Determining key parameters and suitable measures for successful EGS developments

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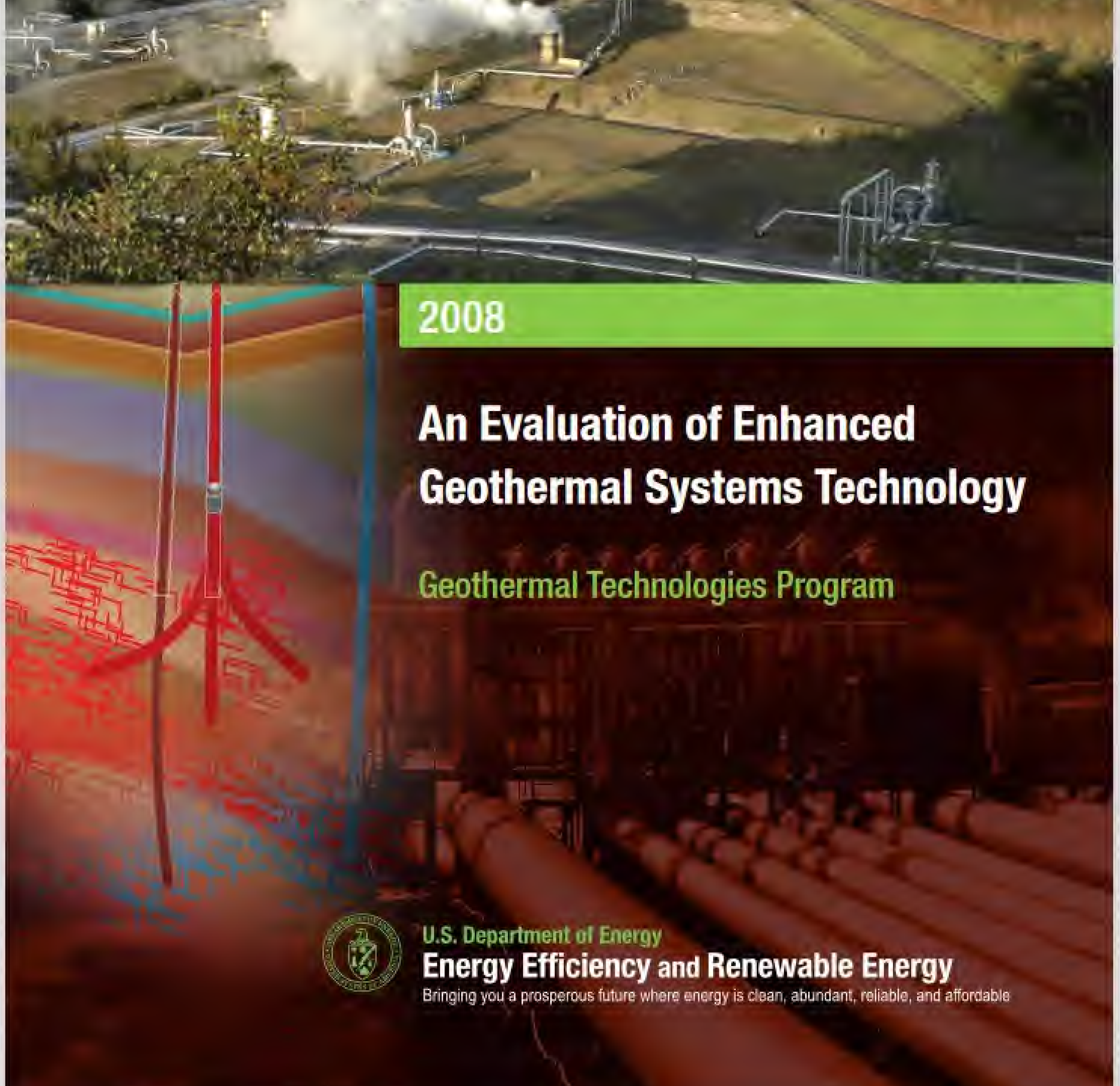

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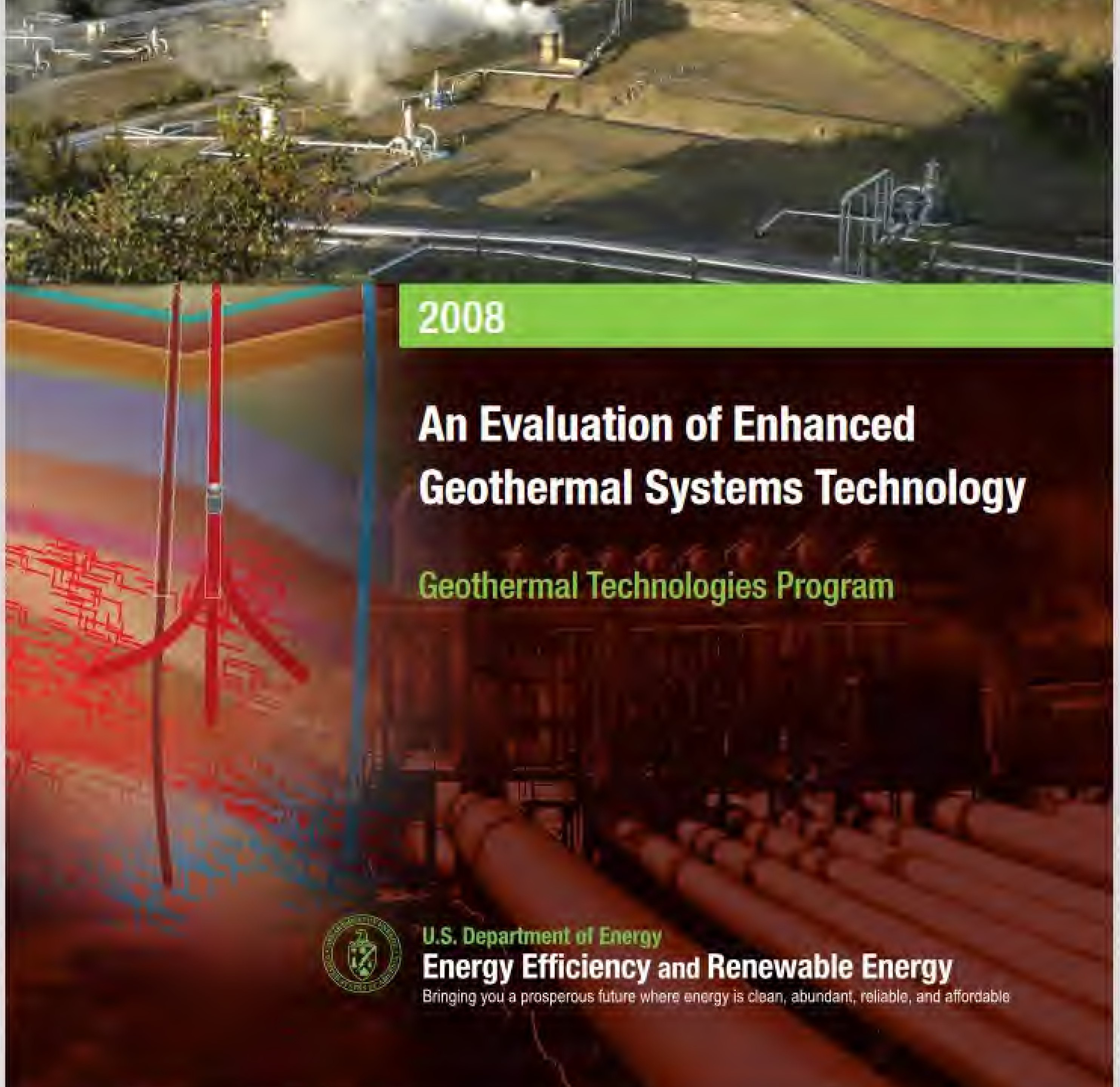

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Key Components

Various site properties that should be known for successful creation of the reservoir include

- Temperature gradient and heat flow
- Stress field
- Lithology and stratigraphy
- Structure and faulting
- In situ fluids and geochemistry
- Geologic history
- Seismic activity
- Proximity to transmission
- Land availability
- Demographics

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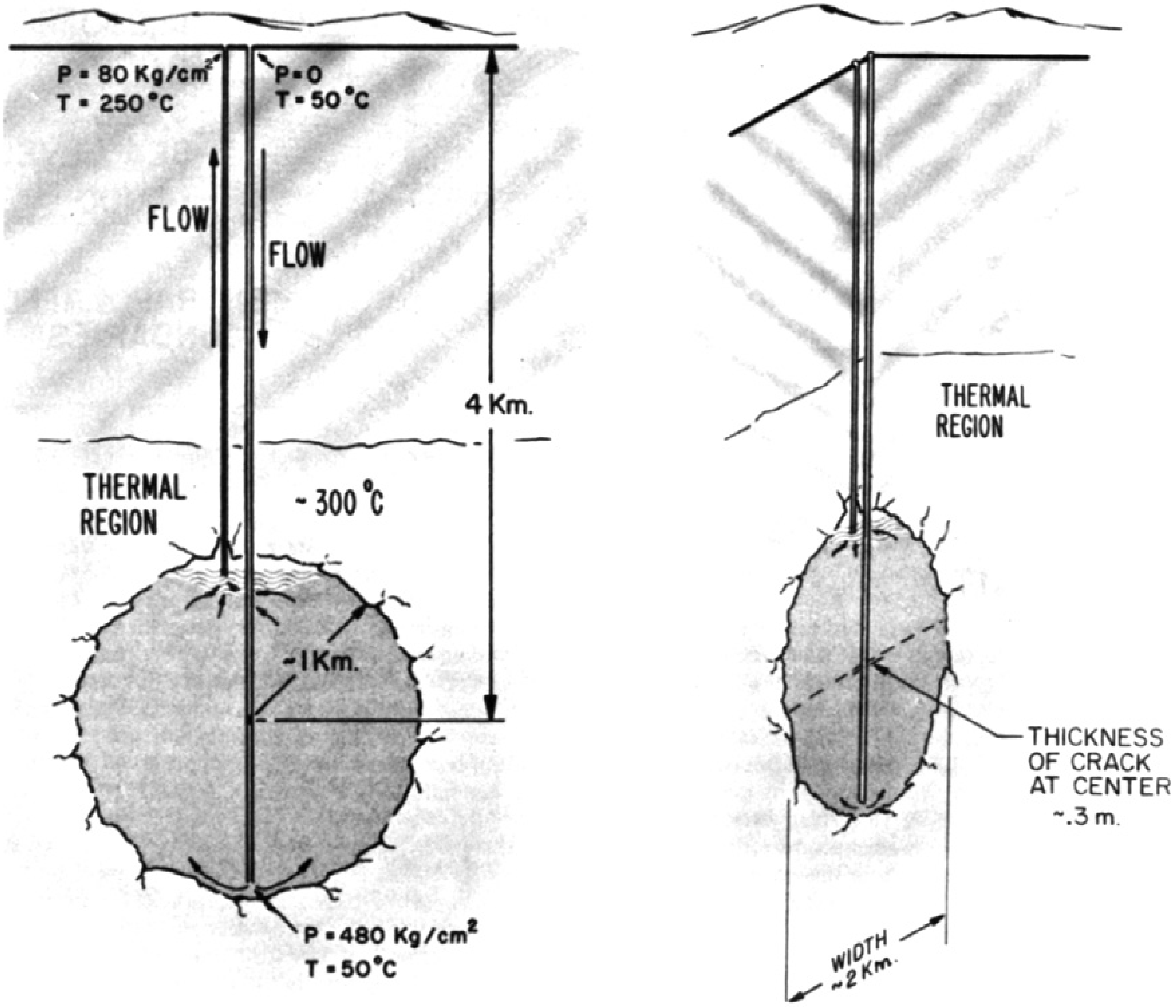
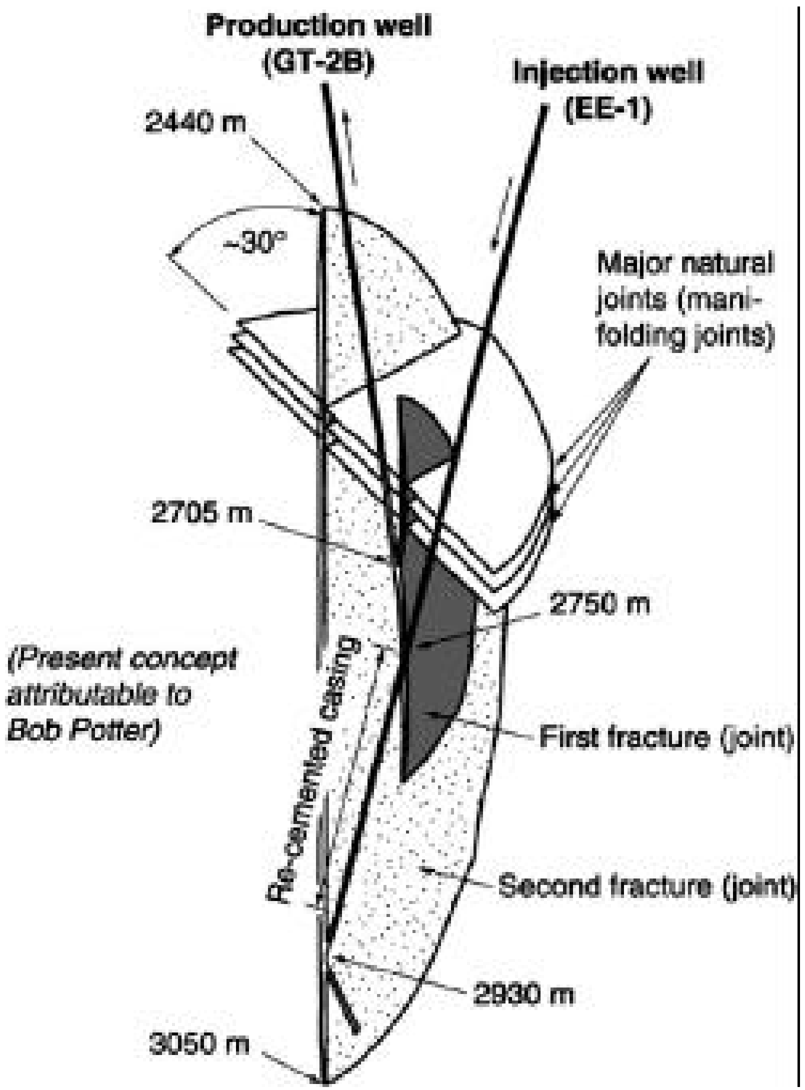
Fenton Hill - First HDR Project 1974-1992



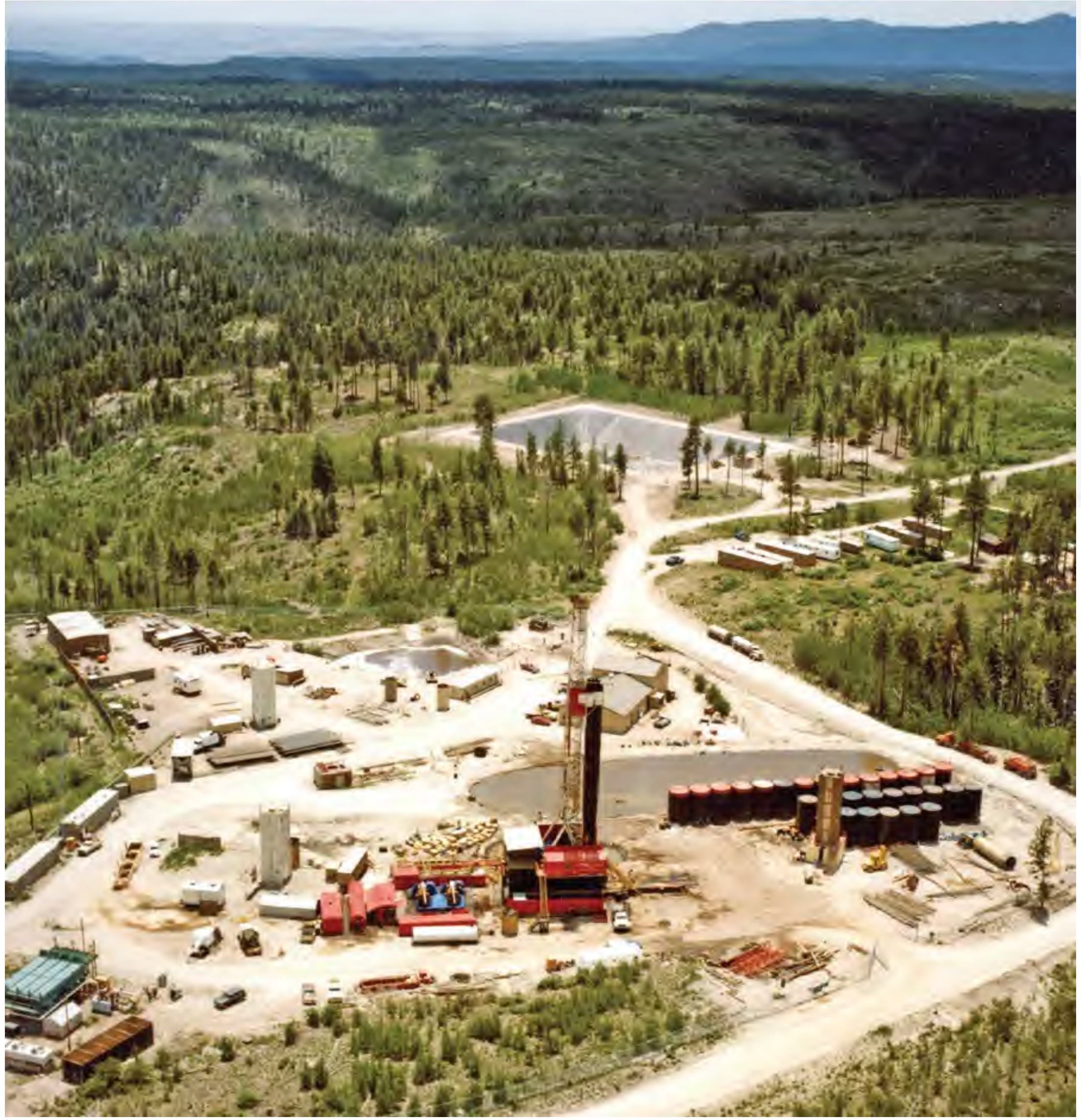
Potter et al. (1974)

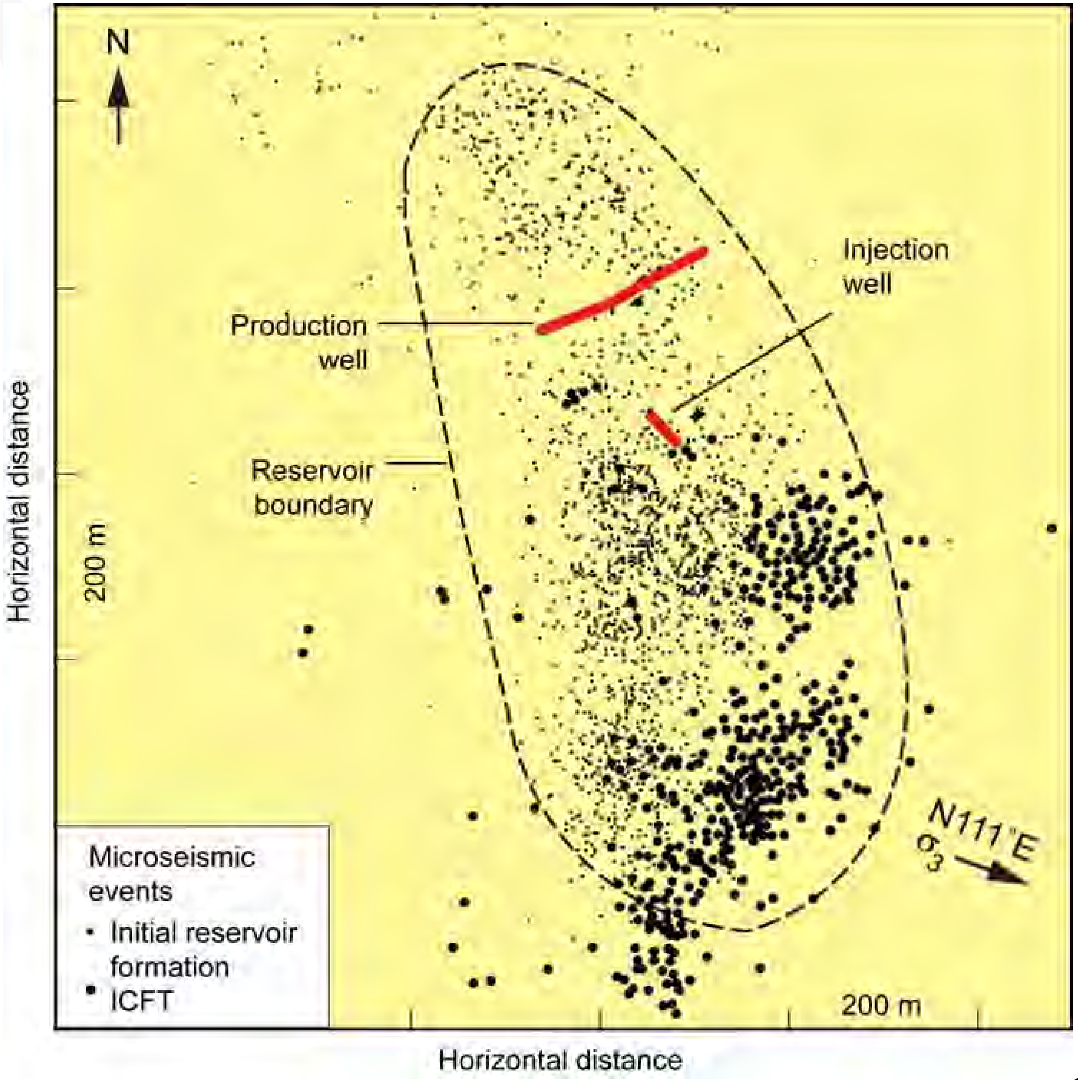


Duchane & Brown (2002)

