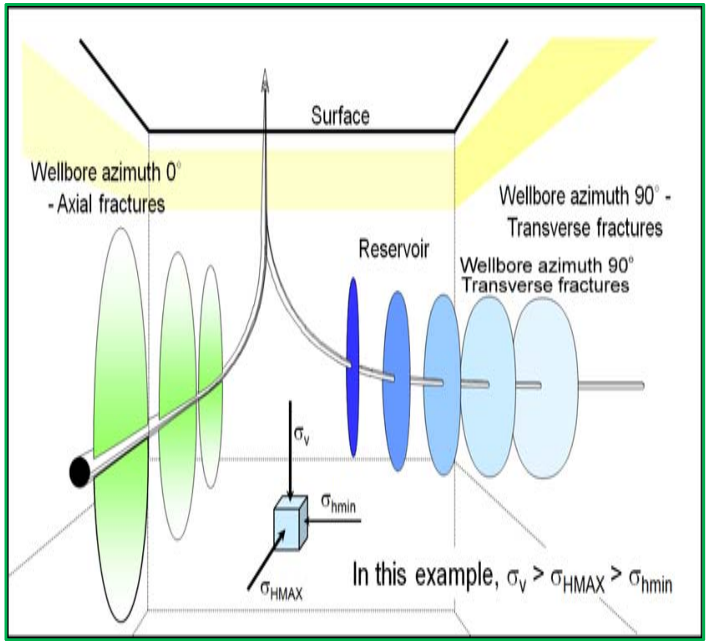
Topics in Energy and Environmental Geomechanics – Enhanced Geothermal Systems (EGS)
Lecture 4. Hydraulic Stimulation
(7, 14 Oct 2013)



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Department of Energy Resources Engineering, Seoul National University

Outline

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- Introduction
- Hydraulic Shearing
  - Hydraulic shearing in geothermal reservoir
  - Design parameters
  - Case study (Rosemanowes project)
- Hydraulic Fracturing
  - Breakdown pressure/Directions
  - Factors
  - Basic models

Hydraulic Fracturing
Introduction

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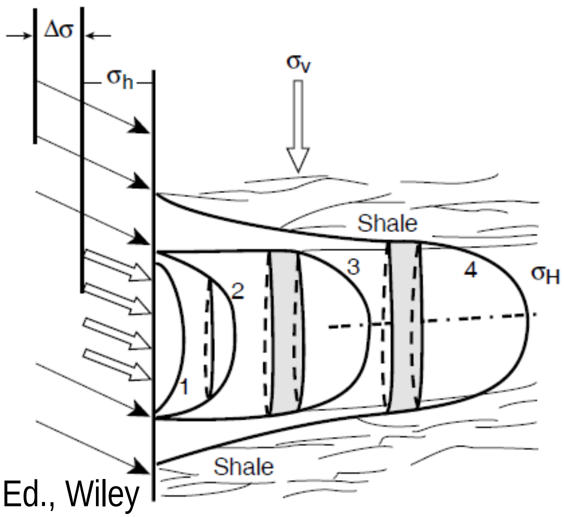
- Why fracture?
  - Bypass near-wellbore damage
    - Drilling-induced damage, …
  - Extend a conductive path far into the reservoir
    - increase productivity above its natural level
  - Reservoir management
    - E.g., Frac-for-sand-control (reduce the pressure drop)
  - In situ stress determination
  - This can happen accidentally when drilling
    - Lost circulation → mud loss
- Complexity
  - Geologic reality
  - Inherent multidisciplinary nature



Smith & Shlyapobersky, 2000, Basics of HF, Eds: Economides & Nolte, Reservoir Stimulation, 3rd Ed., Wiley

Hydraulic Fracturing
Introduction

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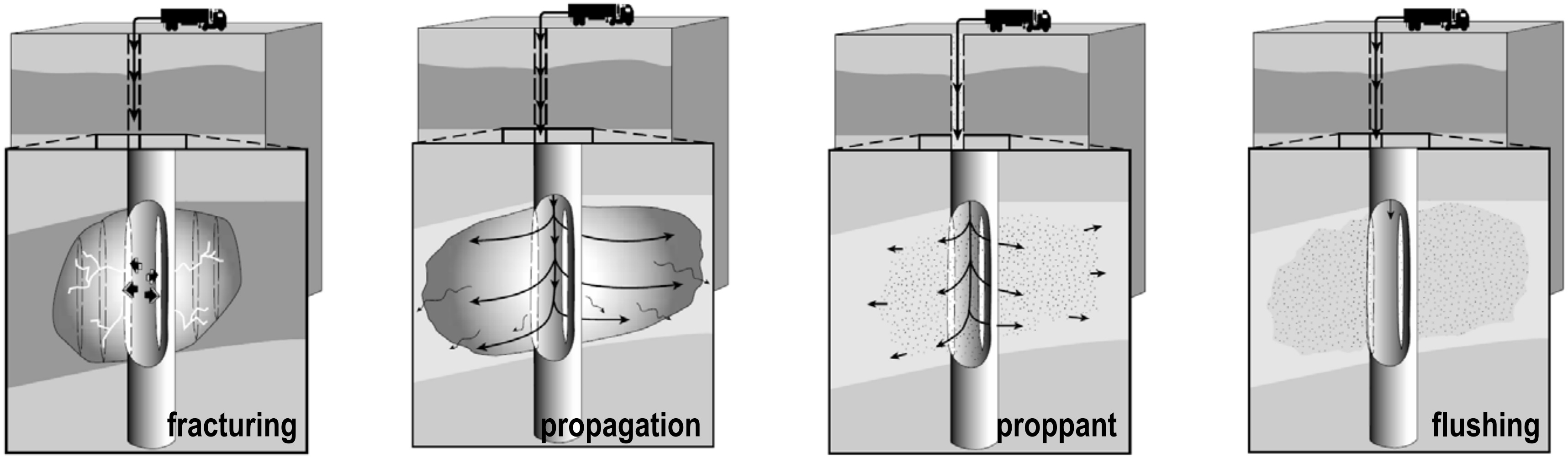
- Complexity of HF

→ Engineering Judgement is important!

  - Fluid Mechanics: flow within the fracture
  - Rock Mechanics: deformation and stress in the rock
  - Fracture Mechanics: all aspects of the failure and fracture initiation/propagation
  - Thermal Process: exchange of heat between the fracturing fluid and the reservoir



Smith & Shlyapobersky, 2000, Basics of HF, Eds: Economides & Nolte, Reservoir Stimulation, 3rd Ed., Wiley

Hydrauilc Stimulation
Hydraulic fracturing vs. Hydraulic shearing

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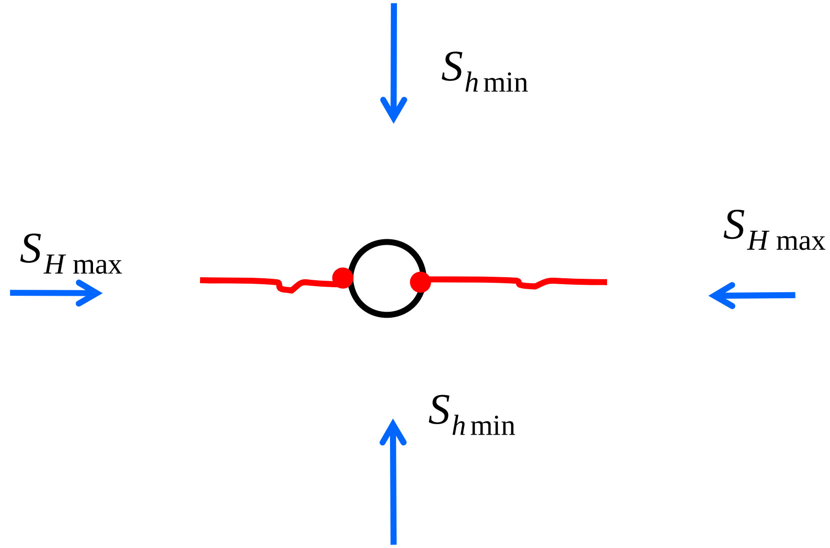
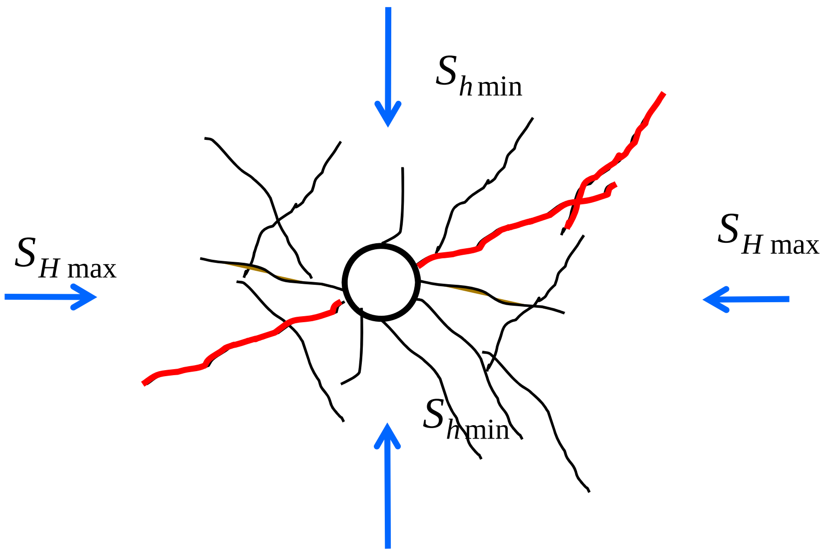


Hydrofracturing
수압파쇄 (인장파괴)

- More dominant in shale gas production

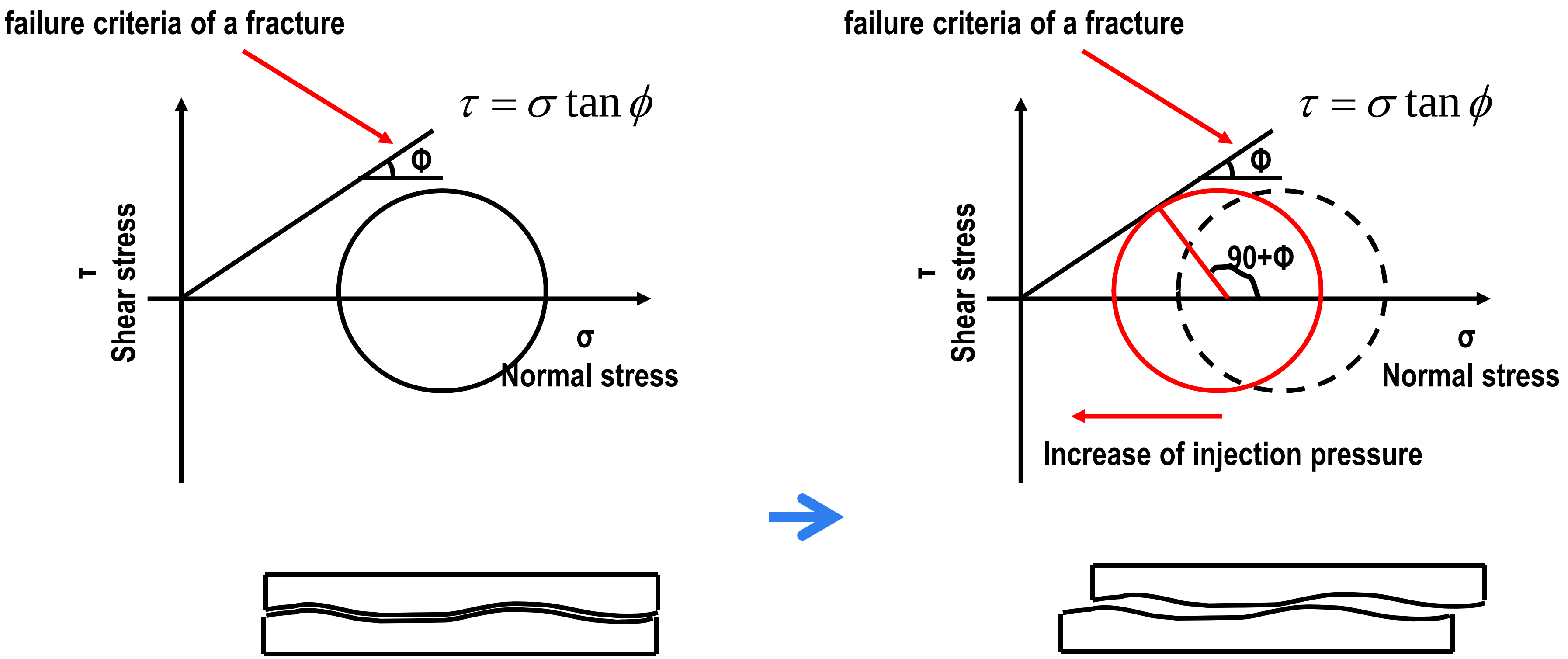


Hydroshearing
절리팽창 (전단파괴)

- More dominant in geothermal reservoir for Enhanced Geothermal Systems

Both hydrofracturing (creating fracture) and Hydroshearing (shearing of existing natural fracture)will play a part for hydraulic stimulation in shale gas reservoir.

Hydraulic Stimulation
Hydraulic shearing



- 절리의 수압이 절리면의 파괴와 팽창을 유발하고, 미소진동(Microseicmic event)이 발생
- 절리의 팽창 특성은 '물성'이며 절리의 연결도 등에 큰 영향 받음

