The role of fluids on strain localization at seismogenic depth: a case study from brittle-ductile faults from Olkiluoto Island, SW Finland

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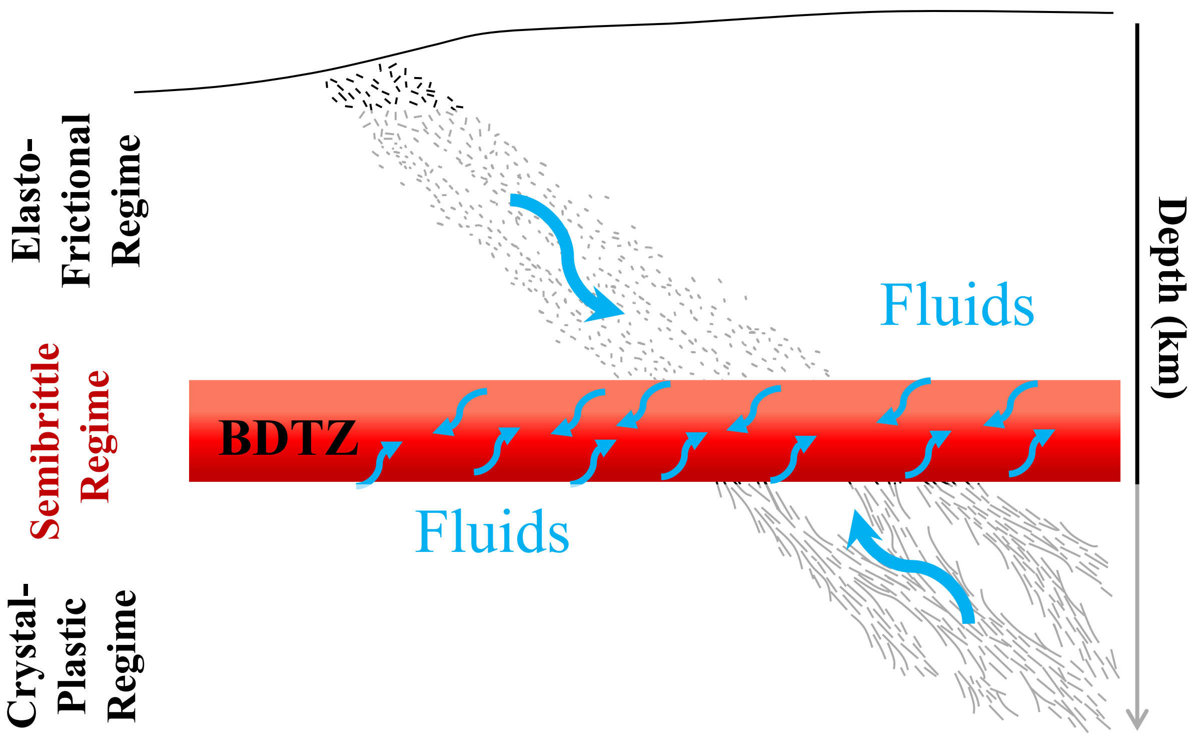
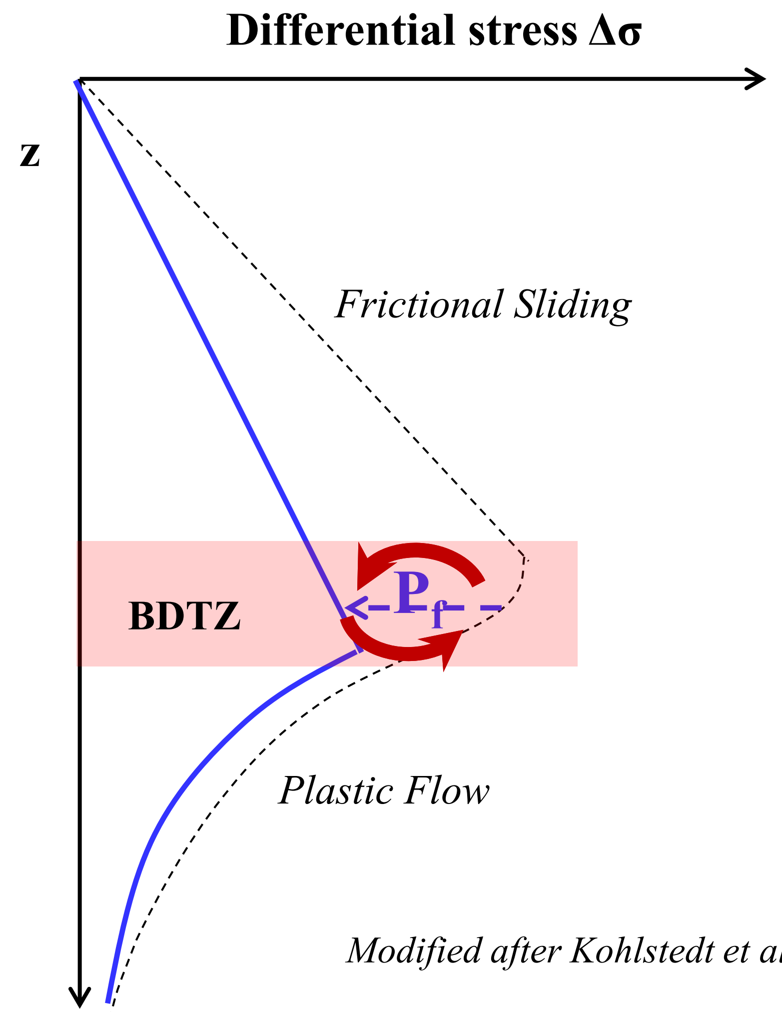
1. Introduction



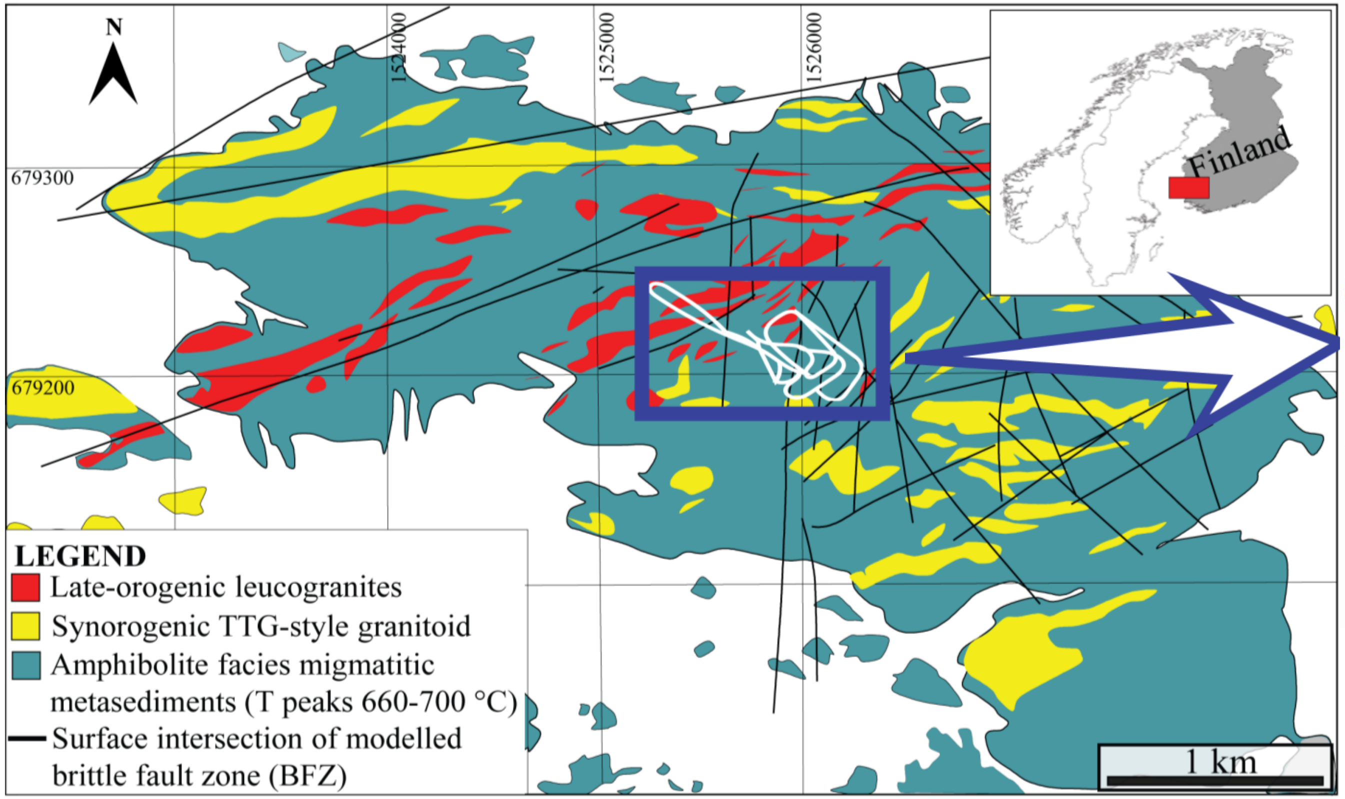
Modified after Sibson (1977)



Modified after Kohlstedt et al. (1995)

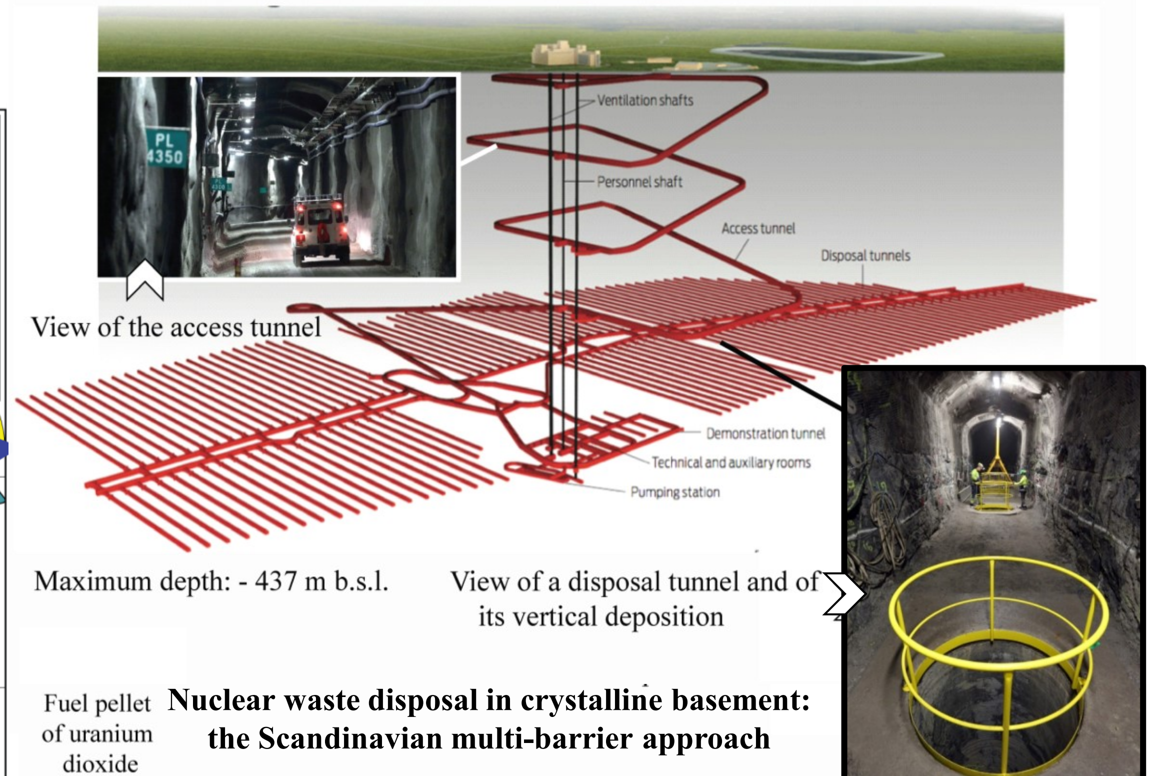
Fluids can induce depth fluctuations of the BDTZ

2.1 Geology of Olkiluoto Island



The Paleoproterozoic bedrock is deformed by intense network of brittle fault zones (BFZ) as a result of a complex history of structural overprinting and reactivation. Two different sets of brittle structures were recognized: i) subvertical faults striking N-S to NW-SE and younger ii) low-angle normal faults, striking from E-W to NE-SW.

