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Influences of pre-structuration of a reservoir on permeability evolution in fracture zones Insights from mechanical testing on an alteration profile

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ABSTRACT

In the international energy transition, geothermal energy plays a role as a renewable energy which almost does not emit CO₂ and allows the reduction of dependency on fossil fuels. Geothermal energy in a crystalline basement is part of the different deep geothermal sources which can be used for heating or electricity production. In 2018, the heating generated from deep geothermal plants was up to 2.6 Twh in France and is planned to increase. For the upcoming 2030, the objective in France is to have 38% of renewable energy in the final heat consumption, where geothermal energy has its place (French energy transition law for green growth n°2015-992).

Geothermal production in crystalline basement relies on the presence of fractures and sometimes stimulation techniques. In France, such exploited sites are located in Alsace (Upper Rhine Graben, URG) where a hot brine is harvested in the granitic basement to produce electricity (Soultz-sous-Forêts) or heat (Rittershoffen). However, recent unexpected seismic events occurred during the stimulation of new sites and lead to stop deep geothermal exploration in Alsace.

For the resource development of geothermal reservoirs, the understanding of the properties of fractures and fracture networks has to be investigated.

Uniaxial compression strength, triaxial compression strength and brazilian disk tests measurements were performed on samples collected along a fault zone from Schauinsland mine in the Black Forest. These samples are considered as analogues of the deep geothermal reservoir of Soultz-sous-Forêts in the URG. A decrease of the tensile strength and elastic modulus was measured along the fault zone while the cohesion value

is much higher than expected in the core zone. The Poisson ratio is the highest in the damage zone which indicates that the samples are heterogeneous and need to be investigated at a smaller scale.

1. INTRODUCTION

Geothermal energy allows the production of a local and permanent source of energy for electricity or heating system with almost no CO₂ emission. This is the case in Alsace (France) at Soultz-sous-Forêts and Rittershoffen exploitation sites where a geothermal brine is collected in a crystalline fractured basement and used for energy production. In this context, the fracture network is the main fluid pathway in the reservoir. The permeability can be increased by stimulations (thermal, hydraulic and/or chemical) to enhance the connectivity between the fractures or enlarge them. The understanding of how fluid circulates in such a reservoir is a key parameter to consider, for a safe and efficient geothermal installation.

The deformation of a reservoir plays a role in fluid circulation pathways by creating fractures and fault zones. The pre-structuration induced by deformation during previous geological events may affect later fluid circulations in fault zones. This may change the behaviour of a fault core to act as a barrier or as a conduit (Glaas, 2021; Klee, 2021). Mechanical testing and geological investigations will give a better understanding of the role of the pre-structuration of a basement reservoir and its influence on later fluid circulation and a potential reason for induced seismicity. Such events occurred recently in France (Schmittbuhl et al., 2021) where shear zones were reactivated during geothermal stimulation.

A surface analogue of a fractured geothermal reservoir was investigated in the Black Forest mines in the URG to be in the same geological context as in the deep

exploited basement but to allow a wider view than in boreholes. This gives access to a 3D view of the structures where a sampling profile was established from a non-deformed gneiss to a high-strain fault core zone rich in clay minerals, through a well-developed damage zone. This study is focused on understanding the differences in the mechanical behaviour of the core zone and damage zone sampled in the mines by realizing mechanical tests.

2. GEOLOGICAL CONTEXT

2.1 THE UPPER RHINE GRABEN AND BLACK FOREST

The URG is a part of the European Cenozoic Rift system (Fig.1) with an NNE orientation, a length and a width of respectively 300 km and 30-40 km (Ziegler, 1992). Its formation took place in an extensional context and is contemporaneous of the Alpine and Pyrenean orogenesis (Schumacher, 2002). The URG is filled with Mesozoic and Cenozoic sediments (Ziegler, 1992) and lies on Hercynian basement rocks. This structure is bordered by major normal faults which delimitate the Vosges massif on the Western side and the Black Forest on the Eastern side. The Black Forest thus corresponds to a shoulder of the graben and is composed of crystalline basement rocks. Mesozoic and

Cenozoic sedimentary rocks are covering the massif (Werner and Dennert., 2004).

