STRUCTURAL MAKE-UP AND GEOPHYSICAL PROPERTIES OF BRITTLE FAULT ZONES IN THE EASTERN AAR MASSIF, SWITZERLAND

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ABSTRACT

Brittle fault zones often generate unstable conditions when encountered during the excavation of a tunnel. In the eastern Aar massif of central Switzerland, these zones can be described as a symmetric succession of brittle fault rocks. This sequence consists of the undeformed host rock, a strongly foliated and fractured zone, a cataclastic zone and a central zone of cohesionless material. Within this sequence the intensity of fragmentation of the rock mass increases towards the central zone. Surface and underground observations are confirmed through detailed study of borehole cores sampled from granitic and gneissic bodies and drilled perpendicular to the fault structure. Subsequent geophysical logging in these boreholes show that increases in tectonic deformation, as seen in the fault sequence, results in a decrease in γ-radiation and P-wave velocity. These decreases can be associated with increasing porosities and fracture densities in the host rock masses. Results from this study highlight the potential for detecting these difficult zones by means of drilling ahead of the tunnel face, combined with the measurement of several geophysical parameters.

INTRODUCTION

Increased tunnelling activity in the central part of the Swiss Alps has raised concerns with respect to encountering geotechnically difficult zones. Such zones are often associated with steeply inclined brittle fault zones which contain fissured material down to great depths. Past experiences in these fault zones have demonstrated that the weak and cohesionless nature of the fissured material results in progressive roof collapses which produce extensive "chimney-shaped" cavities. High water inflows frequently aggravate these instabilities. It is therefore essential to know where these fault zones are to be encountered, to realize when such a zone is being approached during excavation and to know what geotechnical difficulties may be expected.

Studies on the structural make-up and the geophysical and mechanical properties of brittle fault zones have already been reported, for example, by Chester and Logan (1986), Wallace and Morris (1986), Kamineni et al. (1988) and Braathen and Gabrielsen (1998). The behaviour of brittle fault zones in underground excavations has been described by Müller (1963), Brekke and Howard (1973) and Schubert and Riedmüller (1997). In the eastern Aar massif, where parts of the new Gotthard Base Tunnel will be constructed, the presence of steeply dipping faults has been well established (e.g. Jäckli, 1951; Steck, 1968). However, these studies in the eastern Aar massif do not include a full record of the complete fault pattern and fault structure nor have they examined the geophysical or mechanical properties of these fault rocks. This paper presents selected results from an investigation into the structural make-up and geophysical and geotechnical properties of brittle fault zones in crystalline rocks in an attempt to better understand their behaviour in tunneling, especially with respect to current predictive capabilities.

GENERAL GEOLOGICAL SETTING AND FAULT PATTERN IN THE EASTERN AAR MASSIF

The Aar massif is situated in the central part of the Swiss Alps and is exposed in the form of a ridge with a NE strike (Figure 1). The area investigated is located to the East of the line Erstfeld-Realp (framed region in Figure 1).

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The massif consists of a Pre-Variscan, polyorogenic and polymetamorphic crystalline basement (mainly gneisses, schists, migmatites), which was intruded by late Variscan magmatic rocks (granites, diorites, syenites, less abundant volcanics and aplite and lamprophyre dykes). Carboniferous, Permian and Mesozoic sediments cover the basement or are folded and faulted into it (Labhart, 1977; Abrecht, 1994).

Brittle fault zones appear in all formations of the Eastern Aar massif. The fact that most of these fault zones occur parallel to zones with evidence of former ductile deformation (e.g. mylonitisation) or trace geological contacts (e.g. lamprophyre dykes, petrographical changes) points to the reactivation of mechanically weak zones. The strike of these brittle fault zones is, on a large scale, often parallel to the dominant ENE-WSW trend of the steeply southwards dipping Alpine foliation. They mainly dip steeply to the SE or to the NW. In addition to these ENE-WSW striking fault zones, a second, NW-SE striking fault set can clearly be distinguished. These fault zones mainly dip steeply to the NE or to the SW (Laws and Loew, 1999).

In the late Variscan granites, where only minor structural anisotropy exists, the distribution of strike directions is wider than in the Pre-Variscan basement rocks which possess strong compositional banding and pervasive schistosity (Laws and Loew, 1999). This also suggests that the fault pattern is influenced by the formerly existing rock texture.