Hydraulic Stimulation
Hydraulic shearing - direction

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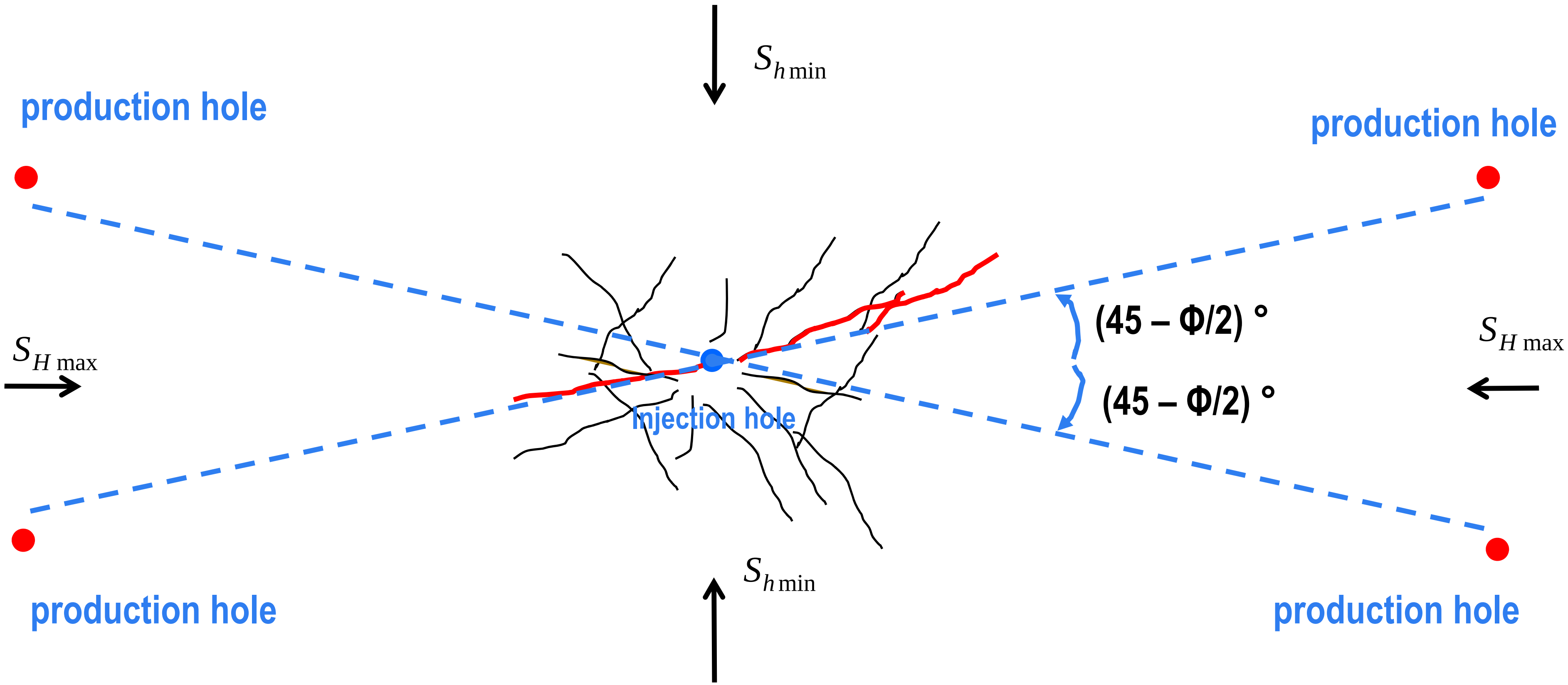
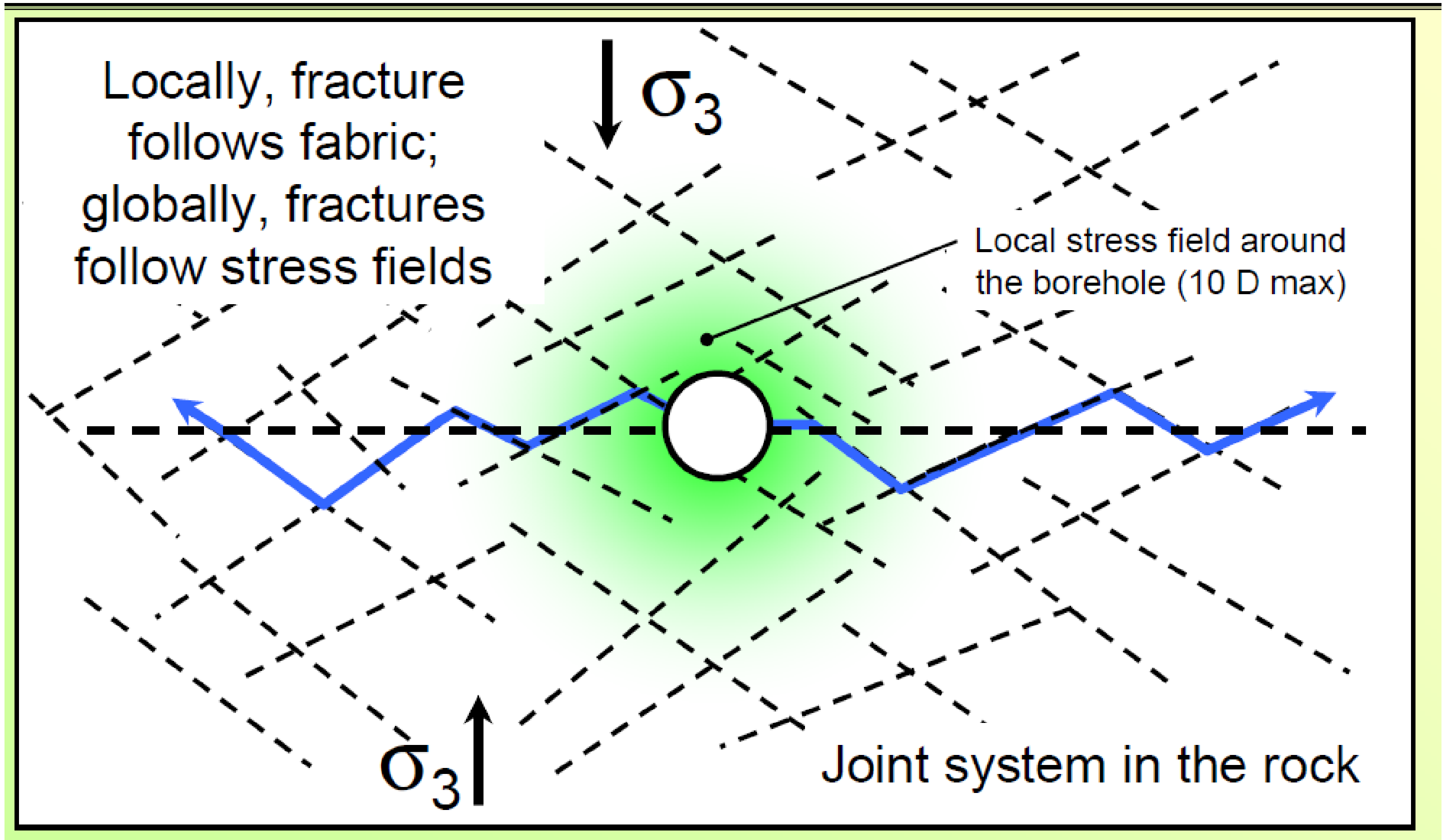


- 수리전단은 최대주응력과 **(45 – Φ/2) °** 의 각도를 이루는 절리면에서 발생 : **~ 30°** (마찰각 **30 °** 인 경우)
- 경사공 및 **3**차원 해석에서는 보다 세밀한 해석 필요

Hydraulic Fracturing
Direction



Dusseault, 2012

수리자극(Hydraulic stimulation)
소요주입압 (injection pressure)

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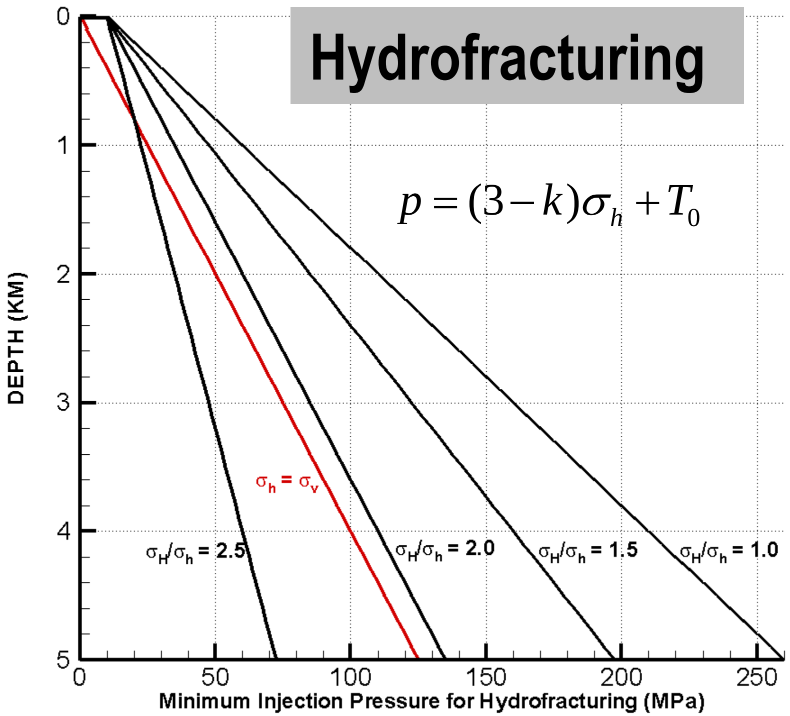

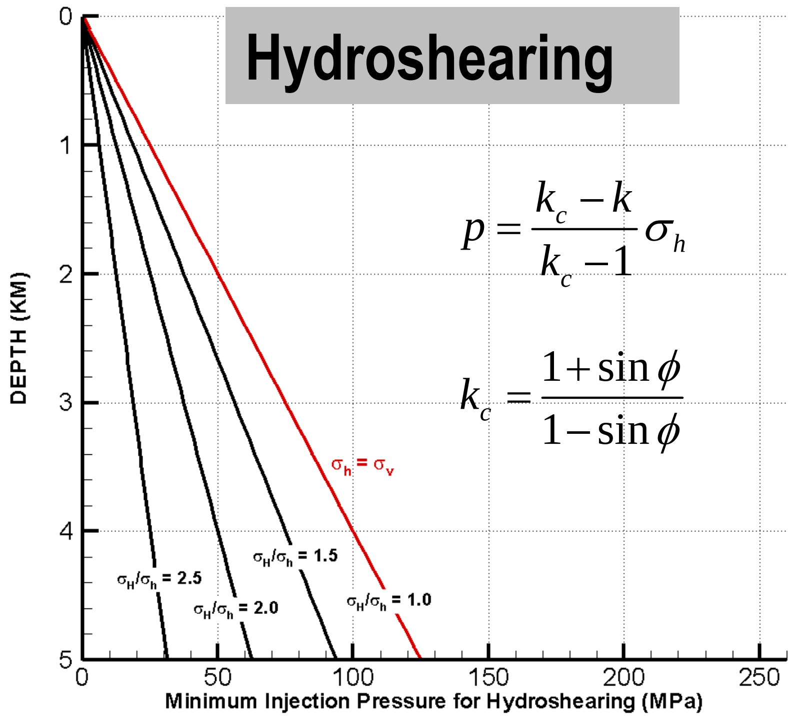

– 초기응력의 이방성이 클 수록 소요주입압은 감소

– 수리전단은 소요주입압이 수압파쇄에 비해 작으며 비가역적(irreversible)인 과정임

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.

Hydraulic Shearing/Hydraulic Fracturing

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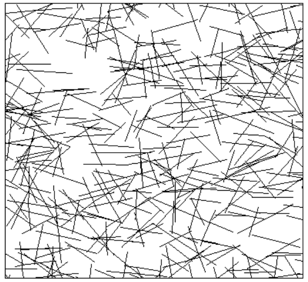
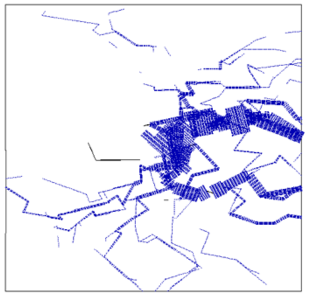
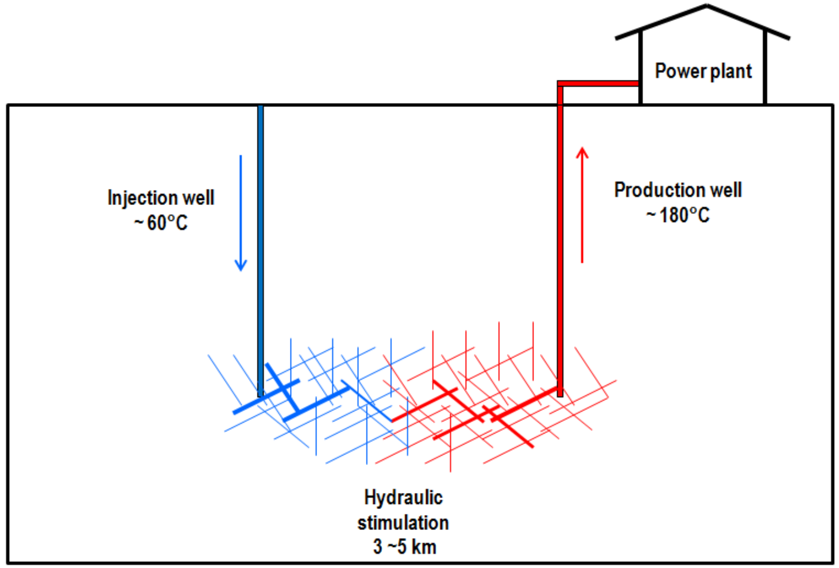
UDEC/3DEC



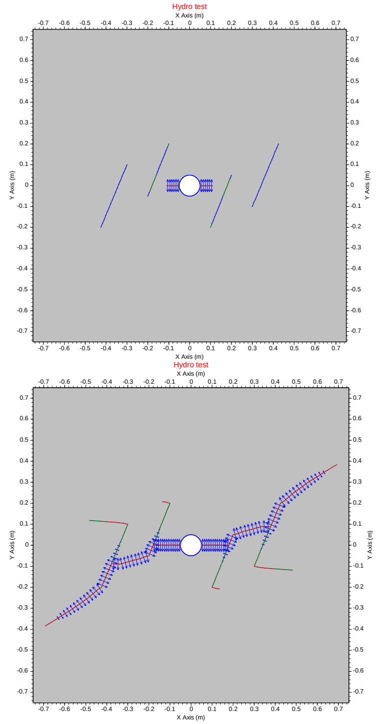




Dilation of existing fractures

Initiation of new fractures

FRACOD



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

Hydraulic Stimulation
Design parameters

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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.*

Hydraulic Stimulation
Design parameters

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- 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%

Hydraulic Stimulation
Pilot Study

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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
Pilot Study

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Project	Stress st.	Well	Frac-int. [km]	Well Traj.	V_{IN} [m^3]	Q_{IN} [L/s]	P_{wc} [MPa]	A [km^2]	Cloud-Dip	Ref.
Falkenberg	normal	HB4a	0.25	vertical	25	3.5	2.2	0.014	60	[23]
Fenton H. I	normal		2.8	sub-vert.	587			0.15		[24]
Fenton H. I	normal		2.8	sub-vert.	761			0.16		[24]
Fenton H. I	normal		2.8	sub-vert.	5018			0.53		[24]
Fenton H. II	normal		3.7	55° II S_h	150			0.027		[24]
Fenton H. II	normal		3.7	55° II S_h	890			0.085		[24]
Fenton H. II	normal		3.7	55° II S_h	3183			0.27		[24]
Fenton H. II	normal		3.7	55° II S_h	3183			1		[24]
Fenton H. II	normal		3.7	55° II S_h	4702			1.1		[24]
Fenton H. II	normal	EE2	3.45-3.47	55° II S_h	22000	108	38	0.7	65	[8,12]
Camb. II	strike s.	RH12	1.74-2.12	60° II S_H	18500	20-90	14	0.6	sub-vert.	[25]
Camb. II	strike s.	RH15	2.1-2.25	60° II S_H	5700*	200	15	0.04	sub-vert.	[13]
Hijiori	normal	SKG-2	1.79-1.80	vertical	2000	17-100	15	0.15	60	[2,26,27]
Hijiori	normal	HDR-1	2.03-2.21	vertical	2100	17-67	26	0.25	60	[2,26]
Ogachi	(rever.)	OGC-1	1.00-1.01	vertical	10140	11	19	0.5	30	[2,28]
Ogachi	(rever.)	OGC-1	0.71-0.72	vertical	5440	8	22	0.3	sub-hor.	[2,28]
Soultz I	strike s.	GPK1	2.85-3.40	vertical	25300	0.2-36	9	1	sub-vert.	[20,29]
Soultz I	strike s.	GPK2	3.21-3.88	sub-vert.	28000	12-50	12	0.8	sub-vert.	[20]
Soultz II	strike s.	GPK2	4.40-5.00	sub-vert.	23400	30-50	14.5	3	sub-vert.	[22]
Cooper B.	reverse	Hab. 1	4.14-4.42	vertical	20000	14-26	60	3	sub-hor.	[9]
Basel	strike-s.	Basel 1	4.63-5.00	vertical	11650	0.2-55	30	0.9	sub-vert.	[30]

Table 1. Stimulation parameters and of major stimulation tests in HDR-projects, V_{IN}: injected volume, Q_{IN}: injection flow rate, p_{wc}: maximum well head pressure, A: area of the "seismic cloud"

Jung R, 2013

Rosemanowes Project
Overview (개괄)

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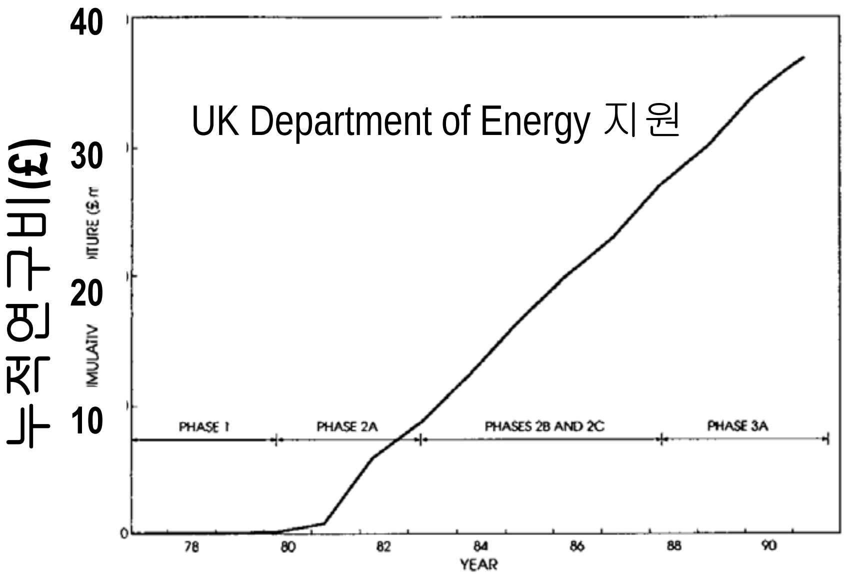
단계	기간	주요 연구
Phase 1	1977 – 1980	시추공 4개 (심도 300 m), 수리 및 발파에 의한 자극
Phase 2A	1980 – 1983	2 km 시추공 2개 (생산공 RH11, 주입공 RH12), 수리자극실시
Phase 2B	1983 – 1986	RH15 (생산공, 2.6 km), 점성유체 주입, RH12-RH15 저류층
Phase 2C	1986 – 1988	저류층 개선 기술 (manipulation)
Phase 3	1988 – 1991	Prototype HDR

