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

Part 1 – Fracture networks, various examples
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

Guadeloupe (Lesser Antilles) andésite

Joints m-scale

Thin section μm-scale

Navelot et al., 2018
Inside geothermal reservoirs, fractures cannot be seen directly.

Faults and fractures km-scale

McNamara et al., 2017
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

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

BHTV, well RK32

McNamara et al., 2017
C - Analogues

Talk by G. Trullenque

J. Klee, MEET PhD
D - Modelling

Soultz-sous-Forêts

Sausse et al., 2010
Fluid flow simulation

Egert et al., 2020
3-How to characterize fracture networks?

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
3-How to characterize fracture networks?

Fractures grouped into clusters separated by non-fractured zones

A – Fractal analysis

Fractures grouped into clusters separated by non-fractured zones

EPS-1 well

Fractal analysis for quantification and prediction

Ledésert et al., 1993
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 probability when fractures are clustered
B – Statistics

Surface area occupied by discontinuities (%)

Surfacic intensity of discontinuities P21 (cm/cm²)

Guadeloupe (Lesser Antilles)
Andésite
Azzimani, 2019, MSc thesis

See Postdoc A. Chabani, MEET
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
On samples in the lab:

- Density
- Permeability
- Porosity
- Thermal conductivity
- P wave velocity

Combination of parameters
Correlations

Flow pathways

After Navelot et al., 2018
4- Conclusion

Conceptual model of fluid circulation

Example: Guadeloupe

+ geophysics $\rightarrow$ exploratory well

After Navelot et al., 2018
Thank you very much for your attention

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Part 2 – Hydrothermal alteration
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 (−) \(\rightarrow\) secondary hydrous minerals + (clays)
- microstructure changes

Petrophysical changes
- density
- porosity
- permeability
  \(\rightarrow\) 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

Unaltered granite

HA 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 (Nishimoto & 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) Structurally controlled (e.g. fracture, vein, etc...)

Magmatic texture preserved
Primary minerals are ± transformed into secondary minerals

Fracture infillings

Beauchamps 2019
HA produces « alteration zones »

Combination of Structurally and rock Controlled HA

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 II
Microcracks of Ill + Qtz

(Nishimoto & Yoshida, 2010)
Schematic scenario of the HA process of a granite along a fracture

Outer zone:
Plg breakdown from core to rim → pore f m inner part of grains
Bt → Chl + Corr along cleavage

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

Phyllic zone:
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

(Nishimito & Yoshida, 2010)
How to identify a rock underwent HA?

Evidences of HA

- Color changes
- Veins
- Mineralized fracture network

HA

\[\text{Hydrothermal fluids (T> 100°C?)} \]
\[\text{Lateral and upwards} \]
\[\text{Saturated with some silicate components} \]
\[\text{Unsaturated with others as T } < \]

WEATHERING

Fracture

\[\text{Meteoric water} \]
\[\text{Downwards} \]
\[\text{Unsaturated in silicate mineral comp.} \]
\[\text{In <-> with CO2 atm.} \]
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, …)

Noble Hills (source J. Klee)

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

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

Fractured and altered granitic geothermal reservoir
Deep exchanger (4500-5000 m)
Triplet (GPK2p-GPK3i-GP4i)

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

Main hydrothermal phases are Calcite and Illite

(modified from Dèzes et al., 2004)
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
The relationship between calcite content and fluid flow differs from one 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

Hebert & Ledesert, 2012
Exemple of Soultz-sous-Forêts

- Present-day permeable calcite vein = Open Fracture (Channel)
- Paleopermeable HA zone = illite sealed
- Present-day permeable illitized zone = HA zone (porous)
- Calcite vein almost sealed or paleopermeable vein

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

Evolution of the productivity/injectivity rate as function of the chronological stimulations

Hebert & et al. 2011

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