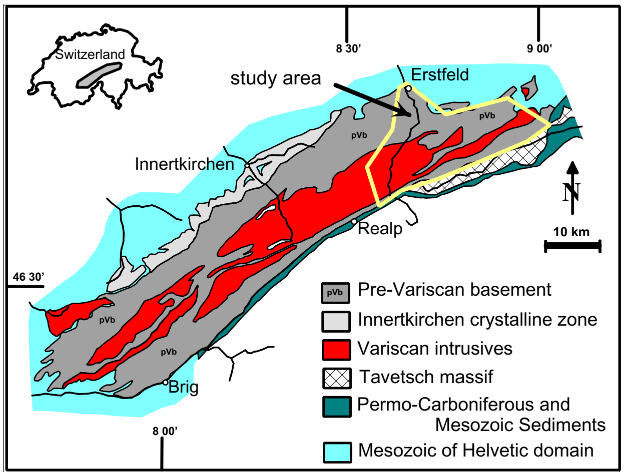

Figure 1 : General geographical and geolgical setting of the Aar massif and location of the study area (after Abrecht, 1994)

STRUCTURAL MAKE-UP OF BRITTLE FAULT ZONES

Brittle Fault Rocks

Previous studies (e.g. Higgins, 1971; Sibson, 1977) have already shown that brittle fault zones are composed of various types of brittle fault rocks. These brittle fault rocks may be classified into cohesionless fault breccia and fault gouge and into cohesive cataclasite (Davis and Reynolds, 1996). Fault Breccia and fault gouge can be differentiated by the amount of matrix material. In this respect, fault breccia is composed of angular and rounded clasts in a finer matrix, where the amount of matrix constitutes less than 30 % of the rock mass volume. The fabric of a fault breccia is usually random. In a fault gouge the entire mass, including the mineral grains, is heavily fragmented (microbreccia) and the matrix makes up more than 30 % of the rock mass volume. The fault gouge may show a crude foliation. As brittle faulting is often accompanied by hydrothermal activity (e.g. Higgins, 1971, Wise et al., 1984), all brittle fault rocks commonly show zones of neomineralisation and alteration (e.g. Passchier and Trouw, 1996).

General Brittle Fault Zone Structure in the Eastern Aar Massif

Surface and underground observations show that the structural make-up of brittle fault zones in the eastern Aar massif can be described as a symmetric succession of brittle fault rocks (Laws and Loew, 1999). Spanning over several meters, this sequence consists of the undeformed host rock, a strongly foliated and fractured zone, a cataclastic zone and a central zone of cohesionless material. Within this succession the intensity of fragmentation of rocks and minerals increases towards the central zone. The thickness and the internal structure of these units can show large variations along both strike and dip, even over short distances of several meters.

Substantial structural differences also occur between different fault zones due to differences in the bulk rock composition (e.g. pelitic, mafic, quartzofeldspatic), the original structure of the host rock (e.g. foliated, isotropic) and the nature of the imposed stresses. For example, it has been observed that the widths of fault zones in isotropic granites are smaller than those in foliated gneisses. These observations correspond with the generally lower compressive strengths of foliated or pelitic and mafic rocks opposed to isotropic granite.

Brittle Fault Zone Structure as Seen in a Granite and a Gneiss Core

Borehole cores were taken from two different sites in the safety tunnel of the Gotthard highway tunnel located in the eastern Aar massif. The first was drilled through a fault zone intersecting the Variscan Aar granite intrusion, and the second was taken from a fault zone in the Southern Gneiss Zone of the Aar massif (Pre-variscan basement). Both boreholes were oriented perpendicular to the strike and dip of the fault zones. In this sense, as the fault zones dipped very steeply, the boreholes were drilled horizontal using triple tube drilling flushed with water to reduce sample disturbance. Based on these cores the observations given in Table 1 have been made. Pictures of the cores can be seen in the Figures 2a and 2b. The observations confirm the previously postulated structural make-up of brittle fault zones.

