Grimsel Test Site: Revisiting the site-specific geoscientific knowledge

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Grimsel Test Site: Revisiting the site-specific geoscientific knowledge

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Foreword

The Grimsel Test Site

Nagra and its partners have been conducting underground research at the Grimsel Test Site (GTS) since 1984. The projects have contributed substantially to the development and confirmation of safe geological disposal concepts and to the characterisation of potential host rock formations. The GTS is reached by an access tunnel belonging to the Kraftwerke Oberhasli AG (KWO), the local hydropower company. The KWO has operated hydropower plants in the Grimsel area since 1925.

The main tunnels of the GTS were excavated in 1983 and 1984 using both a tunnel boring machine and drill and blast techniques. Expansion of the site in 1995 and 1998 provided space for two large-scale demonstration experiments. The branching tunnel system of more than 1 km in length is located at an elevation of 1730 m a.s.l., about 350 to 520 m beneath the flanks of the Juchlistock, in the 300-million-year-old granitoid of the Aar Massif. The local geology is ideal for the investigation of a wide range of experimental concepts and scientific issues in both tectonically overprinted and fractured areas, as well as in zones of relatively homogeneous intact rock. More than 5000 m of cored boreholes have been drilled.

More than two dozen organisations and research institutes from twelve countries, together with the European Union, have participated in the six phases of the research programme. Each phase has focused on the key issues at the time, attempting to anticipate the next steps in national programmes for the long-term management of radioactive waste. The current Phase VI began in 2003 and is dedicated to integrative projects with: a) field experiments under repository-relevant boundary conditions, i.e. large-scale, long-term experiments with realistic hydrogeological settings; and b) focal points addressing the implementation of a geological repository in terms of engineering feasibility, potential construction impacts on the surrounding rock, operational aspects, closure, and monitoring. A radiation-controlled zone of IAEA Level B/C allows field experiments to be carried out with radioactive tracers.

The GTS has established itself as an internationally renowned research laboratory in the field of safe disposal of radioactive waste in deep geological repositories. It fulfills a multitude of roles, such as providing a strong driving-force for scientific and technological progress, an effective platform for international cooperation, a hands-on training centre for knowledge transfer to the younger generation, and a forum for dialogue between numerous parties including decision-makers, academics, politicians, authorities and the public.
Location of Nagra’s underground test facility at the Grimsel Pass in the Central Alps (Bernese Alps) of Switzerland
Grimsel area (view to the west)

1 Grimsel Test Site
2 Lake Raeterichsboden
3 Lake Grimsel
4 Juchlistock

Grimsel Test Site (GTS)

- Central facilities
- KWO Main access tunnel
- Controlled zone
- Laboratory tunnel
Abstract

The Grimsel Test Site was opened in June 1984. Since then it has been dedicated to fundamental research related to the safe disposal of radioactive waste in deep geological repositories. The research performed at the GTS has evolved with the requirements of the RD&D programmes of the numerous partner organisations carrying out experiments. In a first phase, experiments were dedicated to site characterisation techniques, resulting in a geological description of the rock volume surrounding the GTS. In a second phase, processes associated with radionuclide migration, excavation and two-phase flow were evaluated in various projects. The current investigation phase is dedicated to (a) long-term experiments and demonstration experiments aimed at the confirmation and validation of numerical models developed for the safety assessment of a typical repository and (b) the long-term evaluation and monitoring of processes such as corrosion of canister materials.

The geological description of the rock mass around the GTS has benefited from the geoscientific knowledge broadened by all the performed experiments. The work presented in this report revisits multiple experiments and aims to provide an overview of the acquired knowledge. It also compiles milestone publications to facilitate in-depth study.

The following points summarise the current state of knowledge:

- The rock mass surrounding the GTS is composed of Late to post-Variscan (ca. 299 Ma) granitoids (Central Aar Granite and Grimsel Granodiorite). Shortly after emplacement, the granitoids were dissected by numerous dykes, mainly metabasic dykes (formerly termed lamprophyres), but also aplitic dykes.

- During the Alpine orogeny (climax at ca. 25 Ma), the rock volume was metamorphosed under greenschist facies conditions and solid-state deformation initially in the ductile regime led to the development of a pervasive foliation and localised high-strain zones, so called ductile shear zones. Ongoing uplift and resulting cooling yielded a gradual shift from deformation in the ductile regime to deformation in the brittle regime. The retrograde brittle overprint resulted in the formation of complex fault zones localised along former ductile shear zones or margins of metabasic dykes. The fault zones often display an anastomosing arrangement of fault cores that are characterised by the occurrence of fault gouge (fine-grained cohesionless fault-filling material). The highly localised brittle deformation and the preceding ductile deformation yielded a heterogeneous rock mass with strongly deformed zones alternating with unfractured rock matrix.

- The heterogeneity of the rock volume is of central interest and has significant implications for numerous investigations such as characterisation of the stress state. The fault zones at the site decouple individual crustal blocks, resulting in varying stress conditions depending on the distance to the fault zones.

- The heterogeneity is also observed in the hydraulic characterisation of the rock volume, where intervals within major water-conducting fault zones are characterised by transmissivity values ranging over 5 orders of magnitude, while borehole intervals in unfractured rock matrix show typically low hydraulic conductivities of $10^{-11}$ m/s or below.

- Linked to the evolution of the water flow paths is the composition of the groundwater, which differs between fault water and rock matrix water. The fault water composition depends on the mean residence time as the original meteoric water is enriched by water-rock interactions.
• The careful characterisation of baseline conditions allowed the identification and cataloguing of numerous perturbations, both natural and anthropogenic. Identified perturbations include earth tides, annual air pressure changes, nearby lake level changes, experimental work such as hydraulic testing or drilling or tunnel ventilation.

The multiple aspects of the research summarised here are discussed in detail in numerous project reports. These projects and their major outcomes are introduced and summarised in the last chapter of this report. The detailed investigations performed during the last three decades provide a robust basis for future experiments, which can be planned based on the experience and knowledge gained over the last 35 years.
Zusammenfassung


Die folgenden Punkte fassen den momentanen Kenntnisstand zusammen:

• Das Gestein im FLG besteht aus Spät- bis Post-Varizischen (ca. 299 Ma) Granitoiden (Zentraler Aaregranit und Grimsel Granodiorit). Kurz nach der Platznahme wurden die Granitoide von metabasischen (früher oft als Lamprophyre bezeichnet) und aplitischen Gängen durchschlagen.


• Die Heterogenität des Gesteins hat weitreichende Folgen für viele weiterführende Charakterisierungen, wie z.B. Stressabschätzungen. Die auftretenden Bruchzonen entkoppeln einzelne Gesteinsblöcke voneinander, was zu sich verändernden Stresszuständen führt.

• Diese Heterogenität wurde auch in der hydraulischen Charakterisierung des Gesteinsvolumens beschrieben. Beprobte Bohrungsintervalle mit Bruchzonen weisen oftmals eine Transmissivität auf, welche ca. fünf Grössenordnungen grösser ist, als bei Bohrungsintervallen, welche in reinen Gesteinsmatrix liegen.