Final project of the Olkiluoto deep nuclear waste repository



Nuclear waste disposal in crystalline basement: the Scandinavian multi-barrier approach

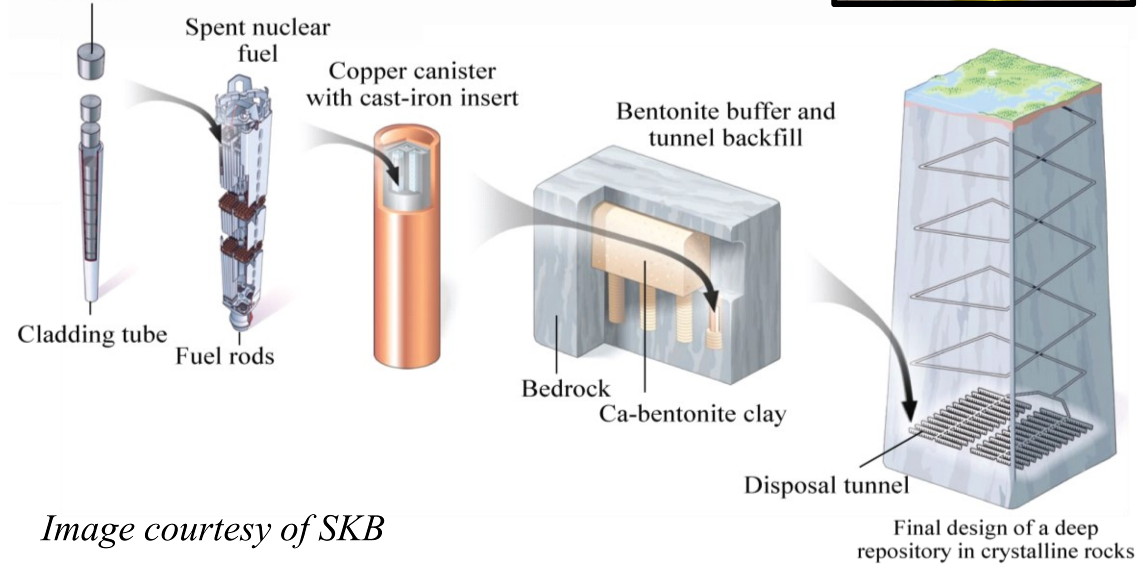
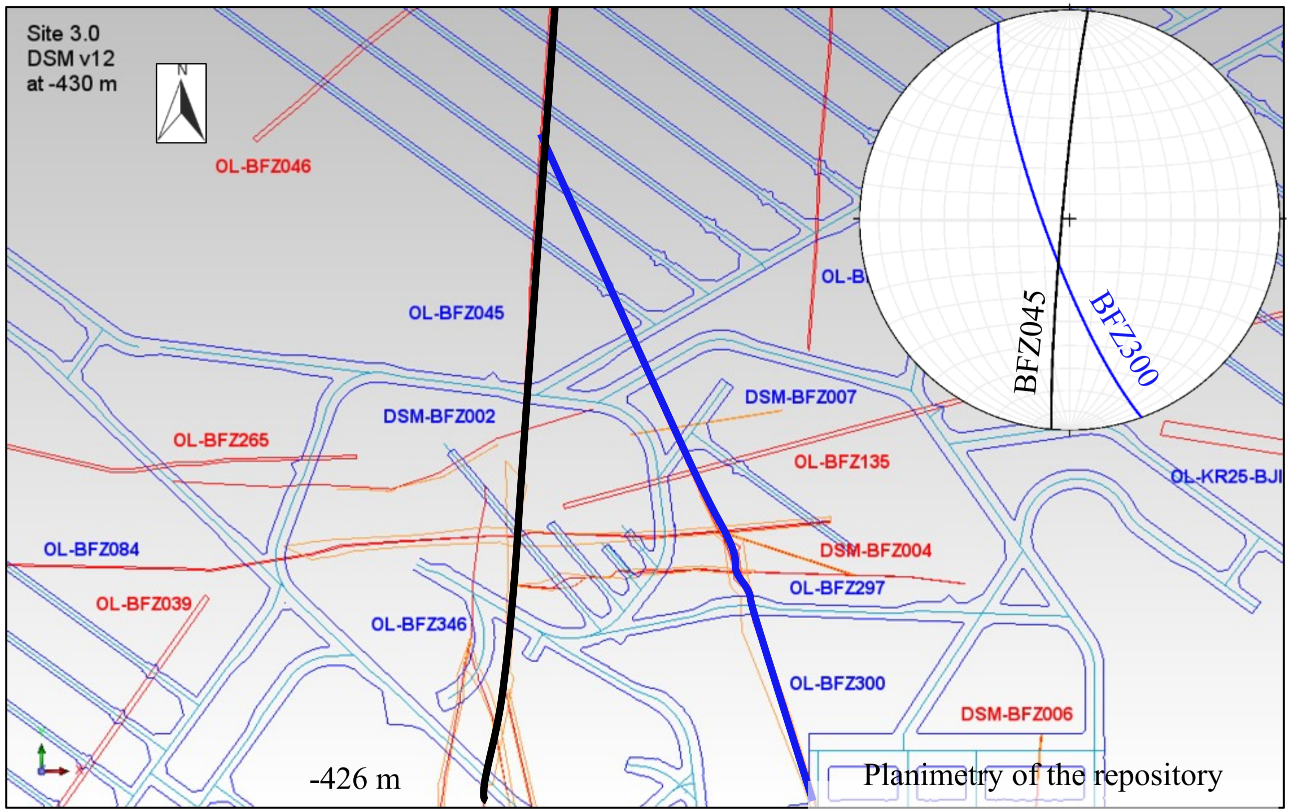
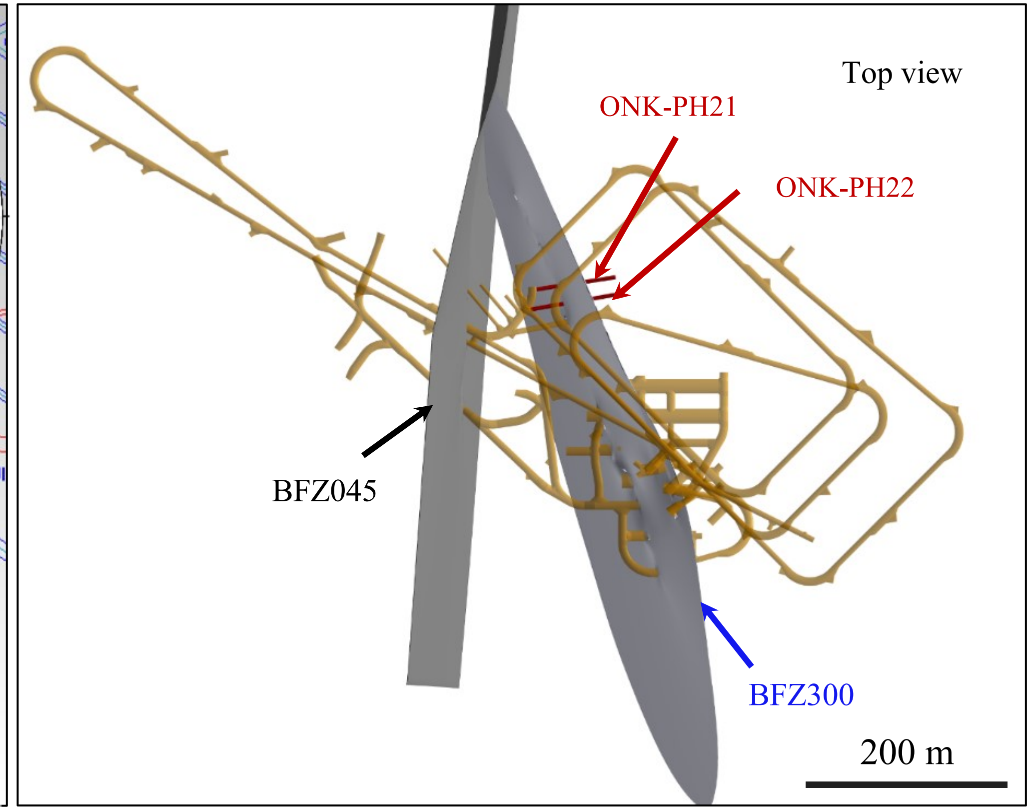


Image courtesy of SKB

2.2 Studied fault system





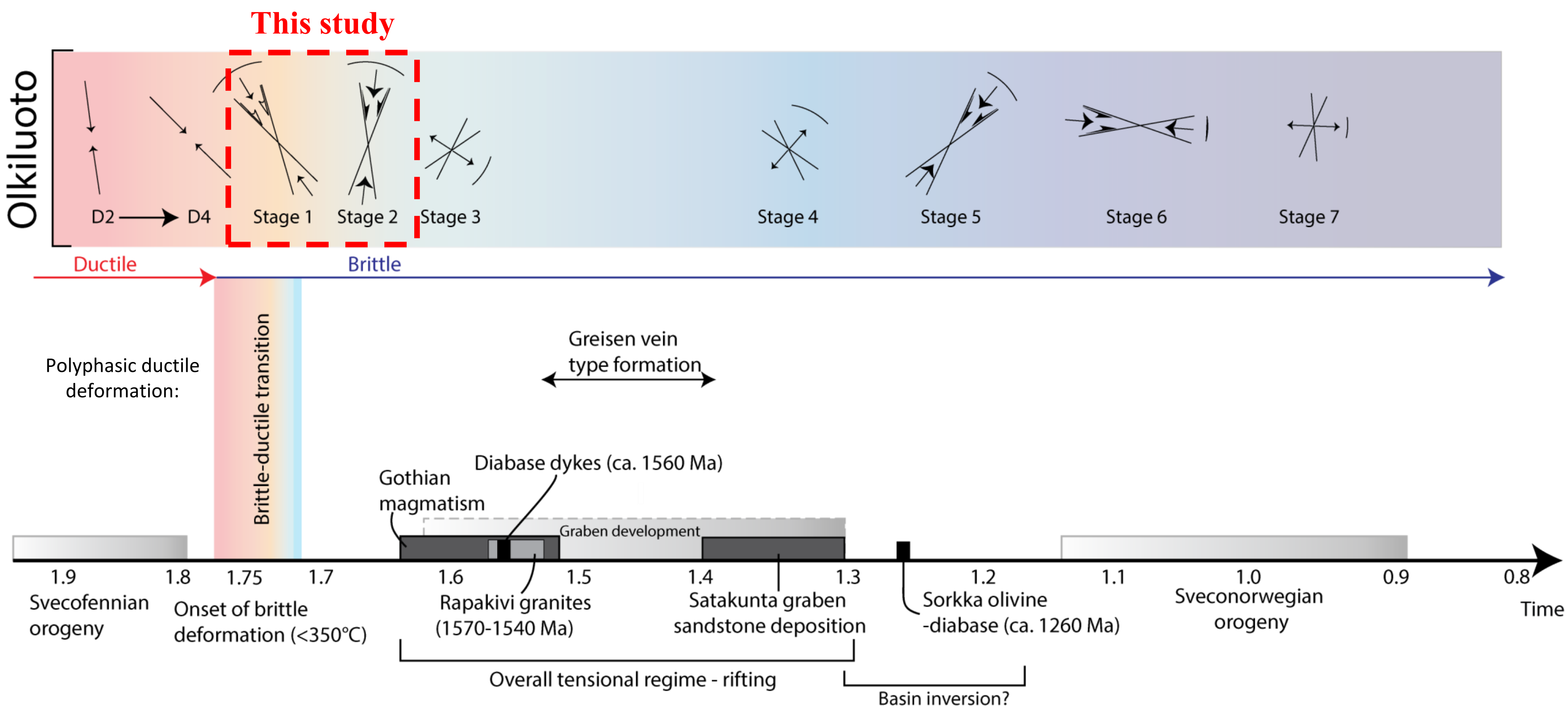
Because of their excellent exposure, a **set of sub-vertical conjugate brittle deformation zones** were used **as analogues** of the regional faults striking **N-S to NW-SE**:

- A N-S-trending sinistral brittle deformation zone overprints and reactivates a dextral mylonitic precursor related to earlier, localized ductile deformation: BFZ045 *(Prando et al. 2020)*.

This study

- A NW-SE dextral brittle deformation zone cuts across the metamorphic foliation without exploiting any ductile precursor: BFZ300 *(Marchesini et al. 2019)*.