Table 1 : Comparison between brittle fault zones in granitic and gneissic bodies as derived from borehole cores

	Fault Zone in Granite	**Fault Zone in Gneiss**
Host Rock	- coarse-grained, isotropic rock consisting mainly of quartz, feldspar and biotite - ductile overprinting near fault zone involving higher chlorite and white mica content and intense foliation	- strongly foliated rock consisting mainly of quartz, mica and chlorite - more fractured than granite host rock
Strongly Foliated and Fractured Zone	- high number of closely spaced fractures parallel to foliation - fracture frequency increases on scale from cm- to mm-separation towards fault center - rock material remains cohesive but contains an increased amount of white mica, chlorite and broken feldspars	- strongly foliated - closely spaced fractures parallel to foliation and numerous fractures at oblique angles to foliation - some subsidiary faults filled with gouge - some quartz veins dipping parallel to foliation - low cohesion and higher porosity due to increased white mica content, broken feldspars and fine-grained nature of rock
Cataclastic Zone	- high number of closely spaced fractures parallel to foliation - subsidiary faults filled with fault gouge (cm's to mm's in thickness) - fracture spacing decreases and thickness of fault gouge increases towards fault center - subsidiary faults may create mesh of anastomosing fractures enclosing lozenge-shaped lenses of intact rock - further fragmentation towards fault center results in disruption of texture and intense grain fracturing in all directions (i.e. development of cohesive cataclasites) - zone marked by fragmented feldspars - rock material is weak and increasingly loses cohesion towards central zone	- strongly foliated - closely spaced fractures - subsidiary faults filled with fault gouge (cm's to mm's in thickness) - cm-thick quartz veins - subsidiary faults may create mesh of anastomosing fractures enclosing lozenge-shaped lenses of intact rock - further fragmentation towards fault center results in disruption of texture and intense grain fracturing in all directions (i.e. development of cohesive cataclasites) - rock material is generally weaker than in the cataclastic zone in granite and increasingly loses cohesion towards central zone
Central Zone	- coarse- to fine-grained sand with some large rock fragments (fault breccia, fault gouge) - distinct and sharp contact with cataclastic zone - distinguished by complete loss of cohesion	- coarse- to fine-grained sand with some large rock fragments and plainly recognizable clay content (> 5%) (fault breccia, fault gouge) - visible foliation - distinct and sharp contact with cataclastic zone - distinguished by complete loss of cohesion