Résumé

Le laboratoire souterrain du Grimsel (Grimsel Test Site ou GTS) a été inauguré en juin 1984. Depuis cette date, il est dédié à la recherche fondamentale liée au stockage des déchets radioactifs en couches géologiques profondes. Les recherches ont évolué en fonction des programmes RD&D des nombreuses organisations partenaires qui réalisent des expériences dans le laboratoire souterrain. La première phase de recherche a porté sur les techniques de caractérisation de la roche, afin de mieux connaître l'environnement géologique du laboratoire. Au cours de la deuxième phase, les recherches ont mis l'accent sur des processus tels que la migration de radionucléides ou le flux en deux phases dans des failles perméables. La phase de recherche actuelle est axée sur (i) des expériences de démonstration ou à long terme qui vont permettre de valider et de confirmer les modèles numériques destinés à l'analyse de sûreté d'un dépôt géologique et (ii) l'étude et la surveillance à long terme de processus tels que la corrosion des matériaux constituant les conteneurs de déchets.

Les expériences réalisées dans le laboratoire ont permis d'affiner progressivement les connaissances géologiques de la roche qui entoure les galeries. Le travail présenté ici passe en revue de nombreuses expériences et donne une vue d'ensemble du savoir acquis. De plus, il énumère les publications-clés où l'on pourra approfondir l'étude d'un processus donné.

Les connaissances actuelles sont résumées ci-dessous:

- La roche qui entoure le laboratoire est composée de granitoïdes tardifs à post-Variscans (env. 299 Ma) (granite central de l'Aar et granodiorite du Grimsel). Les nombreux filons, principalement métabasiques (anciennement appelés lamprophyres), mais aussi aplitiques, qui les traversent remontent à une période proche de leur mise en place.

- La roche a été métamorphosée sous des conditions de faciès vert pendant l'orogénèse alpine. La déformation a débuté par une phase majoritairement ductile, qui est responsable de la schistosité omniprésente et des zones de cisaillements où la déformation s'est concentrée. À la suite du soulèvement des Alpes et du refroidissement de la roche, le régime de déformation est passé de ductile à cassant, entraînant des zones de failles complexes. Ces zones sont souvent localisées le long de zones de cisaillement formées pendant la phase de déformation ductile ou aux abords de filons métabasiques. Les zones de failles sont caractérisées par de multiples noyaux de faille répartis de manière anastomosée et constitués par de la gouge de faille (matériel très fin et sans cohésion). La phase de déformation cassante qui a suivi la phase de déformation ductile a entraîné la formation d'une roche hétérogène où alternent des zones fortement déformées et des zones non fracturées.

- L'hétérogenéité de la roche joue un rôle important dans la description de nombreux paramètres tels que la caractérisation de l'état de stress. Les zones de failles séparent des blocs ints de croûte terrestre les uns des autres, avec pour résultat des états de stress variant en fonction de la distance entre les blocs et les failles.

- De même, l'impact de l'hétérogenéité de la roche a été observé lors de nombreux tests de caractérisation hydrogéologique. En présence de failles, les forages testés présentent des valeurs de transmissivité supérieures – jusqu'à cinq ordres de grandeur – aux forages situés dans la roche peu déformée, où la conductivité est basse (inférieure ou égale à 10^{-11} m/s).

- La composition de l'eau souterraine est liée au développement des voies d'écoulement. On distingue ici l'eau coulant le long des failles et l'eau située dans les pores de la roche. La composition de l'eau de faille est déterminée par le temps de circulation moyen, car cette eau, d'origine météorique, est enrichie par les interactions avec la roche.
La caractérisation rigoureuse des conditions de base a permis de dresser le catalogue de divers facteurs de perturbations, tant naturels que d’origine humaine. Parmi ces facteurs de perturbation, on compte les marées terrestres, les variations annuelles de la pression atmosphérique, la modification du niveau d’eau des lacs artificiels à proximité, la ventilation du tunnel ou encore des travaux en rapport avec diverses expériences comme les tests hydrauliques ou les forages.

Les recherches résumées dans ce rapport sont décrites plus en détail dans les rapports spécifiques aux différents projets. Le dernier chapitre donne un aperçu global des projets et de leurs principales conclusions. Les recherches approfondies réalisées au cours des 35 dernières années constituent une base de connaissances solide sur laquelle les expériences à venir pourront être planifiées.
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Enclosure 3: GTS geological cross section
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## Acronyms

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<tr>
<td>ADUS</td>
<td>Andra Underground Seismic</td>
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<tr>
<td>AU</td>
<td>Auflockerungsversuch (Excavation Effects)</td>
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<tr>
<td>BDZ</td>
<td>Borehole Damaged Zone</td>
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<tr>
<td>BK</td>
<td>Bohrlochkranzversuch (Fracture System Flow Test)</td>
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<tr>
<td>CAGr</td>
<td>Central Aar Granite</td>
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<tr>
<td>CFM</td>
<td>Colloid Formation and Migration</td>
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<tr>
<td>C-FRS</td>
<td>Criepei's Fractured Rock Studies</td>
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<tr>
<td>CP</td>
<td>Connected Porosity</td>
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<tr>
<td>CRR</td>
<td>Colloid and Radionuclide Retardation</td>
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<td>EDZ</td>
<td>Excavation Damaged Zone</td>
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<tr>
<td>EFP</td>
<td>Effective Field Parameters</td>
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<tr>
<td>EM</td>
<td>Electromagnetic</td>
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<tr>
<td>EP</td>
<td>Excavation Project</td>
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<tr>
<td>FEBEX</td>
<td>Full-Scale Engineered Barrier System Experiment</td>
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<td>GAM</td>
<td>Gas Migration</td>
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<td>GAST</td>
<td>Gas Permeable Seal Experiment</td>
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<td>GMT</td>
<td>Gas Migration Test</td>
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<td>GMWL</td>
<td>Global Meteoric Water line</td>
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<td>GrGr</td>
<td>Grimsel Granodiorite</td>
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<tr>
<td>GS</td>
<td>Gebirgspannung (Rock Stress Investigations)</td>
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<td>GTS</td>
<td>Grimsel Test Site</td>
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<tr>
<td>HF</td>
<td>Hydro Fracture</td>
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<td>HPF</td>
<td>Hyperalkaline Plume in Fractured rock Experiment</td>
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<td>HWS</td>
<td>Constant head withdrawal test</td>
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<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
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<tr>
<td>ISC</td>
<td>In-situ Stimulation and Circulation</td>
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<tr>
<td>KWO</td>
<td>Kraftwerke Oberhasli</td>
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<tr>
<td>LASMO</td>
<td>Large-Scale Monitoring</td>
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<td>LCS</td>
<td>Long-Term Cement Studies</td>
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<tr>
<td>LMWL</td>
<td>Local Meteoric Water Line</td>
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<td>LTD</td>
<td>Long-Term Diffusion Test</td>
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<td>MBD</td>
<td>Metabasic dyke</td>
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<tr>
<td>MI</td>
<td>Migration</td>
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<tr>
<td>Nagra</td>
<td>Swiss National Cooperative for the Disposal of Radioactive Waste</td>
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<tr>
<td>NM</td>
<td>Neigungsmessung (Tilt meter)</td>
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<tr>
<td>PSG</td>
<td>Pore Space Geometry</td>
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<tr>
<td>SED</td>
<td>Schweizer Erdbebendienst (Swiss Seismological Service)</td>
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<tr>
<td>TBM</td>
<td>Tunnel Boring Machine</td>
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<td>URL</td>
<td>Underground Rock Laboratory</td>
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<td>US</td>
<td>Underground Seismic</td>
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<td>VE</td>
<td>Ventilation Experiment</td>
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<tr>
<td>VSMOW</td>
<td>Vienna Standard Mean Ocean Water</td>
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<tr>
<td>WCF</td>
<td>Water-conducting Feature</td>
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<tr>
<td>WT</td>
<td>Wärmetest (Heat Test)</td>
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<tr>
<td>ZPM</td>
<td>Zwei-Phasen Fluss in Gesteinsmatrix (Two-phase Flow in Rock Matrix)</td>
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1 Introduction

1.1 Objectives

The Grimsel Test Site was designed as a generic underground rock laboratory and, since the start of its operation, it has served as a source of knowledge for assessing and developing methods for the characterisation and description of fractured rocks, engineered barrier systems and their interaction with the surrounding rocks and, more generally, for contributing to the assessment of features, events and processes that influence repository performance.