2.2 THE SCHAUINSLAND MASSIF

The Schauinsland massif was chosen as a surface analogue of a fractured geothermal system of the URG to understand the role of fault zones in fluid pathways. This massif located in the Black Forest is made of Pre-Cambrian gneiss with various compositions, (Witterbrink, 1999). The massif has recorded deformation events since the Variscan in various directions and is crosscut by a high strain fault zone with an E-W direction called the “Ruschel” in the miner language (Fig.2). This fault zone was reactivated several times, illite and cataclasite can be found inside. The fault zone was most active during the Jurassic (Werner et al., 2002). The interest of this massif is the presence of ore and mineral veins that are almost perpendicular to the Ruschel as it can be transposed to an actual geothermal reservoir where brines encounter shear zones.

From the 13th to the 20th century, the Schauinsland mine was exploited for various materials like lead, zinc and silver. Various ore veins were exploited and can be observed in the mine. These are markers of fluid circulation inside the mine.

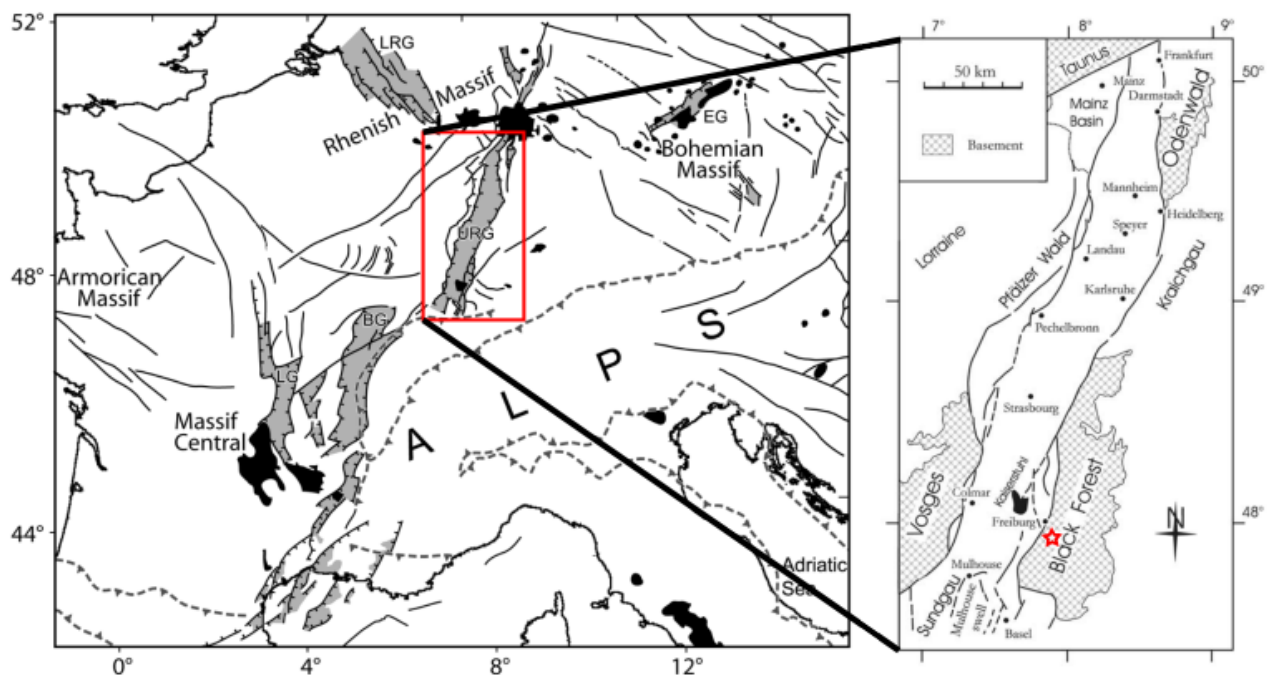


Figure 1: Structural map of the European Cenozoic rift system (on the left part) modified by (Lustrino et Carminati., 2007) after (Dèzes et al., 2004). The Cenozoic faults are represented in black lines, the sedimentary rift in light grey and the volcanic field in black. The dashed lines correspond to the Alpine deformation front. BG—Bresse Graben; EG—Eger Graben; LG—Limagne Graben; LRG—Lower Rhine Graben; URG—Upper Rhine Graben. The tectonic map of the Upper Rhine Graben (on the right part) which has NNE-SSW normal border faults, the Schauinsland massif is located by the red star on the map, modified after (Schumacher, 2002).

