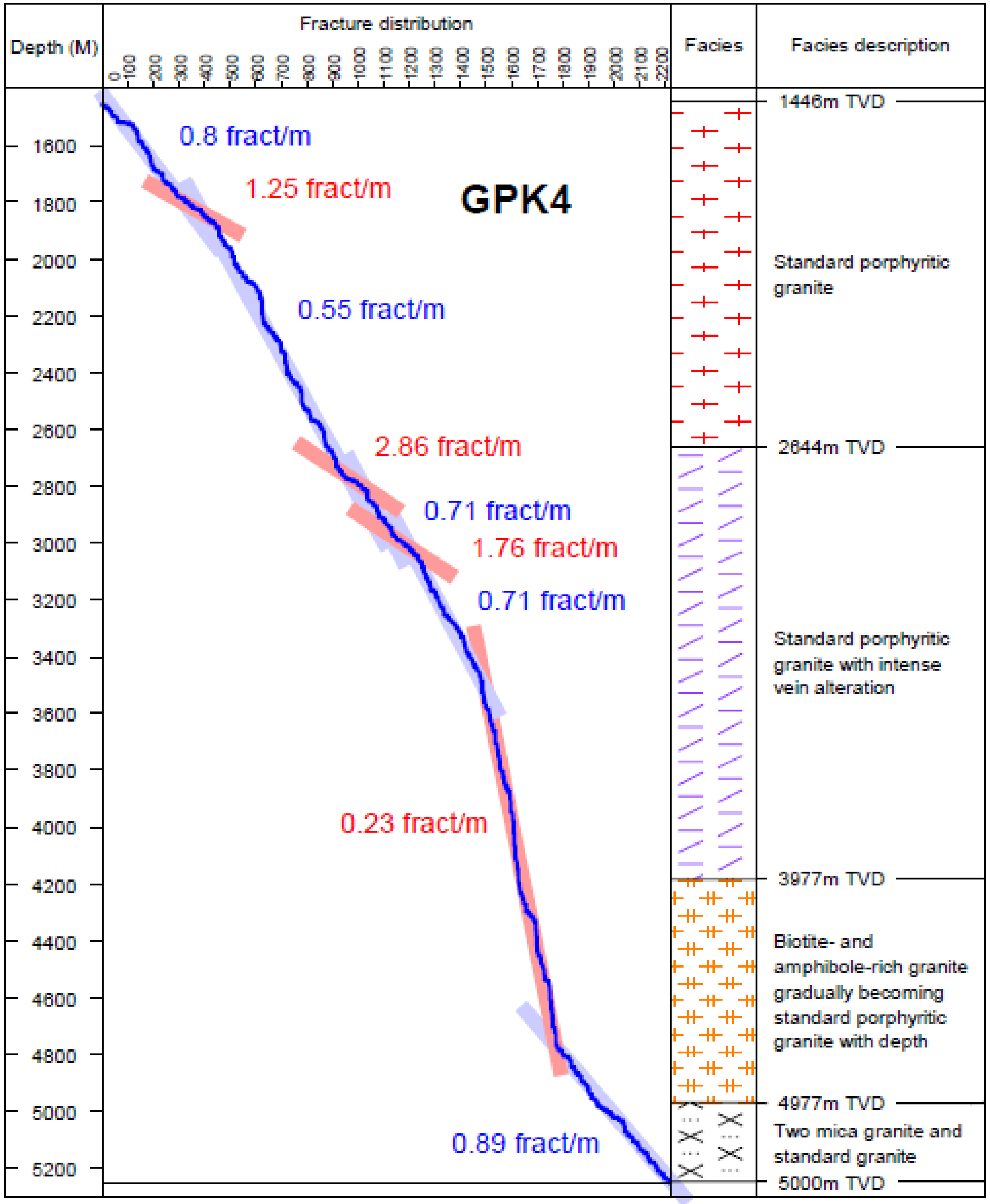
Monzogranite
GPK-1(3510 m)
Plagioclase, quartz, biotite and hornblende



Mica granite
GPK2(5058 m)
biotite and muscovite

Soultz Project
Geology - fractures

- 보어홀 이미지를 통한 자료 취득
- 0.2 ~ 2.9 frac/m (P10)
- 누적 절리 수 ~ 2,200



Dezayes, C., A. Genter, and B. Valley. "Overview of the Fracture Network at Different Scales within the Granite Reservoir of the Egs Soultz Site (Alsace, France)." In *Proc World Geothermal Congress Paper No.3116. Bali, Indonesia, 2010.*

Soultz Project
boreholes

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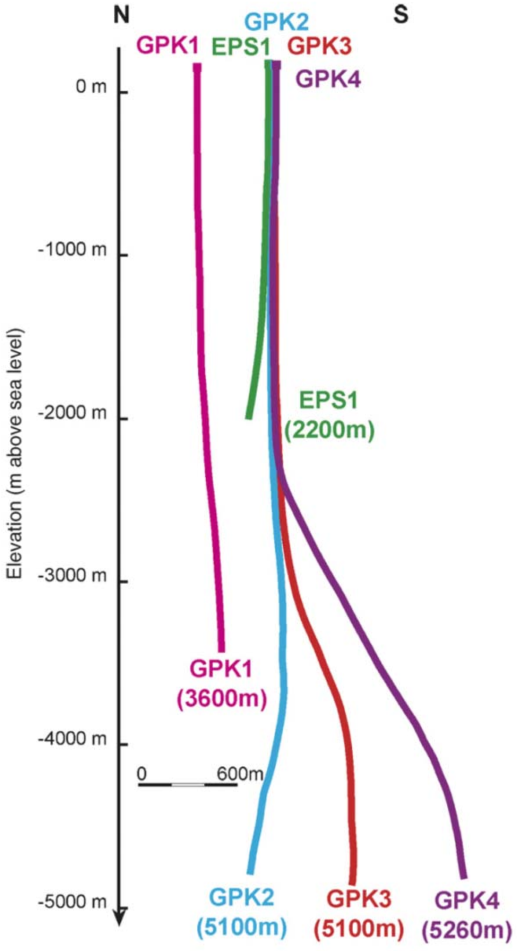
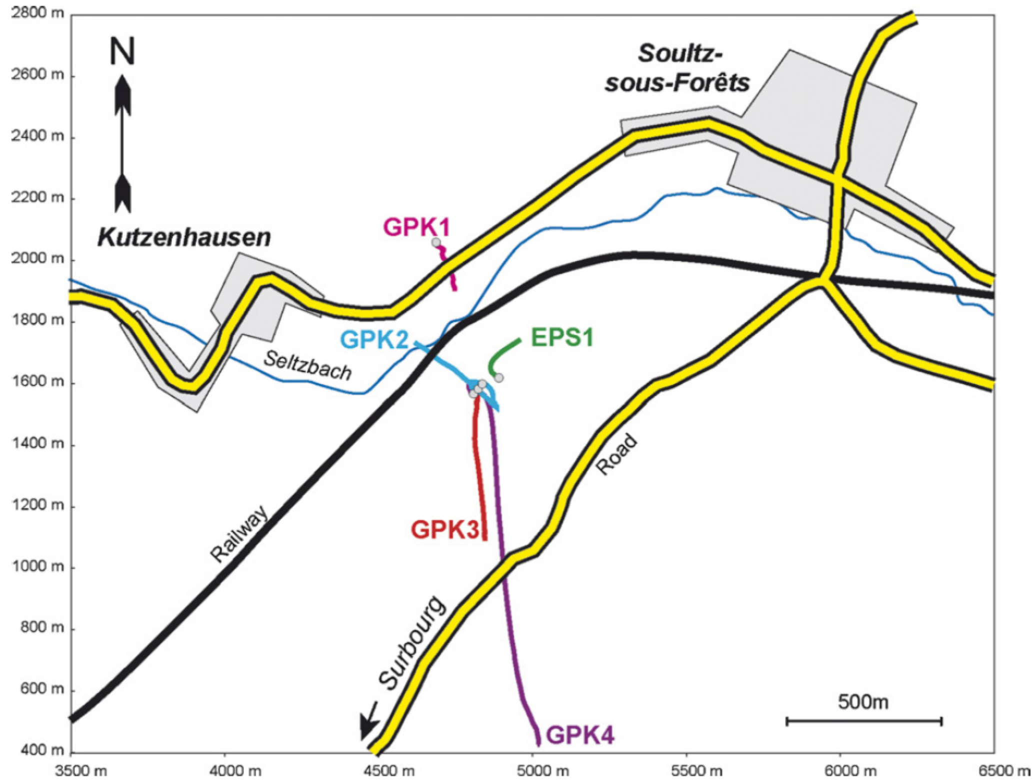
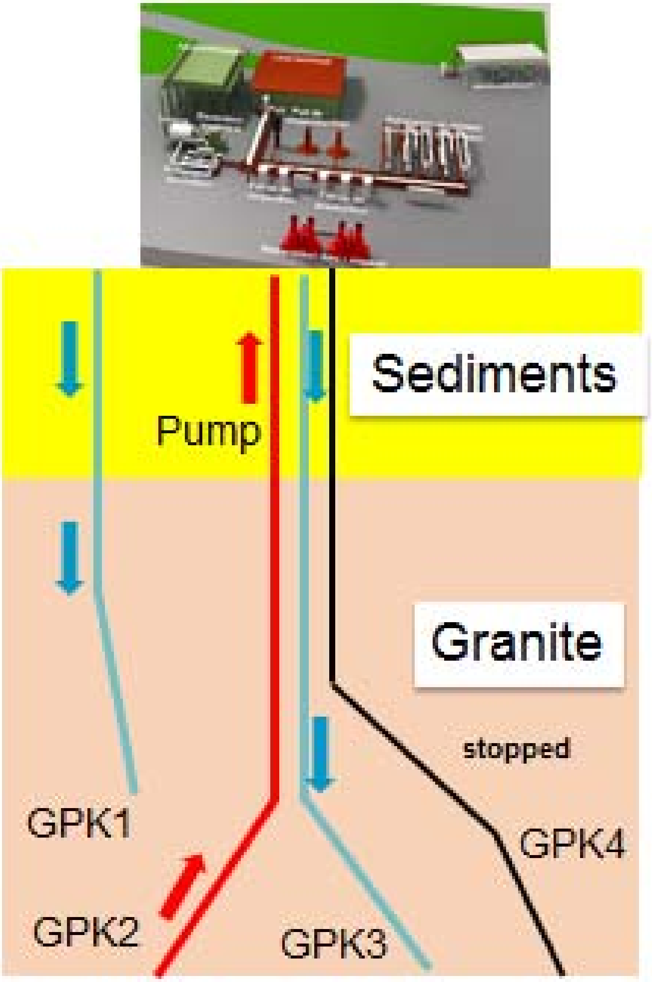