The Grimsel Test Site (GTS) is located near the Grimsel Pass in the upper 'Haslital' in Canton Bern in Central Switzerland. The Aare River originates in the 'Haslital' (Fig. 1.1). The GTS is situated next to Lake Rätrichsboden and beneath the flanks of Juchlistock at an altitude between 1728 and 1730 m a.s.l. and beneath an overburden between roughly 350 and 520 m.

Fig. 1.1: Topographic map showing the location of the GTS, the 'Haslital' and other features relevant to the report

Coordinates are given in CH1903/LN95.
The GTS was constructed as a side tunnel system from the main access tunnel of Kraftwerke Oberhasli (KWO) (Fig. 1.2). The main access tunnel was excavated in 1974 to ensure access to the hydropower plant for maintenance work during winter. Construction of the GTS started in 1983 and the facility was opened on June 20th, 1984. The majority of the GTS tunnel system was excavated with 3.5 m diameter tunnel-boring machine. A few drifts at the GTS and the GMT silo were excavated using drill and blast techniques, when specific experiments such as the Bohrlochkranzversuch (BK; Fracture System Flow Test) required more space or a larger tunnel diameter.

This report aims at compiling site-specific geological knowledge from this generic URL (Underground Rock Laboratory) gained since the operational launch in 1984, including site screening and prior investigations. Geological information was summarised soon after construction in Keusen et al. (1989), however numerous experiments carried out since then at the GTS (Chapter 9) have extended the site-specific knowledge. Moreover, scientific research conducted in the region around the GTS over the past decades has added to the regional understanding of the Grimsel Pass area.

### 1.2 GTS history

The GTS has been in operation since 1984 (Blechschmidt and Vomvoris 2017). It was designed in the late 1970s as a generic underground rock laboratory to study crystalline rocks similar to the bedrock in Northern Switzerland. It is dedicated to research and testing purposes and has not been considered for waste disposal, consistent with the definition of the IAEA (2001) and the NEA (2013).

The three decades of development of the GTS investigation and RD&D programme reflect the evolving requirements of the Swiss national disposal programme (Fig. 1.3). The early experiments performed at the GTS were devoted to the development of methodologies and tools suitable for characterising in detail the geological, hydrogeological and hydrochemical properties of crystalline rocks similar to the crystalline basement in Northern Switzerland (GTS investigation Phases I to II). Investigation Phase III focused on investigating hydraulic and geochemical transport processes in the rock. Additionally, modelling studies associated with the field studies became increasingly important. During GTS investigation Phase IV, the emphasis was on performance assessment issues, followed in particular by testing and verification of models for radionuclide transport, studying the effects on the natural system of materials to be used in repository construction, and investigations of the migration of repository-generated gas.

GTS investigation Phases V and VI include long-term experiments related to the study of radionuclide and colloid migration, repository monitoring, the interaction between canister candidate materials and bentonite, or gas migration. Since the start of operation, 46 major experiments have been carried out at the GTS, with 6 experiments currently running.

The GTS main tunnel is labelled "L-tunnel", referring to laboratory, while the additional tunnels are labelled according to the major experiments performed there. A specific position along each tunnel is indicated by the tunnel section and the metre along the specific tunnel. For example, the position L180 stands for 180 m along the L-tunnel (main tunnel), W100 stands for 100 m along the WT tunnel and AU090 is 90 m along the AU tunnel (Fig. 1.2).
**Grimsel Test Site (GTS)**

- KWO access tunnel
- Laboratory tunnel
- Grimsel Granodiorite (GrGr)
- Transition zone
- Central Aar Granite (CAGr)
- Metabasic dyke
- Shear zone
- Main boreholes
- ZB Central facilities
- BK BK cavern
- VE VE cavern
- GS GS cavern

**GTS Phase VI 2003-2023**

- CFM Colloid Formation and Migration
- C-FRS Criepi Fractured Rock Studies
- CIM In-Situ Migration of C-14 & I-129 in Cement
- ESDRED / TEM Test and Evaluation of Monitoring Systems
- FORGE Fate of Repository Gases
- GAST Gas-permeable Seal Test
- GMT Gas Migration Test in the EBS
- HotBENT High Temperature Buffer
- HPF Hyperalkaline Plume
- ISC In-situ Stimulation and Circulation Project
- JGP JAEA Grouting Project
- LASMO Large-scale Monitoring
- LCS Long-term Cement Studies
- LTD Long-term Diffusion
- MACOTÉ Material Corrosion Test
- PSG Pore Space Geometry

**Fig. 1.2:** GTS overview map with the location of major running experiments (GTS Phase VI 2003–2023)
1980s
• Site and host rock characterisation
• Exploration techniques and tools

1990s
• Radionuclide transport processes
• Post-closure safety analysis
• Engineered barrier systems
• Demonstration of technologies

2000s
• Repository implementation
  • Demonstration
  • Operational phase
  • Post-closure phase
• Radionuclide transport and perturbation effects under repository relevant conditions
• Training

Fig. 1.3: Evolution of the objectives and requirements to be studied at the GTS (modified after Blechschmidt and Vomvoris 2017)
1.3 Organisation of the report

The report presents a compendium of site-specific geoscientific data derived from work at the GTS and selected studies from the surrounding area. It is divided into 9 chapters and a conclusions chapter. Each chapter is dedicated to different properties of the rock volume surrounding the GTS. The rock volume is characterised by the rock and deformation features, the stress field, the groundwater, both fracture and rock matrix porewater, the water-conducting features, and the perturbations induced by the rock laboratory itself, or external changes. Most of the chapters are dedicated to the 'undisturbed' virgin state, which is inferred from baseline monitoring. Here "virgin state" is defined as the state after the excavation of the underground structures and tunnels. Only a thoroughly defined background allows for an accurate characterisation of disturbances. A figure connecting the different chapters with experiments carried out at the GTS is shown in Appendix (A-1).

Numerous experiments carried out at the GTS are referred to in this report. The experiments are described in greater detail in Chapter 9 and in Appendix 3. For further information about a specific experiment, the reader is referred to the Grimsel website (www.grimsel.com).