Fenton Hill - First HDR Project

1974-1992



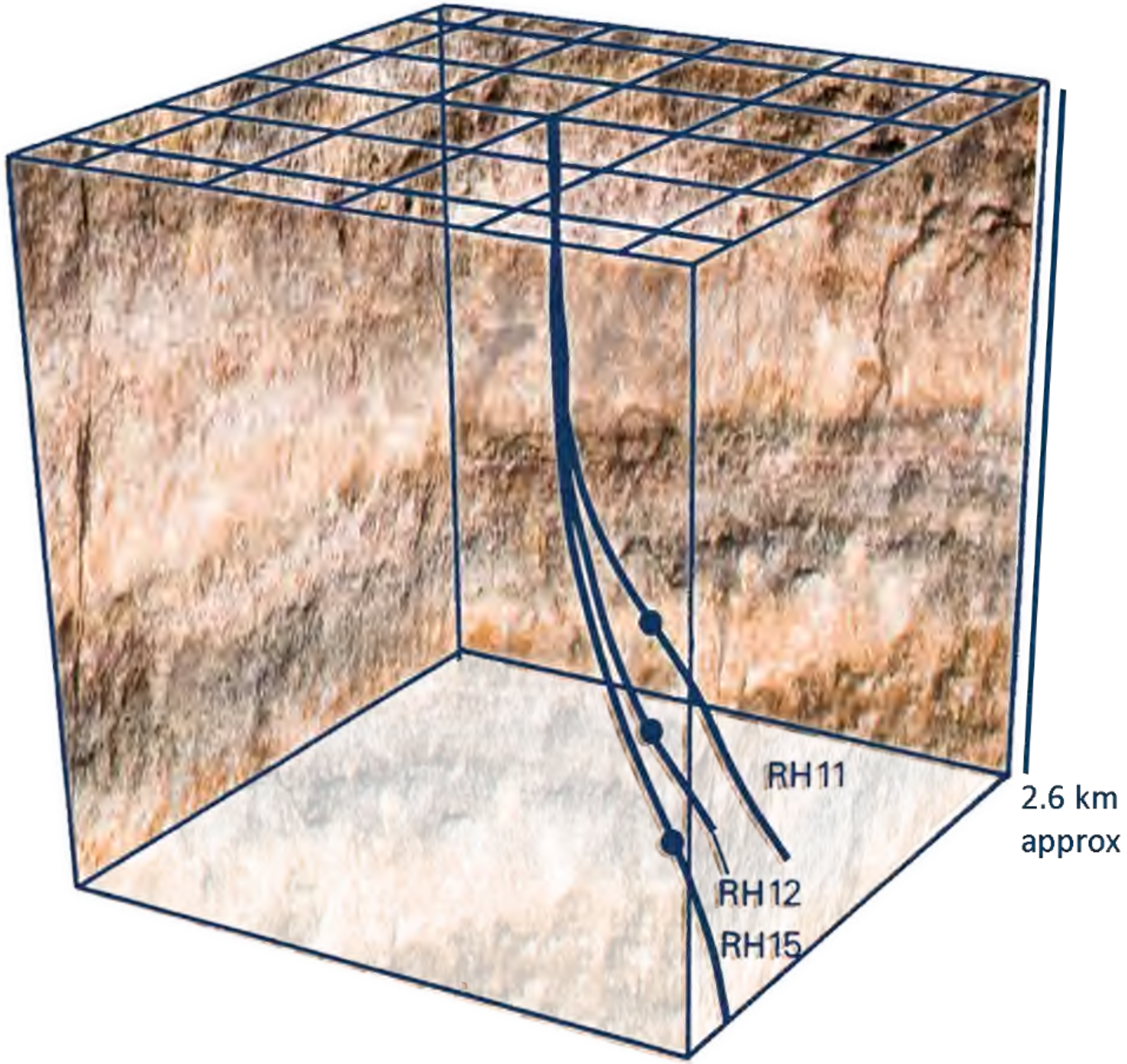


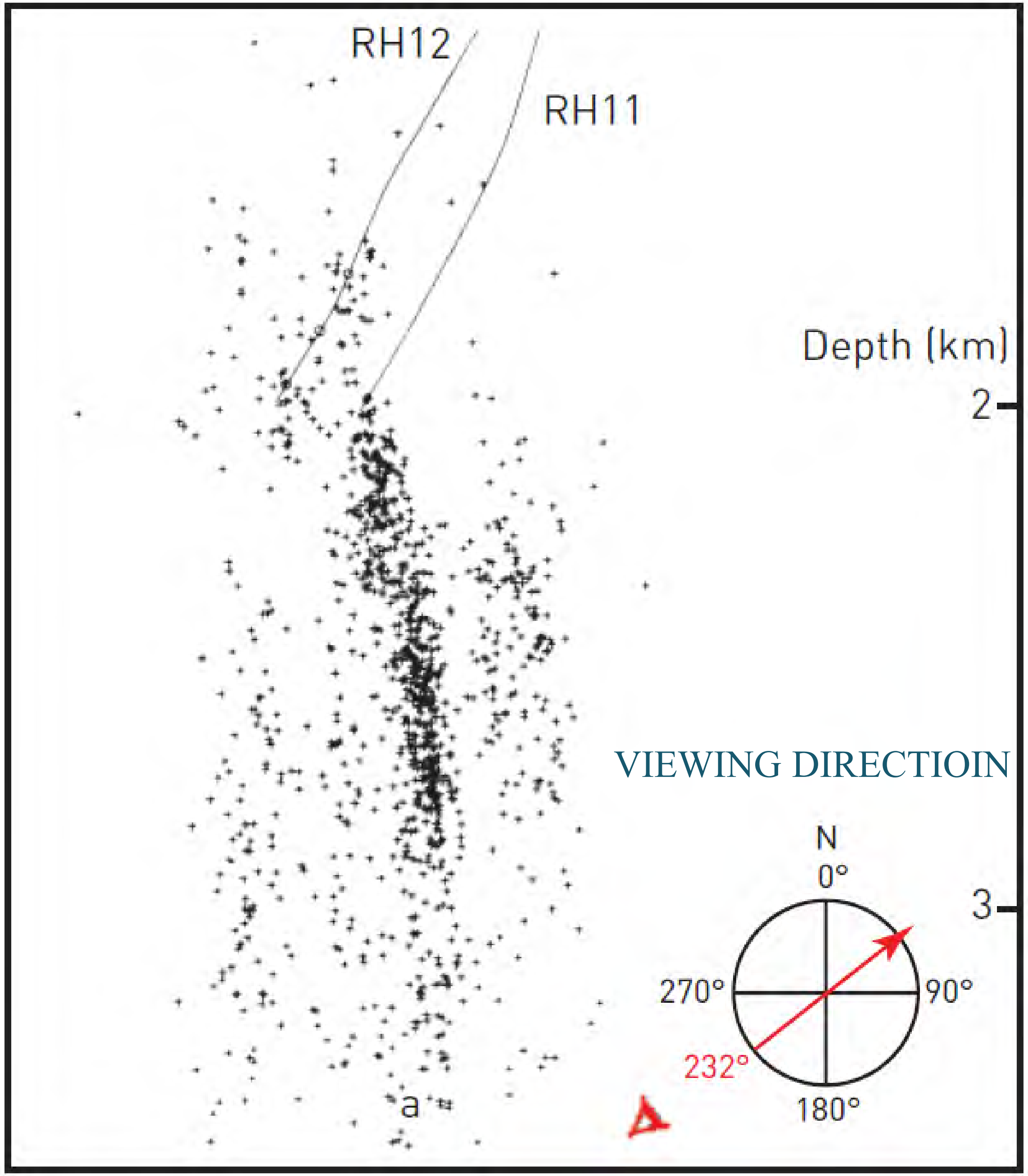
Some Lessons Learnt from Fenton Hill

- Deep (~5 km), high-temperature wells can be completed in hard, abrasive rock
- Low-permeability crystalline rock can be stimulated to create hydraulically conductive fractures.
- Hydraulic-pressurization methods can create permanently open networks of fractures in large enough volumes of rock (>1 km3) to sustain energy extraction over a long time period.
- The EGS reservoir can be circulated for extended time periods and used to generate electricity.
- Creating the connection between wells was a crucial step in developing the EGS reservoir. Connection was easier to establish by drilling into the fractured volume, once it was stimulated and mapped.
- The fracture pattern that was observed did not match that predicted by early modeling.
- If water was injected at high enough pressures to maintain high flow rates, the reservoir grew and water losses were high. If injection pressures were lowered to reduce water loss and reservoir growth, the flow rates were lower than desired, due to higher pressure drop through the reservoir
- The high pressures needed to keep the joints open caused operational problems and required substantial amounts of power.

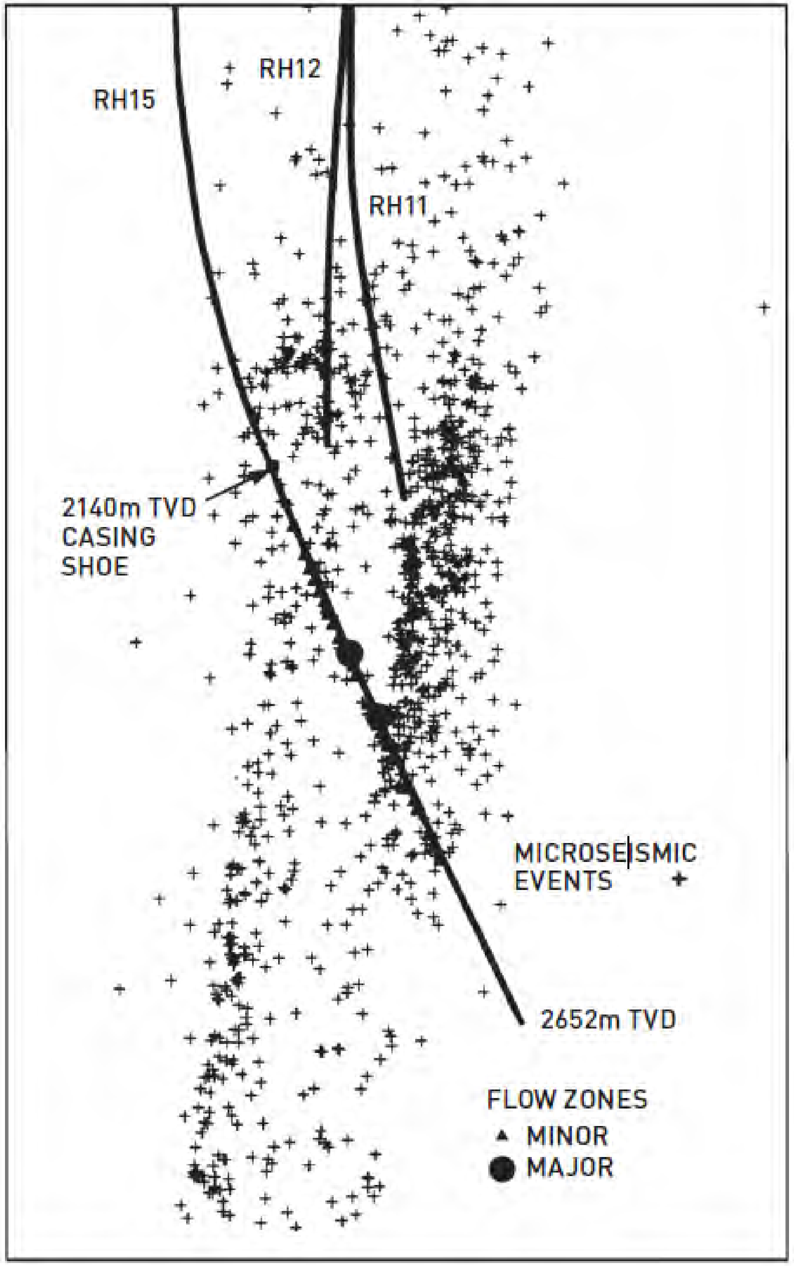
Rosemanowes, UK

1977-1991





Pine & Batchelor (1984)



Lessons Learnt from Rosemanowes

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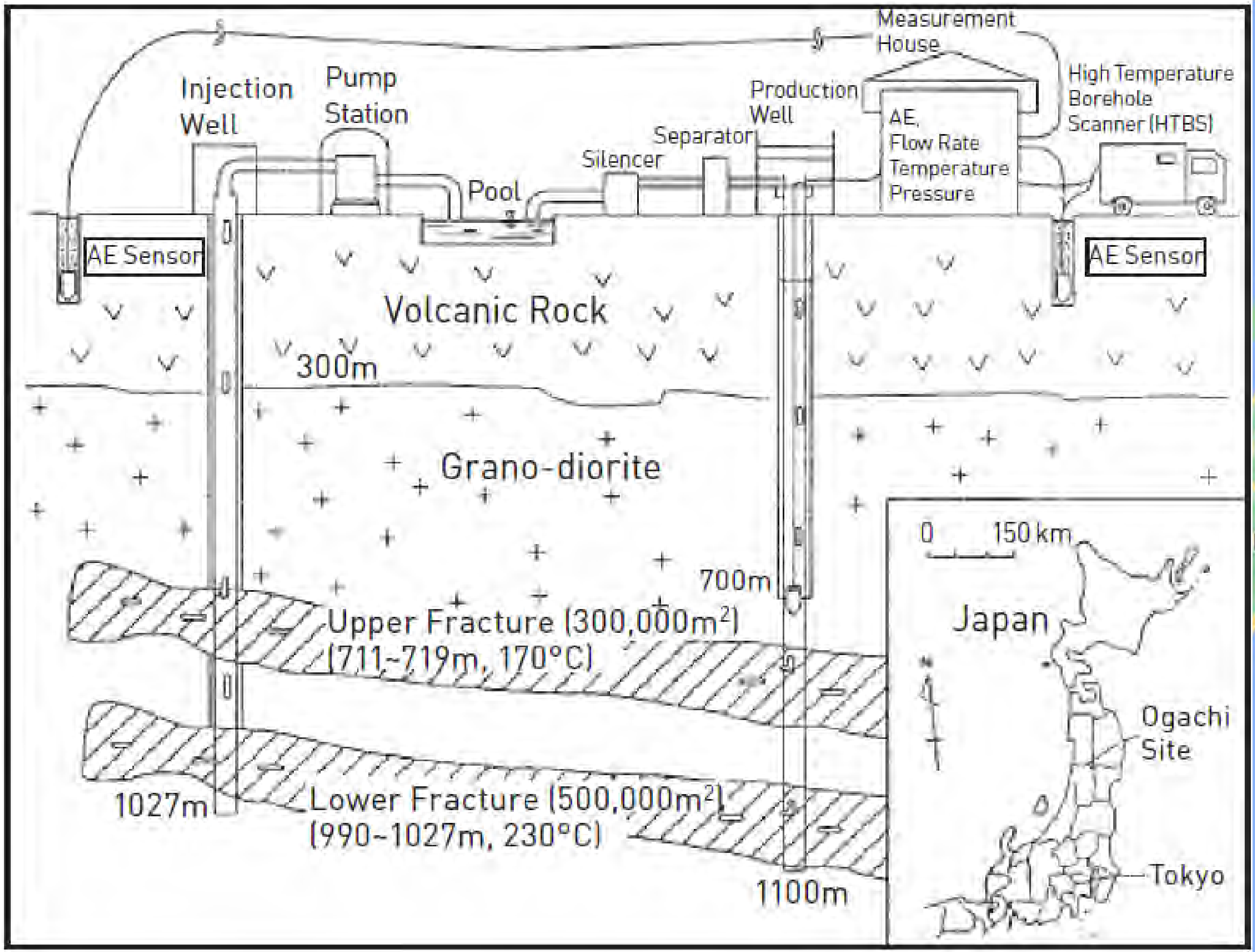
- The fractures created by hydraulic stimulation, which best connect across the reservoir, are not formed through tension. Instead, they are created by shearing on pre-existing joint sets.
- Stress fields in crystalline rock are invariably anisotropic, so the natural fractures fail in shear. Having sheared, the natural fractures then self-prop and stay open.
- It is possible to stimulate natural fractures and improve permeability – and create a connected volume of hot rock.
- A prediction of the direction of fracture growth is difficult in the absence of precise downhole data. Even with near-wellbore data from image logs, the fractures may not grow exactly as predicted. As a result, it is better to create the reservoir first, and then drill into it (Batchelor, 1987).
- Probably the most important single lesson from this experiment is that hydro-fracturing and artificial fractures are almost irrelevant. The natural fracture system dominates everything (Batchelor, 1989).
- Overstimulating pre-existing fractures can result in a more direct connection from injector to producer than is desired, so that cool fluid can "short-circuit" through the reservoir.

Ogachi and Hijori, Japan

1989-2002



Lessons Learnt from Hijori

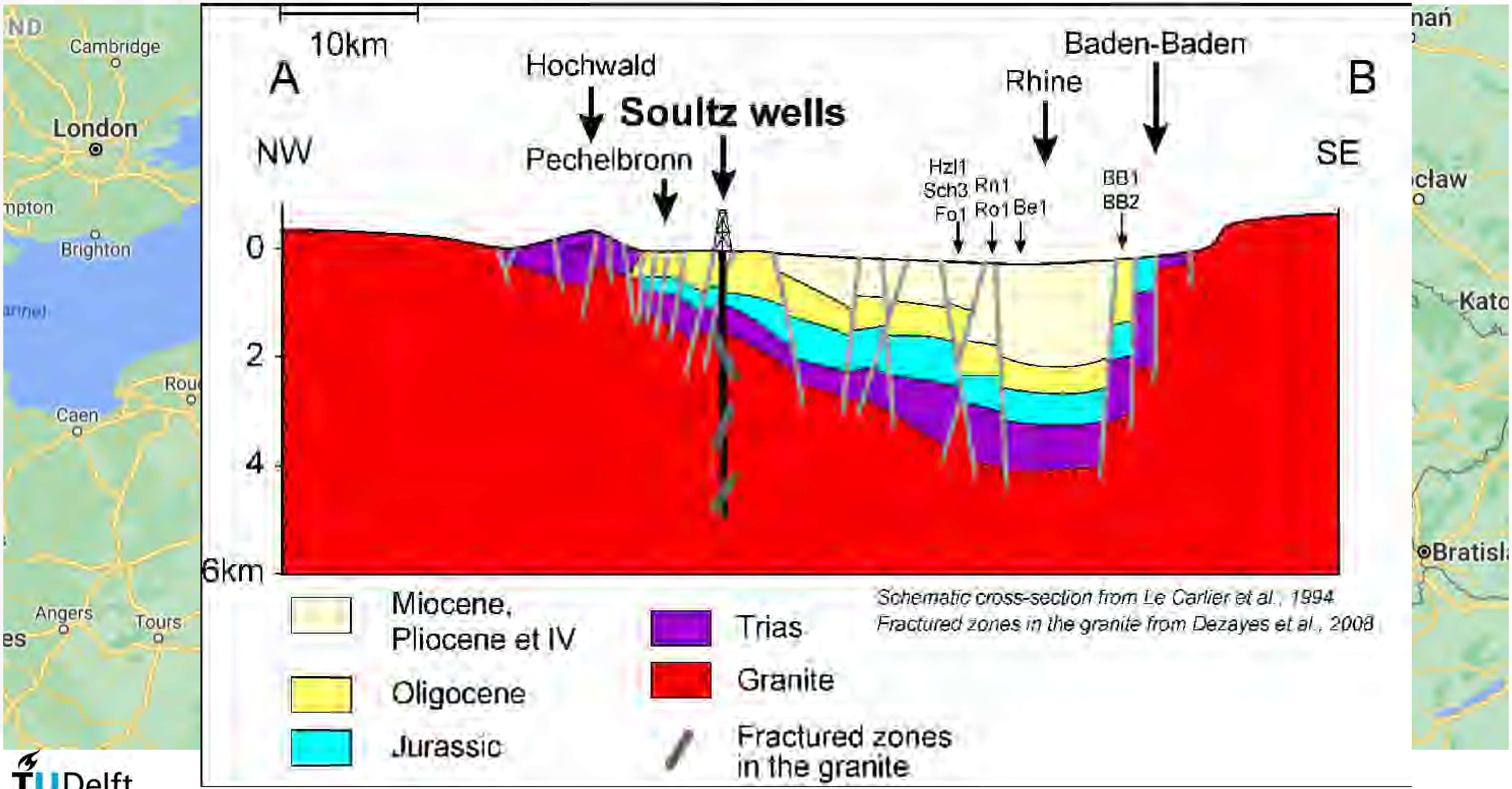
- The reservoir continued to grow during the circulation test.
- If natural fractures already connect the wellbores, stimulation may result in an improved connection that causes short circuiting, particularly if the well spacing is small.
- The acoustic emissions (AE) locations from the deep circulation test suggest that the stimulated fractures or the stress field change direction away from the well.

Lessons Learnt from Ogachi

- The complex geologic history at Ogachi made it difficult to predict the direction of fracture growth.
- The stress state in the original boreholes was not well understood until borehole televiewer data was collected and analyzed after the wells had been stimulated.
- Stress changes with depth in the boreholes

Soultz-sous-Fôrets

1987-

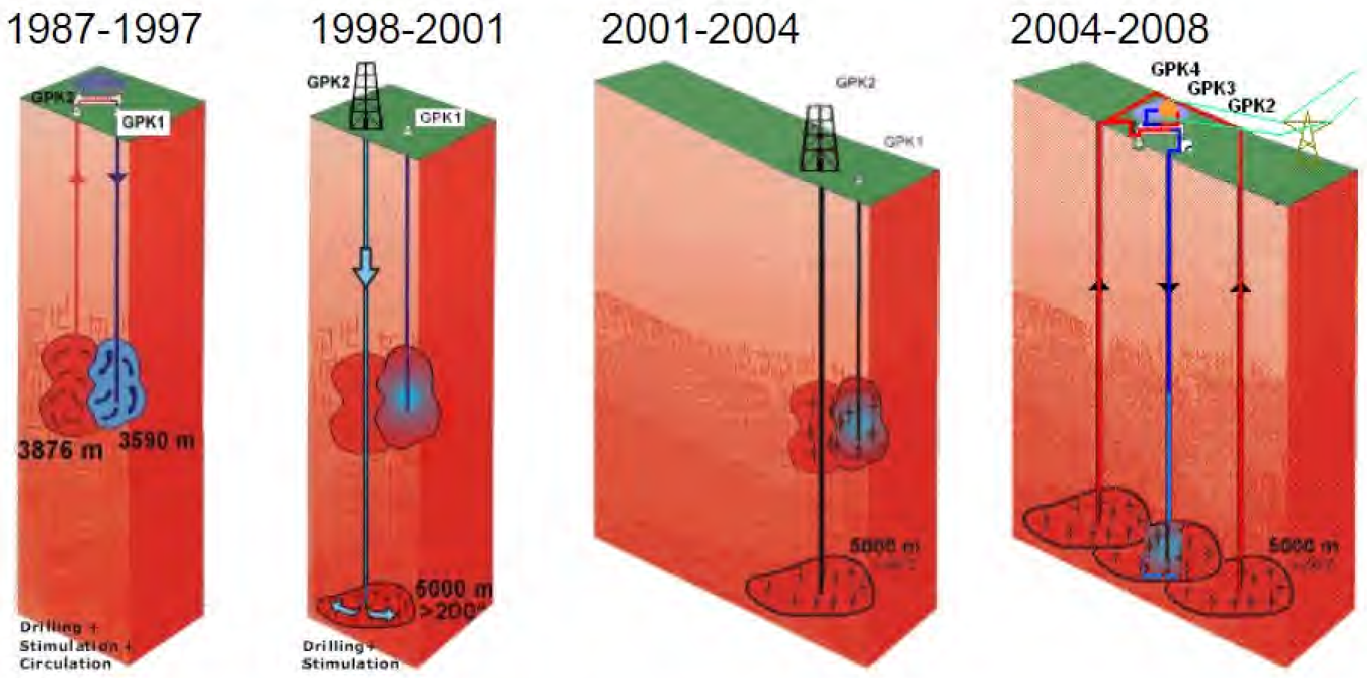


Schematic cross-section from Le Carlier et al., 1994
Fractured zones in the granite from Dezayes et al., 2008

The European EGS test site Soultz-sous-Forêts, France

Objective	2 x 1.5 MW electrical power (1.5 MW capacity currently installed)
Wells	3
Vertical Depth	5.000 m
Temperature	> 180°C
Flow Rate	2 x 125 m^3/h
Reservoir	EGS/HDR/petrothermal
Power Plant	ORC
Research	1987 to 2005
Construction	2005 to 2008
Status	feed-in of up to 1.5 MWe

- target horizon 5000 m
- temperature 200°C
- 35 l/s → 2.0 MWe (well distance 600 m)



Monitoring fracture growth

Asanuma et al. 2002

Development of seismic events during stimulation

Monitoring fracture growth

Asanuma et al. 2002

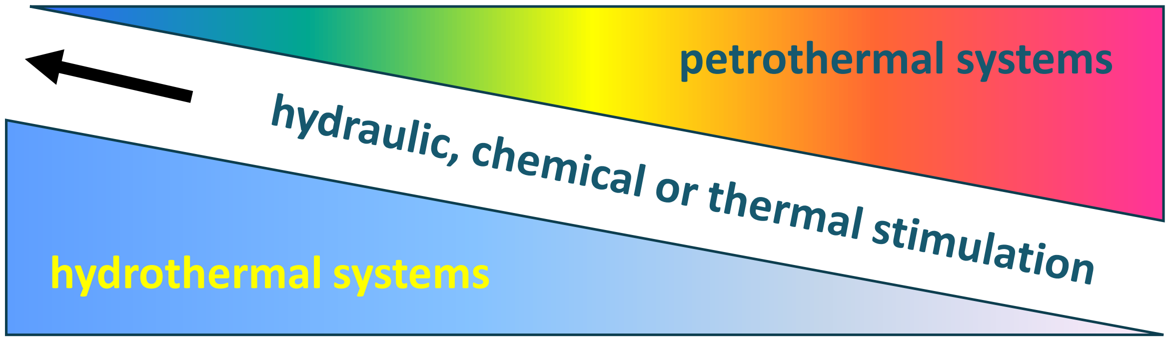
Orientation of seismic events

The European EGS test site Soultz-sous-Forêts, France

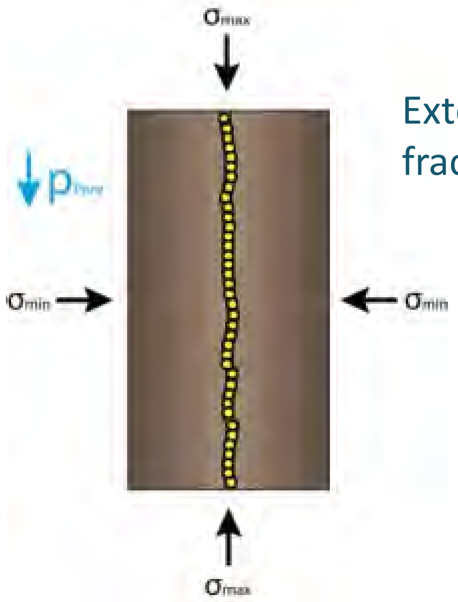
- 22 years of research, from first site investigation to operation and electricity production in 2008
- 80 MEuros spent on RTD and installations: 30 M€ EU, 25 M€ France, 25 M€ Germany.
- The initial French-German cooperation was enlarged by adding the UK experience (Camborne School of Mines -> Rosemanowes)
- 15 research institutions and numerous subcontractors involved
- More than 40 PhD theses, 1000+ scientific publications
- Regional spin-offs in Landau, Insheim, Bruchsal, Rittershoffen, Strasbourg …
- Now operated by ES Géothermie

Enhanced geothermal systems (EGS)