Gerard et al., 2006

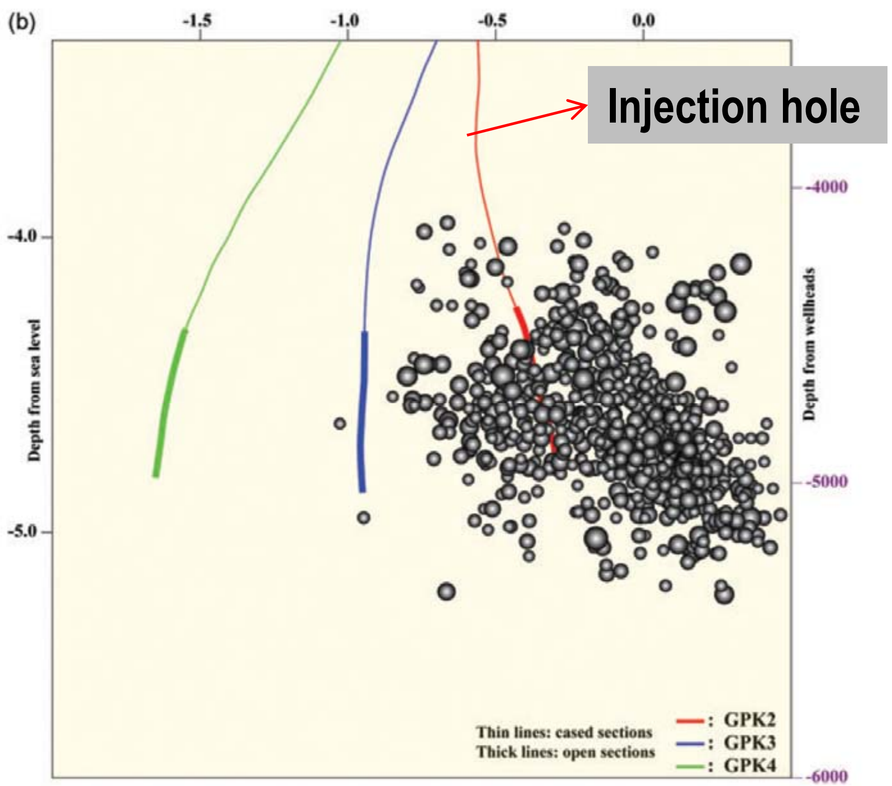
Soultz Project
current status

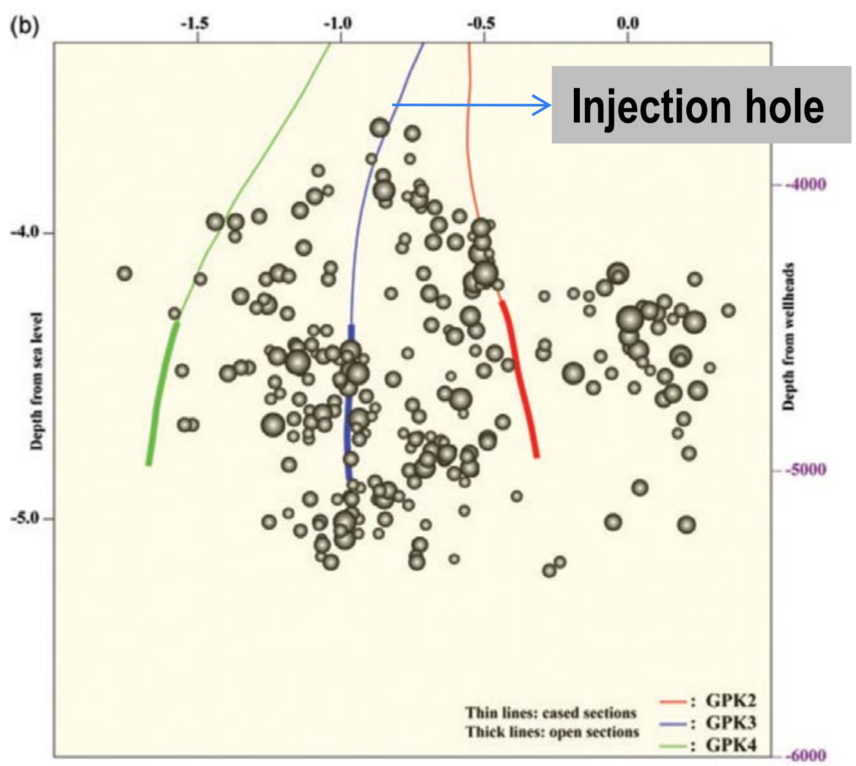


Genter et al., 2012

- Down-hole pump (GPK2) at 260 m.
- Two injection wells & one production well → can reduce the injection pressure & microseismicity
- Microseismic event: 400 (2009) → 25 (2010) → 5 (2011)

Soultz Project
Microseismicity



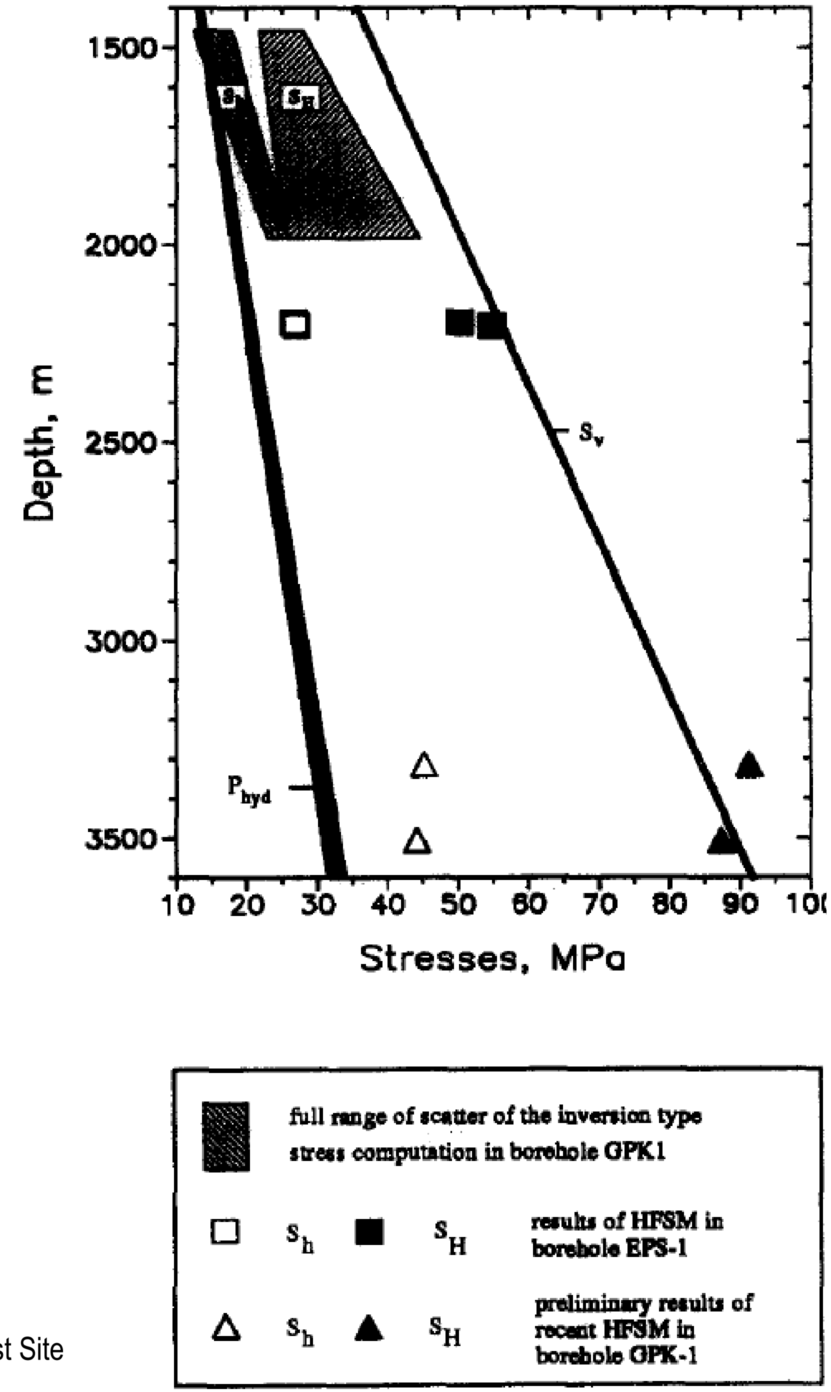


- M > 1.0

Dorbath et al., 2009, Seismic response of the fractured and faulted granite of Soultz-sous-Forets (France) to 5 km deep massive water injections, Geophys. J. Int, 653-675

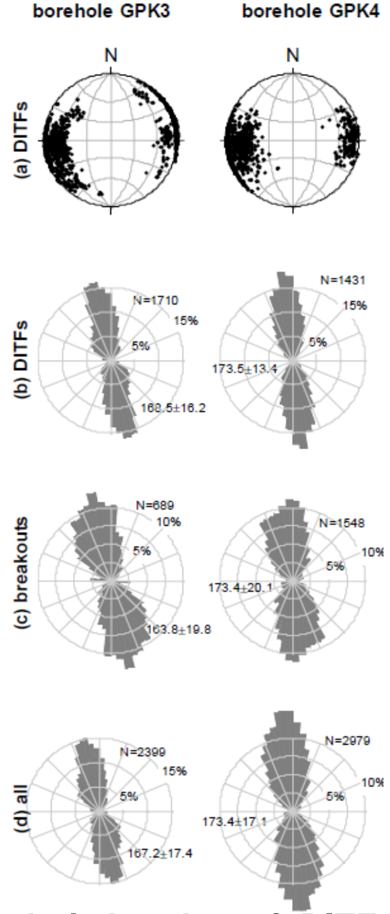
Soultz Project
In situ stress

- 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)

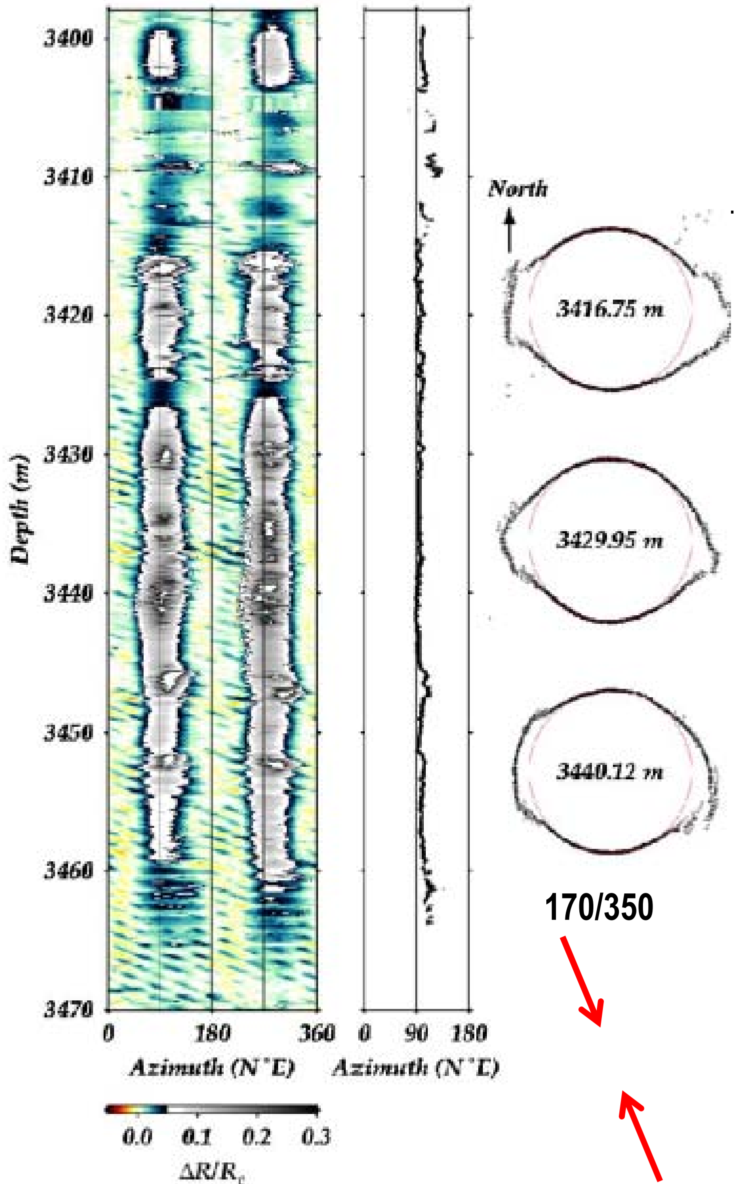


Klee, G., and F. Rummel. "Hydrofrac Stress Data for the European Hdr Research Project Test Site Soultz-Sous-Forets. *Int J Rock Mech Min* 30(7) (1993): 973-76.

Soultz Project
Borehole observation



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.*

Soultz Project
Lessons

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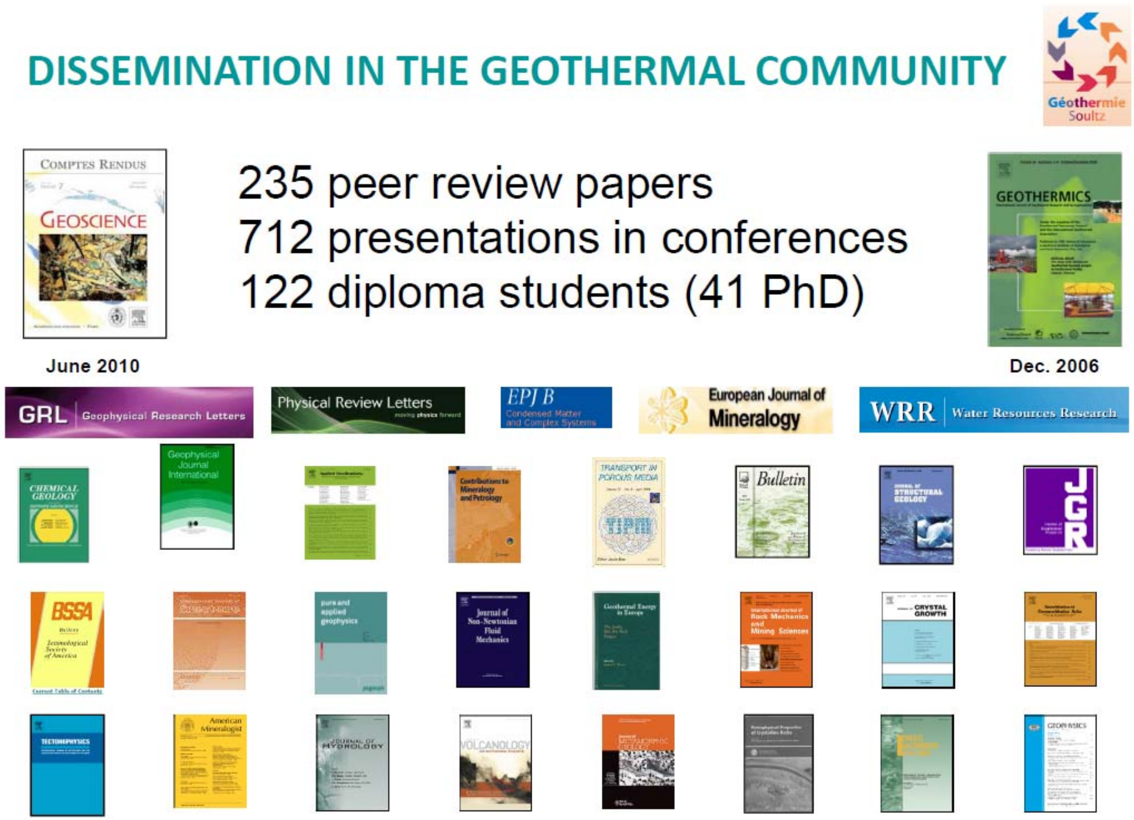
- 지질, 지구화학, 지오메카닉스, 지구물리 등 폭넓고, 깊이있는 연구진행됨. (독일, 프랑스, 스위스, 일본)



