Significance of mechanical behavior and stress heterogeneity in a deep geothermal reservoir

Dr. David P. Sahara

Global Geophysics Research Group, ITB

Motivation

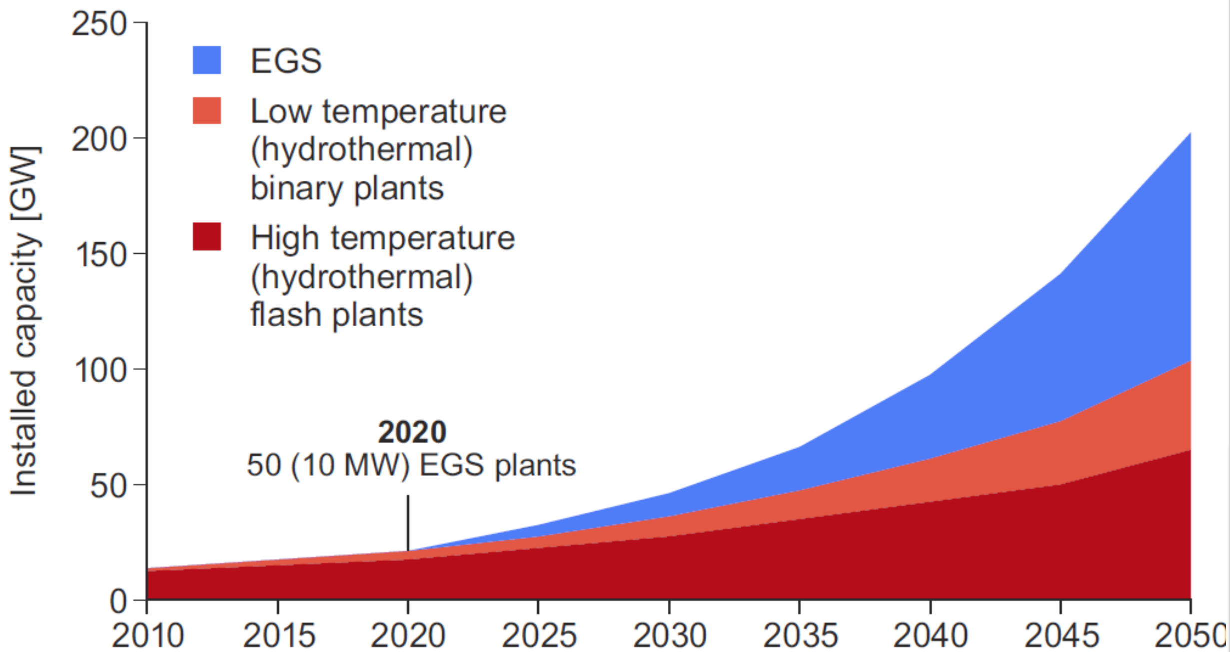
- Vast heat energy stored within the earth
  - The earth thermal energy flow to the surface ~ 960 EJ/year ***[Pollack et al., 1993]***
    - Twice the total energy consumption (560 EJ in 2013) ***[IEA, 2013]***
  - Cooling one cubic kilometer of rock by 1°C equivalent to 70,000 tons of coal
- Geothermal exploitation
  - 1904 – first electricity production at Lardarello (Italy)
  - Dominated by hydrothermal system
  - As of 2015 ***[Lund and Boyd, 2015]***
    - Electrical capacity ~ 11.7 GW_e
    - Direct use ~ 70 GW_t
  - ~2.4% of the total renewables energy

Motivation

- Vast heat energy stored within the earth
- Geothermal exploitation
- Enhanced geothermal system

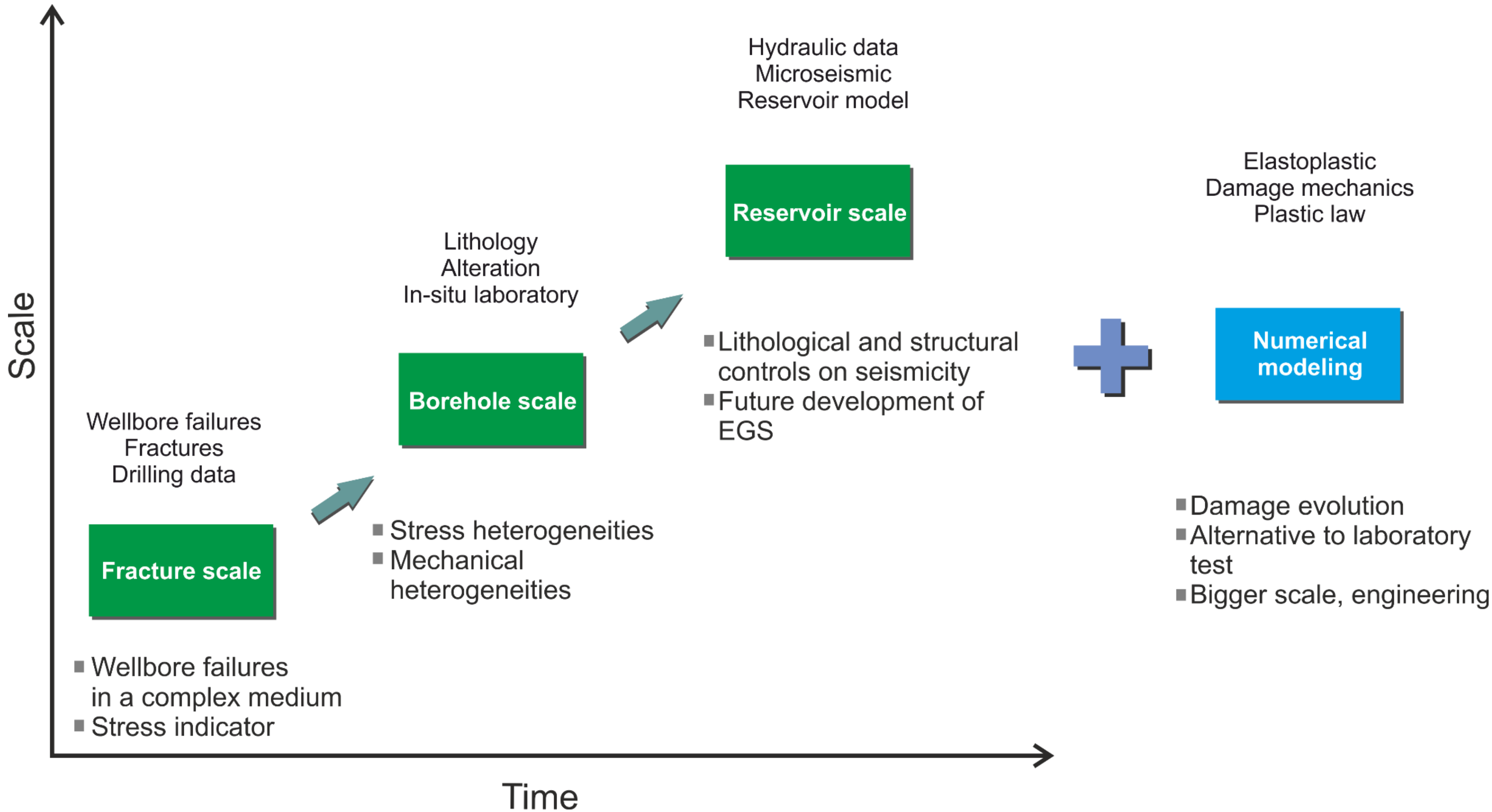
"a body of rock containing useful energy, the recoverability of which has been increased by artificial means such as hydraulic stimulation" ***[AGRC, 2010]***

- In-situ stress field
- Fracture characteristics
- Mechanical behavior (damage evolution)



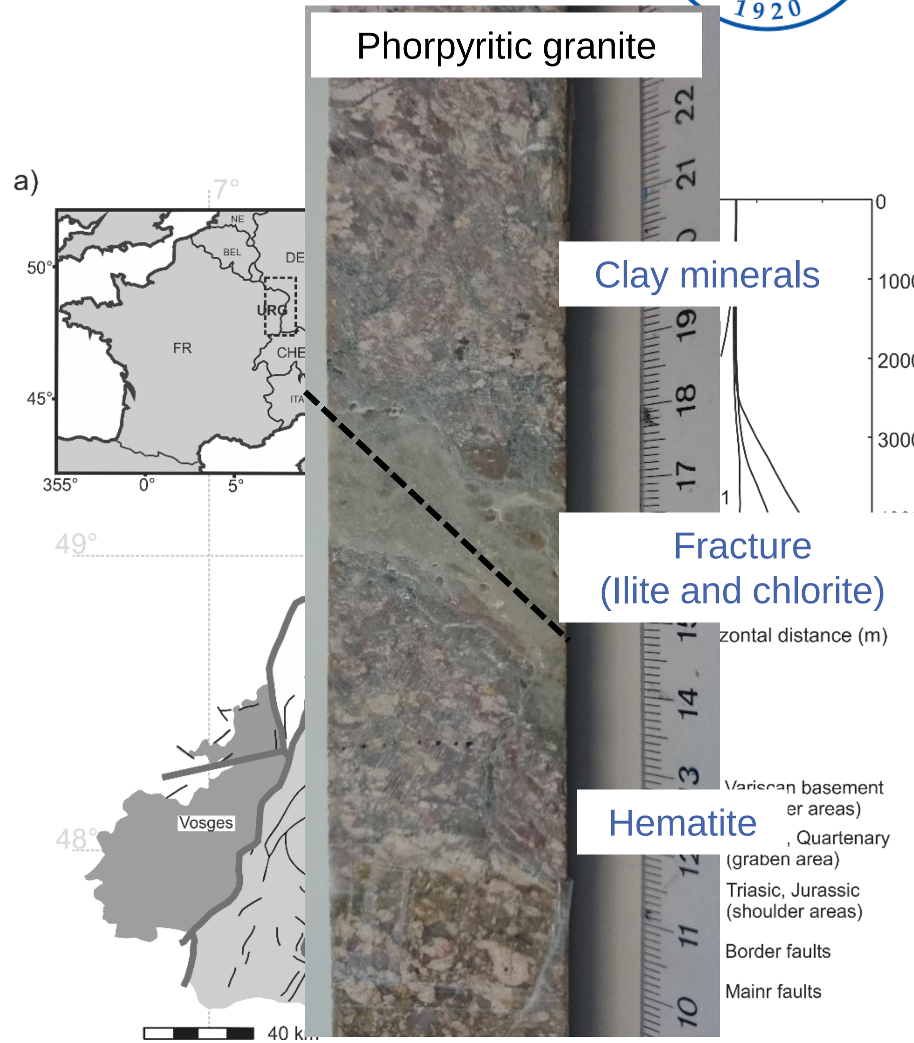
[IEA, 2013]

Procedures


Scale
Time
Wellbore failures
Fractures
Drilling data
Fracture scale
Wellbore failures
in a complex medium
Stress indicator
Lithology
Alteration
In-situ laboratory
Borehole scale
Stress heterogeneities
Mechanical
heterogeneities
Hydraulic data
Microseismic
Reservoir model
Reservoir scale
Lithological and structural
controls on seismicity
Future development of
EGS
Elastoplastic
Damage mechanics
Plastic law
Numerical
modeling
Damage evolution
Alternative to laboratory
test
Bigger scale, engineering

