TECHNICAL REPORT 91-12

GRIMSEL TEST SITE

STRUCTURAL GEOLOGY AND WATER FLOW-PATHS IN THE MIGRATION SHEAR-ZONE

P. BOSSART ¹) NOVEMBER 1991
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with contributions by
K. - H. Helimuth ³), M. Schneebeli ⁴), M. Siitari-Kauppi ³)

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GRIMSEL TEST SITE/SWITZERLAND
A JOINT RESEARCH PROGRAM BY

• NAGRA – National Cooperative for the Storage of Radioactive Waste, Wettingen, Switzerland
• BGR – Federal Institute for Geoscience and Natural Resources, Hannover, Federal Republic of Germany
• GSF – Research Centre for Environmental Sciences, Munich, Federal Republic of Germany

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FOREWORD

Concepts for the disposal of radioactive waste in geological formations lay great weight on acquiring extensive knowledge of the proposed host rock and the surrounding rock strata. For this reason, Nagra has, since May 1984, been operating the Grimsel Test Site (GTS) which is located at a depth of 450 m in the crystalline rock of the Aare Massif of the Central Swiss Alps. The general objectives of the research being carried out in this underground laboratory include

- the build-up of know-how in planning, performing and interpreting field experiments in various scientific and technical disciplines.

- the acquisition of practical experience in the development of investigation methodologies, measuring techniques and test equipment which will be of use during actual repository site explorations.

The GTS is operated by Nagra and, on the basis of a German-Swiss co-operative agreement, various experiments are carried out by Nagra, the Federal Institute for Geoscience and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR) and the Research Center for Environmental Sciences (Forschungszentrum für Umwelt und Gesundheit GSF). The Grimsel projects of both GSF and BGR are supported by the German Federal Ministry for Research and Technology (BMFT). NTB 85-46 (English version) and NTB 85-47 (German version) provide an overview of the German-Swiss investigation programme. In a special issue of the Nagra Bulletin 1988 (English version) and in Nagra Informiert 1+2/1988 (German version) the status of the programme up to 1988 is described.

This report was produced in accordance with the cooperation agreements mentioned above. The authors have presented their own opinions and conclusions which do not necessarily coincide with those of Nagra or its participating partners.
Location of Nagra's underground test facility at the Grimsel Pass in the Central Alps (Bernese Alps) of Switzerland (approximate scale 1 cm = 25 km).

Geographische Lage des Nagra Felslabors am Grimselpass (Berner Oberland) in den schweizerischen Zentralalpen (Massstab: 1 cm = ca. 25 km)
GRIMSEL-GEBIET
Blick nach Westen

1 Felslabor
2 Juchlistock
3 Räterichsbodensee
4 Grimselsee
5 Rhonetal

GRIMSEL AREA
View looking West

1 Test Site
2 Juchlistock
3 Lake Raeterichsboden
4 Lake Grimsel
5 Rhone Valley
Summary

Introduction: The shear-zone in the ventilation tunnel at VT 420 at the Grimsel Test Site (GTS) is a direct continuation of the migration shear-zone AU 96 that is being used for hydraulic and tracer migration experiments. A thick drill-core (diameter 20 cm) was taken from the VT 420 location such that the fragile structures in the central fault breccia remained largely intact. After several hardening steps, thin-sections were produced for all three main deformation planes of the deformation ellipsoid (i.e. parallel/perpendicular to the cleavage and stretching lineation). Vacuum impregnation with fluorescent resin allowed the pore-space to be observed microscopically.

Ductile shear-zone: The ductile shear-zone at VT 420 is 0.15 - 0.90 m thick, strikes WSW-ENE and dips steeply to the SSE and trends parallel to the cleavage (S-zone). The shear direction is sub-vertical, parallel to the mineral stretching lineation. Looking to the E, the shear sense is anti-clockwise, meaning the shear-zones have accommodated thrust displacements. A minimum value for the shear displacement across the shear-zone is 3 m. The structure of the ductile shear-zone can be linked with the Alpine greenschist metamorphism and the development of the regional cleavage. This deformation is purely ductile and includes the formation of a set of mylonitic zones within the shear-zone. Mylonitic zones are mica-rich and more fine-grained than the surrounding rock. The shear-zone is markedly asymmetric, with an abrupt northern boundary (very high deformation gradient) and an indistinct southern boundary.

Brittle deformation: During the course of post-metamorphic regional uplift, the ductile shear-zone was reactivated and underwent brittle deformation. This lead to formation of non-cohesive fault breccias several mm thick, particularly in strongly mylonitic zones which acted as pre-existing zones of weakness (reduced mechanical competence, high deformation gradients). The fault breccias can be interpreted genetically as fault gouges and consist of angular rock fragments embedded in a mica-rich matrix. This matrix is non-cohesive because virtually no hydrothermal alteration and cementation of the porespace has occurred after the brittle deformation event. Hypotheses for the origin of the fault gouges besides differential uplift of individual blocks include the effects of periodic movements such as tides and changes in water levels in the nearby reservoirs.

Quantitative porosimetry: A number of methods (Hg injection, water gravimetry, impregnation with polymethylmethacrylate PMMA) have been applied to quantitatively determine the interconnected pore-space in the different rock types in the shear-zone. Due to the cohesionless structure, the fault gouge porosity cannot be measured but is estimated at 10 - 30 vol% from thin-sections. Ultramylonitic rock portions (in which the fault gouges are often embedded) have a rather low porosity (as low as 0.5 vol%) due to their dense, recrystallized structure. Porosity increases with decreasing degree of ductile deformation, and the granodioritic matrix rocks have open porosities > 1 vol% in many cases. Porosity of weakly deformed granodiorite decreases with increasing distance from the tunnel wall (10% decrease over the first 20 cm), which is interpreted as a consequence of microcrack formation during tunnel construction.
Extrapolation of observed structures to larger scales: Because of the limited outcrop size in the tunnel, an attempt to extrapolate the observed structures to larger scales was made using information from geological mapping on the surface. Similar shear-zones at the Räterichsboden reservoir can be mapped on the meter - dekameter scale. We assume that the shear-zone geometry described can be extrapolated to the 100 m-range.

Implications for water flow and transport: It is brittle deformation which plays the dominant role as far as water flow is concerned today: the central fault gouge is highly porous due to the lack of hydrothermal cementation. The ultramylonitic rock zones bordering the fault gouge are very tight but do contain planar pore-spaces along mica streaks (sheet-silicate porosity). These provide a hydraulic connection between the fault gouge and the less deformed granodioritic gneiss outside the shear-zone. The granodioritic matrix rocks have a well-developed, interconnected network of grain boundary and transgranular pores. Feldspars also have numerous solution pores, interpreted as etching phenomena of Alpine metamorphic fluids.

Suggestions for revised conceptual models: Revised conceptual models are suggested for the geometry of the pore spaces and for the hydrodynamic and transport modeling. The geometrical model is based mainly on microscopic parameters derived from thin-sections (for example pore width, persistence and orientation). The model consists of 3 domains: 1) the fault gouges are represented by a system of plates with variable orientation and thickness, consisting of an equivalent porous medium; 2) the mylonitic rocks are described of a highly anisotropic fracture network (sheet silicate pores); 3) the granodioritic gneisses surrounding the shear-zone are represented by a mildly anisotropic fracture network (grain boundary pores). Within these 3 domains, the pore spaces are interconnected. This small-scale conceptual geometrical model can be extrapolated to larger scales by the use of standard averaging techniques. The relevance of advective, dispersive and diffusive transport in all domains was considered. It is suggested that advection and mechanical dispersion is most effective in the fault gouges whereas molecular diffusion is expected to be relevant in the domains 2 and 3. The migration shear-zone can therefore be described in terms of a dual-porosity transport model.
Zusammenfassung


Quantitative Porosimetrie: Zur Charakterisierung und Quantifizierung des verbundenen Porenraums der verschiedenen Gesteinsteilen in der Scherzone wurden mehrere Methoden angewandt (Hg-Druckporosimetrie, Wasser-Gravimetrie, Imprägnation mit Polymethacrylat PMMA). Wegen ihrer Kohäsionslosigkeit kann die Porosität der "Fault gouges" nicht gemessen werden, wird aber aufgrund der Dünnenschliffsbeobachtungen auf 10 - 30 vol% geschätzt. Ultramytonitische Partien haben wegen ihres dichten, rekristallisierten Gefüges nur geringe Porositäten (0.5 vol%). Die Porosität nimmt mit abnehmender duktiler Deformation zu und erreicht im granodioritischen Nebengestein Werte > 1 vol%. Die Porosität von wenig deformiertem Granodiorit nimmt mit zunehmender Distanz von der Stollenwand ab (10% auf den ersten 20 cm), was als künstlicher Auflockerungseffekt beim Fräsen des Stollens betrachtet wird (Mikroriss-Bildung).
Extrapolation der beobachteten Strukturen auf grössere Massstäbe: Die Untertag-Beobachtungen, welche sich auf die Grösse des Stollenquerschnitts beschränken müssen, wurden durch eine geologische Kartierung an der Oberfläche ergänzt. Ähnliche Strukturen wie im Stollen wurden im Meter-Dekameter-Bereich am Räterichsboden-Stausee angetroffen. Es wird angenommen, dass die beobachteten Strukturmuster bis in den 100 m-Bereich extrapoliert werden können.


Résumé

Introduction: Au site d'essais du Grimsel (GTS), la zone de cisaillement située au point 420 dans le tunnel de ventilation (VT) est une prolongation directe de la zone de cisaillement AU 96 utilisée pour les essais hydrauliques et les essais de migration de traceurs. Au site VT 420, on a prélevé une carotte de 20 cm de diamètre, en y laissant intactes les fragiles structures bréchiques de la faille centrale. Après plusieurs phases de durcissement de la carotte, on y a taillé des lames minces selon les trois plans principaux de l'ellipsoïde de déformation, c'est à dire perpendiculairement et parallèlement au clivage et à la linéation d'étirement. Une imprégnation de résine fluorescente sous vide a permis l'examen au microscope des pores.

Zone de cisaillement ductile: Au site VT 420, la zone de cisaillement ductile présente une épaisseur de 0.15 à 0.9 m. Elle est orientée WSW-ENE et plonge fortement vers le SSE. Elle est subparallèle au clivage (zone S). La direction de cisaillement est subverticale, parallèle à la linéation formée par l'étirement des minéraux. Si l'on regarde vers l'E, le cisaillement s'est effectué dans le sens inverse des aiguilles d'une montre. On peut admettre un cisaillement total d'au moins 3 m. La structure de la zone de cisaillement ductile peut être mise en relation avec le métamorphisme alpin des schistes verts, et avec le développement d'un clivage régional. La déformation est purement ductile. Elle comprend la formation d'une série de zones de mouvement mylonitiques à l'intérieur de la zone de cisaillement. Les zones mylonitiques sont riches en micas, et d'une granulométrie plus fine que celle des roches environnantes. La zone de cisaillement possède une asymétrie marquée, avec une terminaison abrupte sur la bordure nord de la zone de cisaillement (gradient de déformation très élevé), et une transition graduelle sur sa bordure sud.

Déformation cassante: Au cours du soulèvement régional, la zone de déformation ductile a été réactivée et soumise à une déformation cassante. Il en est résulté la formation de brèches de faille non cohésives d'épaisseur millimétrique, particulièrement dans les zones très mylonitisées et dans les endroits à fort gradient de déformation. Génétiquement, les brèches de failles sont le résultat d'un broyage. Elles sont composées d'éléments anguleux noyés dans une matrice riche en micas. Ces brèches de faille peuvent avoir pour origine le soulèvement différentiel des blocs rocheux, ainsi que des mouvements périodiques dus aux marées terrestres et aux fluctuations des niveaux d'eau dans les réservoirs tout proches.