2.3 Major tectonic events: paleostress tensor reconstructions

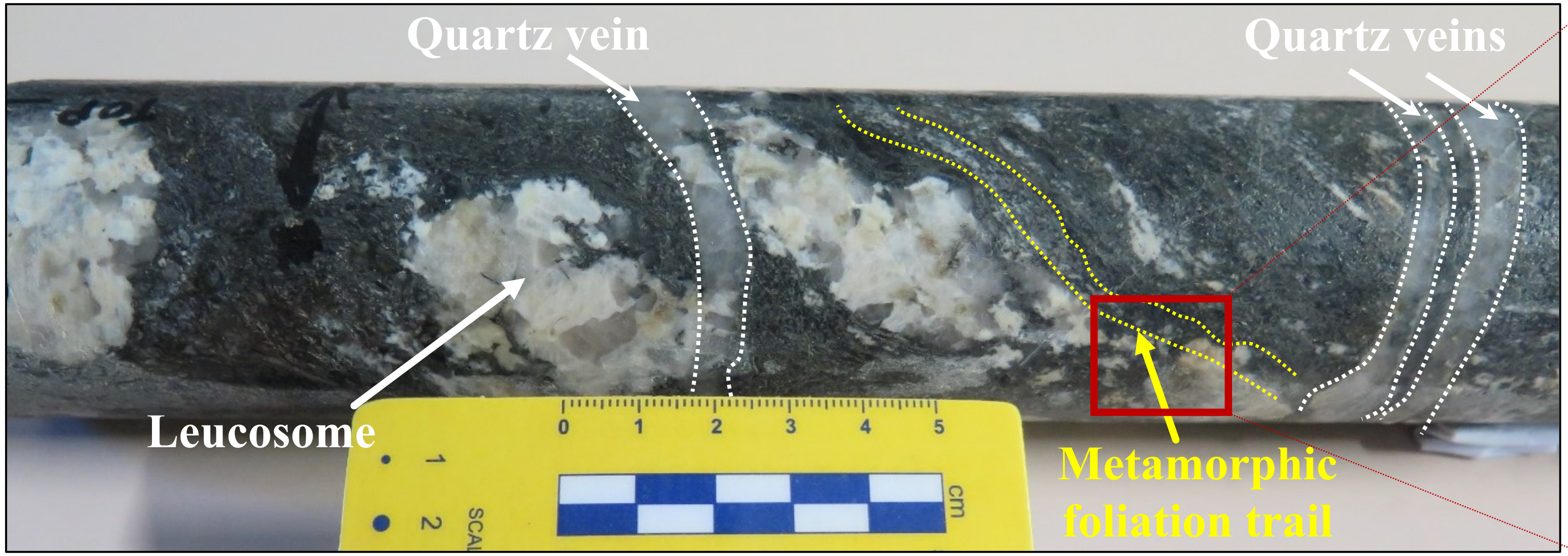


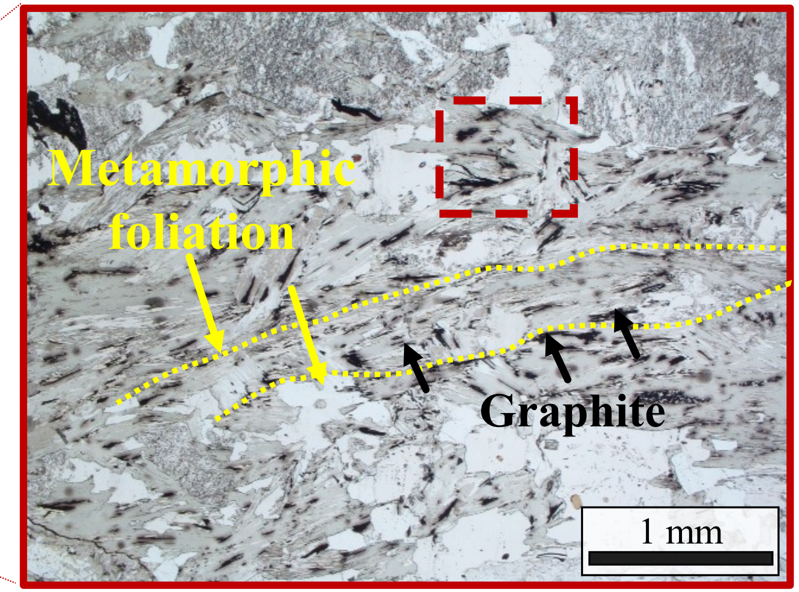
modified after Lahtinen et al. (2005), Mattila and Viola (2014) and Skytta and Torvela (2018)

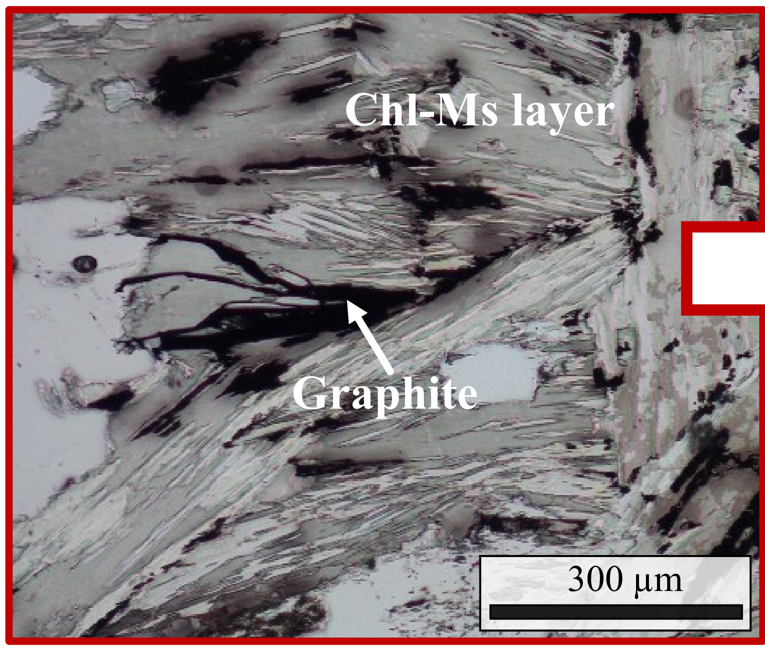
The bedrock of Olkiluoto experienced a complex hystory of reactivation

3.1 Wall rock

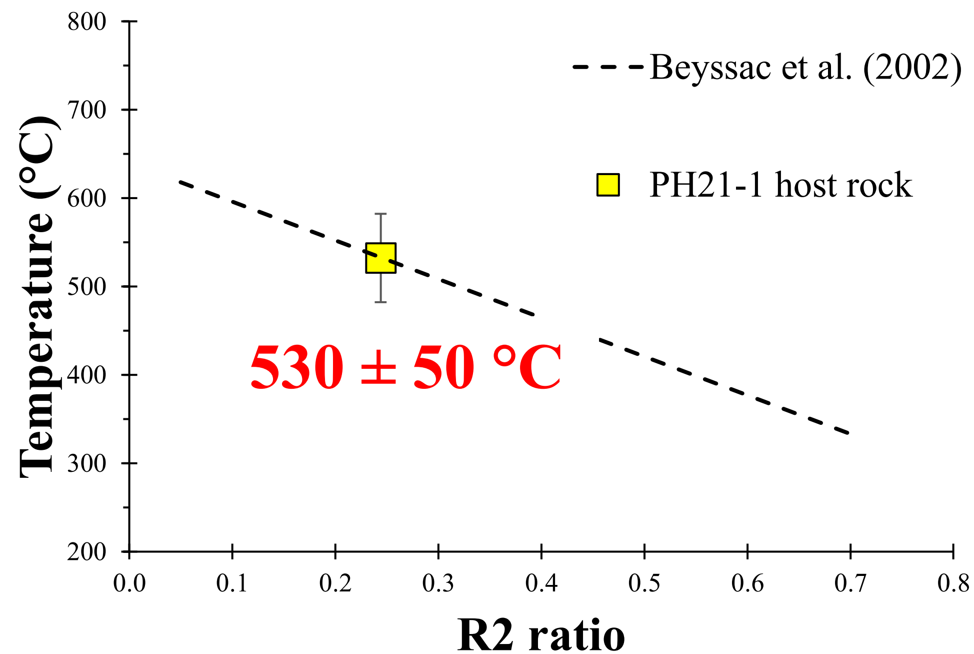
Drill core structural analysis



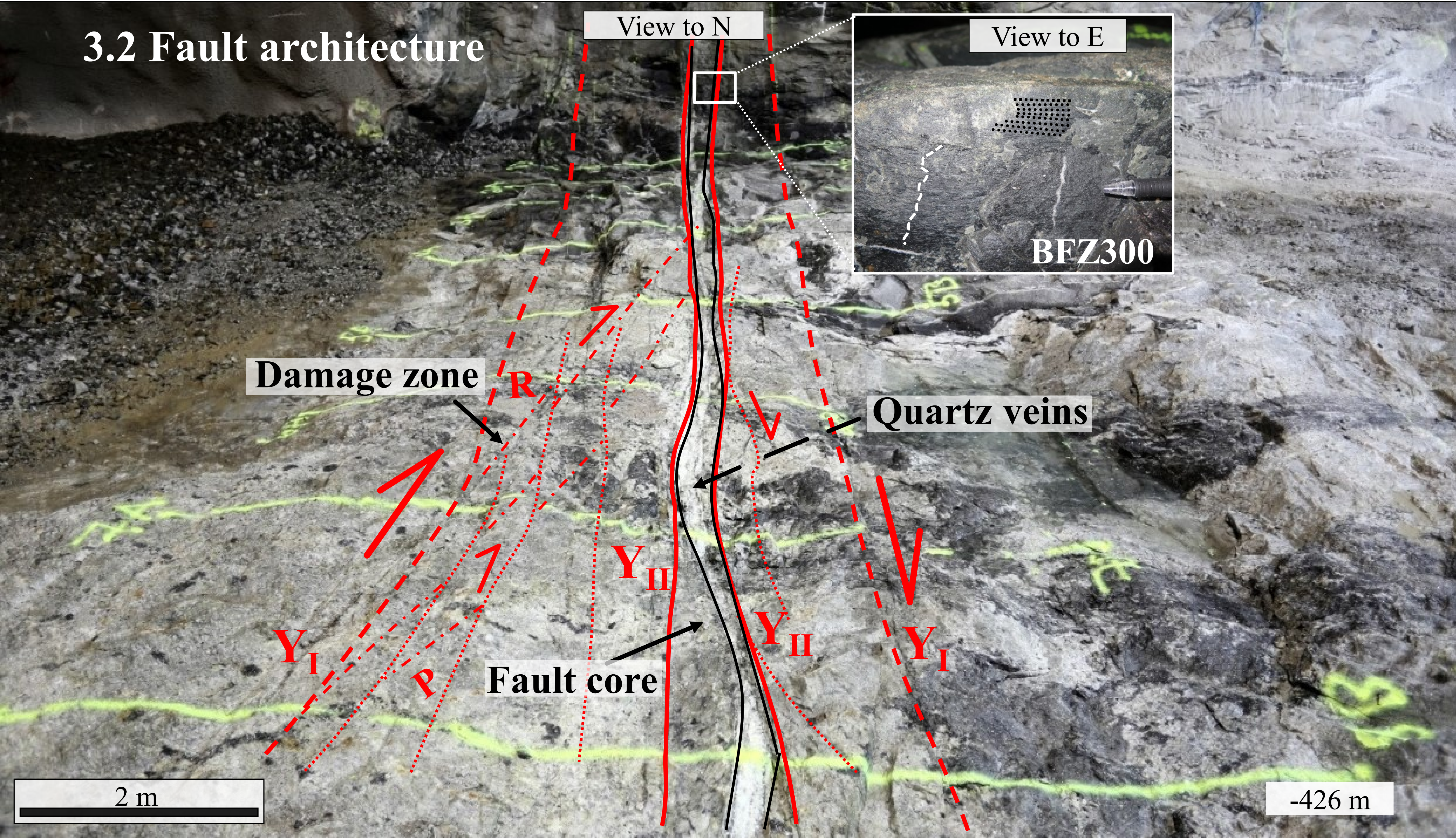




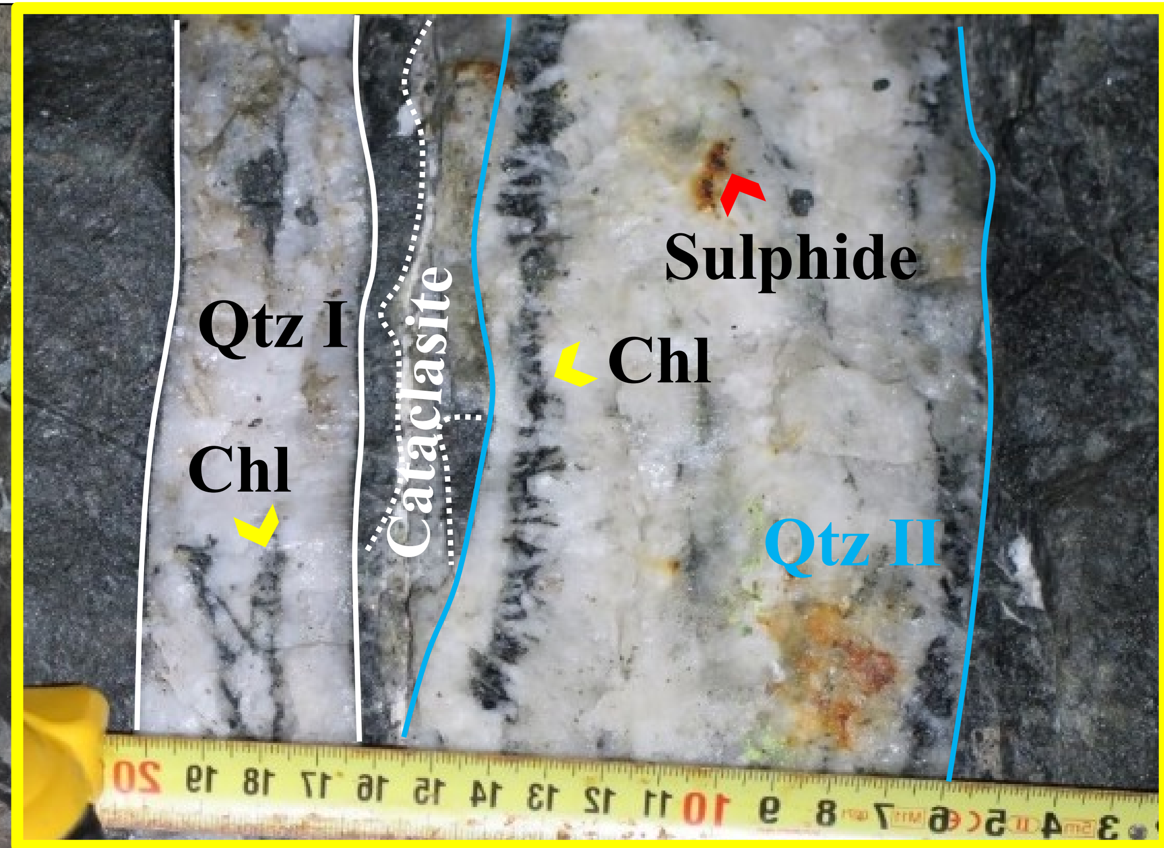
Raman spectroscopy of carbonaceous material and geothermometry