This report first provides a geological overview on a regional scale (Chapter 2) and then on a local scale (Chapter 3). The geology is thoroughly discussed as it defines the boundary conditions for most experiments and thus both controls, and interacts with, the experiments. In Chapter 4, the deformation structures resulting from magmatic state deformation and later Alpine deformation are described. The structures (e.g. faults, ductile shear zones) form mechanical anisotropies that influence, for example, the stress field, but also the water flow paths. In Chapter 5, the stress field of the GTS is characterised. The stress field determines the likelihood that a structure will slip or remain undeformed, as well as the forces acting to close fractures. The hydraulic regime around the GTS is described in Chapter 6, and the water chemistry is described in Chapter 7. In Chapter 8, the natural and anthropogenic perturbations to the baseline conditions acting on the rock volume around the GTS are described. Chapter 9 provides an overview of the major experiments carried out or currently running at the GTS. The data presented and the inferred knowledge are summarised in Chapter 10.
2 Regional geology – Aar Massif

The Grimsel Test Site (GTS) is located south of Guttannen in the upper 'Haslital' in Canton Bern, Switzerland. Geologically, it is situated in the Central Swiss Alps within the Aar Massif. The Aar Massif belongs to the External Crystalline Massifs of the Alps (e.g. von Raumer et al. 1993), forming the basement of the Alpine orogeny. However, its geological record is older than the Alpine orogenesis (e.g. Mercolli et al. 1994). This chapter gives a geological overview of the area surrounding the GTS.

The upper 'Haslital' (Fig. 1.1, Fig. 2.1 and Fig. 2.2) is composed of the following rock units of different geological age: (i) The Guttannen Gneiss Complex, the Ofenhorn-Stampfhorn Gneiss Complex, the Bäregg Gneiss Complex, the Gärstenhorn Gneiss Complex, and the Massa Gneiss Complex form the Pre-Variscan polycyclic metamorphic basement, often referred to as 'Altkristallin' in the German literature (e.g. Abrecht 1994, Labhart 1977, Stalder 1964); (ii) Rocks of the Diechtergletscher Formation and the Trift Formation are Late to post-Variscan volcaniclastic rocks (Berger et al. 2017b); (iii) The Mittagsflue Granite, the Central Aar Granite, the Grimsel Granodiorite, and the Aplitic Boundary Facies are Late to post-Variscan plutonic rocks (e.g. Keusen et al. 1989, Schaltegger and Corfu 1992, Schaltegger 1990). The nomenclature of the rock types mentioned varies in the literature; here we follow the nomenclature proposed by Berger et al. (2017a).

In the following, the geological record of the rock types mentioned will be summarised based on key literature. For further details, the reader is referred to the compilation of Berger et al. (2017b) and the references therein.
Fig. 2.1: Geological overview map of the upper 'Haslital' (modified after Berger et al. 2017a)
2.1 **Pre-Variscan rock units**

Volumetrically, the pre-Variscan polycyclic basement represents the dominant rock types within the Aar Massif (e.g. Berger et al. 2017b). They are termed polycyclic due to their complex tectono-metamorphic history.

The pre-Variscan basement rocks are schists and banded gneisses characterised by a strong metamorphic overprint reaching amphibolite facies conditions in the Ofenhorn-Stampfhorn Gneiss Complex (Abrecht 1994, Berger et al. 2017b, Schenker and Abrecht 1987). Locally, migmatic structures occur as relics of the strong overprint.

2.2 **Pre-Variscan evolution**

The pre-Carboniferous evolution of the area of interest is better recorded in the neighbouring Gotthard Nappe than in the Aar Massif. Relatively little evidence is preserved in the Aar Massif, however what evidence there is indicates that the evolution of the Aar Massif was linked to the evolution of the Gotthard Nappe. This evolution consists of an early high-pressure eclogitic metamorphic event (Oberli et al. 1994) followed by high-temperature metamorphism (upper amphibolite facies to granulite facies) during Middle Ordovician times, leading to anatexis (Berger et al. 2017b). The Ordovician metamorphism was probably caused by subduction and collisional tectonics (Schaltegger 1994). Rapid uplift could be responsible for the observed partial melting (Biino 1994). The Erstfeld Gneiss Complex, outcropping north of the Guttannen Gneiss Complex, bears evidence of amphibolite facies metamorphic overprint, however no relics of an earlier granulite facies metamorphism reported in the Gotthard Nappe are preserved within the Aar Massif (Berger et al. 2017b, Schaltegger 1994). The Ofenhorn-Stampfhorn Gneiss Complex shows evidence of Ordovician amphibolite facies metamorphism with subsequent formation of migmatites (Schenker and Abrecht 1987).

The pre-Variscan polycyclic metamorphic basement also records the Carboniferous and Permian evolution of the Central Alps (Berger et al. 2017b), forming a sequence of SW-NE oriented structures, indicating a north-verging transport direction. This SW-NE trending architecture is proposed to result from Carboniferous nappe tectonics related to the Variscan orogeny (Oberhansli et al. 1988).
2.3 Late to post-Variscan metasedimentary and volcaniclastic rocks

Late to post-Variscan metasedimentary and volcaniclastic formations are mainly composed of thin, steeply dipping discontinuous bands that strike parallel to the Aar Massif (Fig. 2.1, Berger et al. 2017b). Rocks outcropping within the area of interest belong to the Trift Formation or the Diechtergletscher Formation (Fig. 2.1) and are characterised by rhyolite, epiclastic sediments, tuff and coarse pyroclastic rocks and volcanic breccia (Berger et al. 2017b, Oberhänsli et al. 1988).

2.4 Late to post-Variscan rocks

The outcropping Mittagsflüe Granite, Central Aar Granite, Grimsel Granodiorite and the Aplitic Boundary Facies are part of the Haslital Group (Berger et al. 2017b). The Haslital Group belongs to a calc-alkaline to sub-alkaline granitoid suite, with the following differentiation sequence (from most basic to most acidic): Grimsel Granodiorite, Central Aar Granite, Mittagsflue Granite, Aplitic Boundary Facies (Schaltegger 1990, 1994). Different radiometric age datings overlap within error and occurrence of numerous intermingling structures ('Schlieren') indicates a gradual change between the Grimsel Granodiorite (GrGr) and the Central Aar Granite (CAGr) (Schneeberger et al. 2016), corroborating the coeval viscous state. The Haslital plutonic rocks are of Asselian age (299–295 Ma, Schaltegger and Corfu 1992, Schaltegger 1994).

2.5 Variscan evolution

The onset of the Variscan collision orogeny is of Visean age (ca. 346 to 331 Ma, von Raumer et al. 2013), leading to granulite facies metamorphism conditions (Berger et al. 2017b, von Raumer et al. 2013). The granulite facies metamorphism is mostly preserved within the Lauterbrunnen-Innertkirchen Gneiss Complex, which is located north of the study area (north of the map in Fig. 2.1).

During Pennsylvanian times (ca. 323 to ca. 299 Ma), the polycyclic basement was exposed, as rocks of the Diechtergletscher Formation were deposited. Later these rocks were tilted and rapidly transported to 5 – 10 km depth, which corresponds to the intrusion depth of the Central Aar Granite (Berger et al. 2017b). During Asselian (299 to 295 Ma) times, the Haslital Group intruded into the polycyclic metamorphic basement and the volcaniclastic sedimentary rock units. The Haslital Group granitoids are considered to be post-metamorphic and post-tectonic and to be intruded under an extensional tectonic setting (Schaltegger 1990, Schaltegger and Corfu 1992) above a subduction zone at an Andean-type continental margin (Mercolli and Oberhänsli 1988). Variscan metamorphic overprint did not exceed greenschist facies conditions in the area of interest, whereas the southern units of the Aar Massif bear evidence of a metamorphic overprint reaching amphibolite facies conditions (Schaltegger 1994).