Porosimétrie quantitative: La détermination quantitative du volume des pores interconnectés de différents types de roches de la zone de cisaillement a été tentée par différentes méthodes: injection de mercure, pesage de la teneur en eau, imprégnation au métacrylate de polyméthyle. La porosité des brèches de faille n'a pas pu être mesurée directement, faute de cohésion de la roche. Elle a été estimée à 10-30 % du volume par l'examen de lames minces. En raison de leur structure dense et recristallisée, les roches ultramylonitiques dans lesquelles sont souvent noyées les brèches de faille ont une porosité plutôt faible, qui parfois ne dépasse pas 0.5 % du volume. La porosité augmente avec la décroissance du degré de déformation ductile. Elle dépasse fréquemment 1% du volume dans la matrice granodioritique. La porosité des granodiorites faiblement déformées décroît avec l'augmentation de la distance à la paroi du tunnel (10% de décroissance sur les 20 premiers cm). On pense que cela est dû à une microfracturation provoquée par la construction du tunnel.
Extrapolation à une plus grande échelle des structures observées: La surface limitée des affleurements dans le tunnel nous a poussé à tenter d'extrapoler à une plus grande échelle les structures observées, en utilisant les informations des levés géologiques de surface. On peut suivre au réservoir du Räterichsboden des zones de cisaillement similaires à l'échelle métrique ou décamétrique. On pense qu'on peut extrapoler la géométrie de la zone de cisaillement décrite sur une longueur d'environ 100 m.

Conséquences pour les écoulements souterrains: A l'heure actuelle, les déformations cassantes constituent le milieu principal des écoulements souterrains. La brèche de faille centrale n'a pas été cimentée hydrothermallement, elle est donc très poreuse. La roche ultramylonitique en bordure de la brèche de faille est nettement plus étanche que la roche voisine, mais elle contient tout de même des pores planaires le long des stries micacées (porosité de silicates feuilletés). Ces pores fournissent une bonne connection hydraulique entre la brèche de faille et les gneiss granodioritiques moins déformés, en dehors de la zone de cisaillement. La matrice granodioritique présente un réseau bien développé de pores interconnectés, entre et à travers les grains. Les feldspaths présentent aussi de nombreux pores de dissolution, considérés comme la marque des fluides du métamorphisme alpin.

Suggestions pour la révision des modèles conceptuels: on propose une révision des modèles conceptuels en ce qui concerne la géométrie des pores et les phénomènes hydrodynamiques et de transport. Le modèle géométrique est principalement basé sur la définition de paramètres à l'échelle microscopique, à partir de l'observation de lames minces (par exemple largeur des pores, extension et orientation). Le modèle est constitué de 3 domaines: 1) les brèches de failles sont représentées par un système de plaques d'orientation et d'épaisseur variable, les plaques étant constituées d'un milieu poreux, 2) les roches mylonitiques sont décrites par un réseau de fractures très anisotrope (pores de silicates en feuillets), 3) les gneiss granodioritiques entourant la zone de cisaillement sont représentés par un réseau de fractures modérément anisotrope (pores aux limites des grains). Entre ces 3 domaines, les pores sont interconnectés. Ce modèle géométrique à petite échelle peut être extrapolé à plus grande échelle au moyen de techniques courantes de traitement des moyennes. On a examiné dans chacun des domaines l'importance relative du transport par advection, dispersion et diffusion. On pense que dans les brèches de failles la dispersion mécanique et l'advection sont prépondérantes, tandis que dans les deux autres domaines, la diffusion moléculaire joue le rôle principal. La zone de cisaillement utilisée pour les essais de migration peut donc être décrite par un modèle de transport à double porosité.
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Appendix: Glossary of terms
1. Introduction

1.1 General

The Grimsel Test Site (GTS, see Figure 1) is a rock laboratory run by NAGRA in the Central Swiss Alps. Not being a repository site itself, experimental work at GTS is aimed at developing techniques (in a very broad sense) relevant for a future repository. The experimental programme comprises geological, geophysical, geochemical, hydrochemical, geotechnical and modelling projects that are potentially relevant for the construction and safety performance assessment of a repository.

In this framework, an extensive campaign of hydrological/geochemical testing has been run in the so-called “migration shear-zone” (Figure 1) over the last 5 years (FRICK et al. 1991). In this project, the transport of sorbing and non-sorbing tracers in an artificial flow-field through the rock is investigated. The field experiments are accompanied by a laboratory programme (mainly sorption studies, e.g. BRADBURY 1989, AKSOYOLU et al. 1990) and also extensive modelling efforts (e.g. SMITH 1991).

Presently, the feasibility of an excavation project is studied: It is planned to extract large parts of the migration shear-zone (on the scale of meters) after injection of safety-relevant radiotracers. This project is focused at the study of the flow-path geometry, tracer retardation and tracer geochemistry.

1.2 Objectives

This report is intended to provide geological and structural data for current and future projects. The focal point of the work presented here is to provide a macroscopic and microscopic description of flow-paths within the shear-zone and to present information on the inhomogeneity, anisotropy and persistence of potential flow-paths. Specifically, we aim at questions such as:

- Evaluation of hydraulic tests: Are conventional evaluation methods such as the determination of transmissivities and storage coefficients according to the Jacob/Lohman technique (homogeneous, isotropic, infinite aquifer, radial flow from/to the borehole) suitable in the light of the new structural geology results from the migration shear-zone? For which hydraulic parameters should modified analysis techniques and associated conceptual models be considered?

- Hydrodynamic simulations: Are model calculations (such as simulations of advective/dispersive flow or concentration-breakthrough curves) based on overly simplified geometrical conceptual models? Are improvements necessary/possible?

This report basically aims at providing the stimulus for constructing realistic model concepts. The emphasis on geometry accounts in large part for the numerous graphical representations and cartoons in the report.
Figure 1: Plan of the tunnel system and structural relations in the southern part of the Grimsel Test Site.
2. Geological background

2.1 Summary of regional geology

The Grimsel Test Site is situated in the Aar Massif, a basement high in the Helvetic realm of the Alps. The Aar Massif consists of a metasedimentary envelope that was intruded by Hercynian granitoids (320 - 280 Ma) such as the Central Aare granite and the Grimsel granodiorite; the latter is the host rock of the site investigated. All rocks of the Aar Massif have been affected by Alpine greenschist metamorphism and deformation at about 25 Ma b.p. (DEMPSTER 1986). The plutonic rocks were metamorphosed to gneisses. Structures in the Hercynian plutonic rocks are mostly attributed to Alpine deformation (STECK 1968, MARQUER & GAPAISS 1985), as is also the migration shear-zone at the GTS.

2.2 Alpine shear-zones in the Grimsel granodiorite: Relation between temperature and the style of deformation

Peak Alpine metamorphic conditions in the vicinity of GTS are estimated at 400 °C/2.5-3 kbars (CHOUKROUNE & GAPAISS 1983, MARQUER et al. 1985). The following structural elements can be assigned to this greenschist facies metamorphism and associated ductile deformation (cf. Figure 2): cleavage, mylonitisation (including formation of quartz ribbons), mineral stretching lineation, extension fractures and quartz recrystallisation. Most minerals underwent ductile deformation whereas feldspars and allanite (=orthite) show a brittle deformational behaviour.

The formation of brittle structures, that are common in the Grimsel crystalline, postdates the ductile deformation and can be attributed to the post-metamorphic regional uplift that is still operative at present with rates of 1-2 mm/a. In the case of the migration shear-zone, the brittle structural elements include both cataclastic fault breccias and fractures. Brittle deformation occurred at significantly lower temperatures and pressures compared with ductile deformation.

A speculative P-T uplift path for the Grimsel Crystalline is shown on a depth-temperature map (Figure 2). The boundary between brittle and ductile deformation is shown qualitatively; besides temperature and pressure, the location of this boundary also depends on material, grain-size, deformation mechanism (e.g. cataclastic and viscous creep processes) and strain rate. Similar deformation regime maps have been quantitatively discussed by HANDY (1988).

2.3 Results of previous studies relevant to the subject

A number of reports relating to geochemical and structural features of the Grimsel granodiorite at GTS have been produced recently. KEUSEN et al. (1989) contributes a map of brittle structures at the surface above GTS. In that report, no genetic implications are made, and families of structures are defined solely according to orientation. MEYER et al. in BRADBURY (1989) provide a first structural and geochemical characterisation of the migration shear-zone at GTS but also avoids genetic implications. In ALEXANDER et al. (1990), the geochemical interaction between water and wallrock in the migration shear-zone is studied using natural U/Th decay series. Even though the results are not unequivocal, interaction seems to have taken place with a penetration depth of at least several cm. More detailed studies are in progress (MAZUREK et al. 1991).

With respect to the genetic interpretation of ductile and brittle structures at GTS, the following internal reports are relevant: IROUSCHEK & BOSSART (1989) reported the results of logging
of granodiorite drill-cores from the ventilation test tunnel whereas BOSSART & MARTEL (1990) presented small- and large-scale structural maps from the surface above GTS including structural interpretation. In a small-scale study at the US/BK site of the GTS, MARTEL & PETERSON (1990) tried to integrate structural, geophysical, and hydraulic data in order to provide a full characterisation. These studies yield the following important results:

1) **Cleavage:** The orientation of the cleavage varies considerably on all scales (microscopic to outcrop) depending on the geometry of shear-zones and shear bands (BERTHE et al. 1979). This spatial variability should not be characterised, as it has been up till now, by an arbitrary division into S1-S3 orientations. The cleavage variability can best be shown by maps of cleavage strike trend and cleavage intensity. Where only borehole cores exist cleavage variability should be described statistically (mean, variance, density, using Fisher and Bingham statistics). Most cleavage measurements cluster around an azimuth of 160° and a dip of 75°.

2) **Shape of the finite strain ellipsoid:** The shape can be derived by measuring the aspect ratios of deformed markers such as magmatic inclusions (xenoliths). Because of the competence contrast between host rock (e.g. granodiorite) and inclusions, the shape of the strain ellipsoid can only be derived qualitatively (i.e. the aspect ratios of the xenolith axes are not identical to the axes of the finite strain ellipsoid). It can be shown that these xenoliths lie below the 45° line in a Flinn diagram (FLINN 1978), in what is called the apparent flattening field. This means that the xenoliths are disc-shaped (as opposed to cigar-like shapes).

3) **Kinematics of ductile (mylonitic) shear-zones** (see glossary of terms in the appendix): Shear-zones with high finite strain, i.e. mylonites with completely recrystallised structures, vary in thickness from several cm to 10 m. They are parallel to the mean orientation of cleavage in the granodioritic gneisses (strike WSW-ENE, steep dip to SSE). Based on an analysis of shear-zone fabrics, these shear-zones can be interpreted as thrusts where the more southerly units were thrust over the northern ones (cf. Figure 1).

4) **Conjugate shear-zone model:** In crystalline basement rocks, ductile shear-zones commonly occur in two sets with opposite shear sense (RAMSAY 1979). The angle between the two zones (measured such that it encloses the direction of maximum finite shortening, cf. Figure 3) is typically greater than 90° (in brittle shear-zones, this angle is typically less than 90°). Such an array of two sets of ductile shear-zones is called a conjugate shear-zone system. At GTS, these two sets are termed S-zones (shear-zones striking WSW-ENE, parallel to cleavage) and K-zones (shear-zones striking NW-SE, oblique to cleavage). Figure 3 presents three, two-dimensional deformation models (maximum shortening direction and maximum extension direction in the horizontal plane). Case c), where the S-zone is more prominent than the K-zone, agrees best with surface mapping within a shear-zone and also seems most appropriate for the migration shear-zone.