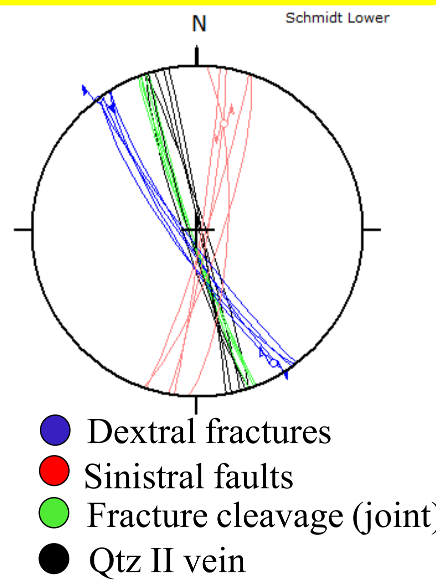
Modified from Prando et al. (2020)


3.2 Fault architecture
View to N
View to E
BFZ300
Damage zone
R
Quartz veins
Y II
Y II
Y I
Y I
P
Fault core
2 m
-426 m

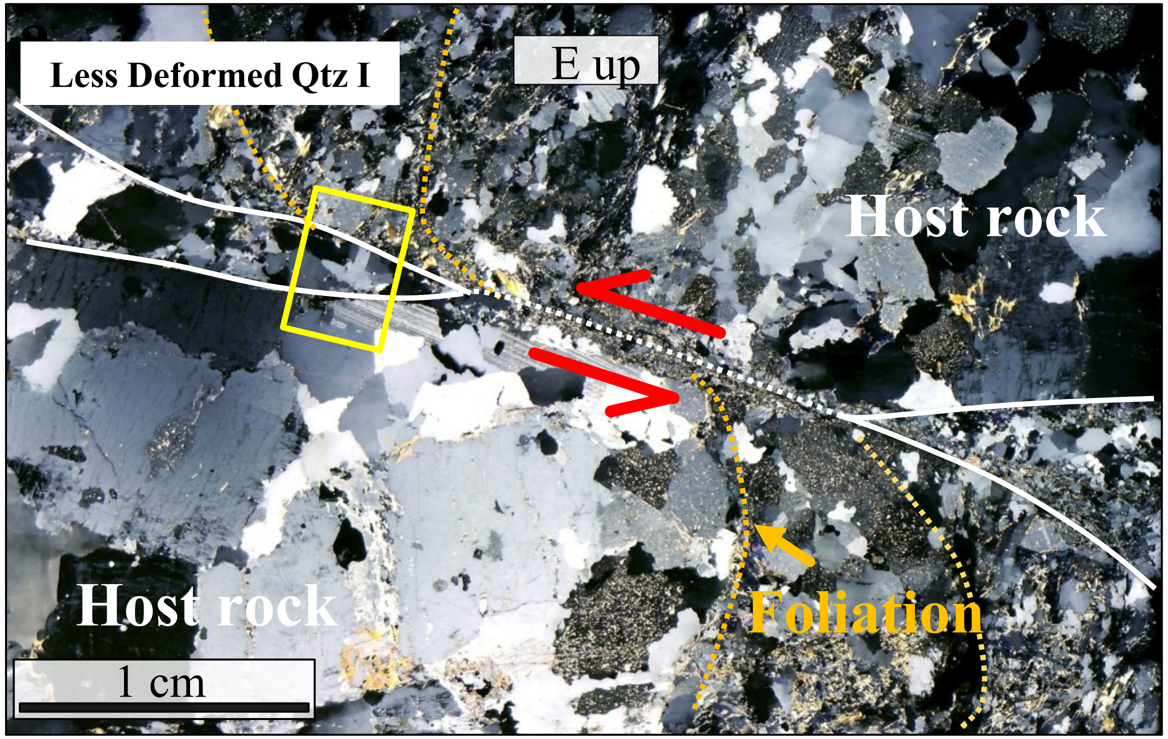
Damage zone
Qtz I- filled joint
Qtz I-filled conjugate fractures
N
Dextral fractures
Sinistral faults
Fracture cleavage (joint)
2 m

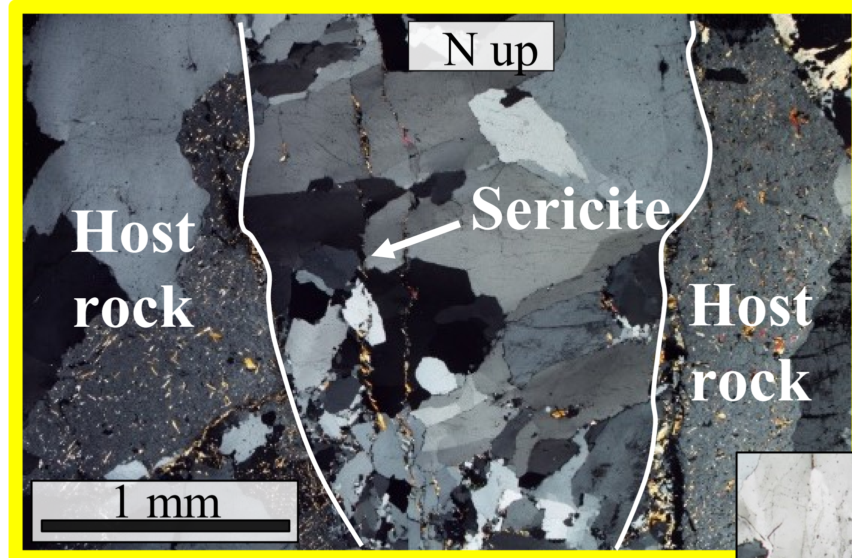


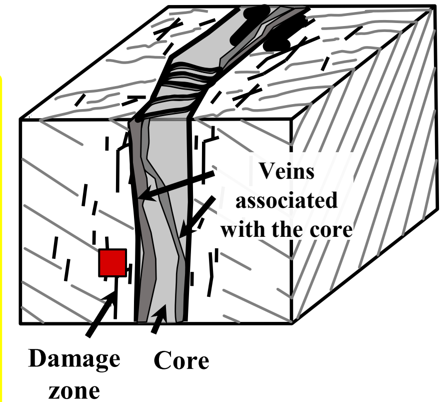
FC is decorated by two distinct generations of quartz veins (Qtz I and Qtz II). Qtz I from the FC shows the same mesoscopic appearance of Qtz I in the DZ. Qtz II is younger and has a milky-white appearance.

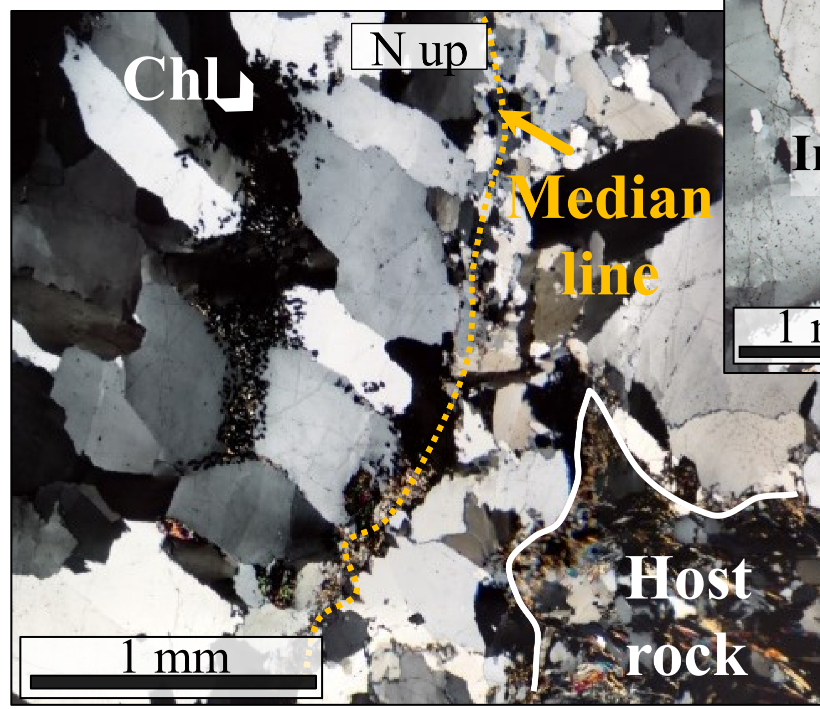


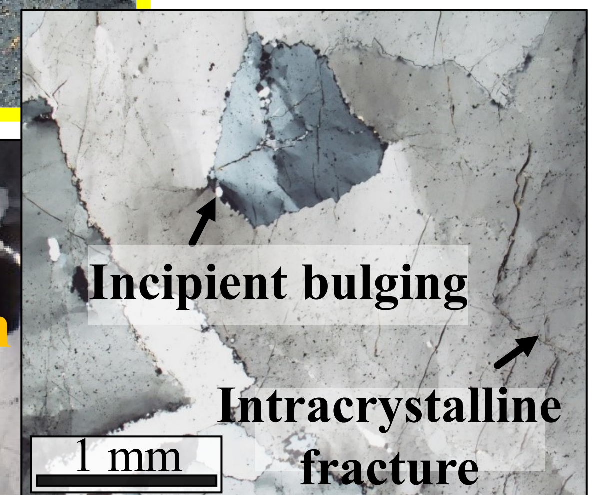
3.3 Microstructural analysis: Qtz I damage zone





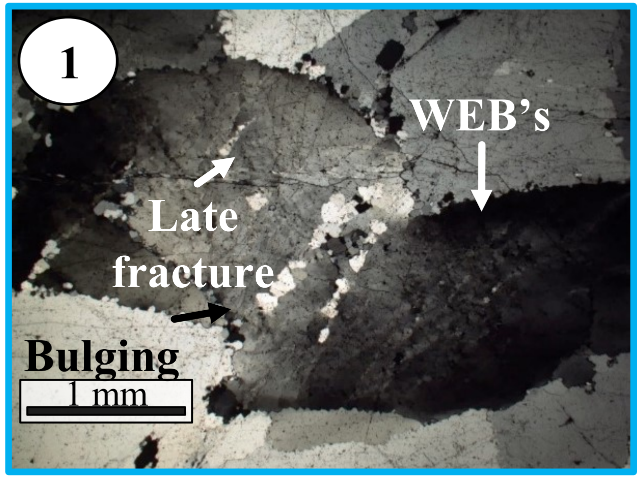




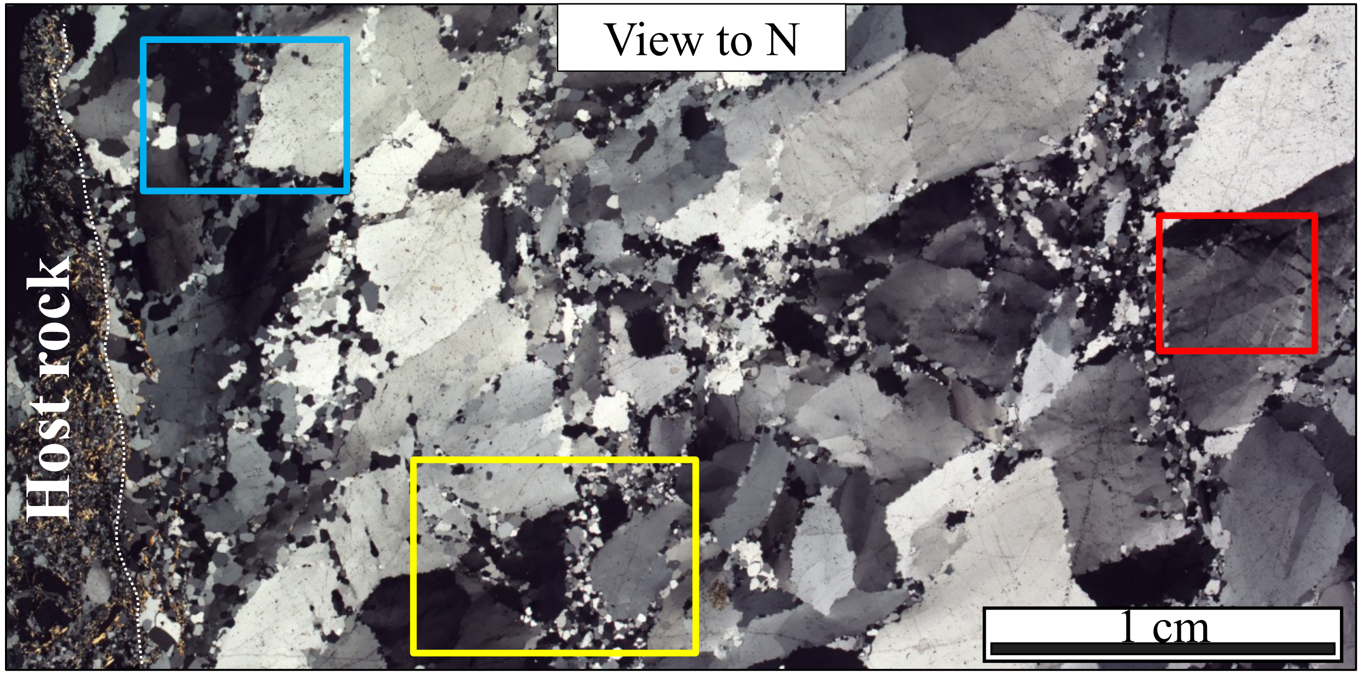


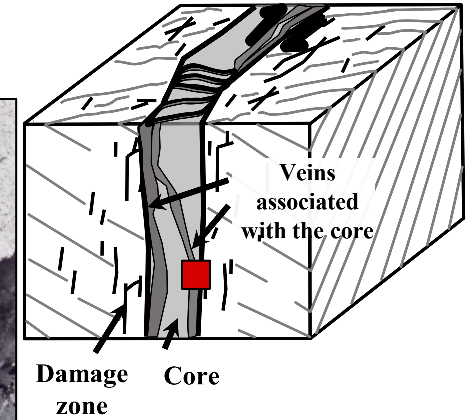
- Qtz I-DZ vein shows both elongated and blocky textures.
- Grain size between 200 μm and 3 mm.
- Sericite microfractures cross-cut Qtz I crystals.
- Medial lines (ML) are locally visible, suggesting repeated crack and seal.
- Internally deformed crystals showing incipient bulging and intracrystalline fracturing.