2.6 Alpine evolution

2.6.1 Regional tectono-metamorphic evolution

The rock volume of the upper 'Haslital' is part of the inverted European basement of the Alps and thus paleogeographically part of the Helvetic realm (Herwegh et al. 2017, Pfiffner 1993, Schmid et al. 1996). The Alpine orogeny, resulting from the closure of the European Tethys (ocean) followed by continental collision (e.g. Schmid et al. 2004), is recorded as a metamorphic overprint and as a deformational stage within the rock volume of the Grimsel area (e.g. Steck 1968). Fig. 2.3 shows an overview cross-section through the Central Alps illustrating the present-day situation resulting from the Alpine orogeny.
The regional metamorphic overprint reached upper greenschist facies conditions south of the Central Aar Granite, whereas the Guttannen Gneiss Complex shows evidence of lower greenschist facies Alpine metamorphism (Berger et al. 2017b, Frey et al. 1980, Niggli and Niggli 1965). Metamorphic conditions were estimated for the rocks in the Lake Rätrichsboden area to be around 450 °C and 6.5 kbar (Challandes et al. 2008, Goncalves et al. 2012). Bergemann et al. (2017) indicates that the pressure-temperature estimates are maximum estimates and probably overestimate the actual peak metamorphic conditions.

The long-lasting Alpine tectonic evolution of the area has been studied extensively and there is still controversy regarding the number of deformation phases (e.g. Choukroune and Gapais 1983, Herwegh et al. 2017, Rolland et al. 2009, Steck 1968, Wehrens et al. 2016, 2017).
Fig. 2.4: Structural map of the surface area above the GTS (Schneeberger et al. 2017)
Structural grouping shown in this figure refers to Tab. 2.1.

Fig. 2.5: Block diagrams showing increasing deformation and strain localisation (modified after Choukroune and Gapais 1983 and Wehrens 2015)
The Alpine solid-state deformation history is best depicted in the post- to Late Variscan plutonites of the Haslital Group, as they are considered to be monometamorphic. Large-scale crustal blocks that are crosscut by kilometre-scale post-collision steep faults form the rock in the 'Haslital' (Fig. 2.4 and Fig. 2.5). The number of faults, the intensity of deformation and the metamorphic grade increase southwards (e.g. Niggli and Niggli 1965, Steck 1968, Wehrens et al. 2017). The ductile deformation resulted in a pervasive foliation and localised high strain shear zones. This results in a pattern of less deformed rock matrix and highly deformed shear zones (Fig. 2.5, Choukroune and Gapais 1983).

The large-scale faults occur as different sets (Fig. 2.4):

- a NE-SW trending fault set (fault set 1, Tab. 2.1), that is a conjugate set of reverse and normal faults with dominant movement south block up.
- a NW-SE and E-W trending predominantly strike-slip fault set (fault set 2).
- the previously mentioned fault sets are crosscut by thrust-related faults that are moderately SE and SW dipping (fault set 3).

Tab. 2.1: Summary of deformation phase models for the Grimsel area

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<td>NE-SW</td>
<td>Fault set 1</td>
<td>Handegg phase</td>
<td>Stage 1</td>
<td>S₁/S₂</td>
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<tr>
<td>NW-SE and E-W</td>
<td>Fault set 2</td>
<td>Oberaar phase</td>
<td>Stage 2</td>
<td>Sᵢ/Kᵢ/Kᵢ₂/Sᵢ₂/Kᵢ₄/L</td>
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<tr>
<td></td>
<td>Fault set 3</td>
<td>Pfaffenchopf phase</td>
<td>Stage 3</td>
<td>S₅</td>
</tr>
<tr>
<td>Brittle reactivation</td>
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Based on newly acquired structural data and a strict separation between brittle and ductile deformation regimes, a novel grouping of the occurring structures is suggested. The first fault set evolved during peak metamorphic conditions (Fig. 2.6, Herwegh et al. 2017, Wehrens et al. 2017). Radiometric age determination of newly formed sheet silicates suggests an activity between 22–17 Ma (Rolland et al. 2009). Members of this fault set were formed as ductile shear zones, localised high strain zones, within the stability field of biotite (> 400°C). These faults correspond to the Stage 1 faults of Rolland et al. (2009) and the Handegg phase faults of Wehrens et al. (2017). The steeply dipping faults show very little evidence of vertical movement (vertical component of offset typically > 0.5–50 m). However, due to the large number of faults, the cumulative vertical movement adds up to several kilometres of reverse faulting movement for the Grimsel Pass area (Herwegh et al. 2017).

The activity of the second fault set started 14–12 Ma (Fig. 2.6, Rolland et al. 2009) and evolved under lower greenschist facies conditions (Wehrens et al. 2017). The change from the first thrust-related fault set to the second strike-slip-dominated fault set is gradual (Herwegh et al. 2017, Bergemann et al. 2017), as evidenced by observed oblique stretching lineation. This change from thrust-related faults to strike-slip faults implies a change in the orientation of the principal stress axes.
Several kinematic models have been proposed for the Alpine evolution of the 'Haslital' and are part of an ongoing debate. They differ mainly between single-phase (Choukroune and Gapais 1983, Gapais et al. 1987) and multi-phase models (Steck 1968, Herwegh et al. 2017, Rolland et al. 2009, Wehrens et al. 2017). As indicated by Wehrens et al. (2017), the single-phase models are based on observations from the northern part of the CAGr and evidence from the southern GrGr-dominated area was not considered.

Geodynamically, the evolution of the Aar Massif sheds light on the evolution of the Alpine orogeny and is summarised in Fig. 2.7 (Herwegh et al. 2017). Alpine subduction ends with the slab breakoff at about 34–32 Ma, slab-pulling forces are reduced, and the European plate is thus decelerated. The remaining weight of the European mantle lithosphere promotes slowed rollback some 30 Ma ago. The Aar Massif delaminates some 22–17 Ma ago from its lower crust, since tectonics are dominated by sub-vertical extrusion (fault set 1, Fig. 2.6). Severe buoyancy forces due to an over-thickened crust induce this sub-vertical extrusion. Despite predominant delamination and buoyancy processes during post-collision, a compressional component persists and becomes more important after 12 Ma, as documented by the formation of strike-slip-dominated faults in the central part of the Aar Massif (fault set 2, Fig. 2.6) and by thrust-related faults in the northern part of the Aar Massif (fault set 3).
Fig. 2.7: Geodynamic evolution of the Aar Massif since Oligocene times (modified after Herwegh et al. 2017)

Aar: Aar Massif, Got: Gotthard Nappe, AAT: Ausserberg-Avat-Tavestch zone, TALP: Tectonically accreted lower plate, GPSZ: Grimsel Pass Shear Zone
2.6.2 Uplift and exhumation

The extrusion inferred from geodynamic considerations (Herwegh et al. 2017) led to a decrease in temperature and therefore to a gradual change in deformation style. The first fault set evolves under ductile regime deformation in the stability field of biotite (> 400°C). These ductile shear zones are later overprinted by ductile shear zones without biotite, thus formed under slightly lower temperature deformation conditions (Wehrens et al. 2017). With decreasing temperature, the rock mass crosses the brittle-ductile transition zone and brittle deformation reactivates former ductile shear zones (Belgrano et al. 2016, Egli et al. 2018, Hofmann et al. 2004, Kralik et al. 1992, Schneeberger et al. 2016, Wehrens 2015, Wehrens et al. 2016, 2017). Evidence of cyclic embrittlement was reported from the Grimsel area (Wehrens et al. 2016).