Soultz geothermal field | Fracture scale | Borehole scale | Reservoir scale | Conclusions

- Power plant ~ 1.5 Mwe
- Reservoir temperature ~ 200°
- Geological setting
  - Soultz horst structure
    - Sediments and crystalline
  - Fractures
    - Present day (NS), Variscan (NE), and Hercynian (NNW)
    - Normal to strike slip
  - Alteration
    - Pervasive and vein alteration



[Sahara et al, 2014]

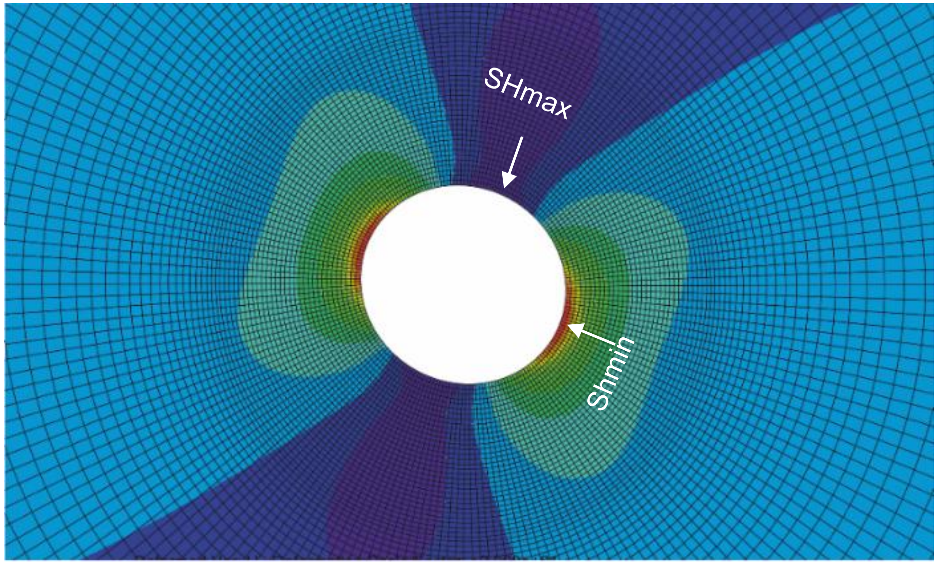
- 1. Stress estimation
  - Previous wellbore failures observations *[e.g. Valley, 2007; Cornet et al., 2007]*
  - Isotropic and plane strain

$$e\left(\frac{\partial^2 \sigma_{xx}}{\partial_x{}^2}+\frac{\partial^2 \sigma_{xx}}{\partial_y{}^2}+\frac{\partial^2 \sigma_{yy}}{\partial_x{}^2}+\frac{\partial^2 \sigma_{yy}}{\partial_y{}^2}\right)+e'\left(\frac{\partial \sigma_{xx}}{\partial_x}+\frac{\partial \sigma_{yy}}{\partial_x}+\frac{\partial \sigma_{xx}}{\partial_y}+\frac{\partial \sigma_{yy}}{\partial_y}\right)=0$$

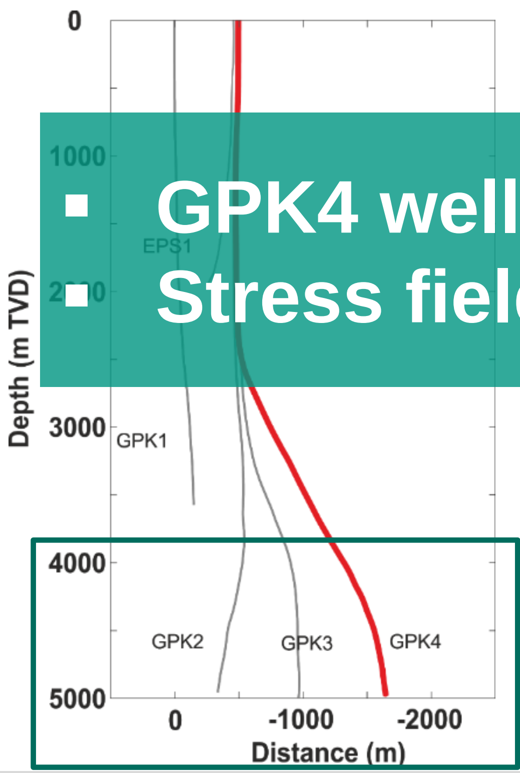
  - Homogeneous $e'=0$

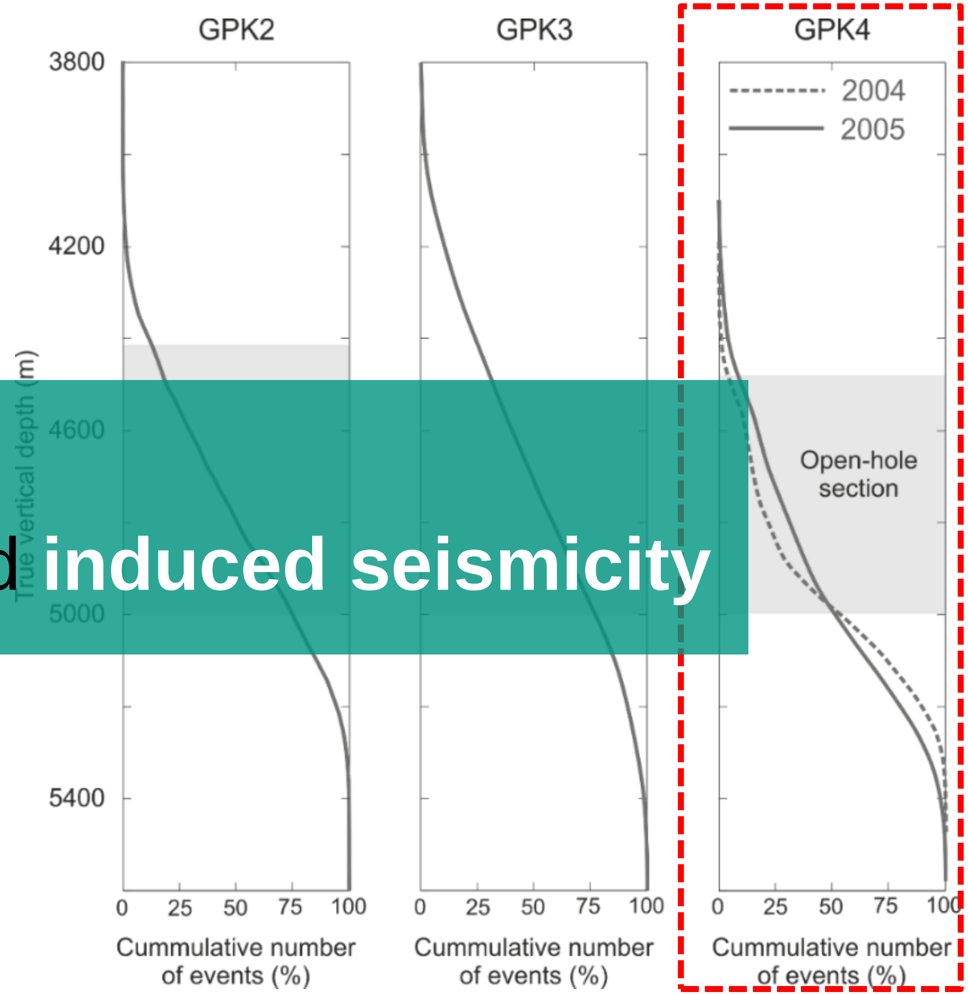
$$\left(\frac{\partial^2}{\partial_x{}^2}+\frac{\partial^2}{\partial_y{}^2}\right)(\sigma_{xx}+\sigma_{yy})=0$$

  - Fractured granite?
  - Numerical modeling



- 2. Hydraulic stimulation
  - Deep reservoir
    - 4400 – 5000m TVD
  - Different injection strategies
  - Unique microseismicity pattern

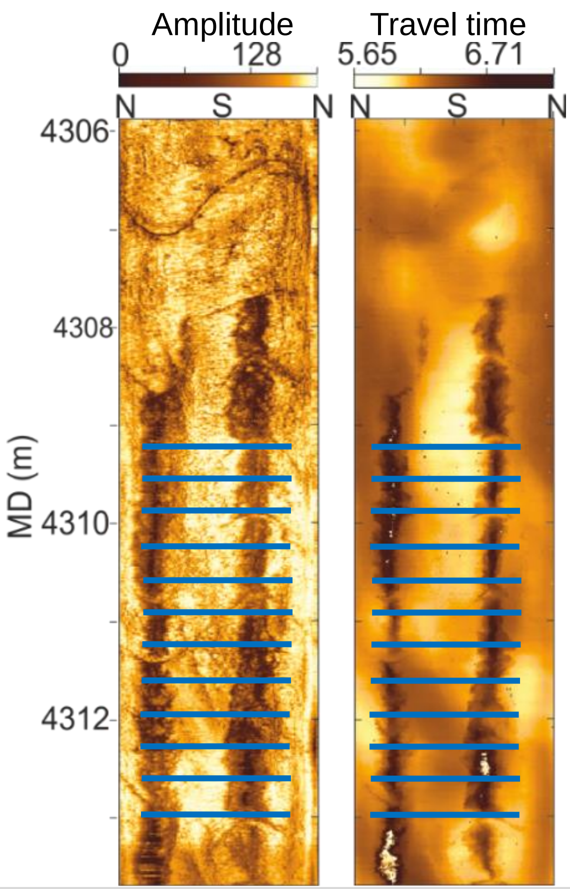


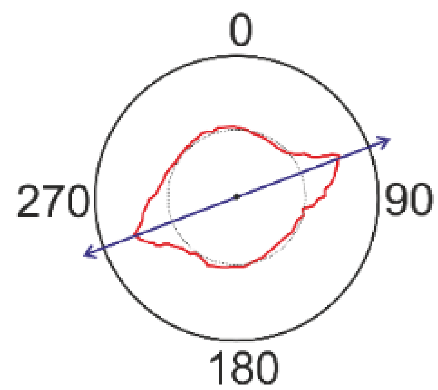


- GPK4 well
- Stress field and induced seismicity

- Wellbore failures observation

  “Localized failure around a borehole due to compressional and tensional stress concentration”