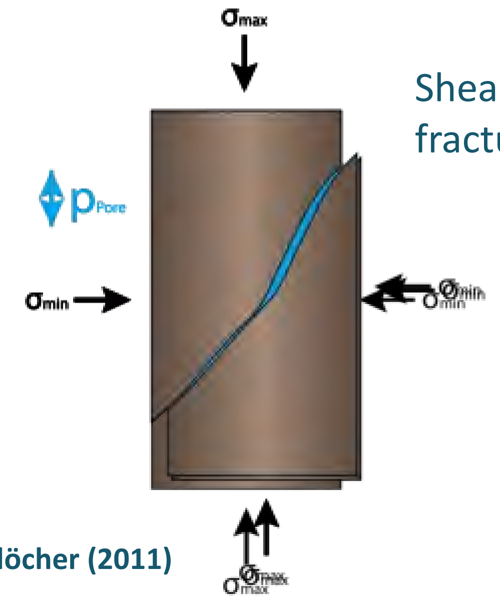
- The EGS concept: artificial improvement of hydraulic performance of a reservoir
- Enhancement is required to develop and exploit geothermal resources that are not economically viable by conventional methods
- Enhanced vs Engineered



high ....natural permeability .... low



Extensional fracture



Shear fracture

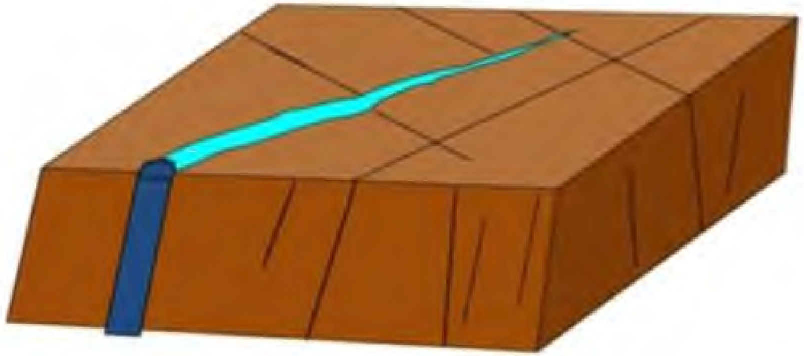
Blöcher (2011)

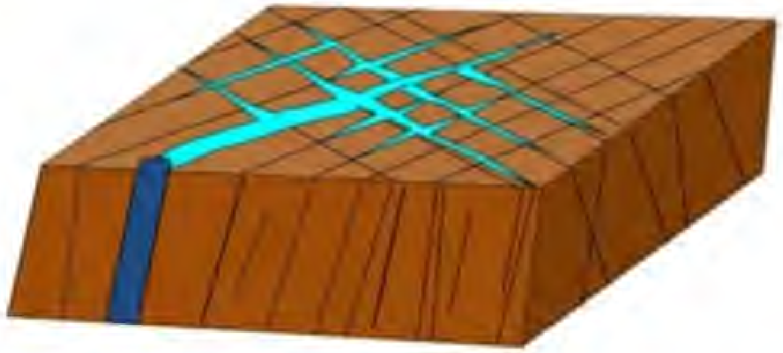
Geology - fractures

Properties
- Fracture sets
- Fracture intensity
- Fracture orientation
- Fracture size
- Fracture conductivity
- Mechanical properties

Exploration
- Well logs (e.g. FMI, PLT,...)
- Seismics (active, passive)
- Production data & well tests
- Outcrop studies

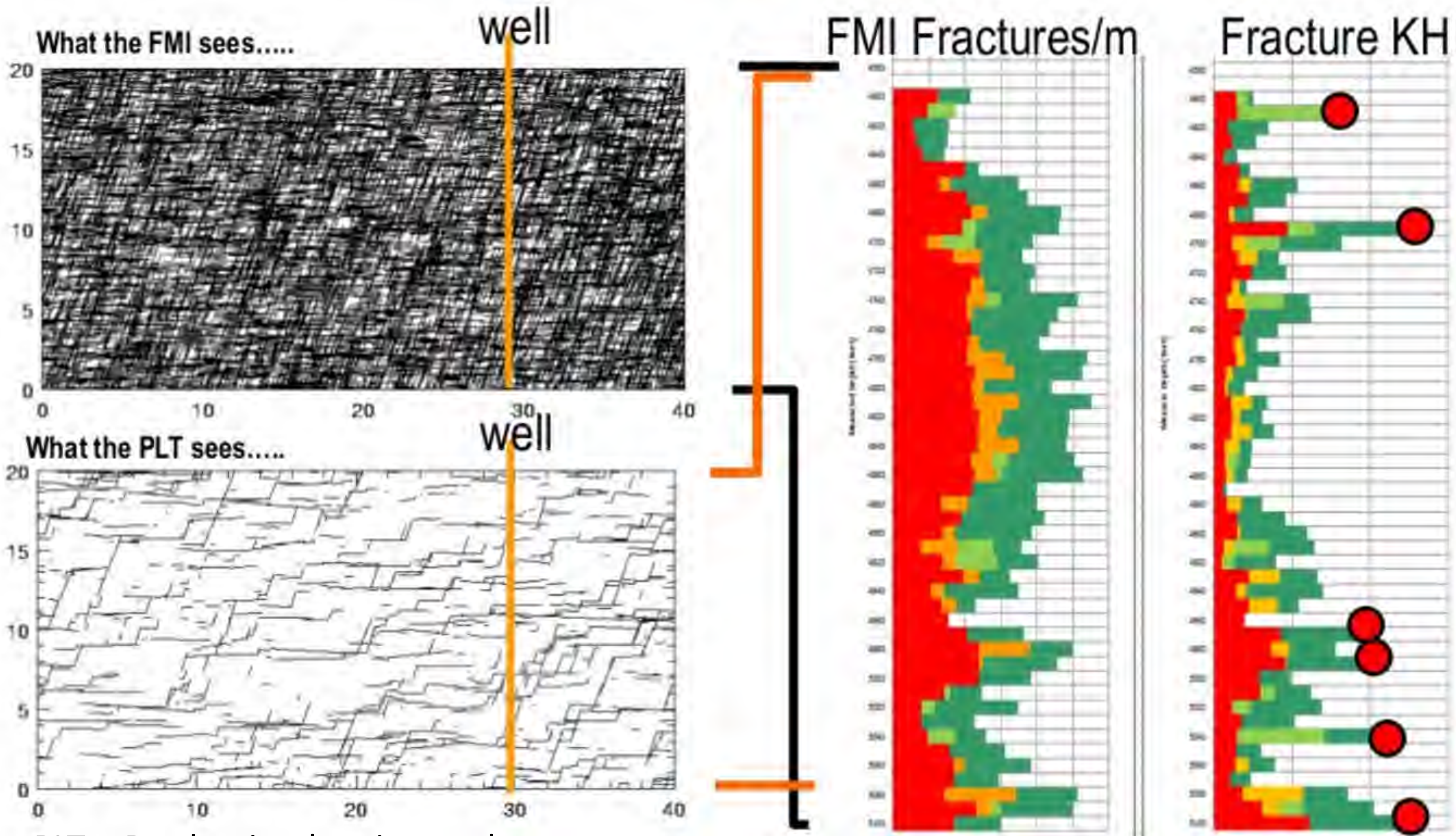
Implications
- Hydro-shearing of critically stressed pre-existing fractures
- Interaction with existing fractures
- Locally fracture follows fabric





McLennan and Potocki (2013)

Geology – fractures from well logs



PLT = Production logging tool
FMI = Formation Micro Imager

Golder Associates

Exploration of fractures with well logs

EXERCISE

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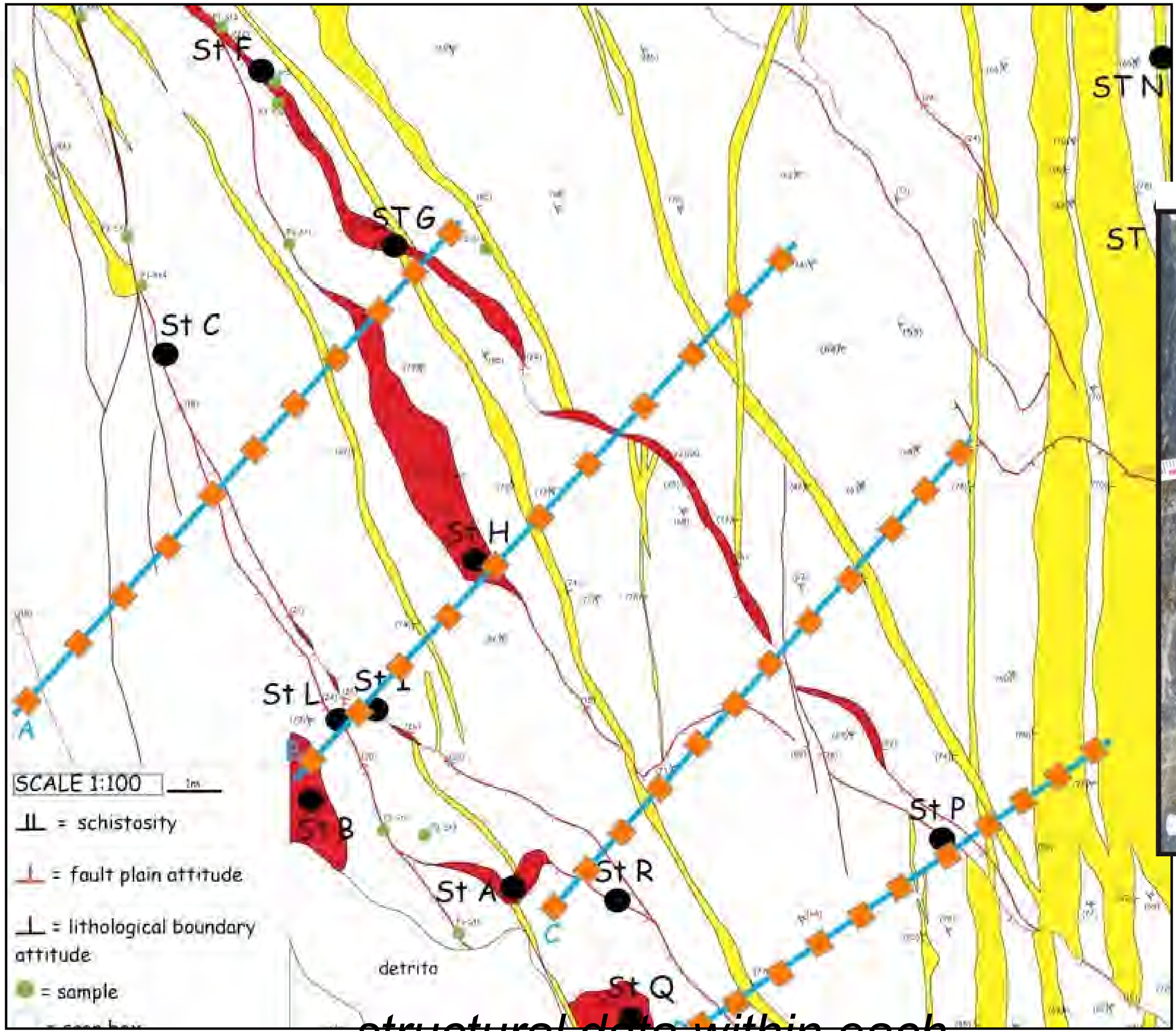
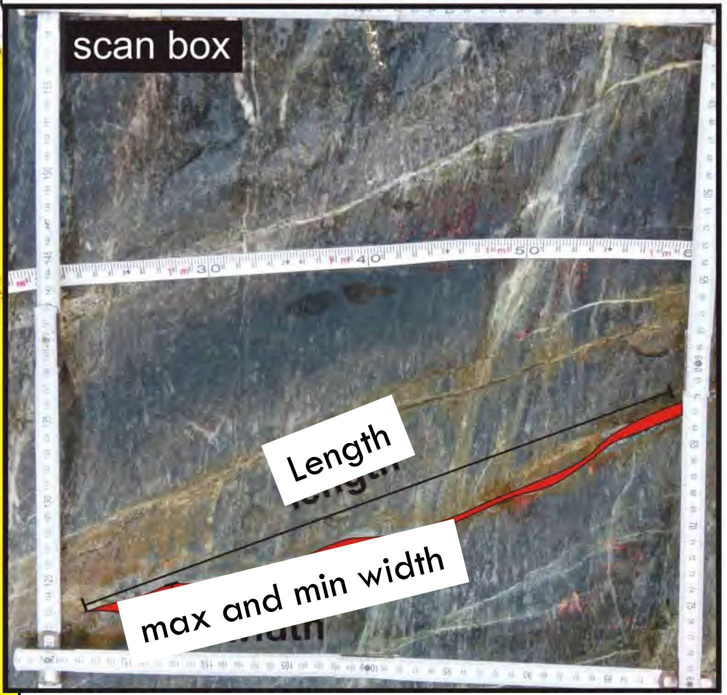
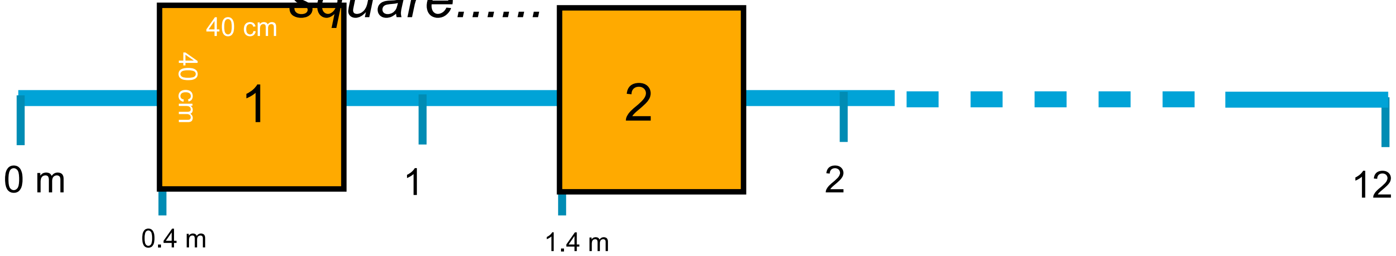
Fracture mapping: Scanlines from analogue sites





.....structural data within each square......



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EXERCISE

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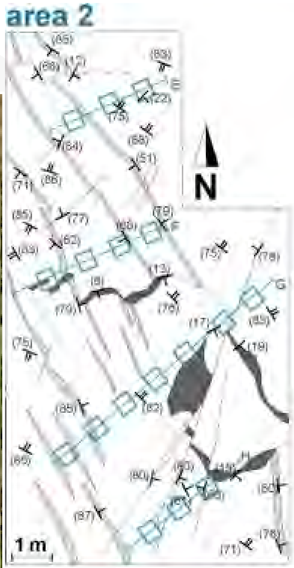
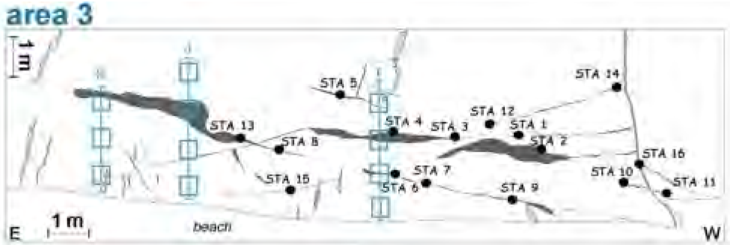
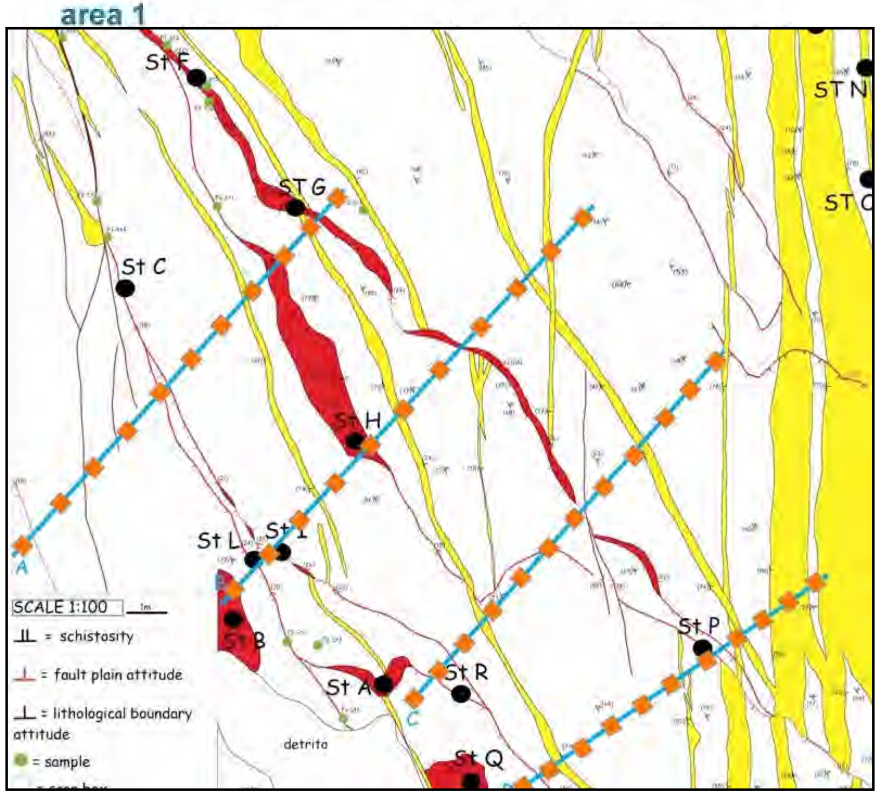
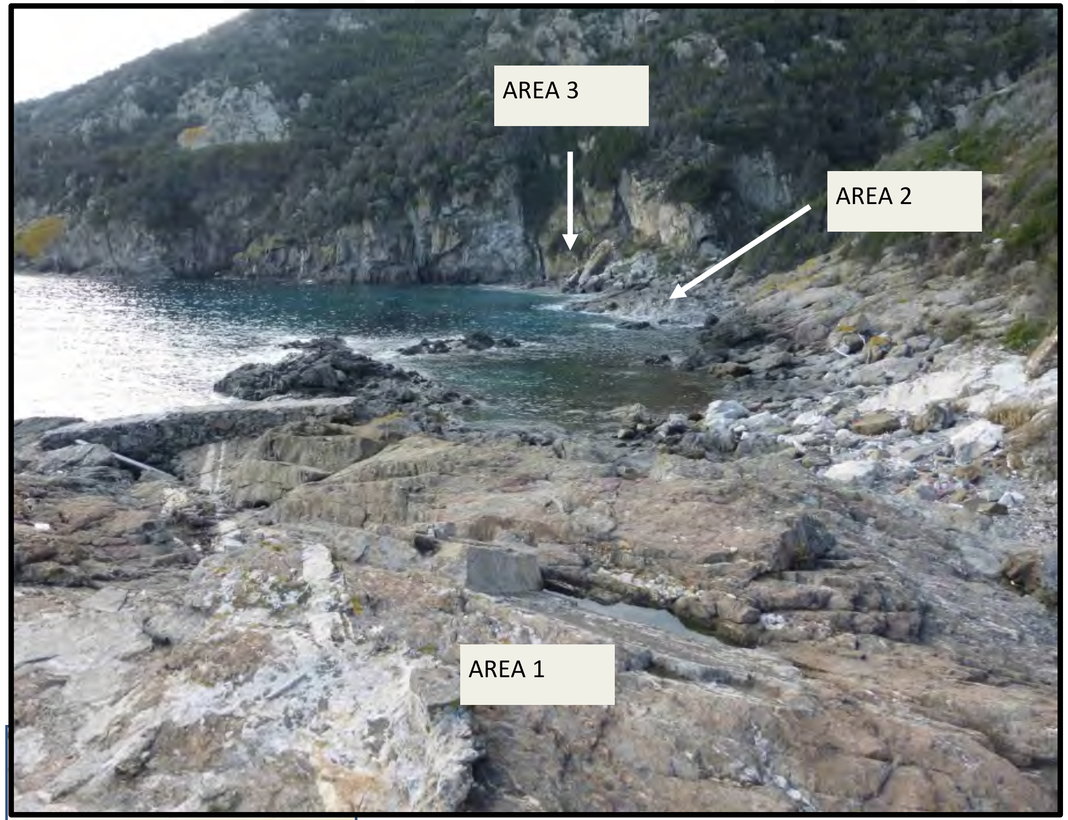
…..TOWARDS PERMEABILITY…..









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PERMEABILITY (m^2)

PARAMETERS

$$k = \left(\frac{2}{3} \times \frac{b^3}{L}\right) \times \left(f \times 10^{-6}\right)$$

Gale (1982) Nicholl et al. (1999)

Zimmerman and Bodvarsson, 1996

b = average fracture width
L = fracture length

f = *assumed as 0.4*

Connectivity among fractures $0.1 < f < 1$

f = constant of connectivity

EXERCISE

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Fracture mapping: Scanlines from analogue sites

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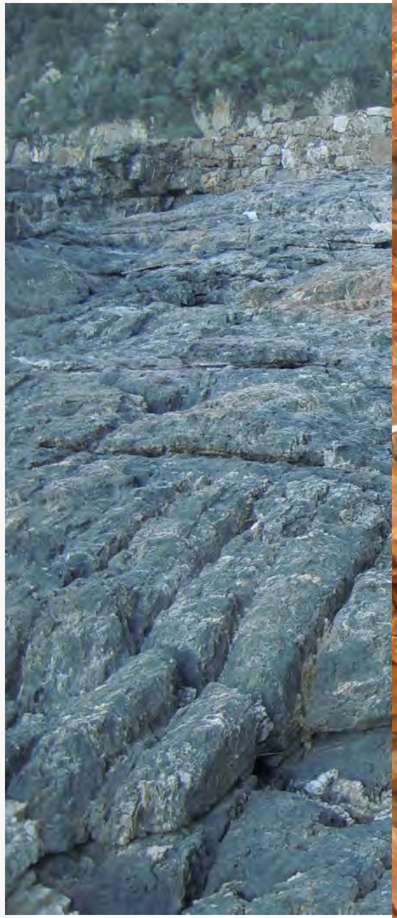

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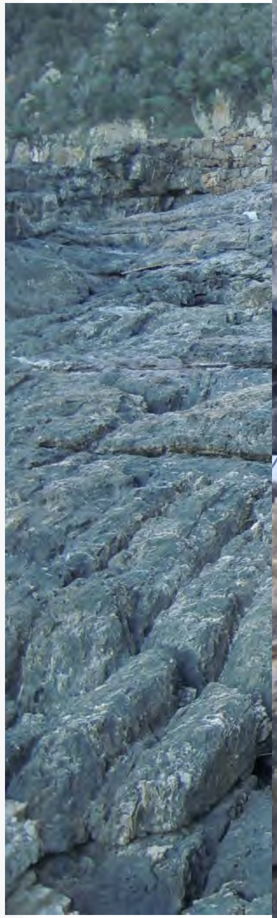
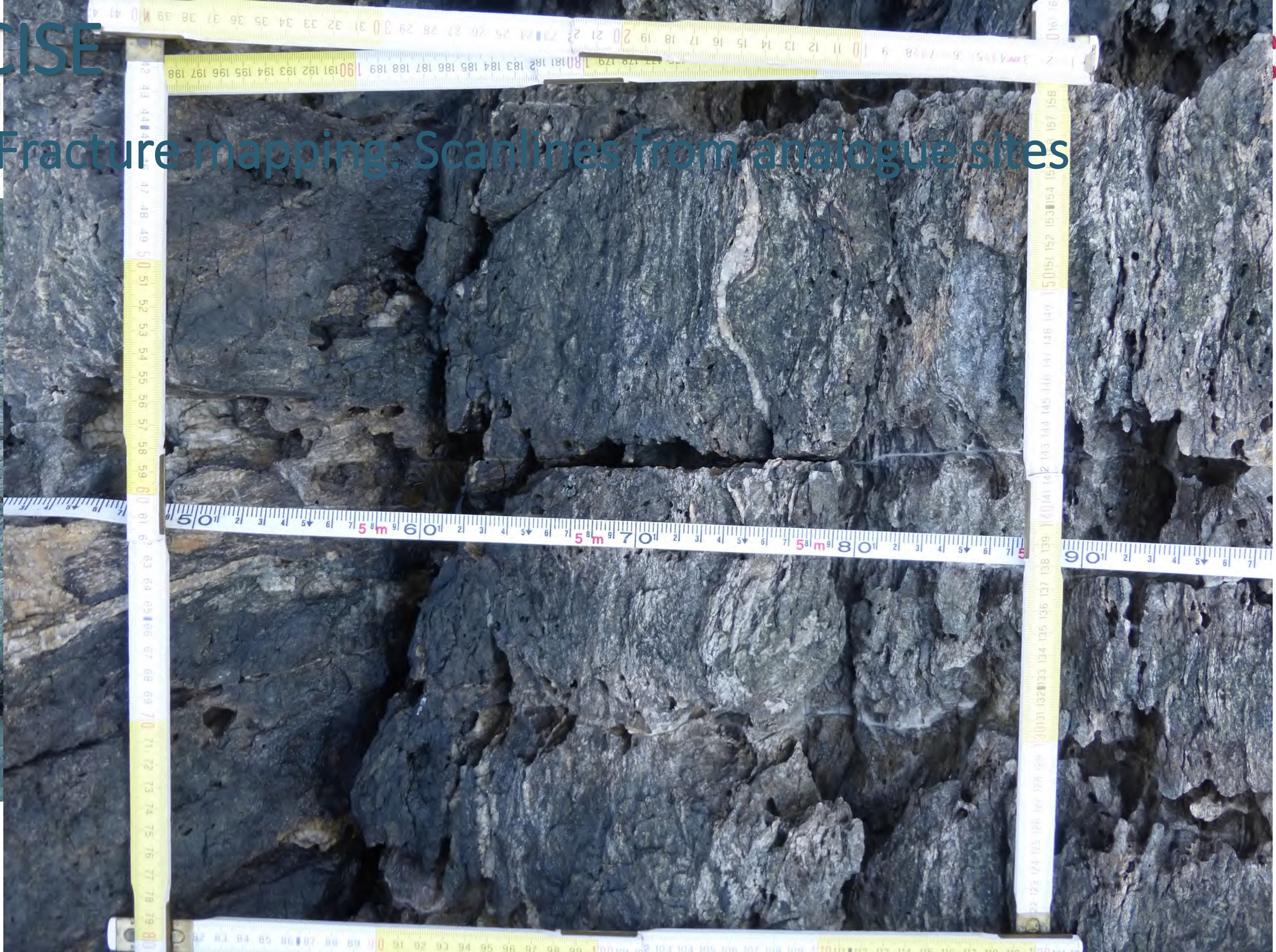
EXERCISE