Genter, 2012

Soultz Project
Lessons

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- EGS 지열발전소 운영의 경험
  - 스케일링, 플랜트 운영, 다운홀 펌프,
- EGS 저류층 장기거동 문제점 파악
  - 물-암석 지구화학 반응
- Triplet system 에 대한 재고/검토
  - 두개의 주입공과 한 개의 생산공
- 첫 번째 수리자극 전 후의 정확한 모니터링이 중요
  - 응력장의 교란이 일어날 수 있음
- 미소진동 저감 실시
- 자료공유를 통한 공동 연구

Genter, 2012

Cooper Basin Project
Overview

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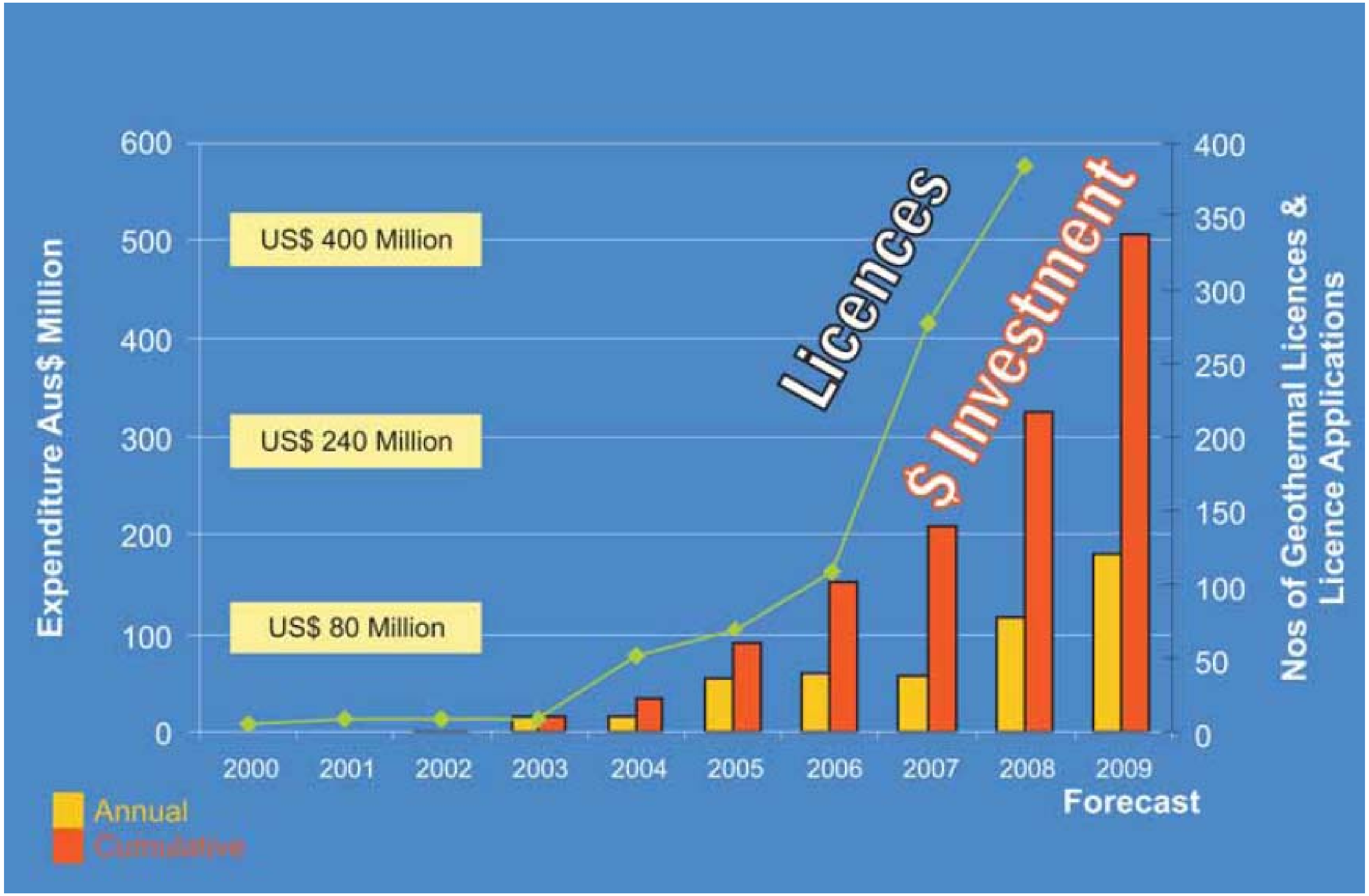

Goldstein et al., 2008

Cooper Basin Project
Australian Geothermal – reporting code

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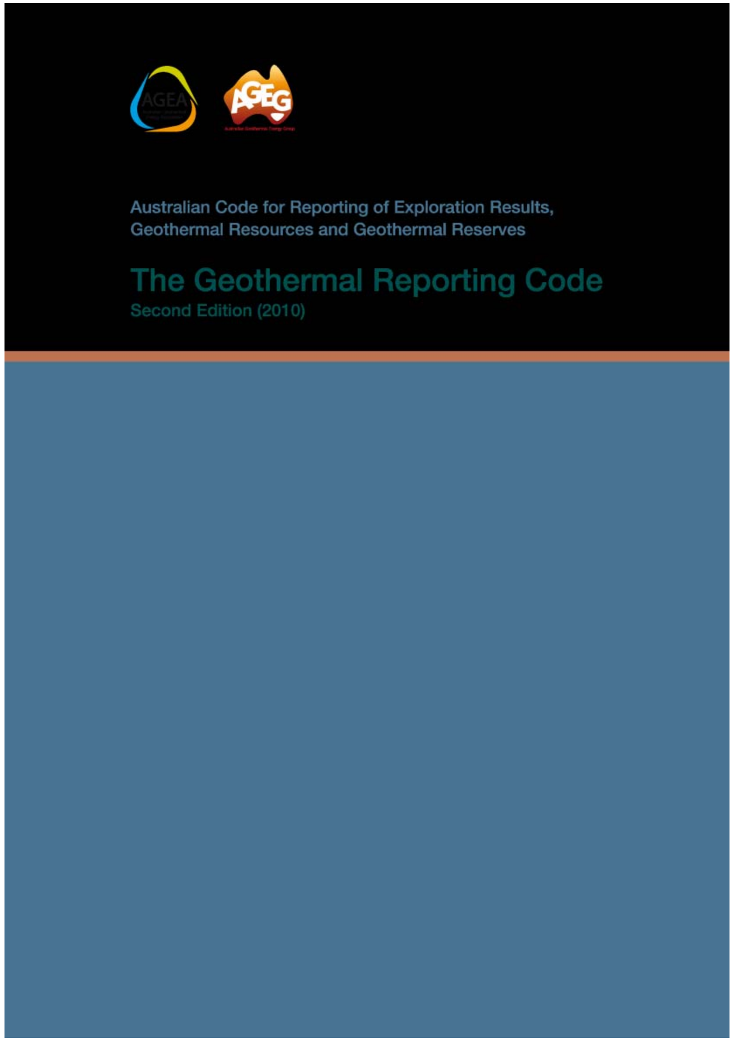
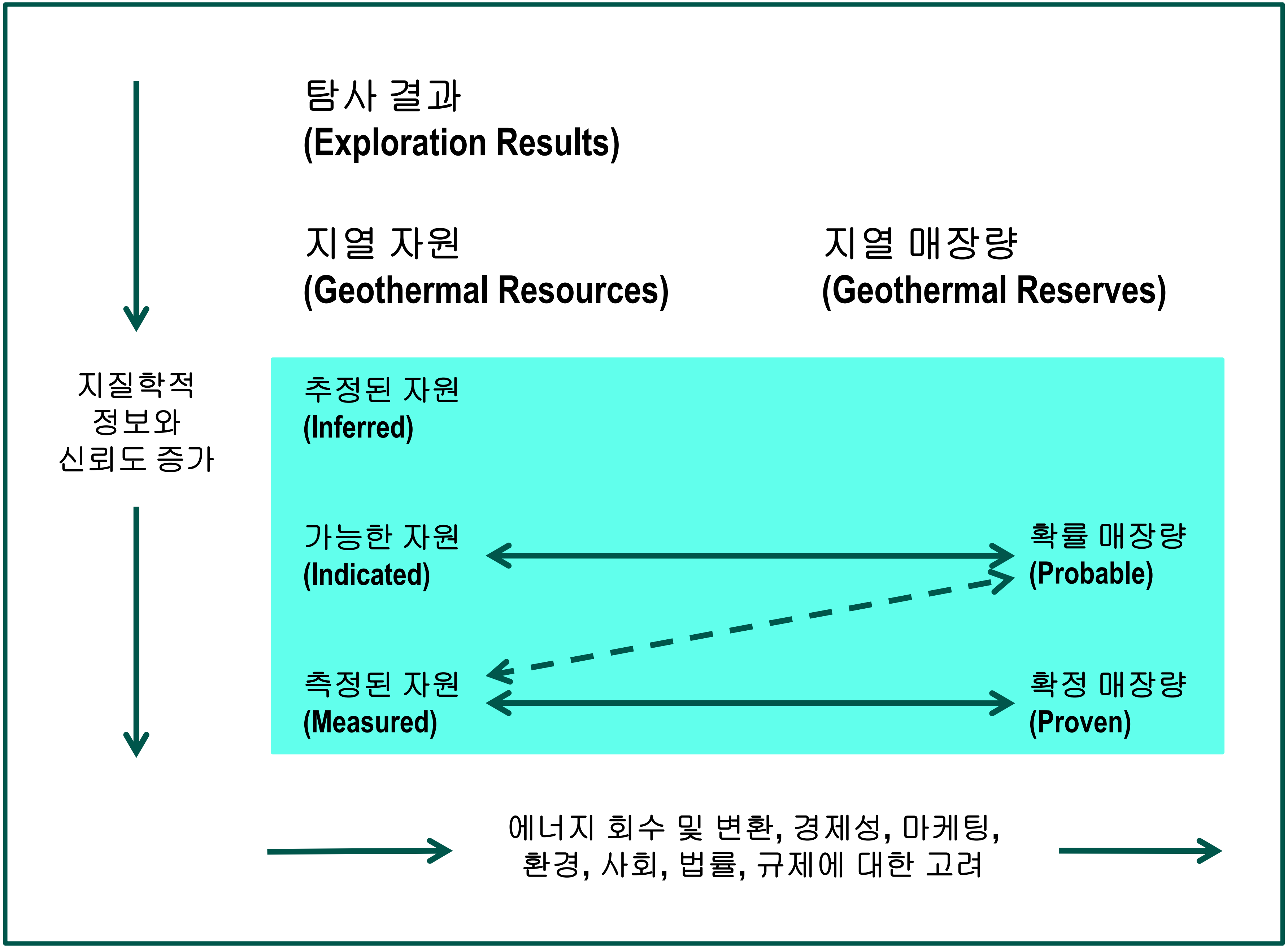


- Uniform code to guide the reporting of geothermal data to the market
- Aims to foster understanding and a good reputation in the market place with investors, regulators and the public
- http://www.pir.sa.gov.au/geothermal/ageg/geothermal_reporting_code


탐사 결과
(Exploration Results)
지열 자원
(Geothermal Resources)
지열 매장량
(Geothermal Reserves)
지질학적 정보와 신뢰도 증가
추정된 자원
(Inferred)
가능한 자원
(Indicated)
확률 매장량
(Probable)
측정된 자원
(Measured)
확정 매장량
(Proven)
에너지 회수 및 변환, 경제성, 마케팅, 환경, 사회, 법률, 규제에 대한 고려

Cooper Basin
Overview

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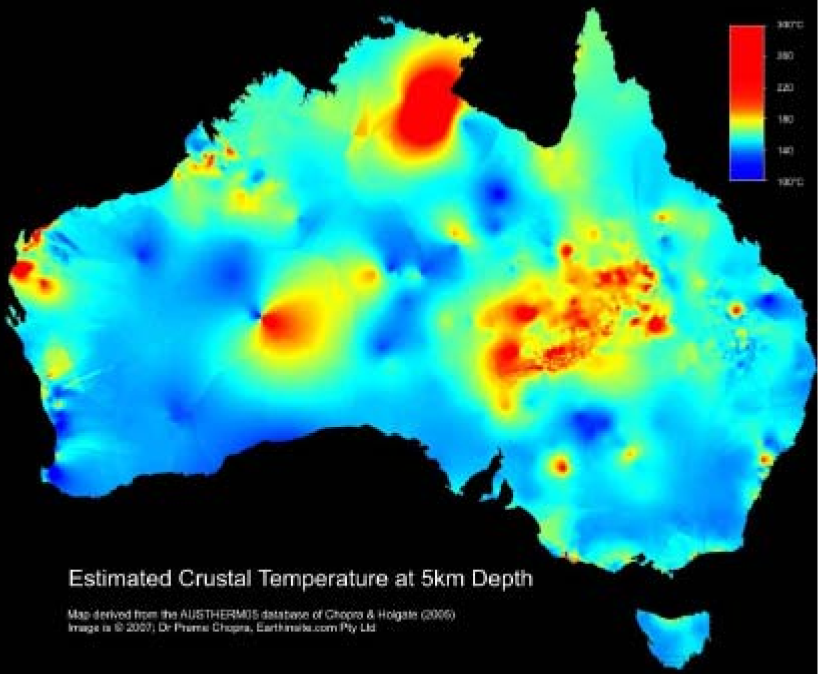
- Significant global EGS resource in the Cooper Basin
- Potential for 10,000 MW of baseload emission free electricity generation capacity
- Long term goal of sub $100 / MWh power cost (delivered into grid)
- Size and quality of resource outweighs any distance concerns