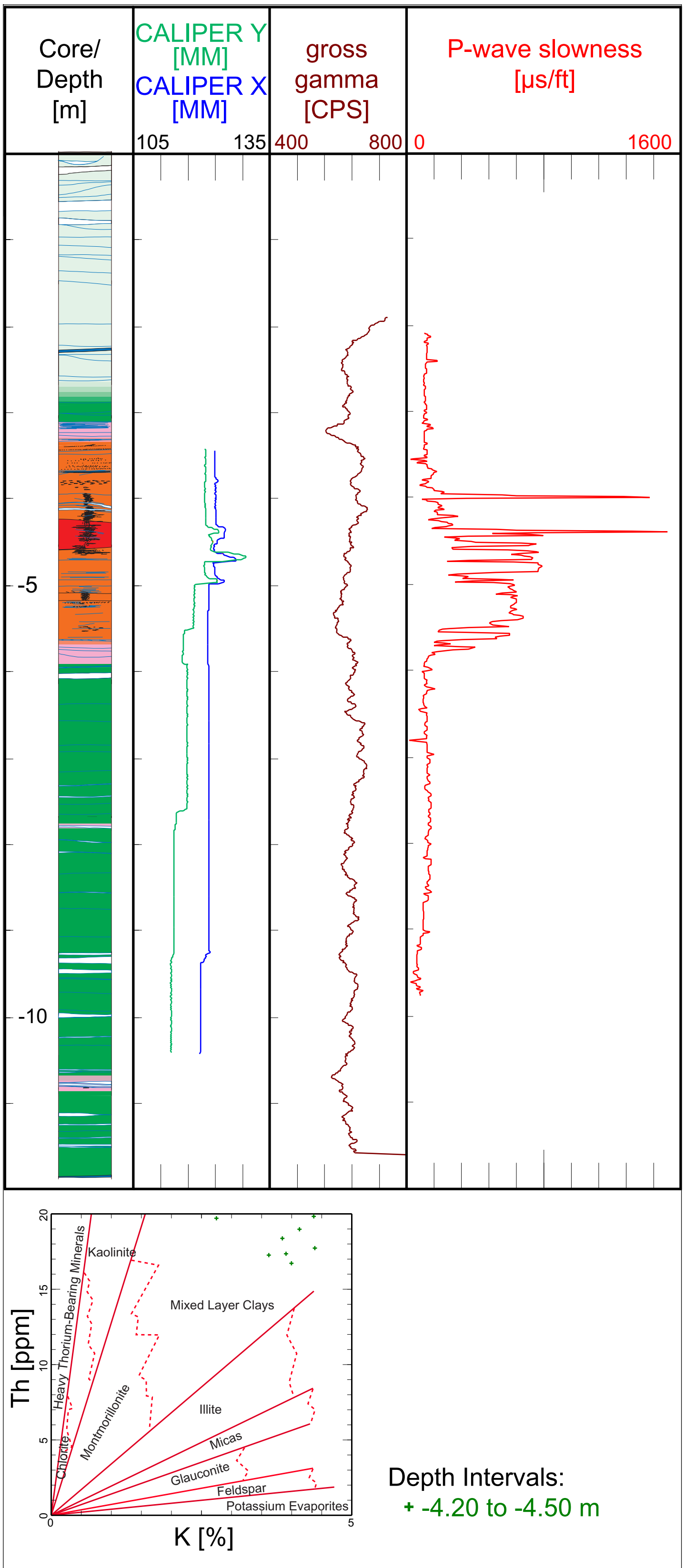

Figure 2a : Geophysical borehole logs and crossplots for boreholes in granite (isotropic rock, foliated rock, strongly foliated and fractured zone, cataclastic zone, central zone, quartz veins, open fractures)

GEOPHYSICAL LOGGING OF BRITTLE FAULT ZONES

Geophysical measurements were made in the boreholes the granite and gneiss cores were taken from. In each case, caliper (borehole diameter), gamma (gross, spectral) and full wave sonic logs were made.

Caliper Logging

Four arm caliper logs were made to measure the borehole diameter in an X- and Y-plane. Results shown in Figures 2a and 2b indicate that the borehole diameter increases as the borehole approaches the center of the fault zone (primarily in the cataclastic and central zone). This suggests small collapses in these zones of weaker rock.

Gamma-Ray Logging

Gamma-rays are produced from the decay of unstable, radioactive atomic nuclei (K, U, Th). Since clays are largely composed of these elements, γ-logs are ideal for locating clay-rich layers (increase in γ-radiation). Furthermore, γ-logs are partly dependent on the porosity of the measured rocks (decrease in γ-radiation). The measurement of natural, spectral γ-rays serves to differentiate and quantitatively determine the content of potassium, uranium and thorium. After methods developed by Schlumberger (1985), plots of K [%] against Th [ppm] can be used to establish the nature of the minerals responsible for the γ-radiation.

Gamma-ray logs from both boreholes (Figures 2a and 2b) show a visible decrease of γ-radiation in the area of structureless material in the cataclastic and central zones, especially in the gneiss material. This decrease may be due to an increase in porosity in these zones.

Cross plots of K [%] and Th [ppm] from the measurements in the central zone partly suggest that the central zone in the granite bodies may contain mixed layer clays. For the gneiss material, cross plots clearly show the existence of montmorillonite and illite.