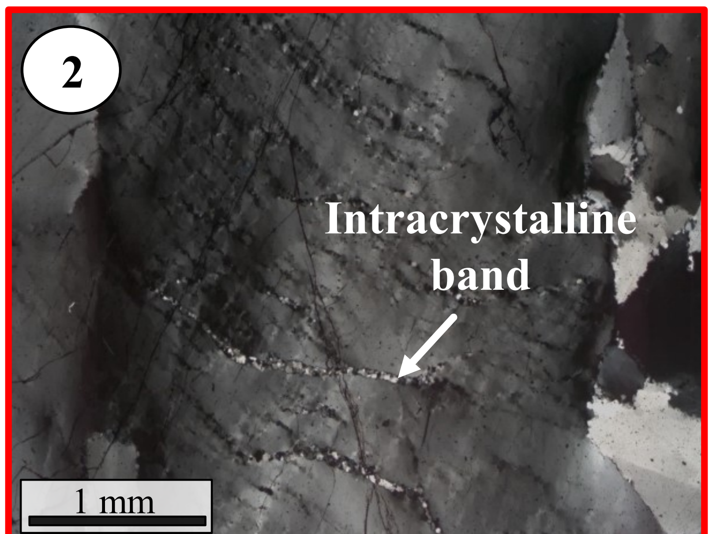
3.4 Microstructural analysis: Qtz I fault core



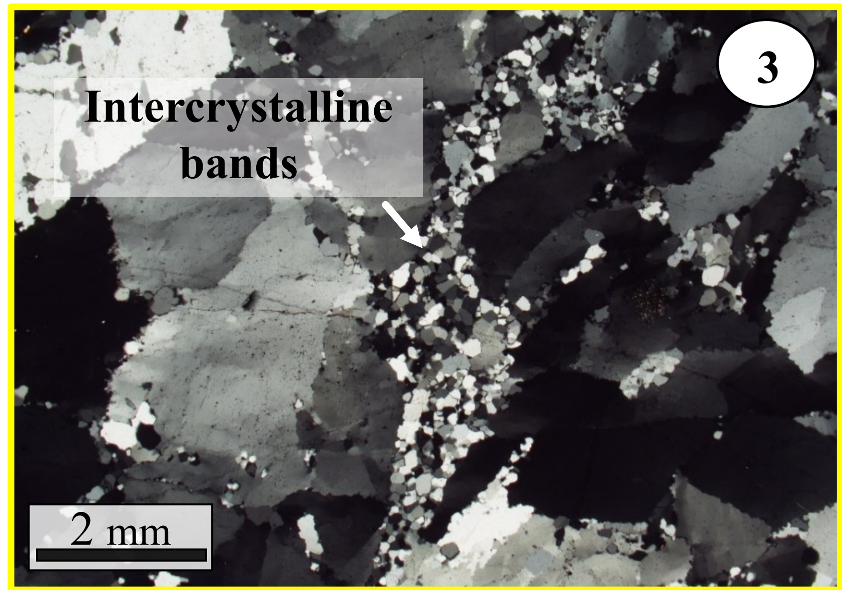
Evidence of low-temperature, intracrystalline deformation of the largest crystals (i.e. undulose extinction; wide extinction bands-WEBs and bulging).





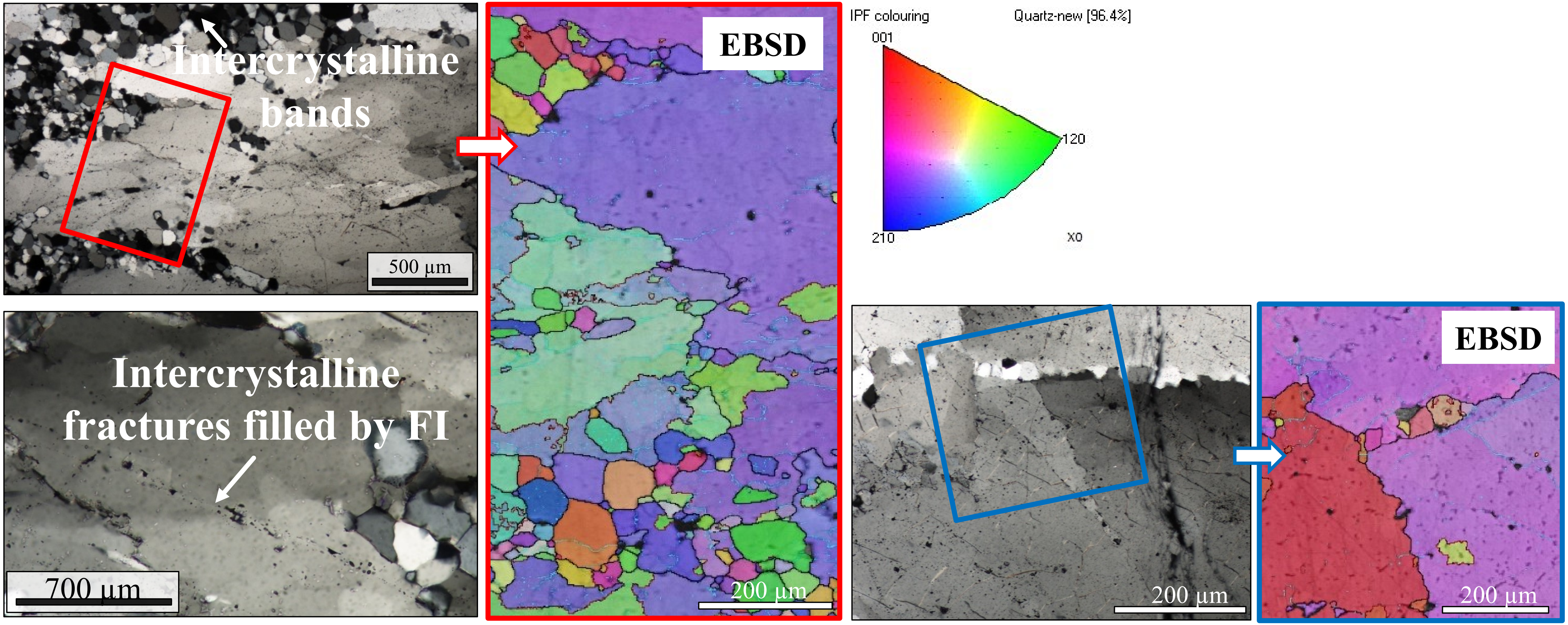


Plastically deformed quartz crystals are crosscut by narrow, intracrystalline fractures of quartz new grains.

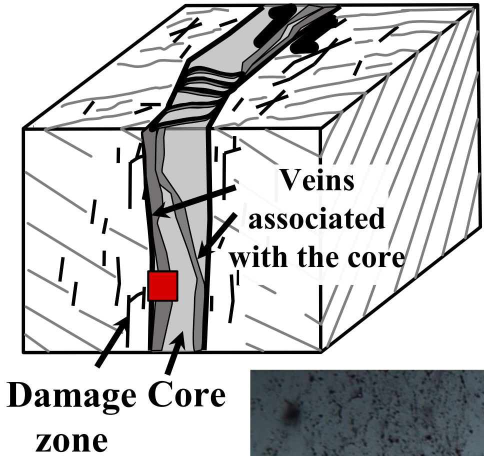


Crystals hosting intracrystalline bands are cut across by another later set of subparallel intercrystalline fractures produced by a later brittle deformation event. These fractures are in turn sealed by new grains of quartz.

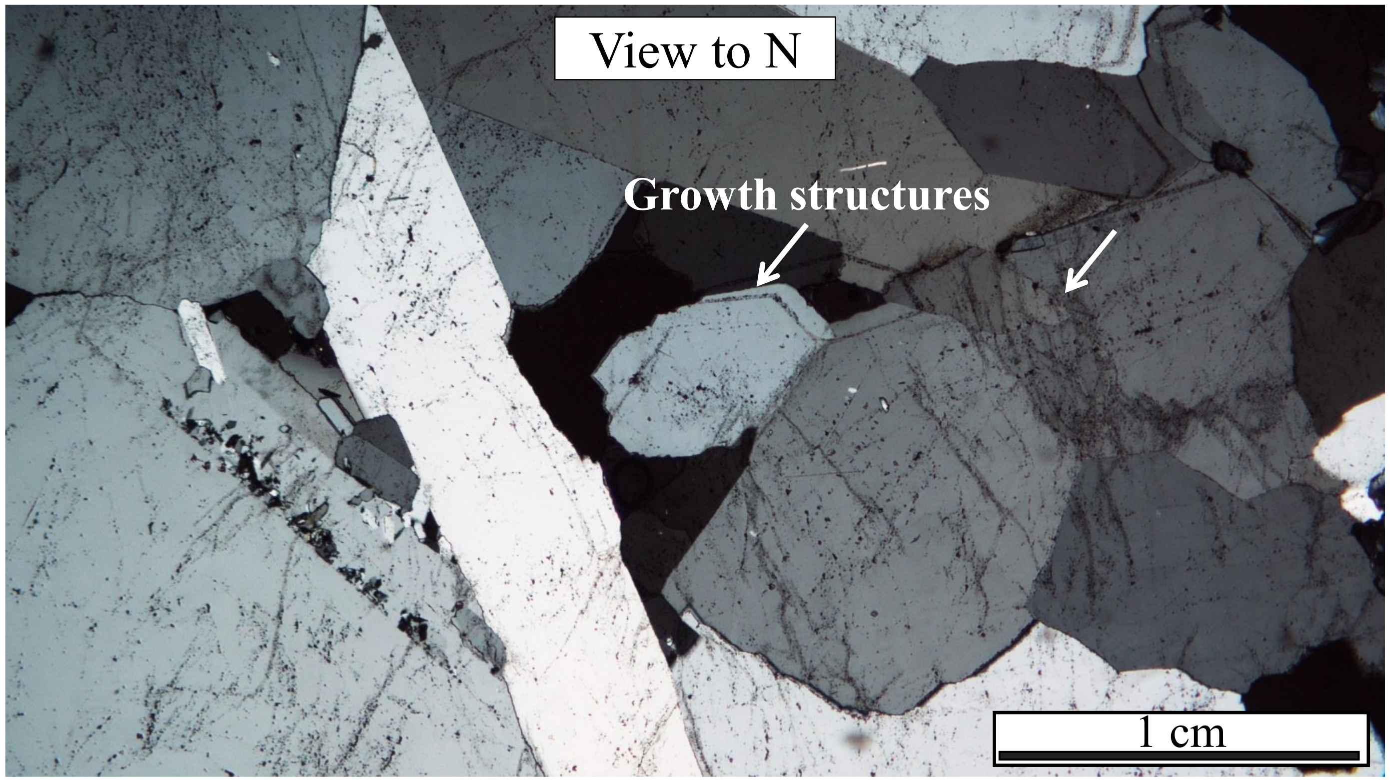
3.4 Microstructural analysis: Qtz I fault core