Fracture mapping: Scanlines from analogue sites





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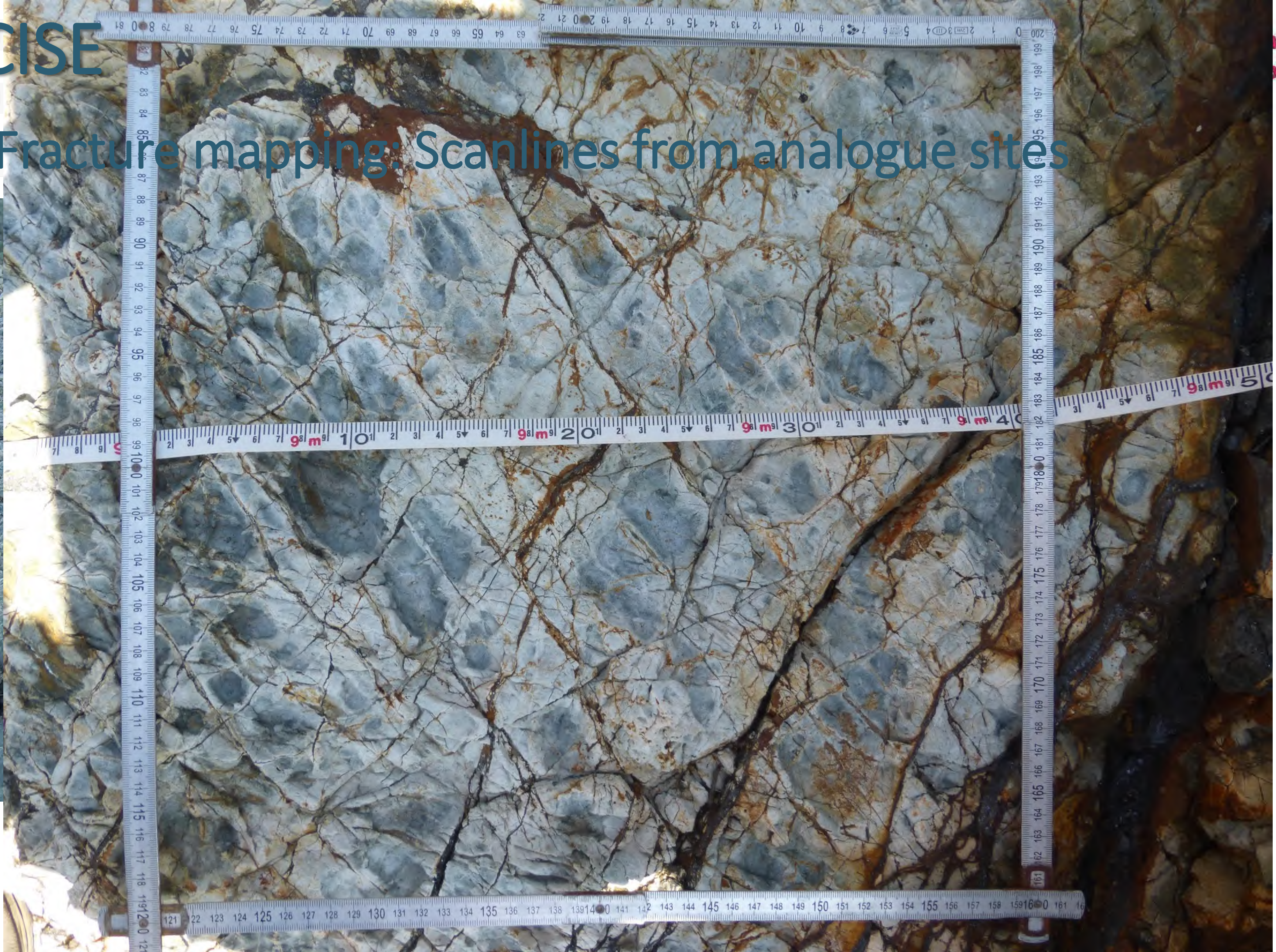
EXERCISE

Fracture mapping: Scanlines from analogue sites



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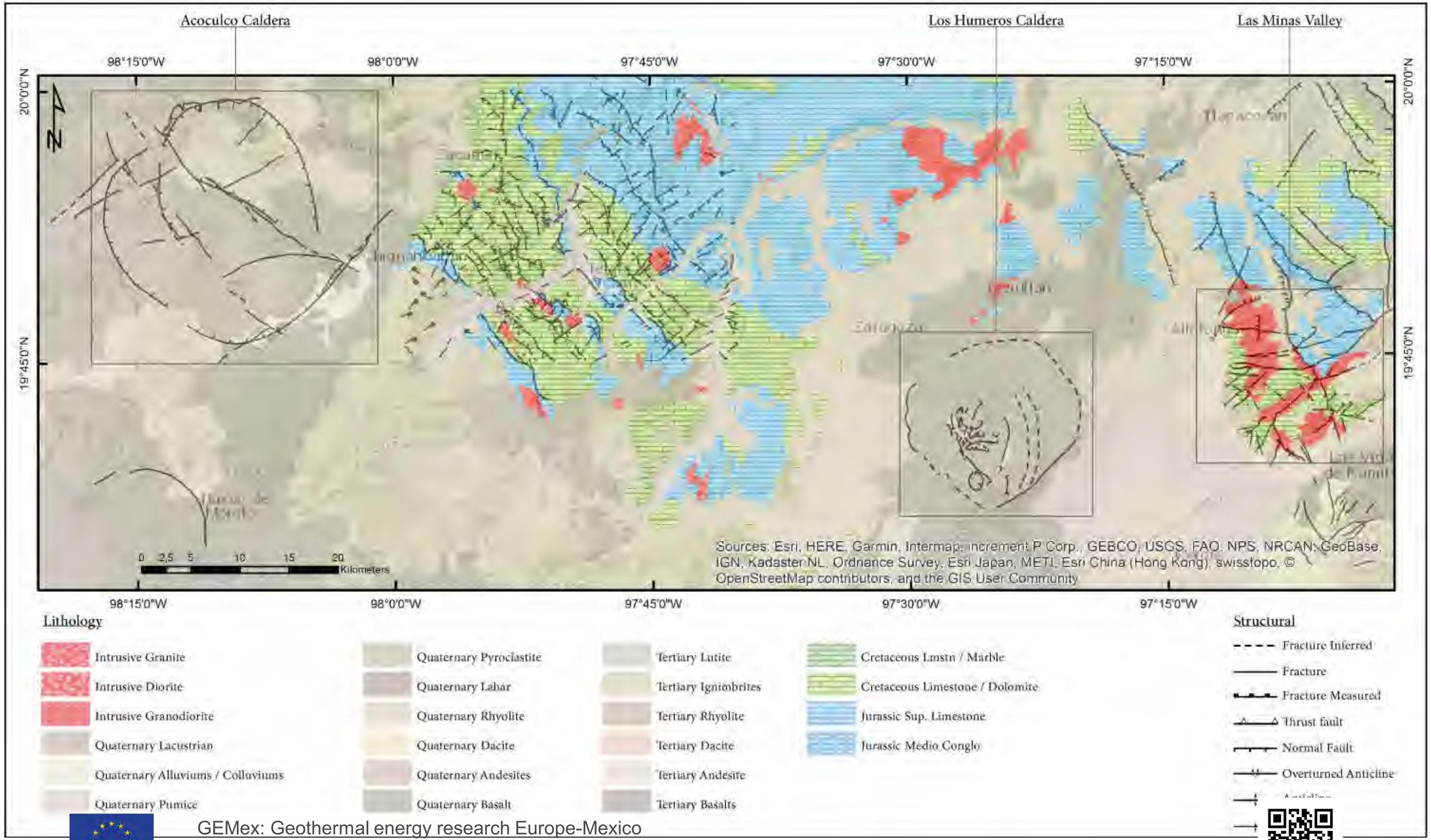
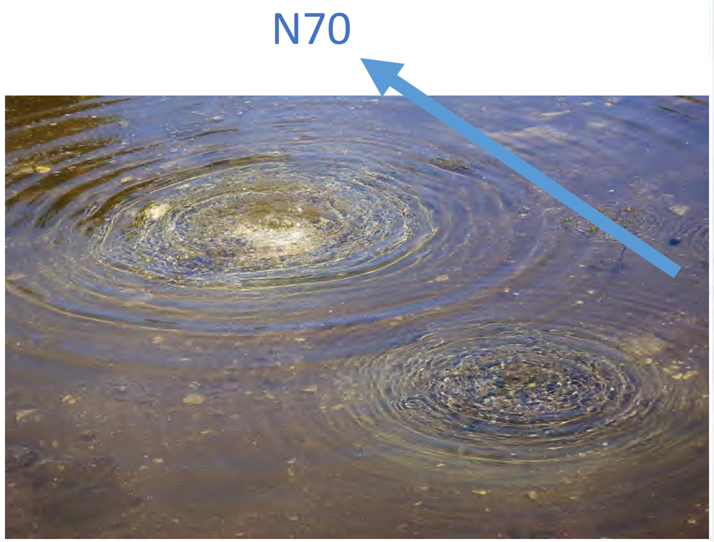
Las Minas analogue site

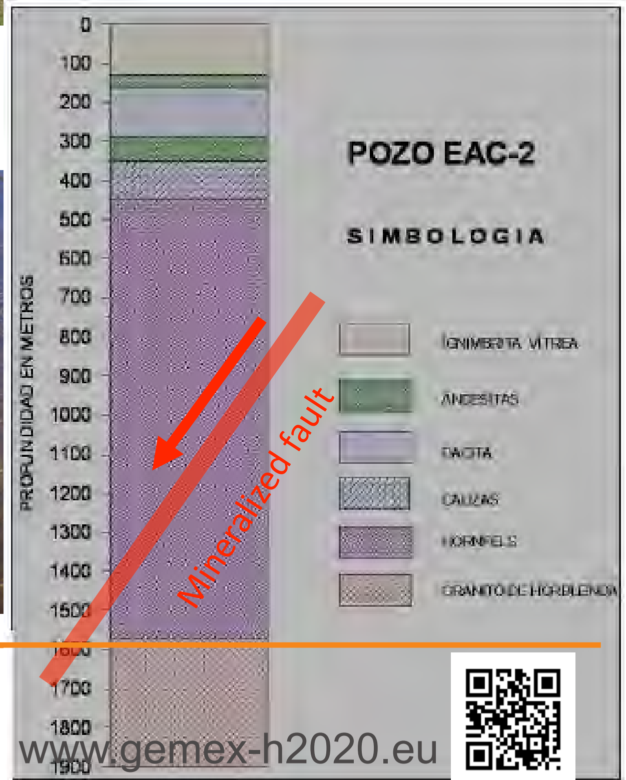


Acoculco

N70°
Borehole
NE
SW

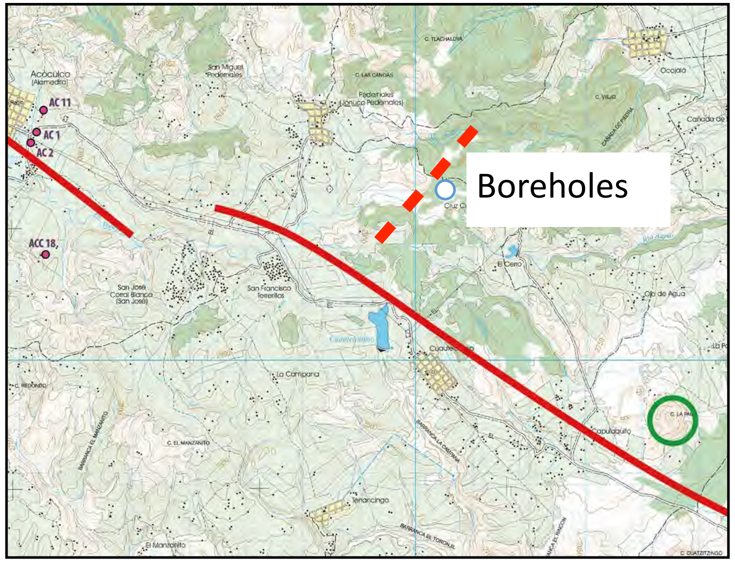


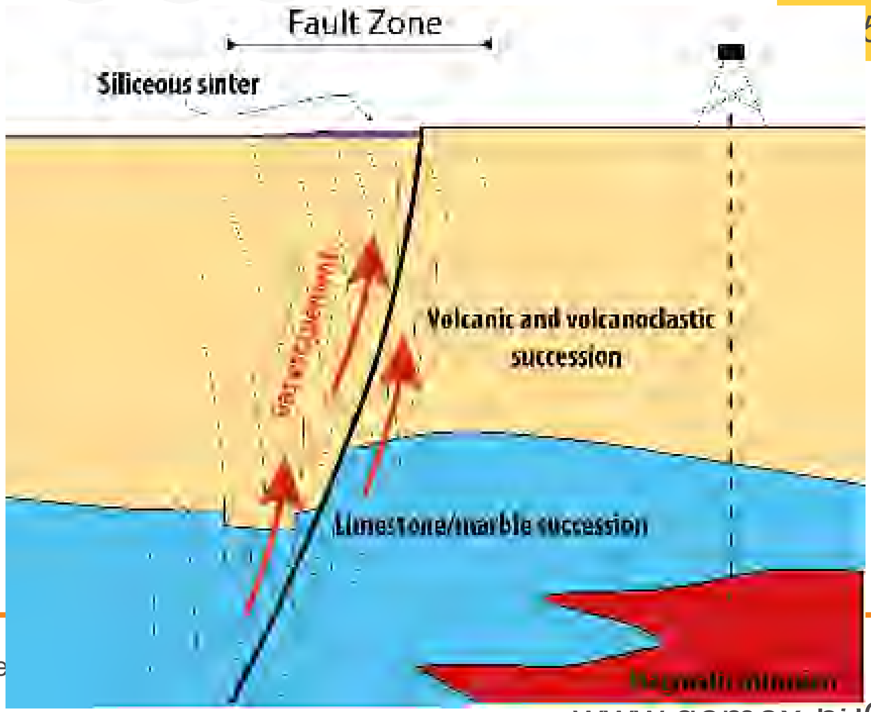
N70



POZO EAC-2
SIMBOLOGIA
PROFUNDIDAD EN METROS
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1700
1800
IGNIMBRITA VITREA
ANDESITAS
DACITA
CALIZAS
HORNFELS
Mineralized fault

Mapping at Acoculco

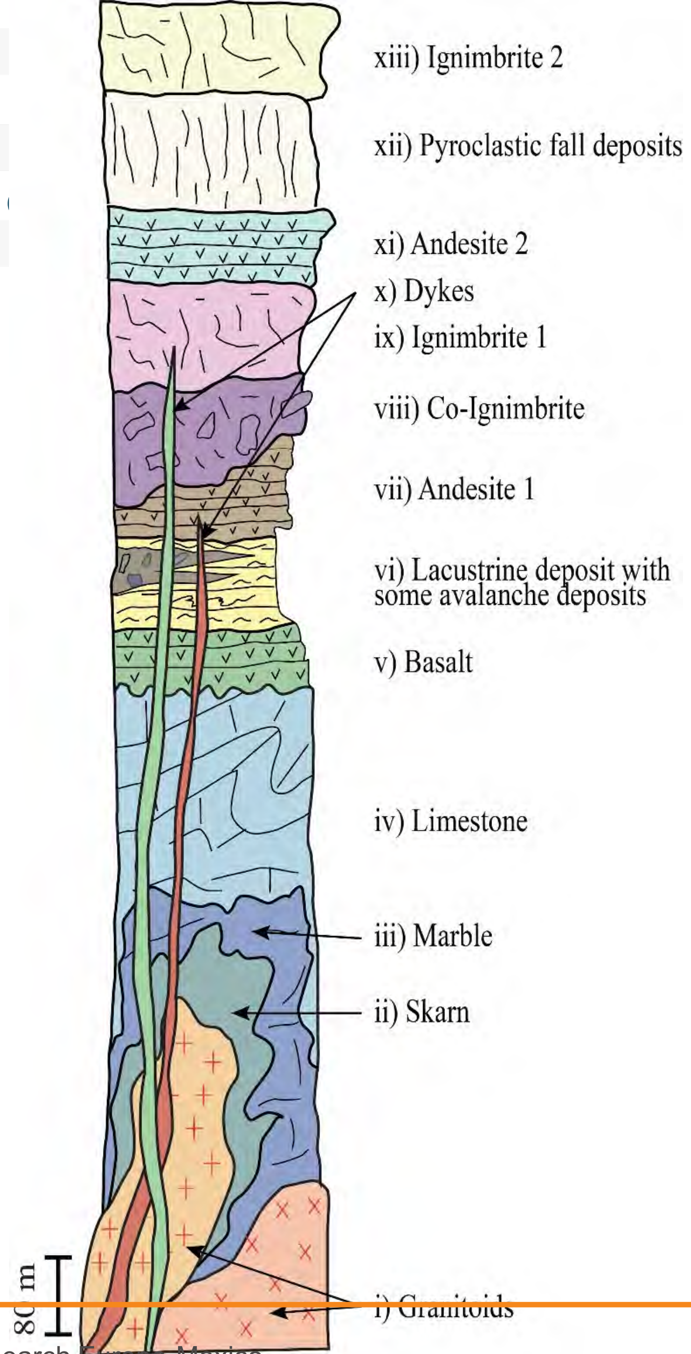




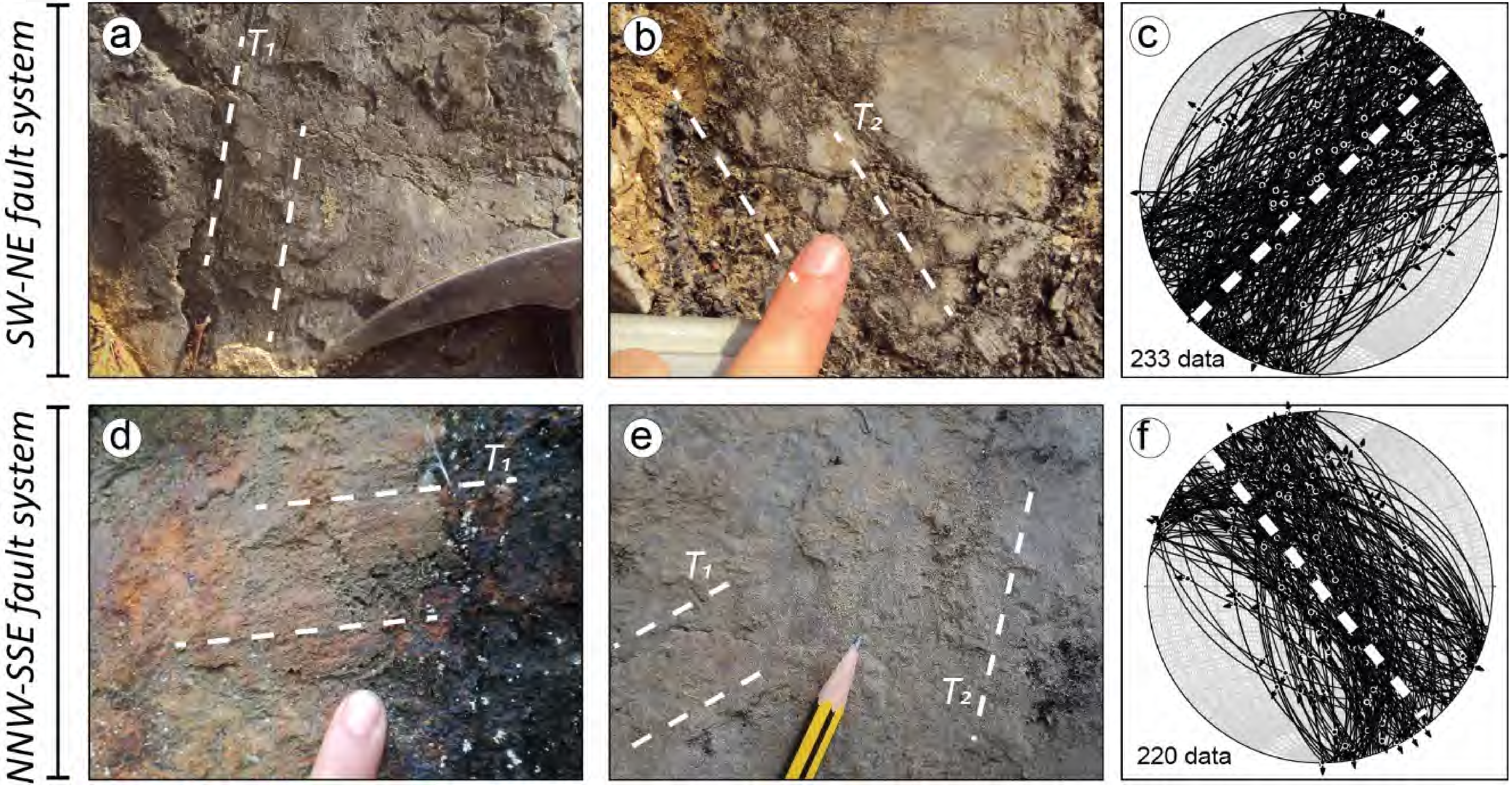
5 - *Brogi et al.*

Lithological Units Las Minas

Analogue site for Accoculco and Los Humeros



nal Winter
ol 2021



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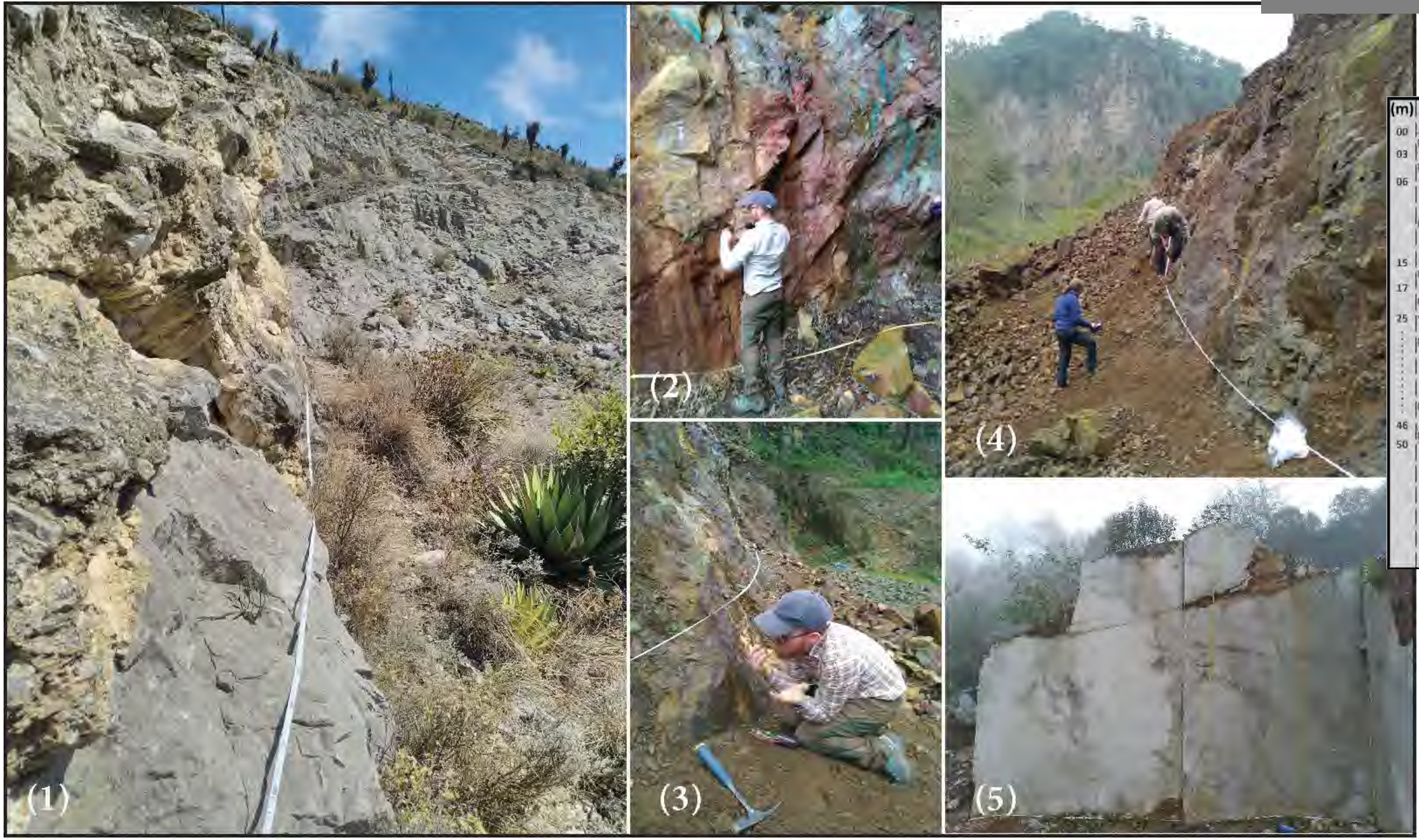
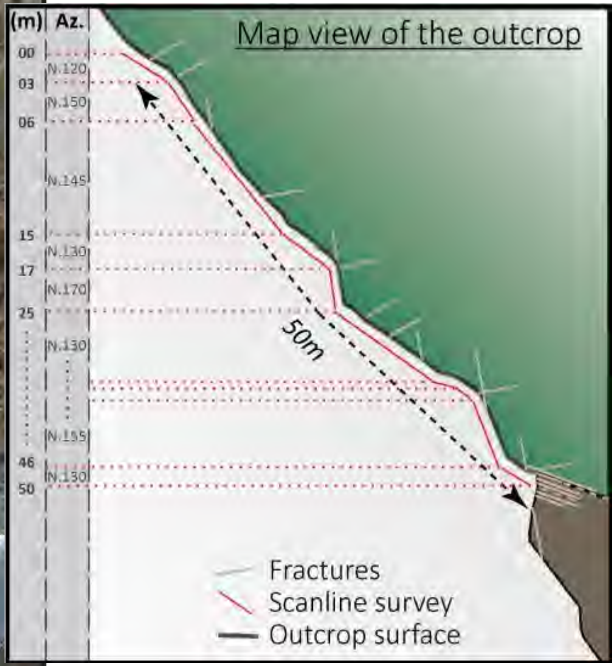
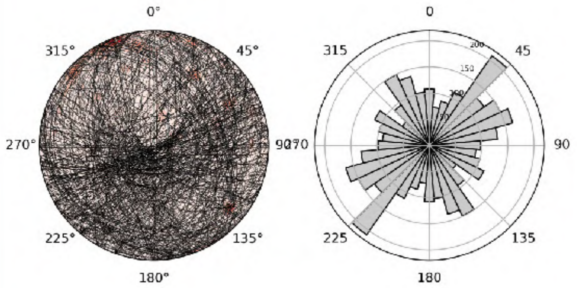