The exhumation history of the Aar Massif is reported by diverse authors (Glotzbach et al. 2010, 2011, Michalski and Soom 1990, Pleuger et al. 2012, Reinecker et al. 2008, Valla et al. 2012, 2016, Vernon et al. 2009, Weisenberger et al. 2012). The Miocene to Pliocene exhumation history of the Central Swiss Alps is generally described as exhumation with a constant rate (0.3 to 0.5 mm/yr) since 10 to 14 Ma and a period of increased exhumation rate (ca. 0.7 mm/yr) between 10 to 8 Ma (Glotzbach et al. 2010, Valla et al. 2012, Vernon et al. 2009 and Weisenberger et al. 2012). Michalski and Soom (1990) report slightly higher exhumation rates, however, and used a higher geothermal gradient of ca. 30°C/km, whereas studies since Vernon et al. (2008) use 25°C/km as the local geothermal gradient. Valla et al. (2012) indicate higher exhumation rates for the time period 10–8 Ma with 2–4 mm/yr, whereas Vernon et al. (2009) discuss the possibility of a constant exhumation rate of 0.4 mm/yr for the last 10 Ma based on modelling.

Valla et al. (2016) distinguished three distinct exhumation events since the Late Neogene based on thermal modelling: (i) Late Miocene tectonically driven exhumation, (ii) Pliocene climatically induced regional exhumation pulse, and (iii) Quaternary exhumation event in response to glacial valley carving since ca. 1 Ma. Mey et al. (2016) present an alternative landscape evolution driver with glacial isostatic adjustment in response to the Last Glacial Maximum (LGM) ice cover being responsible for the denudation. For further details on the debate the reader is referred to Mey et al. (2016) and references therein. From GPS data, a modern-day vertical uplift of ca. 2 mm/yr has been suggested (Sanchez et al. 2018). This is substantially higher than the recent vertical crustal movement inferred from precision levelling for the Grimsel area in relation to a reference point in Laufenburg of ca. 1 mm/yr (Nagra 2008). It has to be noted that the two surveys employ different reference levels.

Uplift and exhumation related to glacial activity (as discussed below) resulted in the formation of so-called exfoliation joints, which occur within the uppermost 200 m of rock volume (Ziegler et al. 2013). Three distinct exfoliation joint types are reported for the Grimsel area: (i) closely spaced (< 1 m) joints that are parallel to today's topography, (ii) moderately spaced (0.6–2 m) exfoliation joints subparallel to today's topography and (iii) widely spaced (>> 2 m) joints that are not parallel to the ground surface but could be controlled by former topographies. Joint spacing inferred from mapping was confirmed on a larger scale based on photogrammetric models (Ferrari et al. 2018). Four exfoliation joint generations were identified: Early Pleistocene (ca. 1.5–1 Ma), Middle Pleistocene (ca. 0.7–0.4 Ma), Late Pleistocene (0.1–0.02 Ma) and Late Glacial/Holocene (< 0.02 Ma).

The latest step of the landscape evolution in the Grimsel area is related to glacial activity (Kelly et al. 2006). Multiple glacial stages throughout the Pleistocene shaped the valley morphology, which is likely to be pre-conditioned by the tectonic setting. Ice coverage was a least 600 m thick on the Grimsel Pass, as evidenced by trimlines and bedrock carving (Florineth and Schlüchter 1998). Recent modelling suggests even greater glacier thicknesses (Seguimot et al. 2018). The highest ice surface during the LGM was attained at 23.0 ± 0.8 ka in the upper 'Haslital' (Wirsig et
al. 2016). It was followed by significant retreat not later than $17.7 \pm 0.8$ ka (Wirsig et al. 2016). Post-glacial tectonic faulting was observed SE of the Grimsel Pass (Ustaszewski and Pfiffner 2008). The fault is characterised by a 7 m crest displacement resulting in a tectonic slip rate of about 0.4 mm/yr since the LGM.

2.7 Regional hydrological setting

The regional hydrological setting has been characterised based on hydraulic modelling validated against measured hydraulic heads (Herzog 1989, Voborny et al. 1991). Generally, principal infiltration areas for hydraulic heads measured at the GTS are the Alplistock and the Juchlistock with discharge in the Aare valley (Lake Grimsel or Lake Rätrichsboden; Fig. 2.8). These "undisturbed" conditions are altered by the presence of the underground facilities (GTS and main access tunnel of KWO, Voborny et al. 1991). Also, at the surface the water has no natural flow due to the numerous engineered systems of KWO (e.g. dams and water tunnels). The GTS and the main KWO access tunnel act as sinks, but with little water inflow due to the low hydraulic conductivity. The occurrence of these sinks leads to high hydraulic gradients in the western part of the GTS (Fig. 2.9). The labelled black lines in Fig. 2.9 represent equipotential lines where their spacing indicates the hydraulic head gradient. The Bächli zone that forms the Bächli valley (Bächlital, Fig. 1.1) is of regional importance and drains part of the Juchlistock/Alplistock catchment into Lake Rätrichsboden (Voborny et al. 1991).
Fig. 2.8: Map showing the equipotential lines for hydraulic heads with regional brittle discontinuity network (black lines) calculated on a horizontal section at the elevation of the GTS (modified after Voborny et al. 1991)

The map is based on model calculations containing the local topography, measured transmissivity values for rock matrix and faults, and measured hydraulic heads at the GTS.
Fig. 2.9: Cross-section through the GTS showing the regional distribution of hydraulic pressure in metres above the GTS level (modified after Frick et al. 1992)

The cross-section is based on model calculations containing the topography, faults and measured hydraulic heads at the GTS.
3 Local geological setting

3.1 Introduction

In this chapter, the regional overview presented in Chapter 2 is complemented by a description of the rock occurring around the GTS. The rock volume mainly consists of Late to post-Variscan members of the Haslital Group (see section 2.4; Berger et al. 2017b). A thorough description of the rocks often enables a more accurate interpretation of investigation results.

3.2 Previous studies

The local geology was described and reported most prominently in the early overview by Keusen et al. (1989). Subsequent rock volume descriptions were focused on the experiment-scale (e.g. Bossart and Mazurek 1991, Martel and Peterson 1991, Möri and Blechschmidt 2006, Möri 2009). An updated working report (Schneeberger et al. 2016) was issued to provide a detailed description of the geology surrounding the GTS because additional site-specific studies (experiment-scale descriptions) had been carried out since the publication of the first overview report (Keusen et al. 1989) and significantly enhanced the knowledge of the geology at the GTS. In the following, major findings from Schneeberger et al. 2016 are summarised.

3.3 Petrographic description

The rock volume surrounding the GTS is composed of Late to post-Variscan intrusive rocks. More precisely, the majority is composed of Central Aar Granite (CAGr) and Grimsel Granodiorite (GrGr, Fig. 3.1), both members of the Haslital Group. As mentioned in Chapter 2, these magmatic rocks form two distinct rock types, but belong to a calc-alkaline differentiation suite and therefore the transition is gradual. A transition zone is mapped in the GTS and included in the report (Enclosure 2). Metabasic dykes, formerly termed "lamprophyres", sporadically crosscut the magmatic rocks (Fig. 3.2).