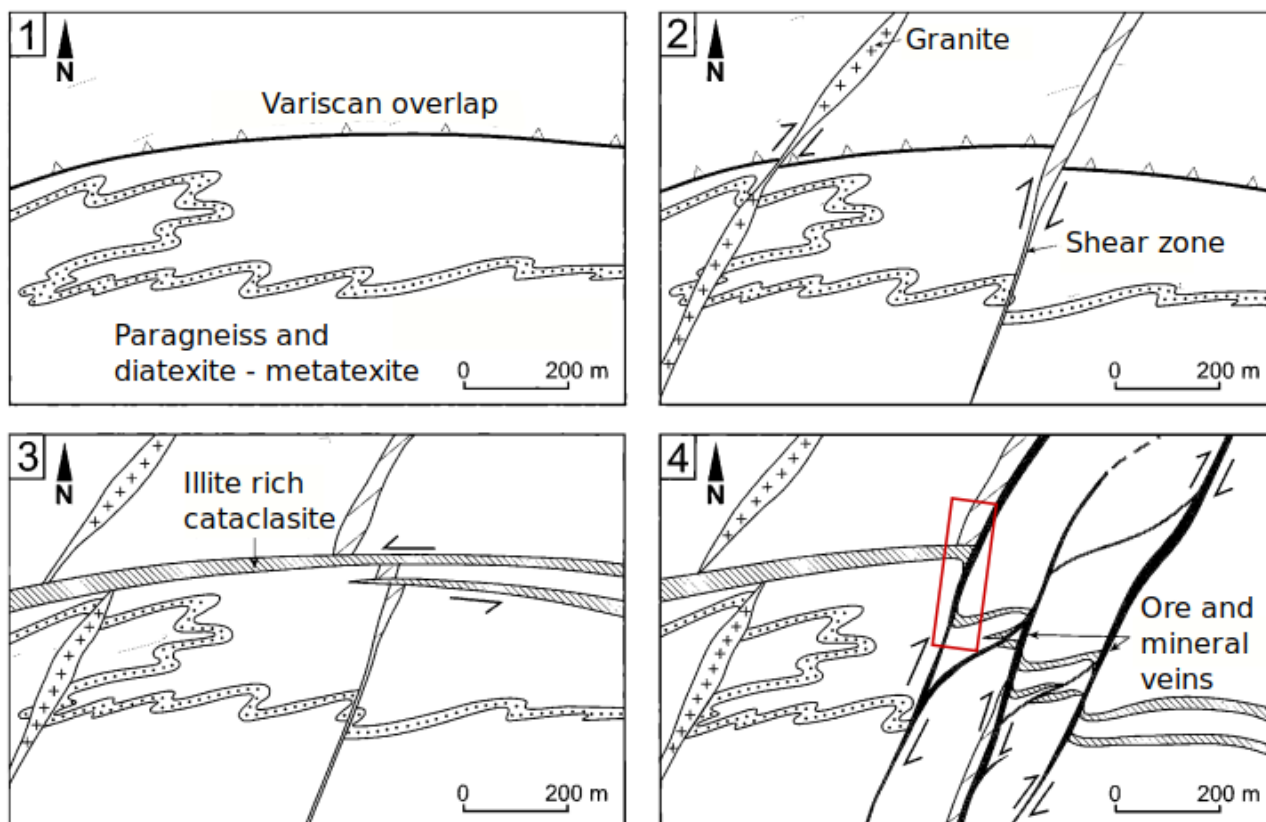


Figure 2: Representation of the tectonic evolution of the Schauinsland massif since the Variscan orogenesis. Here is the tectonic situation at the Upper Carboniferous (1). Afterwards, granitic intrusion and development of shear zones from the Upper Carboniferous to the Permian occurred (2). An E-W shearing of the massif and the creation of the highly sheared zone called the “Ruschel” took place. Cataclasite was developed and illitisation occurred during the Jurassic to the Cretaceous (3). Deposition of ore and mineral veins happened with a NNE-SSW shearing during the Cenozoic (4). The red rectangle corresponds to the geological setting that is investigated as an analogue of a geothermal reservoir, modified after (Werner et al., 2002).

2.3 SCHAUINSLAND MINE

A specific N-S gallery in the mines was investigated, representing the geological context depicted in the Fig.2 in the red rectangle. It follows a decimetric ore vein mostly composed of barite that developed in a paragneiss. This vein vanishes in the vicinity of the high strain zone rich in clay minerals, the Ruschel (Fig.3). As described by Werner et al (2002), this high strain zone was shifted during a late phase of deformation allowing the ore mineral deposition. Ductile deformation and clay smearing features are observed in the gallery, especially in the core of the fault zone (Fig.4). However, the vein (Fig.5) which was deposited later than the E-W fault zone does not crosscut this pre-structuration.

