Fractures and hydrothermal alterations : a review of fluid pathways for geothermal applications

Part 1 – Fracture networks, various examples

MEET Project – Geothermal Winter School – February 2021

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792037

Outlines

Part 1- Why study fracture networks?

Part 2- How to identify fracture networks?

- A- Field work
- B- Well logs
- C- Analogues
- D-Modelling

Part 3- How to characterize fracture networks?

- A- Fractal analysis
- B- Statistics
- C- Petrophysical properties

Conclusion

Thanks for attention

1-Why study fracture networks?

Fractures= pathways for fluids, interconnected

Evidence from surface: weathering

Here, fluid= rainwater


Staple Tor, Dartmoor (UK)

Subsurface, fluids:

*rainwater

*sea water

*magmatic fluids

Temperature gradient

↓

Hot fluid harnessed for geothermal production

↓

Flows through fractures and wall-rocks

hydrothermal alteration (R. Hébert)

2-How to identify fracture networks?

A – Field work

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GEOTREF

Guadeloupe (Lesser Antilles) andésite

Joints
m-scale

↓

Thin section
µm-scale

Navelot et al., 2018

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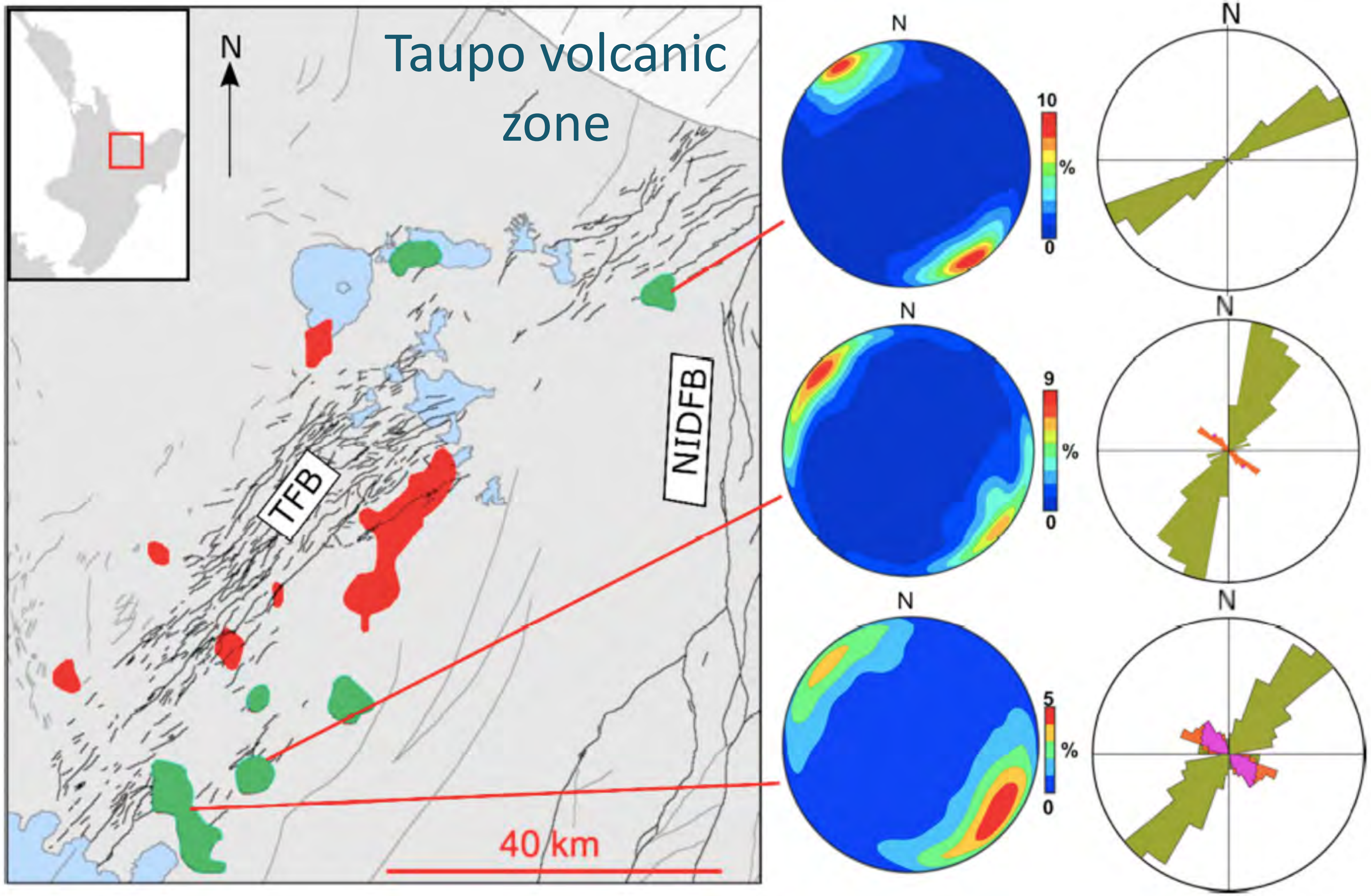
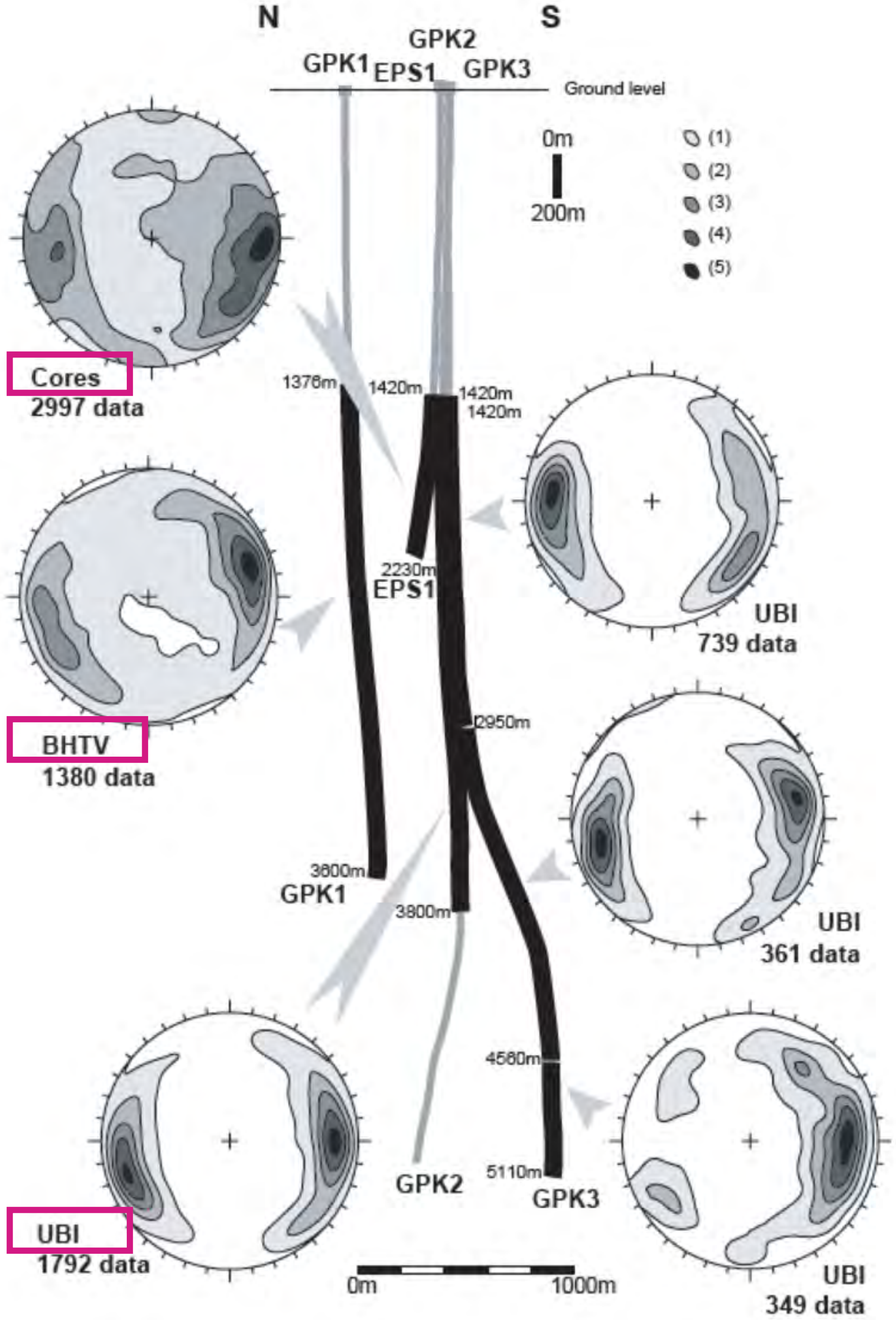
Inside geothermal reservoirs, fractures cannot be seen directly



Faults and fractures km-scale

McNamara et al., 2017

B – Well



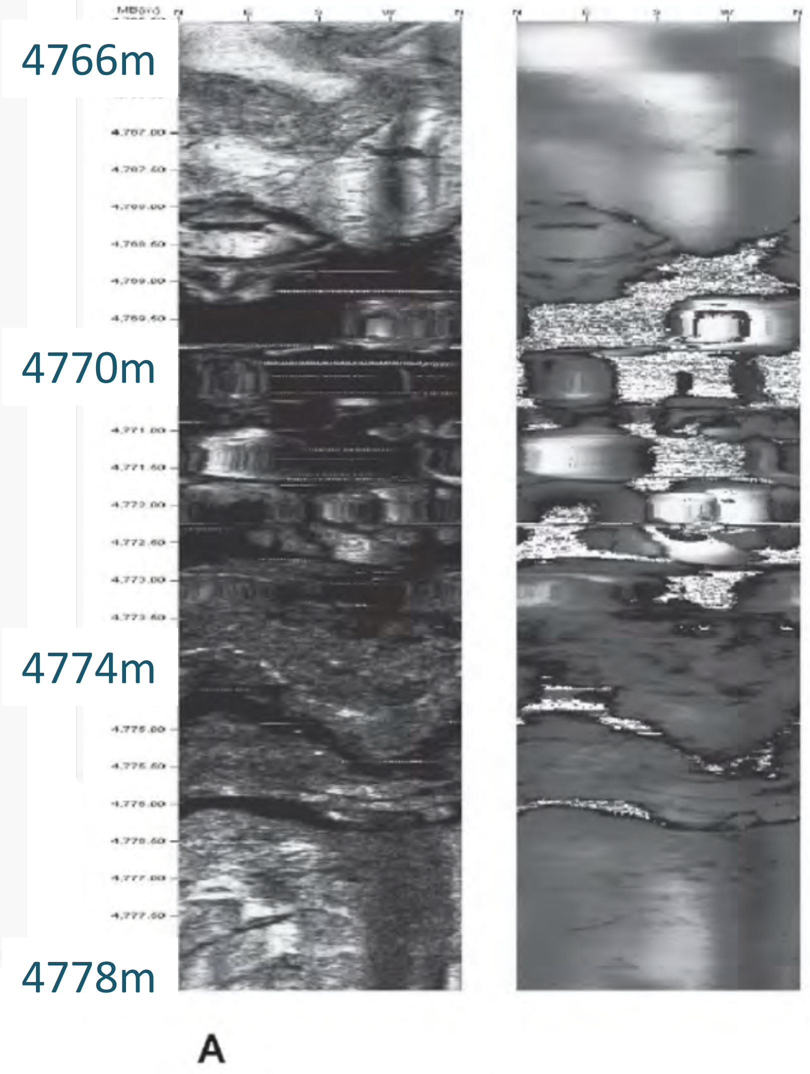
Soultz-sous-Forêts, Rhine Graben (France)

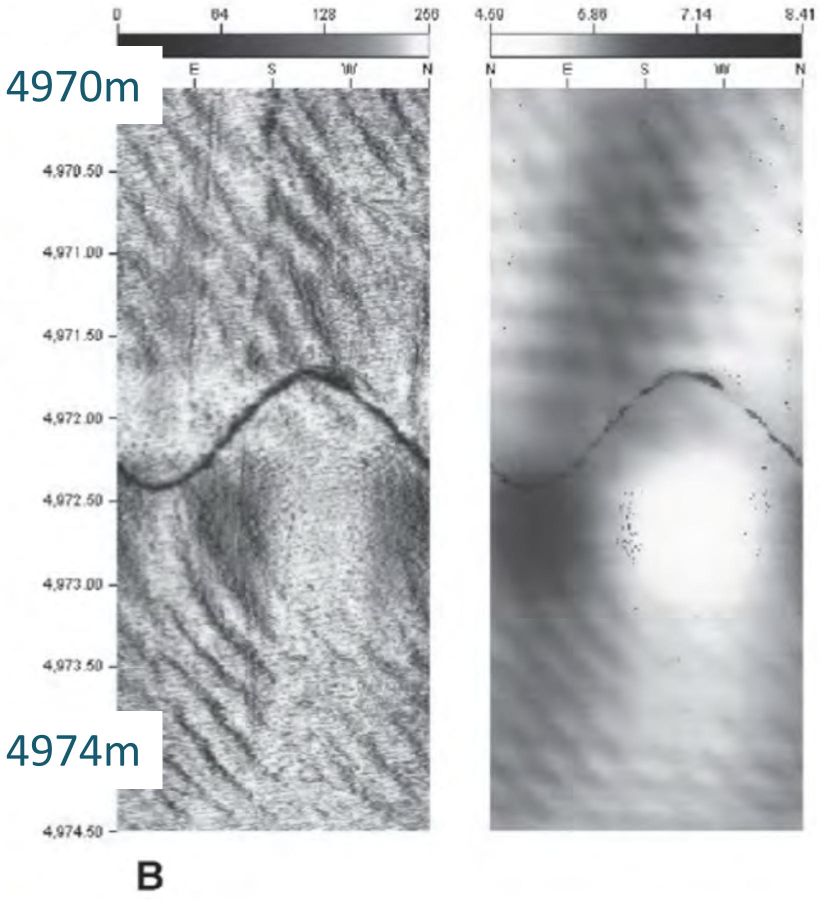
EGS site : electricity, 1.5 Mwe (geothermies.fr)

3 deep wells: GPK-2, GPK-3 and GPK-4 (only 2 in 2004)