The mineralogical composition of the different rock types is summarised in Tab. 3.1.
Tab. 3.1: Mineralogical composition of main rock types around the GTS

CAGr: Central Aar Granite, GrGr: Grimsel Granodiorite, MBD: Metabasic dyke


<table>
<thead>
<tr>
<th>Property/mineral</th>
<th>CAGr Unfractured rock matrix</th>
<th>GrGr Unfractured rock matrix</th>
<th>mylonite Fault gouge</th>
<th>MBD Unfractured rock matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>33 [vol-%]</td>
<td>31 [wt-%]</td>
<td>27 [wt-%]</td>
<td>22 [wt-%]</td>
</tr>
<tr>
<td>Quartz</td>
<td>34 [vol-%]</td>
<td>28 [wt-%]</td>
<td>17 [wt-%]</td>
<td>18 [wt-%]</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>21 [vol-%]</td>
<td>25 [wt-%]</td>
<td>18 [wt-%]</td>
<td>17 [wt-%]</td>
</tr>
<tr>
<td>Biotite</td>
<td>6 [vol-%]</td>
<td>8 [wt-%]</td>
<td>10 [wt-%]</td>
<td>12 [wt-%]</td>
</tr>
<tr>
<td>Chlorite (metamorphic)</td>
<td>1 [vol-%]</td>
<td>0.1 [wt-%]</td>
<td>0 [wt-%]</td>
<td>0 [wt-%]</td>
</tr>
<tr>
<td>Muscovite</td>
<td>1 [vol-%]</td>
<td>6 [wt-%]</td>
<td>24 [wt-%]</td>
<td>27 [wt-%]</td>
</tr>
<tr>
<td>Epidote</td>
<td>2 [vol-%]</td>
<td>0.4 [wt-%]</td>
<td>0.3 [wt-%]</td>
<td>0.3 [wt-%]</td>
</tr>
<tr>
<td>Titanite</td>
<td>0.2 [vol-%]</td>
<td>1 [wt-%]</td>
<td>0.3 [wt-%]</td>
<td>0.3 [wt-%]</td>
</tr>
<tr>
<td>Chlorite (clay mineral)</td>
<td>&lt; 1 [vol-%]</td>
<td>0.2 [wt-%]</td>
<td>3 [wt-%]</td>
<td>3 [wt-%]</td>
</tr>
<tr>
<td>Smectite (hydrothermal)</td>
<td>&lt; 1 [vol-%]</td>
<td>0 [wt-%]</td>
<td>0.2 [wt-%]</td>
<td>0.2 [wt-%]</td>
</tr>
<tr>
<td>Chlorite (metamorphic)</td>
<td>&lt; 1 [vol-%]</td>
<td>0 [wt-%]</td>
<td>0.1 [wt-%]</td>
<td>0.1 [wt-%]</td>
</tr>
<tr>
<td>Illite/smectite mixed layers</td>
<td>&lt; 1 [vol-%]</td>
<td>0 [wt-%]</td>
<td>0.1 [wt-%]</td>
<td>0.1 [wt-%]</td>
</tr>
</tbody>
</table>

Chlorite (metamorphic) refers to chlorite minerals formed conjunctly with white mica during Alpine metamorphism. Chlorite (clay mineral) refers to chlorite detected in the clay fraction with a broad XRD peak indicating low-temperature water-rock interactions.

3.3.1 Grimsel Granodiorite (GrGr)

The GrGr is the most primitive member of the calc-alkaline differentiation suite. It has been age dated to 299 ± 2 Ma (Schaltegger and Corfu 1992). It is composed of plagioclase, K-feldspar, quartz, biotite, chlorite, white mica (muscovite), epidote, titanite, and some accessory minerals (Tab. 3.1, Keusen et al. 1989, Wehrens 2015, Schneeberger et al. 2016). The GrGr appears as dark, moderately to strongly foliated meta-granite (Fig. 3.1), with sporadic augengneiss-type appearance.
3.3.2 Central Aar Granite (CAGr)

The CAGr forms a more differentiated part of the calc-alkaline suite and has an overlapping age with the GrGr (298 ± 2 Ma, Schaltegger 1994). The CAGr outcrops along ca. 340 m in the northern part of the main tunnel in the GTS (Fig. 1.2). In domains with little Alpine deformational overprint, it appears as massy to slightly foliated leucocratic biotite meta-granite with a uniform to weakly porphyritic texture (Fig. 3.1). Mineralogically, it is composed of quartz, feldspars, biotite, white mica (muscovite), chlorite, epidote, titanite, and some accessories. It differs from the GrGr mainly by the lower abundance of biotite (Tab. 3.1).

3.3.3 Metabasic dykes – meta-"Lamprophyres"

Metabasic dykes are ubiquitous in the GTS. They occur as NW-SE striking swarms and crosscut the Haslital Group granitoids. The dykes are macroscopically homogeneous dark greenish dykes with sharp contacts with the neighbouring rock (Fig. 3.2). In some locations (e.g. L130), magmatic intrusion structures such as apophyses are preserved. Dykes range in width from cm to m. The spacing between individual dyke swarms is typically around one hundred metres. The distance between the dykes within the swarms varies from metres to tens of metres. They are mainly composed of plagioclase and biotite. The age and magmatic origin of the metabasic dykes are unknown (Oberhänsli 1986, Schneeberger et al. 2016), but they must be younger than the granitoid hosts.
3.3.4 Quartz and epidote veins

Quartz and epidote veins occur in all parts of the GTS. Quartz veins are of different generations, some predate the Alpine orogeny and others are a product of deformation related to the Alpine orogenesis (Schneeberger et al. 2016).

Epidote veins crosscut the magmatic rocks, but their age is unknown. They are probably related to Mesozoic rifting and hydrothermal alteration of the granitoids.

3.4 Mineralogical composition

Most of the former magmatic minerals are transformed either by pre-Alpine or Alpine metamorphism. The ubiquitous occurrence of the transformations indicates alteration prior to localised Alpine deformation. Major mineral alterations are: (i) sericitisation of K-feldspar, (ii) saussuritisation and albitionisation of plagioclase, and (iii) the presence of partially chloritised biotite.

These alterations led to the observed mineral compositions: Biotite consists of 59% phlogopite and 41% annite; plagioclase contains 95% albite and 5% anorthite; K-feldspar is a mixture of 97% orthoclase and 3% albite (Schneeberger et al. 2016). Furthermore, pyrite was observed in certain thin sections (Schneeberger et al. 2016). In only a few locations, minor amounts of hydrothermal smectite (< 1%) were detected within fault gouge (Mäder and Ekberg 2006, Smith et al. 2001, Wehrens et al. 2016).

In addition, enhanced sheet silicate (biotite and muscovite, Tab. 3.1) concentrations are reported in highly deformed ductile zones (Mäder and Ekberg 2006; Wehrens et al. 2017), leading to differences between matrix rock composition and fault rock composition.

Alpine tension gashes postdate metamorphism and host important mineralogical features (Fig. 3.2), related to Alpine deformation history. They are filled with quartz, adularia, chlorite, fluorite, minor calcite and rarely sulphides, surrounded by leached wall rock depleted in quartz and biotite (Keusen et al. 1989). A prominent example of an Alpine tension gash is the crystal cave in the KWO main access tunnel south of the GTS.
3.5 Rock matrix pore space

The intact GrGr is characterised by an in-situ porosity of 0.4 to 0.6 vol% (measured with Hg porosimetry, Bossart and Mazurek 1991, Möri et al. 2003). Within the framework of the Connected Porosity experiment (Möri et al. 2003), it was observed that non-impregnated core samples were characterised by porosity values slightly above 1% (approximately 2 to 2.5 times higher than the in-situ porosity, Schild et al. 2001); this could be related to the sampling process resulting in additional porosity.