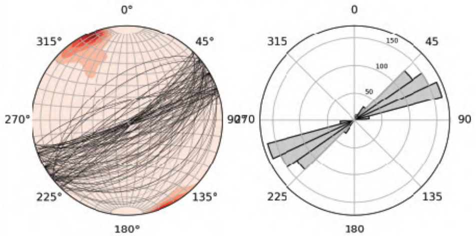
Las Minas

Stereographic projection plots

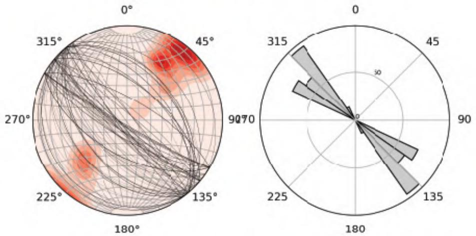
All fracture sets, from every scanlines



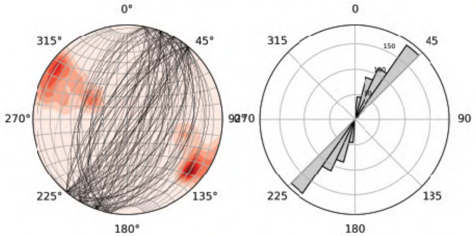
Fracture set (F1)



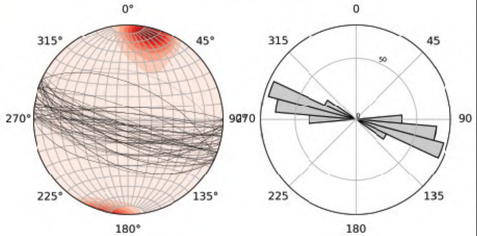
Fracture set (F2)



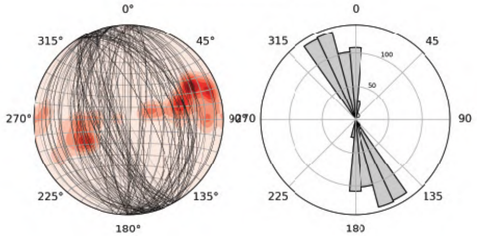
Fracture set (F3)



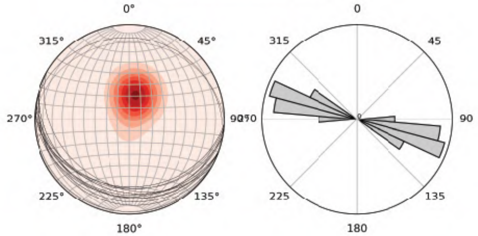
Fracture set (F4)



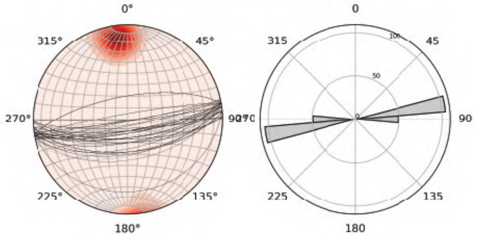
Fracture set (F5)



Fracture set (F6)



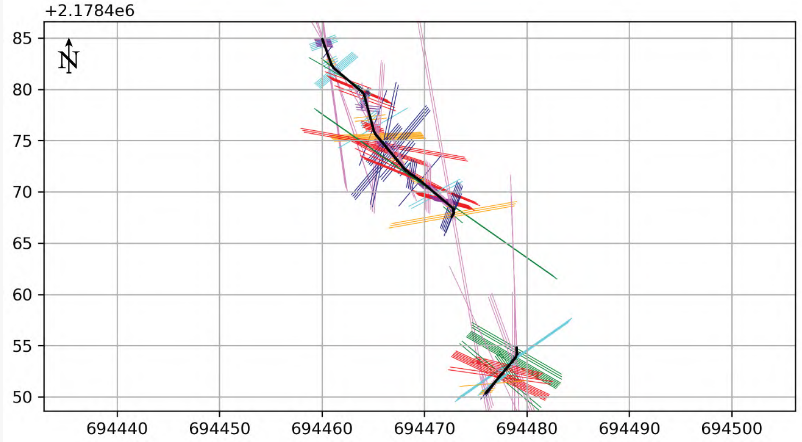
Fracture set (F7)



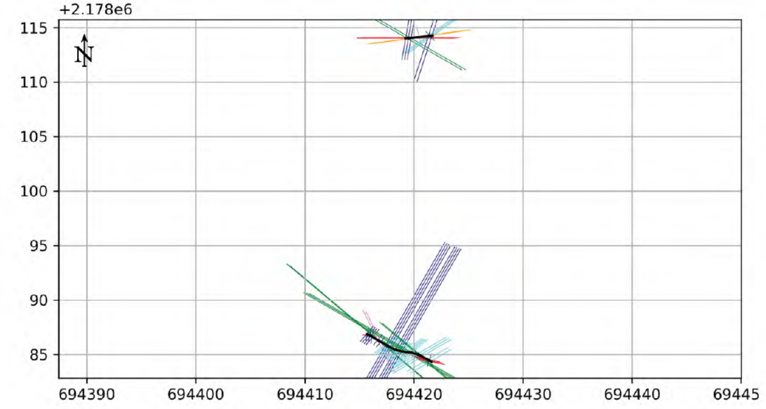
Fracture mapping: Scanlines from analogue sites

Skarn

(1) Boquillas

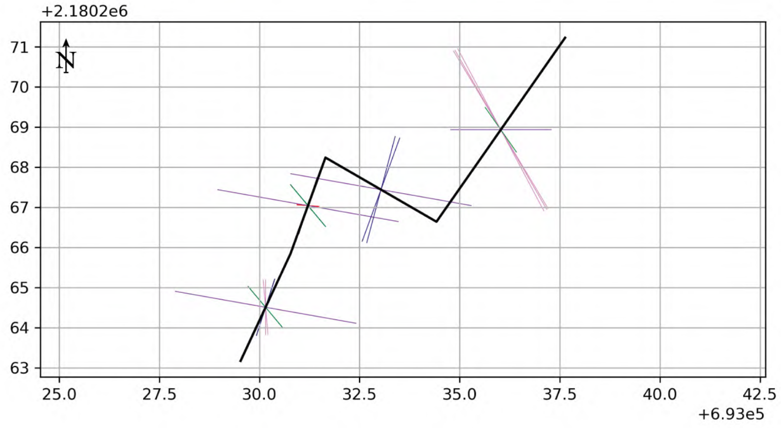


(2) Eldorado

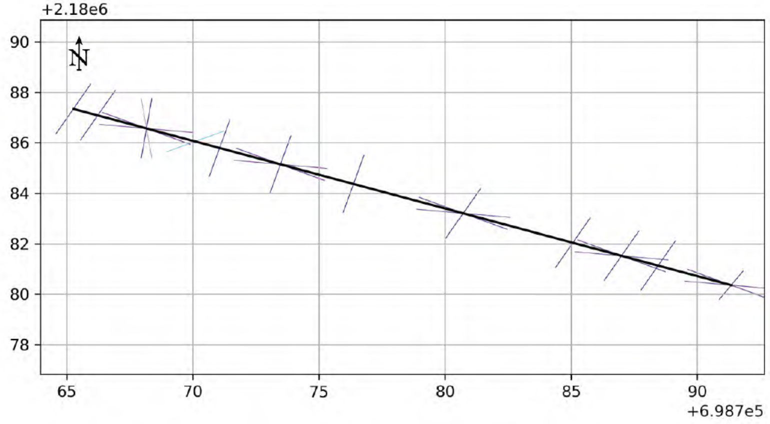


Marble

(3) Pueblo Nuevo

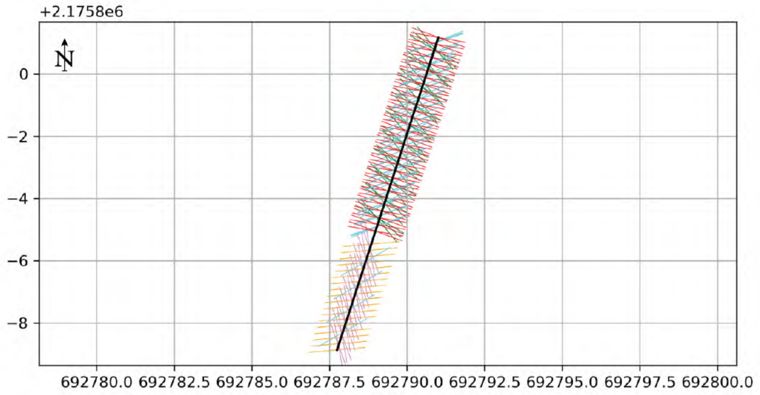


(4) Tatatila

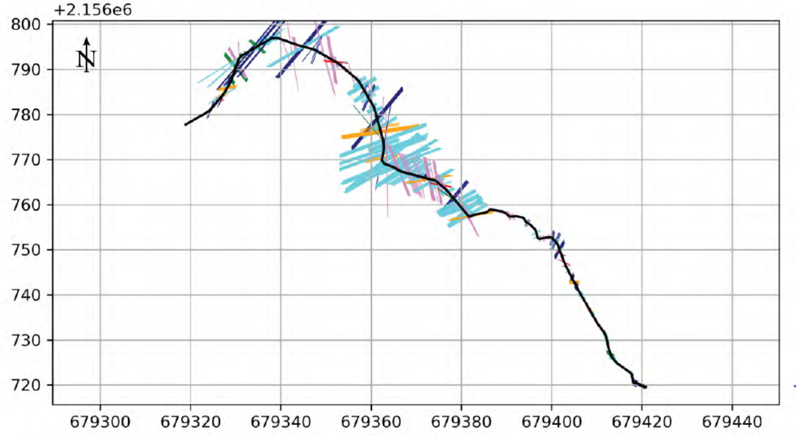


Limestone

(5) Rinconada

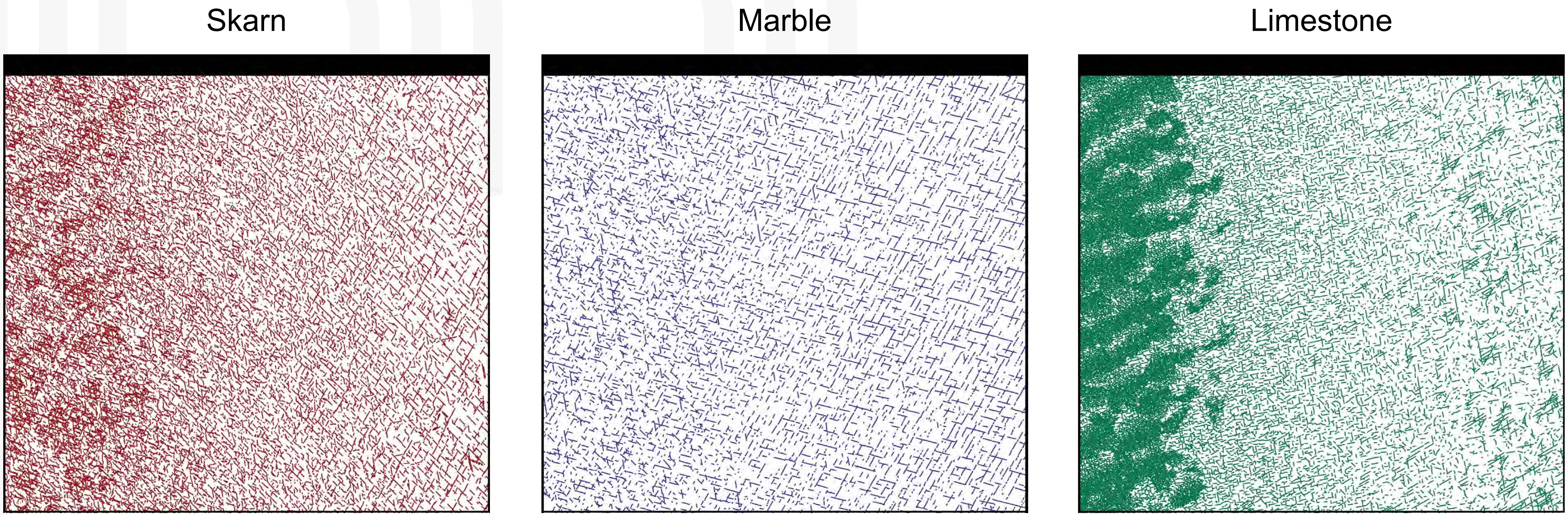


(6) San Antonio Tenextepec

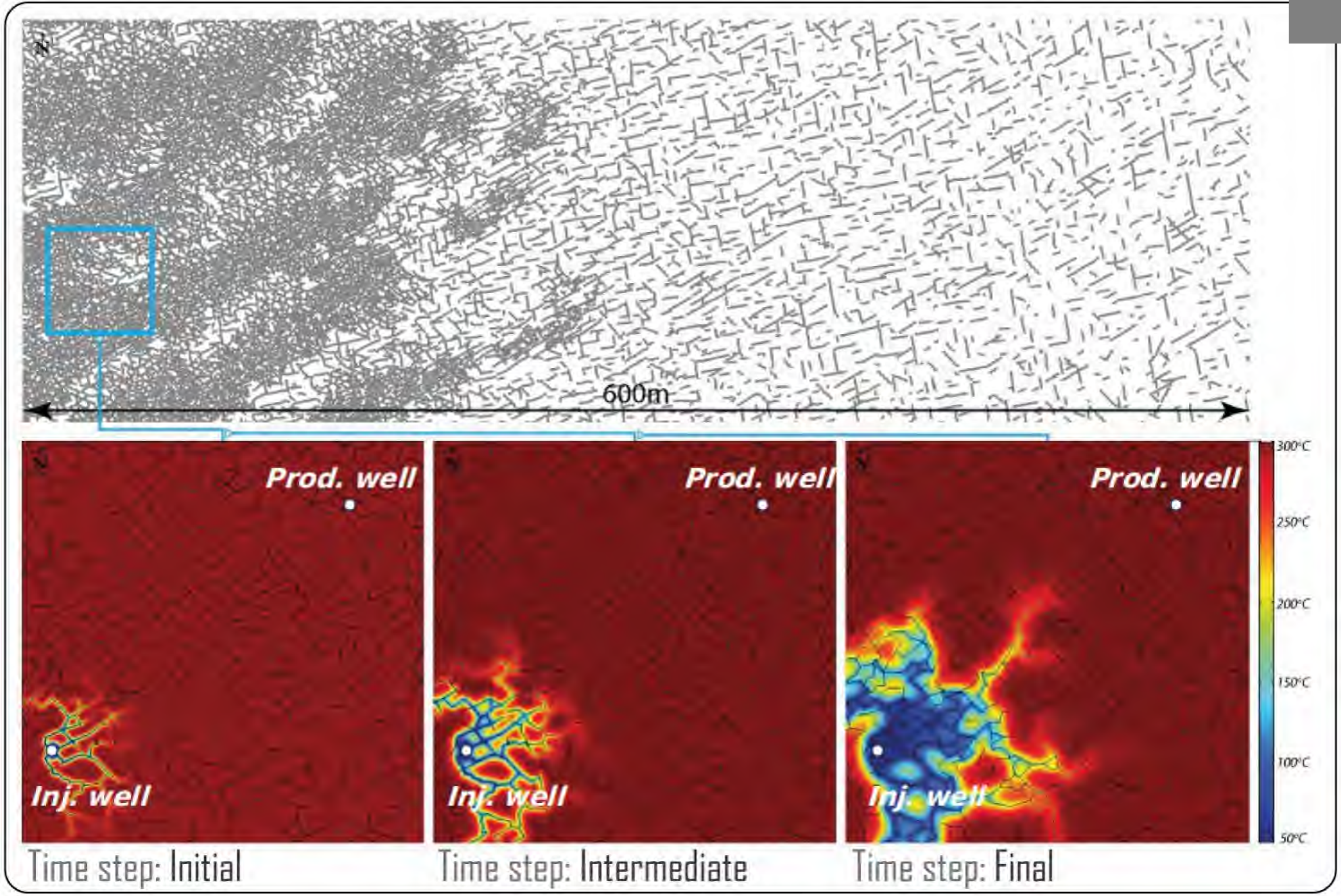


Lepillier (2020)

Computed DFNs using the MPS method



Fracture controlled fluid flow simulation

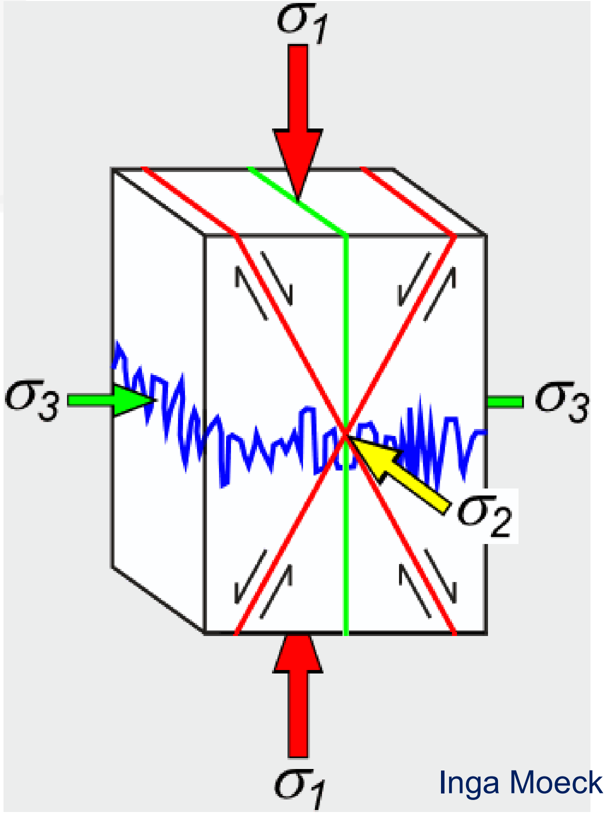


Fractures as result of forces

- Stress and forces in 3 main axes
- material: fracture strength, shear strength
- characteristic angle +/- 30° from max. main stress direction to shearing