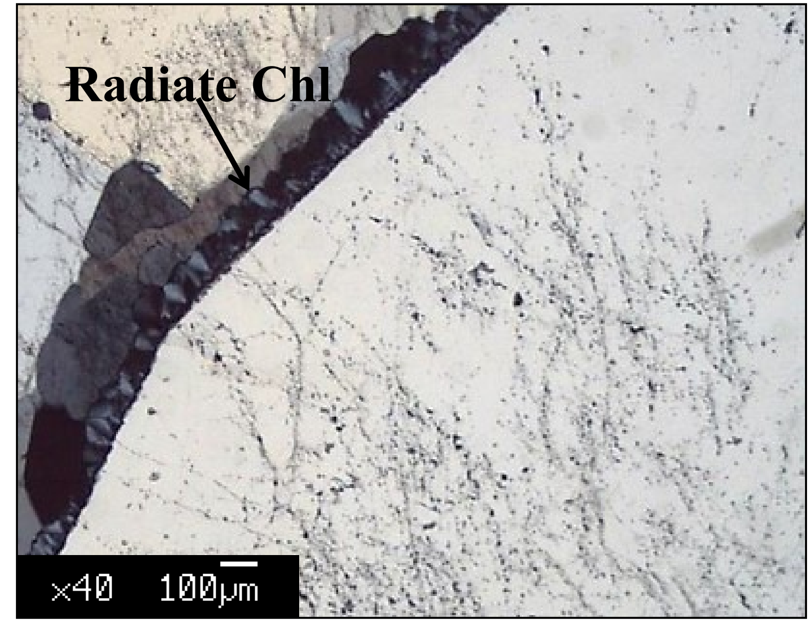


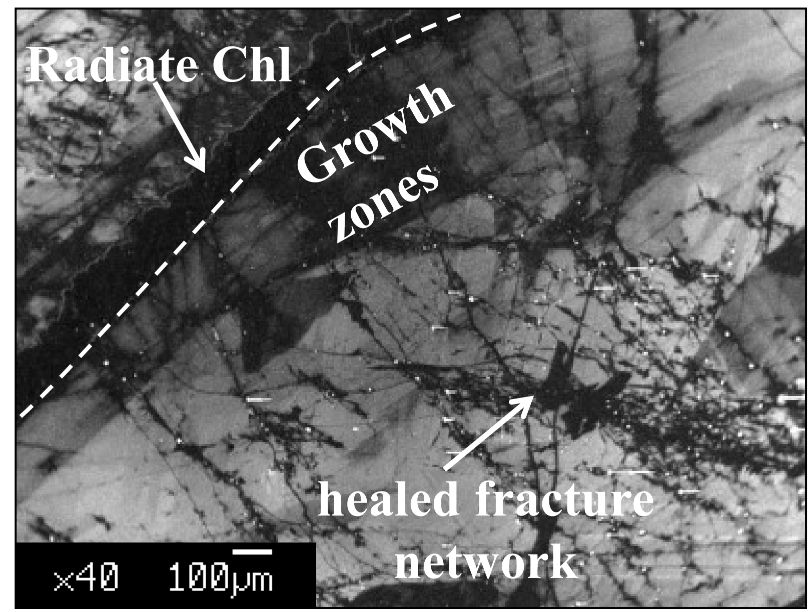
4 • New grains sealing the fractures reflect the combined effect of neocrystallization by nucleation and growth in fractures and by dynamic recrystallization (SGRR).



3. Microstructural analysis: Qtz II fault core

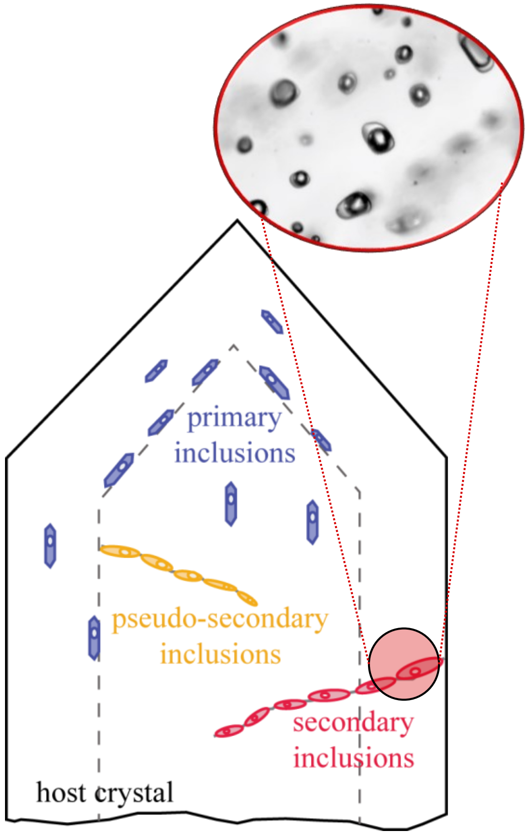


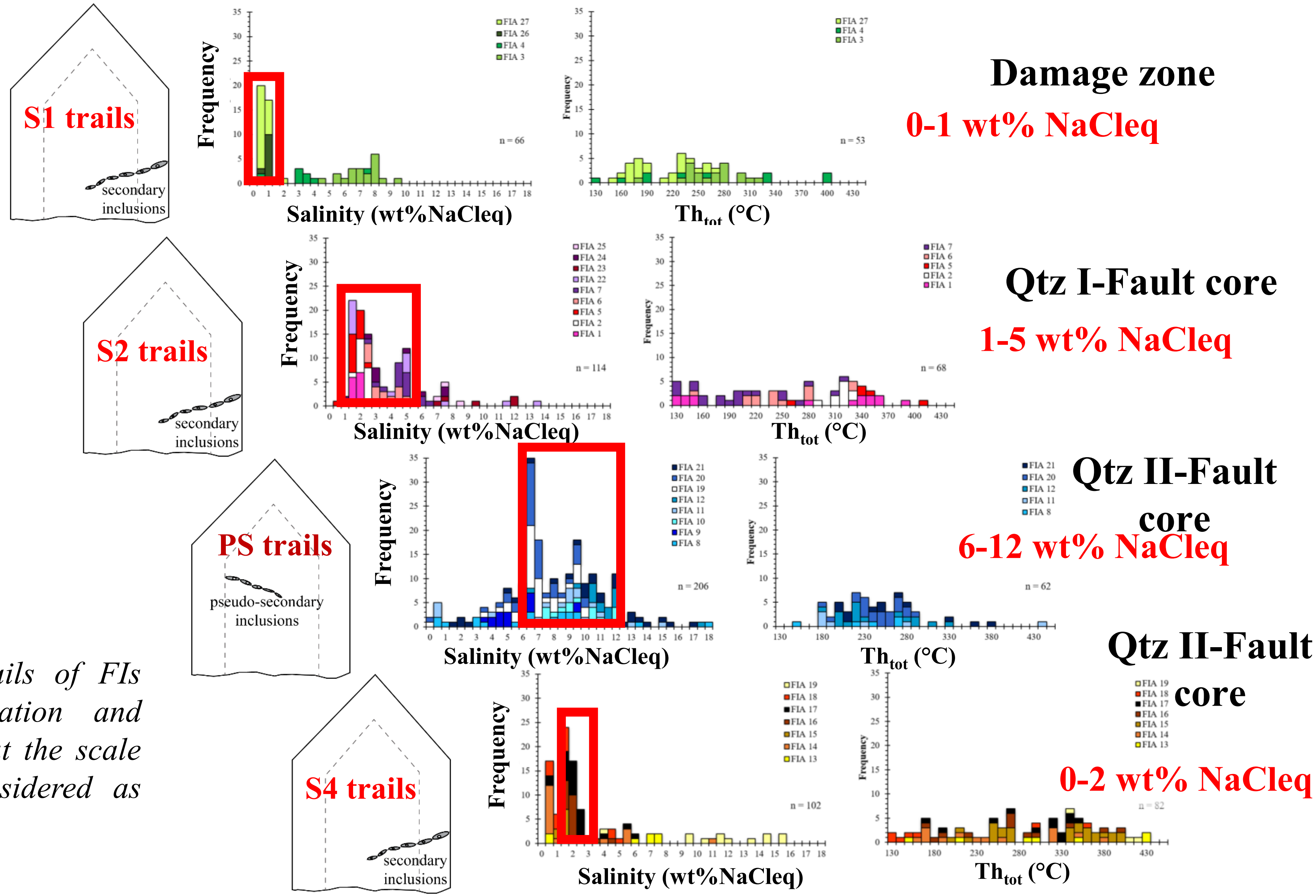




- Coarser grain size (up to a few mm) and straight grain boundaries.
- Scarse internal deformation (internal growth structures are visibles).
- Pervasive fracturing (also as healed fractures) highlighted by cathodoluminescence.

4.1 The study of synkinematic fluids: fluids composition





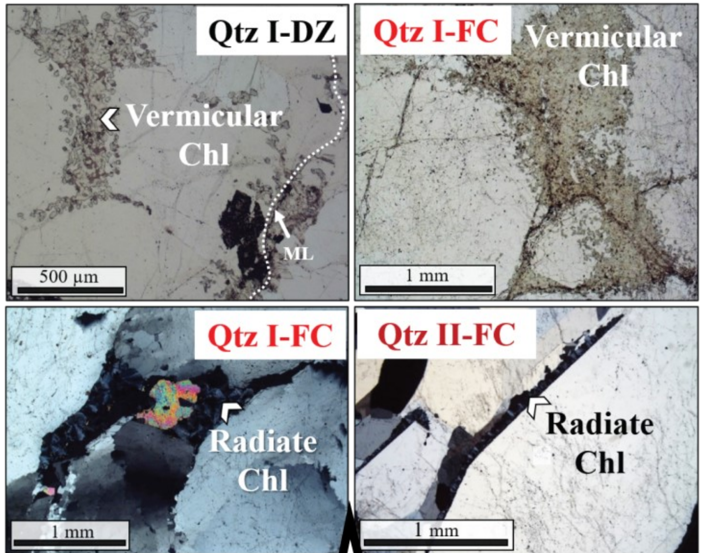
Petrographic approach: *Trails of FIs that exhibit similar orientation and petrographic characteristics at the scale of the thin section are considered as cogenetic.*