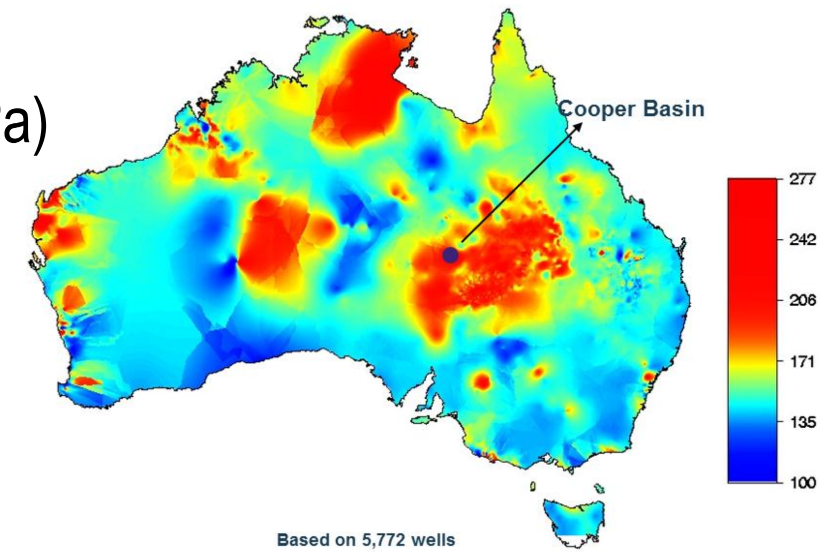


Estimated Crustal Temperature at 5km Depth

Long term goal of the Joint Venture with Origin Energy remains to bring this considerable energy resource to market

Cooper Basin
Overview

- 덮개암(셰일/석탄, 60°C/km) ~3.5-4.5 km, 화강암 (고생대 석탄기, 3억 2천만년)
- 호주 최대의 육상 유/가스전
- 세계최대의 우라늄 매장지대 인근 (올림픽 댐 광산)
- 다량의 방사성 동위원소 7-10 μW/m^3 (화강암 평균 2.8, 다른 암종 ~1 μW/m^{3*})
- 과잉간극수압 상태 (정수압 +35MPa)
- Geodynamics/Origin

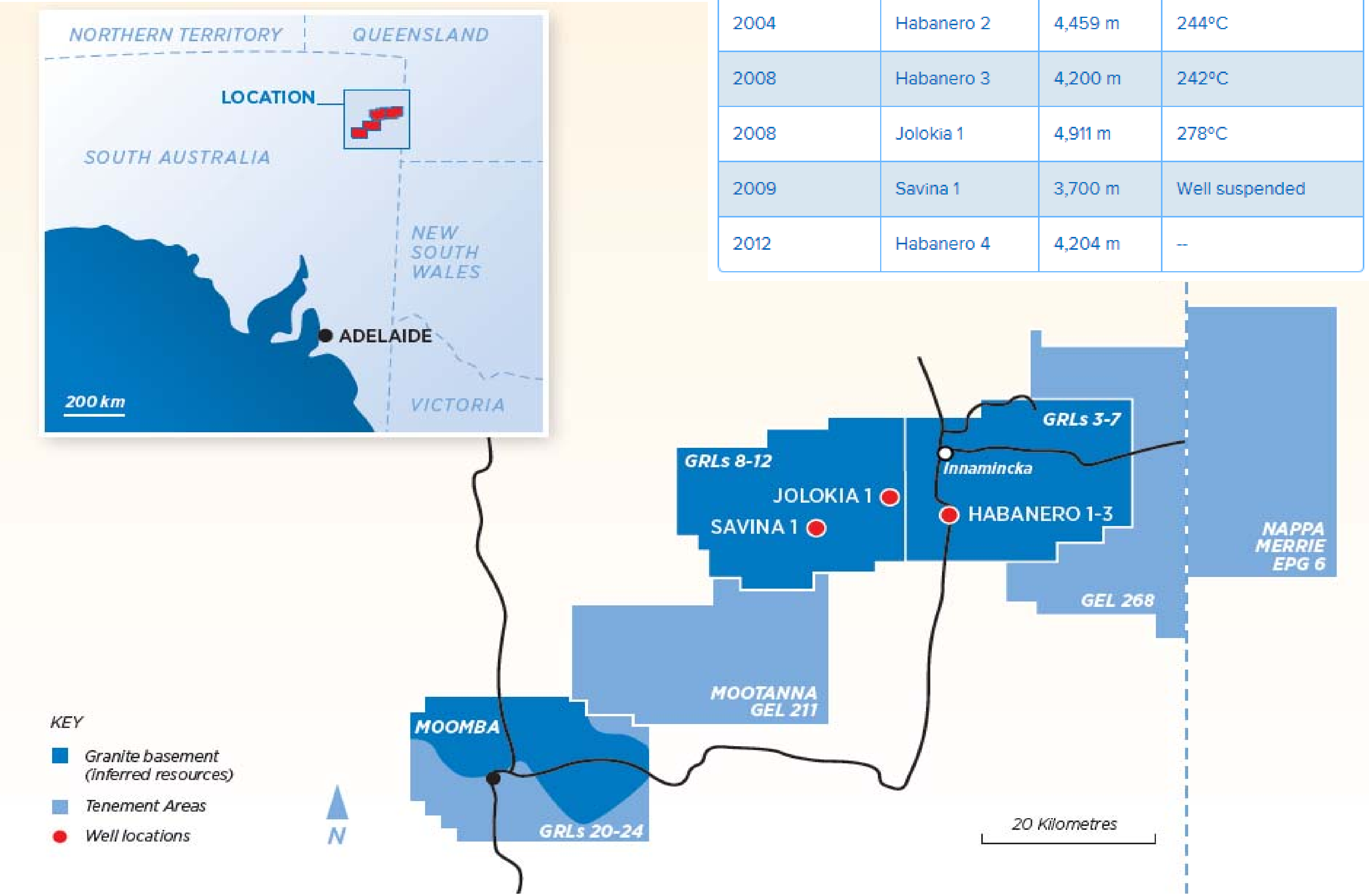


*Beardsmore & Cull, 2001, Crustal Heat Flow, Cambridge Press

Cooper Basin
Overview

Wells to Date

Date Drilled	Name	Depth	Temperature
2003	Habanero 1	4,421 m	243°C
2004	Habanero 2	4,459 m	244°C
2008	Habanero 3	4,200 m	242°C
2008	Jolokia 1	4,911 m	278°C
2009	Savina 1	3,700 m	Well suspended
2012	Habanero 4	4,204 m	--

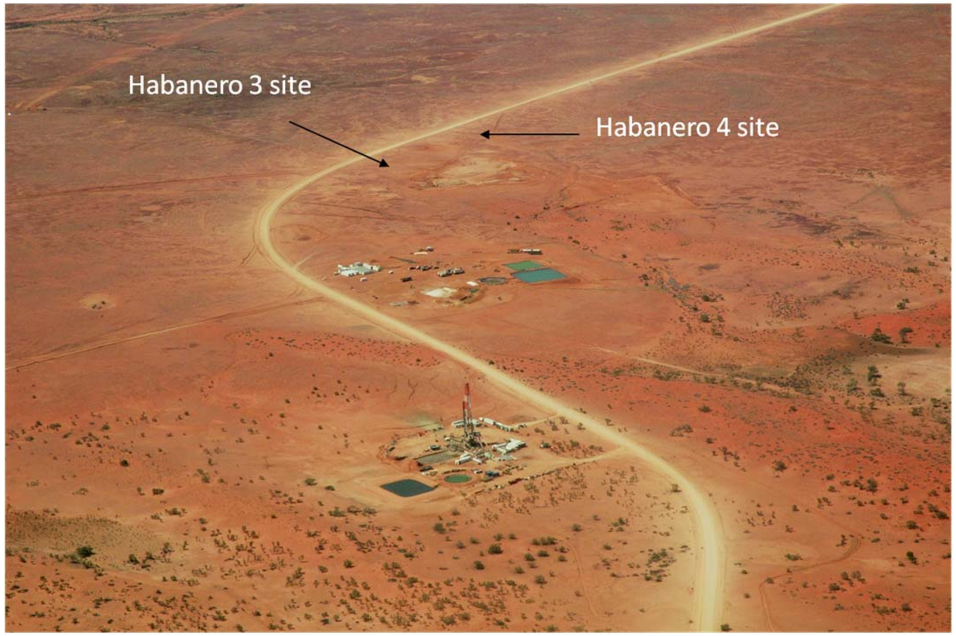


Cooper Basin
Overview

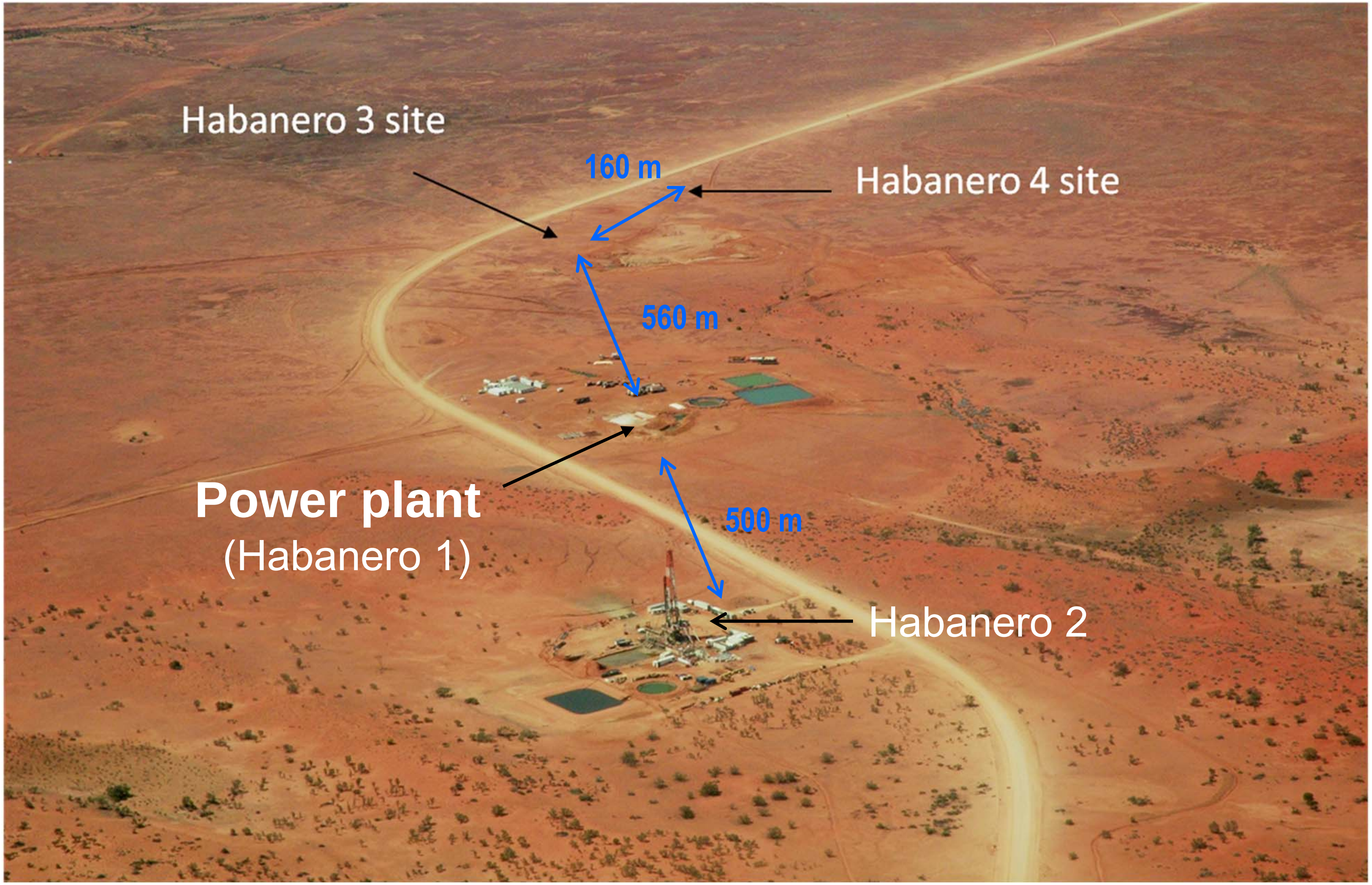
Habanero chili, Jolokia chili and Savina chili : 세계에서 가장 매우 고추