Dezayes et al., 2004, GRC

Soultz-sous-Forêts





GPK-3 UBI

Complex zone (A)
63-78 % of flow
Hydraulic stimulation

Single fracture (B)
4% of flow
Hydraulic stimulation

Dezayes et al., 2004, GRC

New Zealand, Taupo volcanic zone

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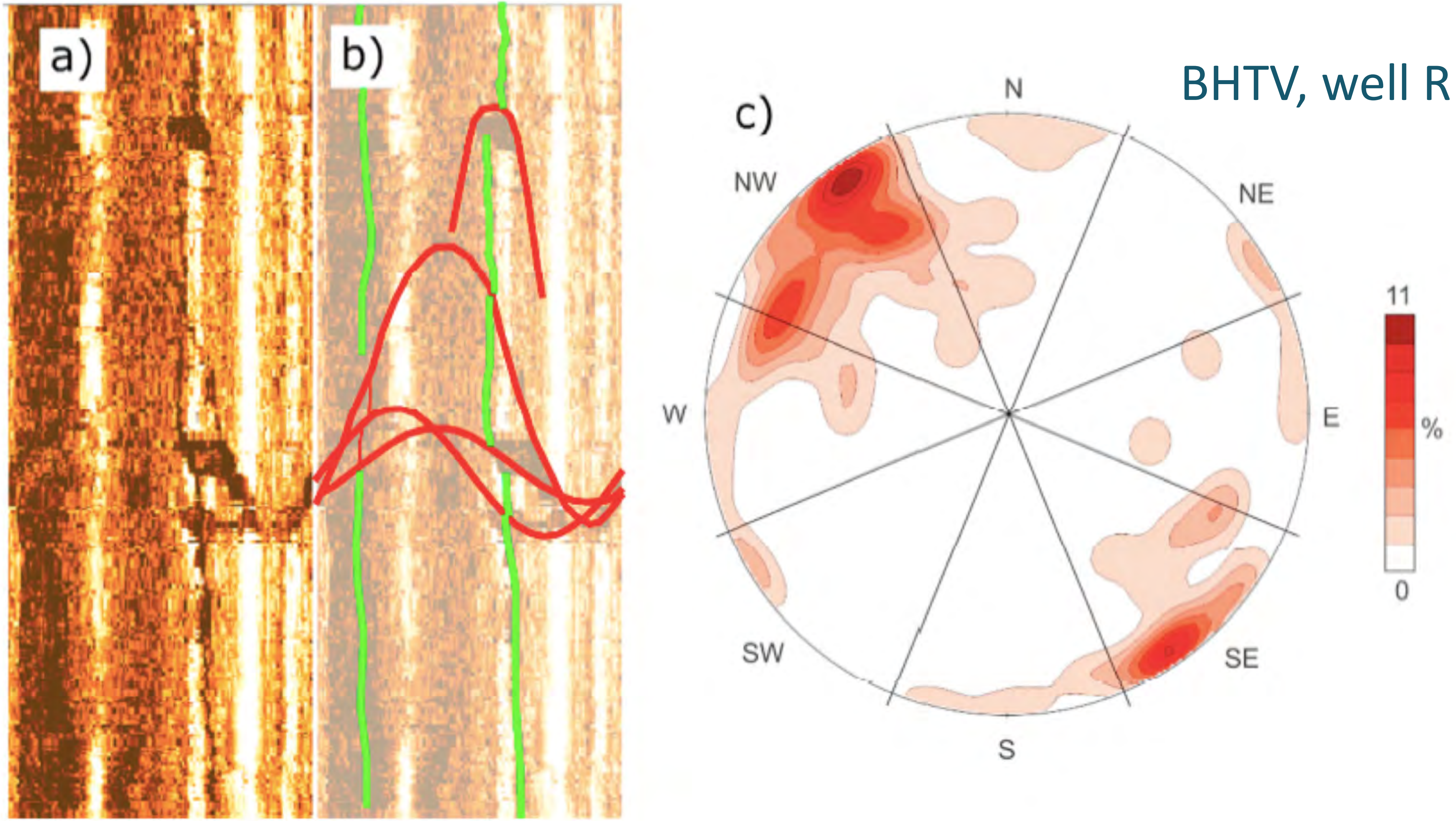
BHTV, well RK32



McNamara et al., 2017

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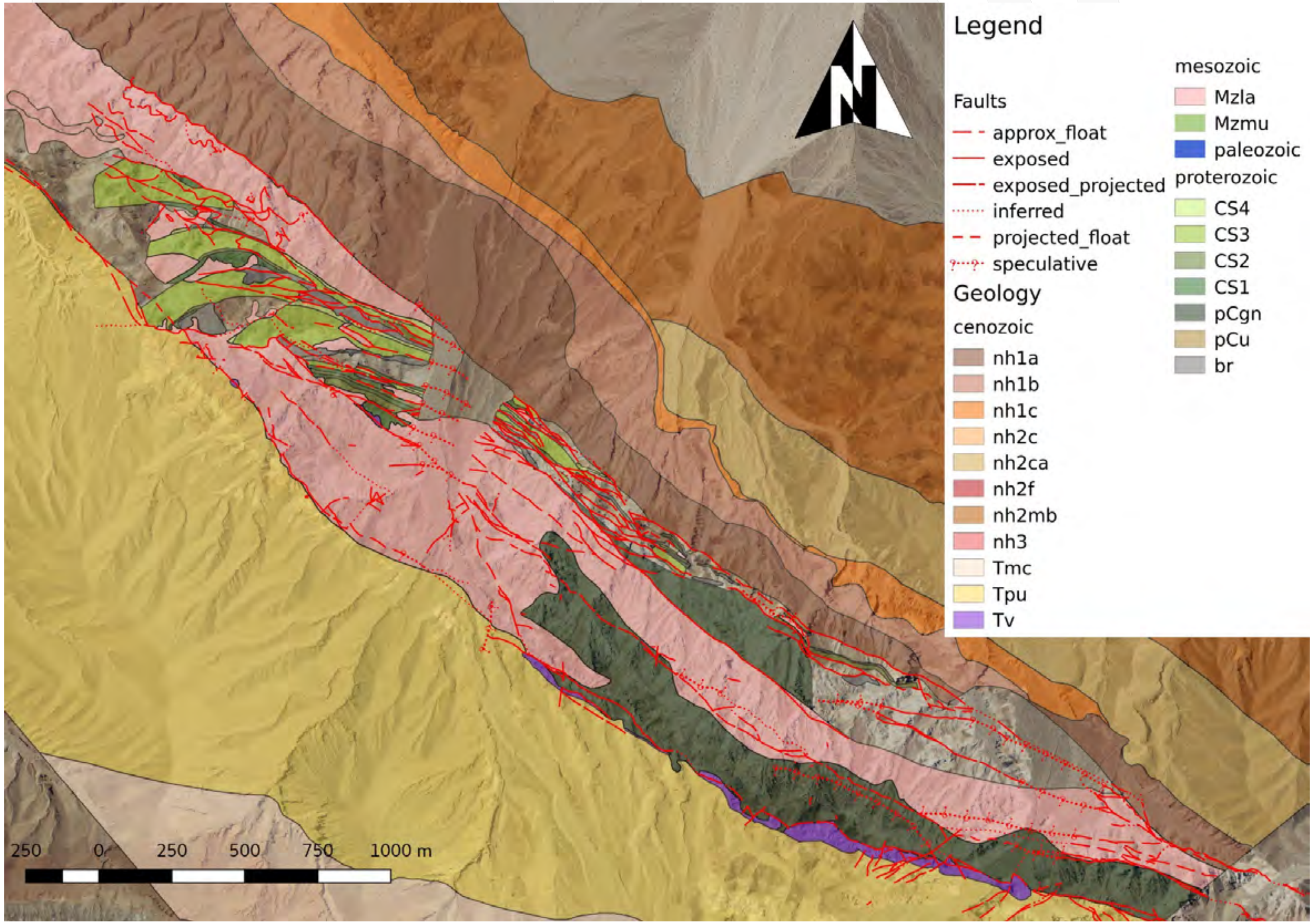
C - Analogues



Talk by G. Trullenque

J. Klee, MEET PhD

D - Modelling

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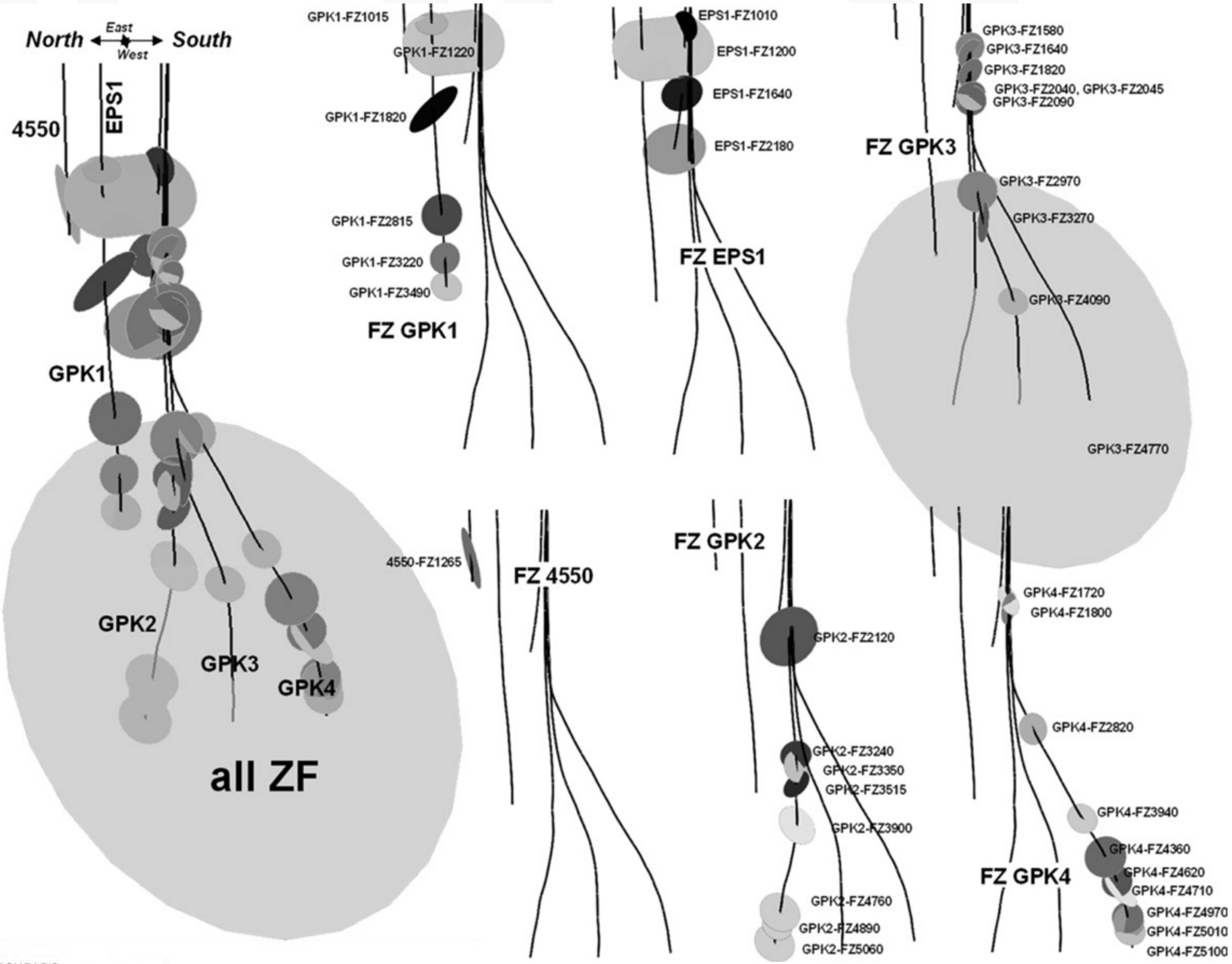

Soultz-sous-Forêts

Sausse et al., 2010

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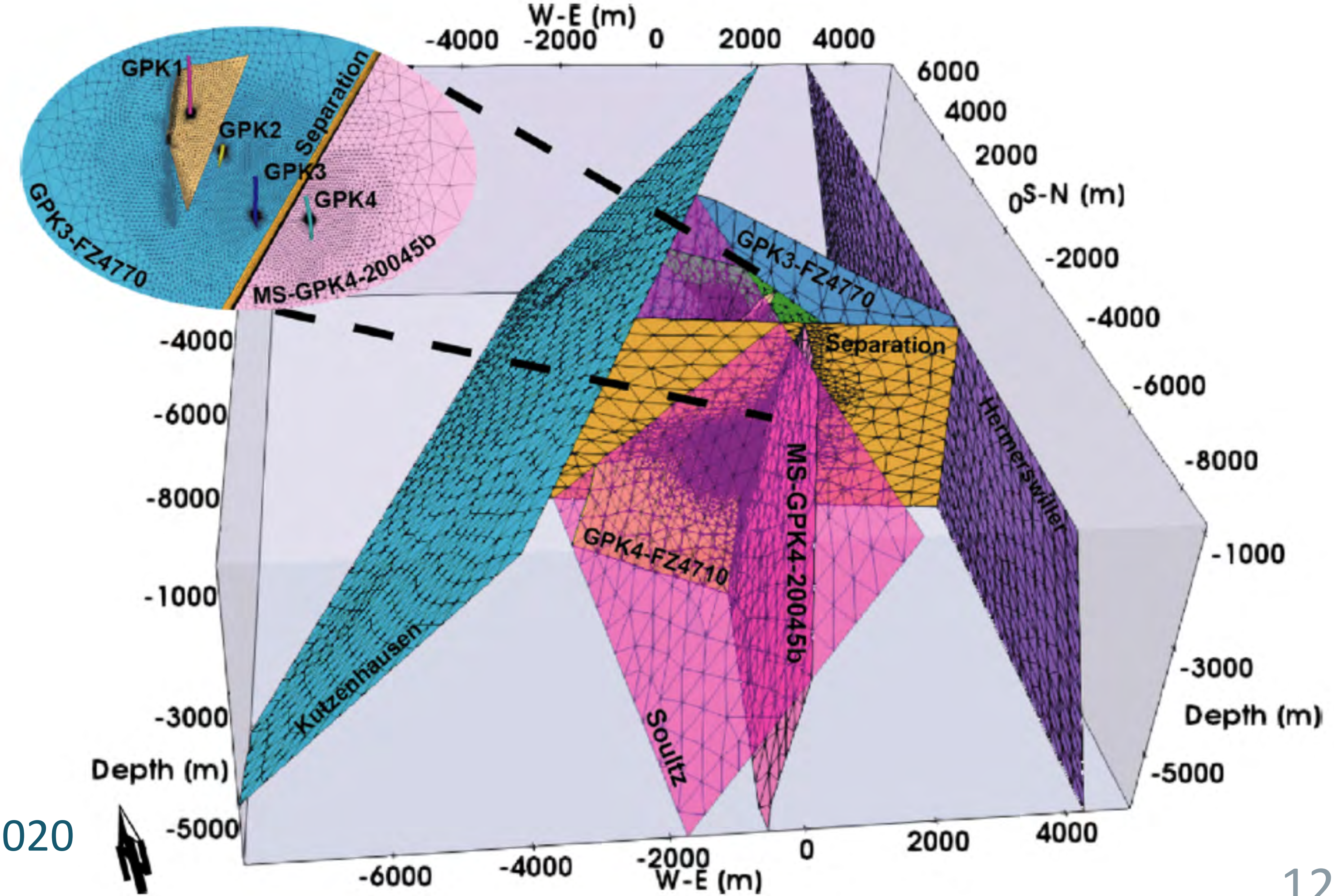
Fluid flow simulation



Egert et al., 2020

3-How to characterize fracture networks?