5) **Relation of ductile and brittle deformation:** In ductile shear-zones, the density of brittle fractures is significantly increased. This observation is interpreted in terms of the significant mechanical competence contrast between granodiorite and mylonite. The mechanically weak mylonitic shear-zones may act to localize subsequent brittle deformation. Therefore, brittle deformation associated with the regional uplift was preferentially accommodated in the mylonitic shear-zones.
Figure 2: Inferred uplift path of the Grimsel Crystalline in a pressure-temperature diagram and the relation to deformation mechanisms (ductile and brittle processes).
Figure 3: 2-dimensional deformation models of ductile conjugate shear-zones. On the left hand side the initial undeformed state (circular shape) is sketched, on the right hand side the deformed state (elliptic shape).

a) Matrix undeformed, enclosed angle of 120° remains unchanged.

b) Matrix deformed (right), angle between S- and K-zone varies between 90° and 110°.

c) S-zone is more pronounced than K-zone.
3. Site description and sample preparation

The migration shear-zone at GTS is cut by the AU tunnel at AU 96 and by the VT tunnel at VT 420 (Figure 1). All migration experiments have been conducted in boreholes drilled from the AU tunnel. Due to possible disturbances of the flow-field in these experiments, all samples for the present study were taken from the VT tunnel some 30 m WSW along strike from the AU site. The main features (geometry, ductile and brittle deformation) of the shear-zone are comparable in both tunnels.

3.1 Macroscopic description of the VT 420 site

Figure 4 illustrates the geometry and cleavage pattern of the migration shear-zone as encountered at VT 420. The main macroscopic characteristics are:

1. **Ductile deformation**: The VT 420 shear-zone is oriented parallel to the regional cleavage trend. It dips subvertically (\(>80^\circ\)) towards SE, in places also towards NW. The mean orientation is 160/82 and the thickness varies between 0.15 and around 0.90 m. A similar but thicker (10 m) shear-zone is exposed in the ventilation tunnel at 470 m, i.e. 30 m away (see Figure 1).

The VT 420 shear-zone is characterised by mica-rich mylonite bands (see glossary for the definition of mylonite). The intensity of cleavage within the shear-zone is high. At the northern boundary of the shear-zone, the deformation gradient from the shear-zone into the granodioritic gneiss is quite abrupt, while on the south side there is a more gradual transition to weakly deformed granodiorite. Similar geometries exist at AU 96, where the shear-zone is also asymmetrically developed (MEYER et al. in BRADBURY 1989). This is also corroborated by most of the numerous boreholes which penetrate the AU 96 shear-zone.

2. **Brittle deformation**: Fault breccia horizons, ranging from a few mm to 1 cm in thickness, can be observed in those parts of the shear-zone that underwent to the greatest ductile deformation. Up to three parallel horizons can be identified in places (Figure 4). They contain fine-grained, cohesionless "rock flour" which can be scratched out using a knife. The brittle deformation is clearly younger than the formation of the ductile, mylonitic shear-zone and occurred under completely different pressure-temperature conditions.

3. **Water inflow points**: With a normal tunnel climate (80% rel. humidity, temperature 13°C), the shear-zone shows no water inflow points or wet locations at VT 420. At AU 96, a water inflow rate of 0.5 liter per minute is reported (HOEHN et al. 1990).

3.2 Field sampling procedure

Sampling of shear-zone VT 420 took place on the eastern tunnel wall (Figure 4). There, the geometry of shear-zone is relatively simple compared with the western wall. Initially, an attempt was made to drill at right angles to the shear-zone surface (drilling diameter 9 cm) using a Hilti hand-drill. It proved impossible to collect continuous intact cores within the shear-zone. Zones of high ductile deformation and associated fault breccia horizons could only be sampled in the form of rock fragments of centimeter size which could not be oriented. In the next attempt at drilling, the largest possible diameter (20 cm) was selected and the hole was drilled in the strike direction of the shear-zone. The drilling operations proceeded very slowly (Hilti drilling
apparatus anchored to the rock, careful manual pressure, Figure 5), with a reduction in the amount of drilling-fluid used. Although the drill-core broke into two axis-parallel halves along a fault breccia horizon, it was possible to preserve most of the small-scale structures.

The most important drill-core data are:
- Location: VT 420, eastern tunnel wall, 1733.50 m.a.s.l.
- Length of drill-core: 0.58 m
- Orientation of borehole axis: 42/-41 (azimuth/dip; negative sign indicates rising borehole).

3.3 Sample preparation in the laboratory

The drill-core was immersed into a fluorescent resin at atmospheric conditions. After solidification of the resin, it was sawn up along the three principal deformation planes XY, XZ, YZ (see Figure 6 and also BOSSART & MARTEL 1990):

- **XY-plane:** parallel to the cleavage
- **XZ-plane:** perpendicular to the cleavage, parallel to the mineral stretching lineation
- **YZ-plane:** perpendicular to the cleavage and the mineral stretching lineation.

The impregnation with fluorescent resin had to be repeated after each individual saw-cut in order to preserve the cohesionless structures (fault breccia). The final step was to impregnate small pieces of the sample with resin under vacuum conditions and then to saw them into blocks of 4.0 x 2.5 x 0.5 cm³. These were then impregnated again under vacuum conditions and carefully polished to remove any surface remnants of resin, without shaving away too much of the impregnated rock. Thin-sections were prepared from 17 of these blocks and a colour control was made for potassium feldspar.

Considering the extremely fragile, often non-cohesive nature of the fault breccia, the quality of the thin-sections is in fact excellent. Artificially created cavities could not be avoided (due to washing-out of breccia), but in nearly all the thin-sections the finely ground rock flour has remained at least partially intact, allowing for microstructural interpretation.

3.4 Structure orientations in the drilled sample

The spatial orientation of the cleavage (XY-plane) and mineral stretching lineation (X-axis) were measured at outcrop and the XZ and YZ planes and the Y and Z axes were determined from this using stereographic projection (Figure 6). The values given below have an uncertainty of ± 10° with respect to the azimuth and ± 5° with respect to the angle of dip.

- **X-axis:** 300/83 (mineral stretching lineation, measured in the field)
- **Y-axis:** 041/01
- **Z-axis:** 129/06

- **XY-plane:** 310/84 (cleavage plane, measured in the field)
- **XZ-plane:** 220/89
- **YZ-plane:** 114/07.
Figure 4: Structural map of the whole (circular) tunnel surface at VT 420 displaying the shear-zone and the drilling location. Fault gouges are shown in red.
Figure 5: Drilling procedure at VT 420
Figure 6: Orientation of the principal axes and planes of ductile deformation in the VT 420 shear-zone, orientation of the sample coordinate system and of the drilling axis.
4. Rock deformation and pore space geometry at VT 420

4.1 Mineralogy and microtextures as a function of the degree of ductile deformation

The primary magmatic parent rock is a medium- to coarse-grained granodiorite with the major components quartz, plagioclase, potassium feldspar (microcline) and biotite and accessory ilmenite, allanite (=orthite), apatite and zircon. The cleavage developed during the course of the Alpine greenschist facies metamorphism and, particularly in the shear-zones, there was a substantial decrease in grain-size. There were also quantitatively significant mineralogical changes, mainly the growth of albite, biotite, chlorite, muscovite, epidote and titanite at the expense of the primary magmatic minerals.

A brief description of the structures encountered at AU 96 and AU 126 (which are similar to the shear-zone at VT 420) is given by MEYER et al. in BRADBURY (1989). That study also reports quantitative information on mineralogical composition, which varies markedly with the degree of deformation. A weakly deformed granodiorite contains 28 vol% quartz, 29% plagioclase, 24% K-feldspar, 18% sheet-silicates (biotite, muscovite, chlorite) and minor accessory minerals. The more advanced mylonitisation is, the higher the proportion of sheet-silicates; these reach over 50 vol% in ultramylonitic zones (mainly at the expense of feldspars). Because of this high proportion of sheet-silicates and the marked decrease in grain-size, these ultramylonitic zones represent areas of reduced mechanical competence.

- In weakly deformed rock portions, quartz shows undulatory extinction and occurs in subgrain aggregates; in mylonitic rock portions it is statically (post-deformatively) recrystallised and occurs mainly in quartz ribbons (Figure 7a). These ribbons, consisting of a fine-grained quartz mosaic, have aspect ratios of 1:10 - 1:20 and are aligned parallel to the cleavage. They represent the deformation products of single magmatic quartz grains. Typical dimensions are 0.5 - 1 mm x 5 - 20 mm.

- In contrast to quartz, plagioclase has been deformed predominantly in a brittle manner and has undergone varying degrees of cataclastic deformation. Oriented pressure shadows in the direction parallel to the stretching lineation (Figure 7b) consist mainly of sheet-silicates and quartz. The magmatic plagioclase was altered during metamorphism and has been pseudomorphed by albite, epidote and muscovite (albitisation/saussuritisation). In the most highly deformed areas, only a few mm-size clasts remain, the majority having been reconstituted to ultra-fine-grained albite in the mylonite matrix.

- K-feldspar with microcline twinning and numerous perthitic exsolutions forms cm-size porphyroclasts which are strongly flattened in the cleavage plane. As in the case of plagioclase, the deformation is cataclastic. Oriented pressure shadows are often very distinct. Alteration of K-feldspar to albite is present along the grain boundaries and along microfractures through the porphyroclasts.

- Biotite occurs in two generations. Primary magmatic biotite has a typical grain-size of around 1 mm, contains exsolved titanium phases, and also can be slightly chloritised. Alpine-time biotite is significantly finer-grained (0.01 - 0.1 mm) and often forms aggregates. Together with chlorite (and elongated feldspar clasts), it defines the mineral stretching lineation, which is thus assigned to the Alpine greenschist facies metamorphism. The Alpine biotite is enriched in the mylonitic shear-zones.

- Muscovite and epidote are very fine-grained (0.01 - 0.1 mm) alteration products of plagioclase. With the exception of strongly mylonitic zones, their occurrence is restricted to plagioclase pseudomorphs.
Figure 7: Criteria for the determination of shear sense: Micrographs of quartz ribbons and rotated feldspar clasts
a) Quartz ribbons in the XZ-section (crossed polars and gypsum plate; left: subtraction -> yellow interference colours, right: addition -> blue colours). The deduced shear sense is anti-clockwise with a shear direction parallel to the ribbons.
b) Rotated feldspar clast in the XZ-section (crossed polars) with asymmetric pressure shadows implying an anti-clockwise shear sense.
4.2 Structures related to ductile deformation

Ductile deformation is mirrored by the intensity of cleavage. In general, this intensity is low in the granodiorite gneiss, but is high in shear-zone VT 420. The cleavage itself can be defined on a macroscopic scale by parallel orientation of micas and by flattened xenoliths in the gneiss (BOSSART & MARTEL 1990). Microscopically, a slight flattening of the potassium feldspar clasts can be observed in the XY- and XZ-sections. This flattening plane is parallel to the cleavage. Recrystallised quartz bands (mylonites: quartz ribbons) are also oriented parallel to the cleavage (Figure 7a).

A weak **mineral stretching lineation** is developed in the cleavage plane (XY-plane). It dips steeply, almost parallel to the dip of the XY-plane. Macroscopically, the lineation can be recognised in feldspar clasts if the XZ- and YZ-planes are compared (XZ-plane: feldspars elliptic; YZ-plane: feldspars slightly elliptic to round). Microscopically this lineation is well-defined in oriented pressure shadows (parallel to the X-axis) of feldspar clasts and in the orientation of Alpine sheet-silicates.