Cooper Basin
Overview

- High Heat Production granites
- Finding buried granites does not require new technology
- Coal measures in the overburden act as an insulator
- Over thrust stress environment leads to potential for large scale development
- Demonstrated 277°C at 4,900m



Cooper Basin
Overview

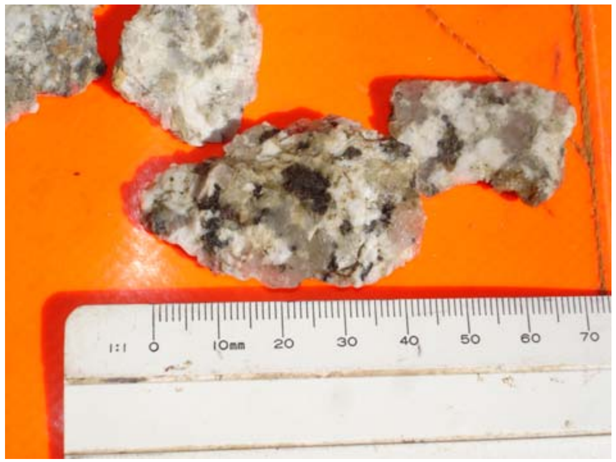


Cooper Basin
Geology

3.5 – 4 km

Sedimentary rock (coal/shale)

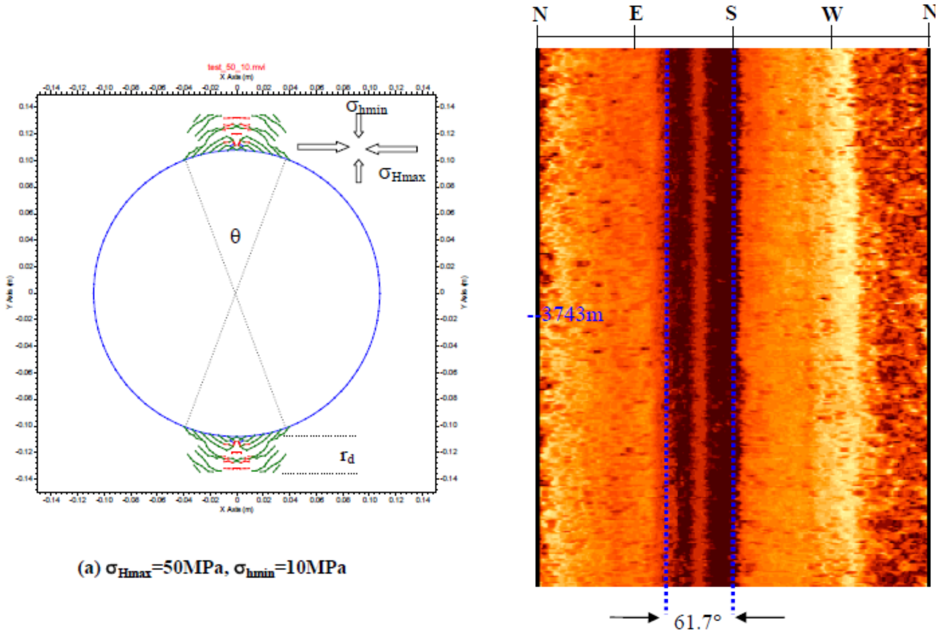
Granite base



Borehole breakout 암편 (Wyborn, 2011)

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.*

Cooper Basin
Borehole Breakout

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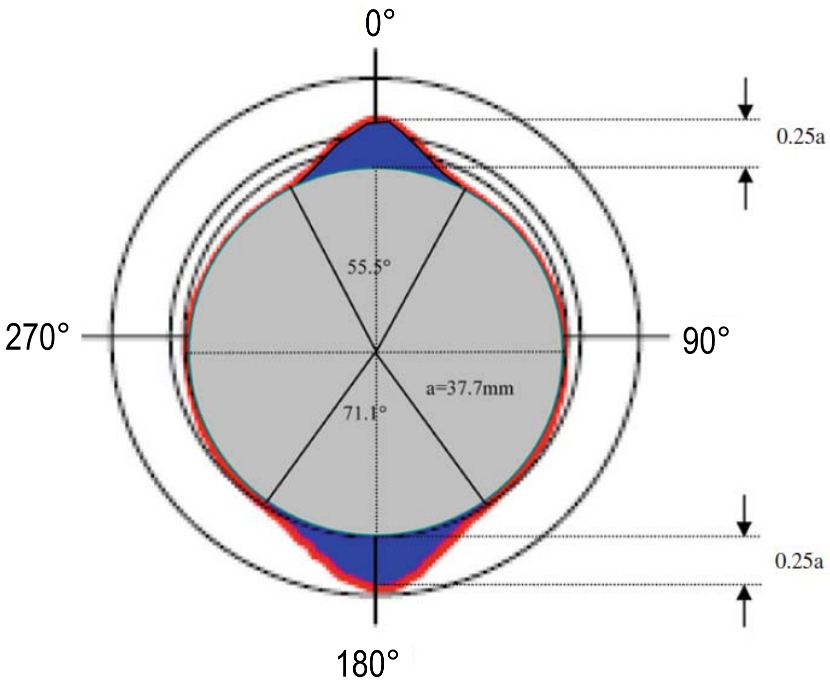

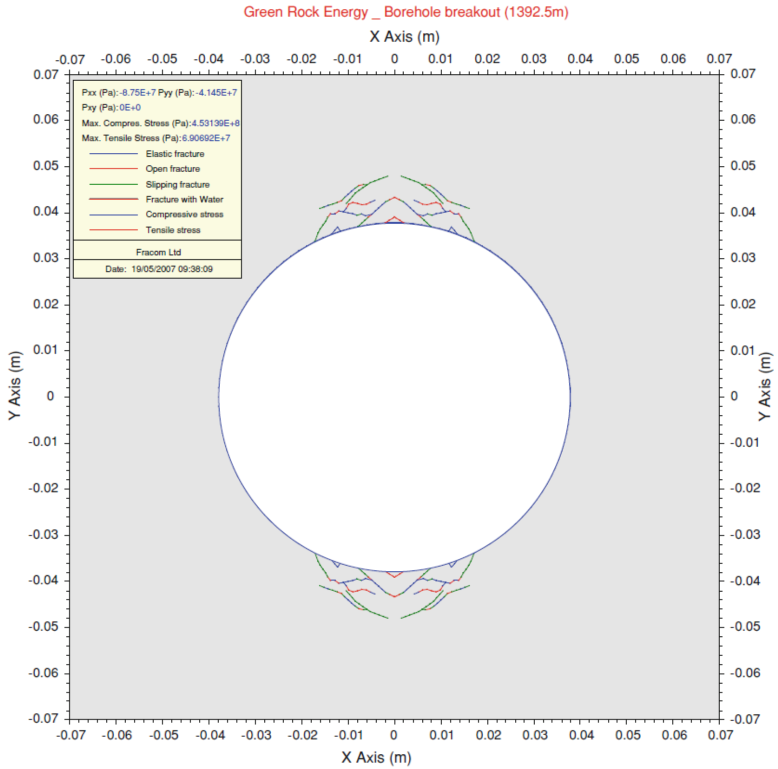

Measured and predicted breakout geometry at borehole Blanche-1 close to Olympic Dam mine near Cooper Basin at the depth of 1,392.5 m for $S_H/S_h/S_v$ = 2.75/1.25/1.0. Prediction made by FRACOD, a DDM fracture mechanics code.

Klee, G., A. Bunger, G. Meyer, F. Rummel, and B. Shen. "In Situ Stresses in Borehole Blanche-1/South Australia Derived from Breakouts, Core Discing and Hydraulic Fracturing to 2 km Depth." *Rock Mechanics and Rock Engineering 44, no. 5 (2011): 531-40.*

Cooper Basin
Overview

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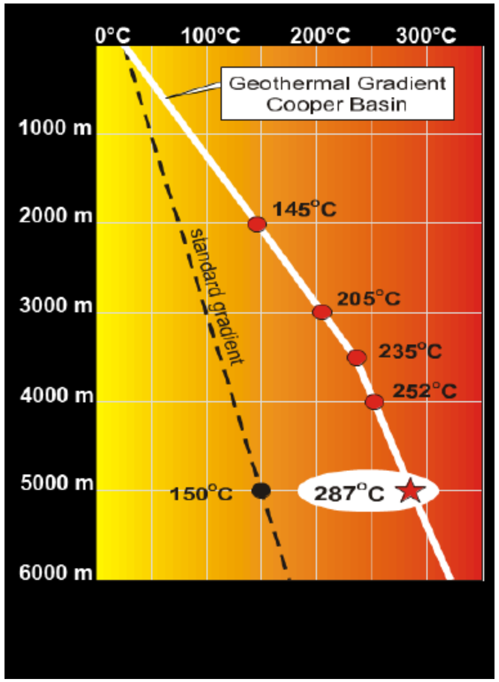
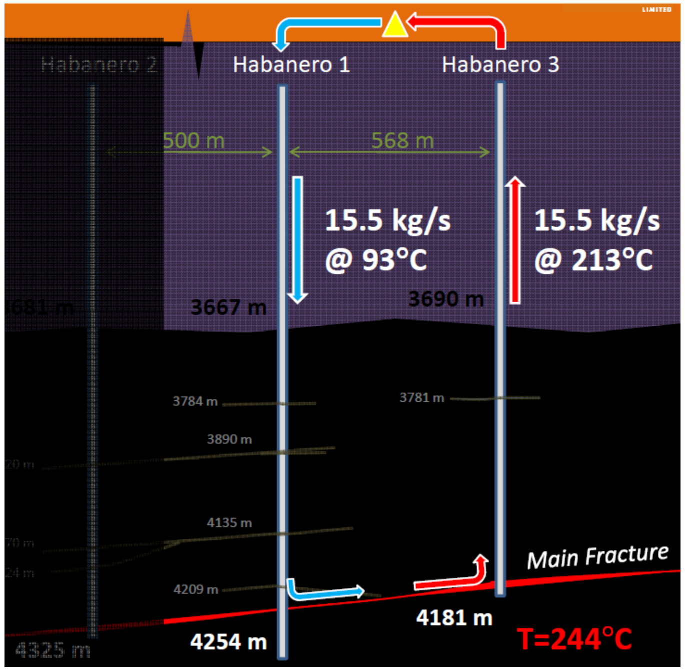
- Cooper Basin Project
  - 5개 보어홀 시추
  - 화강암 저류층 온도 220-285도





Geodynamics, 2010

Cooper Basin
Boreholes

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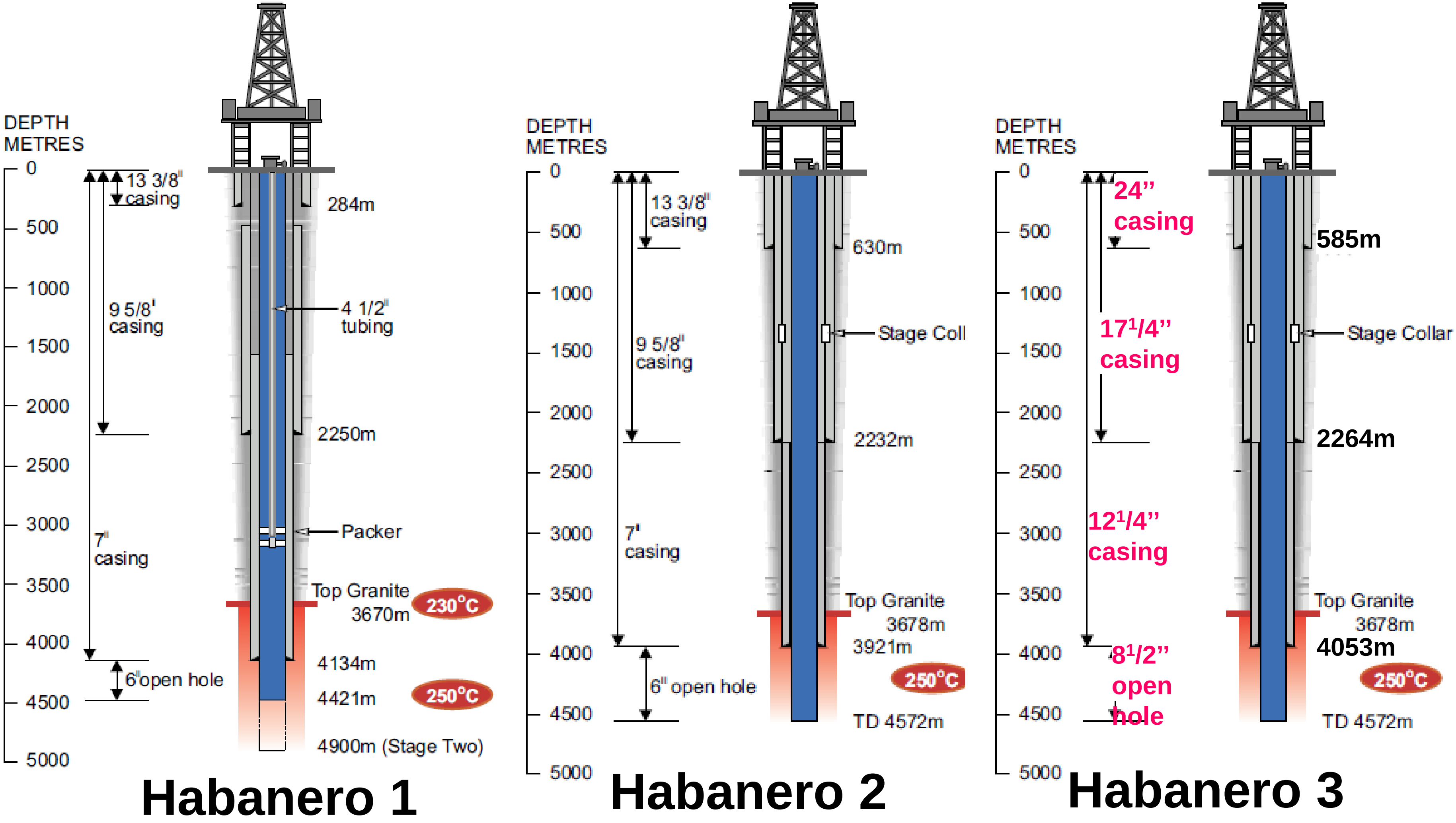