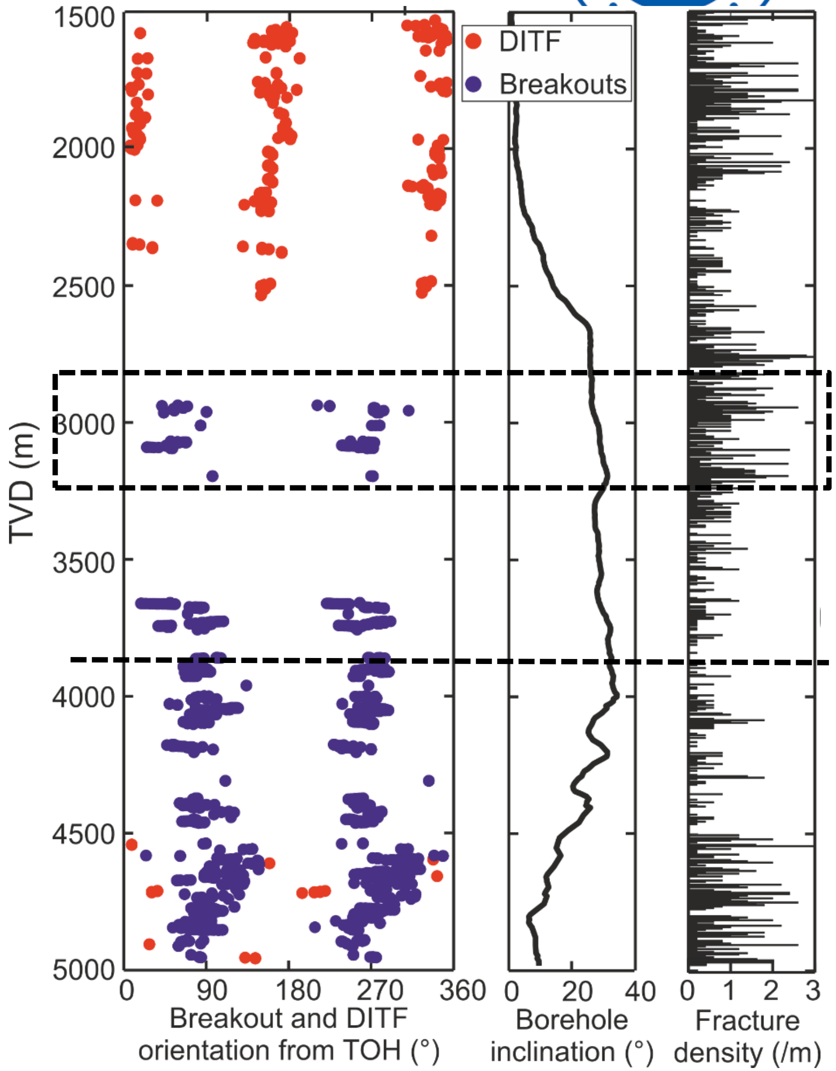


- High resolution failures picking
  - Orientation, width, depth
  - Every 20 cm
  - 1221 breakout pairs
  - 887 DITF pairs
- Natural fractures
  - 1871 natural fractures

Impact of wellbore inclinations

Modeling

- Wellbore inclination ~ no effect on orientation
- Compressional stress ~ 2*Sv
  - Breakouts ~ 3200 m (vertical) or 3800 m (25°)
- Tensile stress ~ greater in vertical well



[Sahara et al, 2015]

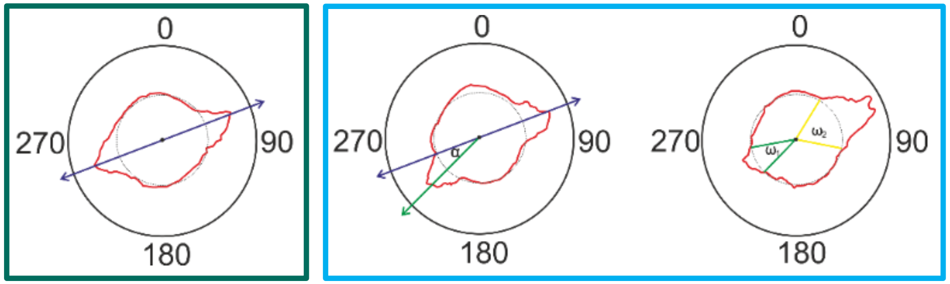
Observation

- DITF when wellbore inclined < 10°
- Breakouts at a greater depth

Fracture-controlled breakouts

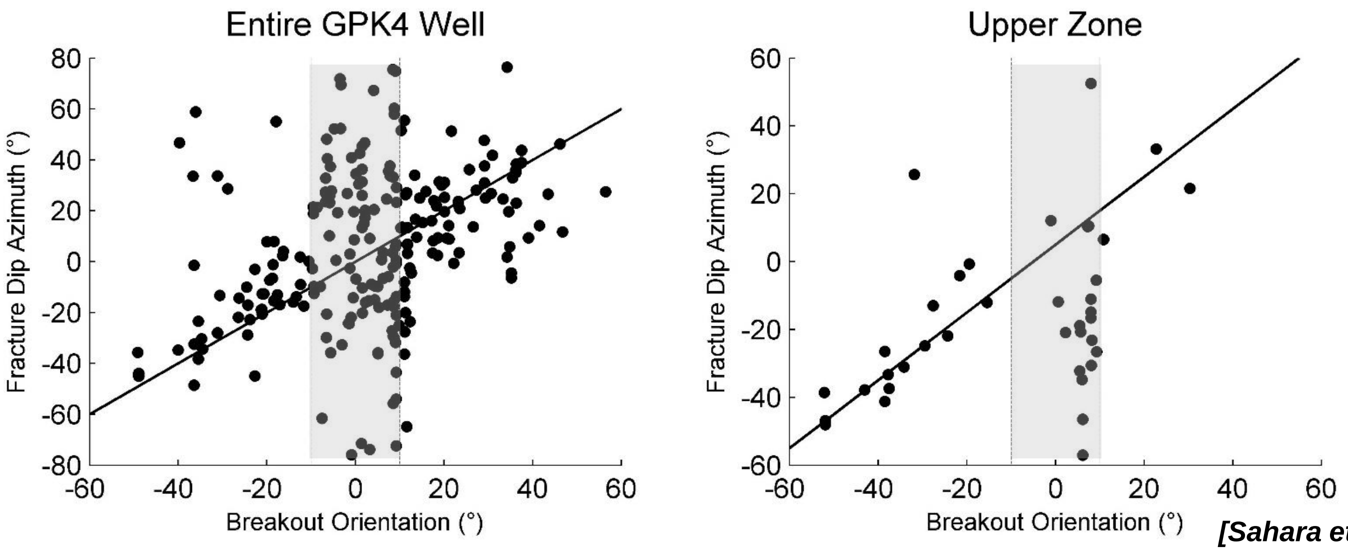
Soultz geothermal | **Fracture scale** | Borehole scale | Reservoir scale | Conclusions

- Two types of breakouts

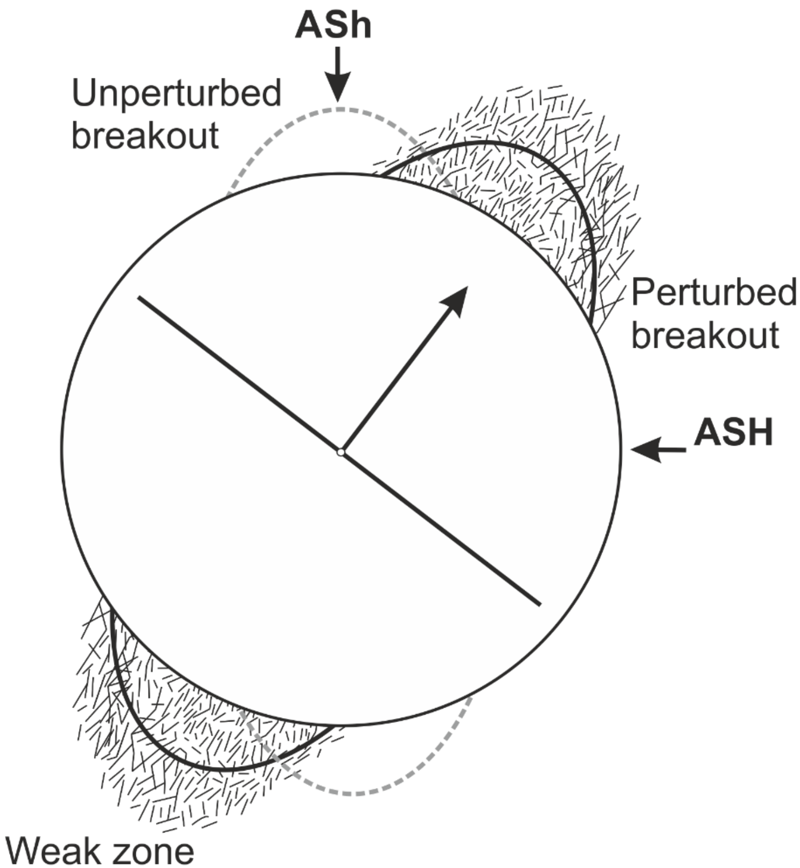


Type I and type II breakouts

- Direct correlation between breakout orientations and fracture dip direction



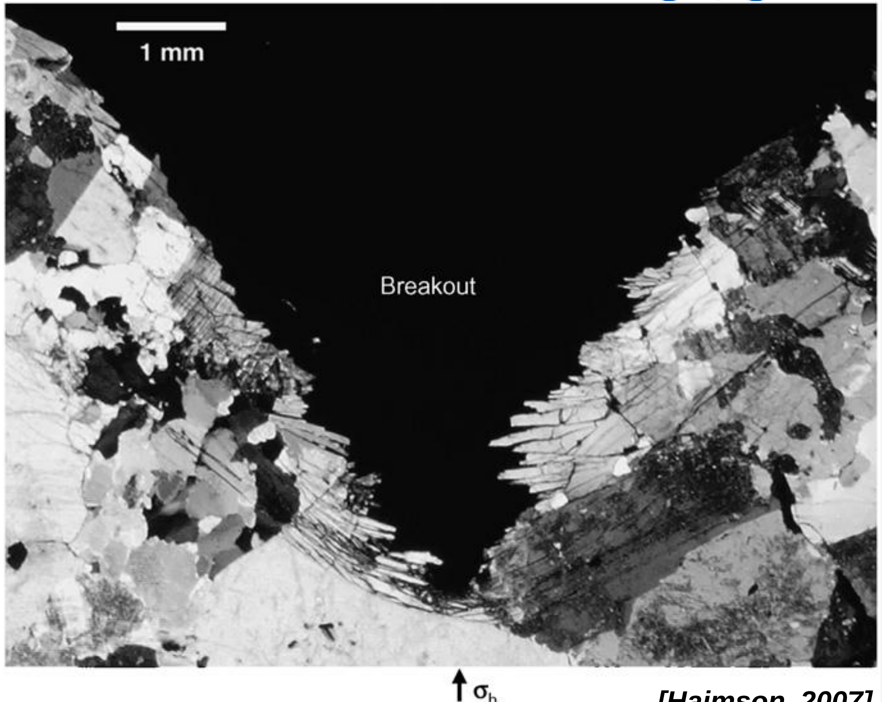
[Sahara et al, 2014]



[Sahara et al, 2014]