Shear-zone VT 420 contains both **mylonitic and ultramylonitic zones** which are minor in extent (a few centimeters thick). These zones occur more frequently at the northern boundary of the shear-zone. In virtually all thin-sections cut in the XZ-plane, a preferred orientation of the crystallographic C-axes of quartz in quartz ribbons could be identified using the gypsum plate method with a polarizing microscope (see Figure 7a: yellow and blue interference colours of the ribbons). Taking into account the presence of a preferred orientation of quartz C-axes, the size of the crystals and the shape of the ribbons, dislocation creep may be inferred to have been the dominant deformation mechanism (SCHMID & HANDY 1991). Static recovery and increase of grain-size postdates dislocation creep.

4.2.1 Direction and sense of shearing in the ductile shear-zone

The shear direction is determined by the mineral stretching lineation (X-axis, Figure 6). The shear sense is determined in the XZ-plane (plane which contains the shear direction and is perpendicular to the shear-zone). A total of six thin-sections oriented parallel to XZ were analysed for crystallographic C-axis orientation of quartz and rotated feldspar clasts (Figure 7, Table 1). A rather consistent anti-clockwise rotation sense could be identified by the analyses of C-axes orientations (where the observer looks towards NE, i.e. in the strike direction of the shear-zone). Criteria for determining rotation senses of feldspar clasts are not unique. Considering only the findings of the C-axes orientations, it is concluded that gneisses to the south-east were thrust over those lying to the north-west.

4.2.2 Geometry of the ductile shear-zone and estimation of finite strain

Ductile symmetric shear-zones can be described geometrically by the orientation of the cleavage trajectories relative to the shear-zone walls (RAMSAY & HUBER 1983) and these trajectories can be used to estimate the shear displacement across the shear-zone. In the XZ-plane, the orientation of these cleavage trajectories can be measured and is given by the angle Θ' (Figure 8). The resulting angular shear strain \( \Psi \) can be calculated from the measured \( \Theta' \) by the relation

\[
\Psi = \arctan \left( \frac{2}{\tan 2\Theta'} \right)
\]
The shear strain $\gamma$ is defined as

$$\gamma = \tan \psi.$$  \hspace{1cm} (2)

The displacement $D$ is determined from the integration of the $\gamma$ (shear strain) distribution over the whole shear-zone:

$$D = \int y(x) \, dx.$$ \hspace{1cm} (3)

In Figure 8, $D$ corresponds to the area under the $\gamma$-x function, where x is distance measured across the shear-zone. The method, as described by RAMSAY & HUBER (1983, p. 45), is based on the following assumptions:

- The geometry of the shear-zone corresponds to that produced by a heterogeneous simple shear ("heterogeneous" means that shear deformation increases continuously from the shear-zone walls towards the centre).
- The shear-zone walls are undeformed ($\gamma = 0$).
- The length of the shear-zone is infinite (Figure 9a, left).

If all these assumptions are valid, the strain ellipse, shear strain and displacement at any point in the shear-zone can be deduced. Such "ideal" shear-zones are virtually unknown in nature; the shear-zone at VT 420 deviates significantly from the ideal too:

- Shear strain increases from SE to NW, but sudden changes (discontinuities) are common. The NW wall of the shear-zone is characterized by an enormous shear strain gradient (Figure 10). A superposition of heterogeneous simple and pure shear (coaxial deformation) rather than simple shear alone seems to be more likely for VT 420 but remains speculative in view of the many problems and possibilities involved in mass conservation.
- The shear-zone walls are not undeformed, but slightly gneissose.
- The length of the shear-zone is finite, but still much larger than our scale of observation.

A simplified schematic shear-zone profile of the VT 420 site with a schematic shear strain distribution is given on the right half of Figure 9a. Figure 9b shows a X'Z' (X'Z' is subparallel to XZ) section of the shear-zone on the eastern tunnel wall.

Despite the conditions being far from ideal, it was attempted to determine the distribution of shear strain over the whole shear-zone and subsequently calculate the shear strain from measurements of the orientation of cleavage (Figure 9b, Table 2). The resulting shear displacement is 290 cm, which is a minimum value for two reasons:

1. During ductile deformation, a certain proportion of the strain is accommodated by dynamic recrystallization (MEANS 1981). In the extreme case, a steady-state foliation can develop which is independent of strain; in such a case, total strain calculated from the orientation of cleavage is an underestimate.

2. At the northern shear-zone wall, the value of $\Theta'$ is small due to the alignment of the cleavage trajectories parallel to the shear-zone wall, and the angular shear strain results in values close to 90° (cf. eq. 1). Consequently, small variations of $\Theta'$ cause large variations in the calculated shear strain (cf. eq. 2). Therefore, the shear strain at the northern shear-zone wall has been limited by an assumed minimum distribution ($\gamma$ curve stippled between 14 and 20 cm, Figure 9b). The southern boundary of the shear-zone has been set at point A’, where the shear strain is small. In addition, to minimize the shear strain at the southern boundary, it was actually set to zero at A’.
Table 1: Determination of the shear sense of ductile deformation in thin-sections cut in the XZ-plane.

<table>
<thead>
<tr>
<th>Thin-section number</th>
<th>Rotation sense deduced from C-axes of quartz</th>
<th>Rotation sense deduced from feldspar clasts (asymmetric pressure shadows, bookshelf clasts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VT 420 XZ 6</td>
<td>anti-clockwise</td>
<td>anti-clockwise</td>
</tr>
<tr>
<td>VT 420 XZ 6</td>
<td>anti-clockwise</td>
<td>clockwise/anti-clockwise</td>
</tr>
<tr>
<td>VT 420 XZ 8</td>
<td>clockwise/anti-clockwise</td>
<td>clockwise/anti-clockwise</td>
</tr>
<tr>
<td>VT 420 XZ 9</td>
<td>anti-clockwise</td>
<td>clockwise/anti-clockwise</td>
</tr>
<tr>
<td>VT 420 XZ 10</td>
<td>clockwise/anti-clockwise</td>
<td>clockwise/anti-clockwise</td>
</tr>
<tr>
<td>VT 420 XZ 11</td>
<td>anti-clockwise</td>
<td>anti-clockwise</td>
</tr>
</tbody>
</table>

Figure 8: The relationship between orientation of cleavage trajectories $\theta'$, angular shear strain $\psi$ and shear strain $\gamma$ in an ideal shear-zone. The displacement $D$ is calculated from the shear strain distribution.
Figure 9:  

a) Distribution of finite strain in an ideal ductile shear-zone compared with structures from VT 420  
b) Estimation of the shear displacement D of the VT 420 shear-zone.
Figure 10: Rock types encountered in the VT 420 shear-zone in a X'Z' section of the drillcore.
In spite of these difficulties, total shear displacement of the VT 420 shear-zone is not expected to exceed 10 m, based on comparison with analogous structures encountered in vertical and horizontal surface exposures whose strain is marked by dyke offsets.

4.3 Structures and mineralogy related to brittle deformation

Horizons of fault breccia with low cohesion can be identified in the shear-zone by eye (Figure 10). In X'Z'-sections of the VT 420 shear-zone, two to three discrete horizons (parallel to the general trend of the shear-zone) with thicknesses in the range of mm can be observed. There is a clear correlation between the location and frequency of fault breccias and zones of high finite ductile strains (e.g. mylonites): Fault breccias mainly occur in ultramylonitic zones. They are also present in zones with high deformation gradients, for example at the NW shear-zone wall. Macroscopically, these fault breccias appear interconnected due to the slightly undulating geometry of the individual horizons on the meter scale (e.g. MARTEL & PETERSON 1991, Fig. 15).

On a microscopic scale, these fault breccias can be interpreted as fault gouges (Figure 11, also see definitions in the appendix). Fault gouges are formed in shallow crustal levels (generally less than 5 km overburden) where brittle deformation dominates. They are due to cataclastic shear movements along fault surfaces (frictional sliding, particle rotation). Wallrock portions adjacent to the faults are broken up and ground down, and angular fragments become embedded in a very fine-grained, non-cohesive groundmass ("rock flour"). Subsequent hydrothermal effects may cause mineralogical alterations and possibly increase the cohesion of the fault gouge (cementation). However, virtually no alterations were identified at the VT 420 site; argillic alteration of micas and feldspars is hardly identifiable. Therefore, the cohesion of

<table>
<thead>
<tr>
<th>distance in X direction (cm) in section AA’ of Figure 9b</th>
<th>orientation of cleavage trajectories relative to the shear-zone wall Θ (degrees)</th>
<th>angular shear strain γ (degrees)</th>
<th>shear strain γ (dimensionless)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2.5</td>
<td>88</td>
<td>24</td>
</tr>
<tr>
<td>21</td>
<td>3</td>
<td>87</td>
<td>19</td>
</tr>
<tr>
<td>22</td>
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<tr>
<td>32.5</td>
<td>22</td>
<td>64</td>
<td>2</td>
</tr>
<tr>
<td>36 (=A’)</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2: Orientation of cleavage trajectories Θ, angular shear strain γ and shear strain γ.
the fault gouge groundmass still appears to be low. The angular rock fragments in the groundmass originate directly from the adjacent ductile shear-zone. Figures 11a and b show a section from a fault gouge in transmitted light and in UV light; in the latter case the pore-space impregnated with epoxy resin fluoresces (the more intensive the yellow colour, the higher the porosity; black, low porosity).

The infill material of the fault gouges (both fragments and matrix) consists of crushed wallrock material because there is virtually no hydrothermal alteration associated with brittle deformation. As the wallrock adjacent to the brittle structures is mica-rich mylonite in most cases, the fault gouge infill is also very mica-rich. The only hydrothermal product encountered in the fault gouges are minor amounts of smectite (~ 1%). In spite of its minor abundance, this swelling and highly sorbing clay mineral will dominate the sorption properties of the porous fault gouges. Cation exchange capacities of the fault gouges lie in the range 5 - 10 meq/100 g rock compared to ~ 1 meq/100 g in the granodiorite (BAEYENS, pers. comm., details to be described elsewhere). The smectite distribution in the fault gouge varies widely over distances of decimeters, indicating a channelized flow of the low-temperature hydrothermal fluid.

4.4 Geometry of the flow-paths

The geometric arrangement of the flow-paths was analysed in XZ- and YZ-sections. XY-sections run parallel to the cleavage and to the fault gouges and are therefore unsuitable. The thin-section analyses relate to a microscopic scale (millimeter to centimeter range). An extrapolation to larger scales (meter range) will be presented in chapter 4.4.3. Both scales will be strictly separated in the following.

4.4.1 Microscopic arrangement of the flow-paths

Despite taking the greatest possible care with sawing and preparation of thin-sections, it was impossible to avoid creating artificial pore-spaces. The fragile material of the fault gouges was sometimes washed out. In addition to this, cleavage-parallel cracks, which occur preferentially in mica-rich rock portions, were artificially broken up or at least enlarged (due to pressure release during tunnel construction, drilling, sawing). As a result, it is commonly difficult to distinguish between natural and artificially generated pore-spaces. Of course, the rocks in the migration shear-zone that have been used for experiments have been subjected to similar artificial effects as the samples investigated here (pressure release, washing-out caused by increased water flow during drilling and due to the imposed pressure gradients during testing).

The microscopic arrangement of the flow-paths is shown for XZ-sections in Figure 12 and for YZ-sections in Figure 13. Both sections originate from the drill-core from shear-zone VT 420. The following types of pore-space were distinguished:

1. **Fault gouge porosity (Figure 11a,b):** The fault gouges, which are non-cohesive and as much as several millimeters thick, are highly porous and undoubtedly of great significance for water-flow and for the migration experiments. The proportion of pore-space is roughly estimated at 10 - 30 vol%. Fault gouges mainly occur in zones of high ductile (mylonitic) deformation within the shear-zone and have a slightly undulating shape.