Geodynamics annual report 2003,2004,2005

Cooper Basin
Overview

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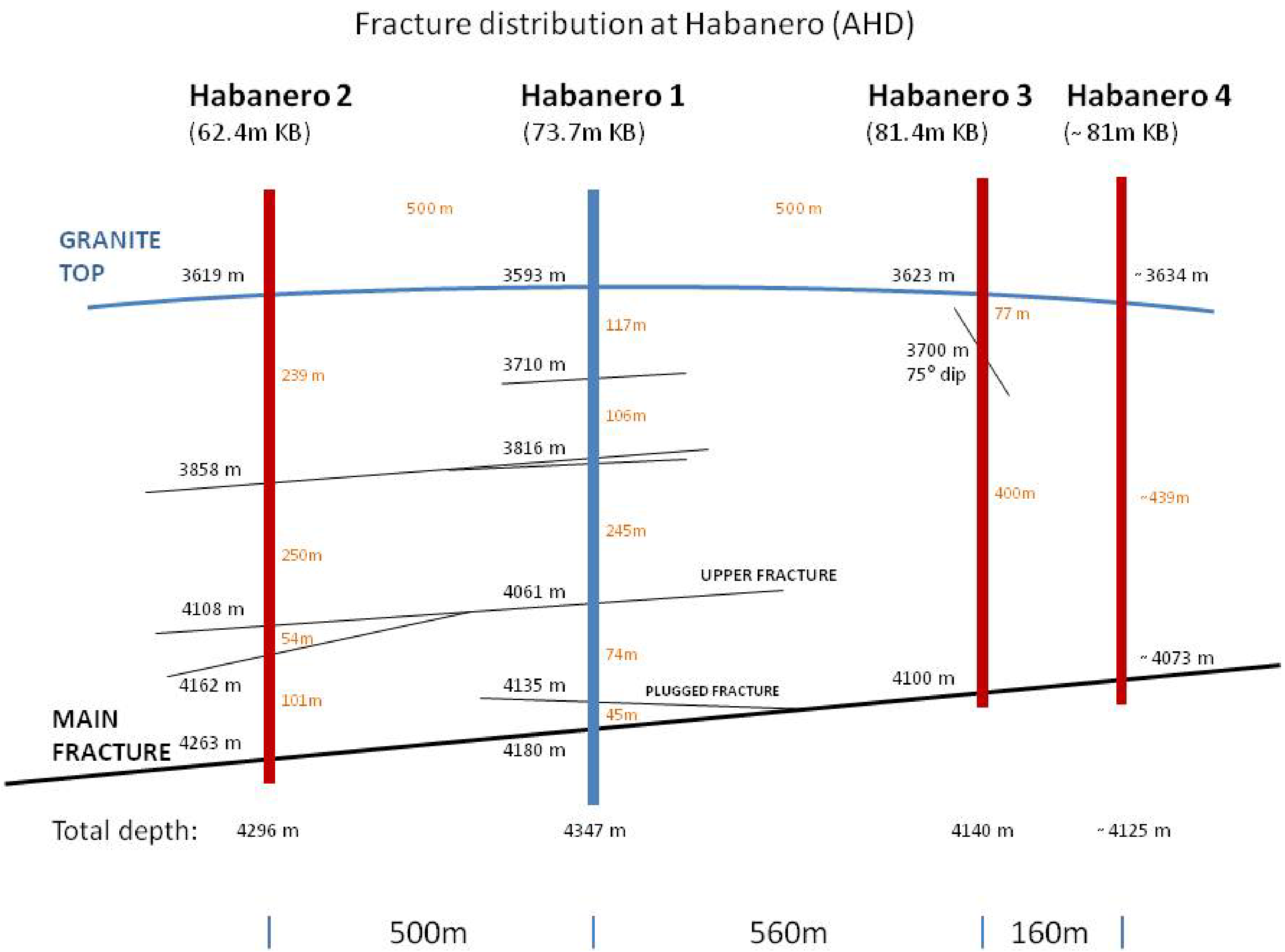
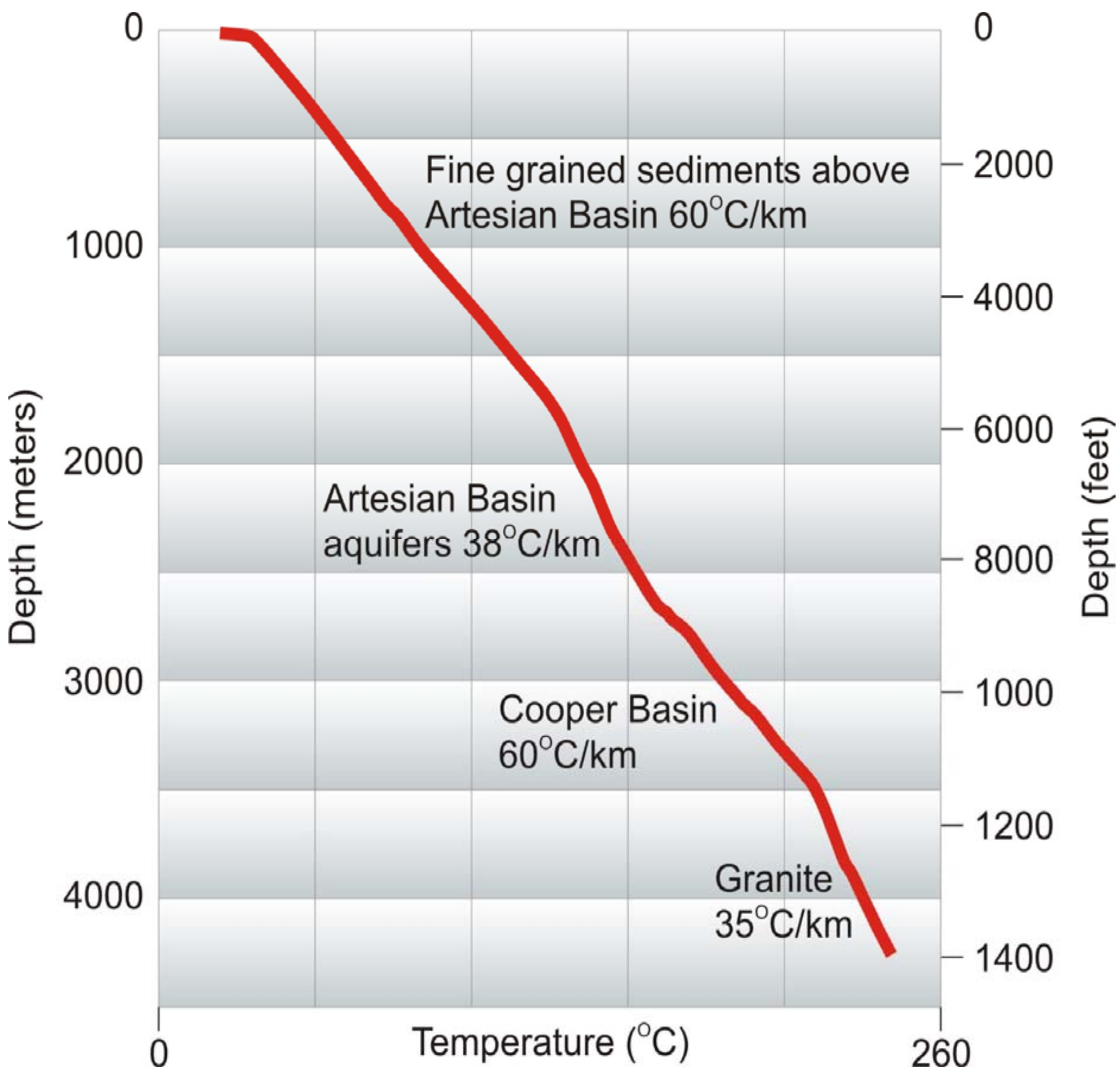


Cooper Basin
Temperature



Cooper Basin
Microseismicity

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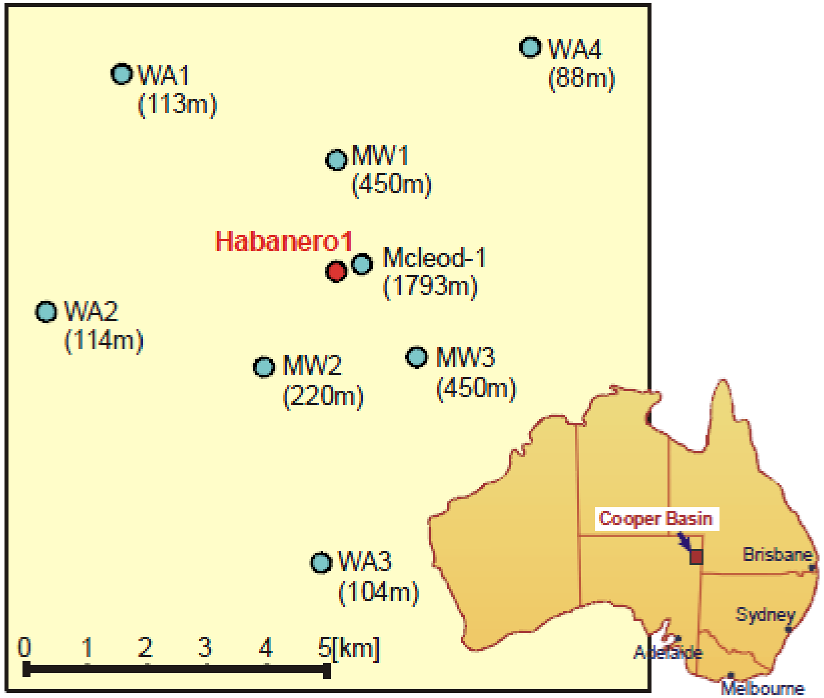

Figure-1: Location of seismic stations at the site

Hiroshi Asanuma & Yasuhiro Kenmoku, 2009

seismic station network

- One deep high temperature station, 1793m with 150 ℃
- Three downhole stations, 200-400m
- Four near surface stations, 100m

Cooper Basin
Microseismicity

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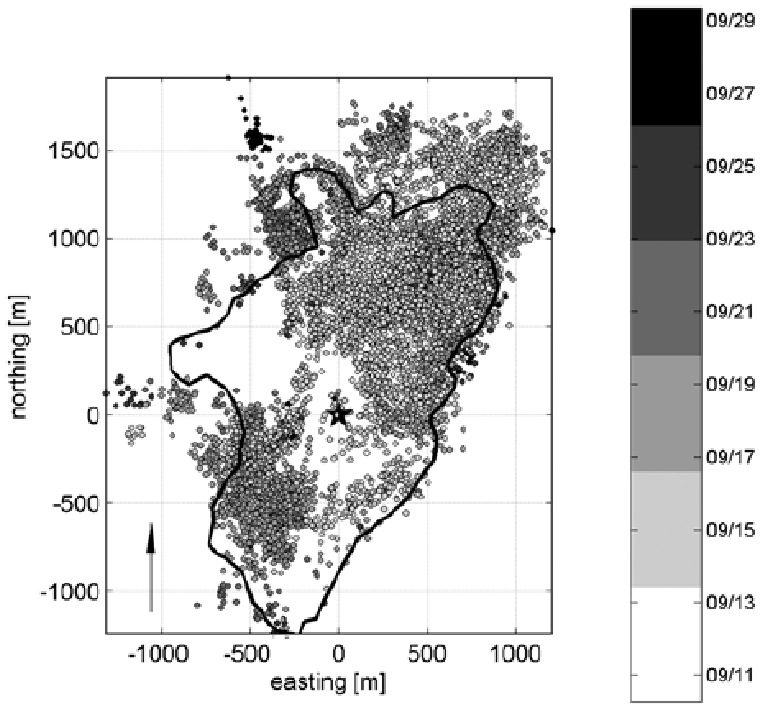