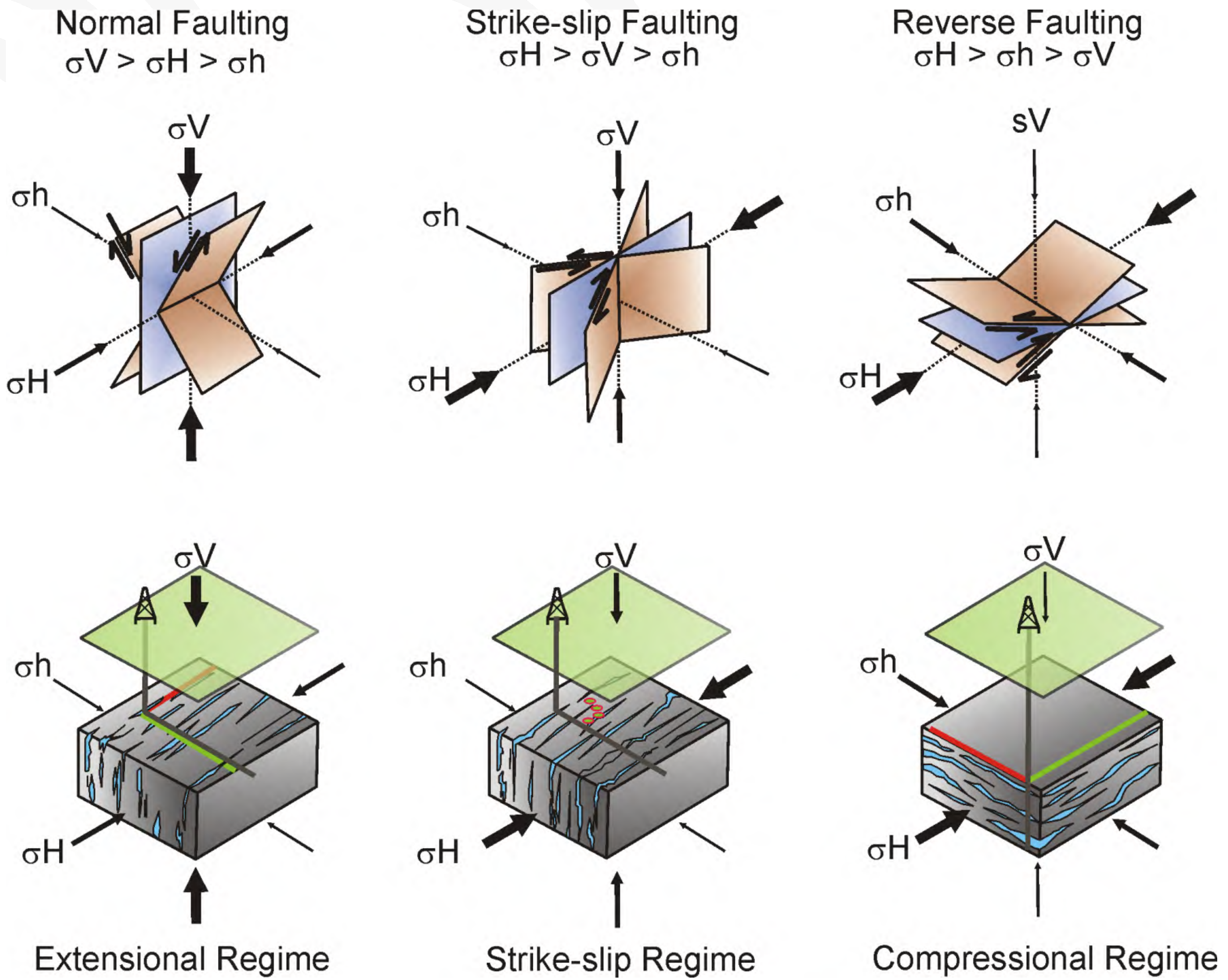
Ian Main

f10-cm , porous aeolian sandstone

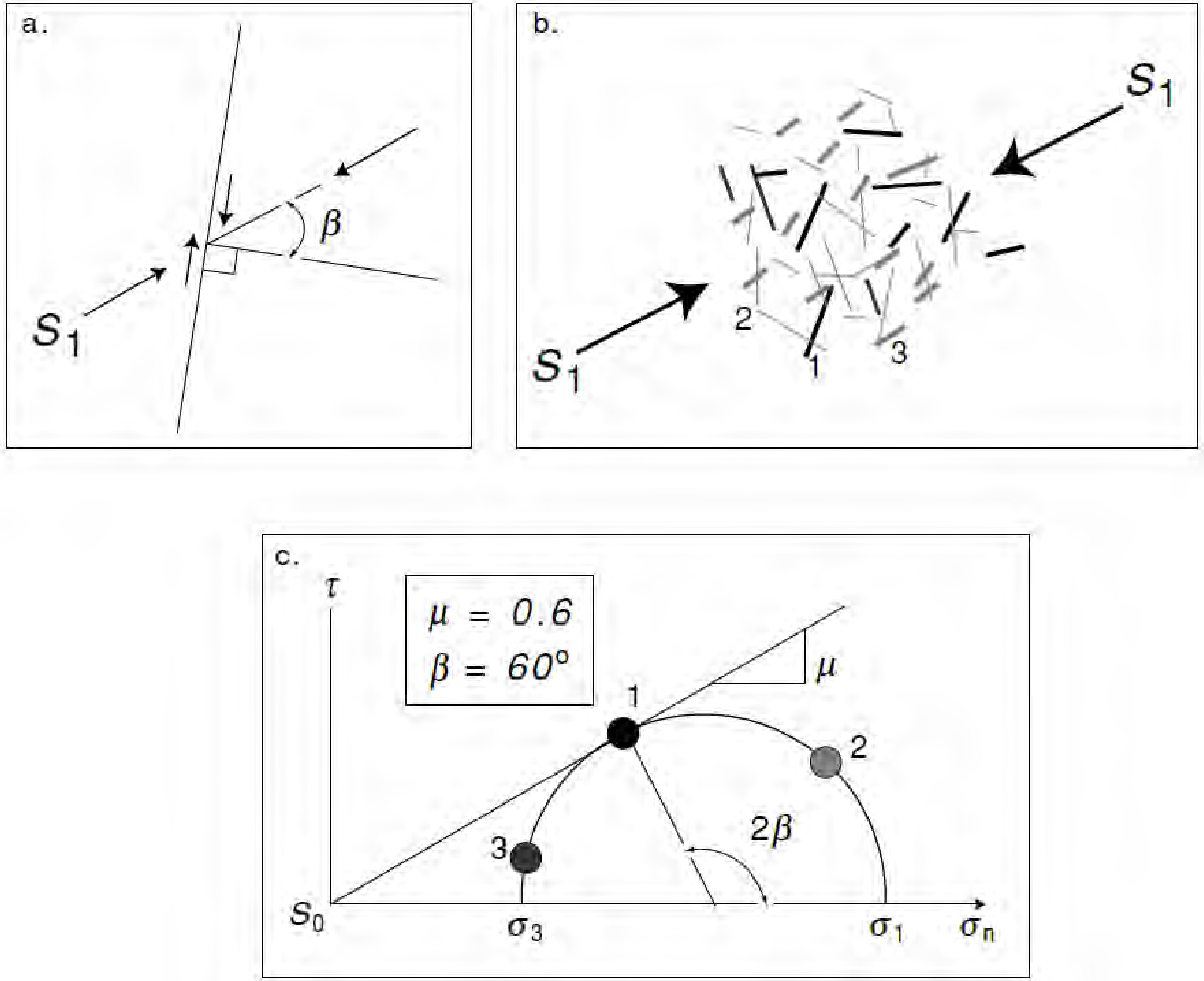


Inga Moeck

Stress Regimes



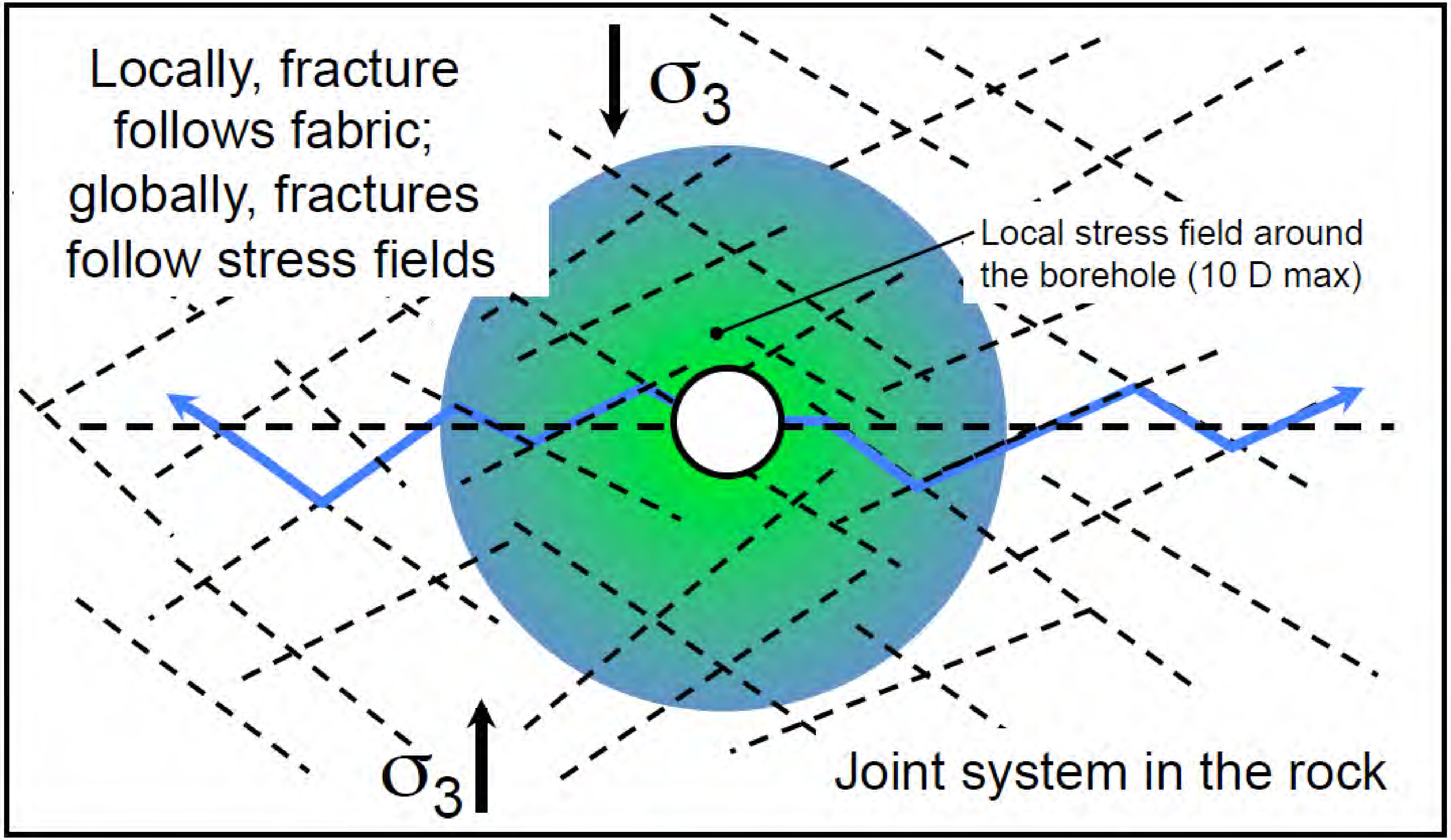
Geology - fractures



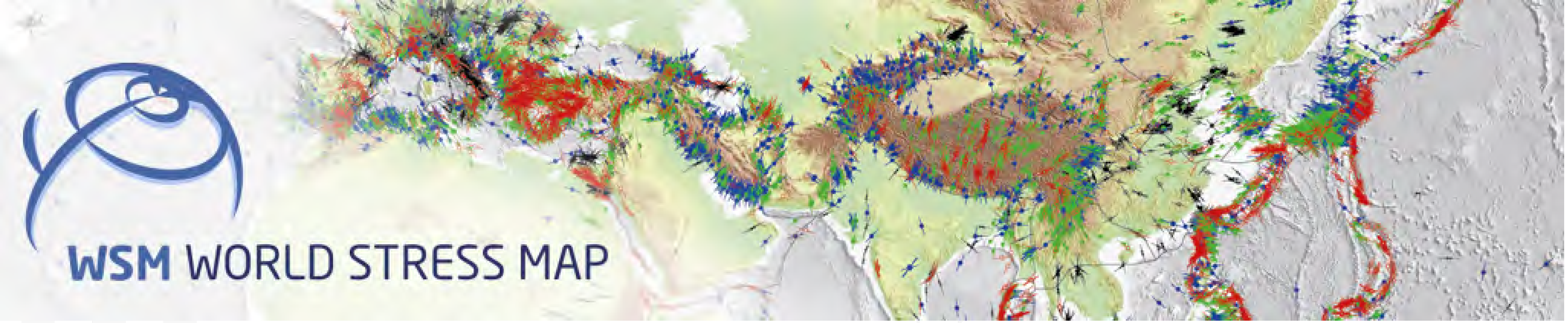
Zoback (2007)

Critically oriented fractures

Stress field



Dusseault



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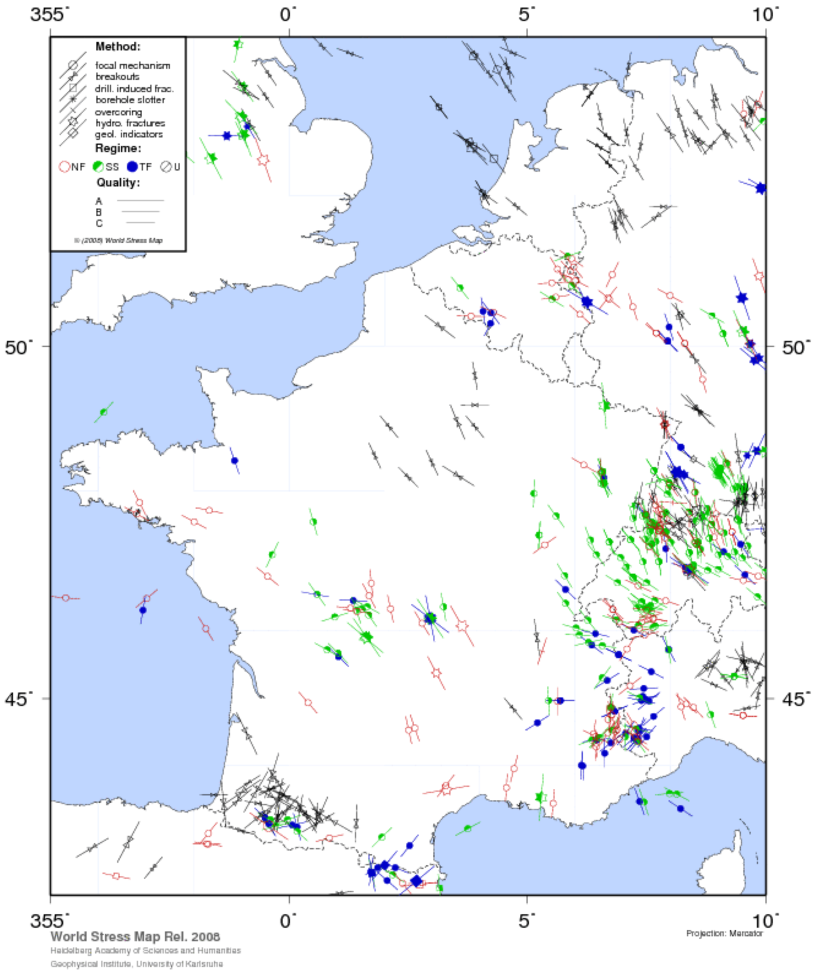

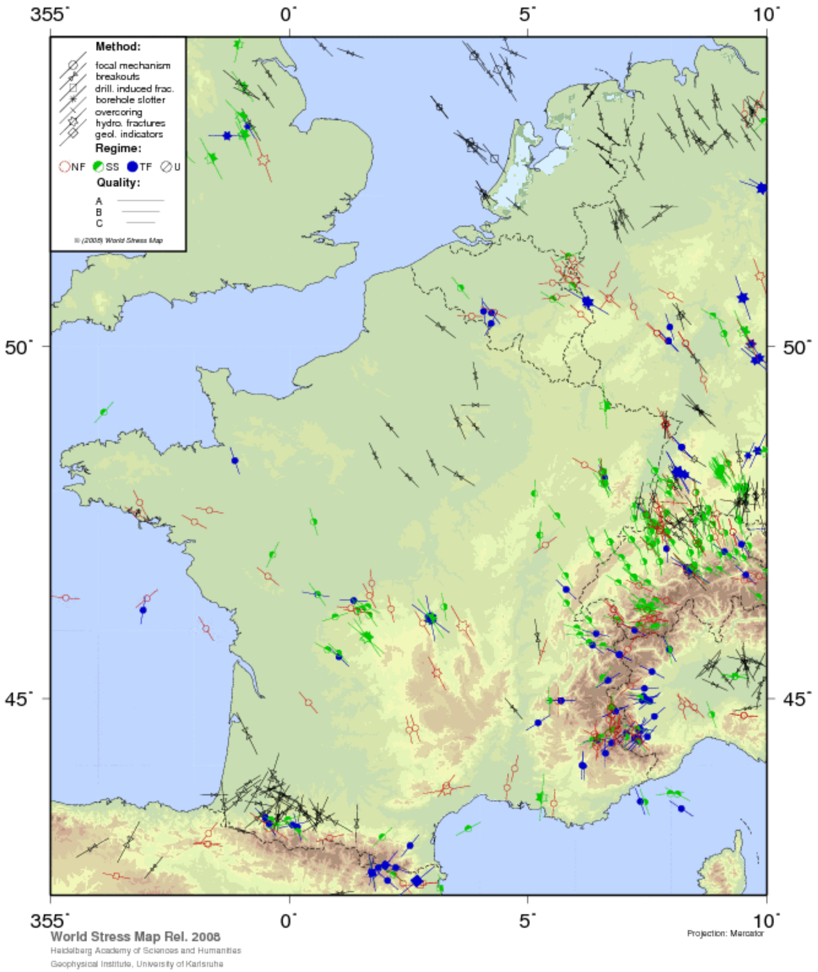

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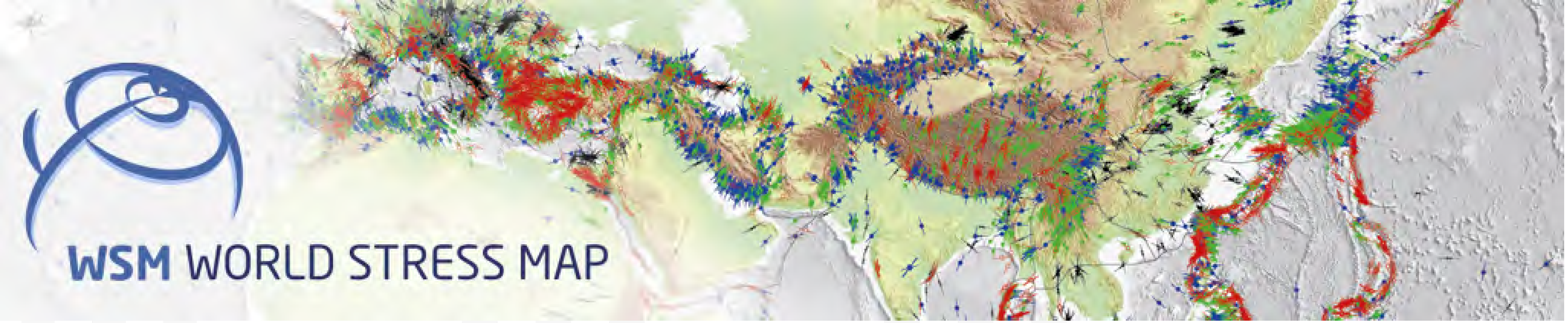

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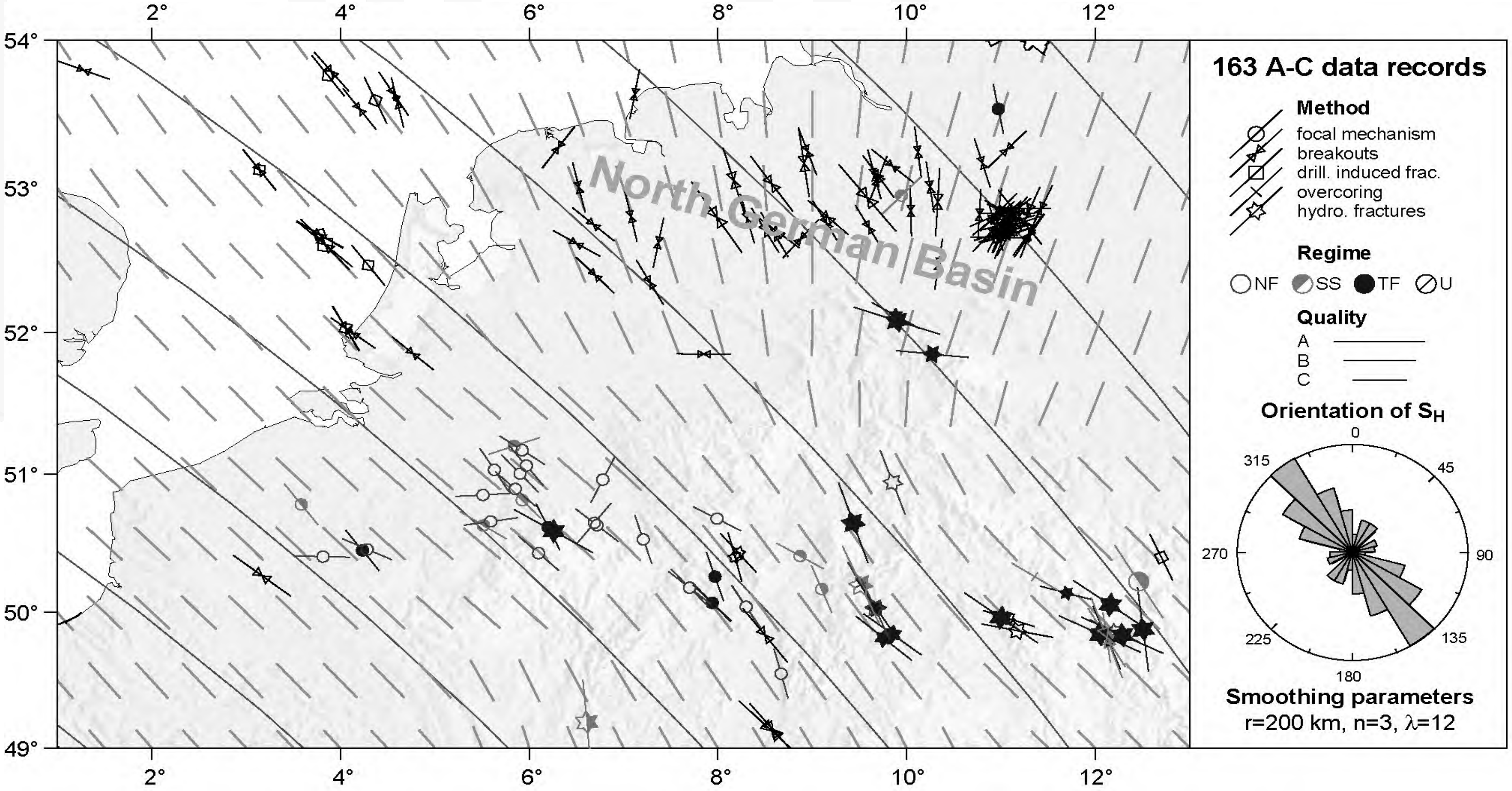

Heidbach et al. (2007)

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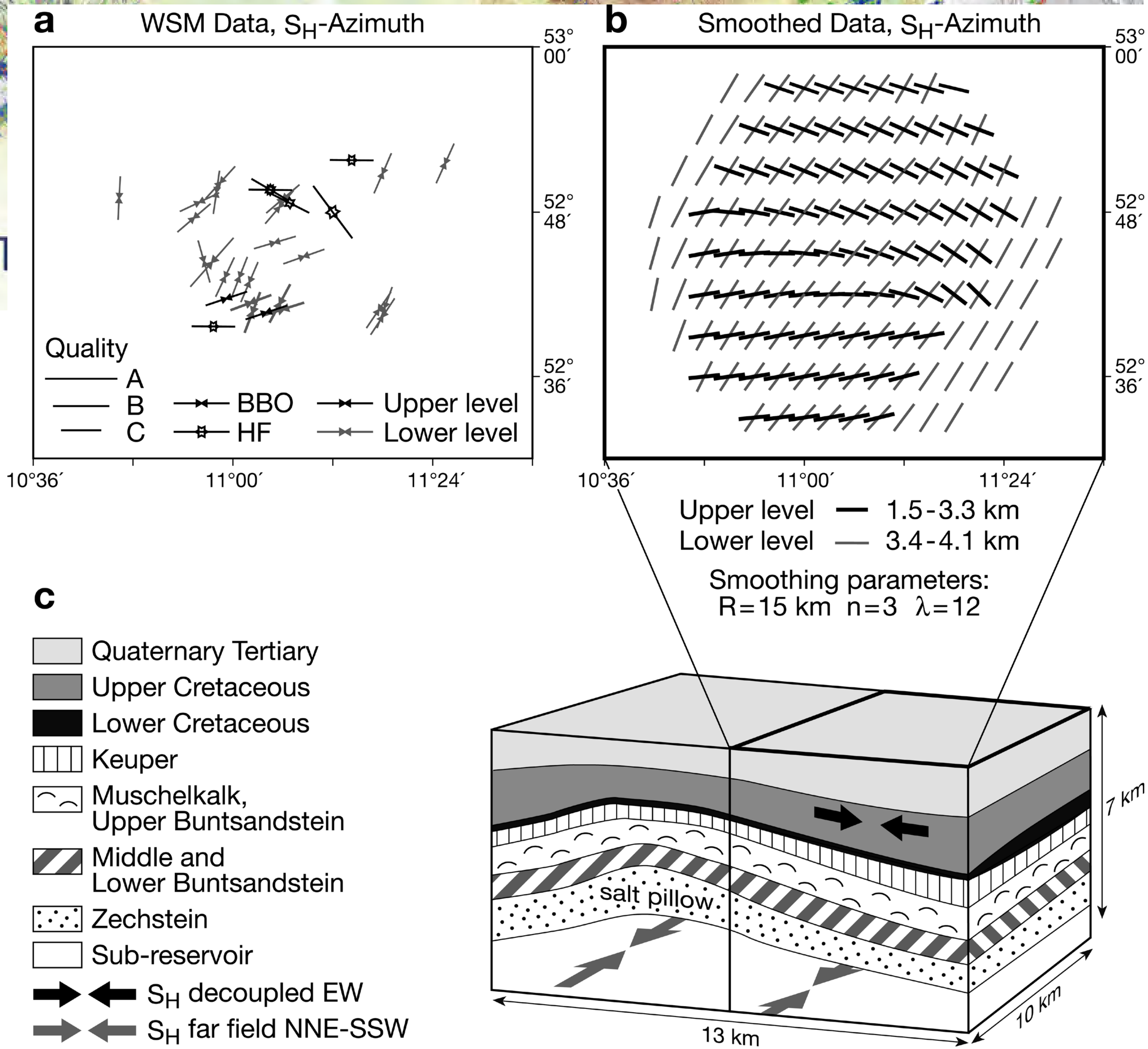
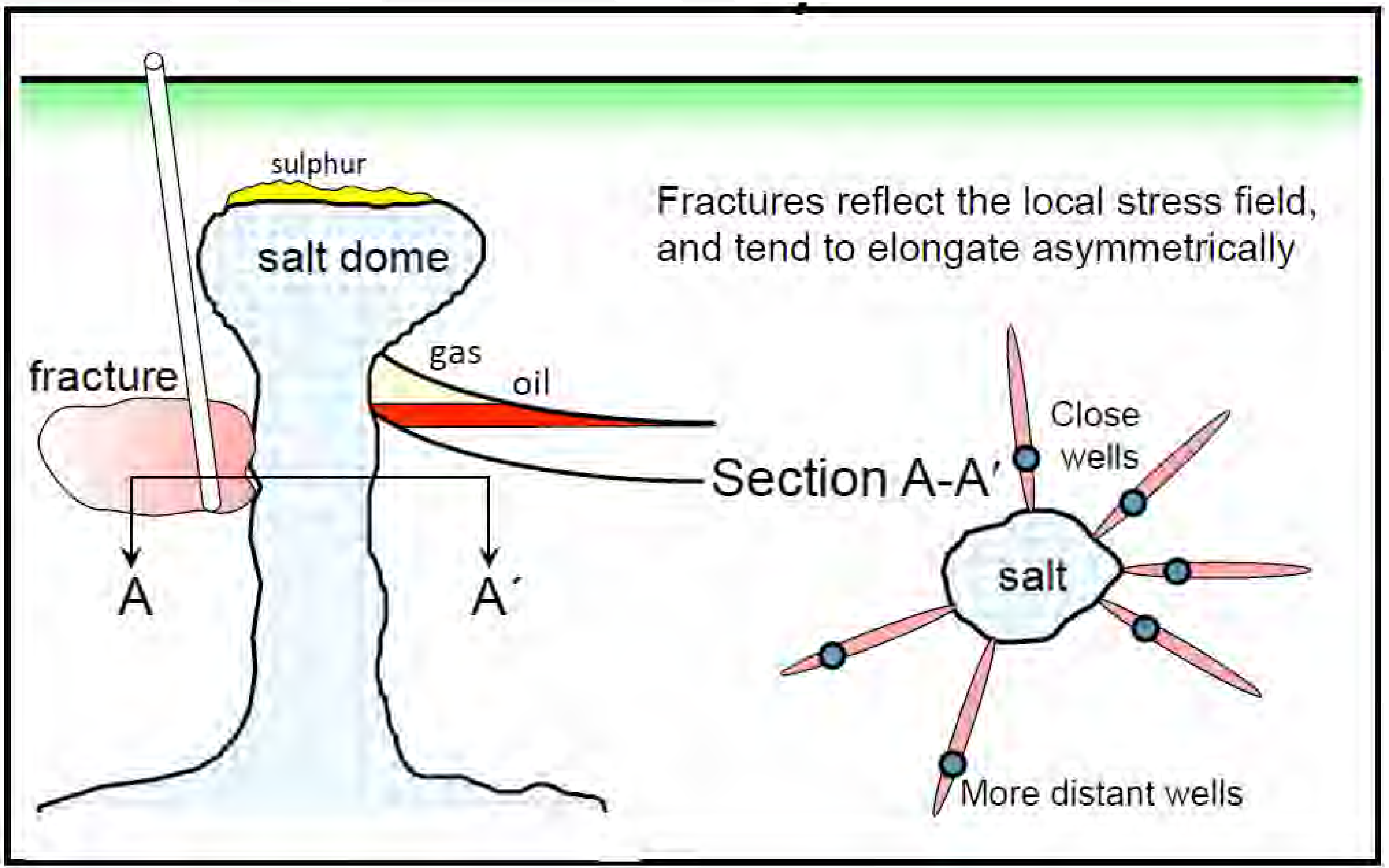