2. **Parallel channels (sheet-silicate porosity, Figure 11b,d):** These channels follow mica-rich bands, particularly in ultramyylonitic areas of the shear-zone. They are generally 0.001 - 0.05 millimeters thick (cf. also Figure 11d); thicker channels (up to 1 millimeter) are probably an artifact of sample preparation. This type of pore space is
spatially very anisotropic and allows water to flow mainly in a direction parallel to the cleavage, although there is some restricted lateral branching. The parallel channels provide limited links between the fault gouges on the one hand and to the granodiorite gneisses out of the shear-zone on the other.

3. Grain boundary and transgranular porosity (Figure 11c,e): The grain boundary pore-type reaches diameters of 0.001 - 0.02 millimeters and is present both in the mylonites (often in quartz ribbons) and, to a greater extent, in the less deformed areas of the granodiorite. It is particularly noticeable in the quartz ribbons where the quartz mosaic structure is reproduced (cf. also Figure 11c). Single pores of 0.01 - 0.02 millimeters are often observed at quartz triple points. These are linked by the grain boundary pores. Quartz-feldspar and quartz-biotite grain boundaries often have grain boundary pores. Grain boundary pores thus form a linked network in the neighbouring rock which is linked with the fault gouges mainly by the parallel channels. The transgranular pores are of secondary importance compared to the grain boundary porosity. Their geometry is similar to that of the grain boundary pores, except that it does not follow grain boundaries but passes through individual grains. Transgranular porosity is relevant only in more coarse-grained rock zones (i.e. weakly deformed granodiorite), and not in the very fine-grained ultramylonites. Grain boundary and transgranular pores are generally closely linked with one another.

4. Solution porosity (Figure 11e): "Cloudy" pore space arrays can be observed to emanate from transgranular pores in K-feldspar and plagioclase (see Figure 11e). Single pores often cannot be resolved by the microscope, but a maximum diameter is estimated at 0.003 mm. These pore spaces are interpreted as corrosion structures generated during Alpine greenschist metamorphism (sericitisation and albitisation of feldspars). Even though minor by volume, solution porosity can create large surfaces which are potentially important for matrix diffusion and sorption processes. To summarize, it can be said that different pore-types will predominate depending on the degree of ductile deformation of the rock. Fault gouge- and sheet-silicate-porosities dominate in zones of higher deformation (mylonites), while grain boundary pores are important in the granodiorite gneisses. What is important is that all these pore-spaces are interconnected and basically represent an open porosity.

Some differences in the arrangement of pore-spaces between the XZ- and YZ-sections could be identified in the thin-sections: As the quartz ribbons are longer in XZ than in YZ sections, the related regions of elevated grain boundary porosity are also. Due to the geometry of cleavage in the shear-zone (discussed above), the parallel channels (sheet silicate pores) in XZ sections trend asymptotically from the SE towards the shear-zone. In YZ sections, however, they are parallel to the shear-zone. Grain boundary pores are longer in XZ (parallel to X) than in YZ sections.

4.4.2 Model abstraction of the microscale pore-space distribution

This section aims at simplifying the findings and summarizing them in a three-dimensional model cube which is presented in Figure 14 based on the information from Figures 12 and 13. There is a high degree of pore connectivity parallel to the shear-zone. If Figures 12 and 13 are compared, the connectivity within the shear-zone appears to be higher in YZ-sections than in corresponding XZ-sections. It is not known whether this is typical for the whole migration shear-zone or is only a local effect. The degree of connectivity is reduced perpendicular to the shear-zone. The hydraulic connection between the shear-zone and weakly deformed gneiss
matrix is weaker at the northern boundary of the shear-zone, but well-developed in the southern section.

The individual structures (dimension of ribbons or orientation of the feldspars in the matrix, etc.) are not represented to scale in Figure 14. The characteristic features from Figures 12 and 13 are presented only schematically. It was attempted to show the three most important pore-types (fault gouge-, sheet silicate- and grain boundary-porosity) clearly and to assign them to an aperture distribution. The aperture distribution in Figure 14 is the result of a detailed survey of brittle structures from boreholes VE 88.001-VE 88.004 (IROUSCHEK & BOSSART, 1989). These boreholes penetrated through a shear-zone similar to VT 420 in the ventilation tunnel and the resultant distribution of fault gouge thicknesses was close to log normal. In contrast to the VT 420 shear-zone in which the fault gouge is usually several mm thick, fault gouges of the ventilation tunnel shear-zone may be as thick as 5 cm. It is assumed that the aperture distribution in both shear-zones will be log normal because the pore-types of the migration shear-zone were also observed in the ventilation shear-zone.

The density (surface density or volume density) of the three pore-types was not investigated. However, first estimates could be derived directly from Figures 12 and 13. The spatial extent and persistence of the flow-paths will be discussed in the next section.

4.4.3 Extrapolation to larger scales

The quantitatively dominant flow-path type in the VT 420 shear-zone are the highly porous fault gouges with thicknesses of as much as several millimeters. At the GTS, the conclusions which can be drawn as to the spatial extent of these fault gouges on an outcrop- or macroscopic-scale are limited (boreholes are unsuitable; tunnel walls: limited information due to still small outcrop area and the round profile). Shear-zones identified from surface mapping close to GTS are similar to VT 420 and therefore are included for comparison. Figure 15 shows a Y'Z'-section (± horizontal plane) from a ductile shear-zone with S-direction from the NW shore of the Räterichsboden reservoir. In this shear-zone, the fault gouges and their relation to ductile structures were mapped. It is seen from Figure 15 that these fault gouges can extend to several meters and are linked to zones with high ductile shear deformation, which is consistent with the findings at GTS. In the two-dimensional cartoon of Figure 14, the thickness of fault gouges varies considerably. Often single fault gouge zones are interrupted and are therefore not interconnected two-dimensionally. However, in three dimensions, interconnection of fault gouges seems to be likely and should be checked by percolation theories. In any case, fault gouges are interconnected by grain boundary and sheet silicate pores.

Interconnection of the flow-paths in the size range of 100 m to km (representing the scale of regional thrusts) has not been investigated but is nevertheless likely. It can also be assumed that, perpendicular to the shear-zones, there is a link to the fine, polygonal grain boundary pore network extending along the whole shear-zone.
a) XZ-section through the highly porous fault gouge. Angular fragments of country rock float in the extremely fine-grained groundmass.

b) Sharp boundary between porous fault gouge (right) and very compact ultramylonite (left). Pores along discrete mica layers (parallel channels, sheet silicate porosity) form the only connection between the fault gouge and the granodiorite outside the actual shear-zone. XZ-section.

c) Quartz ribbon with very marked grain boundary pores along recrystallised quartz grains. A mica band which penetrates the quartz ribbon contains a set of sheet silicate pores. XZ-section.

d) Fine-grained ultramylonitic zone with very low porosity. A mica layer at the contact with less deformed granodiorite (extreme left) contains parallel channels (sheet silicate pores). XZ-section.

e) Potassium feldspar (yellow in transmitted light) and plagioclase (grey in transmitted light) with transgranular pores ( fissures), from which numerous solution pores (etching structures) emanate. XZ-section.

Figure 11: Types of microscopic pore-spaces encountered in the VT 420 shear-zone, illustrated in micrographs. Upper images in transmitted light (a,b: plane-polarised, c-e: crossed polar). Lower images display the same sections in UV-light, the pore space impregnated with resin fluorescing. Image width 0.6 mm in each case.
Figure 12: XZ-section through the drillcore: Relation between macroscopic deformation features (cleavage trajectories stippled, fault gouges black in the sketch) and the microscopic distribution of flow-paths in the micrographs.
Figure 13:
YZ-section through the drill core: Relation between macroscopic deformation features (cleavage trajectories stippled, fault gouges black in the sketch) and the microscopic distribution of flow-paths in the micrographs.
Model cartoons displaying the structure and pore space distribution in the VT 420 shear-zone. Pore structures not to scale. At the bottom, the observed types of pore spaces are related to a pore aperture distribution. Note that “pore aperture” in the case of the fault gouges refers to the total thickness of the structure and not to the apertures of individual pores. Also note that these data have been collected from the ventilation shear-zone some 30 m away from the migration shear-zone (see Figure 1); this structure underwent significantly more ductile and brittle deformation than the migration shear-zone.
Figure 15: Ductile shear-zone encountered on the surface (shoreline of Räterichsboden reservoir): Structural map of ductile structures and fault gouges.
5. Quantitative porosimetry

In chapter 3, types of pores, their geometries, and their distributions in different rock types have been discussed on the basis of observations from impregnated thin-sections. In order to quantify the findings, a number of different methods has been applied to measure quantitatively the porosity accessible to water and dissolved species in rocks adjacent to the main shear-zone. Due to its cohesionless nature, no porosimetric measurements could be conducted on the water-bearing fault gouge itself; a rough estimate from thin-section observations yields 10 - 30 vol% porosity in this central zone.

It was mentioned in chapter 3 that the pore geometry (and presumably also the open porosity) varies as a function of rock type, i.e. as a function of both ductile and brittle deformation of the granodioritic parent rock. An attempt was thus made to differentiate between all relevant rock types encountered in the vicinity of the water-conducting zone in the porosimetric measurements.

5.1 Hg injection porosimetry

5.1.1 Methodology

Aliquots of 10 - 20 g rock were used to determine the connected porosity by Hg injection. A commercial porosimeter at the University of Fribourg (Switzerland) with a maximum injection pressure of 2000 bars was used. During each measurement, pressure was increased in steps and each corresponding volume of injected Hg was recorded. The measured pressure - volume function can be recalculated in terms of pore size distributions assuming planar or cylindrical pore geometries. As pore spaces in rocks are rather planar structures than cylindrical tubes, the following relation is used to calculate equivalent pore apertures:

\[ d = 2r = \frac{4 \gamma \cos \theta}{P} \]

where

\[ \gamma = \text{surface tension of Hg at } 25^\circ \text{C} = 470 \times 10^{-3} \text{ N/m}, \]
\[ \theta = \text{contact angle of Hg} = 141^\circ, \]
\[ P = \text{injection pressure}, \]
\[ d = \text{equivalent aperture of planar pore} \]
\[ r = \text{half equivalent aperture of planar pore ("radius")}. \]

Pores with equivalent radii > 7.5 \( \mu \text{m} \) are arbitrarily termed macropores and those < 7.5 \( \mu \text{m} \), micropores. Hg porosimetric measurements yield data in ml Hg per g of rock and have to be recalculated to vol%:

\[ \pi \text{[vol%]} = 100 \times \pi \text{[ml/g]} \times \text{rock density [g/cm}^3\text{]}]. \]

with \( \pi = \text{total open porosity}. \)

Although the analytical error of Hg injection porosimetry is small, uncertainties arise due to sampling effects that are not easily quantifiable:

1. From the in situ lithostatic pressure (corresponding to the 400 m overburden at the GTS) of 130 bars each sample was decompressed to atmospheric conditions. This pressure release may have opened pore spaces not present prior to tunnel construction.
2. Drilling and sawing may have caused mechanical damage to the microscopic structure of the rock.
3. The representativity of the 10 - 20 g samples for a larger rock body is questionable.
4. Using 2000 bars as the maximum injection pressure, only pores with an equivalent radius > 4 nm will be detected. It has previously been shown that in microporous rocks the Hg injection measurements typically yield lower values than data derived from mass-transfer measurements (such as diffusive access of $^3$H to the pore space; N. JEFFERIES, pers. comm.). This discrepancy has been attributed to the presence of pore-spaces with equivalent radii < 4 nm which were not intruded by Hg. Points 1 and 2 apply to any of the methods used for porosimetric measurements and lead to an overestimation of the open porosity. Efforts to measure in situ-porosities are currently being undertaken in the Grimsel laboratory. Point 4, alternatively, leads to an underestimation. Therefore, the systematic errors in our measurements will at least partially cancel each other out.