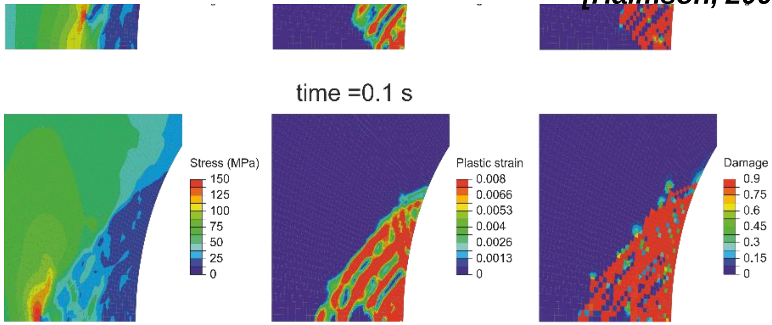
- Experimental test of breakouts
  - Inelastic deformation
  - Micro to macro (brittle) deformation
  - e.g. ***Haimson et al. (2007), Ewy and Cook (1997)***
- Numerical modeling
  - Continuum damage mechanics
    - Implicit model – fracturing
    - Plastic law
    - Different failure mode (opening and shearing)
  - Good comparison with experimental data
    - Width and depth of damaged zone

time =0.002 s



[Haimson, 2007]

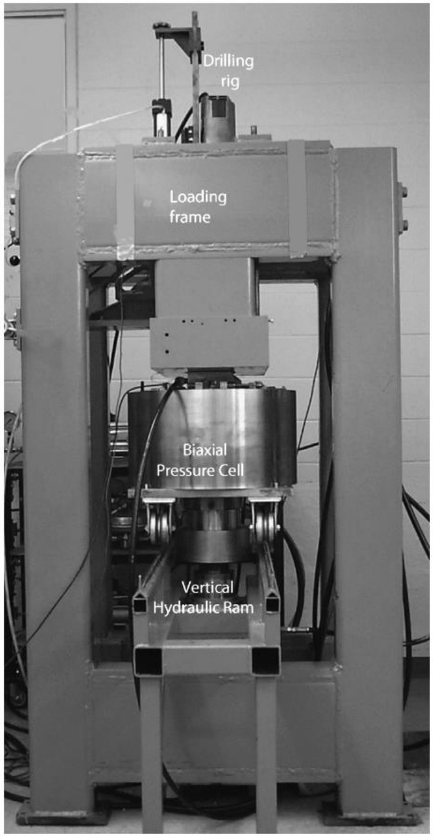
time =0.1 s



[Sahara et al, 2018]

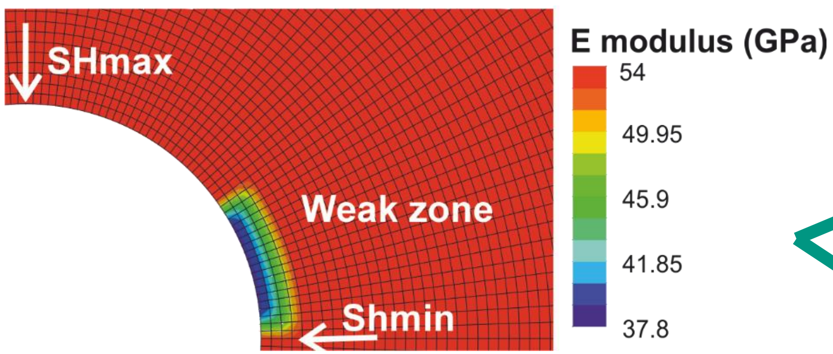
- Indirect comparison with the results from experimental data ***Haimson and Lee, 2004***
  - Drilling experiment in a tablerock sandstone
  - Measured breakout dimension – width and depth
  - Analyze failure mechanism

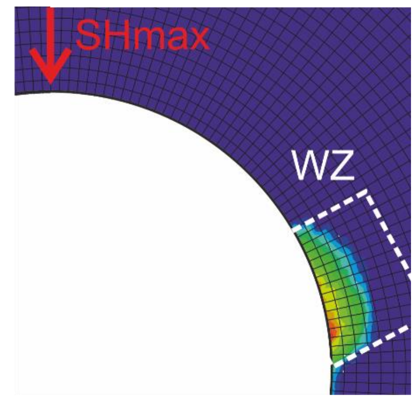
Rock property	Tablerock sandstone	Berea sandstone
Elastic modulus	18.3 ± 0.14 GPa	25.25 ± 2.14 GPa
Poisson's ratio	0.23 ± 0.07	0.25 ± 0.08
Compressive strength	39.5 ± 4.8 MPa	49 ± 8.2 MPa
Tensile strength	4.4 ± 0.2 MPa	6.8 ± 3 MPa



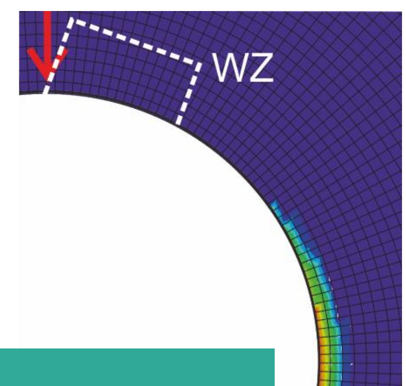
Haimson and Lee, 2004

- Material inhomogeneity





Perturbed



Unperturbed

- Perturbed breakout
  - A function of weak zone position and mechanical contrast

[Sahara et al, 2018]

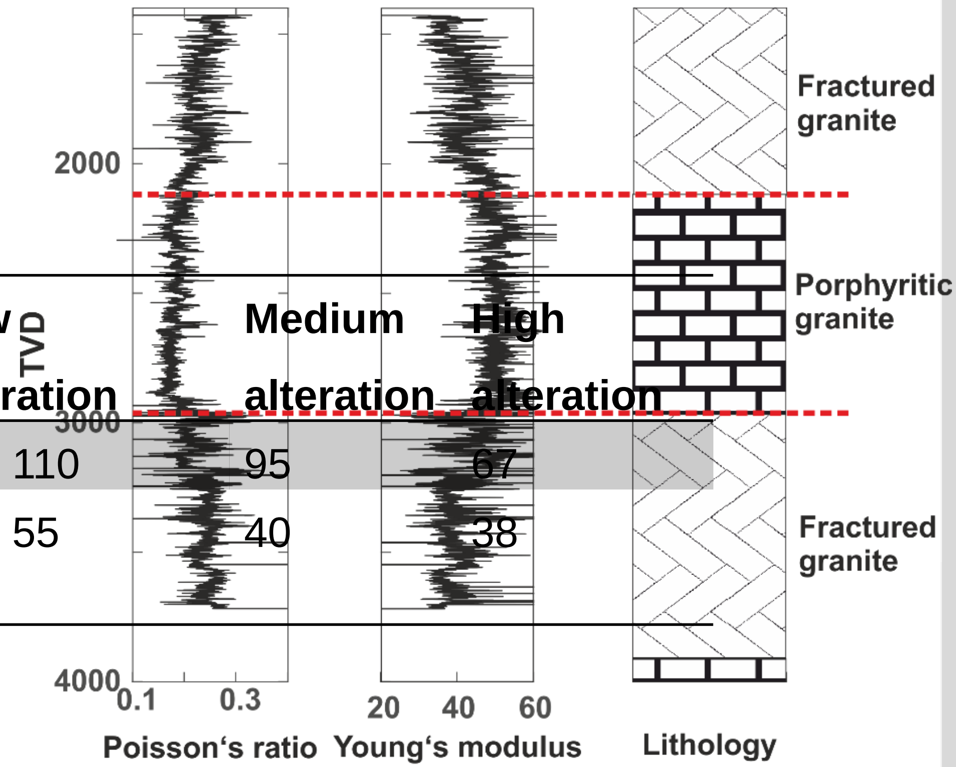
Idea

Breakout as fracture characteristics indicator (qualitative)

Wellbore failures profile + Compressional strength profile → ? → Stress profile

- In-situ laboratory measurements
  - e.g. ***Valley (2007),***
  - In-situ mechanical properties and impact of rock characteristics
  - Very limited
- Sonic log (GPK2 well)
  - Variation of elastic properties with depth
  - Dynamic elastic properties

	None	Low alteration	Medium alteration	High alteration
UCS (MPa)	105 - 132	88 - 110	95	67
E-modulus (GPa)	52 - 58	50 - 55	40	38

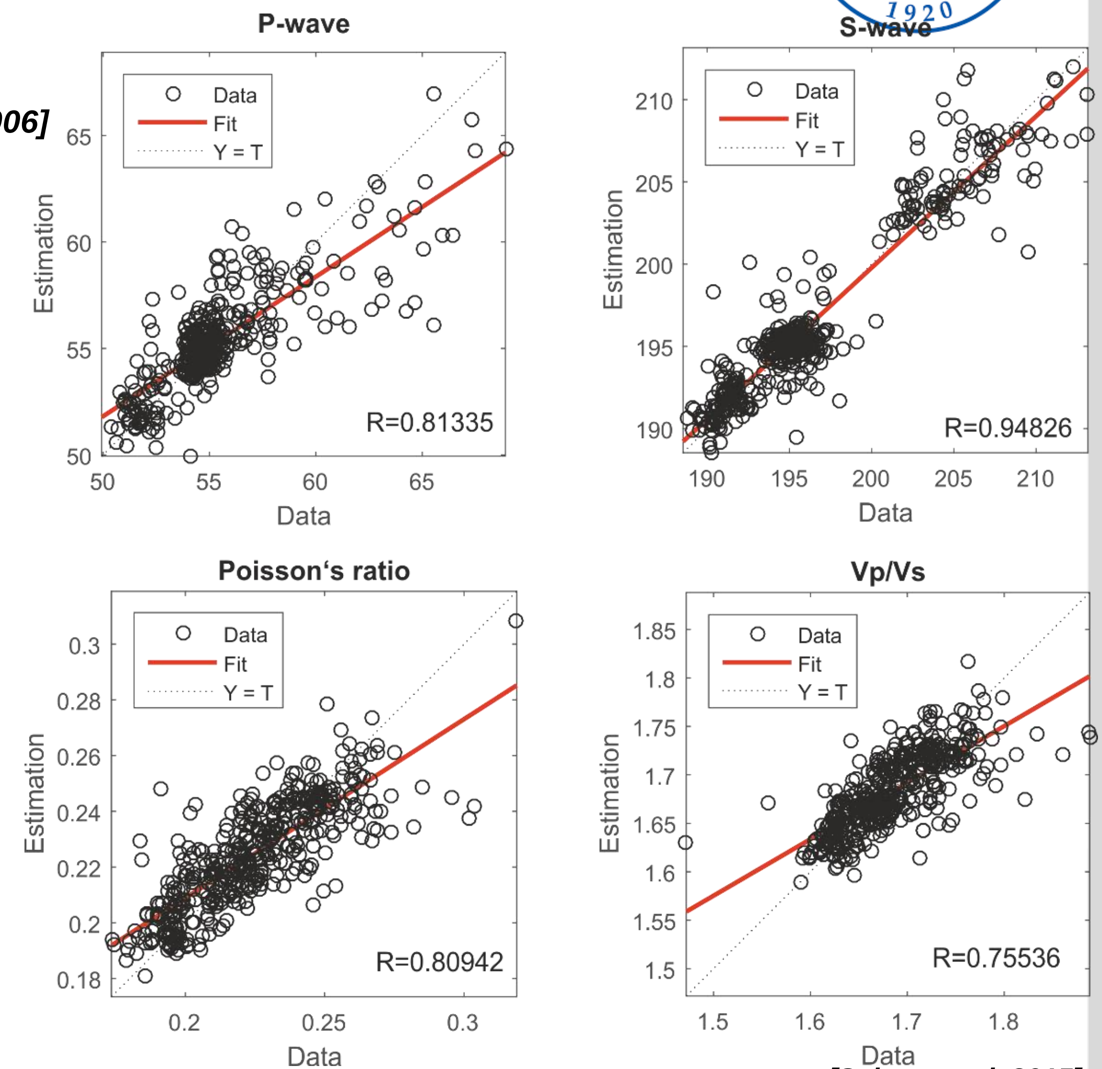


[Sahara et al, 2015]