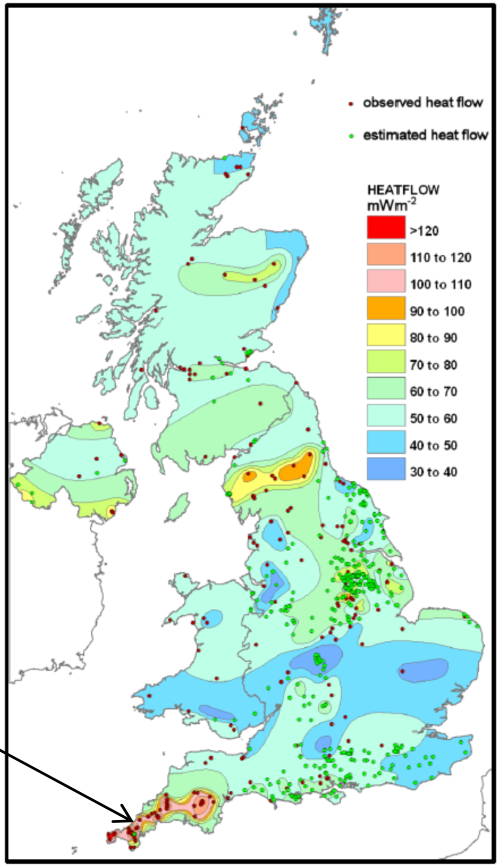


MacDonald, P., A. Stedman, and G. Symons. "The UK Geothermal Hot Dry Rock R&D Programme." In *Seventeenth Workshop on Geothermal Reservoir Engineering, 5-11 (SGP-TR-141). Stanford, CA, USA, 1992.*

Rosemanowes Project
Overview (개괄)

- 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 (지질)

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

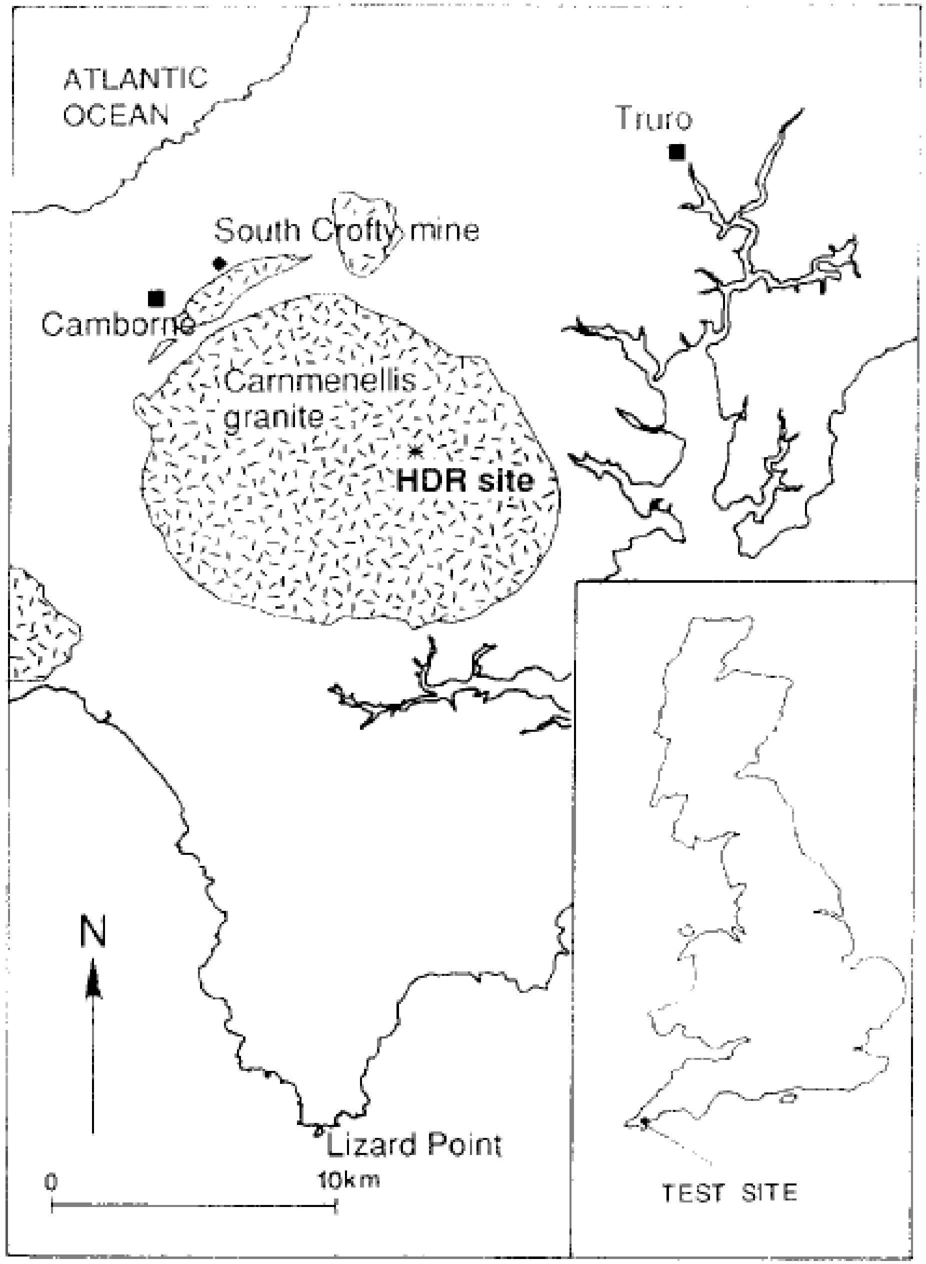


Fig. 3. Location of the Rosemanowes test site.

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	Spacing (m) 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

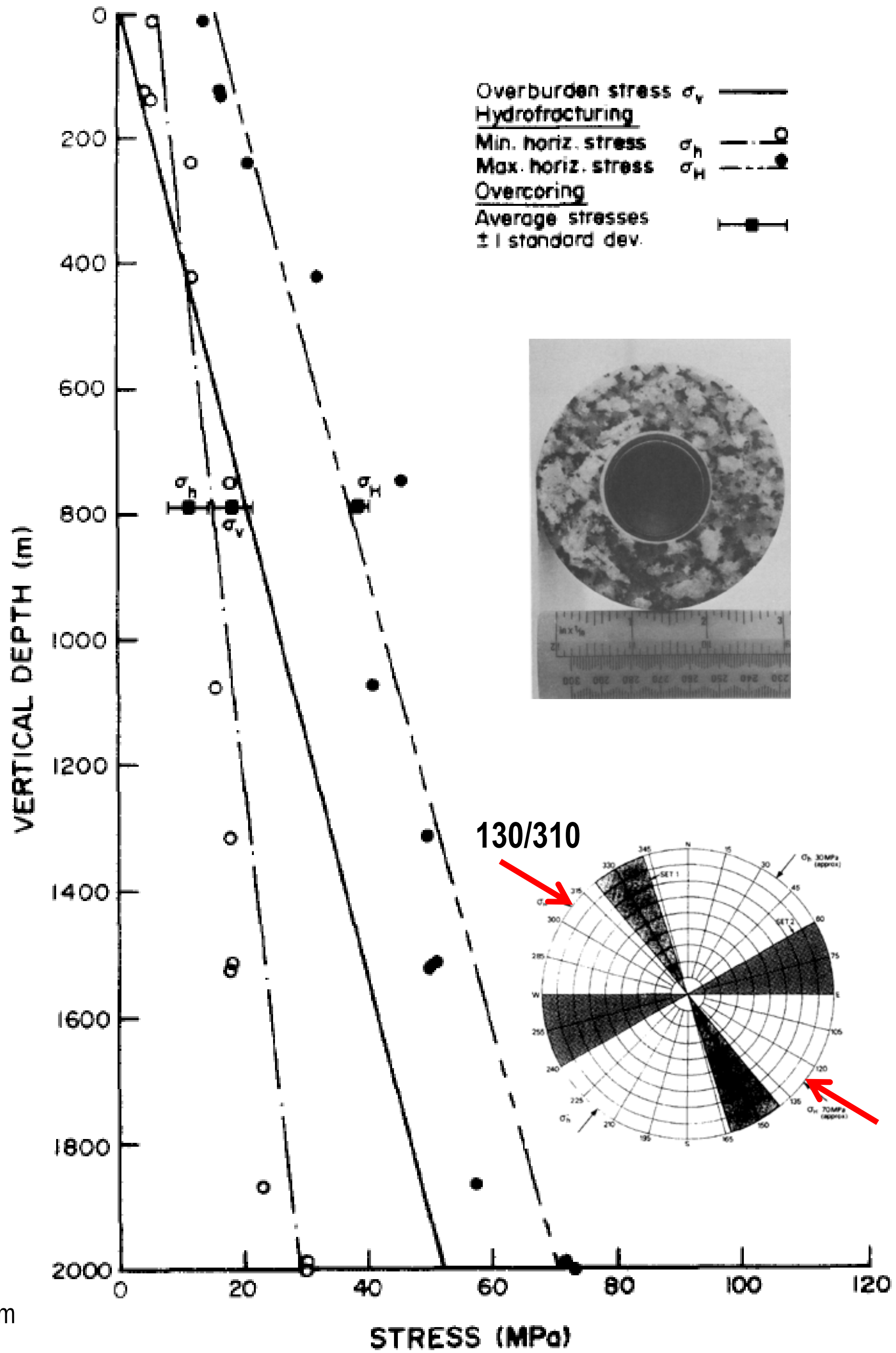
N = number of joints intercepted

- 보어홀 이미지를 통한 자료 취득
- 두 개의 수직절리군, 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 (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.

Rosemanowes Project
Overview (개괄)

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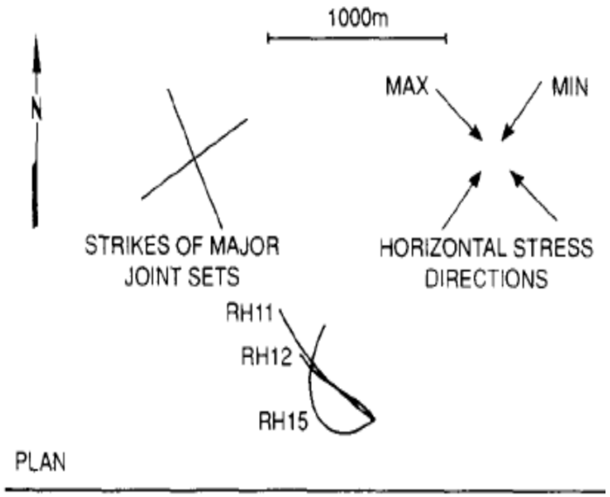
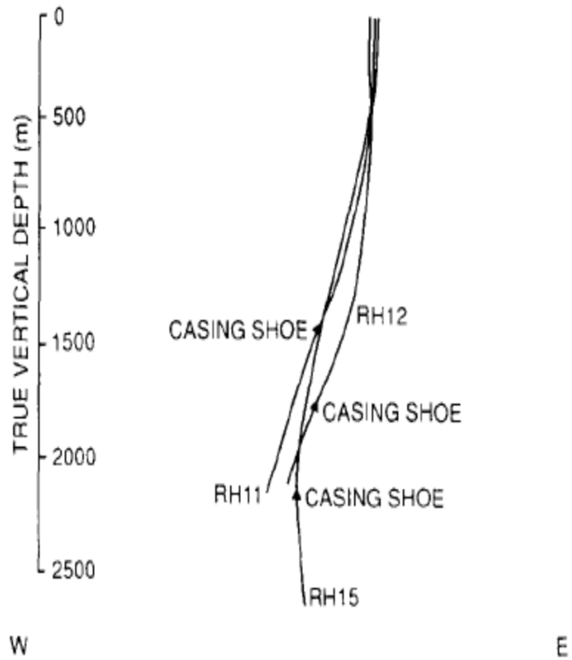
Phase 1	1977 – 1980	시추공 4개 (심도 300 m) 수리 및 발파에 의한 자극
Phase 2A	1980 – 1983	2 km 시추공 2개 (생산공 RH11, 주입공 RH12) 임피던스: 1.5 MPa/(l/s), 주입손실: 75%, 아래로의 인공저류층 형성
Phase 2B	1983 – 1986	RH15 (생산공, 2.6 km), 점성유체 주입, 임피던스 1.0 MPa/(l/s), 주입손실: 20%
Phase 2C	1986 – 1988	저류층 개선 기술 (manipulation) 상업 발전을 위한 성능변수 검토
Phase 3	1988 – 1991	Prototype HDR

Rosemanowes Project
Boreholes

- RH12 (D=311 mm), 경사 최대 32°





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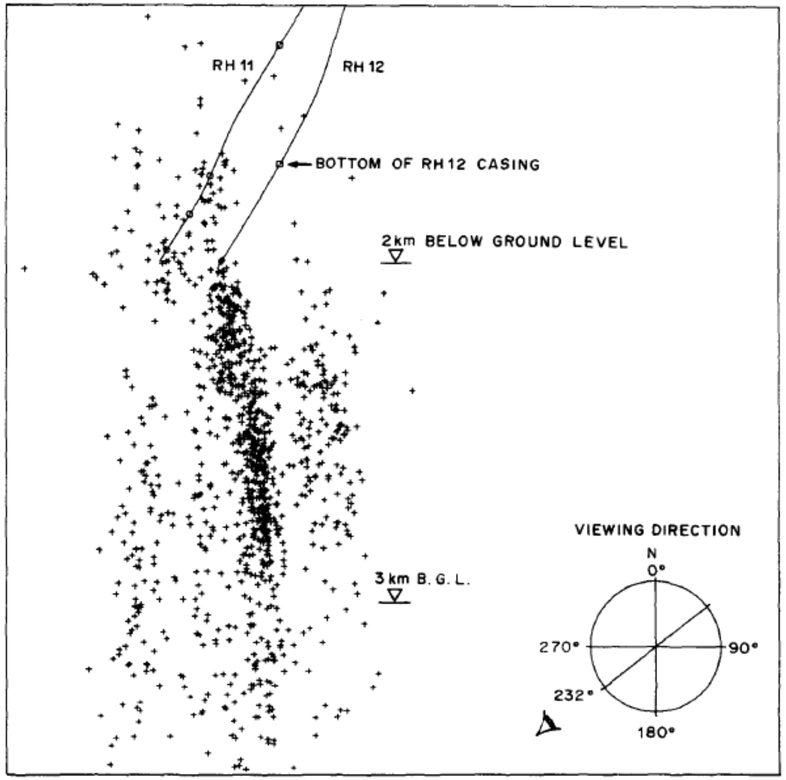
Rosemanowes Project
Hydraulic Stimulation

- 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

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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.*

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Hydraulic Stimulation

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- 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)