To develop such ore veins in a paragneiss, the host rock may have accumulated elastic stress and was fractured leading to the formation of breccia (Fig.5). However, the same stress conditions applied to a rock rich in clay minerals may not induce the same response and clay smearing occurs instead of accumulating stress. This

difference in mechanical response may not let the fluid propagates and develop in the fault core.

These observations highlight the importance of pre-structuration in the case of brine circulation in a pre-structured reservoir. To better understand the system, mechanical testing of samples taken from the core of the fault zone to the less deformed gneiss was performed.

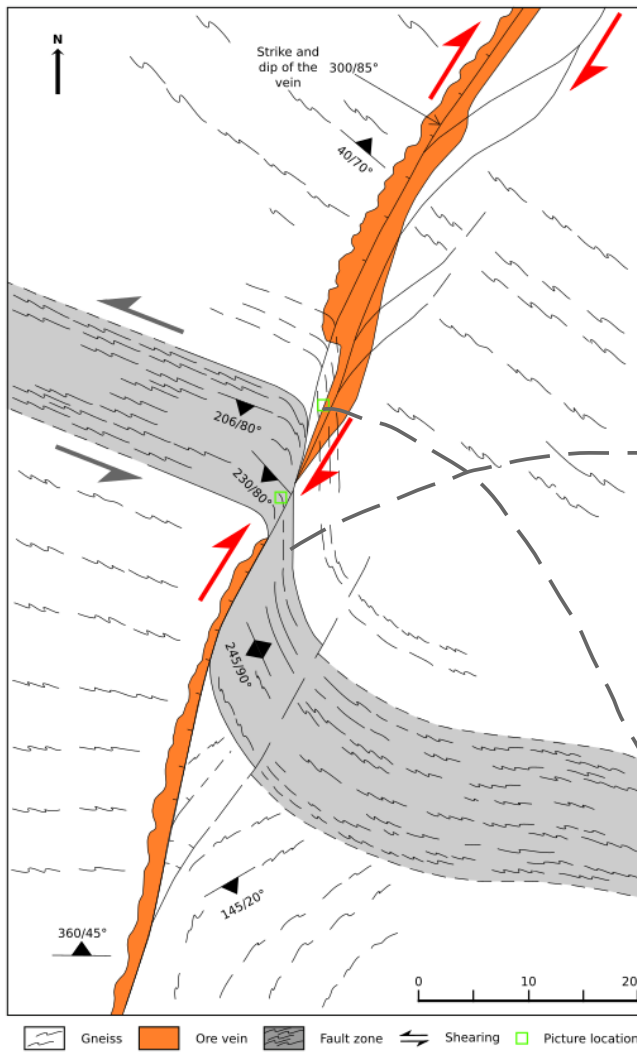


Figure 3: Geological scheme of the Schauinsland gallery (schematic map view), modified after (Werner et al., 2002). The mine has recorded multiple shearing episodes. The first visible one created the highly sheared zone, called the “Ruschel” in mining language (in grey) with a senestral movement and an E-W direction. The second one crosscuts the Ruschel with a dextral movement and a NNE-SSW direction. The ore vein deposited after the Ruschel shearing. It vanishes close to the

fault zone and reappears on the other side. The green squares indicate the location of photographs of the fault core (Fig.4) and the ore vein (Fig.5).