Tool:
Neural network training

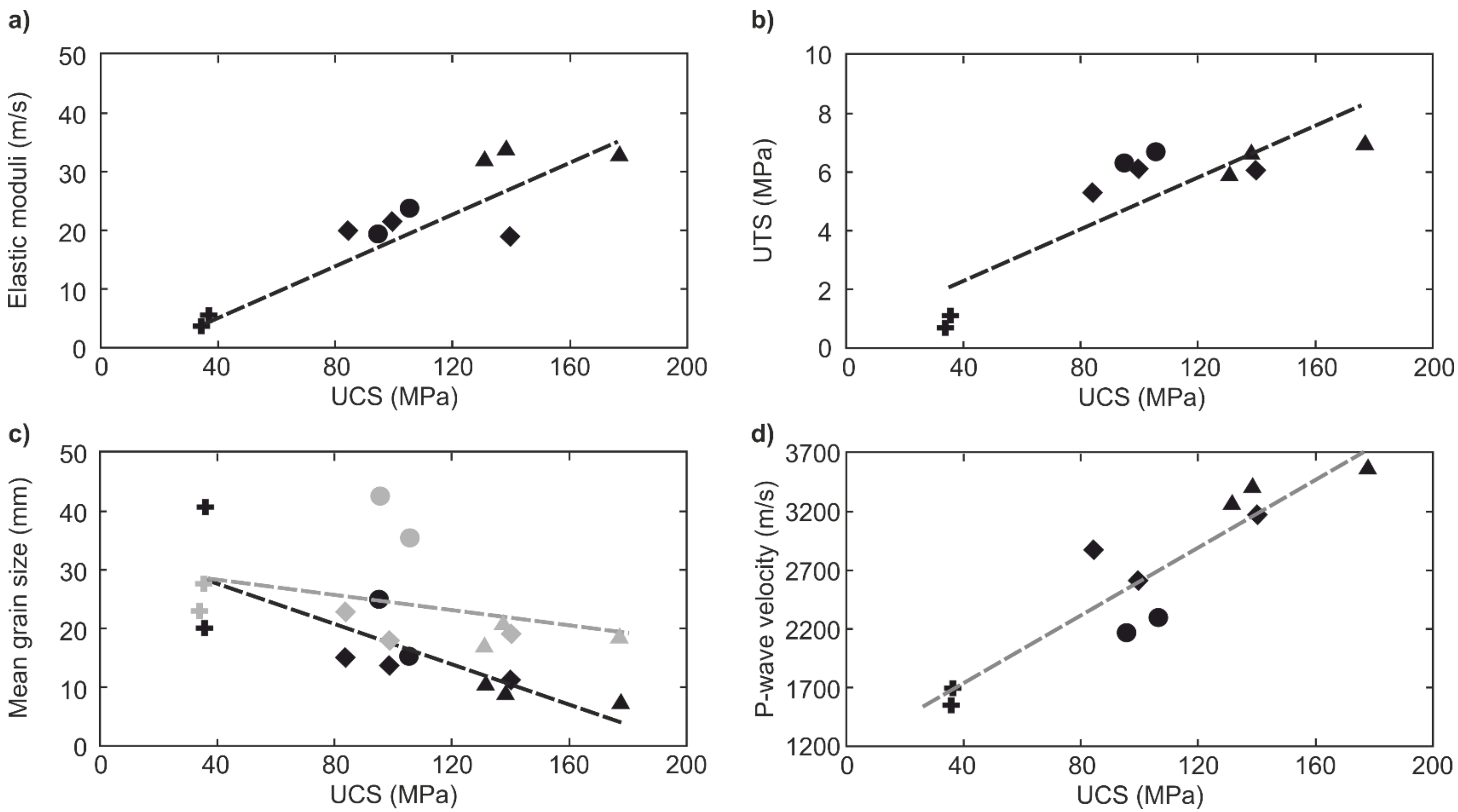
- Neural network training
  - Earthquake prediction ***[Alves, 2006]***
  - Porosity prediction ***[Singh, 2005]***
  - Clay content ***[Meller et al, 2014a]***

- Elastic moduli estimation
  - Lithology (Gamma ray)
  - Fracture
  - Caliper



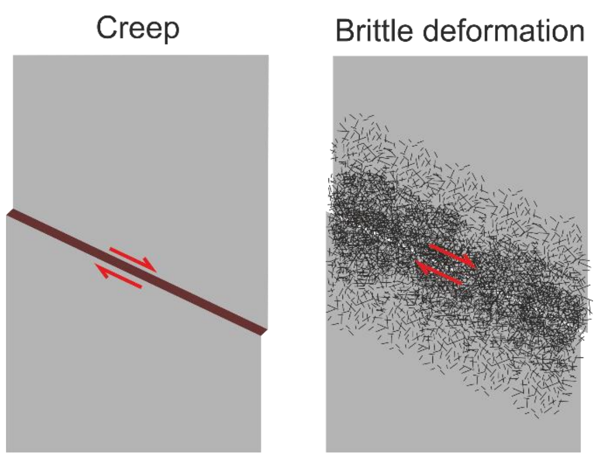
[Sahara et al, 2015]

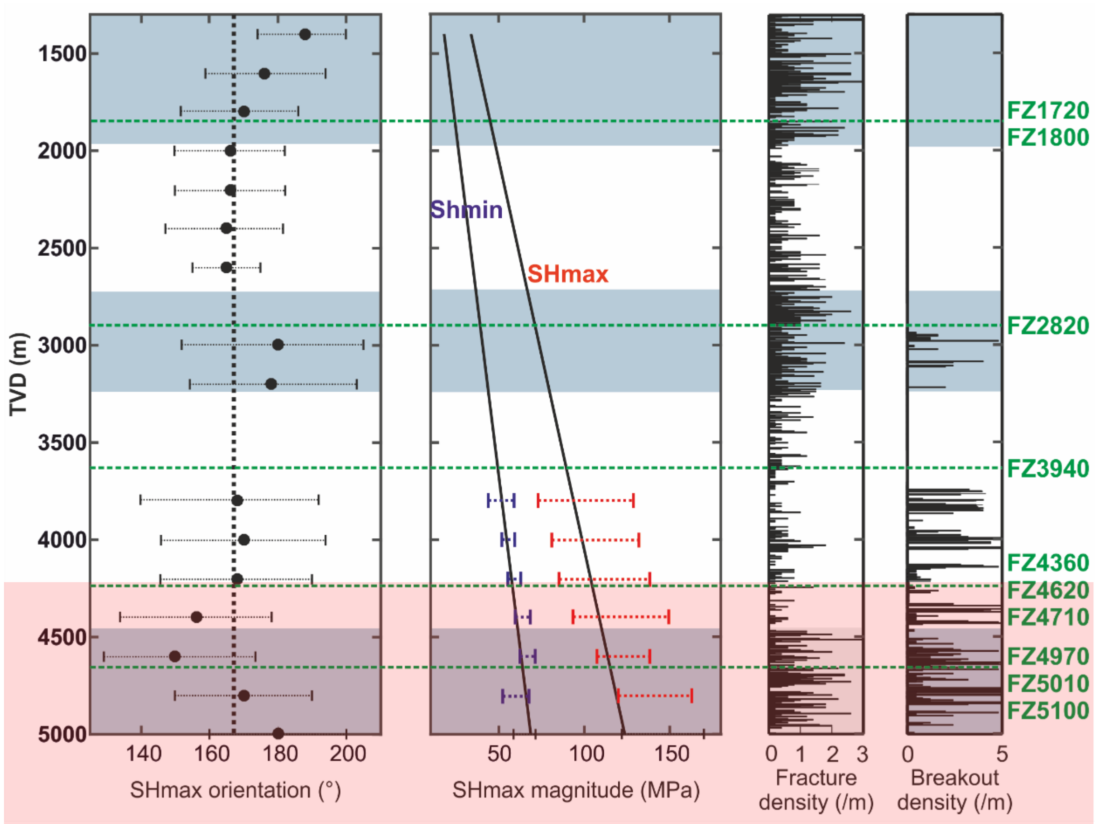
UCS and elastic properties



[modified from Sajid et al., 2016]

- In-situ stress estimation
  - Principal stress orientation
    - Average S_{Hmax} N165°±15°E
    - Anomalies – faults