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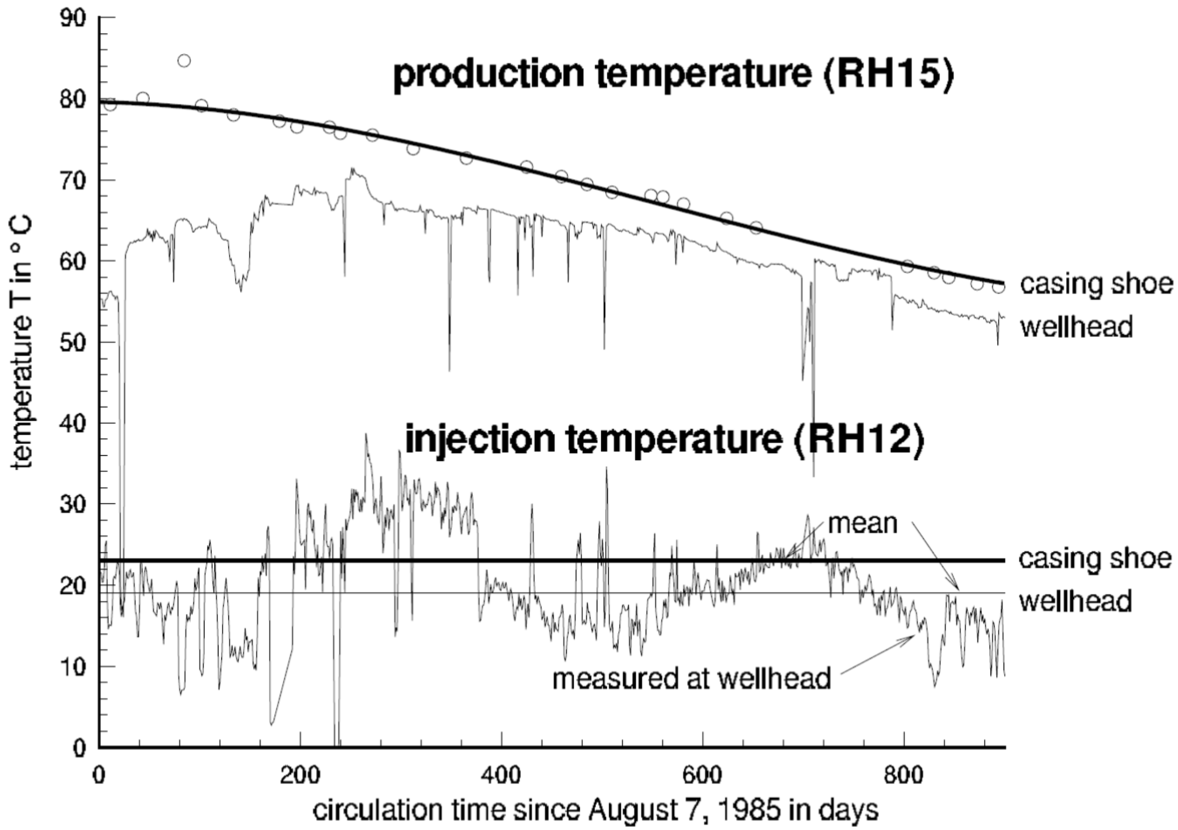

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Hydraulic Stimulation

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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

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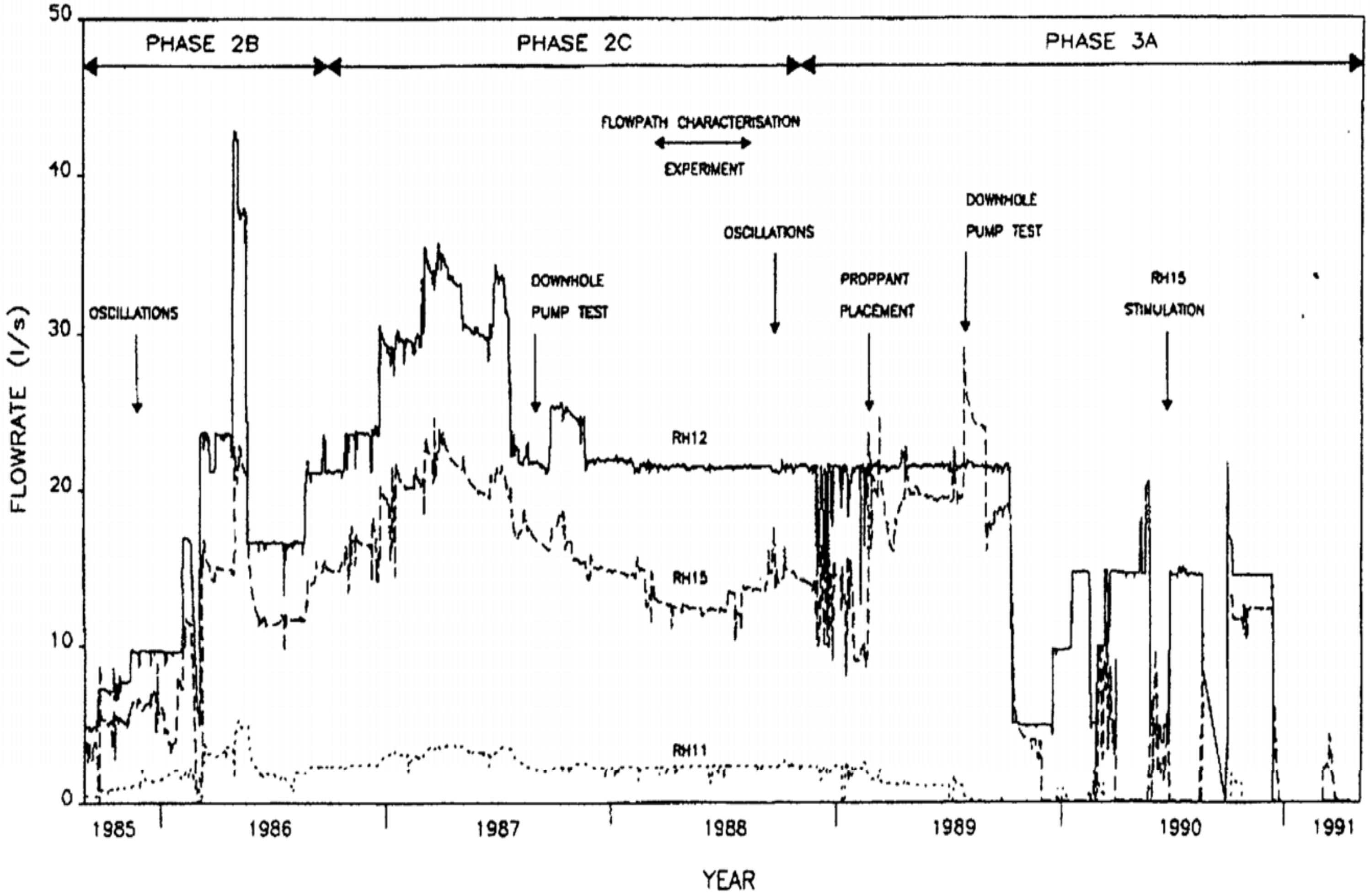
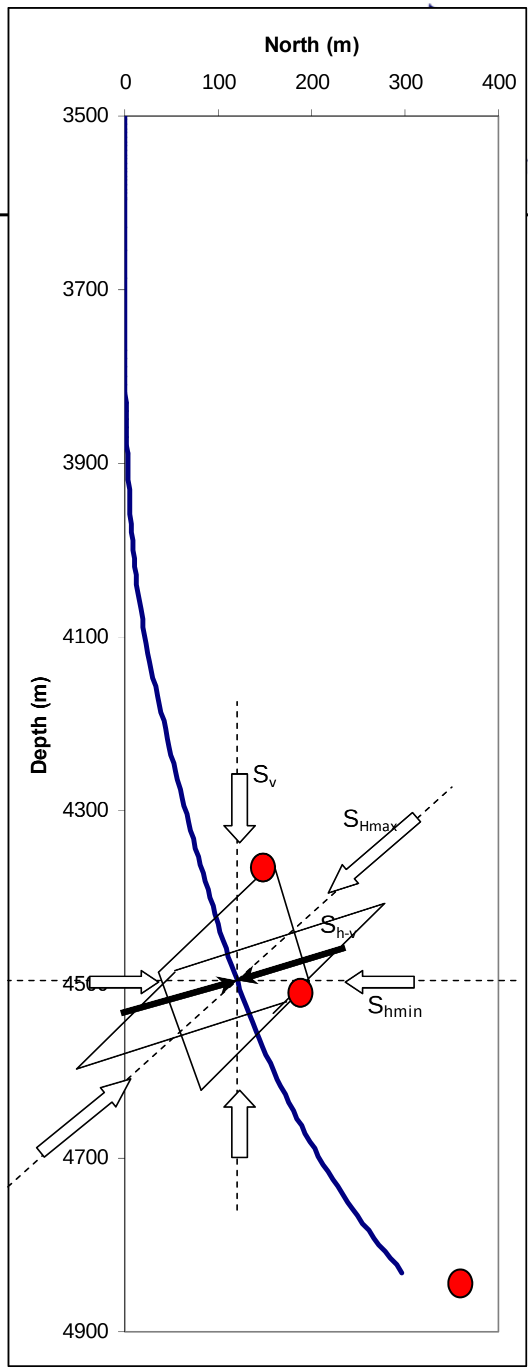


Parker, R. "The Rosemanowes HDR Project 1983-1991." *Geothermics* 28, no. 4-5 (Aug-Oct 1999): 603-15.

Cooper Basin
Jolokia 1 수리자극 시험

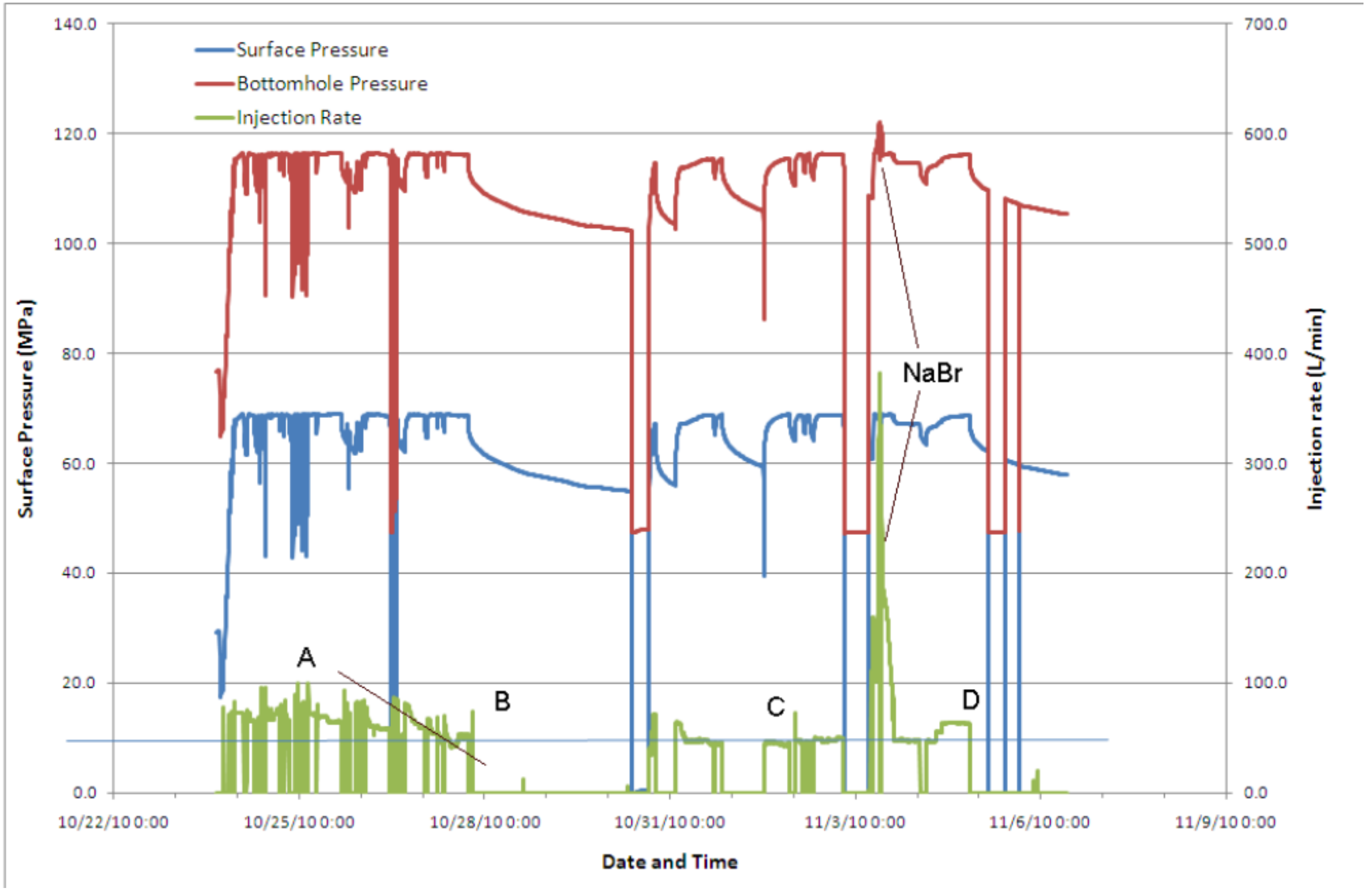
Total depth: 4890m
Well bottom temperature: 278 °C
Open section: 586m

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



Shen, 2010

Cooper Basin
Jolokia 1 수리자극 시험



Rosemanowes Project
시사점

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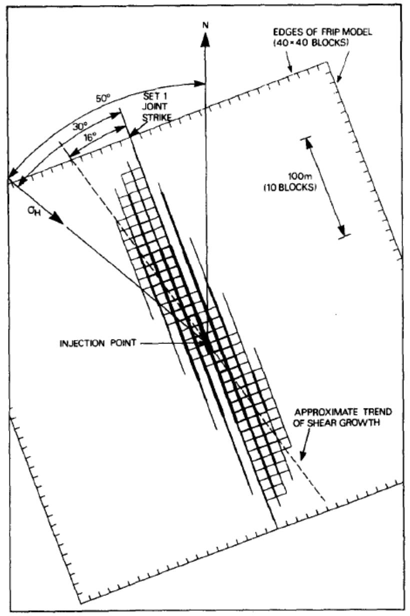
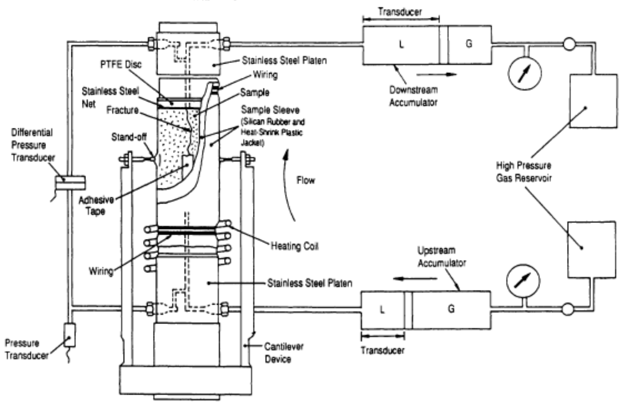
- 지열저류층 수리자극시 전단파괴의 중요성
- 균열암반의 수리역학적 수치해석 프로그램 개발
  - UDEC의 시초
- 균열암반의 열-수리-역학적 거동
  - Zhao and Brown (1992)
- 다운홀펌프, 프로판트, 점성유체시도 등





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
시사점

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- 생산공과 주입공의 위치선정
  - 초기응력, 절리분포와 밀접히 연관
- 주입수로서의 점성유체의 역할
  - 활용 가능성 검토 필요함 (Cooper Basin)
- 충분한 사전 연구 필요
  - 성능인자, 저류층 핵심인자, 운영인자 등 이론적 확립
- 초기응력 모델 수립 계획

Hydrauilc Stimulation
Hydraulic fracturing vs. Hydraulic shearing

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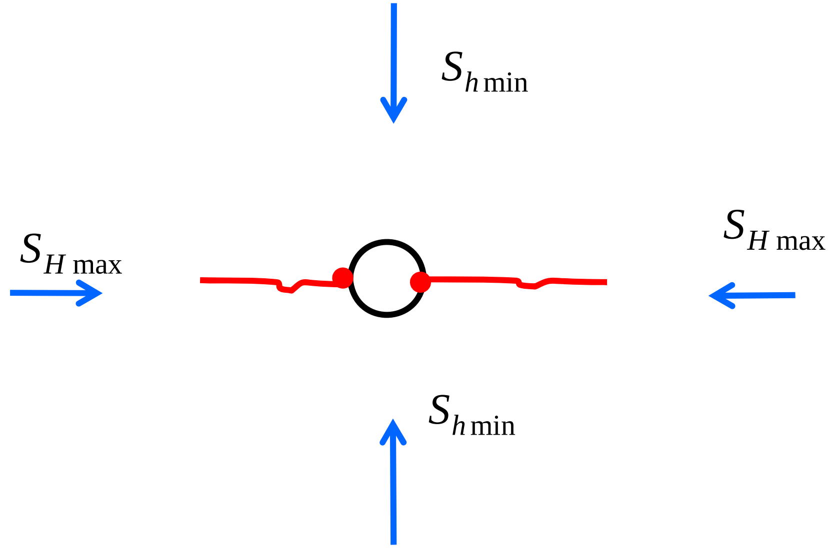
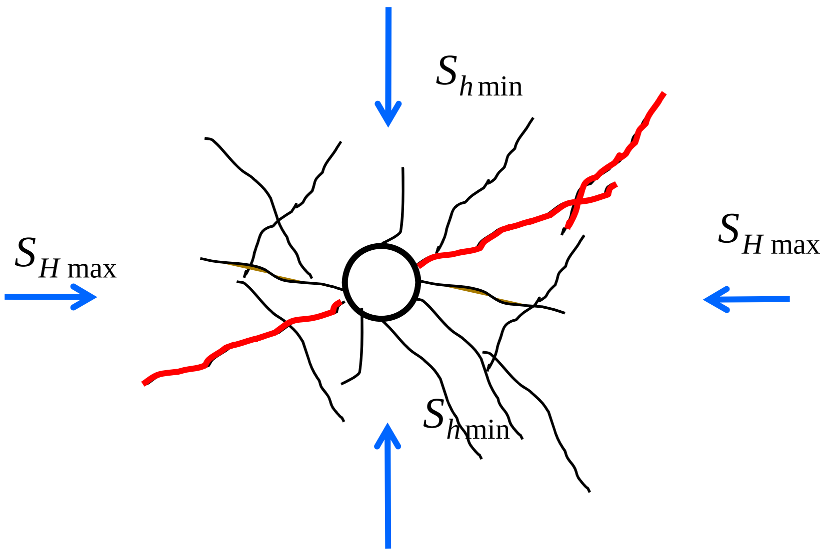
Hydrofracturing
수압파쇄 (인장파괴)

- More dominant in shale gas production





Hydroshearing
절리팽창 (전단파괴)

- More dominant in geothermal reservoir for Enhanced Geothermal Systems

Both hydrofracturing (creating fracture) and Hydroshearing (shearing of existing natural fracture)will play a part for hydraulic stimulation in shale gas reservoir.