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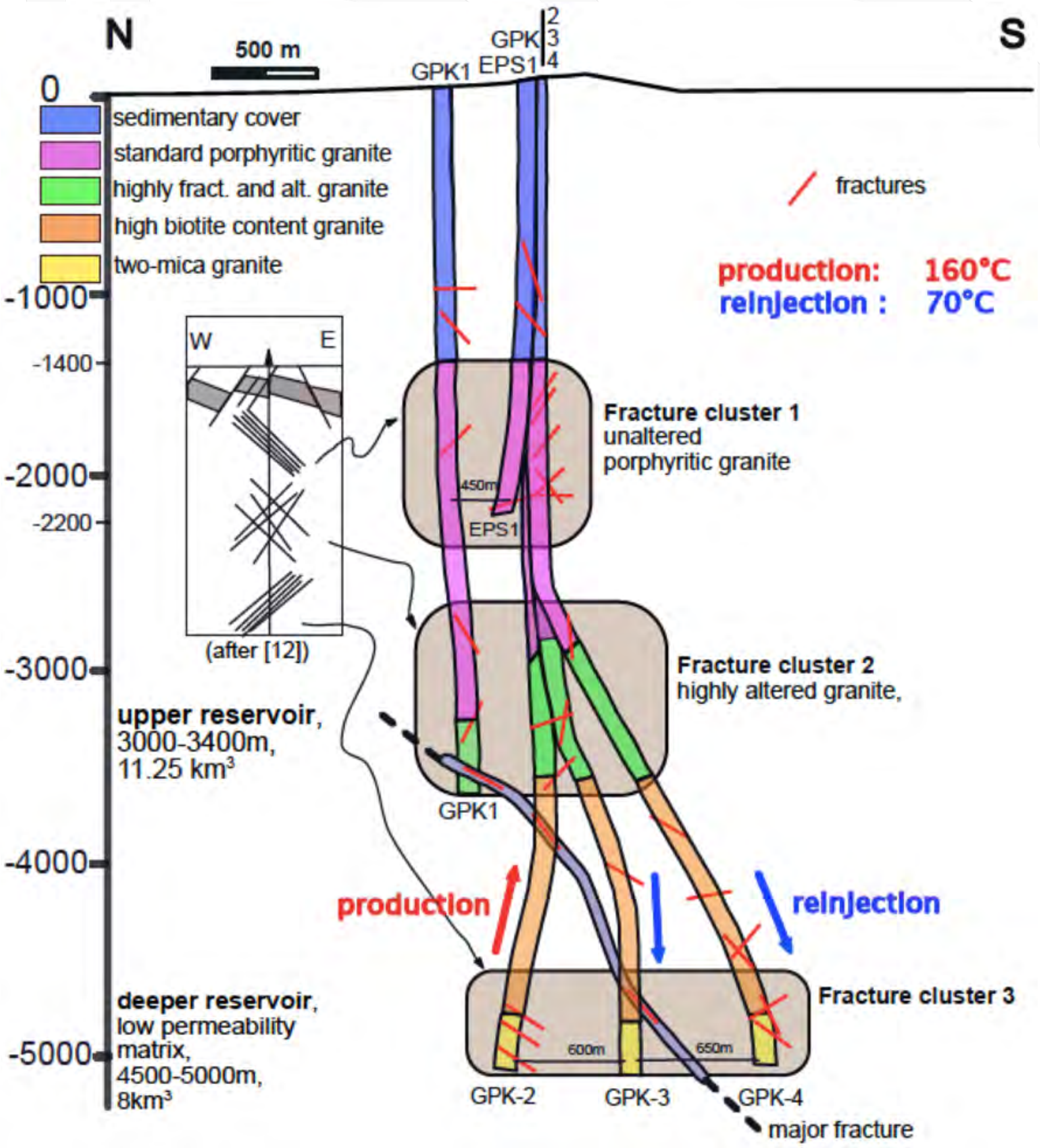

Soultz-sous-Forêts EGS site
Granite

Fractures grouped into clusters separated by non-fractured zones

⬇

Fractal analysis

Ledésert and Hébert, 2020
After Dezayes et al., 2004

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3-How to characterize fracture networks?

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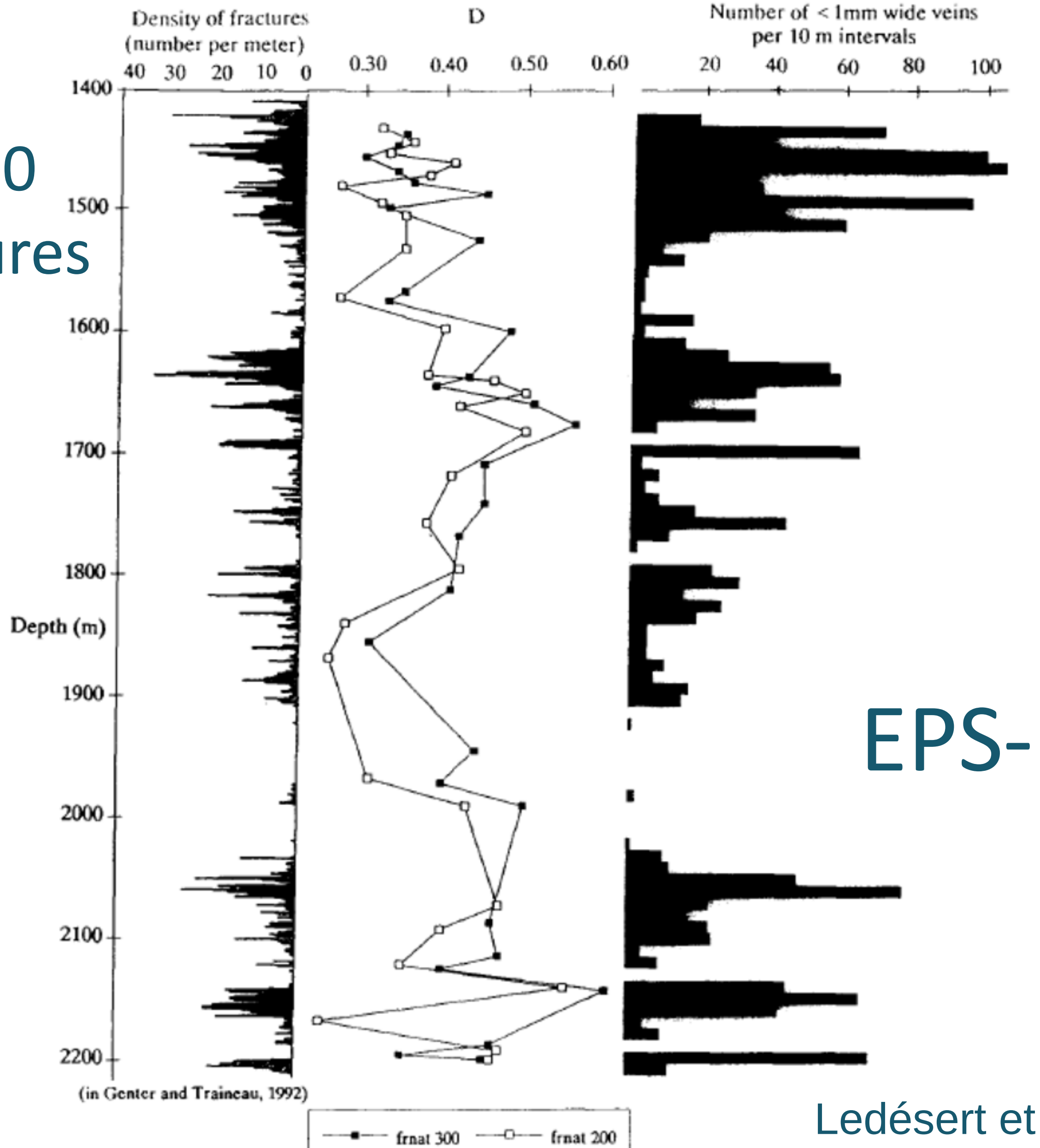
3000 fractures



EPS-1 well

Ledésert et al., 1993

A – Fractal analysis

Fractures grouped into clusters separated by non-fractured zones

Fractal analysis for quantification and prediction

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Analysis line : probability of intersection of fractures

x : variable characterizing the length of measure unit

P : probability

D: Fractal dimension, between 0 and 1

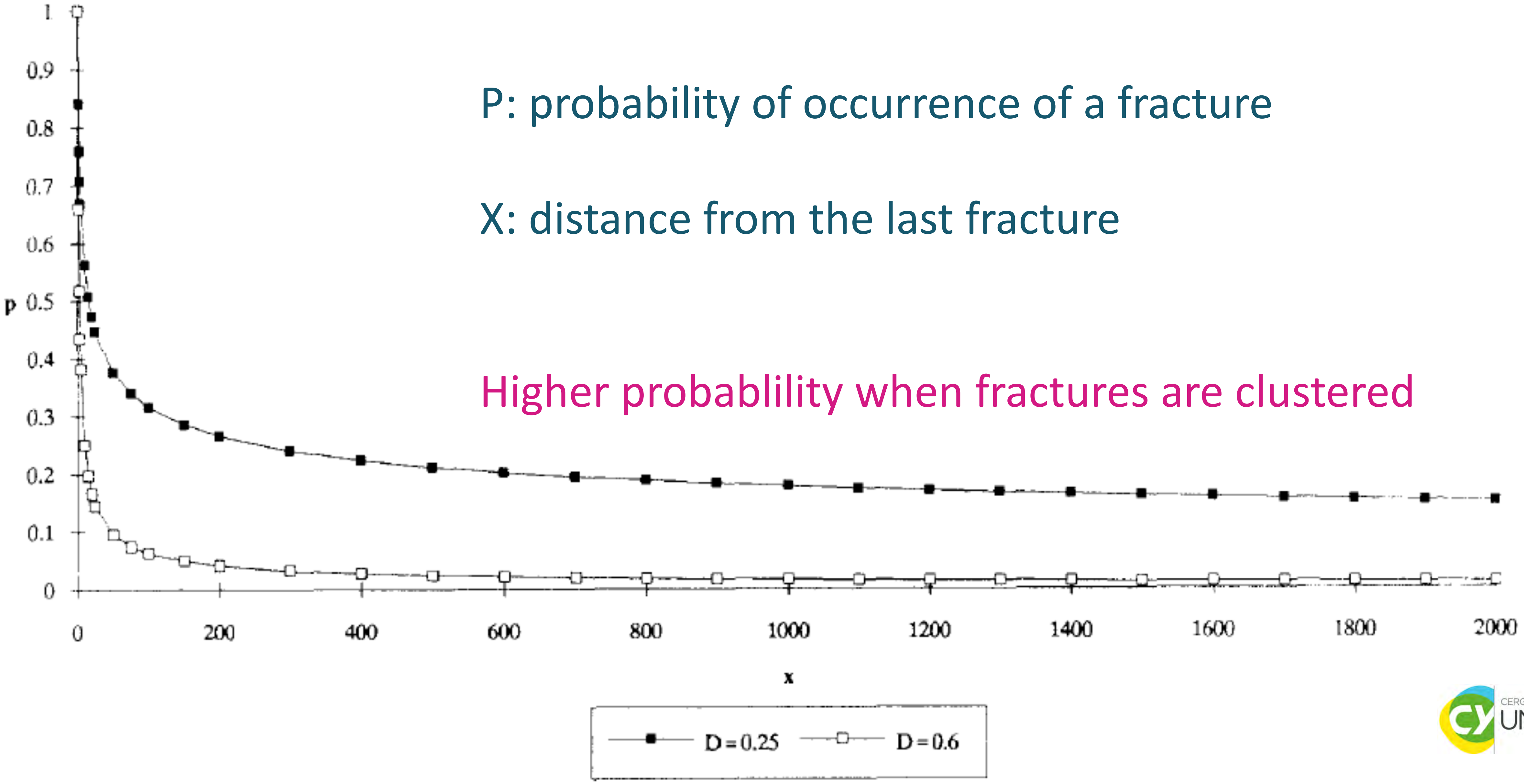
$P= x^{-D}$

Quantification:

Low D : clustered events, heterogeneous distribution along the well

High D : homogeneous distribution

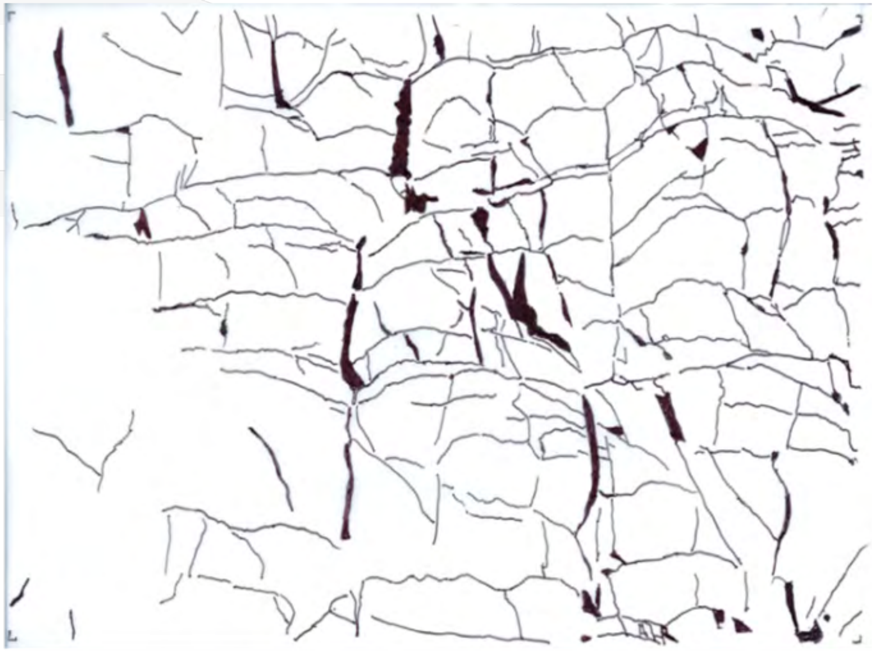
Prediction of fracture occurrence



P: probability of occurrence of a fracture

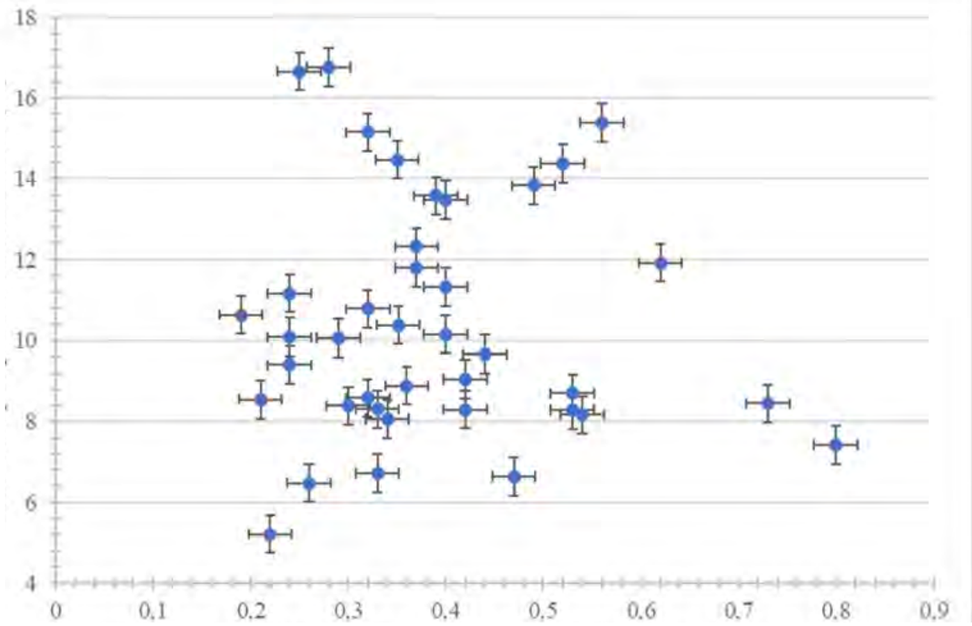
X: distance from the last fracture

Higher probablility when fractures are clustered



B – Statistics

GEOTREF



Surface area occupied by discontinuities (%)

Surfacic intensity of discontinuities P21 (cm/cm^2)

Guadeloupe (Lesser Antilles)

Andésite

Azzimani, 2019, MSc thesis

See Postdoc A. Chabani, MEET

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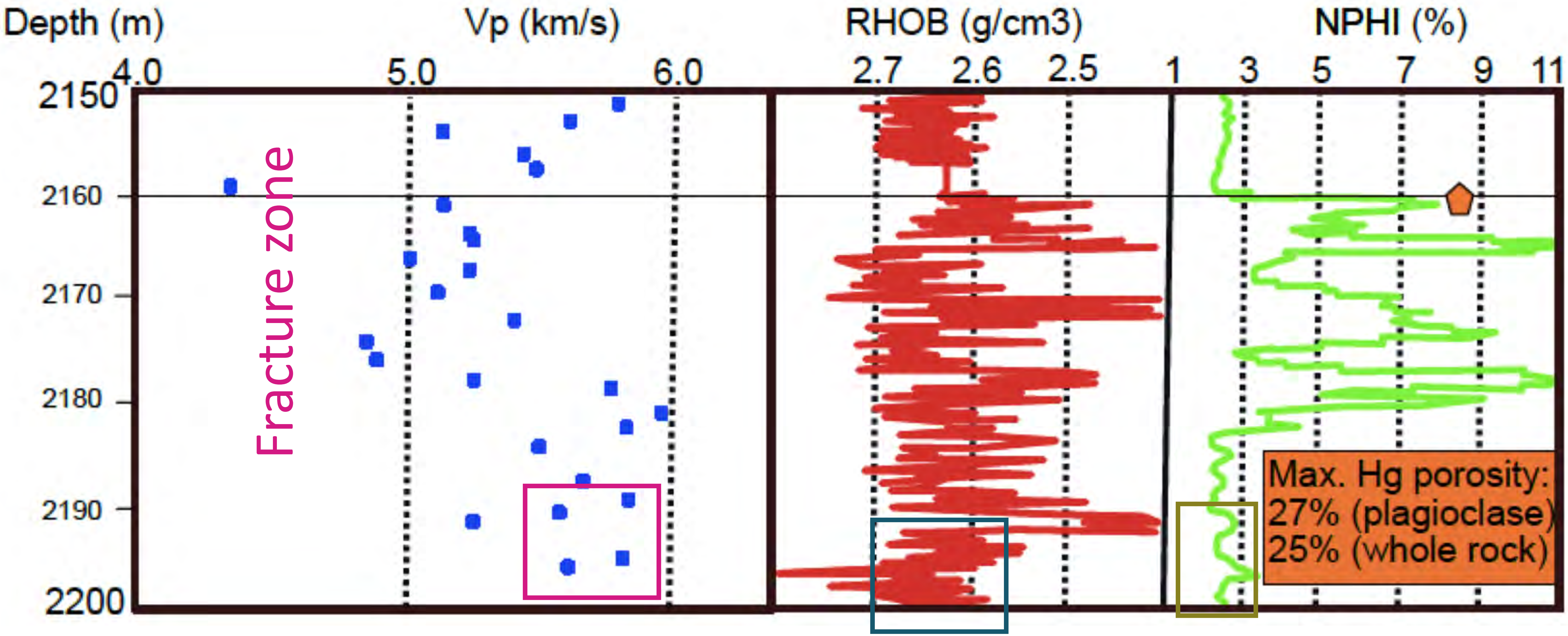
C – Petrophysical properties

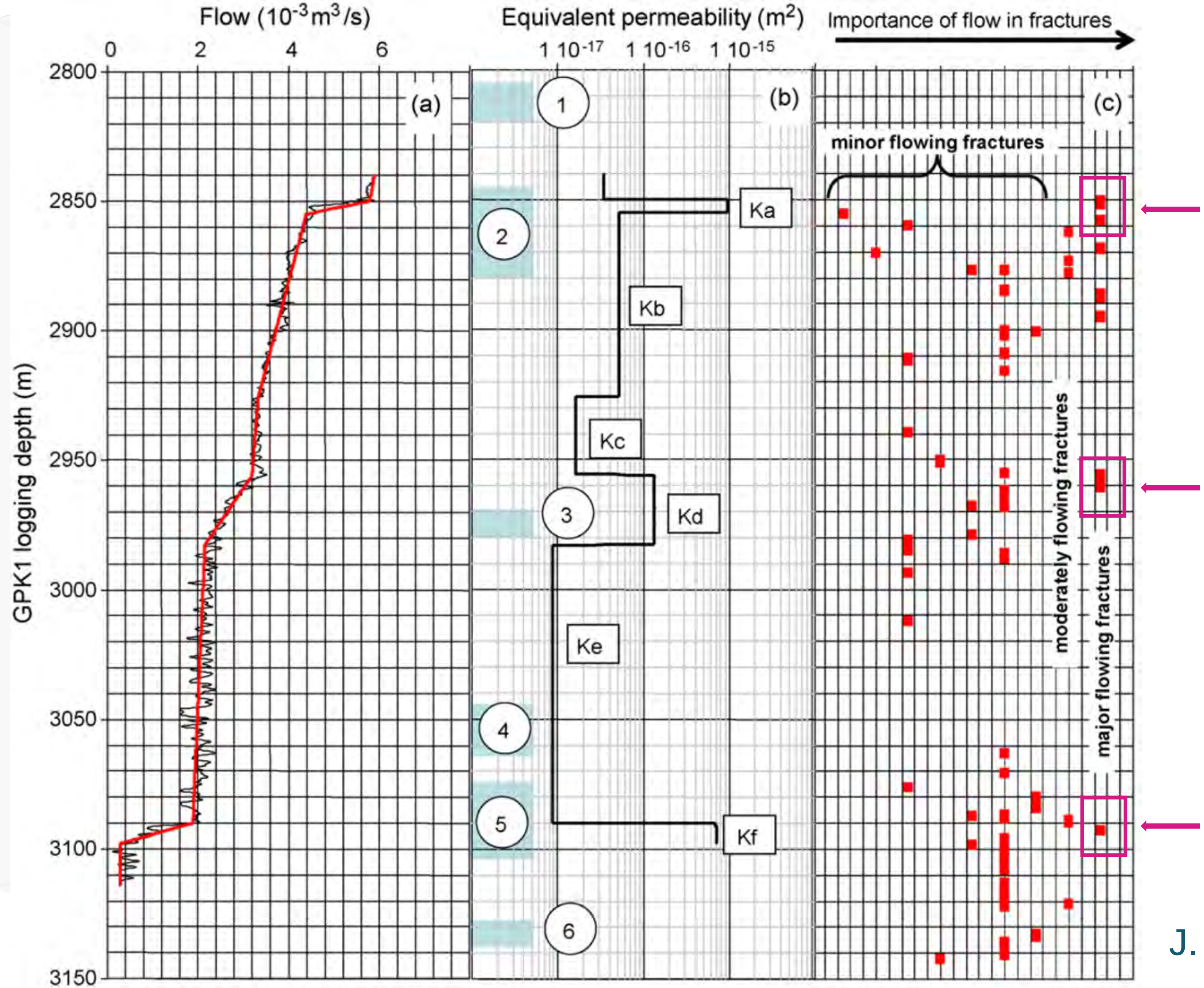
Soultz-sous-Forêts, granite

Fractured zone

EPS-1 well log



Ledésert and Hébert, 2020, Geosciences



Soultz-sous-Forêts

GPK-1 well

J. Sausse et al., 2006

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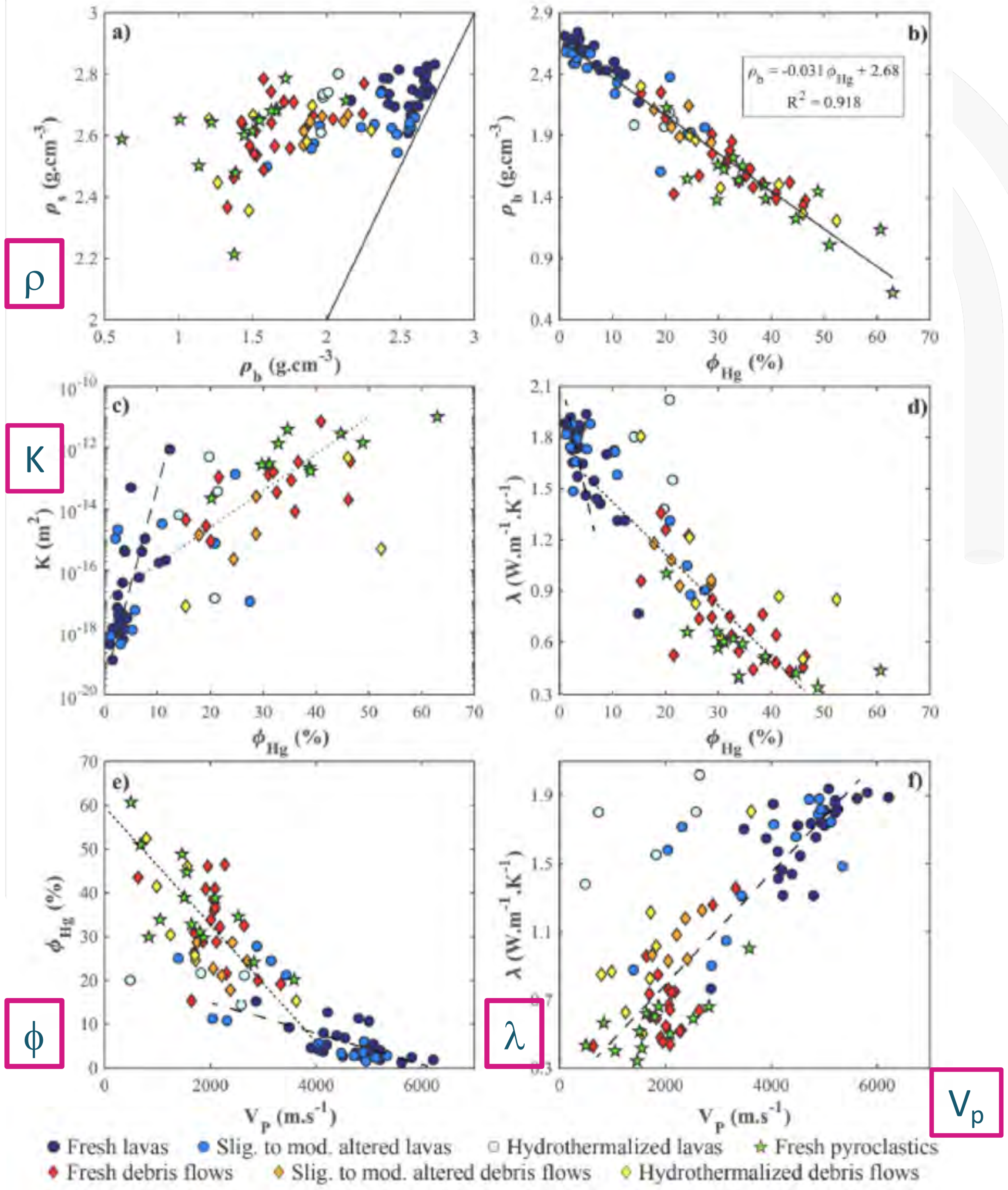

On samples in the lab:

Density

Permeability

Porosity

Thermal conductivity

P wave velocity

Combination of parameters

Correlations

Flow pathways

After Navelot et al., 2018

GEOTREF

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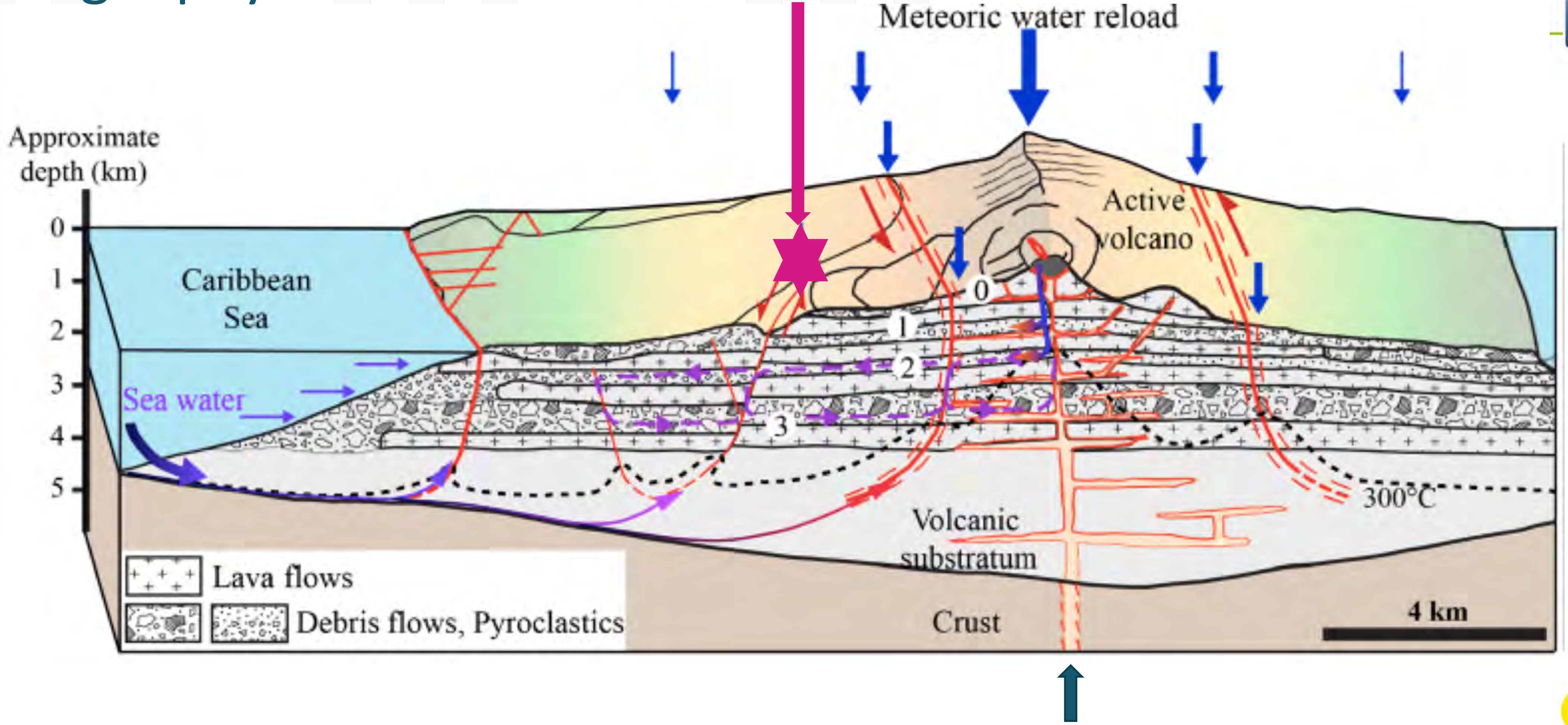
4- Conclusion

Example: Guadeloupe

Conceptual model of fluid circulation

+ geophysics → exploratory well



After Navelot et al., 2018

Thank you very much for your attention

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MEET Multi-sites EGS Demonstration

és géothermie

- *This work was performed in the framework of the H2020 MEET EU project which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792037*

GEC géosciences environnement Cergy

MEET Multi-sites EGS Demonstration Geothermal Winter School 2021

Fractures and hydrothermal alterations : a review of fluid pathways for geothermal applications

Part 2 – Hydrothermal alteration

B. Ledésert & **R.L. Hebert** – Geothermal Winter School - February 2021

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What is Hydrothermal Alteration (HA)?

« hot » fluid/rock interactions
(Temperature, fluid composition, fluid/rock ratio, time, permeability, Pressure)

Rock transformations

Petrological changes

- Chemical/Mineralogical reactions
  - dissolution/precipitation
  - transformation of primary minerals (−) → secondary hydrous minerals + (clays)
- microstructure changes

Petrophysical changes

- density
- porosity
- permeability
  → channel/barrier

Where does HA take place?

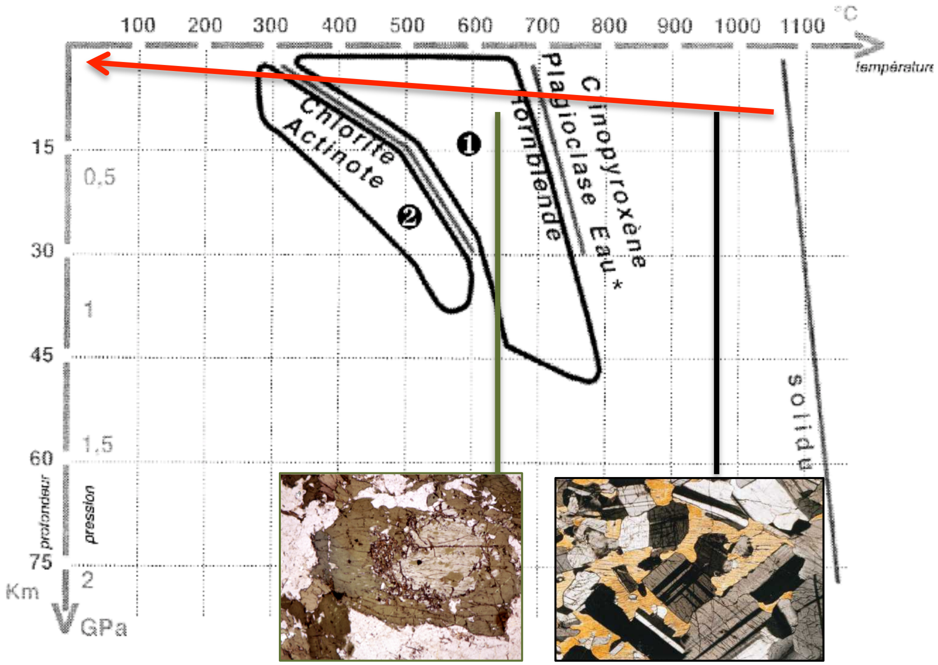
Anywhere with heat source + water + permeability = Hydrothermal systems

Heat source: thermal anomaly
- magmatic contexts
- metamorphic contexts
- Rifting

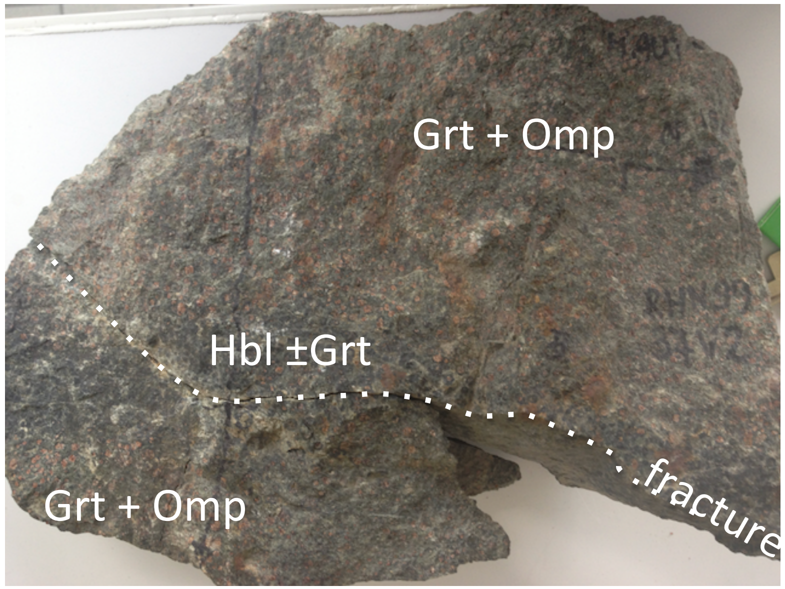
Fluids
- Magmatic
- Metamorphic
- meteoric

Permeability
- Fracture
- Fault
- joint
- unconformity
- grain boundary

Oceanic metamorphism



Fluid assisted retrogression of eclogite into amphibolite



Where does HA take place?

Anywhere with heat source + water + permeability = Hydrothermal systems

Heat source: thermal anomalie
- magmatic contexts
- metamorphic contexts
- Rifting

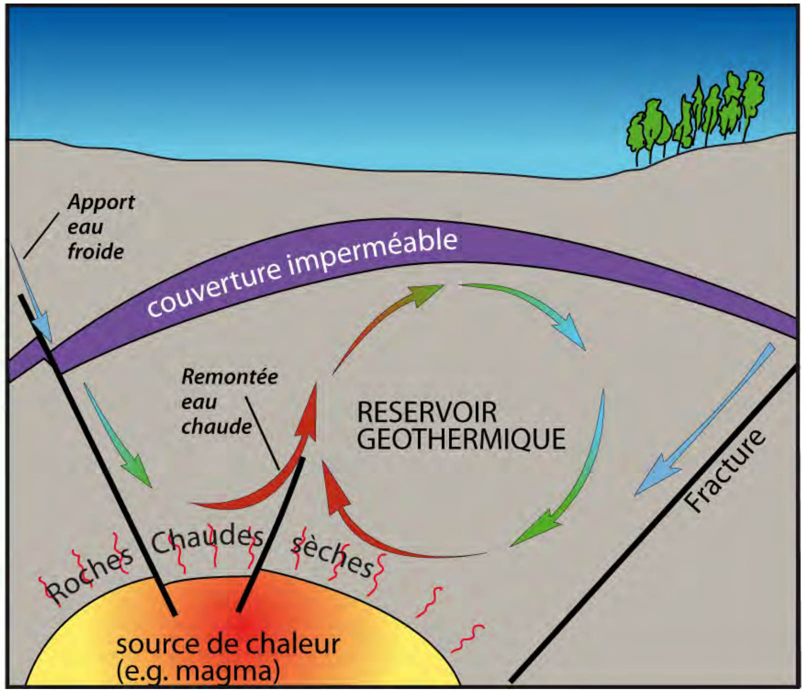
Fluids
- Magmatic
- Metamorphic
- basin

Permeability
- Fracture
- Fault
- joint
- unconformity
- grain boundary

HA is a common phenomenon in geothermal system where there is
Heat + fluids + Permeability (if not EGS)

+ Impermeable layer → Caprock

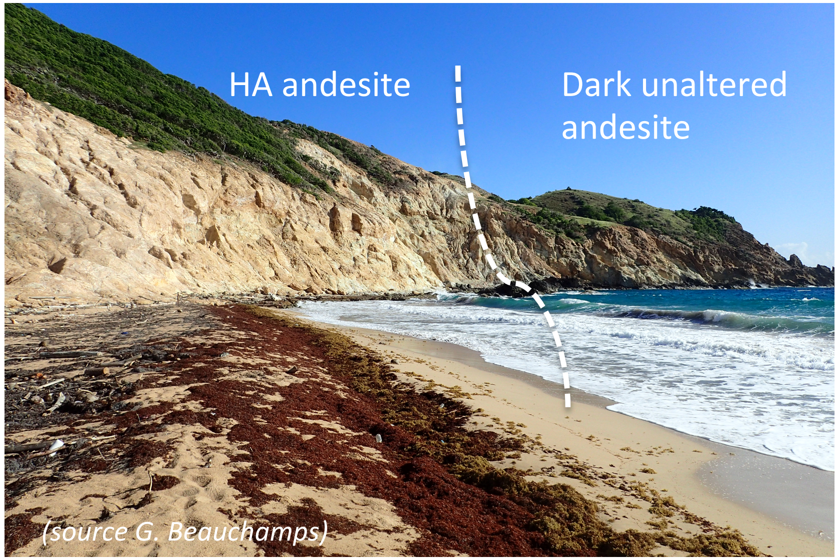
→ Geothermal ressource



HA produces « alteration zones »

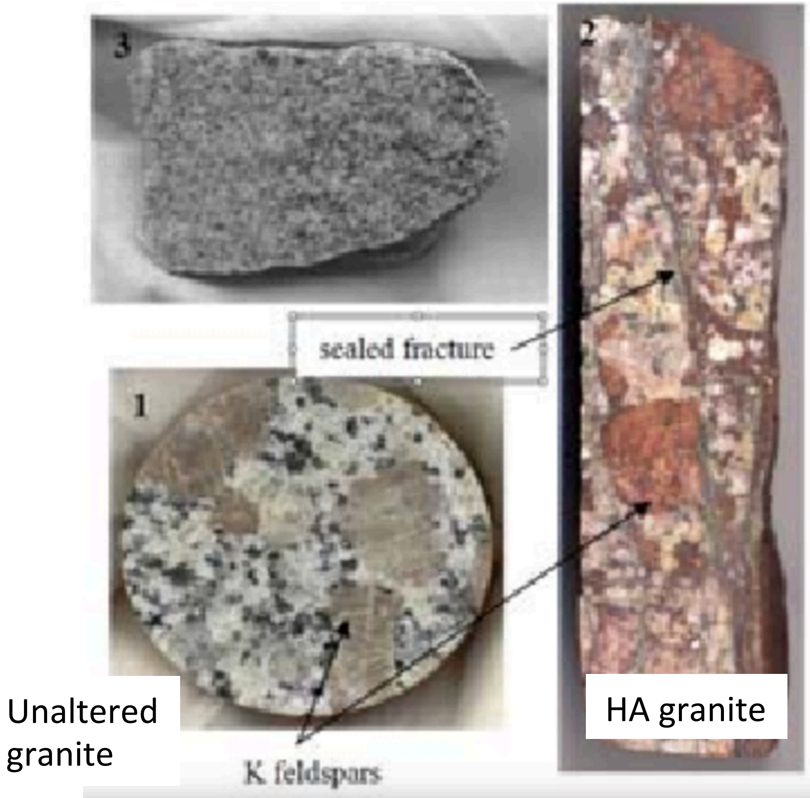
Characterized by several features visible at ≠ scales:

- Color changes

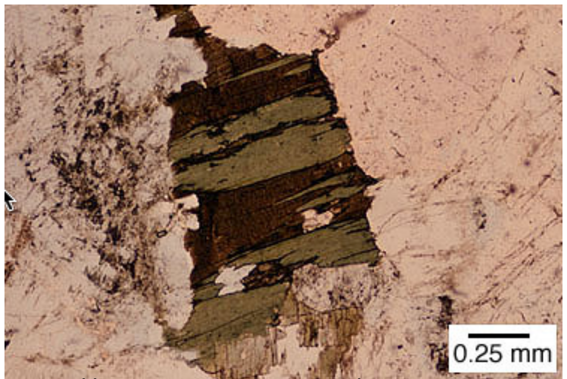


Fossil geothermal system of Terre de Haut

Soultz granite



Massart et al. 2010

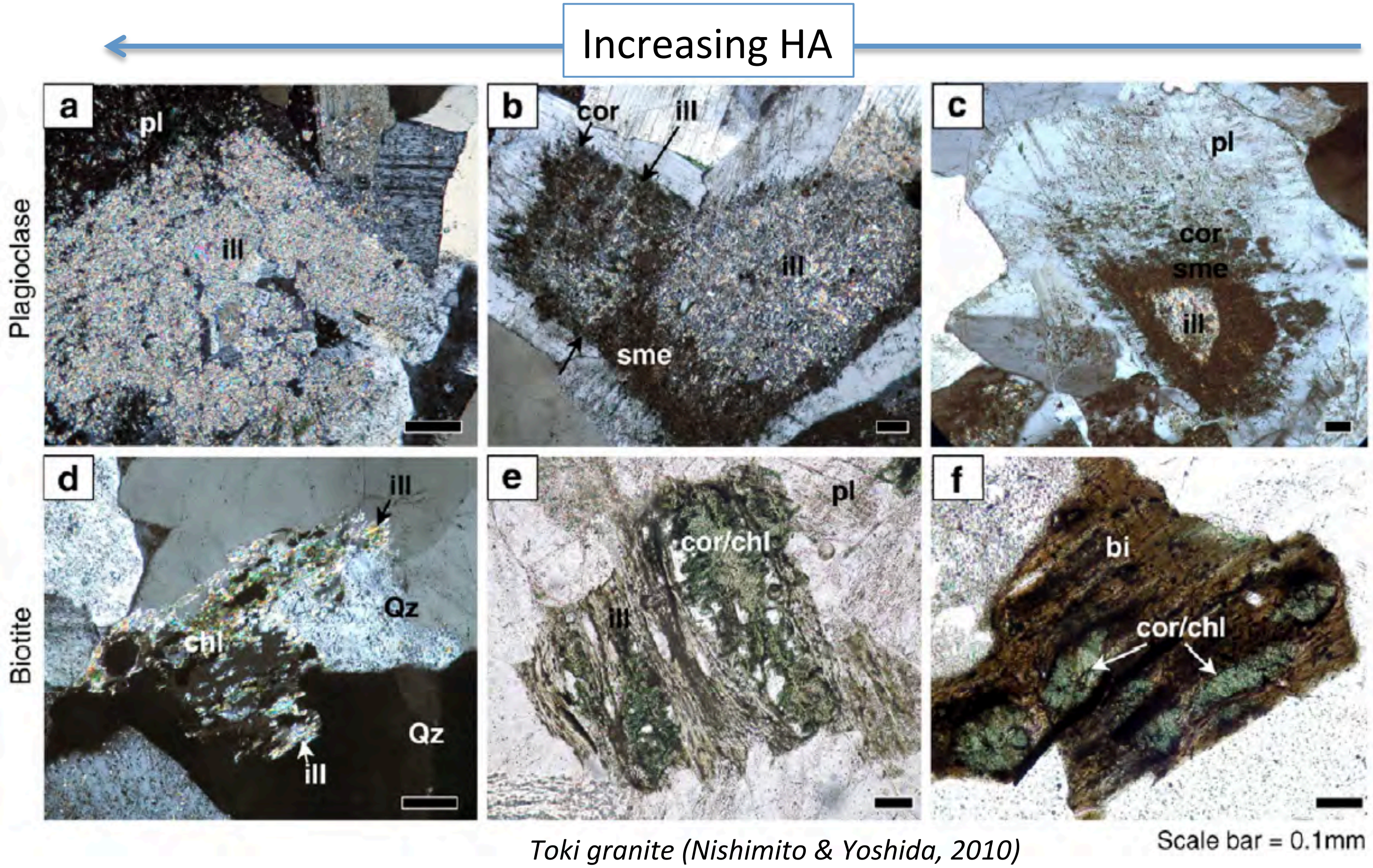


http://www.geolab.unc.edu/

HA produces « alteration zones »

Characterized by several features observables at ≠ scales:

- Color changes
- New (set of) phases (mainly hydrous minerals→ clay minerals)



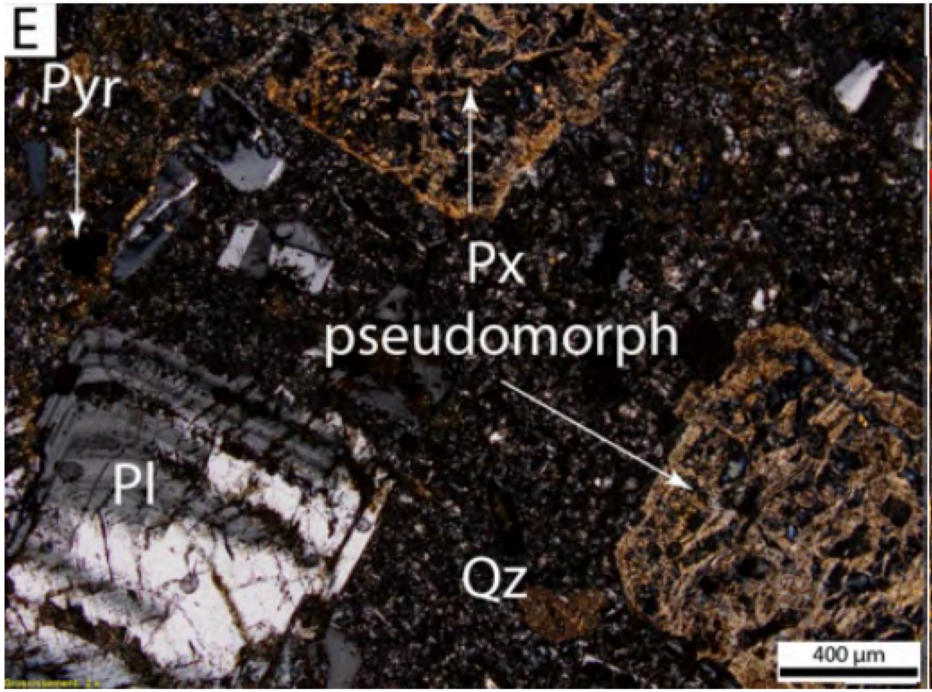
Toki granite (Nishimito & Yoshida, 2010)

Hydrothermal **zones**

Fossil geothermal reservoir in andesites (Les Saintes)

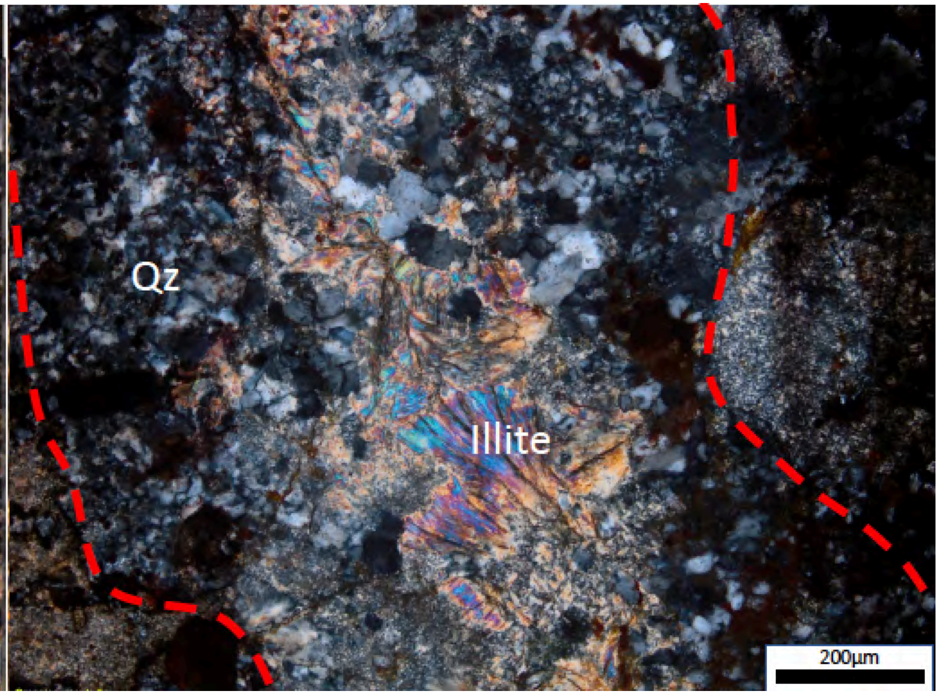
→ New phases occur either in the whole rock and/or structures

« rock » controlled (e.g. grain boundaries, porous network)



Magmatic texture preserved
Primary minerals are ± transformed into secondary minerals

Structurally controlled (e.g. fracture, vein, etc…)



Fracture infillings

Beauchamps 2019

HA produces « alteration zones »

Combination of Structurally and rock Controlled HA

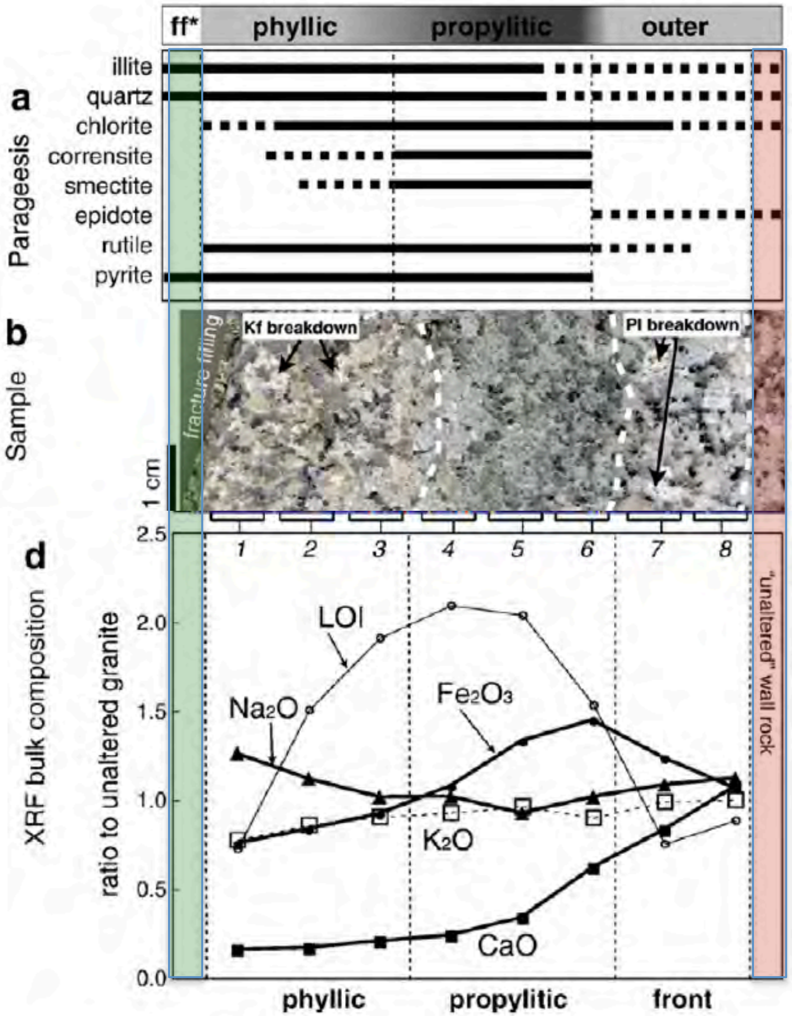


Fig. 2. Illustration of the alteration halo and chemical compositions of minera assemblage. a) Paragenetic sequence of secondary minerals. b) sample photo; c) SXAM compositional maps of Ca, Fe and K; d) bulk compositional of Fe_2O, CaO, Na_2O, K_2O and LOI within the alteration halo. *ff: fracture filling.

Open fracture filled with unsolidified compacted green clay without pores

Unaltered granite

ALTERATION HALO

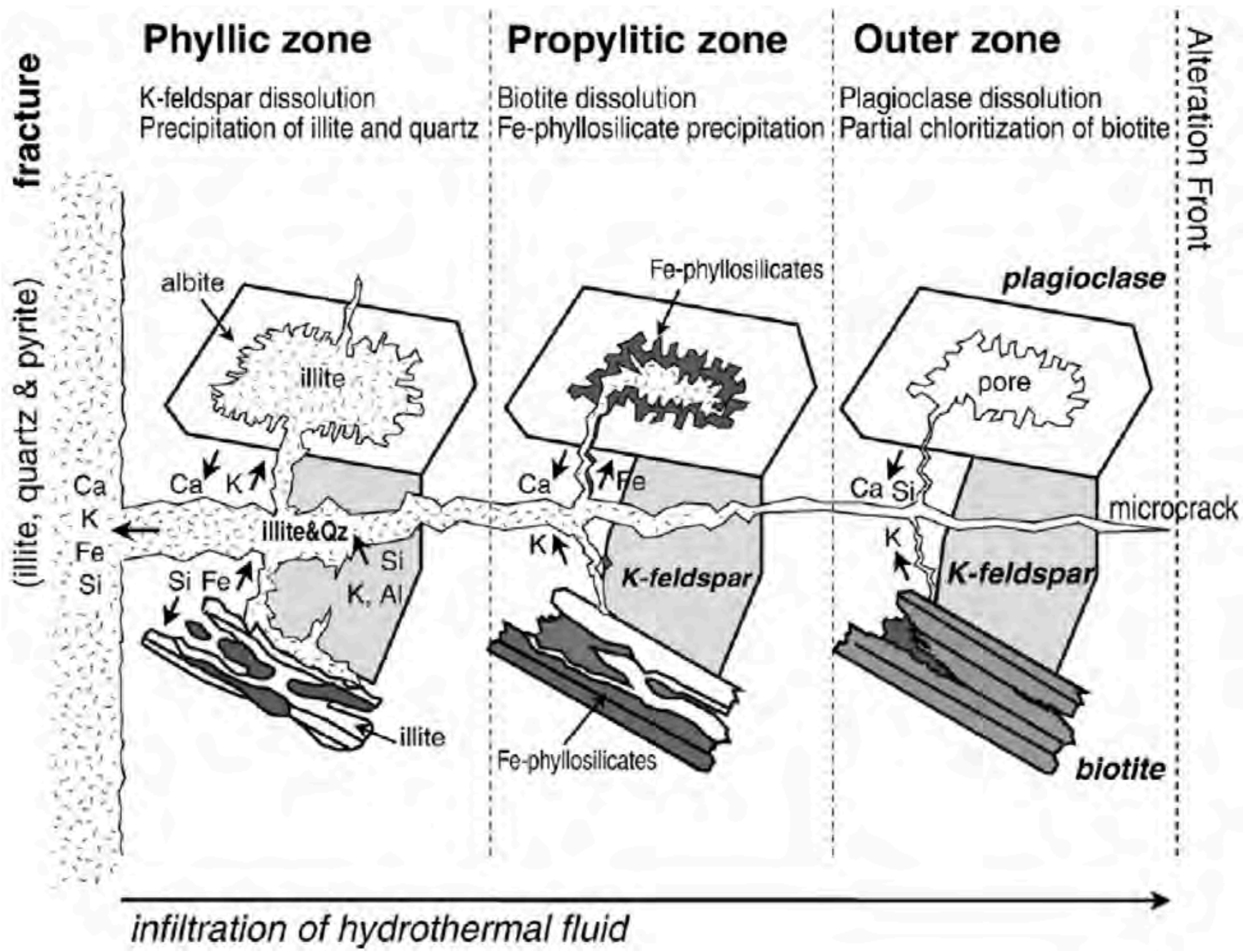
Outer zone:
Little change of color and beginning of primary phases breakdown (Plg, Bt)

Propylitic zone:
Green
Secondary phyllosilicates Chl , Corr (Chl/S)
Bt→ Chl + Corr + Ill

Phyllic zone:
White
Large amount of phases Il
Microcracks of Ill + Qtz

(Nishimito & Yoshida, 2010)

Schematic scenario of the HA process of a granite along a fracture



(Nishimito & Yoshida, 2010)

<u>Outer zone:</u>
Plg breakdown from core to rim →
pore f^{m} inner part of grains
Bt→ Chl + Corr along cleavage

<u>Propylitic zone:</u>
Secondary phyllosilicates Chl , Corr (Chl/S)
Bt→ Chl + Corr + Ill

<u>Phyllic zone:</u>
Kfs breakdown
Plg strongly illitized
precipitation of Ill + Qtz in microcracks indicating that fluid infiltrated along this pathway.
Bt and alteration products (chl + Corr)
Dissolution pores filled by Qtz

How to identify a rock underwent HA?