Zang + Stephansson (2010)

Stress field

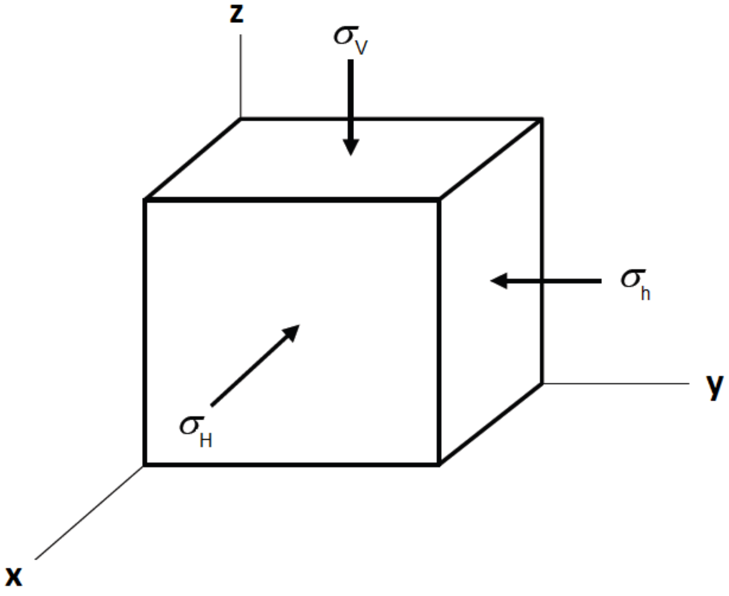


Dusseault

Local stress field may differ from regional stress field

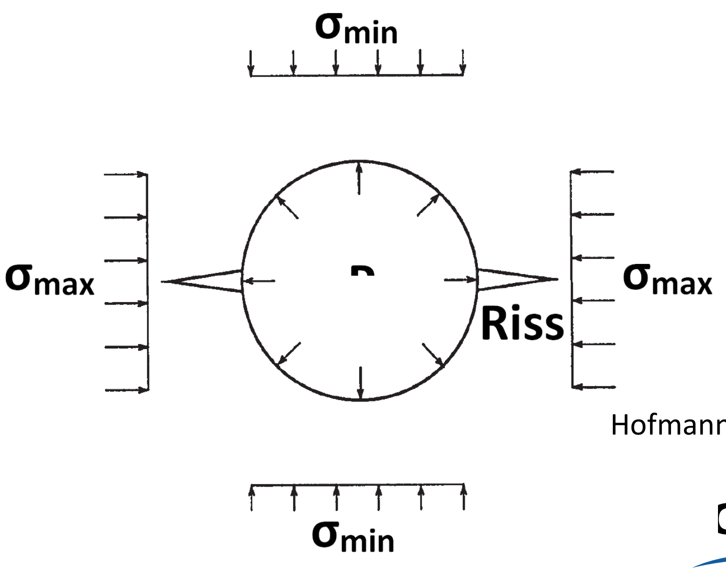
Stress field

Properties
- Stress magnitudes
- Stress directions
- Stress gradients
- Pressure



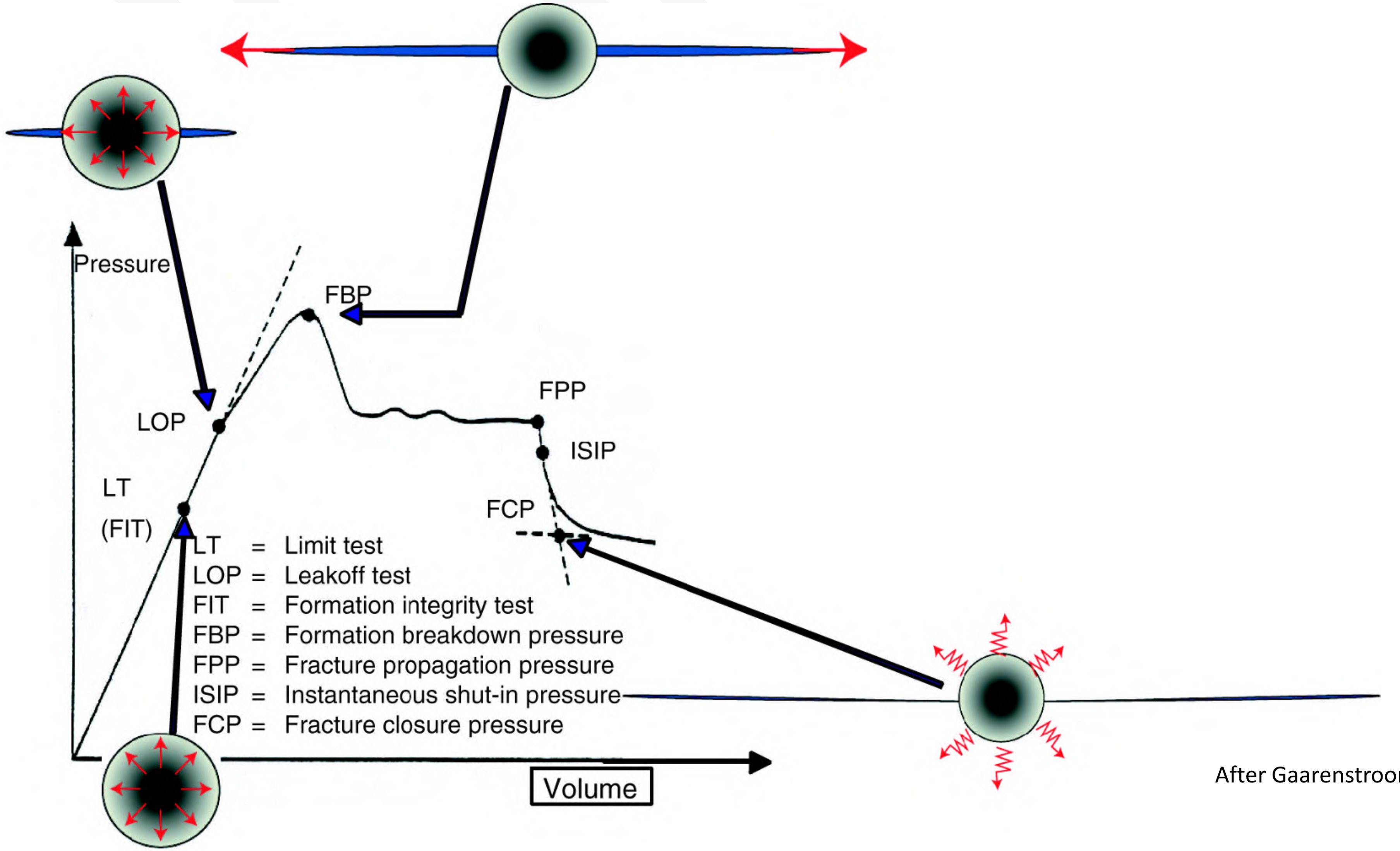
Exploration
- SV: Density log
- Sh: Minifrac/LOT
- Orientations:
  - Breakouts
  - Tensile fractures
  - HF orientations
  - Focal mechanisms
  - Shear velocity anisotropy
  - Geological indicators
- SH: constrained based on the parameters above
- P: direct measurement

Implications
- Fracture growth directions
- Containment
- Critical pressures for fracture opening/ shearing/closure
- Active/inactive faults
- Shear failure potential



Hofmann (2012)

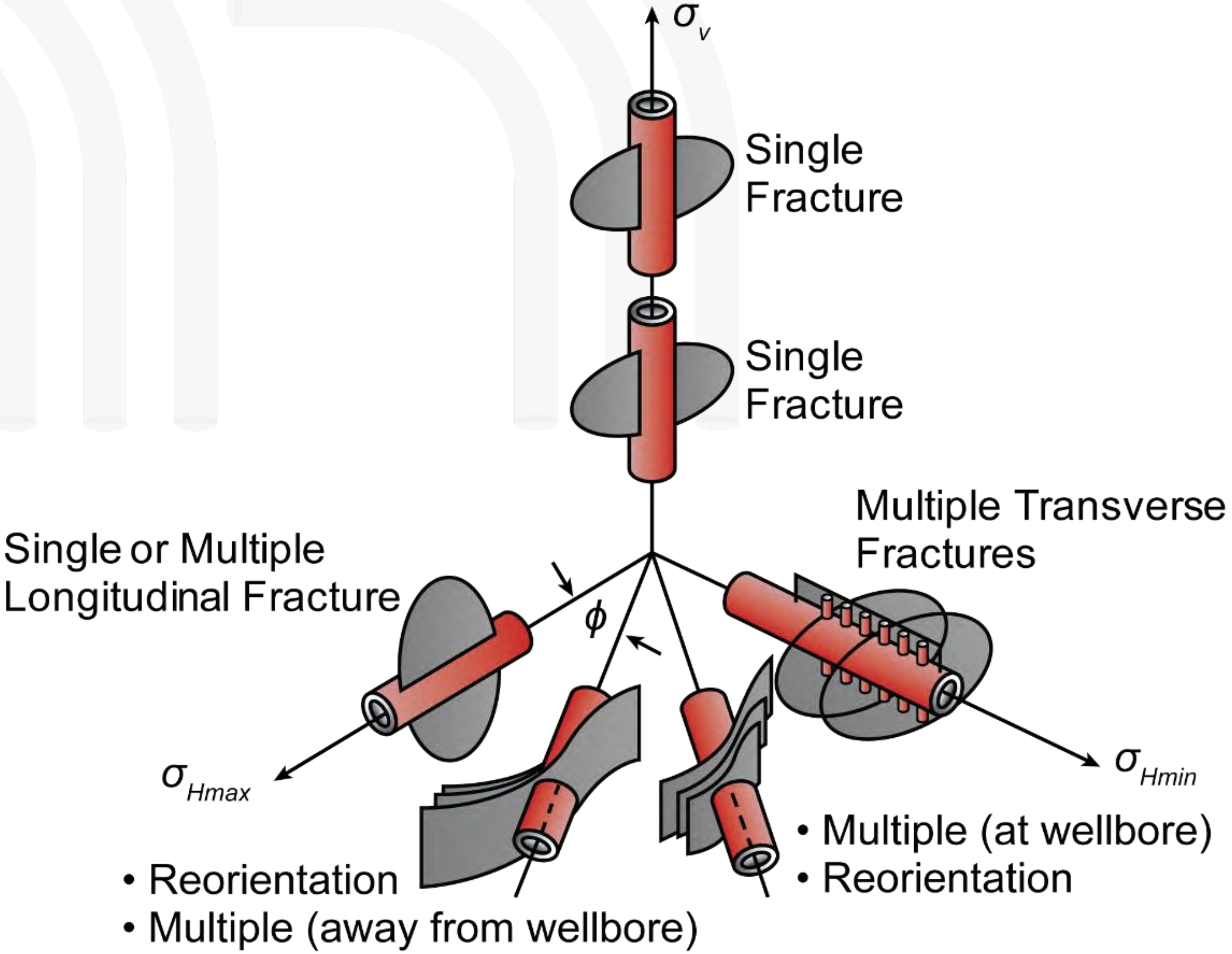
Stress field - downhole



After Gaarenstroom et al. (1993)

Leakoff test to determine minimum principle stress magnitude

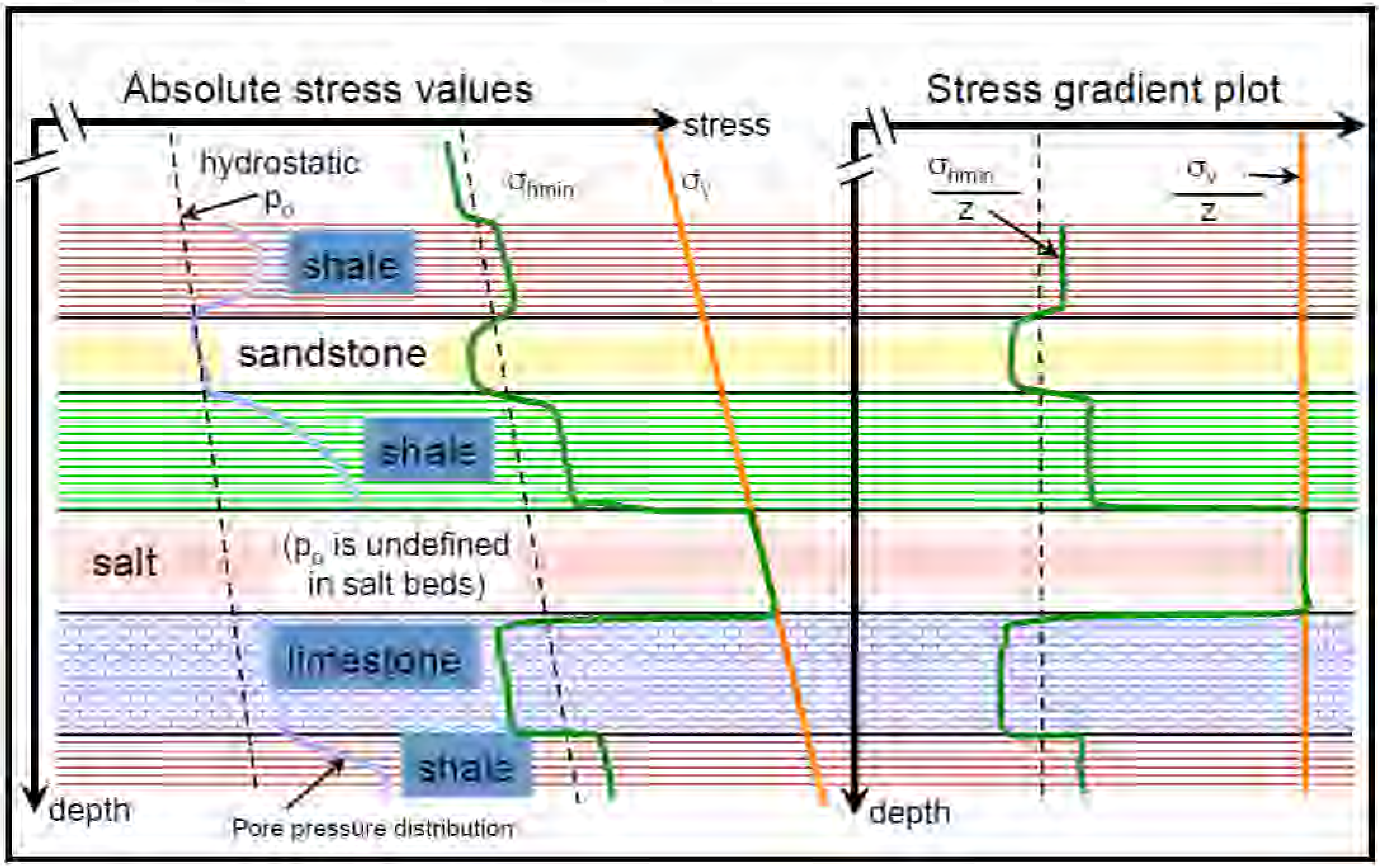
Stress field



EPT International

Influence of well path and stress on fracture growth

Stress field

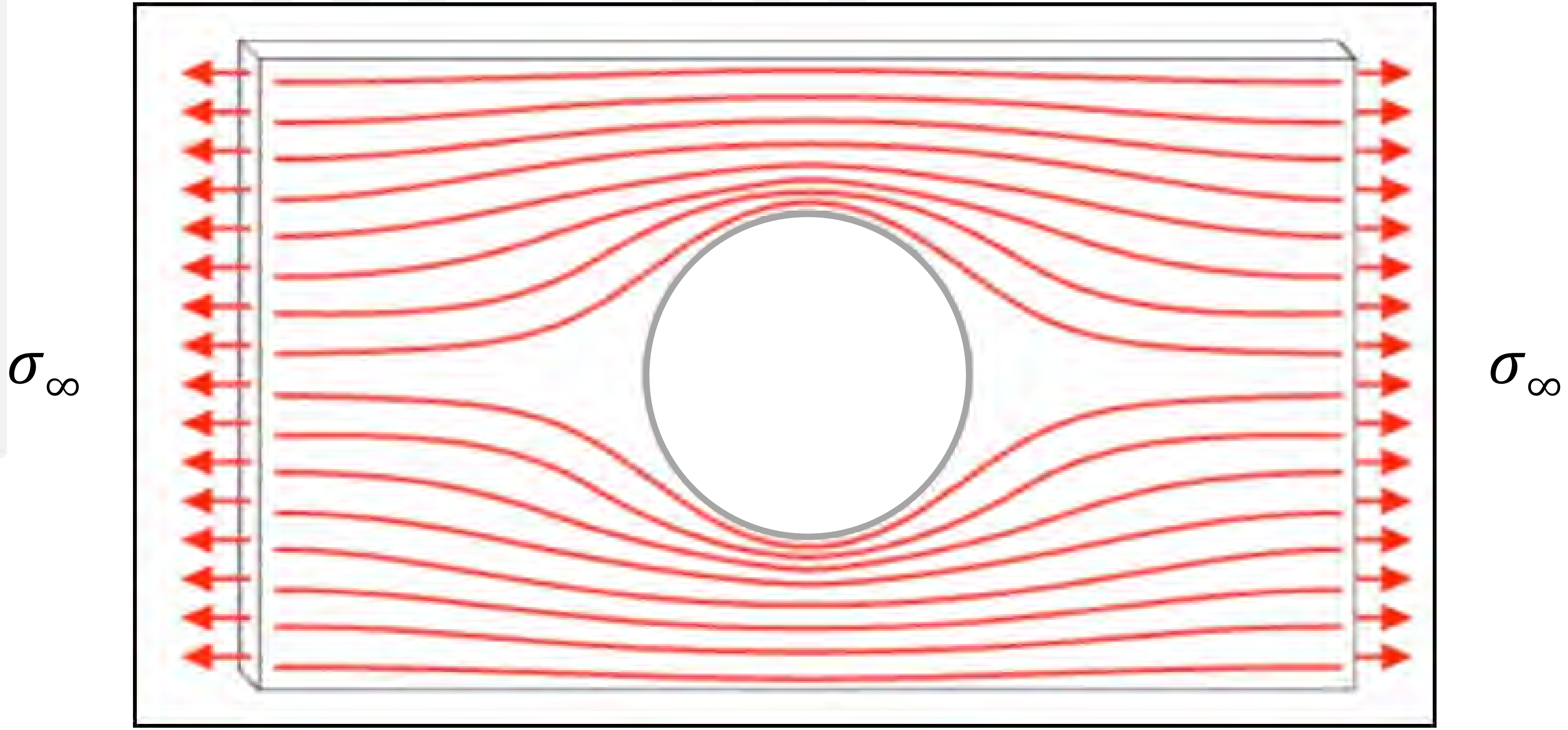


Dusseault

Stress variations with depth in different lithologies

EXERCISE

Stress Concentration Around Borehole



EXERCISE

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Wellbore Fracture Initiation: Impermeable Borehole Wall, $\sigma_h \neq \sigma_H$

$$p_w^{frac} = 3\sigma_h - \sigma_H - p + T_0$$

For the isotropic stress case $\sigma_h = \sigma_H$
simply replace $3\sigma_h - \sigma_H$ with $2\sigma_h$

$$p_w^{frac} = 2\sigma_h - p + T_0$$

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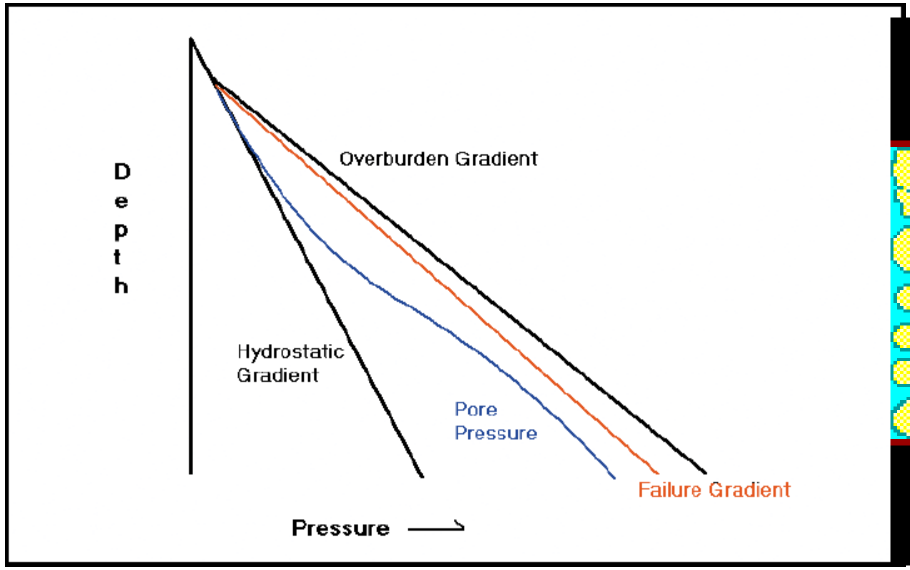
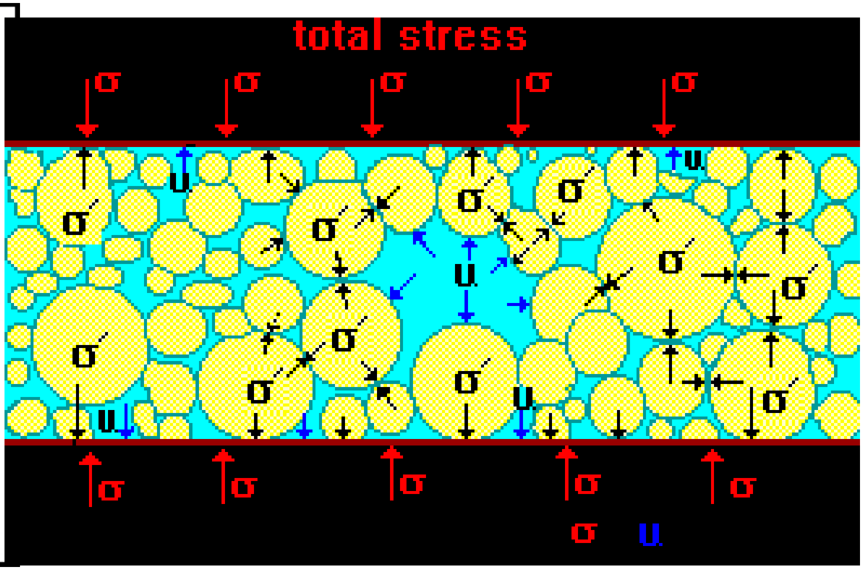
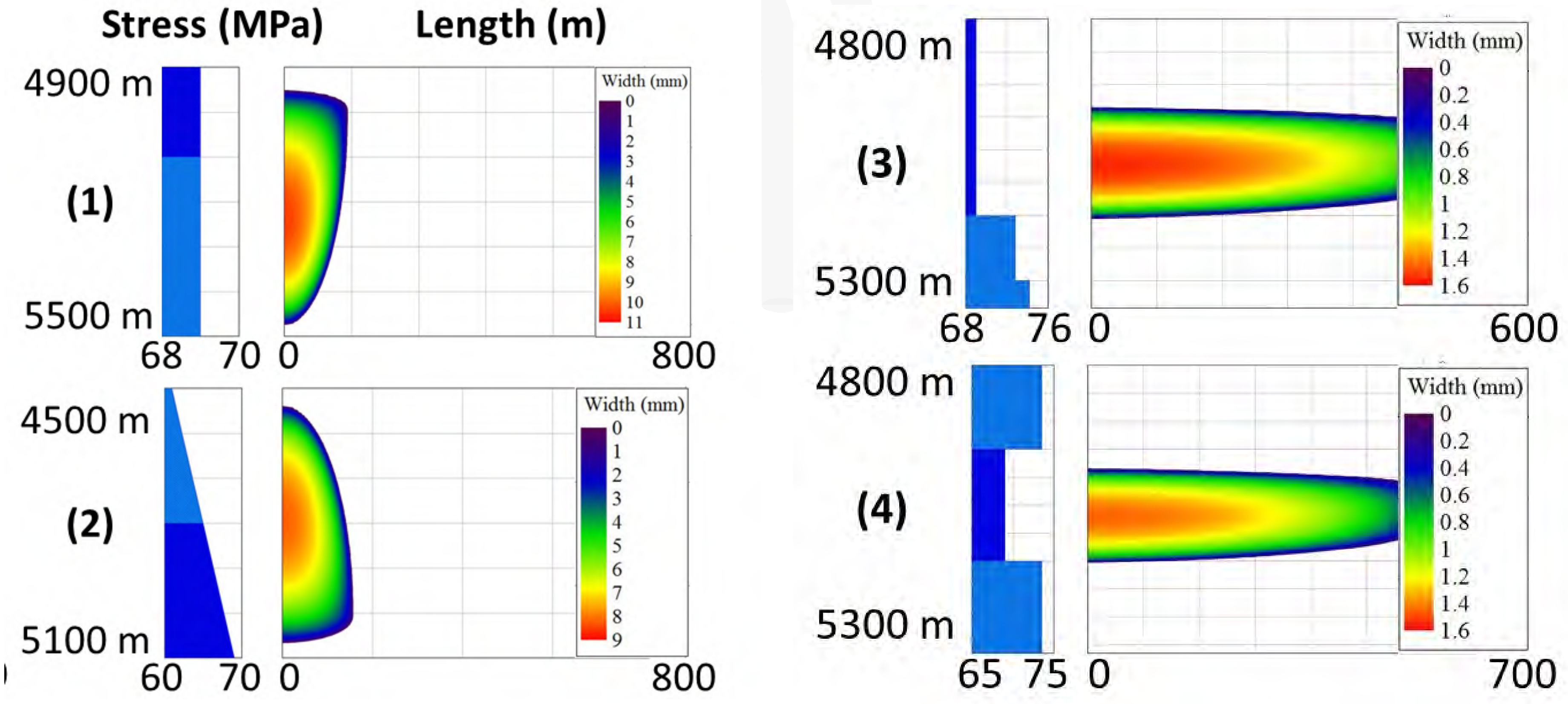
Pore pressure vs. stress

pore pressure	$p = \rho g h + p_0$
vertical stress (overburden)	$\sigma_V = \rho_s g h$
mean stress	$\sigma = (\sigma_V + \sigma_H + \sigma_h)/3$
effective stress (Terzaghi, 1936)	$\sigma_{eff} = \sigma - p$