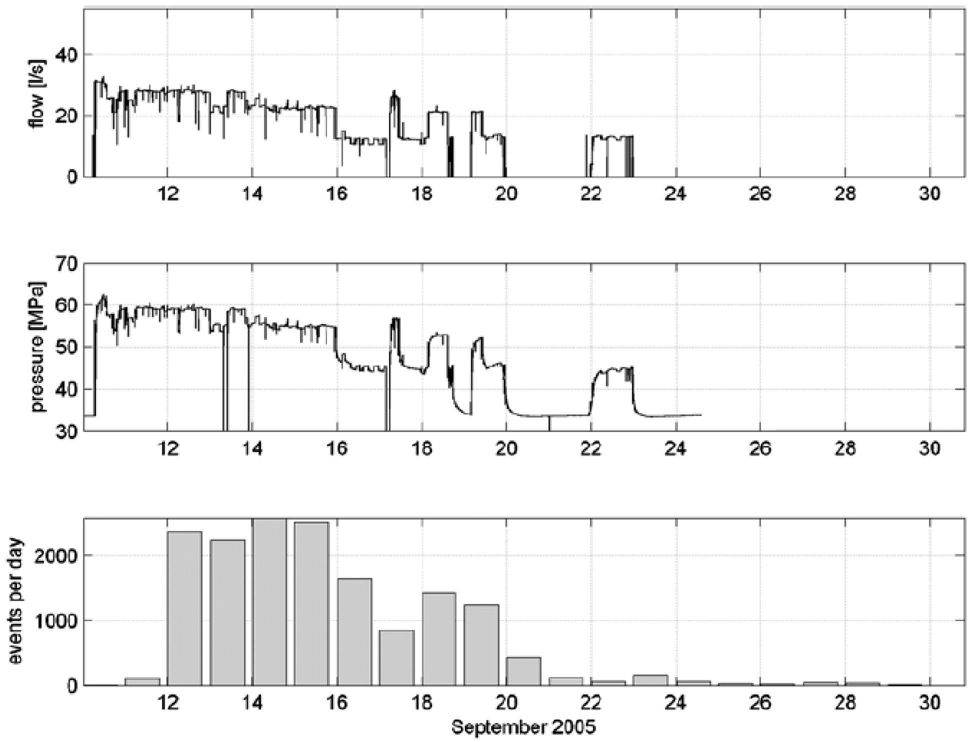

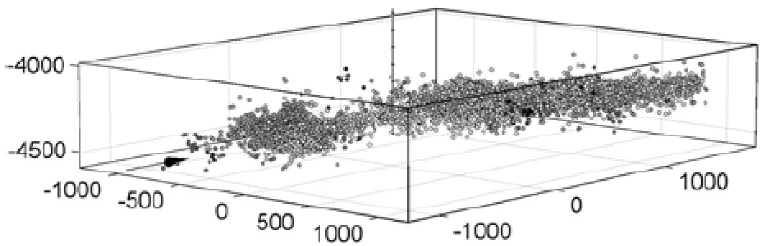

Stefan Baisch, 2009

Second stimulation of Habanero 1:

- ➢**Quasi-Kaiser effect was observed, events were monitored after one day injection**
- ➢**Enlarged the sub-horizontal fracture zone,**

Cooper Basin
Microseismicity

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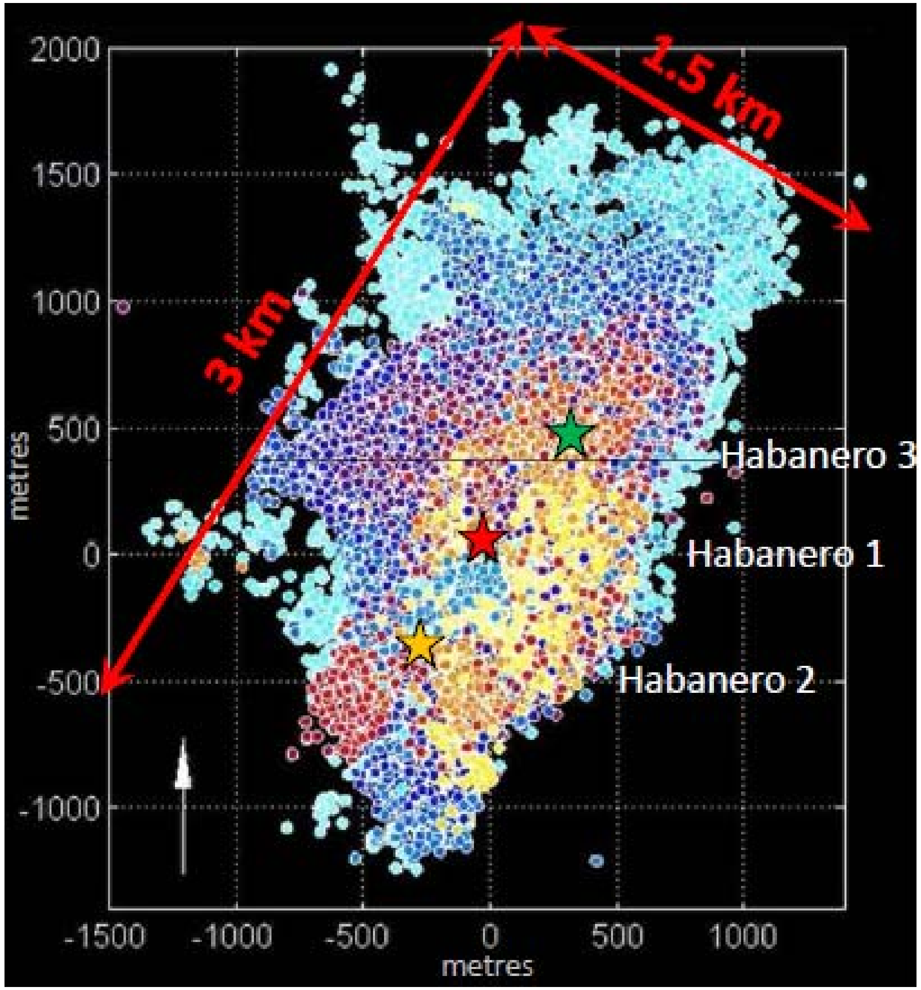
Stimulations:

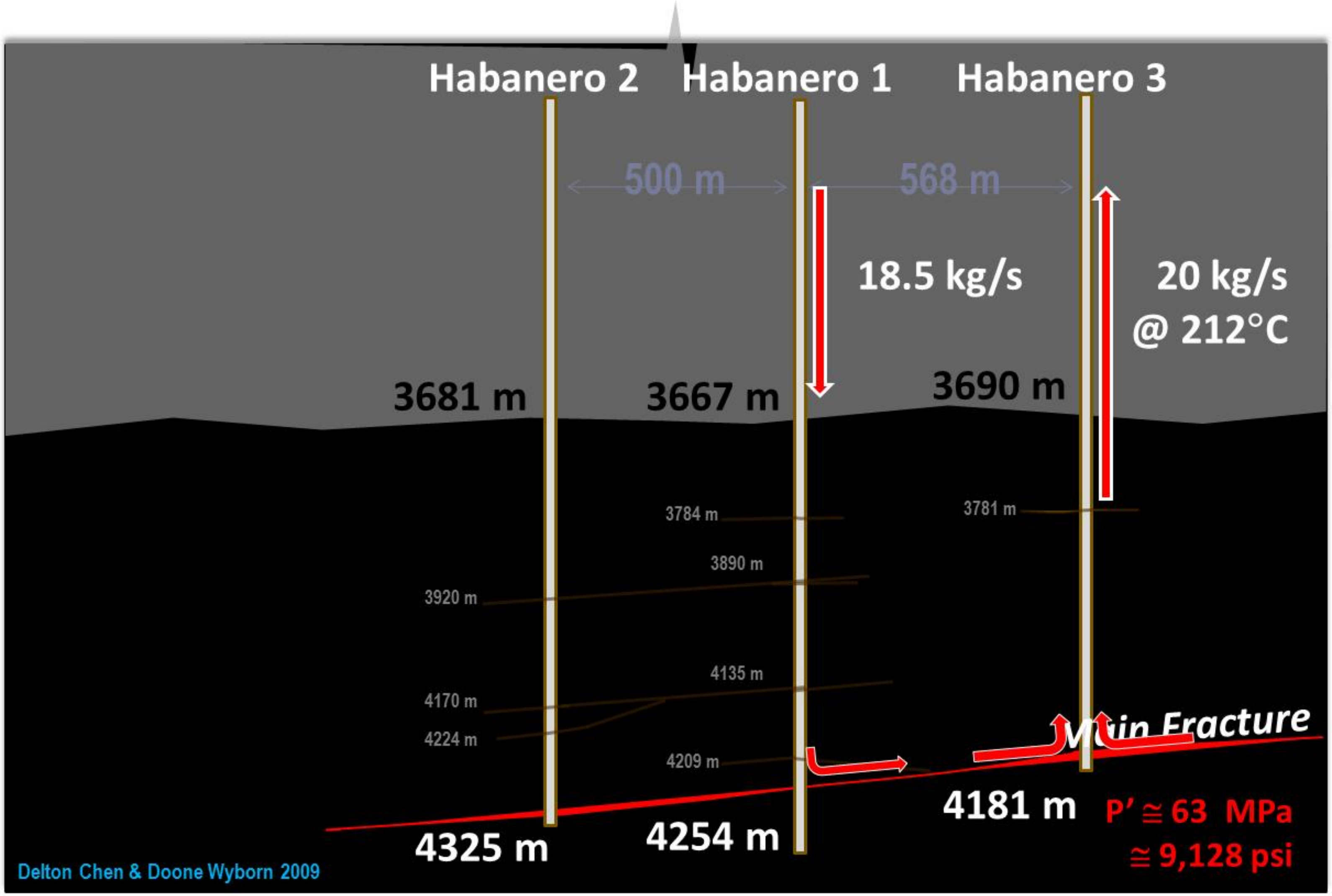
1) Habanero 1: 20,000 m^3 →2.5 km^2
2) Habanero 2: 7,000 m^3 → 0.4 km^2
3) Habanero 1: 20,000 m^3 → 4.0 km^2
4) Habanero 3: 2,200 m^3 → 0.2 km^2

Note: A second layer, 150m above the main fracture, was stimulated between Habanero 1 and Habanero 2.