Evidences of HA

- Color changes
- Veins
- mineralized fracture network

Look very similar
@ low T

fracture

HA

Hydrothermal fluids (T> 100°C?)
Lateral and upwards
Saturated with some silicate components
Unsaturated with others as T ↘

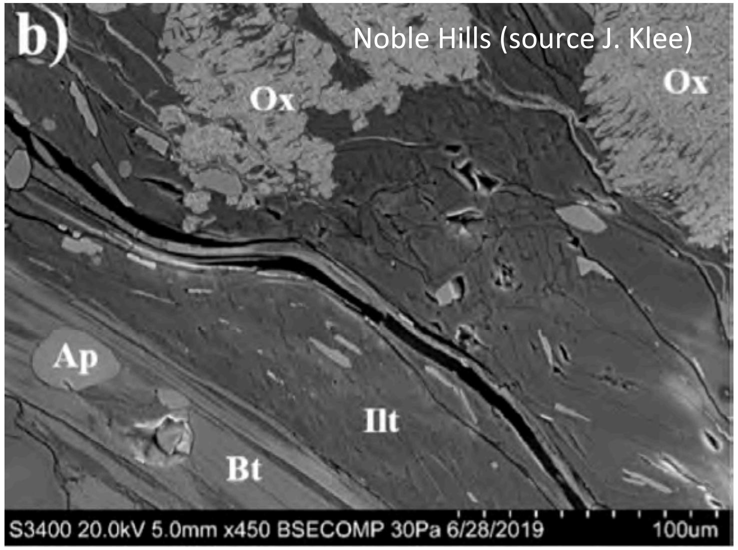
WEATHERING

meteoric water
Downwards
Unsaturated in silicate mineral comp.
In <-> with CO_2 atm.

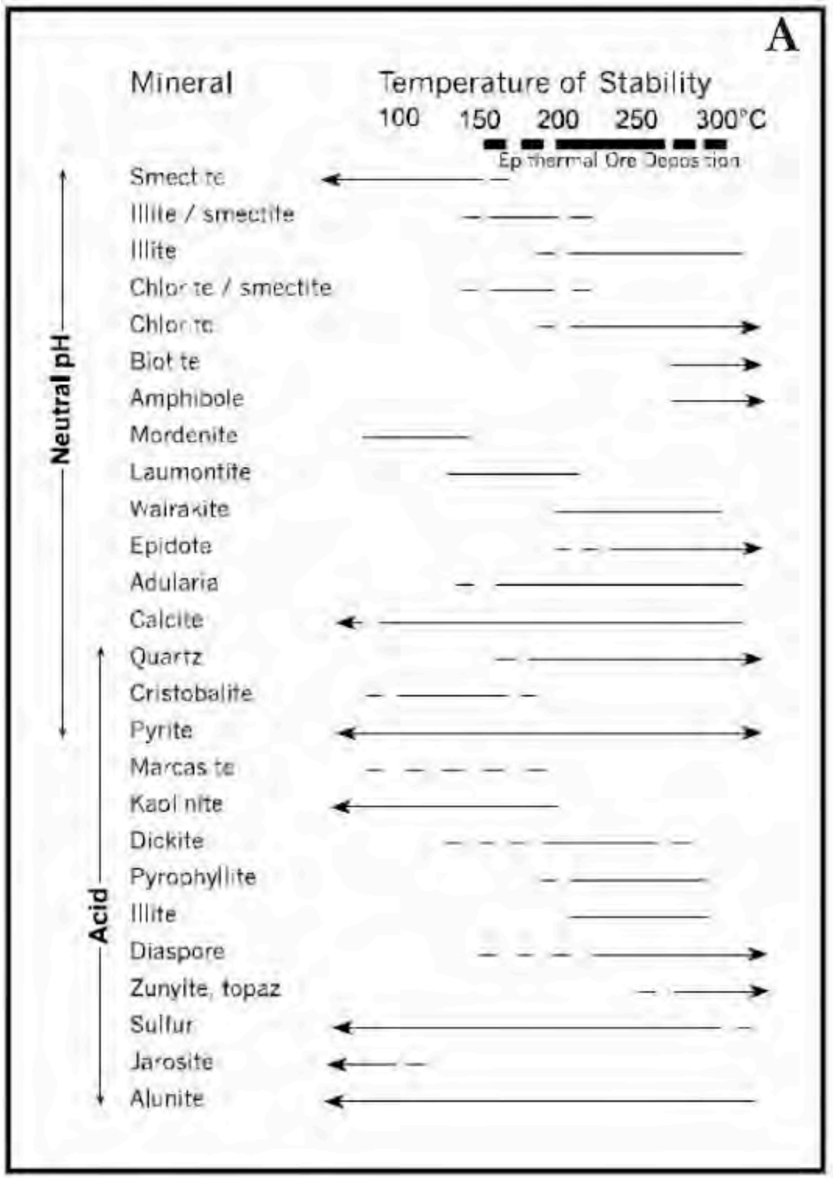
How to identify a rock underwent HA?

Evidences of HA

- Color changes
- Veins
- mineralized fracture network
- Occurrence of secondary key phases (indicator minerals)



Clay minerals but not only
Some ubiquist minerals (calcite, quartz)
Some specific minerals (e.g. adularia, alunite, …)



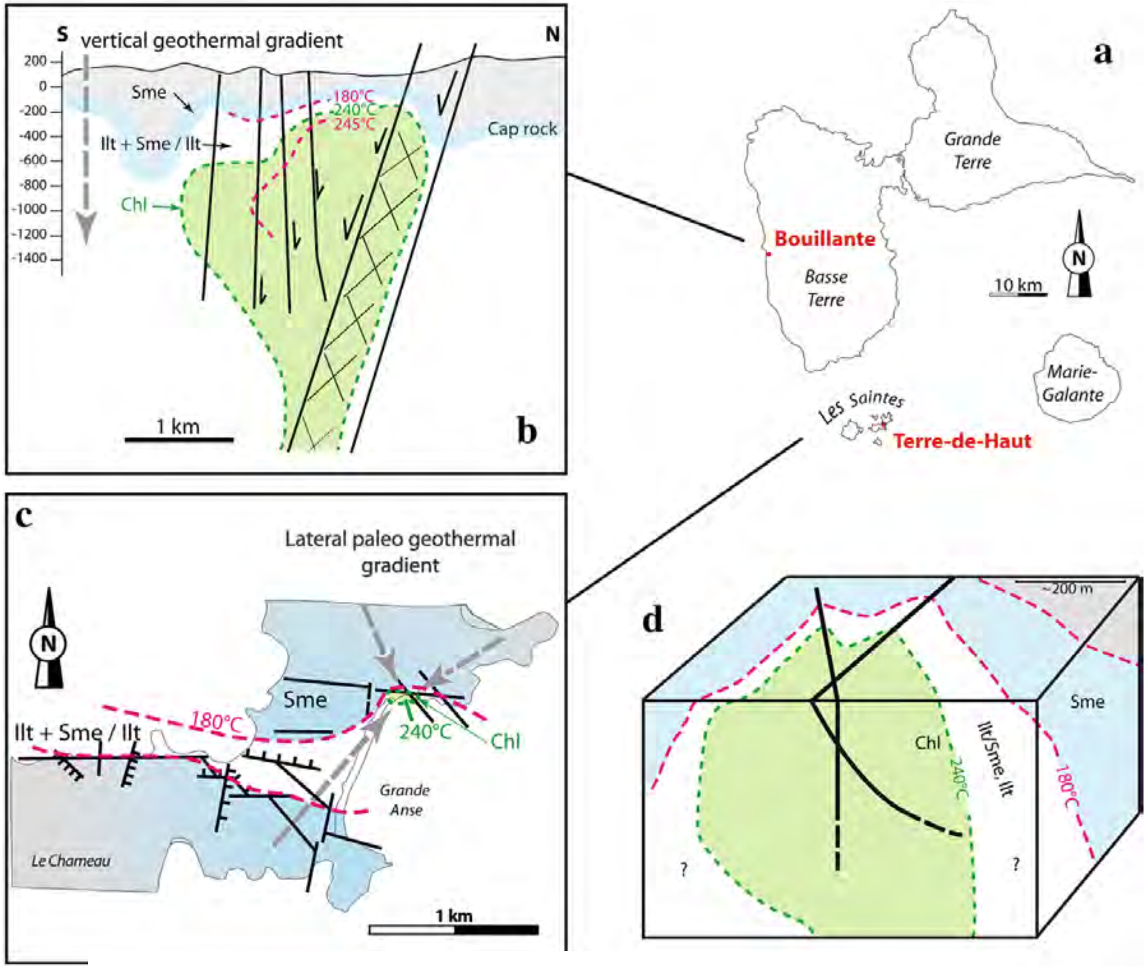
White & Hendequist, 1995

How to identify a rock underwent HA?

Evidences of HA

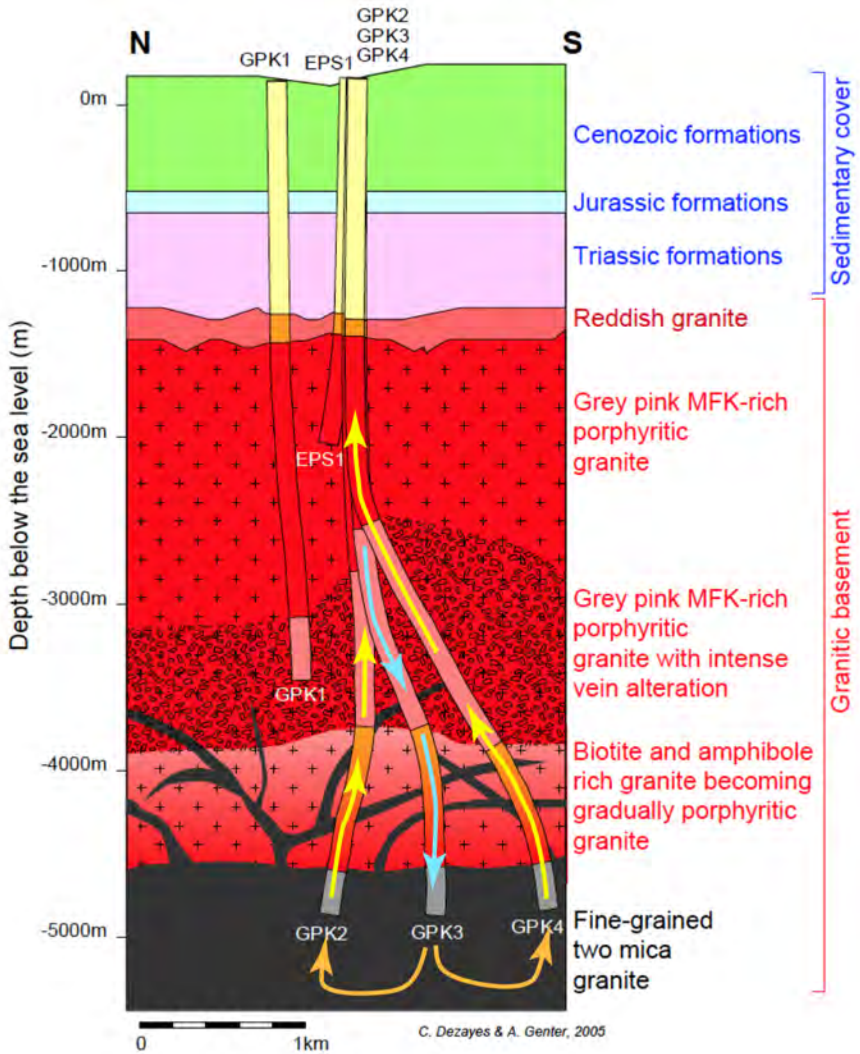
- Color changes
- Veins
- mineralized fracture network
- Occurrence of secondary phases (key minerals)
- Alteration zones

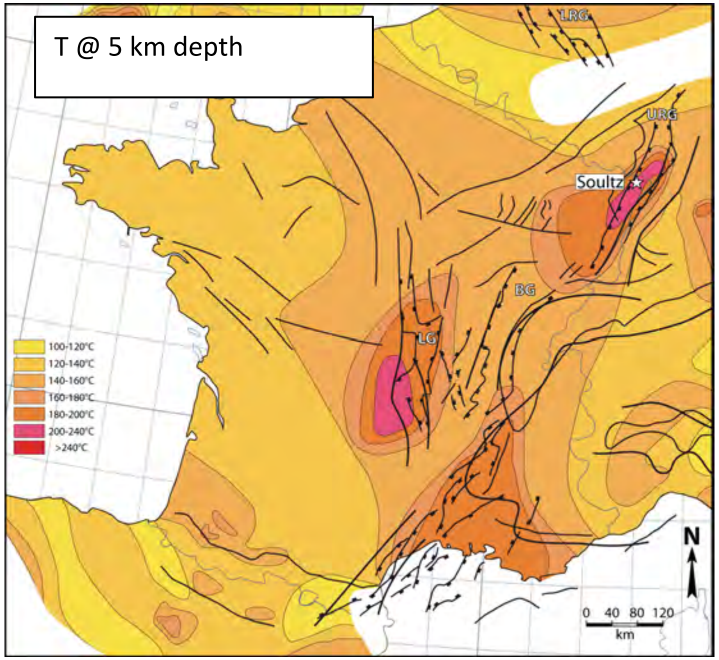
Common zonation of clay minerals: Sme→ Ill→Chl