5.1.2 Sample description

Rock types around the main shear-zone (granodiorite, mylonite, fault gouge) vary dramatically on the scale of centimeters, and all rock types are present within 10 cm of the main water-conducting structure. 10 samples were chosen for analysis, mostly from the immediate vicinity of the shear-zone. They include 5 different rock types that are illustrated in Figure 10:

1) almost undeformed granodiorite
2) gneissose granodiorite
3) mylonitic granodiorite
4) mica-rich mylonite
5) crumbly ultramylonite.

The rock types 1) to 5) represent a sequence of increasing ductile and also brittle deformation. 1) and 2) are the least deformed rock types and are characteristic of the whole rock mass in the ventilation tunnel that was not affected by shear-zones. In the nomenclature of groundwater modelers, these rocks are sometimes referred to as the "rock matrix" and are represented in the lower third of Figure 10. Rock types 3) and 4) are characteristic of shear-zones that have been affected by significant ductile and possibly some younger brittle deformation. They correspond to the central section of Figure 10. Rock type 5) has undergone extreme ductile deformation and also contains most of the brittle deformation (fault gouges) due to its low mechanical competence, as illustrated in the upper third of Figure 10.

5.1.3 Results and discussion

Porosimetry results are listed in Table 3 and equivalent radius distributions of micropores are sketched in Figure 16. It is evident from Table 3 that there is no simple and obvious relation between open porosity and distance from the main water bearing structure. However, a clear dependence of porosity on rock type can be seen. Figure 17 shows the measured macro- and microporosities as a function of the degree of rock deformation. Undeformed granodiorite has open porosities in the range 0.8 - 1.5 vol% which decrease to 0.5 - 0.9 vol% in mylonitic granodiorite. This is consistent with microscopic observations which show that recrystallized, fine-grained mylonites have a denser structure than granodiorite. The most strongly deformed mylonite and ultramylonite samples show a very pronounced increase both of the micro- and the macroporosity up to 2 vol%, which is probably due to brittle deformation that reactivated and overprinted the dense mylonitic fabric. The association of brittle deformation (related to movements in the fault gouge zone) with mylonitic rock types is discussed in previous sections and is mainly a consequence of the high content of perfectly oriented sheet silicates producing a low mechanical competence in the mylonites. It can be seen from Figure 16 that the equivalent pore aperture spectra of the ultramylonites are skewed towards larger apertures; these micropores with apertures > 1 μm represent brittle microcracks in rock immediately adjacent to
Figure 16: Size distribution of micropores as determined from Hg injection analyses. The area below each curve is proportional to the total open microporosity. Two analyses were run for each rock type (therefore two curves per graph).
Figure 17: Dependence of open porosity on ductile and brittle deformation as determined from Hg injection analyses.
the cataclastic fault gouge zones.

In summary, the Hg injection data can be consistently interpreted in terms of variable degrees of rock deformation. Whereas ductile deformation reduces porosity, subsequent reactivation by brittle deformation again increases open porosity and also permeability. Mylonites unaffected by brittle deformation have low porosities whereas those reactivated by subsequent brittle deformation are highly porous.

<table>
<thead>
<tr>
<th>sample no.</th>
<th>rock type</th>
<th>distance from fault gouge, cm</th>
<th>deformation ductile</th>
<th>brittle</th>
<th>densitometry rock density, cm³/g</th>
<th>Hg injection porosimetry open macro-porosity, vol%</th>
<th>open micro-porosity, vol%</th>
<th>total open porosity, vol%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>almost undeformed granod.</td>
<td>3.5</td>
<td>very weak</td>
<td>absent</td>
<td>2.72</td>
<td>0.25</td>
<td>0.56</td>
<td>0.81</td>
</tr>
<tr>
<td>2</td>
<td>almost undeformed granod.</td>
<td>3.5</td>
<td>very weak</td>
<td>absent</td>
<td>2.67</td>
<td>0.62</td>
<td>0.90</td>
<td>1.53</td>
</tr>
<tr>
<td>7</td>
<td>gneissose granodiorite</td>
<td>2.0</td>
<td>moderate</td>
<td>absent</td>
<td>2.65</td>
<td>0.50</td>
<td>0.63</td>
<td>1.13</td>
</tr>
<tr>
<td>8</td>
<td>gneissose granodiorite</td>
<td>2.0</td>
<td>moderate</td>
<td>absent</td>
<td>2.65</td>
<td>0.15</td>
<td>0.54</td>
<td>0.69</td>
</tr>
<tr>
<td>9</td>
<td>mylonitic granodiorite</td>
<td>7</td>
<td>strong</td>
<td>very weak</td>
<td>2.71</td>
<td>0.15</td>
<td>0.36</td>
<td>0.52</td>
</tr>
<tr>
<td>10</td>
<td>mylonitic granodiorite</td>
<td>7</td>
<td>strong</td>
<td>very weak</td>
<td>2.73</td>
<td>0.42</td>
<td>0.50</td>
<td>0.92</td>
</tr>
<tr>
<td>3</td>
<td>mica-rich mylonite</td>
<td>1.5</td>
<td>very strong</td>
<td>weak</td>
<td>2.71</td>
<td>0.25</td>
<td>0.42</td>
<td>0.67</td>
</tr>
<tr>
<td>4</td>
<td>mica-rich mylonite</td>
<td>1.5</td>
<td>very strong</td>
<td>weak</td>
<td>2.63</td>
<td>0.42</td>
<td>0.67</td>
<td>1.09</td>
</tr>
<tr>
<td>5</td>
<td>crumbly ultramylonite</td>
<td>1</td>
<td>extr. strong</td>
<td>strong</td>
<td>2.71</td>
<td>0.34</td>
<td>0.75</td>
<td>1.08</td>
</tr>
<tr>
<td>6</td>
<td>crumbly ultramylonite</td>
<td>1</td>
<td>extr. strong</td>
<td>strong</td>
<td>2.70</td>
<td>0.69</td>
<td>1.41</td>
<td>2.09</td>
</tr>
</tbody>
</table>

Table 3: Results of Hg injection analyses.

5.2 Water saturation gravimetry

5.2.1 Introduction and aims of the measurements

The principle of the porosity determination is to measure the weight difference of the completely dry and the water-saturated sample. This weight difference corresponds to pore-filling water and can be recalculated into open porosity. The analyses are by-products of an analytical campaign aimed at the measurement of desorption curves (SCHNEEBELI et al. 1990) and were conducted at the ETH Zürich (M. Schneebeli, Institut für Terrestrische Ökologie, Bodenphysik). The aim of the gravimetric analyses was to measure open porosity as a function of the distance from the tunnel wall, i.e. to survey possible artificial effects of tunnel construction on porosity.
5.2.2 Methodology

Half cores ($\varnothing = 11$ cm, thickness 1.8 cm) were dried in an oven at 105 °C until weight constancy was attained ($\Delta$ weight [g] / $\Delta$ time [h] < 0.05). Subsequently each sample was installed in a desiccator and held under vacuum conditions for 4 h and then slowly saturated with water (still under airless conditions). Sample weight was determined each 24 h after wiping with a dry cloth. The weight of the water-saturated sample was measured when weight constancy was attained ($\Delta$ weight [g] / $\Delta$ time [h] < 0.05).

5.2.3 Sample description

Because desorption measurements require polished surfaces of several cm in size, it was impossible to use strongly deformed, friable samples. All samples were taken from a single core ($\varnothing = 11$ cm) of homogeneous, almost undeformed granodiorite corresponding petrographically to the Hg injection samples 1, 2, 7 and 8 and taken at a distance of 1 m from the shear-zone.

5.2.4 Results and discussion

Results are listed in Table 4 and set out graphically in Figure 18. Measured porosities are in the range 0.67 - 0.85 vol%, which is consistent with Hg injection data of the same rock types (samples 1, 2, 7, 8: open porosity = 0.69 - 1.53 vol%, $\varnothing = 1$ vol%). The gravimetric data also show that there is a slight but distinct decrease of porosity from the tunnel wall (0.81 vol%) to 0.72 vol% 20 cm away from the tunnel. It may well be that the slightly increased porosities adjacent to the tunnel wall reflect mechanical damage the rock sustained during tunnel construction. Longer cores should be used in future analytical campaigns in order to characterize the total thickness of the damaged zone around the tunnel.

<table>
<thead>
<tr>
<th>sample</th>
<th>distance from tunnel wall (cm)</th>
<th>open porosity (vol%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-2</td>
<td>2.5</td>
<td>0.81</td>
</tr>
<tr>
<td>5-3</td>
<td>3.2</td>
<td>0.85</td>
</tr>
<tr>
<td>5-4</td>
<td>4.0</td>
<td>0.72</td>
</tr>
<tr>
<td>5-5</td>
<td>5.5</td>
<td>0.80</td>
</tr>
<tr>
<td>5-6</td>
<td>7.0</td>
<td>0.82</td>
</tr>
<tr>
<td>5-7</td>
<td>8.6</td>
<td>0.70</td>
</tr>
<tr>
<td>5-8</td>
<td>10.2</td>
<td>0.72</td>
</tr>
<tr>
<td>5-9</td>
<td>11.8</td>
<td>0.80</td>
</tr>
<tr>
<td>5-10</td>
<td>13.4</td>
<td>0.85</td>
</tr>
<tr>
<td>5-11</td>
<td>15.0</td>
<td>0.74</td>
</tr>
<tr>
<td>5-12</td>
<td>16.6</td>
<td>0.79</td>
</tr>
<tr>
<td>5-13</td>
<td>18.2</td>
<td>0.75</td>
</tr>
<tr>
<td>5-14</td>
<td>19.7</td>
<td>0.67</td>
</tr>
<tr>
<td>5-15</td>
<td>21.2</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Table 4: Results of porosimetric measurements using the water gravimetric method.
5.3 Characterisation of pore space geometry by impregnation with $^{14}$C-polymethylmethacrylate (PMMA)

5.3.1 Introduction and presentation of the method

Impregnation with $^{14}$C-labeled PMMA is a new technique developed at the Finnish Centre for Radiation and Nuclear Safety (STUK) (HELLMUTH & SIITARI-KAUPPI 1990), where also the present study was conducted. The method yields information on the geometrical distribution of pore spaces in rocks on the scale of $\mu$m to cm and the relation of pore spaces to mineralogical and textural features. To a certain extent, semi-quantitative values of total open porosity can be obtained too.

The analytical procedure is as follows:

1. Drilled cores with diameters of a few cm are impregnated with $^{14}$C-labeled PMMA under vacuum conditions. $^{14}$C-labeled PMMA in its monomeric form (=MMA) fills the open pore space in rock roughly to the same extent as groundwater.

2. Subsequently, the sample is irradiated by a $^{60}$Co source, which induces polymerization and thus solidification of the PMMA. (NB: The irradiation has nothing to do with the production of $^{14}$C!)

3. The impregnated sample is then cut in half parallel to the drillcore axis. Subsequently, autoradiographs on $\beta$-sensitive film are prepared on the axial cut surfaces through the
core. As $^{14}$C is a β-emitter (with no associated γ radiation), the autoradiographs represent replicas of the pore space impregnated by PMMA.

4. Digital image processing of the grey levels on the autoradiographic film is used to display regions in the sample that exceed a selected porosity value. A total porosity can also be derived.