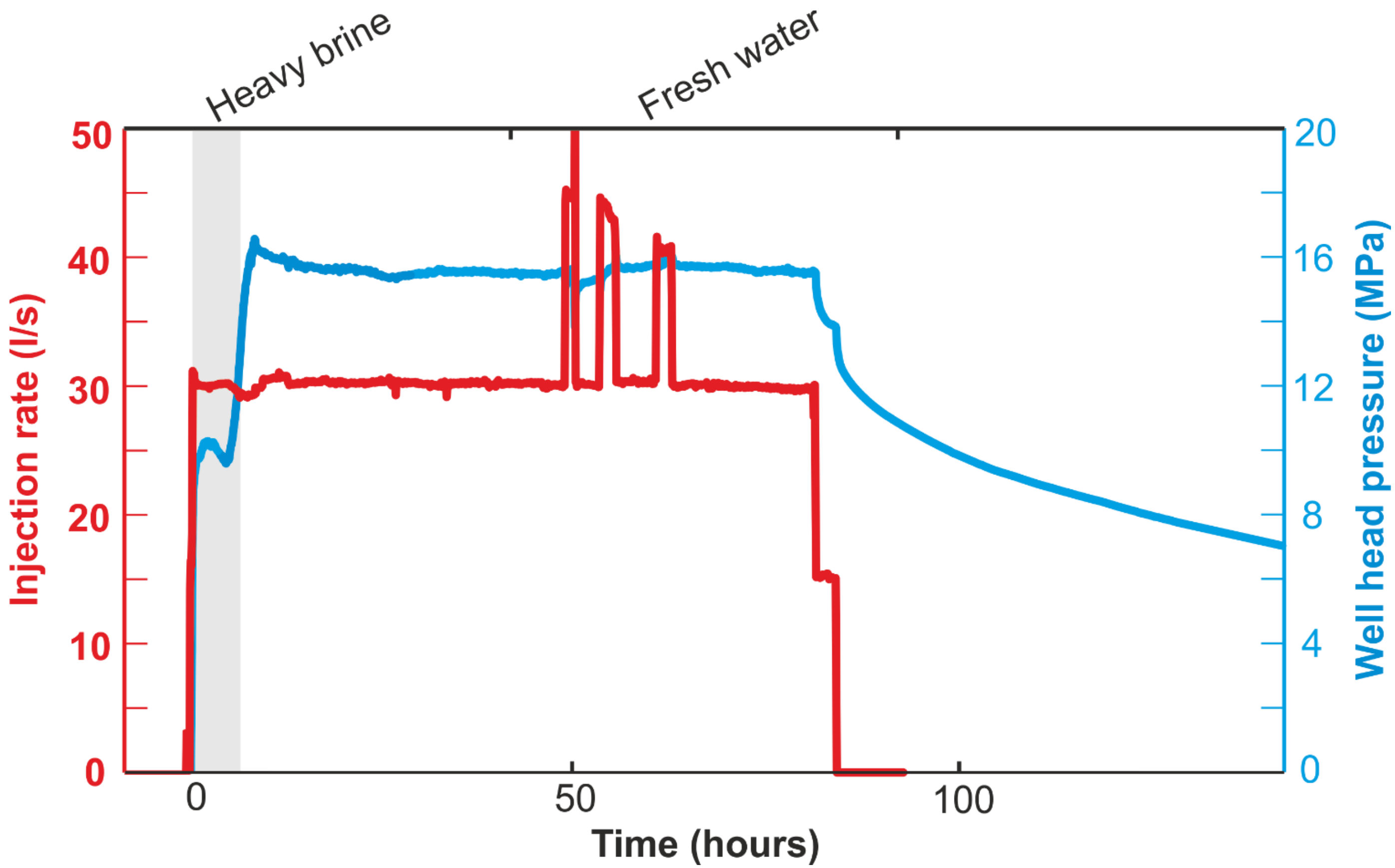


[Sahara et al, 2015]

  - Principal stress magnitude
    - $S_{Hmax} \approx 0.85 - 1.15\ S_v$
    - $S_{hmin} \approx 0.62\ S_v$

Soultz geothermal | Fracture scale | Borehole scale | Reservoir scale | Conclusions

- Hydraulic stimulation
  - Heavy brine and fresh water injection
  - Low injection rate of 30 l/s



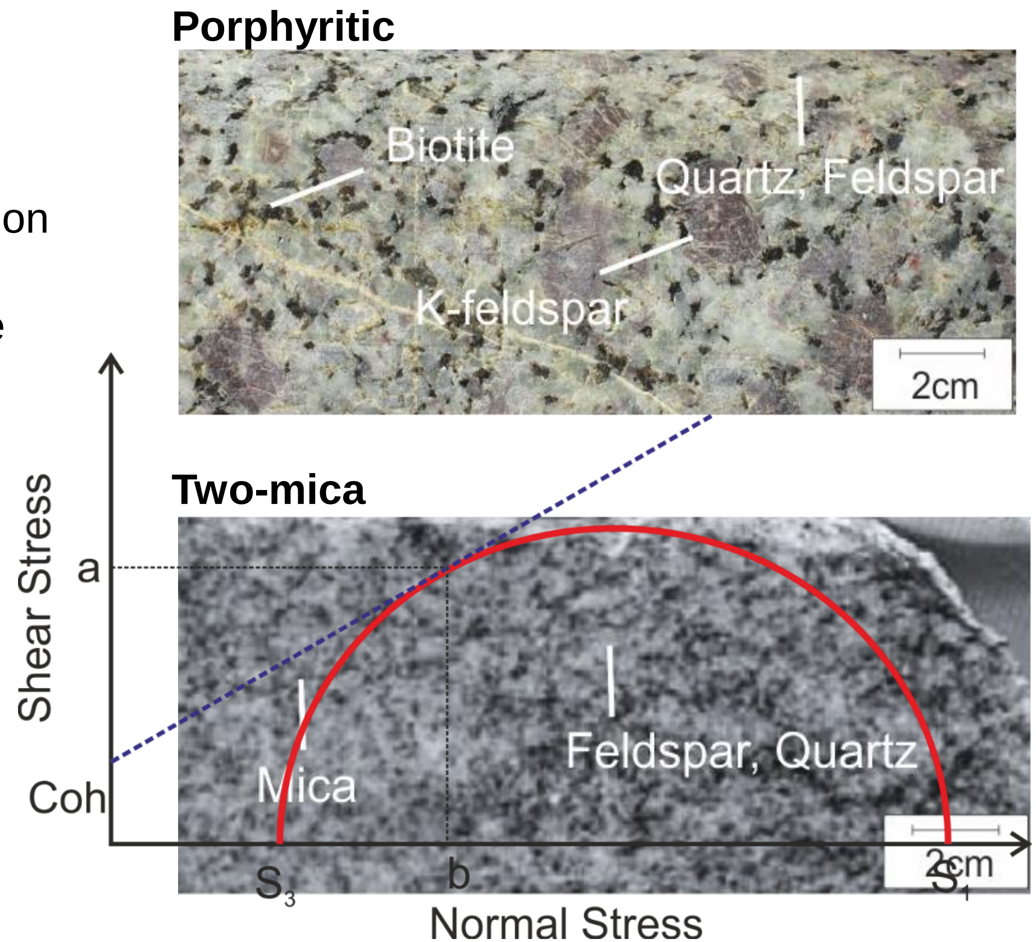
- Hydraulic stimulation
  - Heavy brine and fresh water injection
  - Low injection rate of 30 l/s

- Target

Hydraulic stimulation ~ fracture reactivation
(at a greater depth)

  - Porphyritic and two mica granite
  - Fractures
  - Alteration

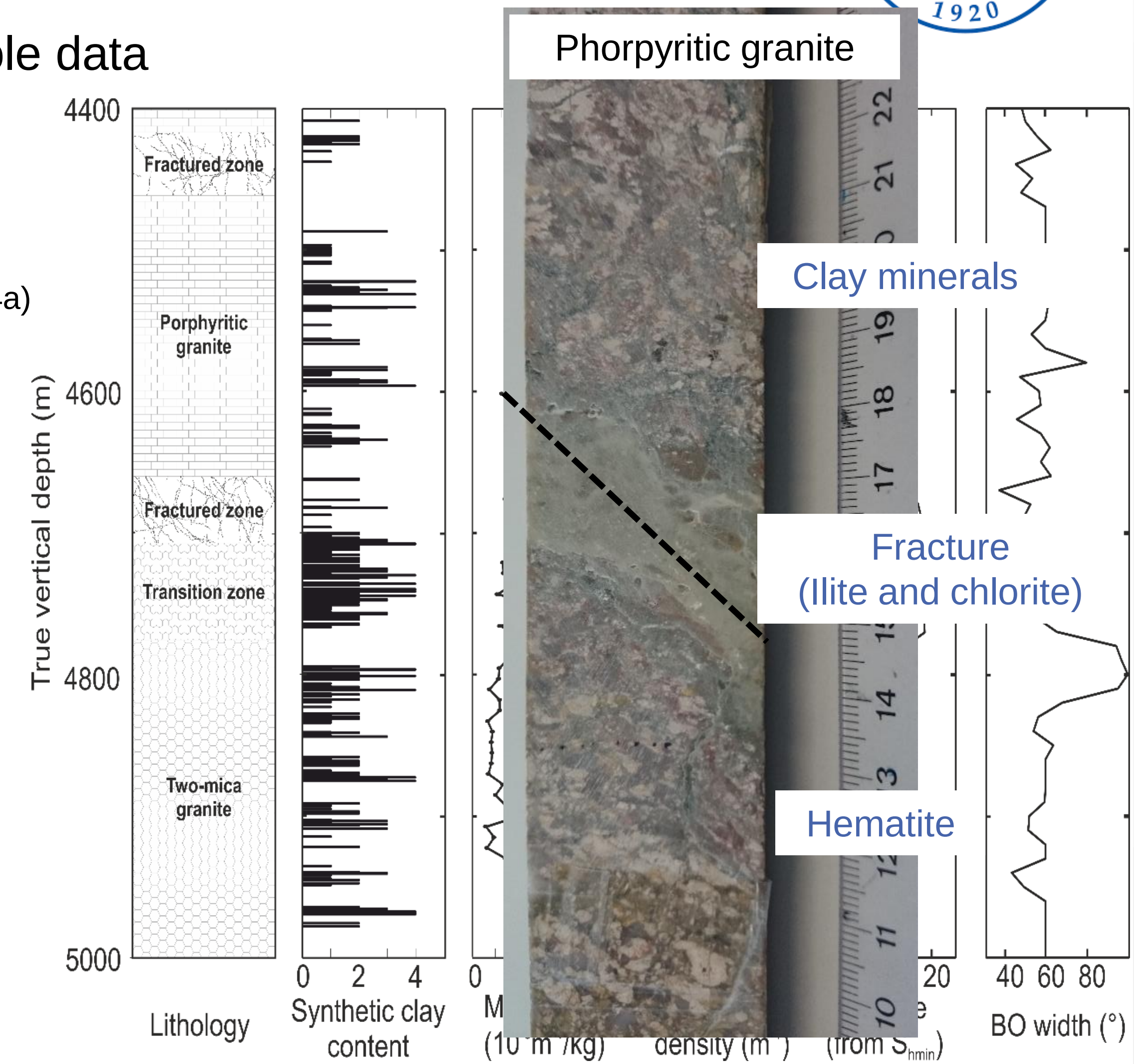
- Slip tendency ***[Morris et al., 1996]*** ?