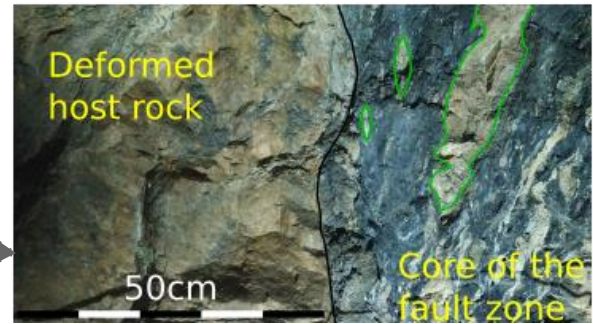


Figure 4: Picture of the deformed host rock and the core of the fault zone. The fault core (“Ruschel”) is rich in clay minerals (grey color) and contains clasts of the host rock 10(green shapes in the figure). An alternation between the deformed host rock and a high-strain zone rich in clay minerals can be observed multiple times on the gallery wall.

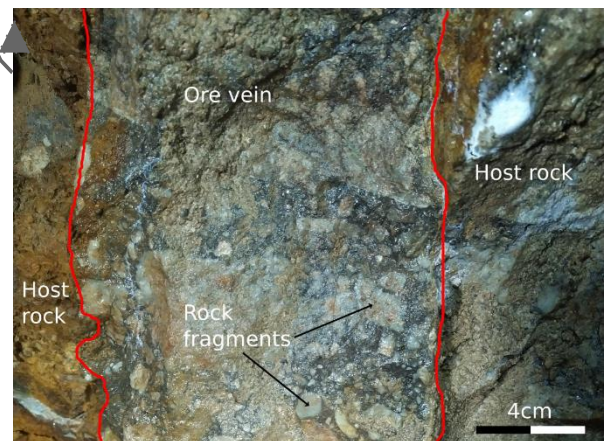


Figure 5: Picture of the ore vein (delimited by the red lines on the figure) developed in the host rock, filled with galena containing some small host-rock fragments. The ore vein is visible when leaving the fault zone and increases in width.

2. METHODS

The rock mechanical behaviour was analysed by a series of brazilian disk, uniaxial compression strength and triaxial compression strength tests. The samples were collected in the Schauinsland mine from where the extraction and transportation of rock materials are difficult. Therefore, only a minor amount of samples was investigated. Moreover, the rocks were difficult to extract due to the high-strain zone they had overcome during their history. Hence, the tested cylindrical samples had small dimensions with a diameter of 30 mm and a length of 60 or 15 mm for all mechanical tests.

The brazilian disk (BD) test was conducted at the Mechanical Testing System (MTS) of GFZ Potsdam with a loading rate of 0.001 mm/s until failure (Fig.6). In total 53 samples were investigated.

The uniaxial compression strength (UCS) test was executed in the same device. Hereby, the samples were covered by a shrink tube and two LVDT extensometers for lateral and vertical strain measurements were applied. The constant loading rate was identical to the Brazilian Disk test. In total three samples were analysed.