Hydraulic Fracturing
Introduction

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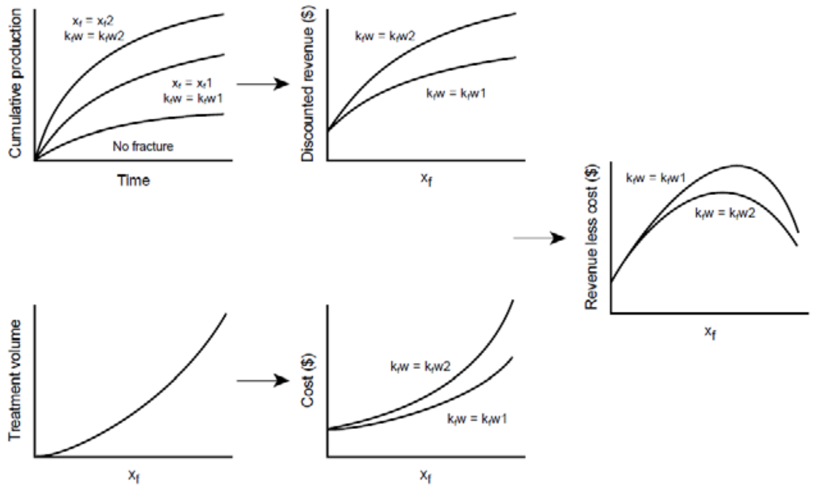
- Reasons to develop Hydraulic Fracturing Model
  - Perform economic optimization
    - What size treatment provides the highest rate of return
  - Design a pump schedule
  - Simulate the fracture geometry and proppant placement by a specified pump schedule
  - Evaluate treatment (compare prediction with actual behavior)



Smith & Shlyapobersky, 2000, Basics of HF, Eds: Economides & Nolte, Reservoir Stimulation, 3rd Ed., Wiley

Breakdown Pressure
Generalized Kirsch's solution

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

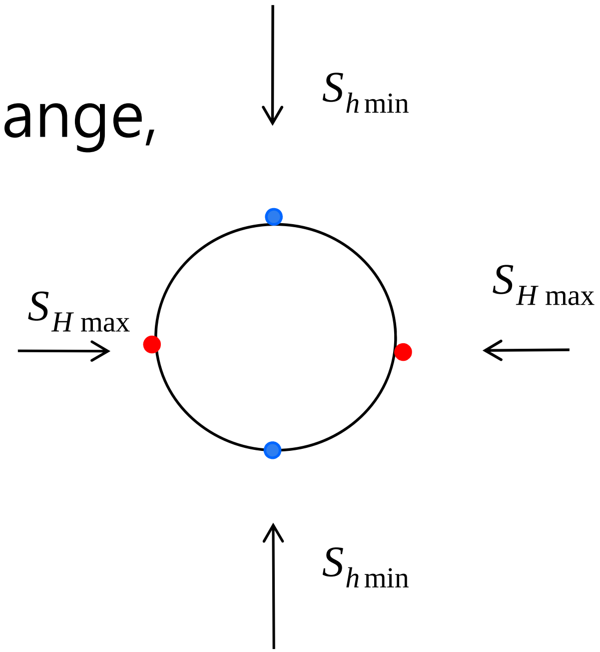
- $$\sigma_{\theta,\min} = 3S_{h\min} - S_{H\max} - P_w + \frac{E}{1-\nu}\alpha\left(T_w - T_0\right)$$

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

– Without considering temperature change,

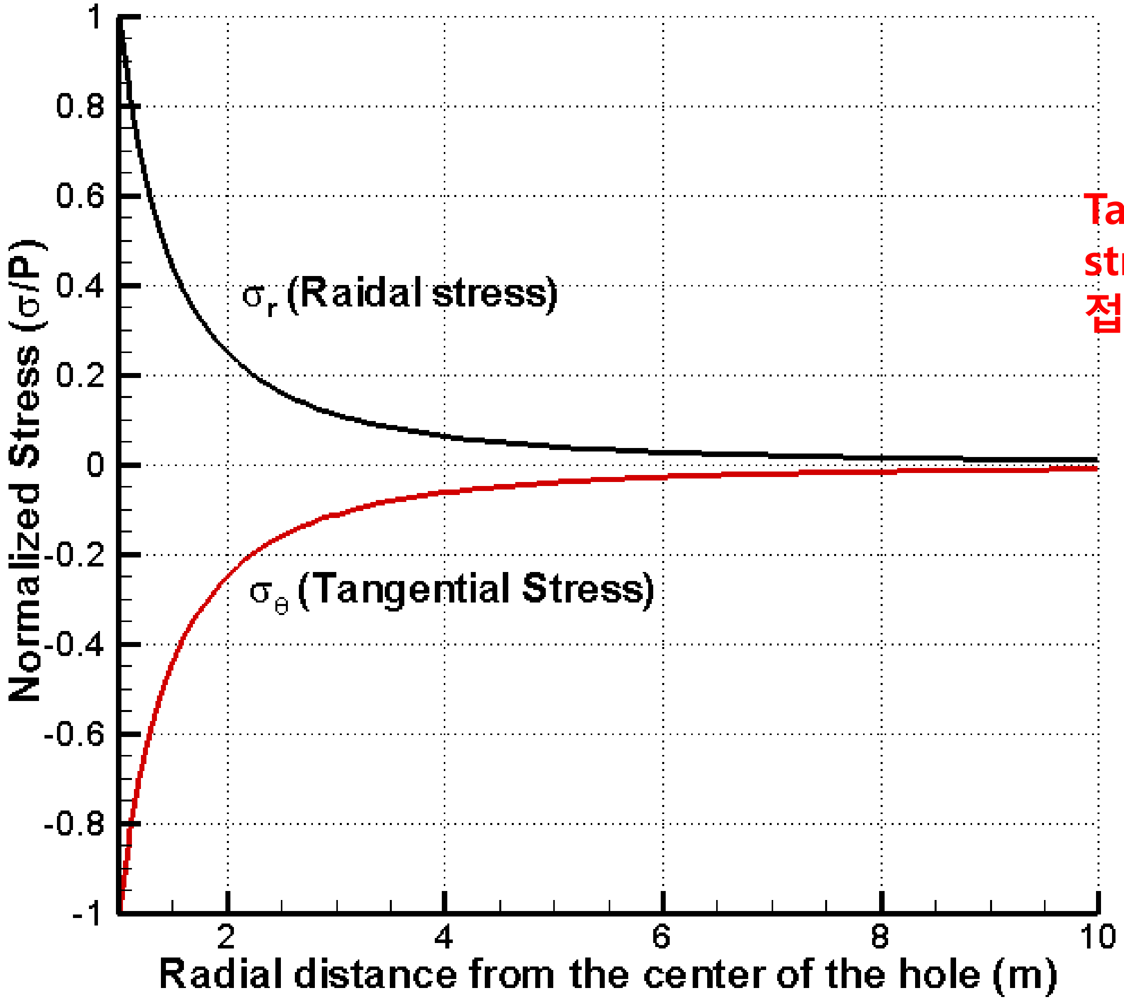
$$\sigma_{\theta,\min} = 3S_{h\min} - S_{H\max} - P_w$$

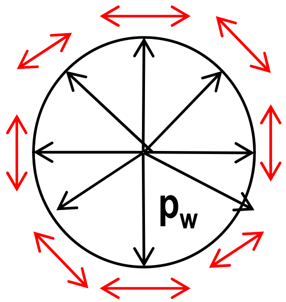
$$\sigma_{\theta,\max} = 3S_{h\max} - S_{h\min} - P_w$$



Breakdown Pressure
Internal hydraulic pressure

- Increase of internal mud/hydraulic pressure





$$\sigma_r = P_w \frac{R^2}{r^2}$$

$$\sigma_\theta = -P_w \frac{R^2}{r^2}$$

Hydraulic Fracturing
Direction

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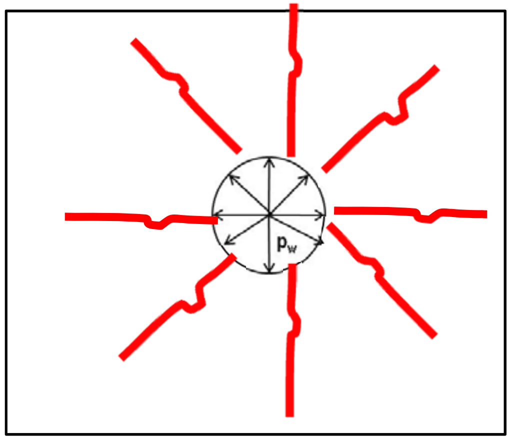
1) Stress free condition

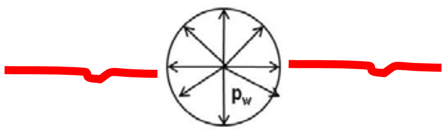
- Direction of fracturing?
- Condition for fracturing?
  - 1) Tensile strength
  - 2) Compressive strength
  - 3) Elastic modulus
  - 4) Poisson's ratio

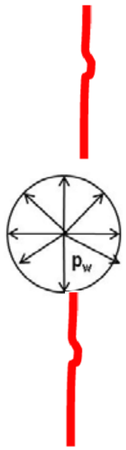


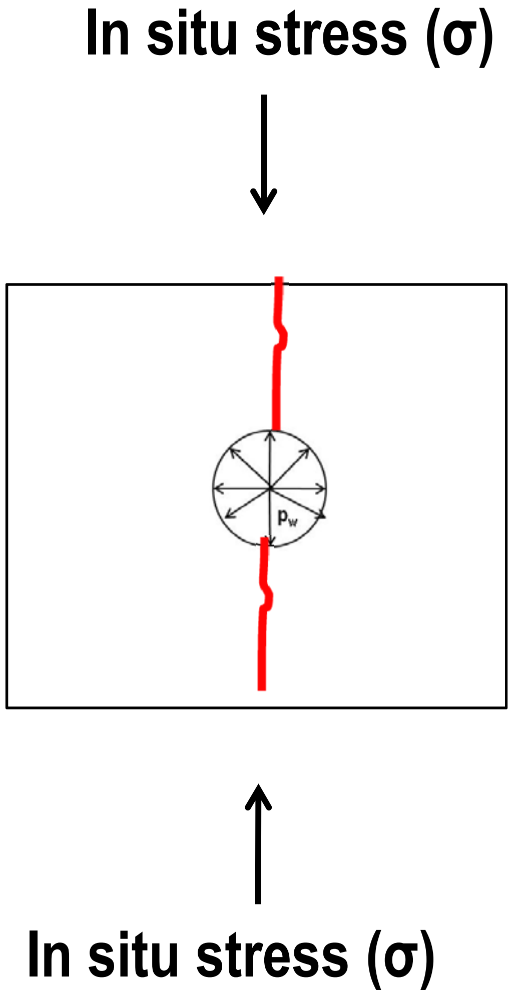
Hydraulic Fracturing
Direction

1) Stress free condition

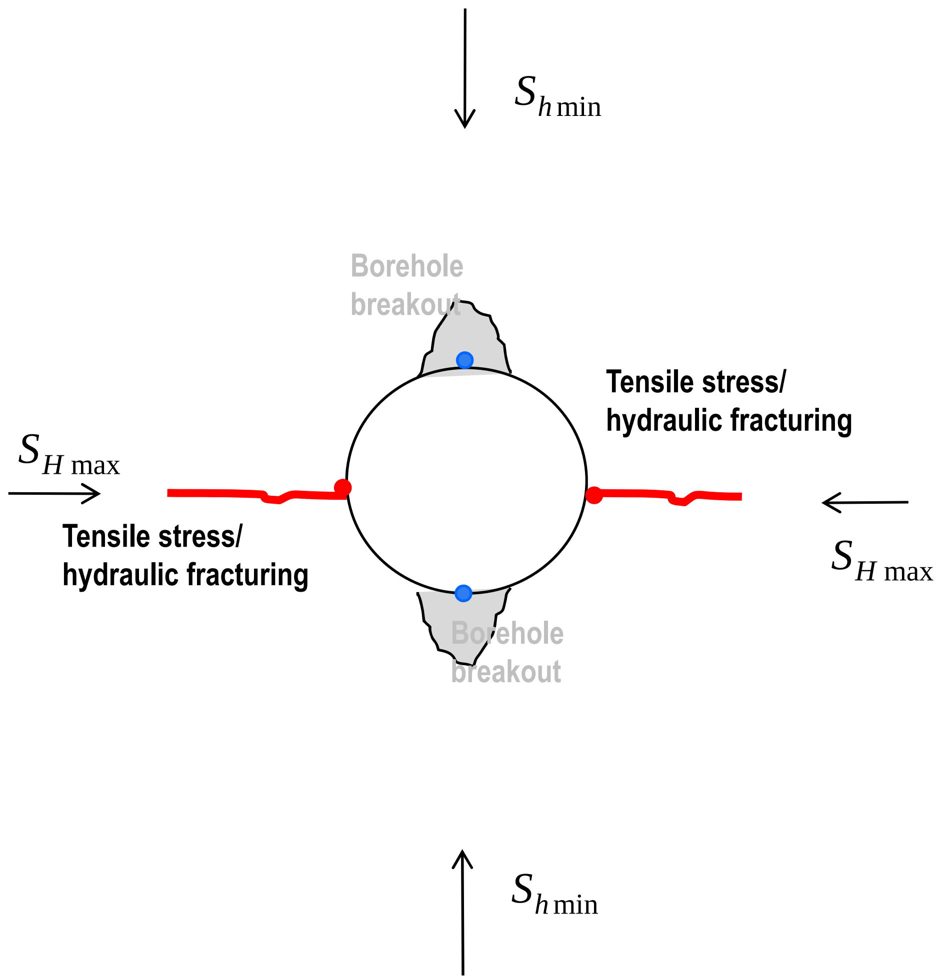
- Direction of fracturing?
- Condition for fracturing?