Beauchamps et al., 2019

Exemple of Soultz-sous-Forêts





(modified from Dèzes et al., 2004)

Upper Rhine Graben (east of France)
Thermal anomaly (~200°C – 5 km)

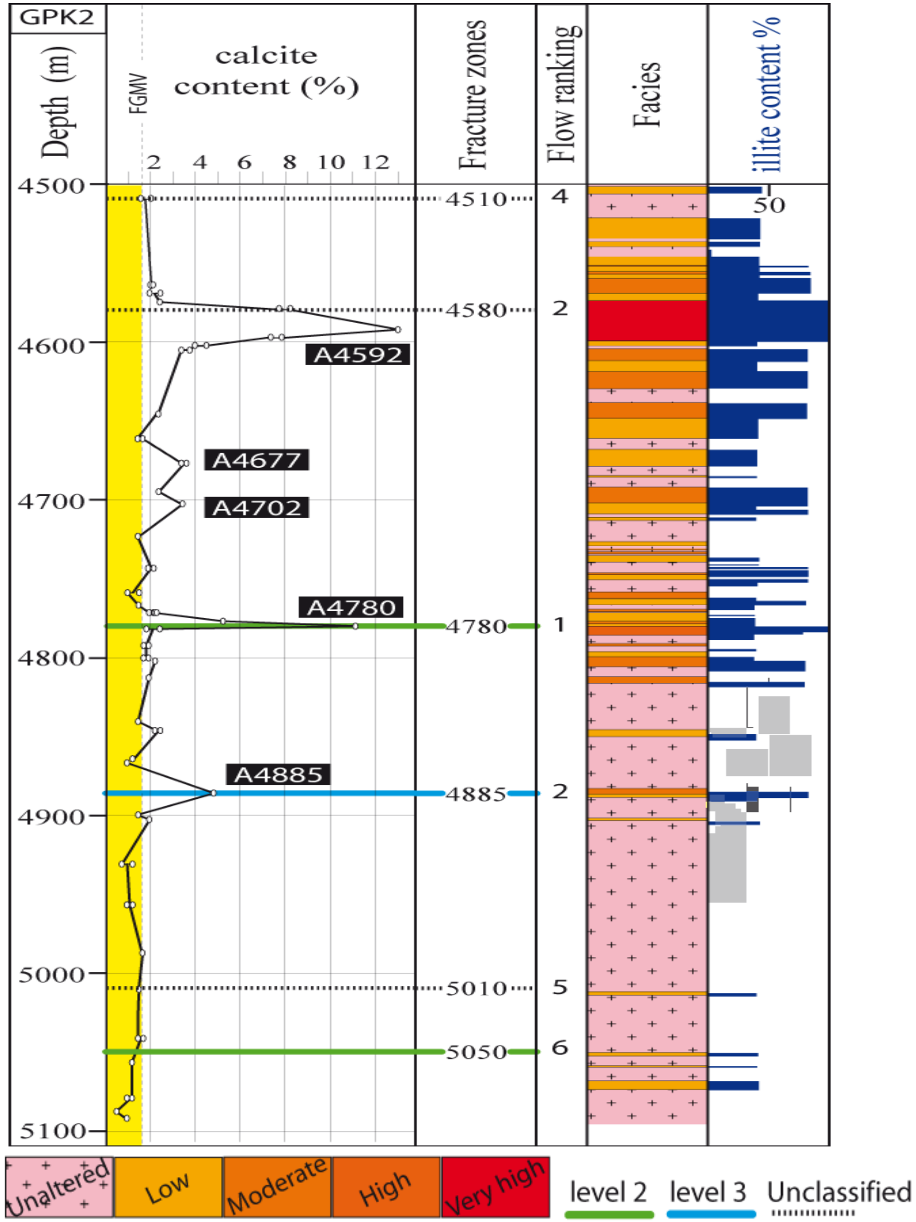
Fractured and altered granitic geothermal reservoir
Deep exchanger (4500-5000 m)
Triplet ($GPK2_p$-$GPK3_i$-$GP4_i$)

Geothermal fluid flows through a fracture network along which HA takes place

Main hydrothermal phases are Calcite and Illite

Exemple of Soultz-sous-Forêts

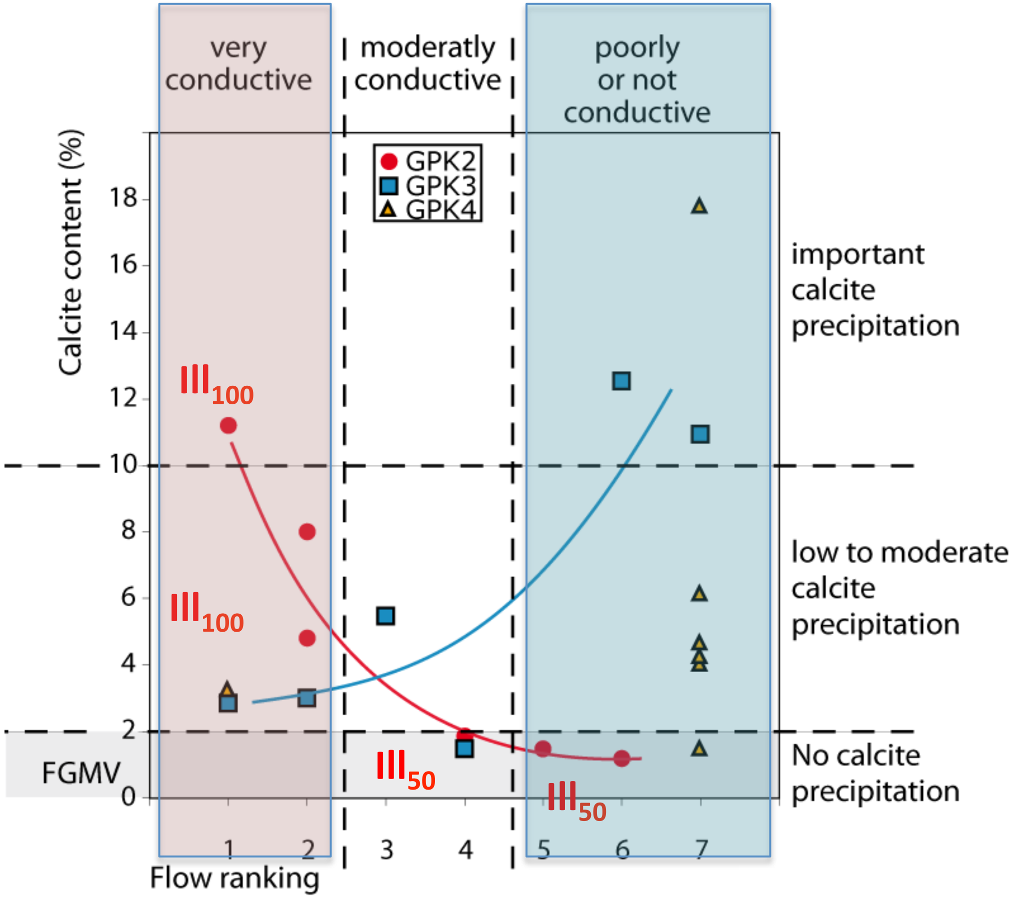
GPK2 borehole



- fluid flow is fracture zone controlled
- fracture zones correspond to HA zones
  - most conductive: High Cal and Ill contents and granite highly altered
  - Less conductive: No Cal, low to moderate content of Ill, granite with low degree of alteration
- Unaltered granite do not show abnormal calcite content or occurrence of Ill
- HA zones (Cal + Ill) with no fluid flow, granite with low degree of alteration

Hebert & Ledesert, 2012

Exemple of Soultz-sous-Forêts



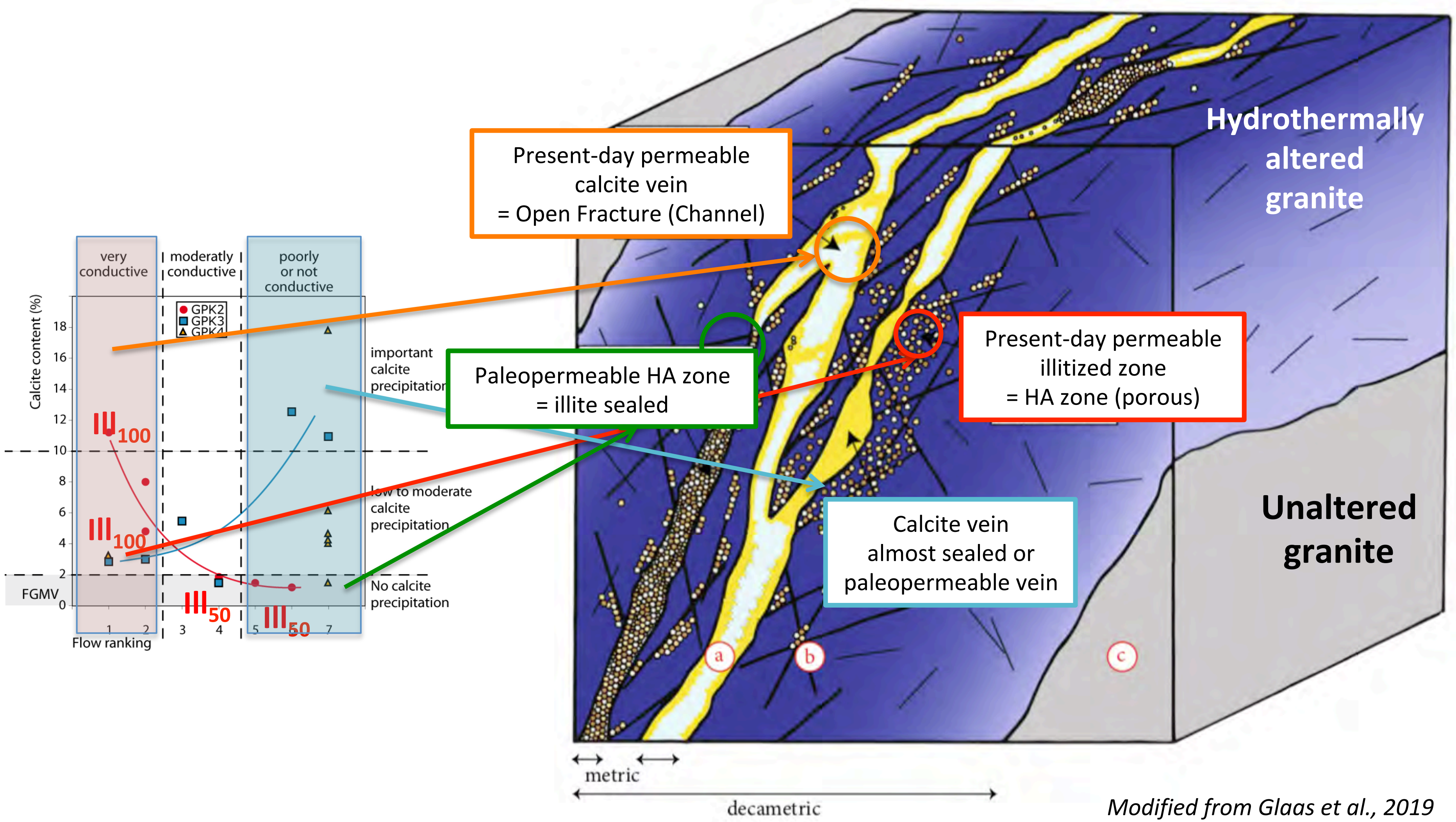
Hebert & Ledesert, 2012

The relationship between calcite content and fluid flow differs form a well to another → different permeability properties → ≠ stages of HA

- Very conductive → Open fractures with alteration halo (illitization) and calcite precipitation

- Poorly or not conductive → clugged or in way of clugging fractures. Low fluid flow through remaining space of fracture zone or in the HA damage zone

Exemple of Soultz-sous-Forêts

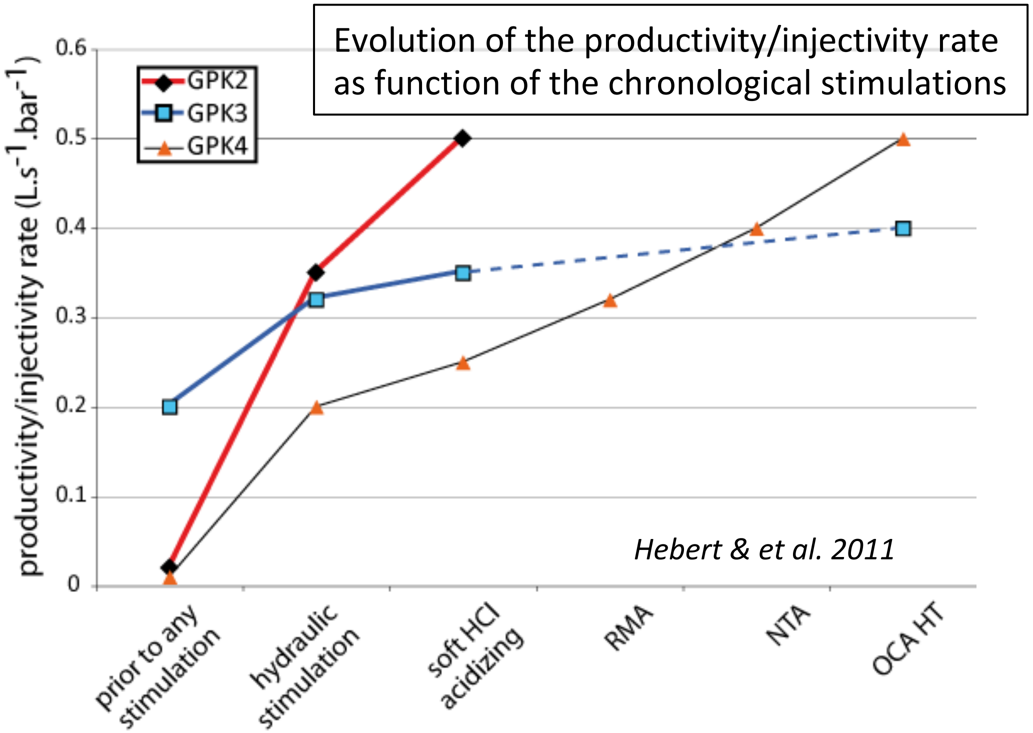


Modified from Glaas et al., 2019

Conclusion about HA in geothermal context

• Studying HA provides a better understanding of (past and present) fluid flow within the reservoir

• Characterization of sealing/clugging secondary phases allows to choose appropriate stimulation to remove clogging phases
→ enhancing or maintaining the performance of the reservoir through its lifetime



Soultz-sous-Forêts

Initial poor productivity/injectivity rates

High amount of calcite precipitation within fracture zones
-> Soft HCl stimulation improve connectivity by ~43%

Thank you for your attention