A major advantage of this method is that the rock surface to be examined is cut after impregnation, whereas thin-sections have to be cut and polished prior to impregnation due to the very limited penetration of the fluorescent dye. Therefore, fewer artificial structures can be expected when using the PMMA method. However, the spatial resolution of the PMMA method is limited and correlation of observed pore spaces with mineralogical and textural features is not as straightforward as in thin-sections. Resolution is a function of the range of the emitted β radiation (i.e. 100 - 200 μm) and of the size of the laser beam used for scanning (0.72 x 0.05 mm$^2$).

5.3.2 Experimental details

The core samples were carefully dried at 120 °C under oil pump vacuum for ten days. Prior to impregnation, the partial pressure of water was lowered using a liquid nitrogen trap for several hours. Impregnation with the $^{14}$C-labeled MMA monomer was conducted under vacuum conditions by first allowing MMA vapour to infiltrate for about 15 minutes and then adding MMA until the specimen was completely covered. After an impregnation time of two weeks, the samples were removed from the labeled MMA, rinsed and immersed in inactive MMA. This step was followed by irradiation with γ-rays from a $^{60}$Co source up to a dose of 5 Mrad, resulting in polymerization of liquid MMA to solid PMMA. The impregnated cores were subsequently heated to 110 °C for three hours in order to destroy thermoluminescent effects of minerals. The cores were then cut in two perpendicular to the rock cleavage with a thin-bladed diamond saw. β-autoradiographs were prepared on the freshly cut surfaces with exposure times varying between 14 and 21 days on Kodak X-OMAT MA film.

Autoradiographs were scanned with a laser densitometer (LKB 2202 Ultro Scan). The resolution of densitometric grey scales exceeds that of any photographic emulsion. Subsequently, the scanned pictures were studied using a digital image processing equipment (Quantimet 520, Cambridge Instruments, UK). Results can be displayed as false-colour binary images showing areas of porosities above a given (and adjustable) level and superimposed on the respective autoradiograph.

5.3.3 Sample material

Three drilled cores (Ø = 36 mm, h = 60 mm), all from the vicinity of the main shear-zone described above, were examined and are listed in Table 5.

5.3.4 Results and discussion

Photographic reproductions of the rock sections, autoradiographs and processed false-colour binary images superposed on the autoradiographs are displayed in Figures 19-21. A few key points emerge from a review of these figures:
Table 5: Characterisation of samples used for PMMA resin impregnation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description, rock types</th>
<th>Corresponding Hg injection samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>weakly deformed granodiorite and mica-rich mylonite, separated by a sharp contact (no brittle deformation)</td>
<td>1 - 4</td>
</tr>
<tr>
<td>G3</td>
<td>homogeneous, mylonitic granodiorite (no brittle deformation)</td>
<td>9 - 10</td>
</tr>
<tr>
<td>G4</td>
<td>homogeneous, weakly deformed granodiorite, containing a mm-thin mylonitic shear-zone (no brittle deformation)</td>
<td>7 - 8</td>
</tr>
</tbody>
</table>

1. It is evident that granodiorite has a higher open porosity than mylonite. This is especially clear from Figure 19 where both rock types occur together.

2. Pore spaces in the granodiorite are mainly constituted by an interconnected network of grain boundary and transgranular pores, and the spatial anisotropy of pore orientations (and thus the anisotropy of permeability) is weak.

3. Pore spaces in the mylonitic rock portions are very anisotropic, and only a very limited number of pores can be identified making connections in the direction perpendicular to cleavage, i.e. in the direction perpendicular to the shear-zone.

4. Large K-feldspar porphyroclasts appear to be porous in Figures 19-21. However, this is in contradiction with thin-section observations and probably due to analytical artifacts such as thermoluminescent effects. The effect did not disappear upon repeated heating of the sample. Tests are in progress with a thin aluminized mylar foil between sample and film during exposure in order to prevent luminescence phenomena. Tests should also be conducted with inactive rock samples.

Values of total open porosities can also be calculated from the optical densities on the autoradiographs. Calibration was attempted by exposing the film to pure PMMA sources with known specific activity and equating the obtained optical density with 100% porosity. Because the range of the $^{14}$C $\beta$-radiation (0.156 MeV) varies significantly between resin ($\approx$ 0.3 mm) and silicate minerals ($\approx$ 0.1 mm), a correction must be applied to compensate the different $\beta$-absorptions. The corrected results for the investigated samples are:

- G4, weakly deformed granodiorite: 0.23 vol% (+)
- G1, weakly deformed granodiorite: 0.28 vol% (+), 0.32 vol% (-)
- G3, mylonitic granodiorite: 0.16 vol% (-)
- G1, mica-rich mylonite: 0.10 vol% (+)

(+) using a mylar foil between rock and film (shielding of thermoluminescence effects)
(-) no mylar foil used
The relative values obtained for the total porosities in different rock types are consistent with thin-section observations as well as Hg injection measurements because a significant decrease of porosity with increasing ductile (mylonitic) deformation is evident. However, absolute porosities are too low when compared with the other methods. The source of this systematic error is as yet unclear; some problems may be related to the β-absorption correction or to saturation of the film density in some highly porous regions of the samples.
Figure 19: Polymethylmethacrylate (PMMA) impregnation of sample G1 (weakly deformed granodiorite and mica-rich mylonite). a), rock photograph (width = 6 cm); b), autoradiograph (width = 6 cm). The black frame depicts the area shown in the processed images; c), processed images displaying in red the regions where porosity lies above 0.2 vol% (left) and 0.6 vol% (right).
Figure 20: Polymethylmethacrylate (PMMA) impregnation of sample G3 (homogeneous, mylonitic granodiorite). a), rock photograph (width = 6 cm); b), autoradiograph (width = 6 cm). The black frame depicts the area shown in the processed images; c), processed image displaying in red the regions where porosity lies above 0.3 vol%.
Figure 21: Polymethylmethacrylate (PMMA) impregnation of sample G4 (homogeneous, weakly deformed granodiorite). a), rock photograph (width = 6 cm); b), autoradiograph (width = 6 cm). The black frame depicts the area shown in the processed images; c), processed images displaying in red the regions where porosity lies above 0.2 vol% (left) and 0.6 vol% (right).
6. Interpretation and discussion

6.1 Qualitative and quantitative description of the flow-paths

The pore space geometry was qualitatively described by studying thin sections (Figures 11 - 13). It was found that the fault gouges are the dominating flow-paths in the migration shear-zone and represent the only structures where advective and dispersive transport occurs. All other pore types have apertures of some \( \mu \text{m} \) or less and are accessed solely by diffusive transport processes.

Together with the sheet silicate porosity, the fault gouge porosity is restricted to zones of high ductile strain, i.e. to the mylonites, whereas grain boundary pores dominate in the mildly deformed granodiorites of the adjacent wallrock. Thus the spatial arrangement and persistence of the pore spaces and water flow-paths is correlated to a high degree with the heterogeneity and anisotropy of the fabric generated by ductile deformation. Hg injection porosimetry was applied on rocks in variable states of ductile and brittle deformation (with the exception of the fault gouges which cannot be analyzed for technical reasons). A clear dependence of porosity on the deformation state of the rock type was found. Therefore, there is a good correlation between thin-section observations and Hg injection data.

A 2-dimensional distribution of the pore spaces can be derived from thin-sections whereas in the Hg injection method a 3-dimensional distribution of equivalent pore apertures is obtained. Sample sizes represented by thin-sections (several cm\(^2\)) are about the same as those used for Hg injection porosimetry (several cm\(^3\)). Because of the good correlation of both methods, quantitative porosimetric results could be obtained directly from thin-section analyses. It is unclear how many thin-section analyses would be required to obtain representative values of porosity, something which could then be used to calculate permeabilities. It could then be attempted to calculate permeabilities from these data. Alternatively, permeabilities could be measured in the laboratory. Analyses are currently underway to measure permeabilities as a function of ductile mylonitic deformation and orientation relative to the strongly anisotropic (schistose) rock fabric.

6.2 Speculative processes for the formation of fault gouges

The geometry of fault gouges was described in detail in section 4.3. The following processes can account for fault gouge formation:

1) Cataclastic (frictional) deformation due to differential block movements during the course of the regional uplift of the Grimsel Crystalline.

2) Cataclastic (frictional) deformation due to periodic, long-duration movements such as earth tide effects and changes in water-level in the reservoirs (Räterichsbodensee, Grimselsee).

The averaged uplift rate in the Grimsel region is about 1 mm/a. To the best of our knowledge, there are no quantitative data available on differential block movements which are based on current uplift of the Grimsel Crystalline in the region of the GTS. The situation with regard to earth tide effects is different: data compiled from water pressure measurements in the GTS boreholes clearly show two pressure maxima and two pressure minima per day, which can be attributed to earth tides. As shown in Figure 22, the measured water pressure changes are about 0.015 bars. The pressure fluctuations must be explained by elastic, periodic opening and closing movements of pore spaces. Additionally, a tiltmeter experiment performed at different sites in the GTS (FLACH & NOELL 1989, NOELL & ZÜRN 1991) confirms also on a larger
scale the Earth tide induced differential movements along discontinuities. The idea we wish to put forward here is that the origin of the fault gouges could be explained by earth tide-induced movements and associated periodical opening and closing of discontinuities such as the VT 420 shear-zone. Shear movements due to earth tides are very small (on the order of 1-10 milli-arcseconds, FLACH & NOELL 1989). However, the time period over which such twice-daily elastic movements have occurred is very large (supposedly since the formation of the ductile mylonitic shear-zone 25 Ma b.p.). The question is therefore whether the frictional energy is sufficient to produce mica-rich, porous fault gouges (Figure 11a,b) in the mylonites. One important parameter is the reduced mechanical strength of the mylonitic rocks with respect to weakly deformed granodiorite and their response to cyclic deformation (loading/unloading).
Shear movements induced by changes in the water levels of the reservoirs are much greater than those caused by tide effects. Recent data from tilt measurements at the base of the Albigna dam (Graubünden, Switzerland) yield relative movements (tilt changes) of 35 μm per m in response to a water level change of 25 m (MEIER 1990). The periods of such movements vary between days and several months, and the duration (since operation of the reservoirs began) is relatively short. In principle, such long-periodic changes would be a possible factor causing fault gouges to form. We can also think of a fault gouge formation due to differential regional uplift that was (and is being) enhanced by periodic movements as outlined above. The next step would therefore be to compare relevant data for both periodic movements (tides and changes in water-level in reservoirs) and to quantify the movements along discontinuities.

6.3 Consequences for the hydraulics of the shear-zone

The transmissivity of the migration shear-zone is mainly governed by the geometry of the fault gouges, including parameters such as connectivity, thickness, grain-size distribution, lateral extent and persistence. This finding is confirmed by transmissivity values calculated from in-situ hydraulic tests. There seems to be a close positive correlation between open porosity of the different rock types and their transmissivity. Also, there is a strong spatial anisotropy of the transmissivity. A current analytical programme shows that transmissivity of mylonitic granodiorite is 1 order of magnitude lower in the direction normal to planar structures when compared with transmissivity parallel to them. This anisotropy is expected to be even much more pronounced in rocks with higher fabric anisotropy such as ultramylonites.