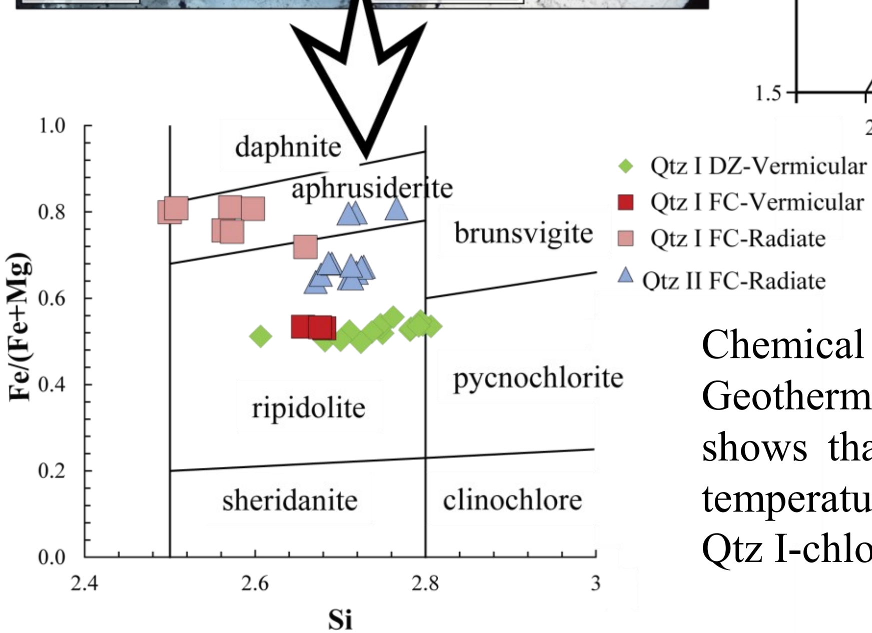
H_2O-NaCl system

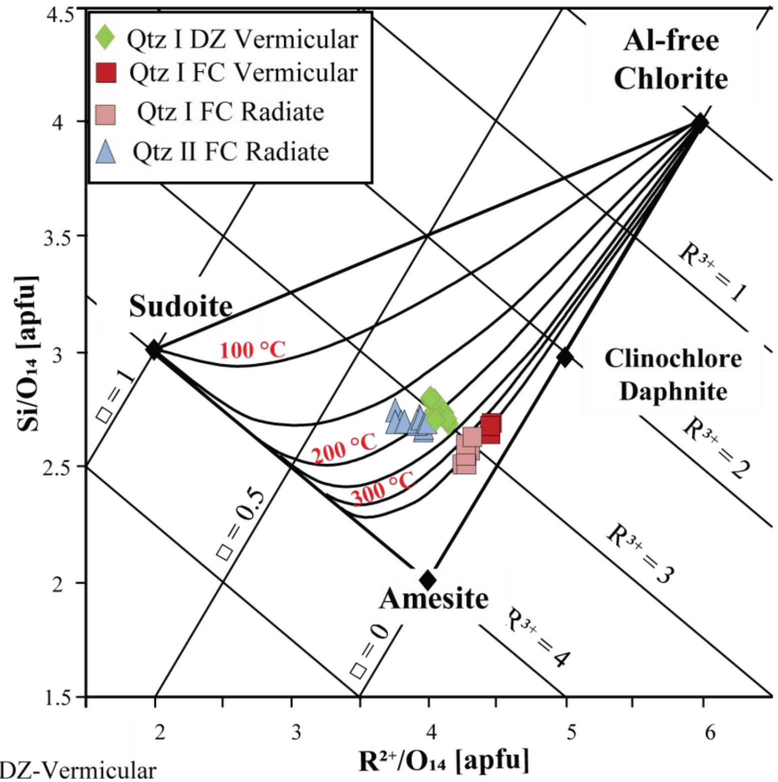
most probable salinity ranges

4.2 The study of synkinematic fluids: mineral-pair geothermometry

Chlorite-Quartz pair

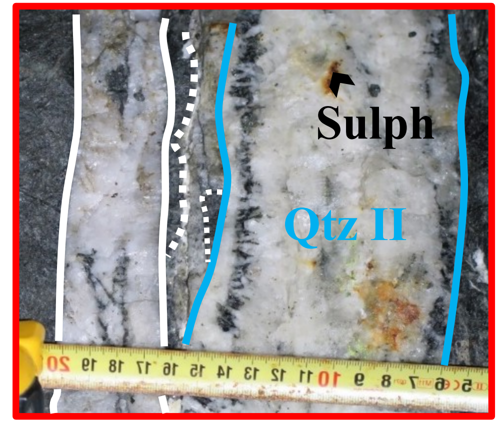


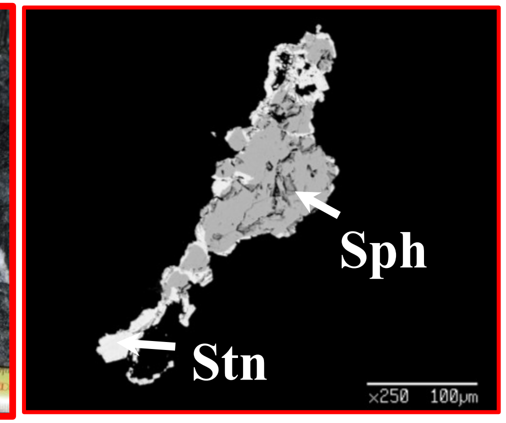


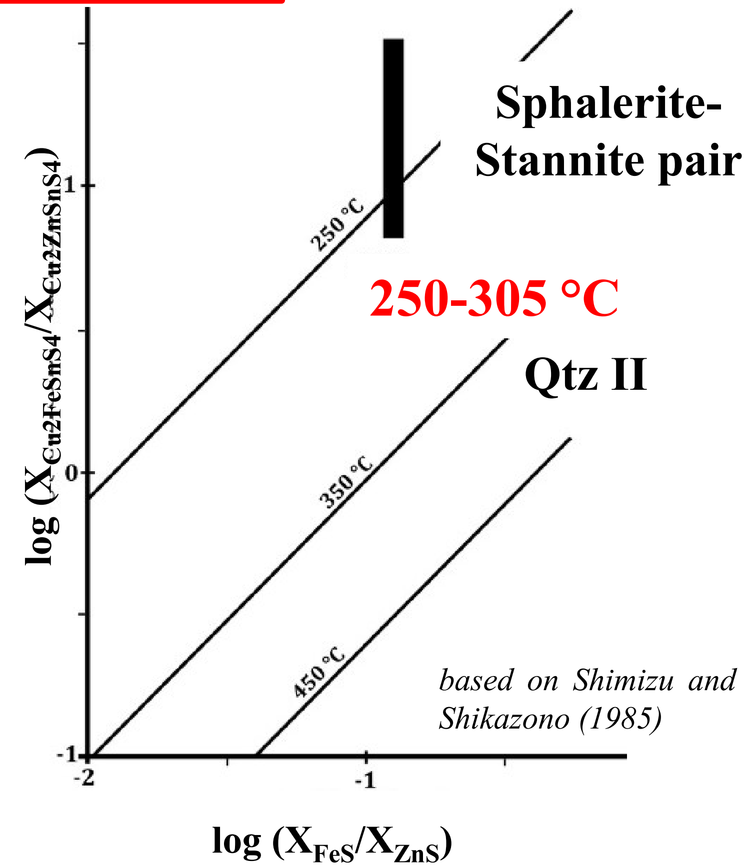


based on Bourdelle and Cathelineau (2015)

Chemical data on suggest distinct fluid compositions. Geothermometric constrains on quartz-chlorite pair shows that they precipitated from fluids with distinct temperatures. The maximum temperature is from the Qtz I-chlorite pair from the fault core.

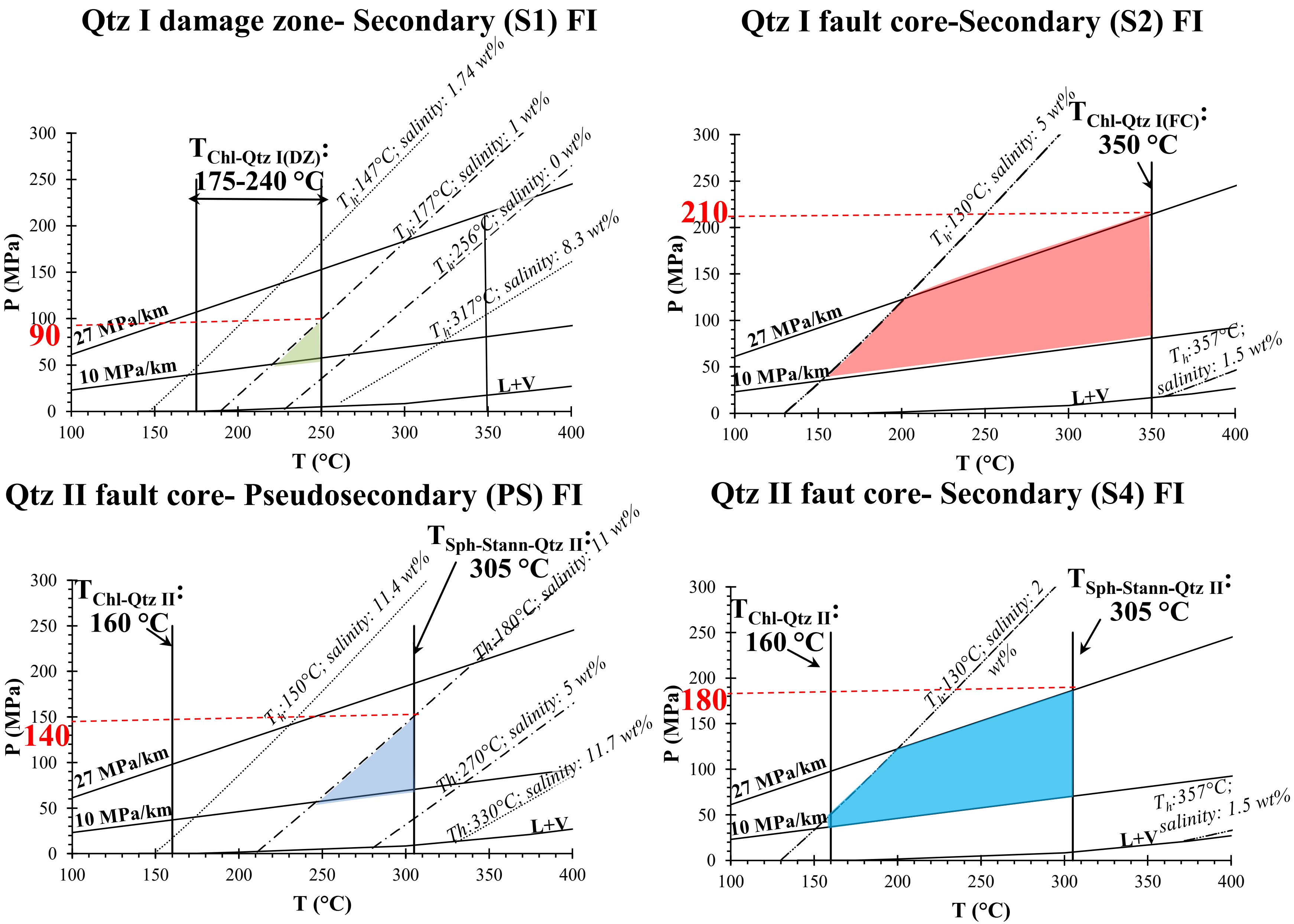






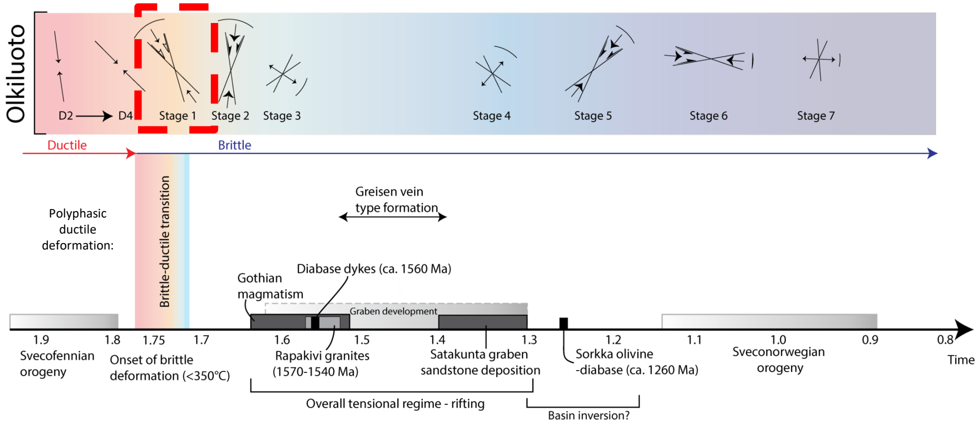
based on Shimizu and Shikazono (1985)

4.3 The study of synkinematic fluids: fluid pressure estimates



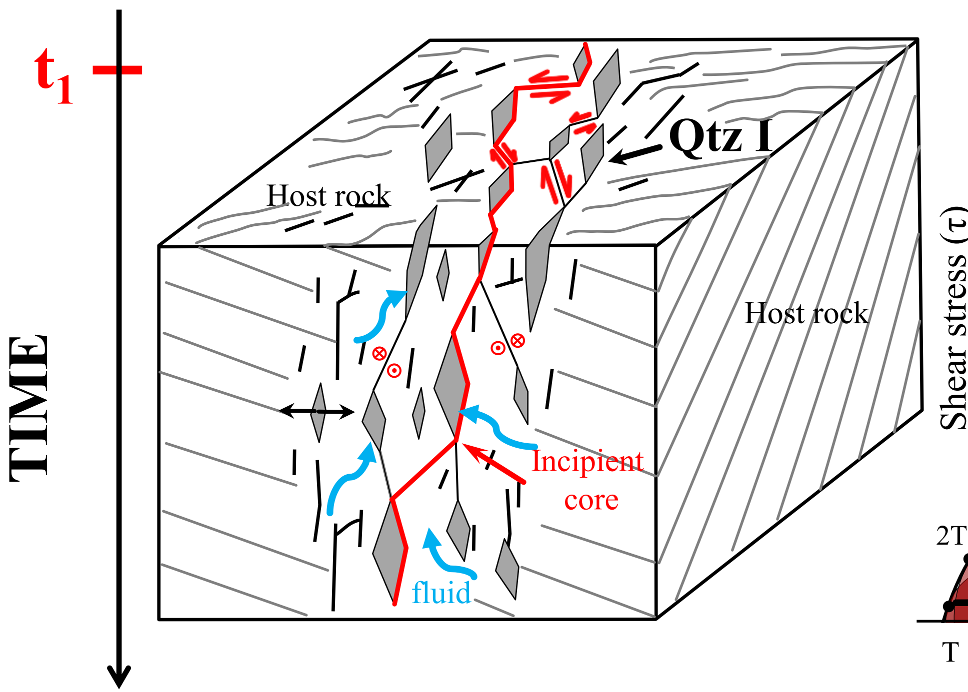
PT trapping conditions of the synkinematic fluids (coloured areas) were derived by combining i) the most representative salinity estimates for each structural domain with ii) the pair-mineral geothermometry estimates and iii) the hydrostatic and lithostatic fluid pressures computed assuming a regional geothermal gradient of c. 40°C/km (assuming retrograde conditions of 4 kbar and 650°C, from Kärki and Paulamäki, 2006). Estimated peak conditions (i.e. likely fluid pressure in case of hydrofracture) are highlithed in red.