Soultz geothermal | Fracture scale | Borehole scale | **Reservoir scale** | Conclusions

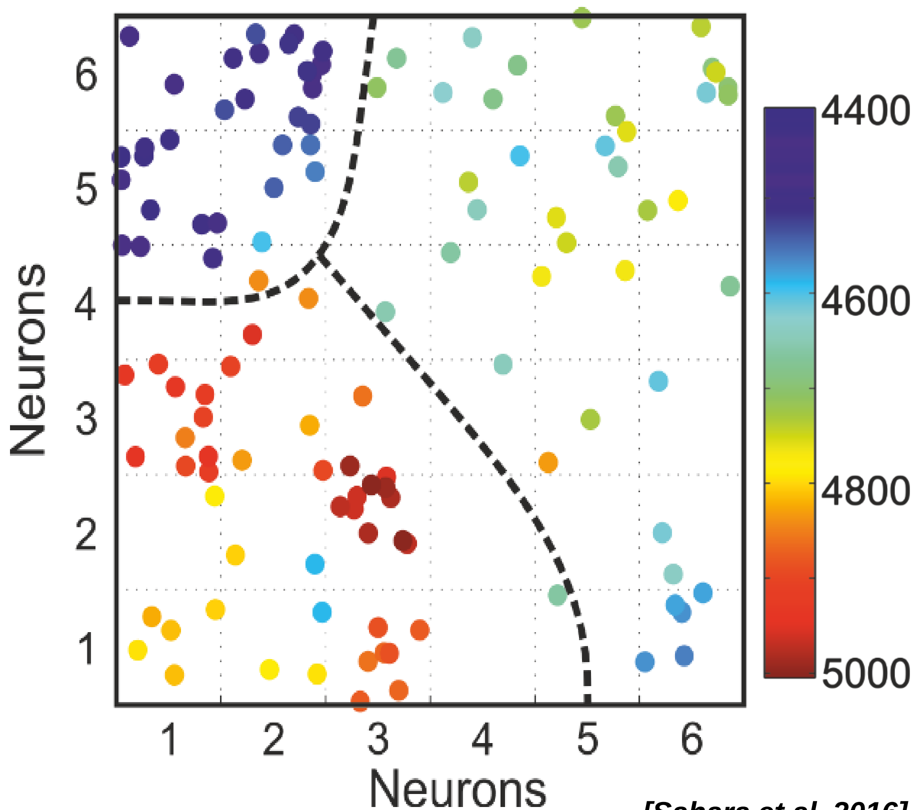
- Integrated analysis of borehole data
  - Lithology (Hooijkaas et al., 2006; Meller et al, 2014b)
  - Fracture
  - Mineral filling (Meller et al, 2014a)
  - Breakout (Sahara et al., 2014)

Tool:
Neural network clustering



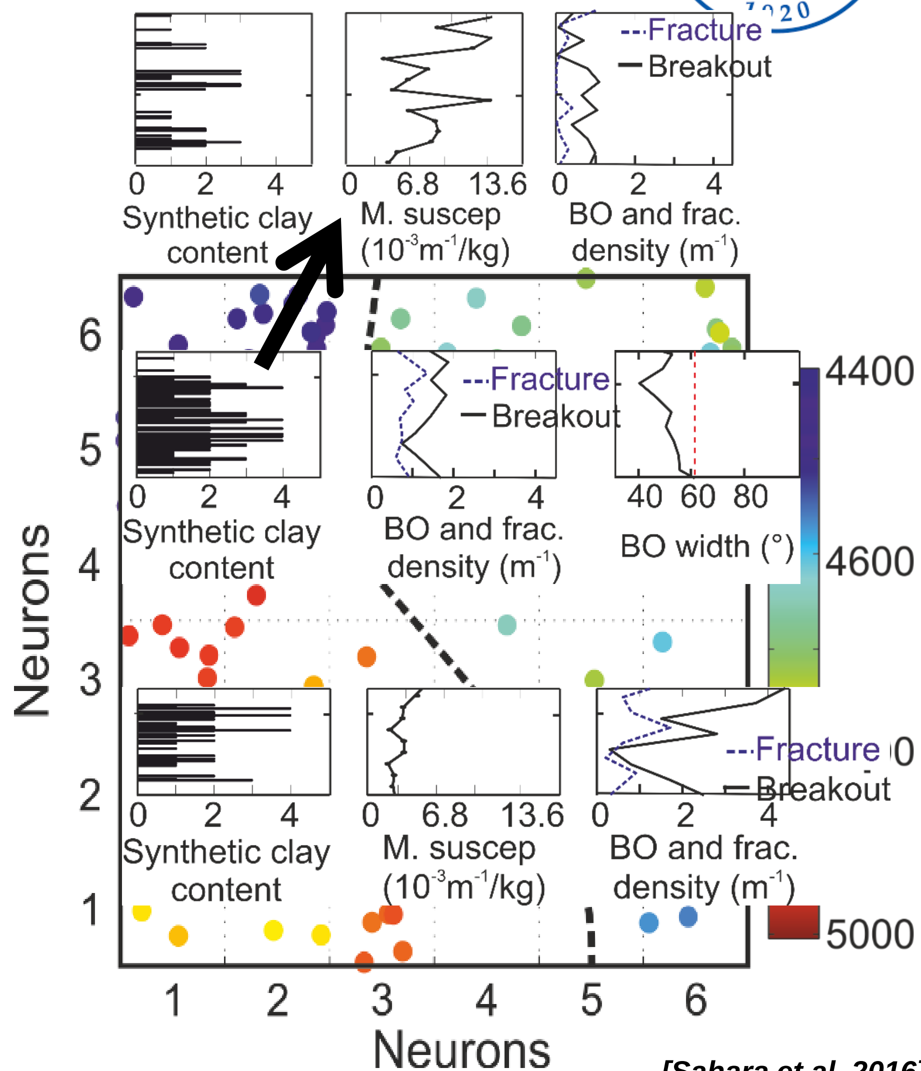
[Sahara et al, 2016]

- Integrated analysis of borehole data
  - Lithology (Hooijkaas et al., 2006; Meller et al, 2014b)
  - Fracture
  - Mineral filling (Meller et al, 2014a)
  - Breakout (Sahara et al., 2014)



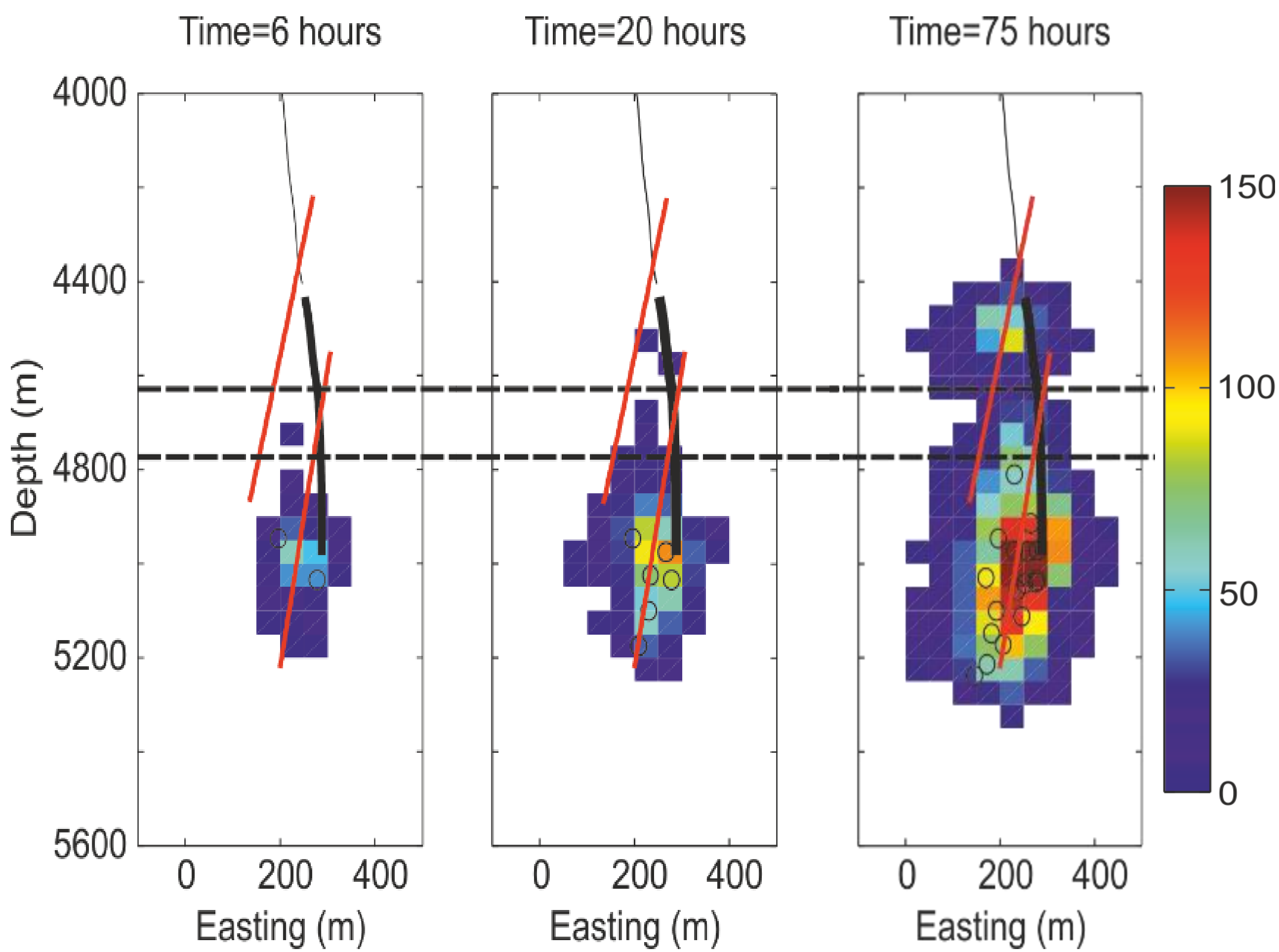
[Sahara et al, 2016]

- Integrated analysis of borehole data
  - Porphyritic granite (4480 – 4630 m)
    - Bigger grain size
    - Less fractured and altered
  - Transition zone (4630 – 4780 m)
    - High clay content
    - Narrow breakouts
    - Creep ?
  - Two-mica granite (4780 – 4980 m)
    - Smaller grain size
    - Highly fractured
    - Stress heterogeneity



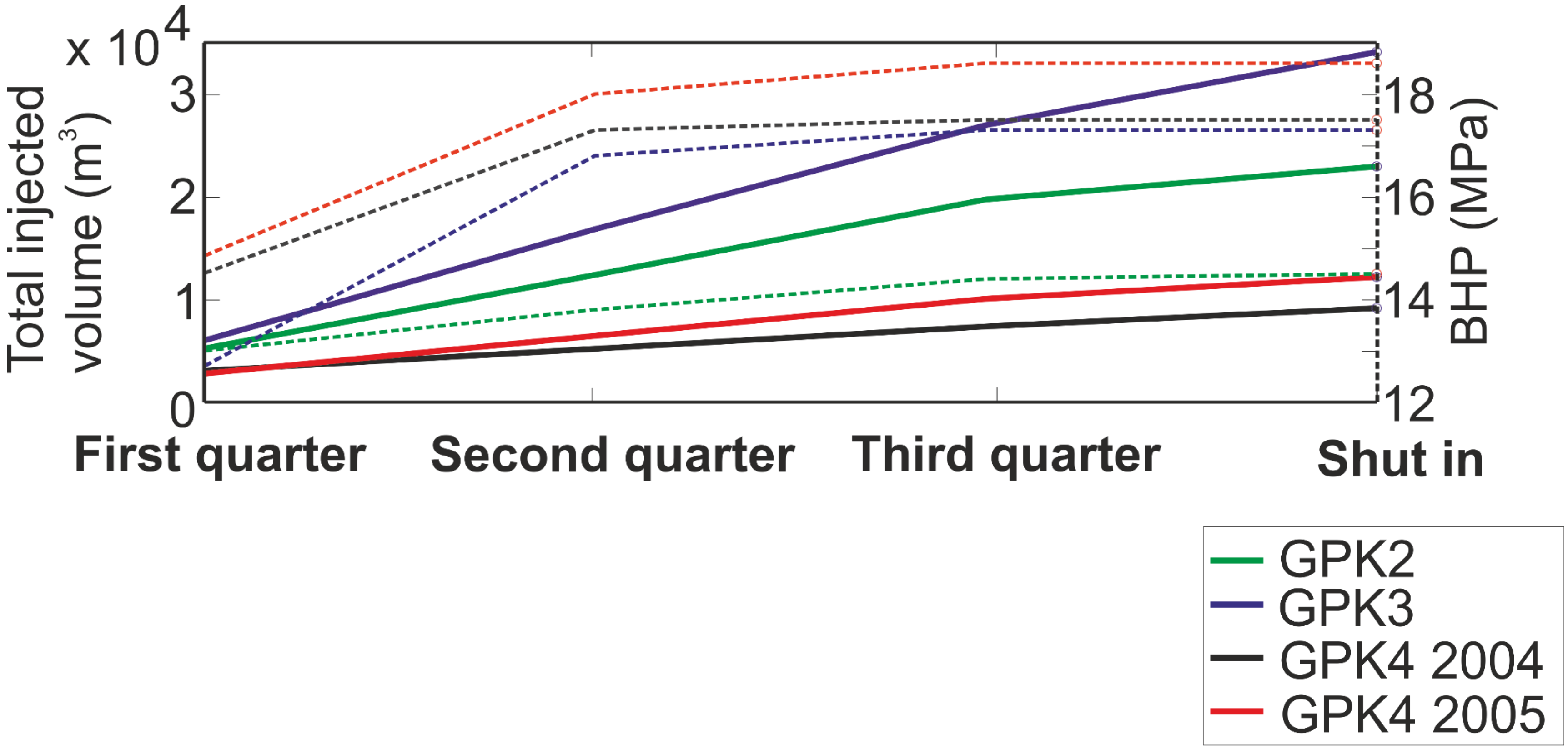
[Sahara et al, 2016]