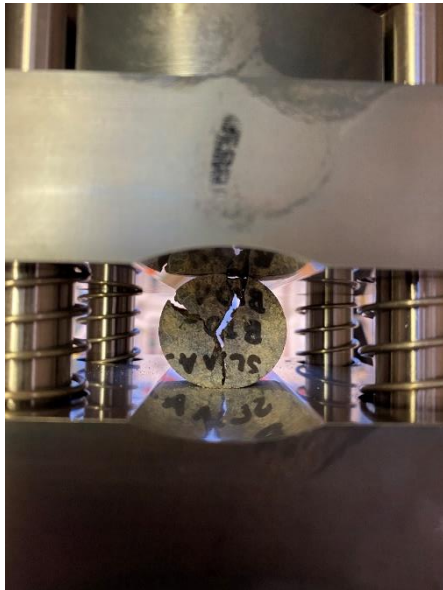


Figure 6: The setup of the brazilian disk test in the MTS of GFZ Potsdam.

The triaxial compression strength (Triax) test was conducted with a loading rate of 0.5 MPa/min and the same setup as in the UCS test was utilized. For the confining pressure, 20 MPa, 40 MPa and 60 MPa were applied in single measurements until the failure. In addition, two multiple failures were applied with all three confining pressure maxima. Hereby, the axial loading was stopped shortly before the failure occurred and the next higher confining pressure was applied. At 60 MPa confining pressure the axial loading was

increased until failure. In total, ten samples were investigated.

3. RESULTS

The results of the mechanical testing are divided into the three different experiments BD, UCS and Triax. The results of the tests are displayed for the three different zones of the profile (Fig.7, Table 1).

Table 1: Results of the brazilian disk test, Zone 1 describes the basement, Zone 2 transition zone and Zone 3 close to the inner core of the damage zone with the tensile strength (TS in MPa)

Zone	TS [MPa]	amount
1	9.48	16
2	7.07	22
3	4.93	15

The three samples of the UCS experiments are shown in Table 2.

Table 2: Results of the UCS with the elastic modulus (E-Modul) and the maximum compressive strength (Co)

Zone	E-Modul [GPa]	Co [MPa]
1	42.9	112.1
1	41.0	96.4
2	30.9	87.5

For the Triax experiments, the results are provided for the different confining pressure values and for the single and multiple triaxial failure tests (Table 3).

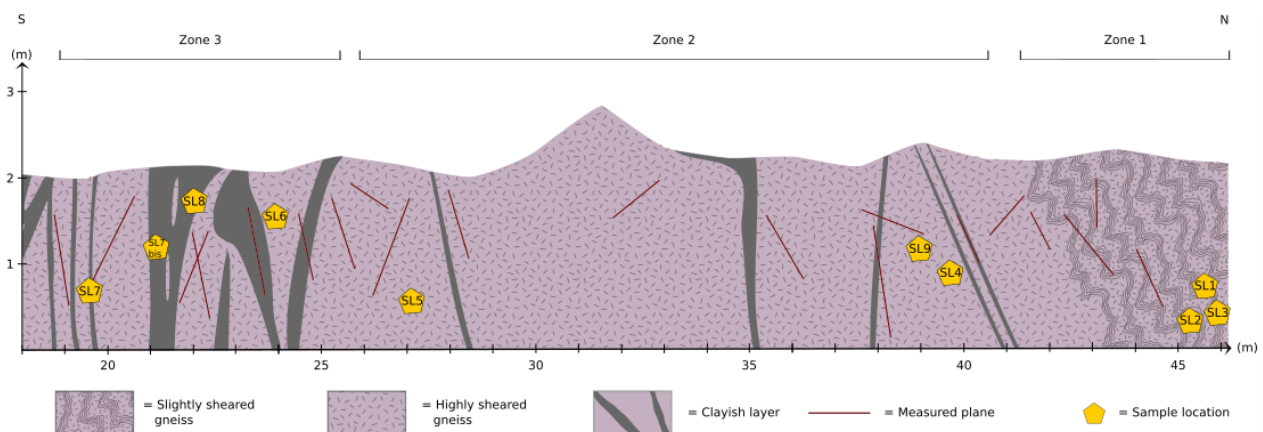


Figure 7: Cross-section of the studied gallery indicating the location of the samples (in yellow) and the delimitation of the Zones. Zone 1 corresponds to the less deformed gneiss, the basement. Zone 2 is the transition zone of the fault zone and Zone 3 to the inner core of the damage zone. Samples in the fault zone are more sheared and the presence of clay-rich bands is represented in grey. Planes were measured along the profile (in red). The foliation on the right represents the limit where it was no longer visible on the outcrop but is not represented with the right strike/dip directions.