The standard approach for the calculation of hydraulic conductivity/transmissivity and specific storativity is based on classical conceptual models implying an infinite, homogeneous, isotropic porous medium and radial flow. These concepts should only be used as first estimates of the parameters. More refined models should be used when parameters such as the connectivity of a given geometry, anisotropy and non-radial flow are taken into account:

a. **With saturated transport** phenomena such as matrix diffusion or sorption, a revised geometric concept should be used as a basis for determining parameters. Interconnection of potential water flow-paths in the shear-zone and the matrix is given (cf. Figures 11 to 13), and a fluid exchange between shear-zone and surrounding gneiss matrix is possible. The specific surface of the pore space is very large in the fault gouges and small in the parallel channels (sheet-silicate porosity) of the surrounding mylonites. It increases again in the gneiss matrix (grain boundary and solution pores in feldspars). A quantitative determination of the surface area and its correlation with mineralogy are important for understanding sorption processes in the shear-zone and the matrix. Figures 12 and 13 can be used for a first estimate for the compact rock types whereas the surface of the fault gouge material could be determined by other methods such as BET.

b. **In the case of unsaturated transport** processes, parallel channels and grain boundary channels act as capillaries. The presence of two phase flow (i.e. vapor and water) in these pore spaces rather complicates the quantitative description of transport processes. An unsaturated zone in granodioritic rock clearly exists close to the tunnel wall, and it was shown that negative pressures decrease slowly when the tunnel wall becomes more saturated (SCHNEEBELI et al. 1991). Due to the high negative pressures, effective stresses in the unsaturated zone may be quite high and could also enhance micro-scale brittle deformations in the "disturbed zone" adjacent to the tunnel wall.

Given a normal tunnel climate (13°C, 80% rel. humidity), the migration shear-zone at AU 96 supplies around 0.5 litres of water per minute into the tunnel, while shear-zone VT 420 is dry. This can be explained by artificial washing-out of the fault gouge material during the migration experiments that were conducted close to the AU 96 site (cf. Figure 11 with an example of
washing-out). Advective flow velocities of several meters per hour during the migration experiments were calculated for AU 96. It is also likely that other artificial changes in the flow-field such as the development of a pressure sink during tunnel construction and hydraulic tests in different borehole intervals have partially washed out the fault gouges by internal erosion and continually bring the hydraulic system out of equilibrium. These artificial effects obviously enhance the transmissivity.

6.4 Implications for modelling studies

A number of flow and transport modelling studies have already been conducted on data from the migration shear-zone. The aim was to simulate radionuclide transport and to deduce the relevant sorption mechanisms (FRICK et al. 1991). Both conservative (e.g. Na-fluorescine, I, $^{82}$Br) and weakly sorbing tracers (e.g. $^{22}$Na, $^{85}$Sr) have been used.

6.4.1 Previous modelling studies

One of the first conceptual models (HERZOG 1989) assumed the flow-path to be a single plane consisting of a heterogeneous, isotropic equivalent porous continuum. The steady-state flow field was satisfactorily simulated when compared to the measured borehole interval pressures.

SMITH (1991) tested a single-porosity and a dual-porosity model to simulate the break-through curves of non-sorbing and weakly sorbing tracers obtained from laboratory experiments on mildly deformed granodiorite ("mini-migration" on the scale of some cm; no brittle deformation, no fault gouges). The relevant parameters in both models were obtained by fitting the model curves to the measured break-through curves. The dual-porosity model was based on the following assumptions:

1) The shear-zone is represented by parallel plates with constant aperture and infinite extension. Advective and dispersive flow takes place in a direction parallel to the plates. The space between the plates is assumed to be a void (i.e. free of fault gouges) or partially filled.
2) Perpendicular to the shear-zone, matrix diffusion occurs into two limited rock-zones (porous matrix on both sides of the parallel plates). These zones are only a few millimeters thick and end at an assumed impervious outer boundary.

The single-porosity model was able to simulate the behaviour of the sorbing tracers whereas the dual-porosity model was needed to reproduce the tails of the break-through curves of the non-sorbing tracers.

6.4.2 Suggestion for a revised geometrical conceptual model

The conceptual models described above refer to a scale of several centimeters to meters and thus assume that microscopic rock properties can be described by macroscopic (continuum) parameters. Using results based on the microscopic geometrical findings, a revised, 3-dimensional model is suggested. Some simplifications considering 2 rather than 3 dimensions appear to be justified in certain cases. The model consists of a dual-porosity description of the shear-zone geometry (equivalent porous medium and fracture network, see Figure 23):
1) The fault gouges can be represented deterministically as a system of interconnected plates of variable aperture, orientation and persistence, consisting of an equivalent porous medium (see Figure 23, right bottom).

2) The mylonitic zones, which are dominated by sheet silicate pores (parallel channels), are represented by a 3-dimensional, highly anisotropic fracture network. This network can be stochastically described by frequency data determined using thin-sections (such as orientation, frequency, thickness and persistence). The fault gouges are embedded within the mylonitic zones or are located at the contacts between the highly mylonitic rocks and the surrounding granodioritic matrix (Figure 23).

3) The granodiorite matrix is represented by a 3-dimensional, mildly anisotropic fracture network which consists of grain boundary and solution pores (Figure 23, right side of each sketch). Porosities and pore space geometries are different from those in the highly mylonitic parts but could also be characterised in terms of frequency distributions.

Figure 23: Geometrical conceptual model of the migration shear-zone, based on geometric relations in the mm-cm scale (cf. Figure 14).
6.4.3 Suggestion for a revised conceptual model for flow and solute transport

All three domains of the geometrical conceptual model are hydraulically interconnected and therefore open to flow and solute migration, provided all pore spaces are saturated. The spatial distribution of flow velocities will vary both in magnitude and direction due to the quite significant differences in permeability between the three domains. Tracer molecules injected into the shear-zone will migrate in a large number of different flow-paths (heterogeneous and anisotropic flow velocity field) and therefore spread over a volume of rock that increases with time. In our microscopic geometrical model (see scale in Figure 23), this process can be described as mechanical dispersion. Molecular diffusion is a second mass transport phenomenon and is caused by tracer transport down concentration gradients. Both mechanical dispersion and molecular diffusion are superimposed on the sharp advective front. The relative contributions of these two transport processes are a function of the Darcy velocity, which governs advective transport and therefore mechanical dispersion. If the hydraulic gradient in a rock portion (model cube in Figure 23) is small, then the flow velocities become small and mechanical dispersion is negligible whereas molecular diffusion dominates. On the other hand, if the flow velocities become high, then advection and mechanical dispersion dominate over molecular diffusion.

Applying this concept to the geometrical conceptual model of the migration shear-zone, the following conclusions can be drawn: High permeabilities and large Darcy velocities are expected in the fault gouges (domain 1), and advection and mechanical dispersion will be the dominating transport processes. This is certainly true for the in situ migration experiments with high hydraulic gradients imposed on the shear-zone. On the other hand, the contribution of mechanical dispersion is expected to be small in domains 2 and 3 because of the low permeabilities of the sheet silicate and grain boundary pores, and molecular diffusion is expected to dominate the solute transport. These relations in the migration shear-zone constrain and justify the application of the dual-porosity transport model.

Radionuclide retardation processes occurring during the in situ migration experiments are spatially confined to a very narrow zone around the main water conducting channels (fault gouges) because molecular diffusion into the rock matrix is a slow process (mainly grain boundary pores) and is limited by the short timescales of the experiments (days to months). This is another justification for the use of a microscopic conceptual model as suggested above. The microscopic conceptual model could also be transferred to a mesoscopic or macroscopic continuum (e.g. the introduction of macro-dispersion) by applying well established averaging techniques (e.g. BEAR 1979).

Mineralogical variations between the three domains are evident (mica-rich fault gouges vs gneiss matrix of granitic composition). The different sorption properties of the three domains can be taken into account by using rock-dependent sorption values as evaluated in situ (FRICK et al. 1991). As a result, the microscopic distribution of a solute (mm to cm scale) in a small part of the migration shear-zone could be calculated as a function of time.

The authors feel that the conceptual model outlined here can be used for better predictions of small-scale tracer concentration distributions in the migration shear-zone or in laboratory samples and result in a better fit of observed and calculated break-through curves, although presently, it is not known if appropriate numerical codes applicable to the model exist.
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Appendix: Glossary of terms

In the glossary, we try to give simple definitions and explanations of geological and structural terms used in the text. More detailed and illustrated explanations are given in RAMSAY & HUBER (1983).

Ductile and brittle deformation: When a stress field is applied to a certain rock volume, the rock body either deforms a) continuously or b) discontinuously. In case a), there are no macroscopically visible cracks or discrete fractures. Continuous deformation mainly occurs at higher temperatures or at low strain rates in the Earth's crust, where the fabric tends to flow plastically and behaves like a viscous fluid. This process is called ductile deformation, and the rocks produced are often mylonites. Discontinuous brittle deformation b), on the other hand, produces macroscopically visible cracks and fractures. These form when the elastic strength of the rock is exceeded, which leads to failure (fracturing) of the material. This type of deformation mainly occurs at shallow crustal levels where temperatures are low, or in regimes of high strain rates. Brittle shear deformation is called cataclasis. In many cases (also in the Grimsel crystalline), brittle and ductile deformations are superimposed.

Ductile and brittle shear-zone: A shear-zone is a rock domain (with subparallel walls) where high deformation is localized. If the strain gradient is continuous across the zone (e.g. no abrupt changes in shear strain occur on a macroscopic scale), this domain is called a ductile shear-zone. On the other hand, shear-zones with discontinuities in strain gradient across the zone are called brittle shear-zones or, on a larger scale, faults (see fractures, joints and faults).

Mylonite: A mylonite is a rock produced by ductile deformation, and it can occur in almost any rock type. The term is used for a rock whose fabric has been partly or fully recrystallized during metamorphism and/or progressive deformation. Macroscopically, mylonites are characterised by small-scale banding, and the cleavage intensity is often high. Microscopically, a considerable reduction of the grain-sizes with respect to the undeformed source rock is typical; recrystallisation of deformed grains can be syn- or postkinematic. Recrystallized grains of quartz often show a preferred orientation of the optical axes.

Cataclasis, fault-gouge: Cataclasis is a process of brittle shear deformation. Shear stress is accommodated by frictional sliding and grain rotation. Cataclasis can be localised to discrete horizons where the rock may be ground to a very fine-grained powder. Such focussed cataclasis, together with mechanical mixing of the particles, leads to the formation of fault gouges which are incoherent and cohesionless planar horizons in shear-zones.

Fractures, joints and faults: Fractures are structural discontinuities in the broadest sense. Depending on the type of displacement along them, two types can be distinguished: Faults are characterised by major shear deformation along the fracture and mostly contain cataclastic features. Joints, on the other hand, are extensional features characterised by a "pull-apart"-movement normal to the discontinuity where no or little shear deformation occurred.

Finite strain ellipsoid: This ellipsoid is defined as the body produced by homogeneous deformation (strain) of a sphere with unit radius. "Finite" means that only the final shape of the ellipsoid is considered (which may not coincide with the incremental (infinitesimal) ellipsoids of progressive deformation). The finite strain ellipsoid has 3 orthogonal axes, which correspond to the principal axes of strain (X, Y, and Z).
The planes containing two of the principal axes are defined as principal planes. These are the XY, XZ, and YZ planes.

**Cleavage**: Cleavage describes a planar structure of rocks which is due to a deformation-induced preferred orientation of minerals. In the Grimsel region, it is defined by the parallel alignment of sheet silicates (bittite, muscovite, chlorite) and, to a minor extent, also feldspars and quartz. Orientation of the minerals is such that the shortest grain dimension is parallel to the inferred maximum finite shortening direction (SE-NW at Grimsel). In our case, the maximum shortening direction is parallel to X and normal to XY (see finite strain ellipsoid).

**Mineral stretching lineation** is a linear feature in the plane of cleavage (i.e. XY). At Grimsel, it is defined by the preferred alignment of minerals (mainly sheet silicates) or the development of pressure shadow wings around feldspar clasts. It is parallel to X (see finite strain ellipsoid), which is the maximum extension direction.

**Angular shear strain, shear strain**: These terms describe the angular relationships in rocks that have undergone deformation. Two initially perpendicular lines may lose their orthogonality during deformation. The angular shear strain is defined as the final deviation (in degrees) from the initial state. The shear strain is defined as the tangent of the angular shear strain.