Breakdown Pressure
Hydraulic fracturing vs. borehole breakout



- Required internal hydraulic pressure to induce hydraulic fracturing (assuming that the formation is impermeable)
  - Impermeable, fast pressurization (upper limit)

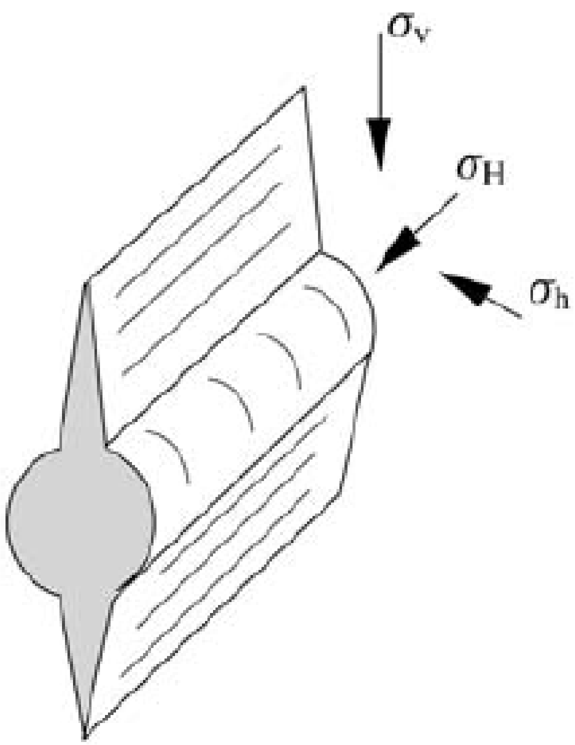
$$P_w = 3S_{h\min} - S_{H\max} + T_0$$

  - Permeable, slow pressuration (lower limit)

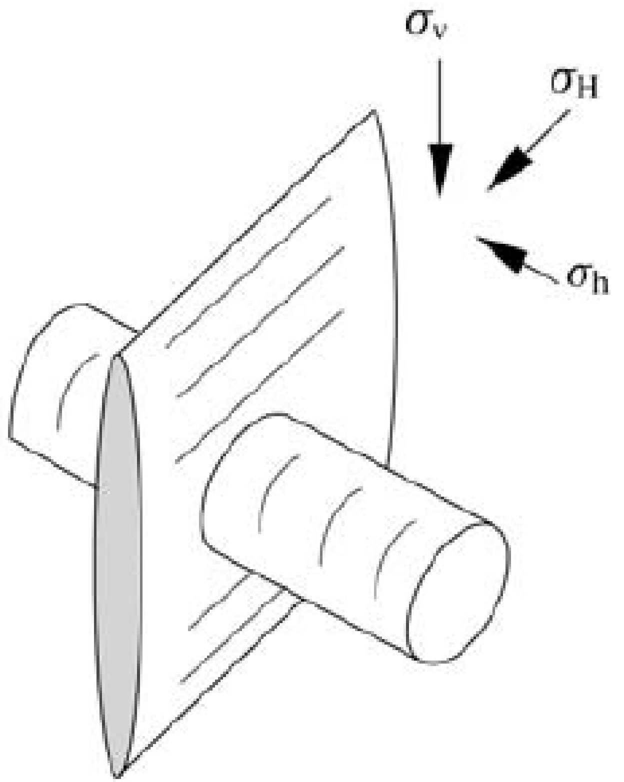
$$P_w - P_f = \frac{3S_{h\min} - S_{H\max} + T_0}{2 - \alpha(1-2\nu)/(1-\nu)}$$

- Fracturing occurs perpendicular to the minimum horizontal stress

Hydraulic Fracturing
Direction



Fracture parallel to the borehole



Fracture normal to the borehole

- For massive hydraulic fracturing for shale gas???

Fjaer et al., 2008, Petroleum related rock mechanics, 2nd ed., Elsevier

Hydraulic Fracturing
Direction

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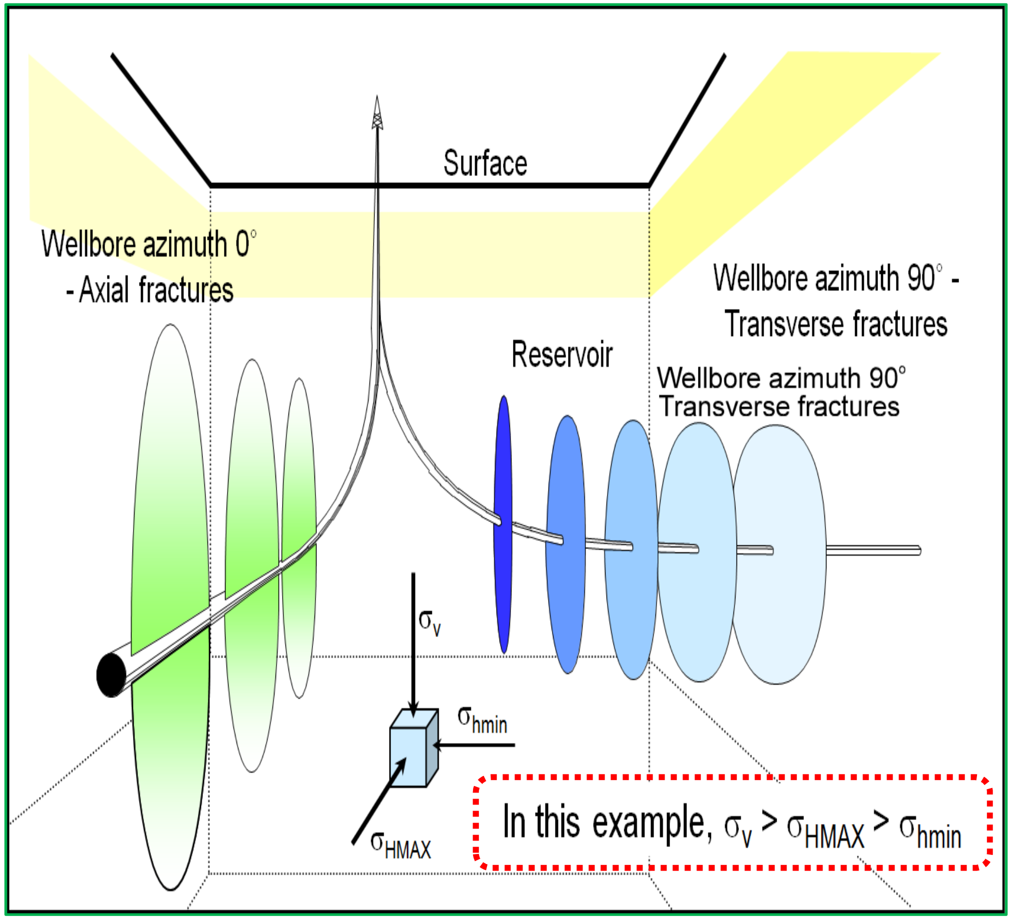
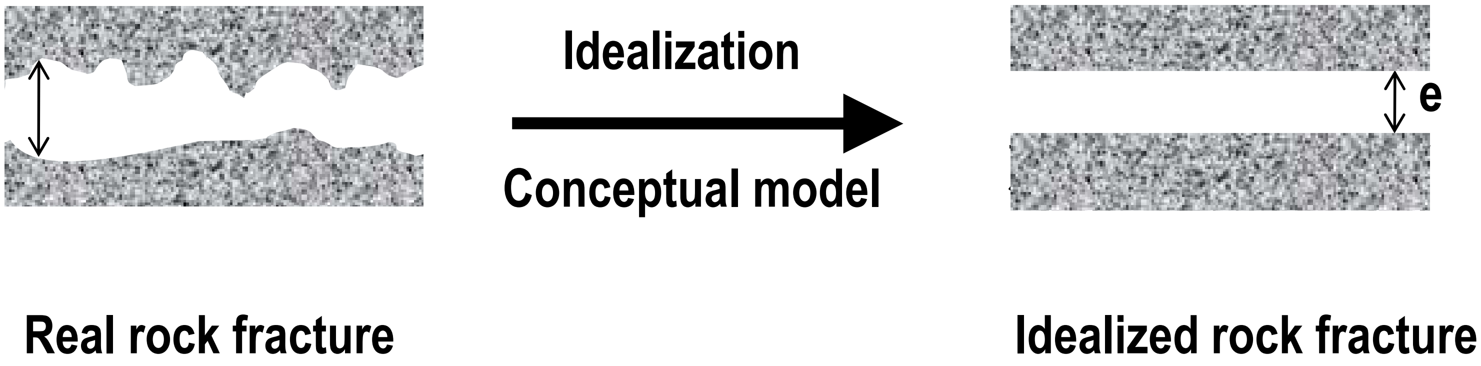
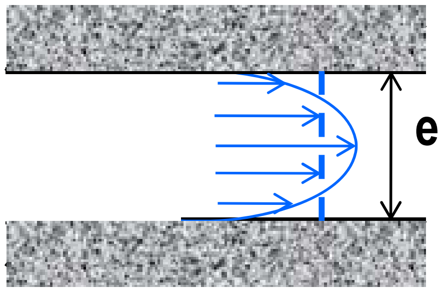


(MA Dusseault, 2011)

State of in situ "dictates" the direction of hydraulic fracturing

Hydraulic Fracturing
Fluid flow





$$Q = -\frac{e^3}{12\mu}\frac{\partial p}{\partial x}$$

- Cubic law: for a given gradient in head and unit width (w), flow rate through a fracture is proportional to the **cube** of the fracture aperture.
- Other equations exist for various kind of geometry

Hydraulic Fracturing
pressure-time response

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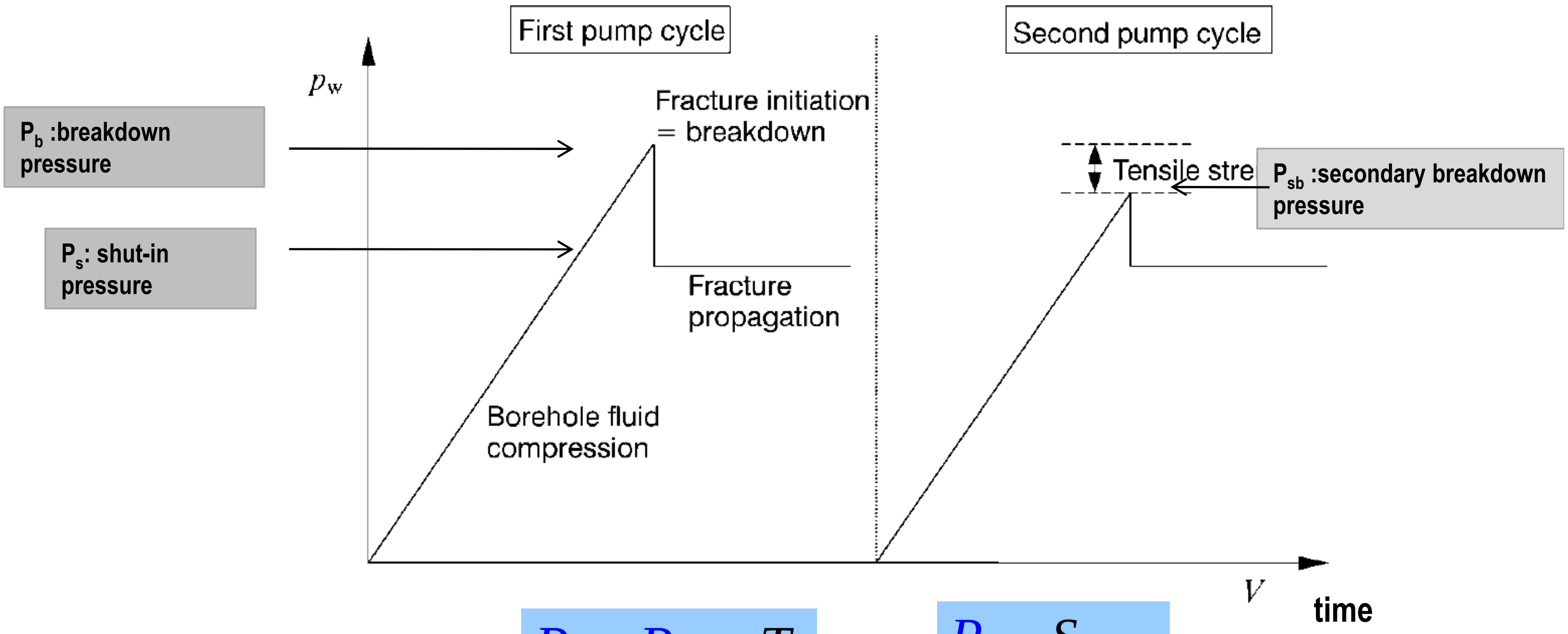

$$P_b - P_{sb} = T_0$$

$$P_s = S_{h\min}$$

Fjaer et al., 2008, Petroleum related rock mechanics, 2nd ed., Elsevier

Hydraulic Fracturing
pressure-time response

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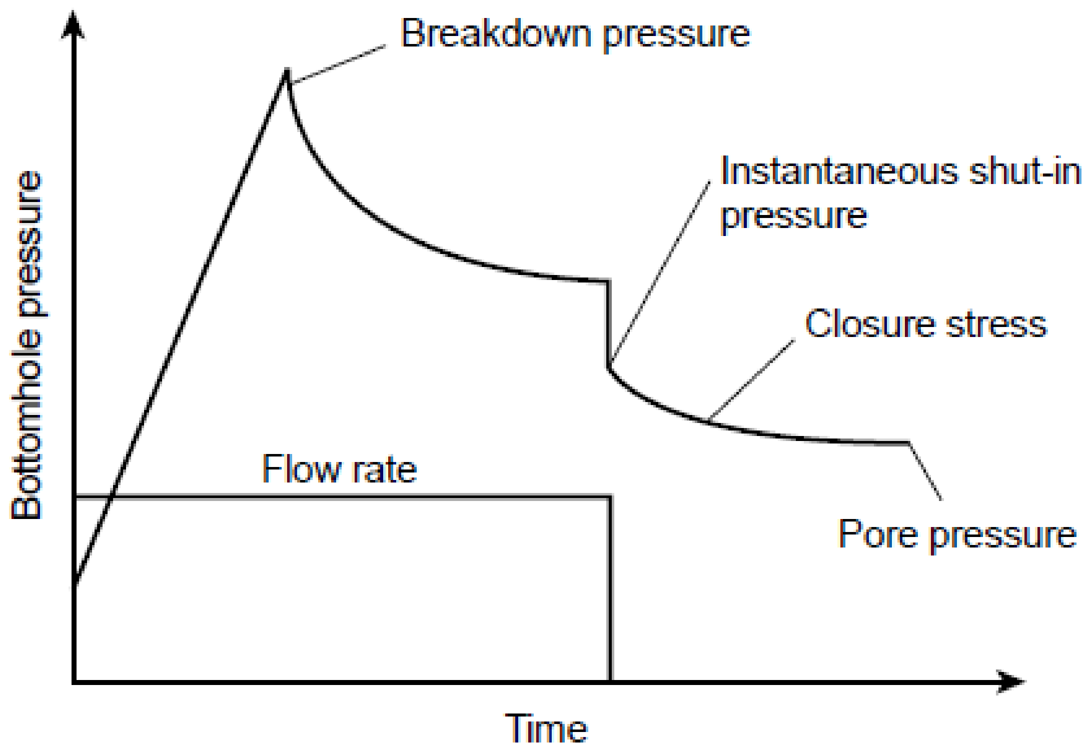

Roegiers JC, 2000, Formation Characterization: Rock Mechanics, Eds: Economides & Nolte, Reservoir Stimulation, 3rd Ed., Wiley

Hydraulic Fracturing
Factors - Brittleness

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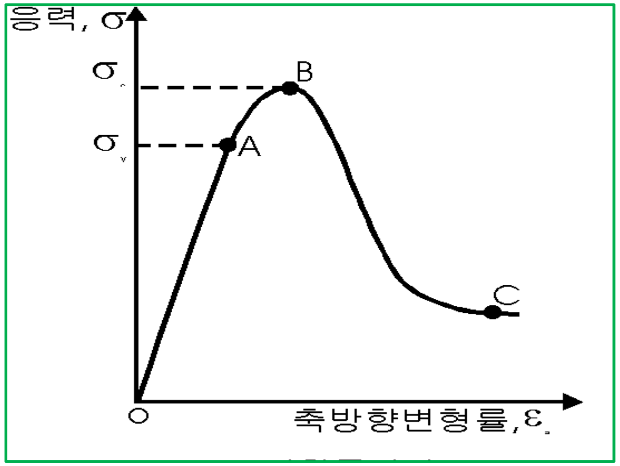
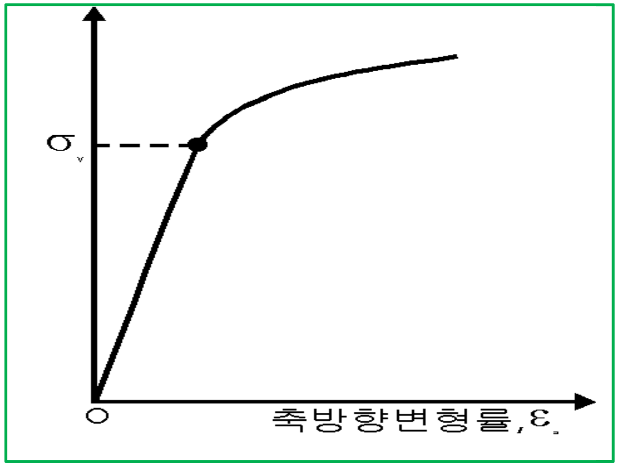