- Induced seismicity
  - Initiated from Two-mica granite
  - Events at Porphyritic
  - Anti-correlation: seismicity and clay content



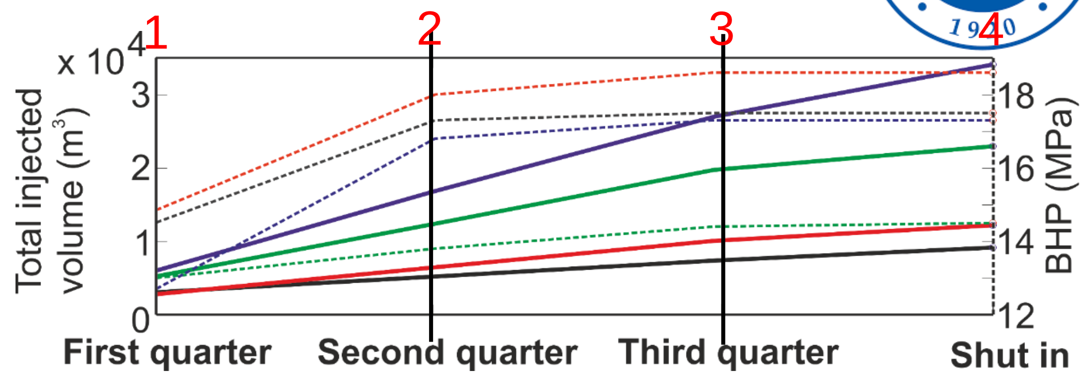
[Sahara et al, 2016]

- All deep well stimulation



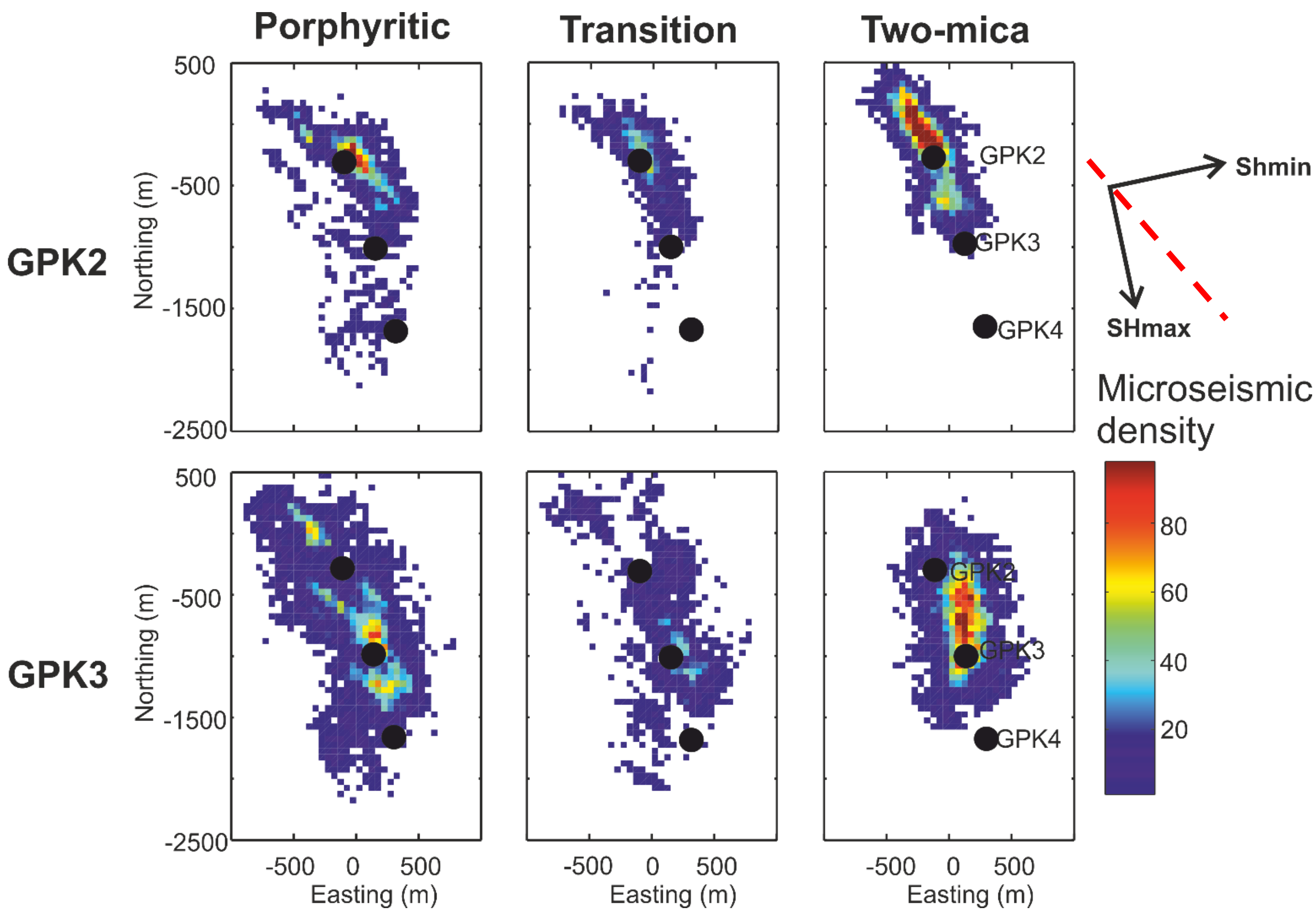
[Sahara et al, in preparation]

- All deep well stimulation



[Sahara et al, in preparation]

Damage area

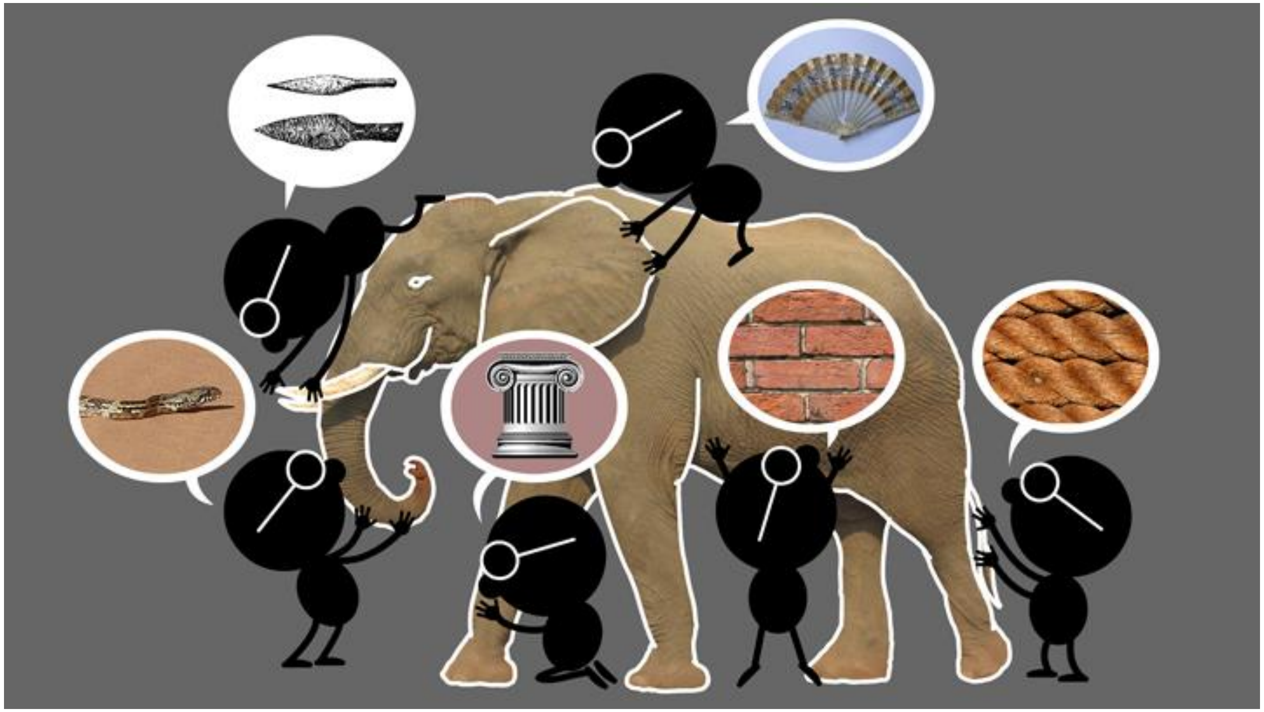


[Sahara et al, 2016]

- Every failure is stress related!
  - Consideration:
    - Material inhomogeneity
    - Inelastic deformation
  - Localized failure

- Indirect estimation of the mechanical properties from borehole data
  - Limitation of core data
  - Compressional strength profile, fracture characteristics
  - ……….

- Mechanical behavior of reservoir
  - Controlled by the lithology and fracture characteristics
  - Injection strategy (injection rate and volume)



The elephant (geothermal reservoir) is much more complex than I thought

HELMHOLTZ | ASSOCIATION

EnBW

DAAD
Deutscher Akademischer Austausch Dienst
Servicio Alemán de Intercambio Académico

DIREKTORAT JENDERAL
PENDIDIKAN
TINGGI