Delton Chen & Doone Wyborn 2009

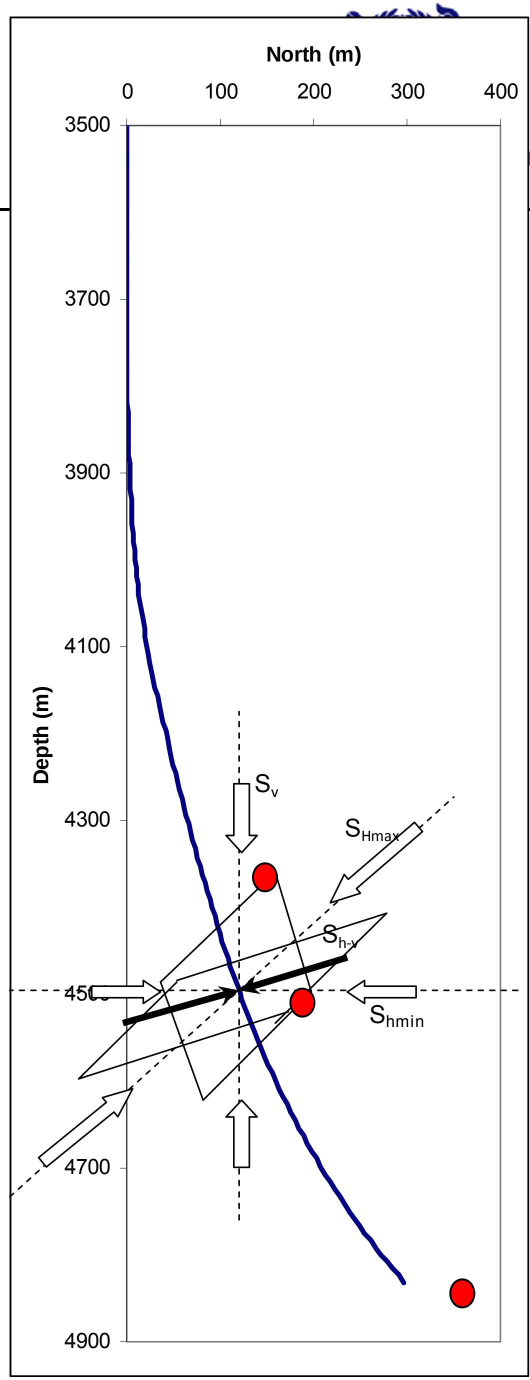
Cooper Basin
Hydraulic Stimulation



Cooper Basin
Jolokia 1 수리자극 시험

Total depth: 4890m
Well bottom temperature: 278 °C
Open section: 586m

Inclined bottom section:
4350m 14.53 °
4500m 18.13 °
4890m 39.06 °



Shen, 2010

Cooper Basin
Jolokia 1 수리자극 시험

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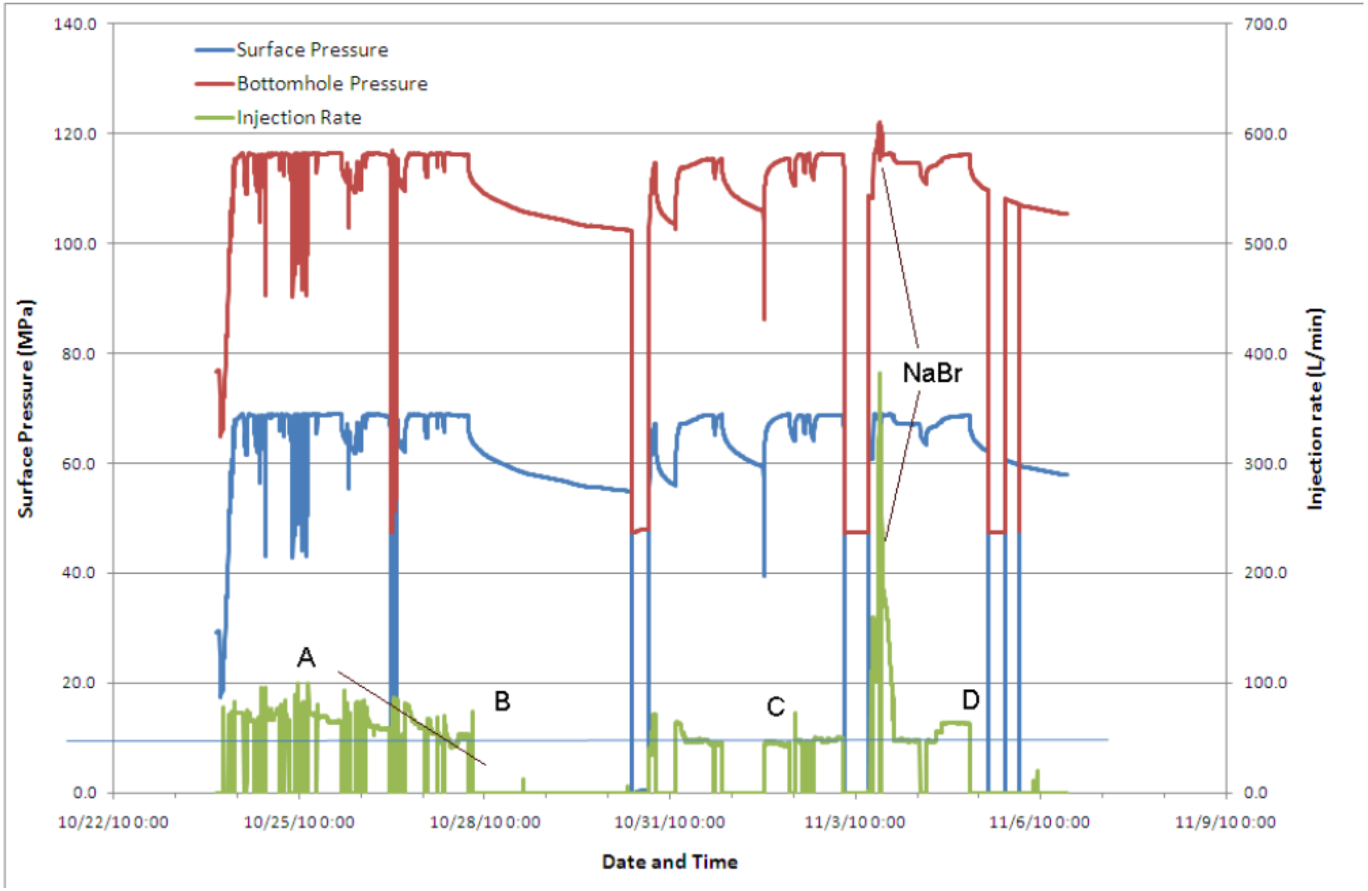


GEODYNAMICS
COOPER BASIN HOT DRY ROCK (HDR) GEOTHERMAL ENERGY PROJECT
A NATIONAL PROJECT
HABANERO #1
AUSTRALIA'S FIRST DEEP GEOTHERMAL WELL - Target depth 4,900m
Unveiled by Senator The Hon. Nick Minchin
Minister for Finance and Administration
6th August 2003
Drilled by: Century Resources

Rig 100 Driller

The deposited mud and collection for drilling chips: no cores available for mechanical and hydraulic parameter tests

Casing and centralizer

Pore pressure meter

- ❑**Natural over pressure**
- ❑**Pressure response during stimulation and circulation**

Surface barrier

1 MW plant facilities

Exchanger

Air cooler and injection pump


sharp airlines


GEODYNAMICS

Case Study
Australia

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- Currently only 120kW geothermal power plant in Birdsville
- GEL (Geothermal Exploration License)
  - first in 2001, now 385 licenses in 360,000 km2
- 48 geothermal companies with 10 ASX (Australian Security exchange) listed
- Expenditure more than 1,500 million A$ from 2002 – 2013 (700 million A$ in the US for 3 years)
- 5.5 GW (6.8%) by 2030
- 17,000 new employment expected

Cooper Basin
Geodynamics의 주가

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Geodynamics Limited Share Price 2007 – 2012

Geodynamics Annual Report 2012

Cooper Basin
Lessons

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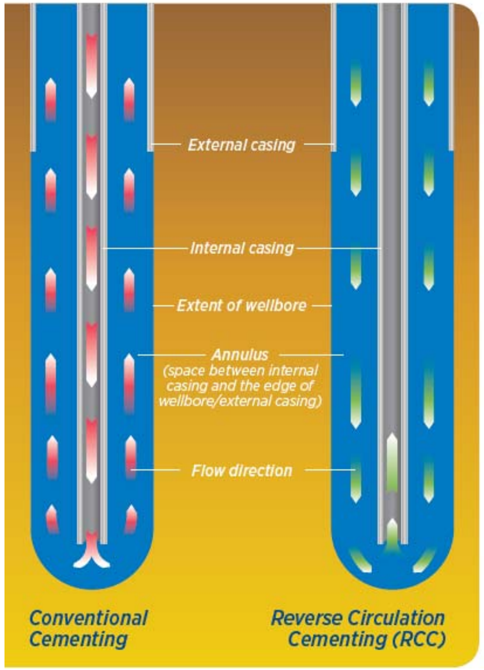
- 공벽 케이싱 문제
  - 예상 가능한 문제점에 대한 검토
- Jolokia 1 수리자극 실패의 경험
  - 암반의 절리 분포는 근처에서도 매우 다를 수 있다.
- 고립된 실증와 연구 → 폭넓은 자료공유 및 문서화 필요



Geodynamics Annual Report 2012

Cooper Basin
시사점

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- Stimulation of Jolokia 1,October 2010:

“Injectivity was low and higher pressure, afforded by concentrated brine, were needed to achieve a rate of injection capable of returning micro-seismic activity indicative of fracture activation. Despite the overthrust stress environment only steeply dipping fractures were activated and did not reseult in the creation of an extensive enhanced permeability zone. “ “our initial assessment of these fractures at Jolokia is that optimally oriented, shallowly dipping fractures were not available in the depth interval stimulated between 4325m and total depth of 4911m. “ “Based on this result it is unlikely that the fractures present in the well will be suitable for use as an underground heat exchanger in power production.”

Case Study
Landau Geothermal Power Plant

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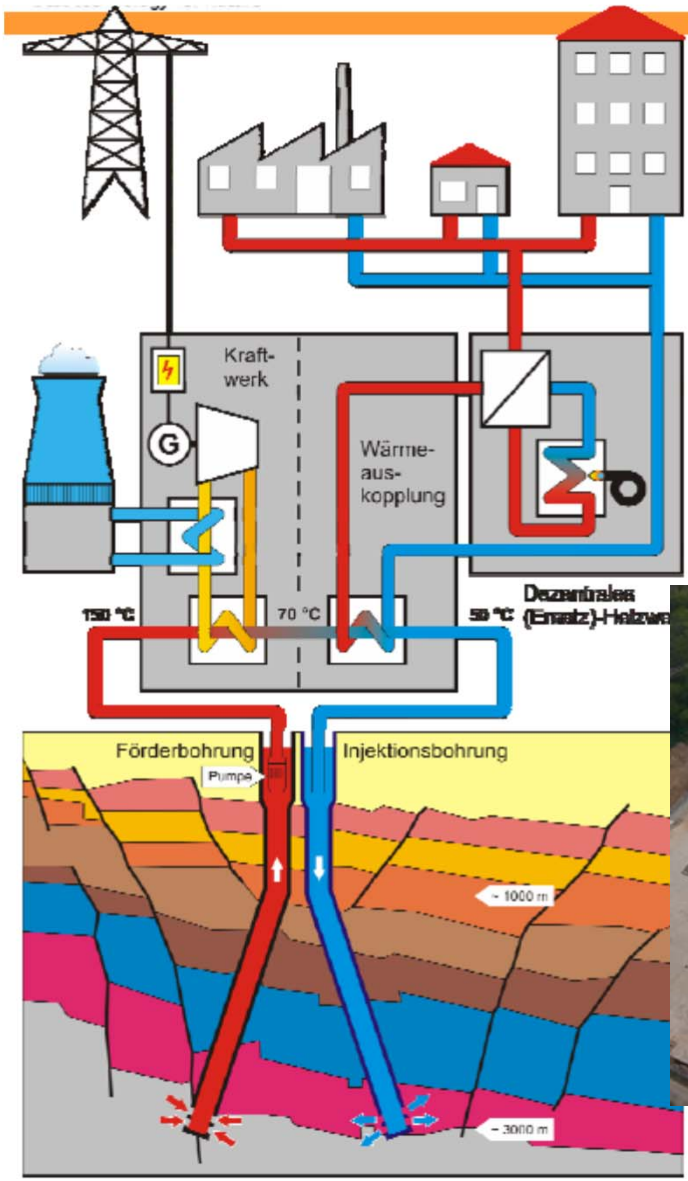

- Project Start: 2004
- Power Production: 2007
- Temperature: 155 ℃, 70 – 80 ℓ/sec at 3,300 m depth
- Installed capacity: 2.9 Mwe
- Thermal capcity: 6 MWt
- Total investment: 15.2 million euro

Case Study
Landau Geothermal Power Plant

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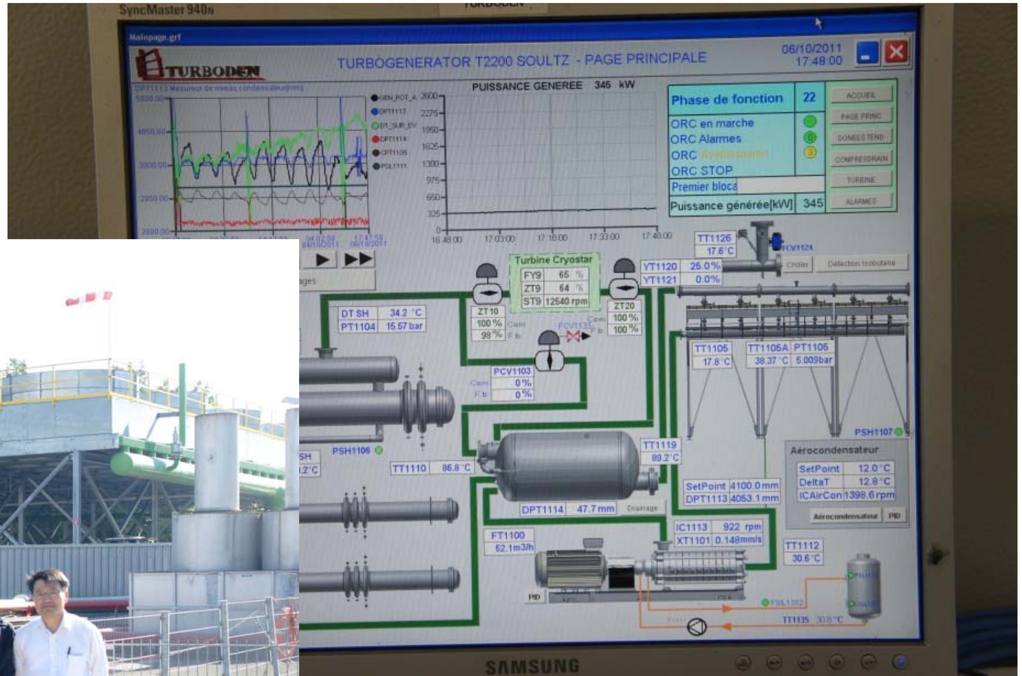

Enhanced Geothermal System
The things that we know

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- 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

- 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
Remaining technical issues

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- Site selection
- Equipment and Instrumentation
  - Downhole pumps
  - High-temperature packers/well-interval isolation systems
- Rock property quantification
- Fracture design model/Fracture mapping method
- Reservoir connectivity

Enhanced Geothermal System
Remaining technical issues

- Understanding the seismic event and its impact on environment
- Characterizing rock fluid interactions
  - Will mineral deposition occur over time that will diminish connectivity and increase pressure drop?
  - Is mineral dissolution going to create short circuits or improve pressure drop?

Enhanced Geothermal System
Remaining technical issues

- Preventing short circuit
  - Short circuit reduce the effective heat-exchange area of the system
  - We cannot stimulate specific fractures
- Better understanding the influence of major fractures and faults as subsurface barriers or conduits to flow
  - Barriers or conduits
  - Method of characterising these features are needed

Enhanced Geothermal System
Microseismicity

- 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

Environmental Challenges
Induced seismicity

- Thorough scientific study should be carried out before drilling to determine the geologic and tectonic conditions
- Monitor the site for any unexpected natural or induced microseismic events
- Education program should be put in place to inform residents of the possibility of felt seismic events.

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