Brittle rock



Ductile rock

Hydraulic Fracturing
Factors - Brittleness

Brittleness Index (취성도)

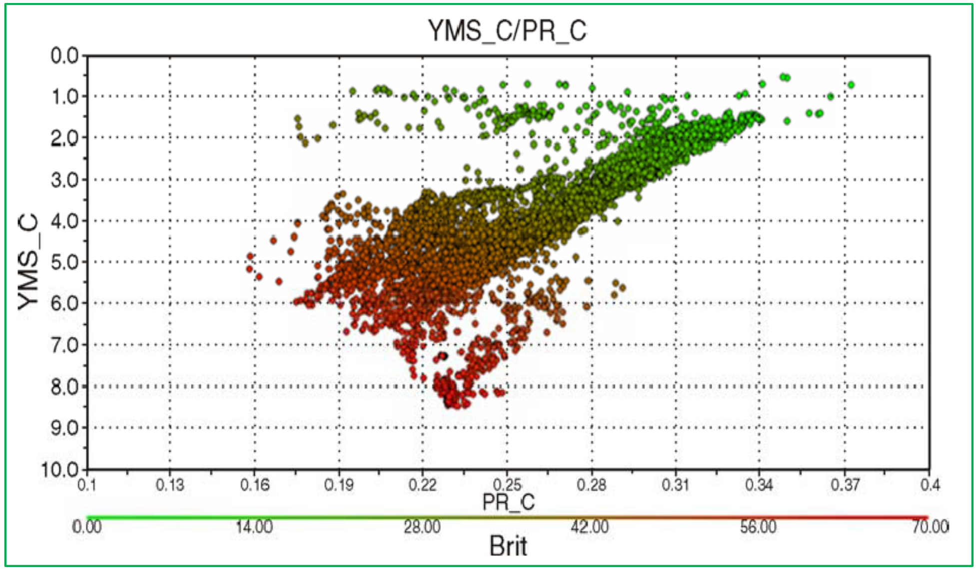
- **Different definition exist**
- **Hucka and Das (1974)**

$$취성도\ (B_i) = \frac{압축강도\ (\sigma_c)}{장강도\ (\sigma_t)}$$

$$취성도\ (B_i) = \frac{(\sigma_c - \sigma_t)}{(\sigma_c + \sigma_t)}$$

- **Altindag (2002)**

$$취성도\ (B_i) = \frac{(\sigma_c \cdot \sigma_t)}{2}$$

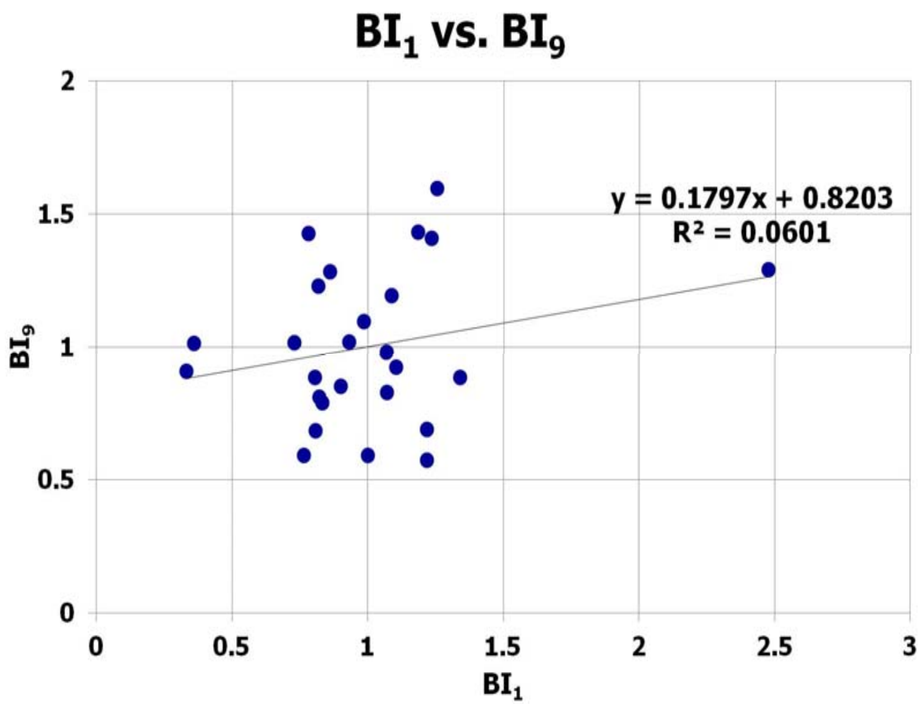


(Rick Rickman et al., 2008)

Itasca Consulting Group, 2012

Hydraulic Fracturing
Factors - Brittleness

- Brittleness from 26 shale cores
- Various definitions exist for brittleness



$$BI_1 = \frac{C_0\ (\text{일축압축강도})}{T_0\ (\text{인장강도})}$$

$$BI_9 = \frac{1}{2} \cdot \left(\frac{E_{dyn}\,[\text{Mpsi}](0.8 - \phi) - 1}{8 - 1} + \frac{\nu_{dyn} - 0.4}{0.15 - 0.4} \right) \cdot 100$$

Hydraulic Fracturing
Factors – Well configuration

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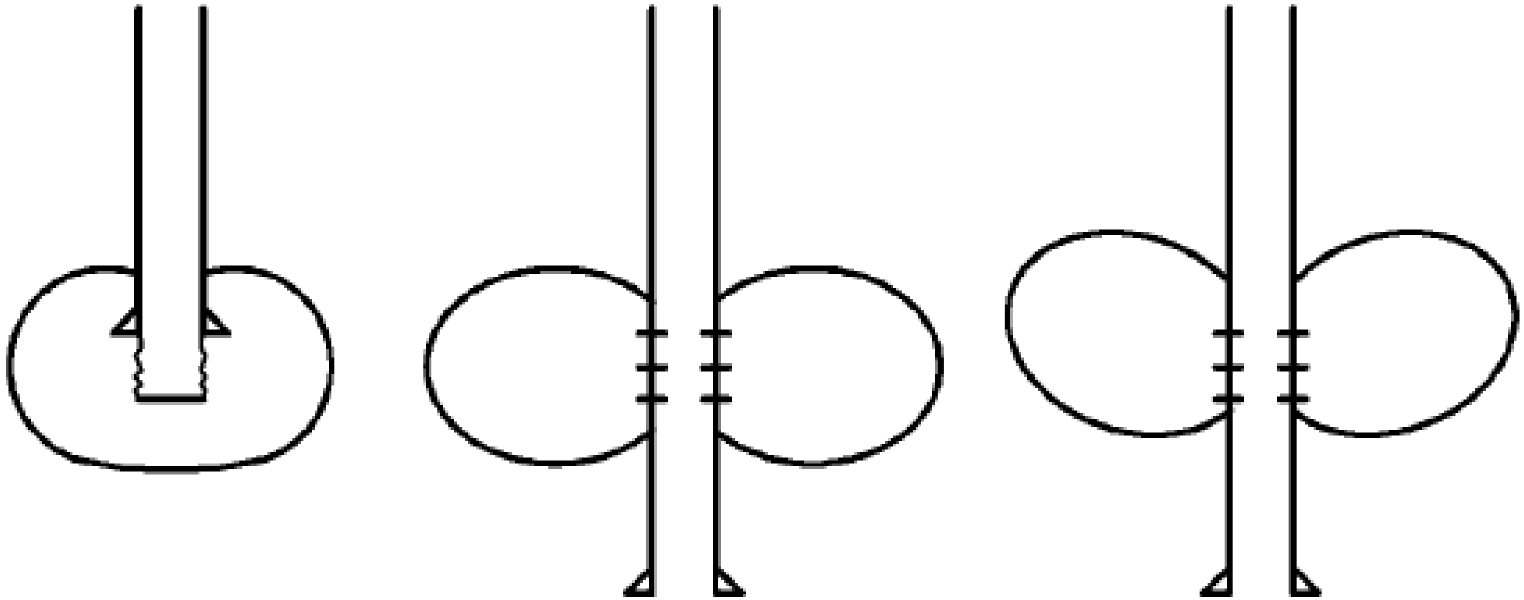
- Well configuration effect on fracture growth



Casing shoe **Perforations** **Effect of gravitational stress**

Fjaer et al., 2008, Petroleum related rock mechanics, 2nd ed., Elsevier

Hydraulic Fracturing
Factors - Confinement

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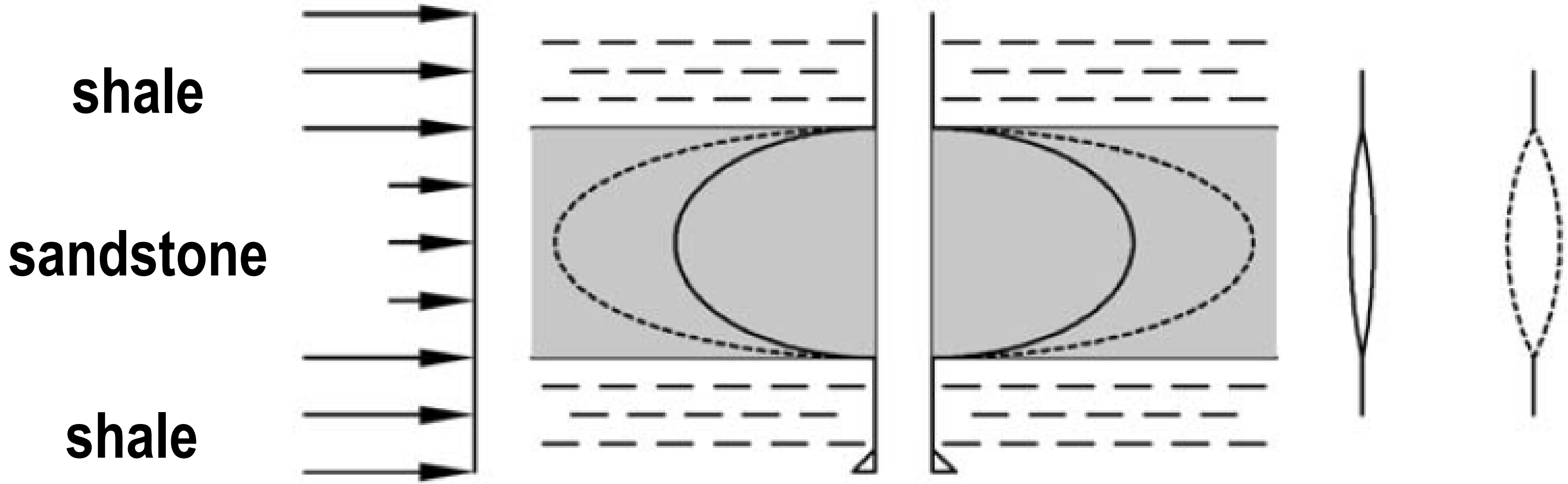
- Confinement of a fracture between layers of higher stress



Pressure required to extend the fracture

$$p_e = p(\sigma_h) + p(\text{flow}) + p(\text{tip})$$

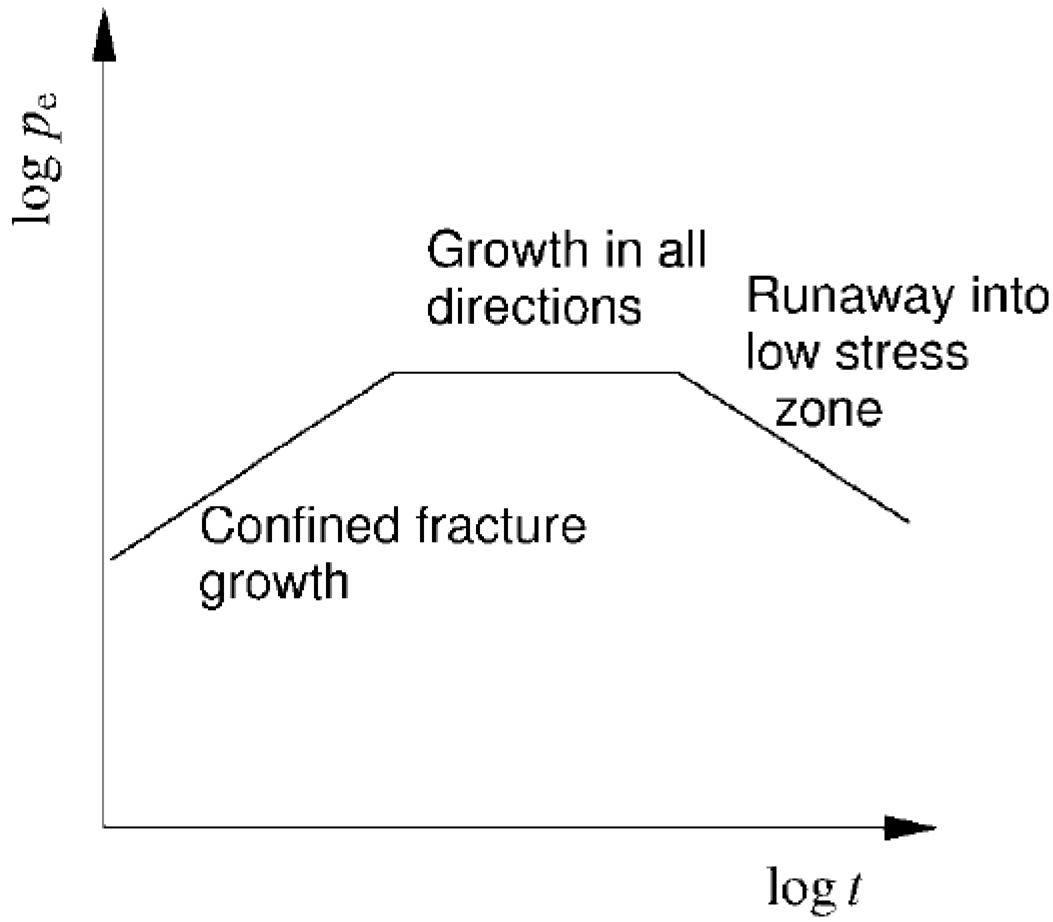
Keep the fracture open

Drive the fluid flow

Overcome the resistance at the fracture tip

Fjaer et al., 2008, Petroleum related rock mechanics, 2nd ed., Elsevier

Hydraulic Fracturing
Pressure response



Fjaer et al., 2008, Petroleum related rock mechanics, 2nd ed., Elsevier

Hydraulic Fracturing
Factors

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- Controllable
  - Injection rate (2-3bpm to 60 bpm)
  - Fluid viscosity (1cp to 10000cp)
  - Perforation location
- Might control
  - Fracture half length (through injection volume..)
  - Fracture perm (through proppant…)
- Uncontrollable
  - Stress
  - Formation stiffness
  - Temperature

Increasing Flow Capacity

Darcy's Law

$$q \approx \frac{kh \times \Delta p}{\mu \times \Delta x}\left(\frac{A}{h}\right)$$

Where: q=flow rate
k=permeability
h=height/thickness
Δp=pressure drop
μ=viscosity
Δx=length of flow system

Hydraulic Fracturing
Factors

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Prats' Dimensionless Fracture Conductivity