5. Fluid controlled strain localization

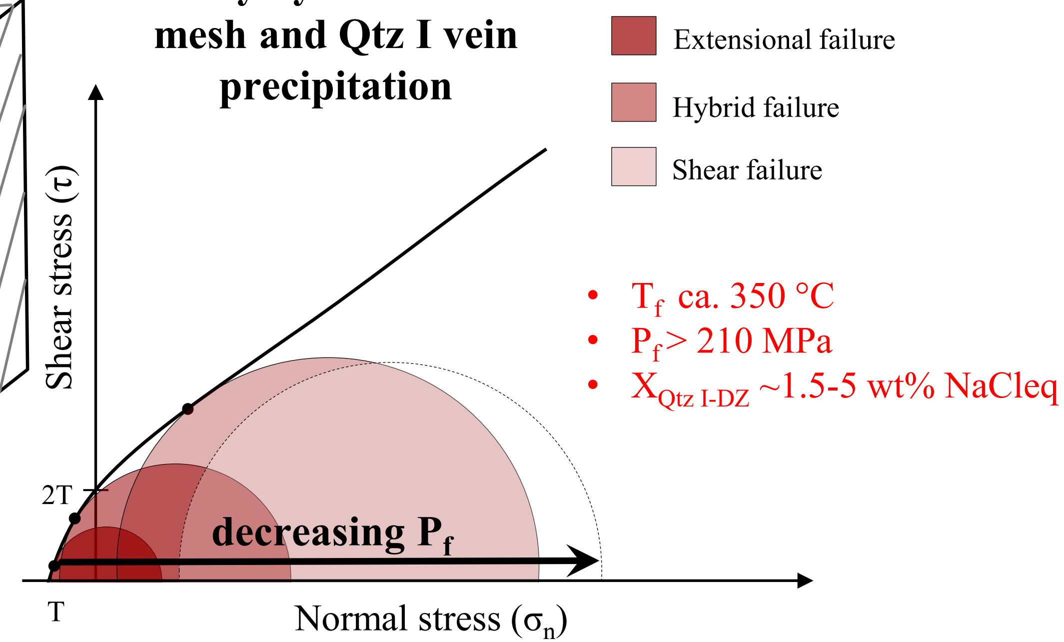


modified after Mattila and Viola (2014)

We correlated this deformation stage to the earliest onset of brittle conditions in southwestern Finland c. 1.75 Ga ago, under overall NW-SE to NNW-SSE transpressive conditions (Stage 1 of Mattila and Viola, 2014) .

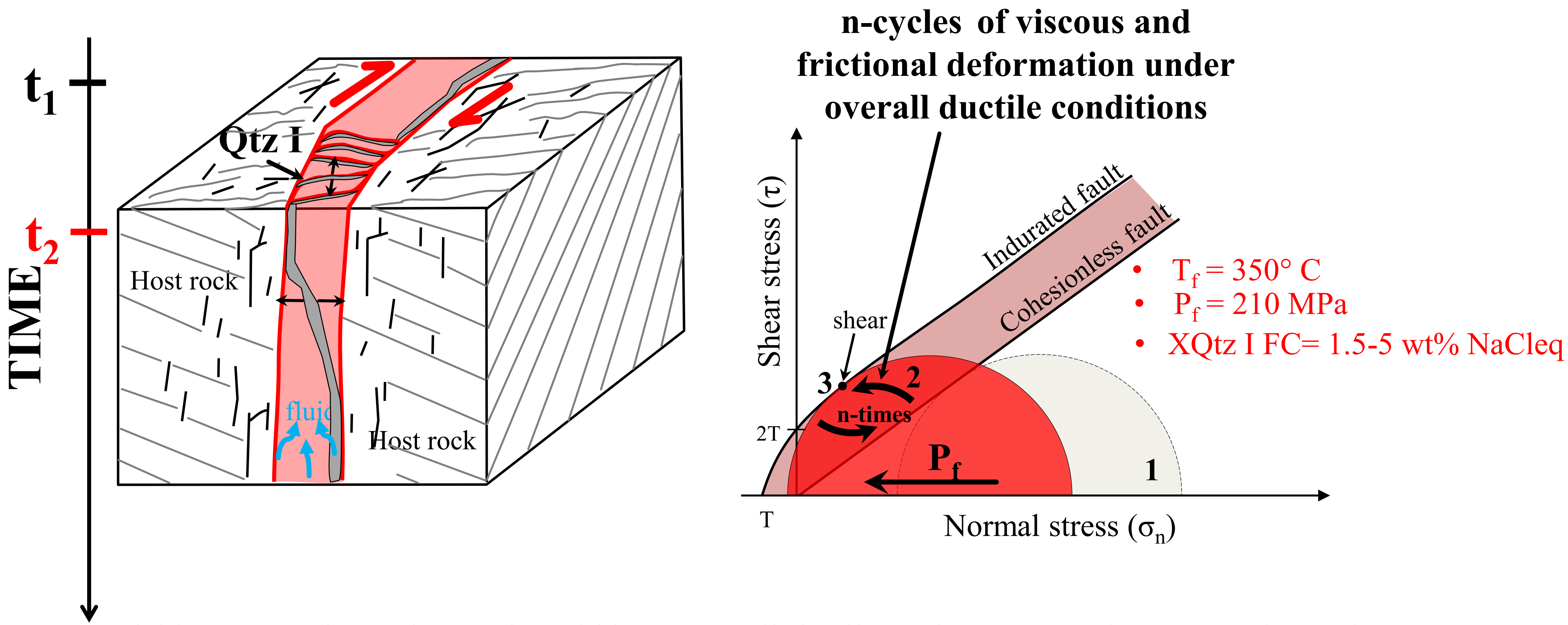


Progressive shear stress recovery by fault-fracture mesh and Qtz I vein precipitation



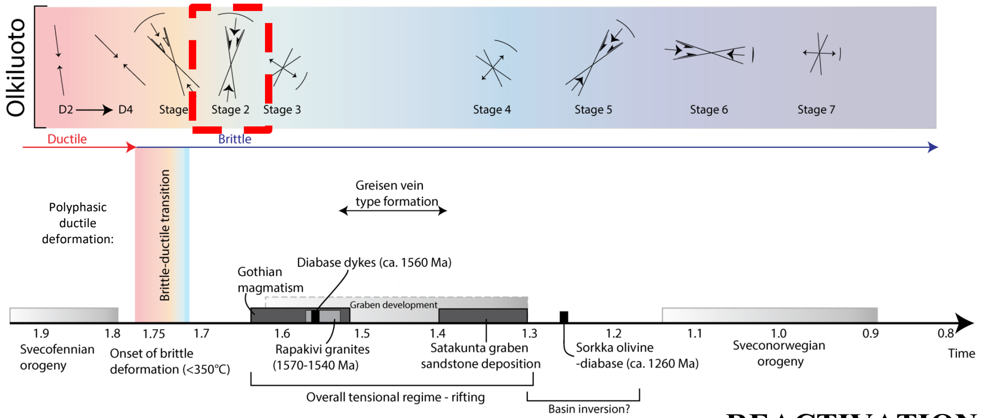
Embrittlement of the Olkiluoto basement and fracture coalescence in an overall ductile environment (< 530 °C).

5. Fluid controlled strain localization



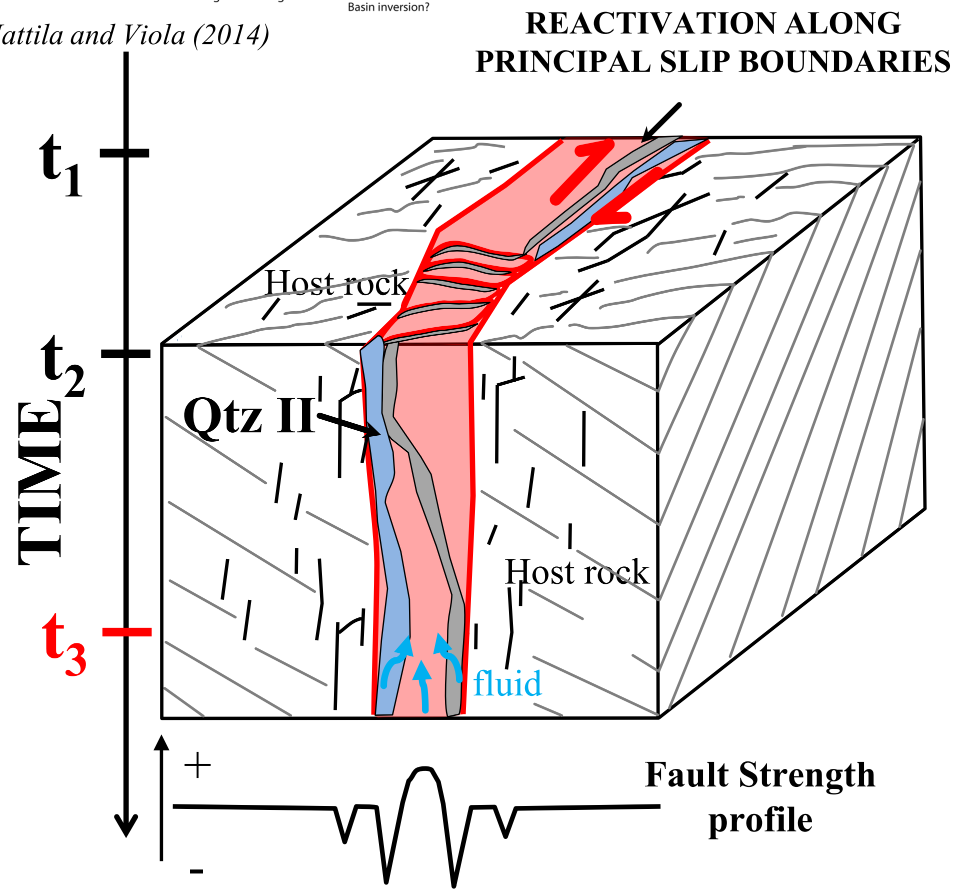
Fluid pressure fluctuation cycles within an overall ductile environment at the BDTZ triggered brittle–ductile cyclicity via fracturing, veining and crystal–plastic deformation, before renewed and fluid-induced embrittlement.

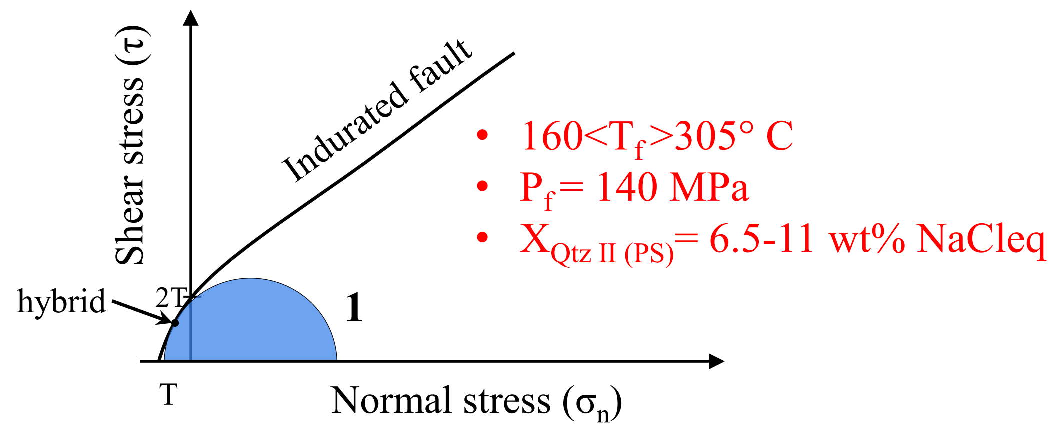
5. Fluid controlled strain localization

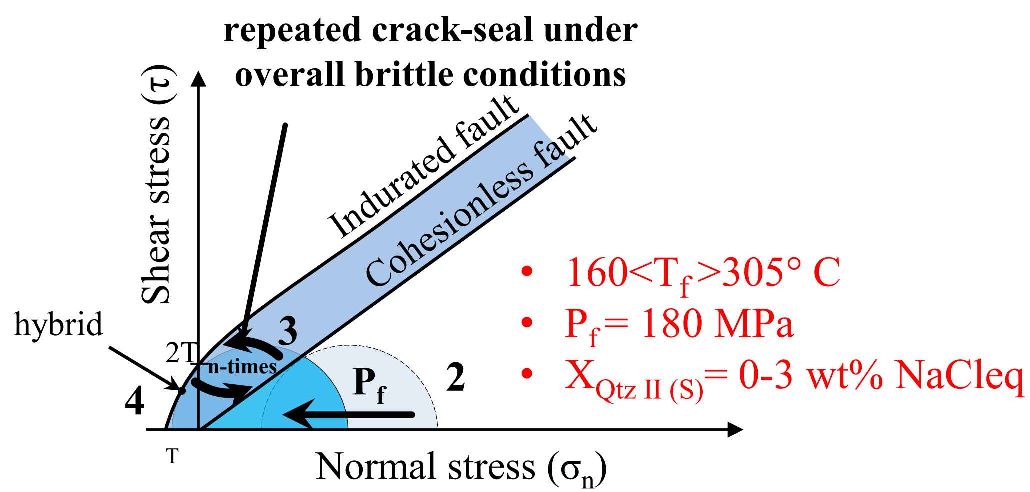


modified after Mattila and Viola (2014)

Later exhumation and cooling of the fault system to fully brittle conditions was aided by selective reactivation of the core and Qtz II emplacement along the pre-existing principal slip zones, weakest part of the fault. We correlated this stage to Stage 2 by Mattila and Viola (2014), i.e. a second brittle stage during which a c. N-S to NNE-SSW-oriented episode of transpressional deformation affected southwestern Finland.







Conclusions

- Faulting results from embrittlement due to fluid overpressure followed by fluid rock interaction during multiple reactivation events.

- This fault-valve behaviour at the brittle-ductile transition led to a strain localization in which plastic deformation combined with fracturing and cementation, leading to progressive strength recovery and sealing of the fault zones which promoted brittle-ductile cyclicity.

-Thank you for reading!-

Thanks to:

POSIVA

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