Table 3: Results of the triax test under a confining pressure of 20, 40 and 60 MPa with the elastic modulus, the maximum compressive strength and the Poisson ratio (ν), $m =$ multiple tests

20 MPa confining pressure			
Zone	E-Modul [GPa]	Co [MPa]	ν [-]
1	37.6	159.3	0.12
1 (m)	47.3	160.8	0.1
2	33.7	148.3	0.15
2 (m)	31.7	148.9	0.14
3	18.1	169.2	0.06

40 MPa confining pressure			
Zone	E-Modul [GPa]	Co [MPa]	ν [-]
1	50.1	252.1	0.12
1 (m)	-	290.9	0.08
2	41.6	197.5	0.15
2 (m)	-	187.2	0.2
3	22.0	218.3	0.08

60 MPa confining pressure			
Zone	E-Modul [GPa]	Co [MPa]	ν [-]
1	47.7	262.7	0.17
1 (m)	-	340.8	0.11
2	36.5	230.3	0.17
2 (m)	-	229.5	0.21

The results of the BD showed a decrease in tensile strength from Zone 1 to Zone 3. The UCS tests were only executed in Zone 1 and 2 due to the small number of samples. Hereby, the same trend was visualized as in the BD test. It has to be highlighted that Zone 1 already shows two quite different Co values. For the elastic modulus, the results were more distinct between the two zones. The triaxial results presented for the elastic modulus had the same trend as the UCS results. For the Co, the results of Zone 3 were higher than Zone 1 and Zone 2 by 20 MPa confining pressure. For 40 MPa confining pressure the value of Zone 3 was still higher than Zone 2. The Poisson ratio displayed no clear difference between the Zones. Zone 2 has the highest values in all three Tables and Zone 3 has the smallest. For Zone 1 they are in between Zone 2 and Zone 3 but the two measured values show great differences.

The post-failure analysis displayed a brittle to a tendency of ductile behaviour, especially for the Zone 3. At the maximum confining pressure already Zone 1 demonstrated a slower decrease in pressure after failure but comparatively small to the Zone 3 at lower confining pressure values. The post failures occurred along previous existing structures. Compared to other mechanical tests led on gneiss, these results give a lower value of the TS, E-modulus and Poisson ratio than those obtained by Eloranta (2006).

3. CONCLUSIONS

From the results of the Mechanical testing, it can be seen that there is a decrease in tensile strength over the profile from Zone 1 to Zone 3. It is similar for the elastic modulus from the UCS and Triax tests. The Co and Poisson ratio are not that clear. For Co, Zone 3 demonstrates higher strength than expected and shows similar or even higher than Zone 1. For the Poisson ratio, Zone 2 shows the highest values and differences in each Zone are quite large. These differences in one Zone show that the declared zones are quite heterogeneous and have to be analysed at a smaller scale with more experiments. The post-failure analysis presents a similar picture to the calculated parameters. Hereby, no clear behaviour can be detected concerning the type of failure. Some samples show a tendency of ductile behaviour while other samples have a clear brittle failure. Therefore, the extent of the Zones has to be questioned and may be changed after a more detailed analysis of the whole profile including geochemical and petrographical analysis. The results of the mechanical testing showed that there are clear changes over the profile length e.g. the tensile strength and for other cases, it can be highlighted that possible changes are smaller than expected or due to the complex geological past more differentiated than assumed. There might be a transition from brittle behaviour in Zone 1 to plasticity in Zone 3. The comprehension of fluid pathways which vanishes to the fault zone is still not clear.

The ongoing research goes into detail for geochemical and petrographical analysis at a narrow scale to find answers for questions raised. In this next step, processes of hydrothermal alteration will be taken into account as the pre-structuration might have changed the properties of the host rock, enhancing the heterogeneity and differences in mechanical behaviour between the Zones.

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