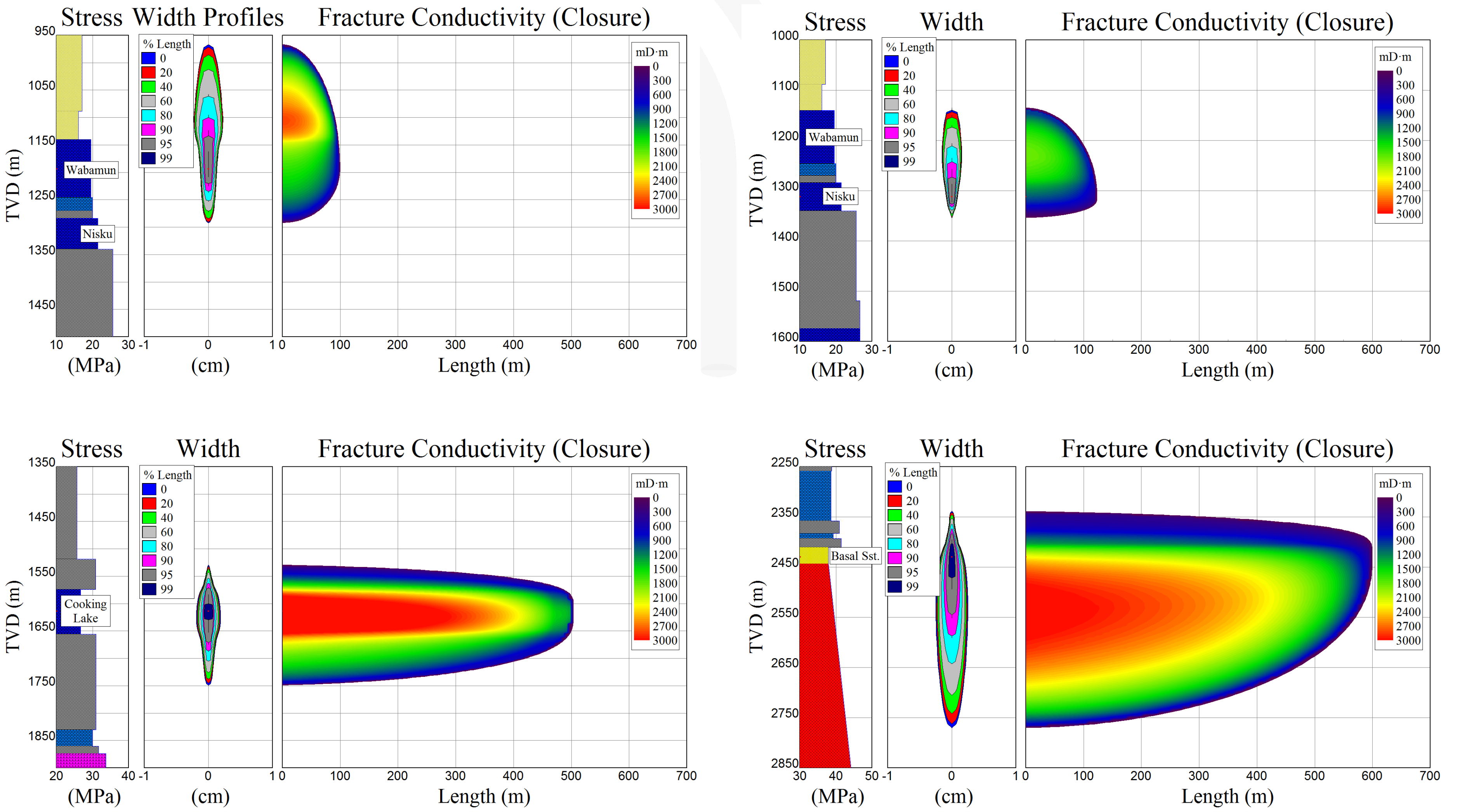
Stress field



Hofmann et al. (2014)

Fracture height growth containment due to stress barriers

Geology - Stratigraphy



Hofmann et al. (2014)

Different fracture geometries in different target horizons

Rock properties - hydraulic

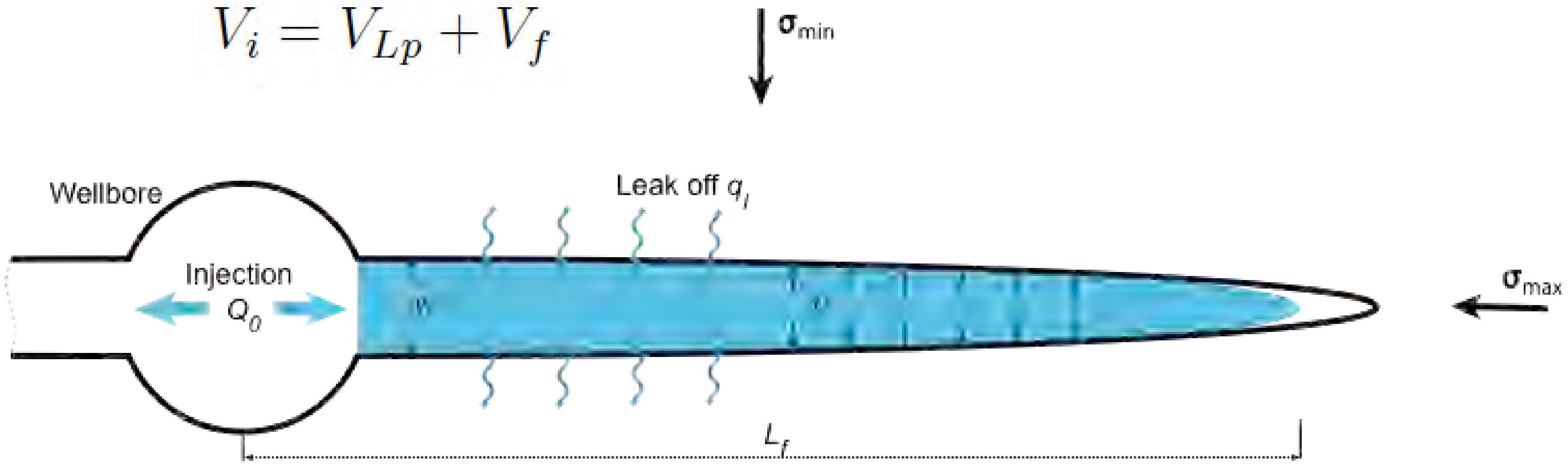
Properties
- Permeability
- Porosity
- Which fractures are conductive

Exploration
- Well logs
- Well tests
- Core samples
- Production data

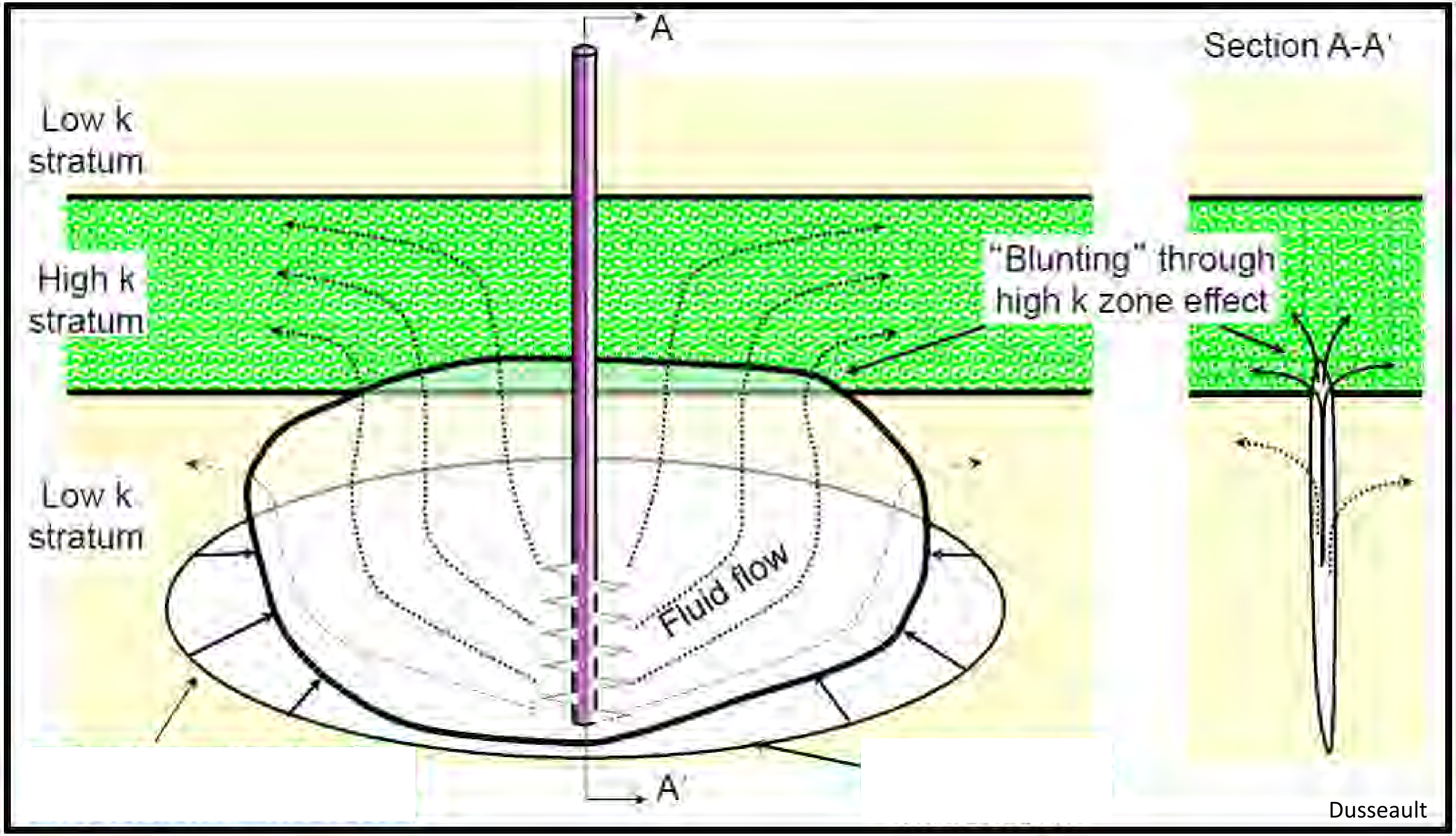
Implications
- Fluid leak-off
- Fluid loss
- Frac fluid volume
- Zonal isolations
- Leak-off barriers

Mass balance:

$$V_i = V_{Lp} + V_f$$



Rock properties - hydraulic



Leak-off barrier

Rock properties - mechanical

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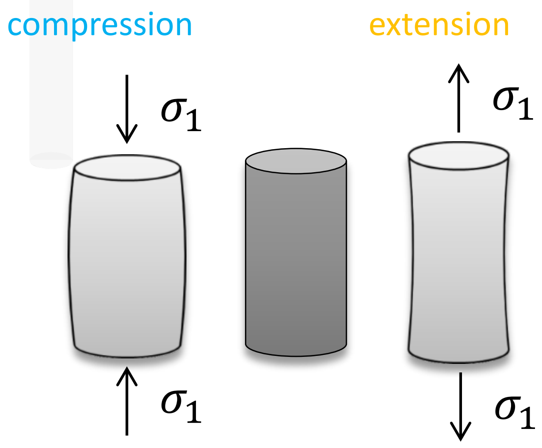
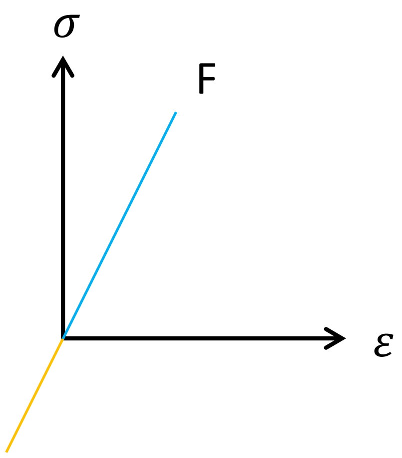
<u>Properties</u>
- Young's modulus
- UCS
- Tensile strength
- Cohesion
- Friction angle
- ...

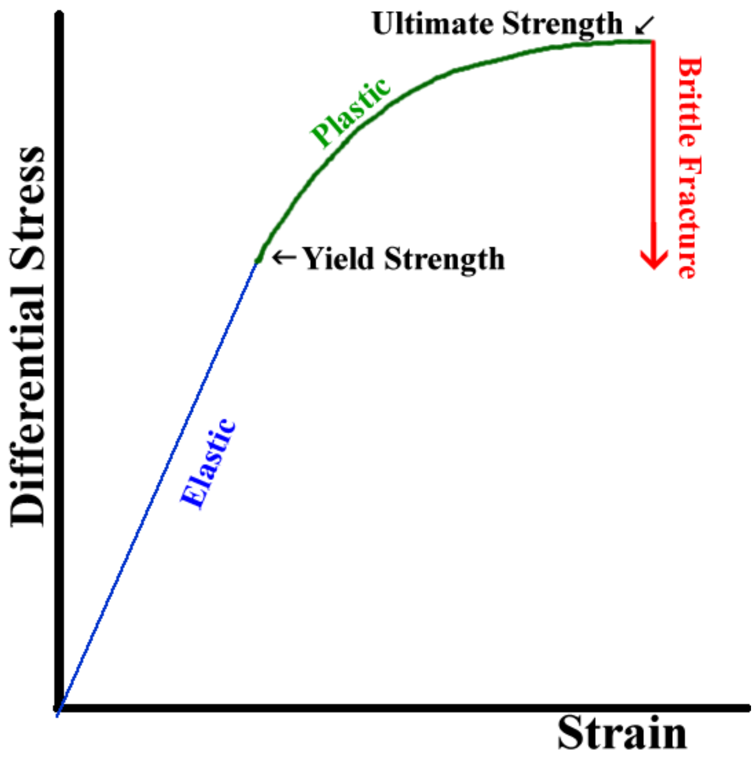
<u>Exploration</u>
- Core samples (lab tests)
- Well logs

<u>Implications</u>
- Fracture aperture
- Self-propping
- Fracture mechanics

uniaxial







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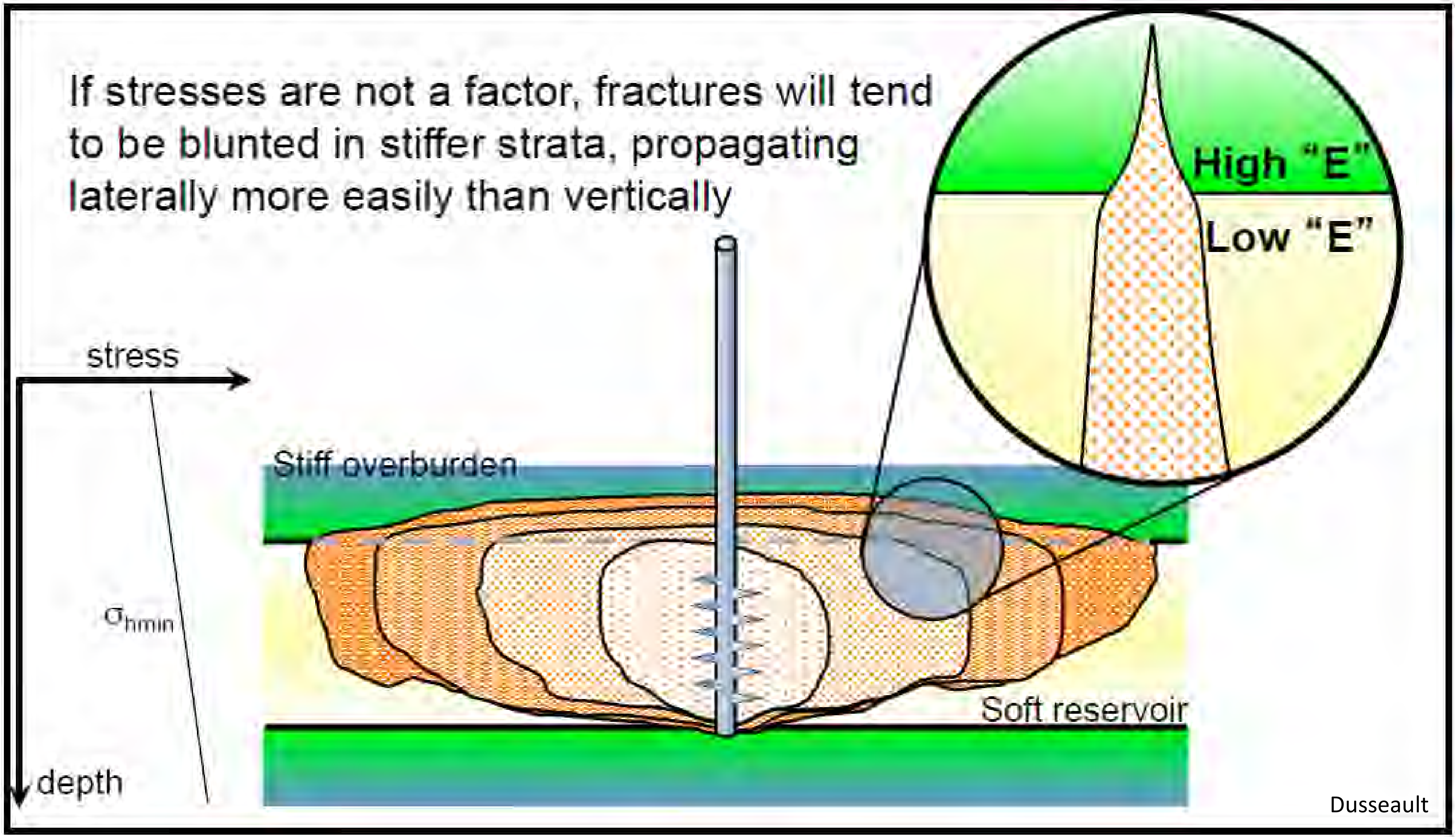
Rock properties - mechanical



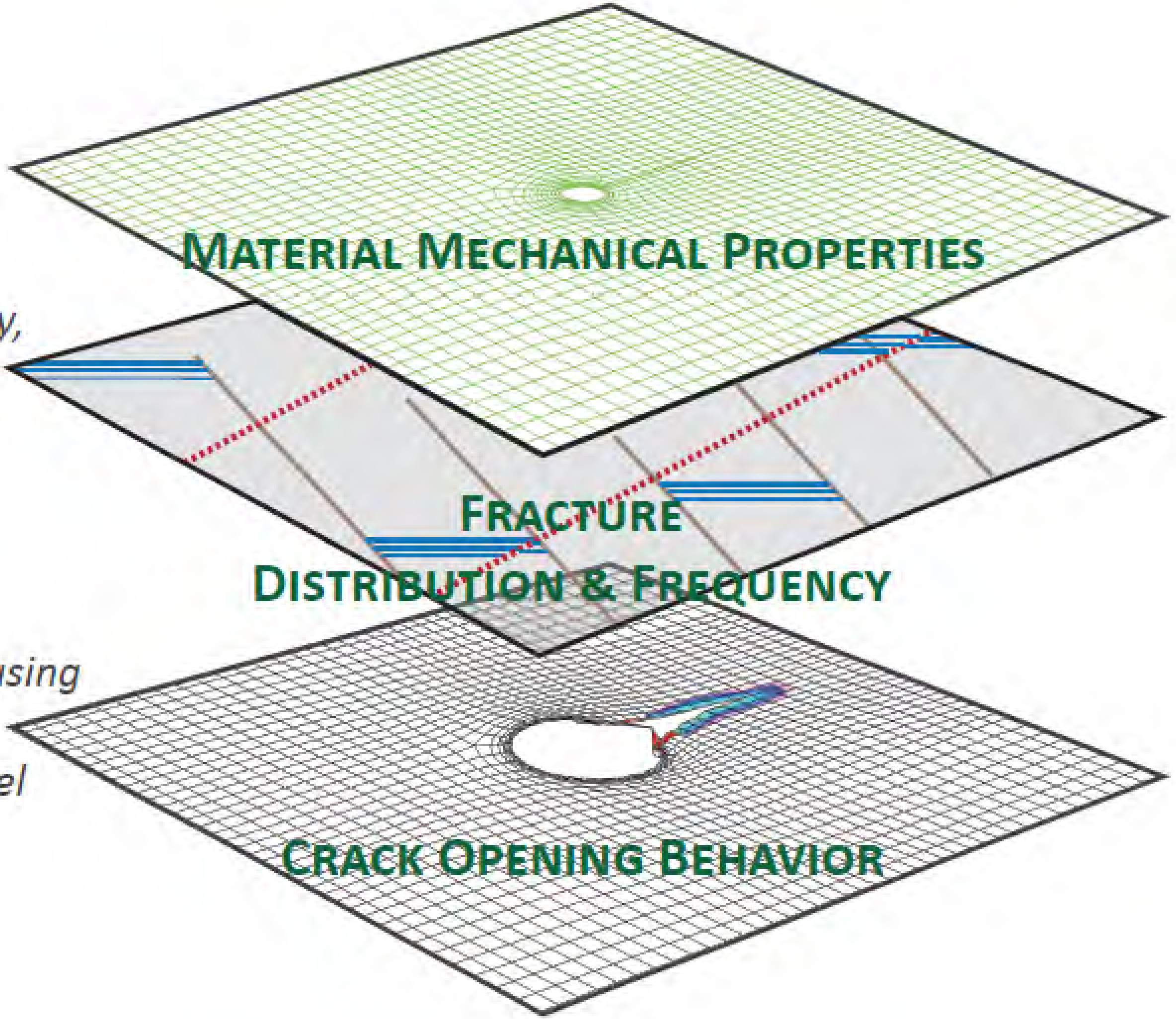
Stiffness governs fracture aperture during treatment

Key Components for EGS

Rock properties — *Varying rock Material Properties (E, v)*

Fracture networks — *Varying fracture geometry, frequency, and interactions*

Stress — *The fracture propagation is calculated using the non-local damage approach, combined with a cohesive-zone model*



Thank you very much for your attention

MEET

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