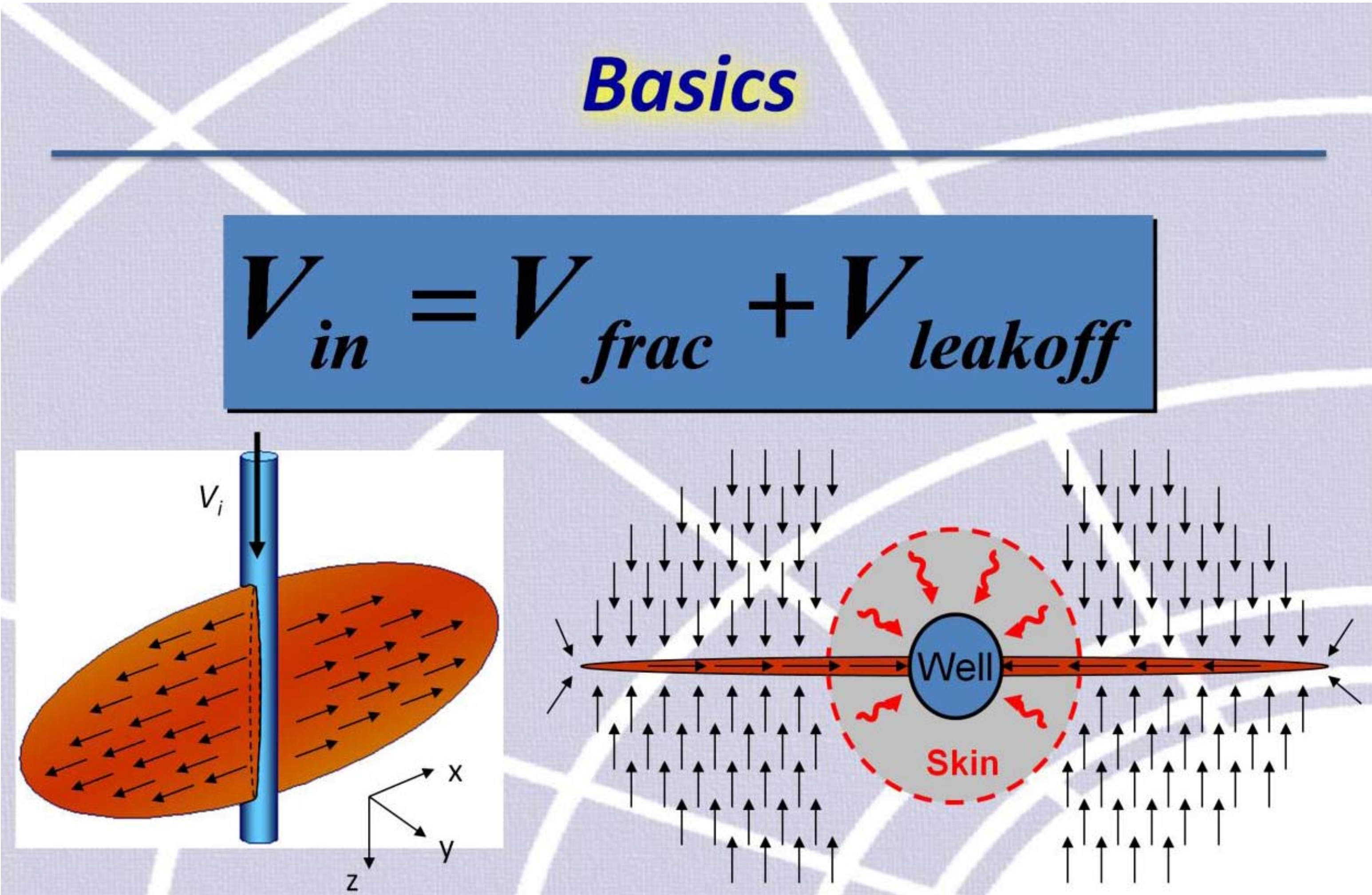
$$C_{fd} = F_{cd} = \frac{k_f w}{k X_f}$$

Where: C_{fd}=F_{cd}=Dim. Conductivity
k=reservoir permeability
k_f=fracture permeability
w=fracture width
X_f=fracture half-length

Not all fractures have infinite conductivity. In this case, Prats devised the concept of Dimensionless Fracture Conductivity, which is essentially the ratio of fracture capacity to reservoir capacity.

The numerator, $k_f w$, represents the flow capacity of the fracture itself. The denominator, kX_f, represents the ability to feed the fracture.

Hydraulic Fracturing
Factors



Itasca Short course, 2011

Hydraulic Fracturing
Factors

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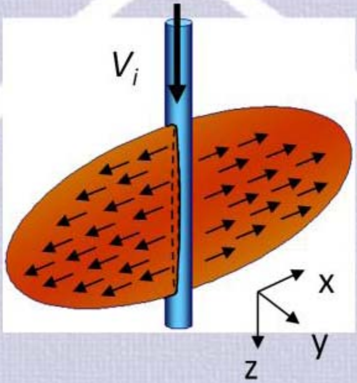
Basics



$$V_i = Q_i\, t_i$$

$$V_L = H_P\, L\left[3\,C\,\sqrt{t_p} + 2\,S_P\right]$$

$$V_f = \overline{w}\; H\; L$$

$$L = \frac{Q\, t_P}{3\,C\,H_P\sqrt{t_p} \;+\; 2\,S_P H_P + \overline{w}\;H}$$

Q : Pumping rate (ft3/min)
C : Fluid loss coeff. (ft/√min)
H : Total fracture height (ft)
w : average fracture width (ft)

t_P: Pumping time (min)
H_P : Propped length (ft)
S_P : spurt loss (ft^3/ft^2)
L : tip-to-tip length (ft)

This equation is the basis of hydraulic fracturing design (Smith, 2002)

Sneddon (1946) and Sneddon & Elliot (1946) on penny shaped crack

- ✓ **Pressure required to extend a Crack Radius of R** ($p_{net} = p_{crack}$ – pressure against crack opening)

$$p_{net} = \sqrt{\frac{\pi \gamma_F E}{2(1-v^2)R}}$$

Derived using linear elastic fracture mechanics

- ✓ **Volume of Crack**

$$V = \frac{16(1-v^2)R^3}{3E} p_{net}$$

- ✓ **Width of a Static Penny-shaped Crack** (R = penny-shaped crack radius)

$$w(r) = \frac{8 p_{net} R(1-v^2)}{\pi E} \sqrt{a-(r/R)^2}$$

Derived using theory of linear elasticity

HF Models
Basic models

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Perkins & Kern (1961)

✓ **Pressure required to extend a Crack Radius of R = Work done by the pressure in the crack to open the additional width**

$$p_{net} = \sqrt{\frac{\pi \gamma_F E}{2(1-\nu^2)R}} \longrightarrow p_{net} = \left(\frac{2\pi^3 \gamma_F^3 E^2}{3(1-\nu^2)^2 V} \right)^{\frac{1}{5}}$$

✓ **Volume of Crack (q_i : constant injection rate, t : time)**

$$V = q_i t = \frac{16(1-\nu^2)R^3}{3E} \left(\frac{2\pi^3 \gamma_F^3 E^2}{3(1-\nu^2)^2 q_i t} \right)^{\frac{1}{5}}, \quad R = \left[\frac{9 E q_i^2 t^2}{128 \pi \gamma_F (1-\nu^2)} \right]^{\frac{1}{5}}$$

✓ **Max. Width of a Static Penny-shaped Crack (h_f : fixed height)**

$$w = \frac{2 p_{net} h_f (1-\nu^2)}{E}$$

HF Models
KGD vs. PKN Model

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	KGD Model	*PKN Model*
	Khristianovich *et al.* (1959) Geertsma and de Klerk (1969)	Perkins and Kern (1961) Nordgen (1972)
3D -> 2D	• Plane strain in Horizontal Direction - Independent horizontal cross section • Fracture Height >> Fracture Length • Completely Confined Fracture	• Plane strain in Vertical Direction - Independent vertical cross section • Fracture Height << Fracture Length • Fixed Height
Focus on	• Fracture Mechanics and Fracture Tip	• Fluid Flow and Pressure Gradient
Ignore	• Flow Rate and Pressure in Fracture	• Fracture Mechanics and Tip Region Play

Similar to

- Planar Fracture
- 1D-Direction Fluid Flow : along the length of the fracture
- Newtonian Fluids
- Leakoff Behavior : Governed by filtration theory (refer to Carter(1957))
- Fracture Propagation : Continuous, Homogeneous, Isotropic Linear Elastic Solid

HF models
Leak off

- Fluid loss rate, q_L

$$q_L = \frac{2C_L A}{\sqrt{t-\tau}}$$

  - C_L : fluid loss coefficient
  - A : fracture area
  - T : time measured from the start of pumping
  - τ : the time when a fracture is created
  - Highest rate of fluid loss is always at the fracture tip

HF Models
KGD vs. PKN Model

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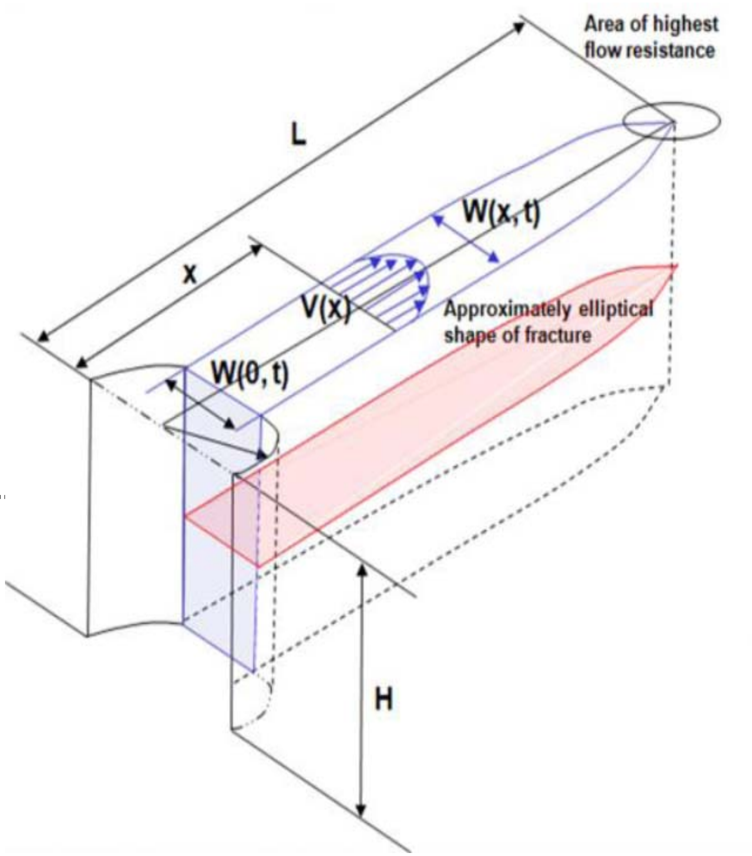
KGD Model	*PKN Model*
Khristianovich *et al.* (1959)	**Perkins and Kern (1961)**
Geertsma and de Klerk (1969)	**Nordgen (1972)**

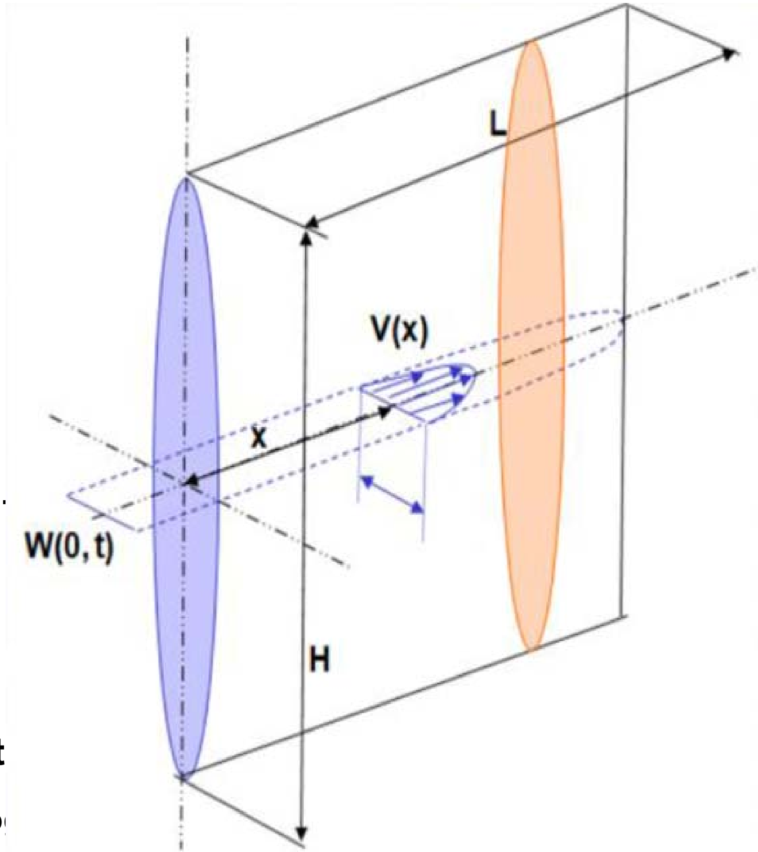
3D -> 2D

Focus on

Ignore

Similar to





Mack & Warpinski, 2000, Mechanics of hydraulic fracturing, Eds: Economides & Nolte, Reservoir Stimulation, 3rd Ed., Wiley

HF Models
KGD vs. PKN Model

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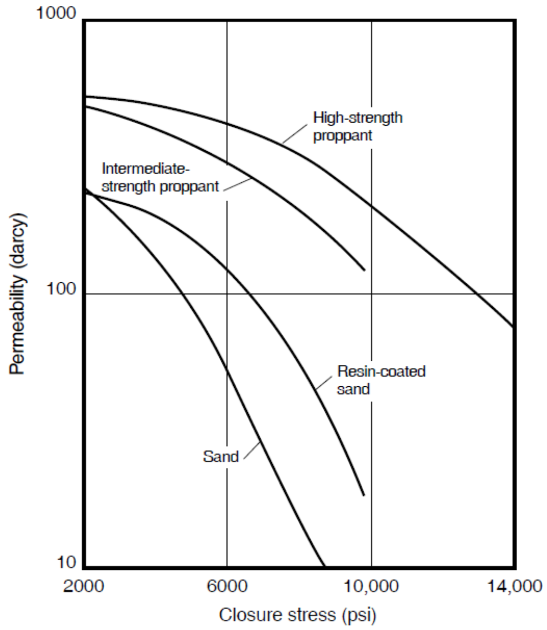
	KGD Model	***PKN Model***
	Khristianovich *et al.* (1959) **Geertsma and de Klerk (1969)**	**Perkins and Kern (1961)** **Nordgen (1972)**
Fluid Flow Rate	$\frac{dp}{dx} = -\frac{64q\mu}{\pi h_h w^3}$	$\frac{\partial p}{\partial x} = -\frac{12q\mu}{h_h w^3}$
Net Pressure	$p_{net} = \left[\frac{16\mu q_i E'^3}{\pi h_f^4} L\right]^{1/4}$	$p_{net,w} = \left[\frac{21\mu q_i}{64\pi h_f L^2} E'^3\right]^{1/4}$
Width at Wellbore	$w_w = 0.38\left(\frac{q_i \mu L}{E'}\right)^{1/4}$	$w_w = \left(\frac{84}{\pi}\frac{\mu q_i L^2}{E' h_f}\right)^{1/4}$
Fracture Length (fn of time)	$S = \frac{2C_L\sqrt{\pi t}}{\overline{w}}$	$S = \frac{8C_L\sqrt{\pi t}}{\pi w_w}$

Leak off

Mack & Warpinski, 2000, Mechanics of hydraulic fracturing, Eds: Economides & Nolte, Reservoir Stimulation, 3rd Ed., Wiley

HF Models
Proppant

- Physical properties that has impact on fracture conductivity
  - Proppant strength
  - Grain size and grain-size distribution
  - Quantities of fines and impurities
  - Roundness and sphericity
  - Proppant density
- Strength comparison
  - Sand ~ 6,000 psi,
  - resin-coated proppant(RCP) ~ 8,000 psi,
  - Intermediate-strength proppant (ISP) ~10,000 psi,
  - high strength proppant > 10,000 psi



HF Models
Proppant

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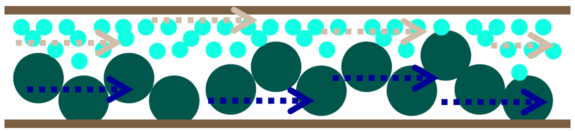
- Once pumping stops → injected fluids leak off → fracture will close and new formation area will not be available for production.
- Proppant : sand or high strength granular substitute

Proppant maintain the fracture width to provide a conductive path for production.

1) Effect of Proppant on Fluid Rheology (유동학)
- viscosity of proppant-laden slurry > viscosity of fluid alone
2) Convection (Gravity Current)
- Effect of convection↑(with large width)
-



3) Proppant Transport
- Hindered settling & clustered settling occur
- …

Presentations

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- Historical papers
  - Hubbert & Willis, 1957, Mechanics of HF
  - Haimson & Fairhurst, 1969, HF in porous permeable materials, J Pet Tech, 21(7):811-817
- EGS Hydraulic Stimulation
  - Rosemanowes: Pine, R. J., and A. S. Batchelor. "Downward Migration of Shearing in Jointed Rock During Hydraulic Injections." *IJRMMS* 1984;21(5): 249-63.
  - Soultz: …
  - Germany: Gross Schenebeck (GFZ), Gunter Zimmerman et al.
- Shale Gas HS
  - …