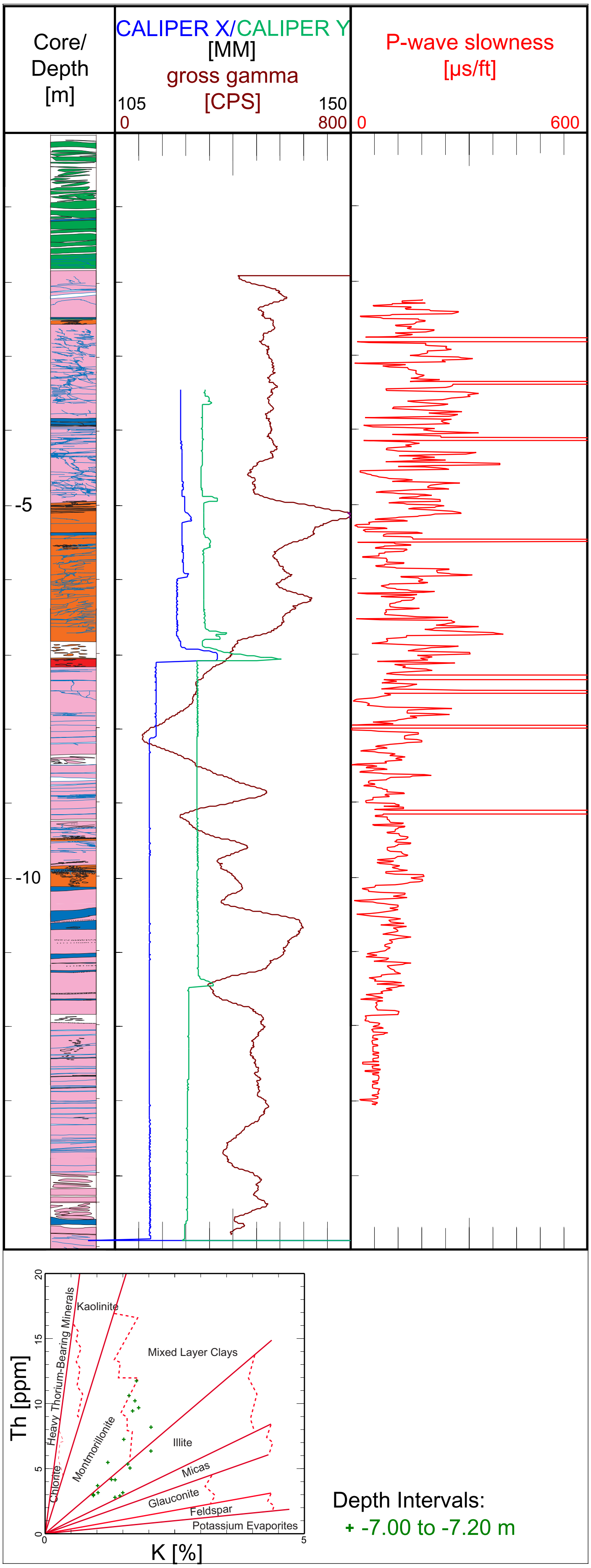

Figure 2b : Geophysical borehole logs and crossplots for boreholes in gneiss (see legend in Figure 2a)

Full Waveform Sonic Logging

Full waveform sonic logging consist of the measurement of velocity, frequency and amplitdude for several wave types including P-, S-, Pseudo-Rayleigh-, Stoneley- and fluid-waves. The velocities, frequencies and amplitudes are largely dependent on the elastic properties and density of the tested material through which the transmitted waves travel. Velocities, for example, generally decrease with increasing porosity and/or fracture density. The plots in Figures 2a and 2b show P-wave slownesses, the inverse of velocity.

The measurement of P-wave velocity in the granite borehole (Figure 2a) clearly shows a decrease of velocity in the area of the fault zone. These decreases are already visible at the beginning of the strongly foliated and fractured zone. Further decreases in the velocity are seen in the cataclastic zone with peak lows found in the central zone. This decrease is likely due to an increasing porosity and fracture density as seen in the core samples of the fault zone rocks. Borehole P-wave velocities taken from the Southern Gneiss Zone show a less distinct decrease in P-wave velocity in the area of the fault zone (Figure 2b) which is likely due to the heavier fractured nature of the host rock itself.

CONCLUSIONS

Brittle fault zones in the eastern Aar massif can generally be described by a symmetric succession of brittle fault rocks. This sequence consists of the undeformed host rock, a strongly foliated and fractured zone, a cataclastic zone and a central zone of cohesionless material. The sequence could also be observed in borehole cores drilled through brittle fault zones located within both granite and gneiss host bodies.

In the boreholes, the cores were taken from, caliper, gamma and full wave sonic logs were made. The logs show that an increase in tectonic deformation results in a decrease in γ-radiation and P-wave velocity and causes systematic collapses in the borehole. The decreases can be associated with increasing porosities and fracture densities in the host rock masses.

The studies thus demonstrate how the structural make-up of the fault zones strongly controls specific geophysical properties, i.e. distinct geophysical properties may be attributed to the different fault zone units. It should therefore be possible to detect brittle fault zones in investigative drilling ahead of the tunnel with a combination of different geophysical measurements. Furthermore, with the help of the geophysical logs, it should be possible to predict the geotechnical difficulties the detected fault zone may cause. The strength- and deformation-characteristics of the different fault zone units are currently under study in field and laboratory tests.

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