Möri (2009) reports an in-situ resin impregnation study performed as part of the LTD (Long-Term Diffusion) experiment using a customised resin of water-like viscosity using mercury porosimetry, water gravimetry measurements and the $^{14}$C-PMMA porosity method. The results provide a consistent picture of 1) the in-situ porosity, 2) the porosity derived from desaturated laboratory samples and 3) the porosity created during coring and sampling of in-situ impregnated samples (Tab. 3.2).

**Tab. 3.2: Matrix porosity determined from in-situ impregnation studies (Möri 2009)**

<table>
<thead>
<tr>
<th>Method</th>
<th>Lithology</th>
<th>Porosity determined on in-situ impregnated samples and naturally saturated samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impregnation porosity on in-situ impregnated samples by mass spectrometry</td>
<td>Granodiorite, massive</td>
<td>0.21 – 0.31 %</td>
</tr>
<tr>
<td></td>
<td>Granodiorite, weakly foliated</td>
<td>0.30 – 0.48 %</td>
</tr>
<tr>
<td>Impregnation porosity on in-situ impregnated samples by infrared absorption</td>
<td>Granodiorite, massive</td>
<td>0.22 – 0.39 %</td>
</tr>
<tr>
<td>Isotope diffusive exchange</td>
<td>Granodiorite, massive</td>
<td>0.38 – 0.46 %</td>
</tr>
<tr>
<td>Gravimetric water content on naturally saturated samples</td>
<td>Granodiorite, massive</td>
<td>0.40 – 0.46 %</td>
</tr>
<tr>
<td></td>
<td>Granodiorite, weakly foliated</td>
<td>0.62 – 0.77 %</td>
</tr>
</tbody>
</table>

The measured in-situ porosity of the massive granodiorite ranged from 0.21 – 0.46%, with slightly higher values of 0.30 – 0.77 vol.% for weakly foliated granodiorite. These values are typically lower than those derived from desaturated laboratory samples of 0.45 – 1.03% for the massive granodiorite and 0.55 – 0.86 vol.% for the weakly foliated granodiorite (Möri 2009).

The studies show that the porosity within the granodiorite under in-situ conditions is connected, and that a considerable amount of the connected granodiorite porosity at the GTS is related to solution porosity in alkali feldspars. In mylonites (ductile shear zones), deformation leads to a reduction in porosity and, in the weakly foliated rock, an anisotropy in the pore network (observed from the resin impregnation distance).
Further detailed characterisation of the matrix porosity has been performed in a range of experiments:

- **FEBEX EDZ studies**: water gravimetry, $^{14}$C-PMMA porosity, SEM/EDX (Bazargan Sabet et al. 2004)
- **LTD monopole 1**: water gravimetry, $^{14}$C-PMMA porosity (Fonteneau 2010)
- **LTD monopole 2**: water gravimetry, $^{14}$C-PMMA porosity, argon pycnometry (Muuri 2019)
- **PSG (Pore Space Geometry) experiment**: water gravimetry, $^{14}$C-PMMA porosity, mercury porosimetry (Kelokaski et al. 2006 and 2010)

In the various studies, four different categories of pores could be discriminated: (i) grain boundary pores, (ii) sheet silicate pores, (iii) solution pores, and (iv) micro-fractures (Fig. 3.3, Möri et al. 2003). Major characteristics are summarised in Tab. 3.3 and shown in Fig. 3.3.

**Tab. 3.3**: Major pore types occurring around the GTS (Möri et al. 2003)

<table>
<thead>
<tr>
<th>Pore type</th>
<th>Thin section shape</th>
<th>Aperture range [μm]</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain boundary pores</td>
<td>fine channels</td>
<td>&lt; 5 – 20</td>
<td>- in weakly deformed matrix along feldspars and quartz grains</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- shear bands</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- quartz ribbons</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- mica bands</td>
</tr>
<tr>
<td>Sheet silicate pores</td>
<td>very fine, cleavage parallel</td>
<td>0.1 – 10</td>
<td>- shear bands</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- mica bands</td>
</tr>
<tr>
<td>Solution pores</td>
<td>cloudy spots</td>
<td>&lt; 5</td>
<td>- altered plagioclase</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- along perthitic lamellae in K-feldspar</td>
</tr>
<tr>
<td>Micro-fractures</td>
<td>channels</td>
<td>&lt; 5 – 10</td>
<td>- feature-independent</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- drilling-parallel cracks only adjacent to borehole</td>
</tr>
</tbody>
</table>
Fig. 3.3: Thin section images of various pore spaces observed in the GTS

Right column shows images under crossed nicols and left column under UV light. Pictures (a) and (b) show fault gouge porosity, quartz grain boundary porosity (yellow square), micro-fracture porosity (green shape) and intragranular plagioclase porosity (white square). Images (c) and (d) show sheet cleavage pores, and (e) and (f) cleavage pores in K-feldspar.
Grain boundary pores are the most prominent pore type in weakly deformed rock. Porosity analyses were based on resin-filled pores, representing the undisturbed connected porosity (Tanaka et al. 2014). Scanning electron microscopy analyses showed that not all the porosity was resin-filled and thus connected (Möri et al. 2003). Reconstructions of the matrix porosity in 3D revealed a non-planar porosity geometry with microchannels and barriers (Möri et al. 2003).

A borehole excavation damaged zone is observed based on microscopic analyses of thin sections, showing pores extending radially 3–4 cm from the investigated borehole. It is noteworthy that the borehole is only 2.5 m away from the GTS tunnel wall and thus less than one tunnel diameter (Möri et al. 2003, Schild et al. 2001). The extent of the borehole damaged zone was inferred from a decrease in frequency of the grain boundary pores and the micro-fractures. However, all the above pore types were resin-filled beyond the borehole damaged zone and thus are interconnected.

3.6 Rock mechanical properties

Measurements of rock mechanical properties are part of a thorough site characterisation and are of interest for numerous subsequent applications including stress field characterisation, assessment of excavation damage, hydraulic fracturing tests or seismic studies. In the GTS, several programmes to characterise rock mechanical properties have been performed and key properties are compiled in Tab. 3.4 (Keusen et al. 1989, Pahl et al. 1989, Schneefuss et al. 1989, Kazerani and Zhao 2014, Krietsch et al. 2017, Wenning et al. 2018). Investigations were carried out either onsite at the GTS (e.g. Krietsch et al. 2017, Bouffier et al. 2015) or in specialised laboratories (e.g. Wenning et al. 2018). Generally, properties vary with the rock type and are strongly anisotropic due to the prevailing foliation (Nejati 2018). As shown by Nejati (2018), the occurrence of micro-fractures may strongly affect the rock mechanical property measurements.

The observed differences in properties may have multiple origins:

- Differences in measurement protocols and measurement ranges. Nejati (2018) showed a non-linear behaviour for Young's modulus, Poisson's ratio and the shear modulus with increasing stress.
- Differences between in-situ and laboratory measurement methods and effects of sampling. Pahl et al. (1989) recommend the use of solely in-situ measurements, as the representative volume of laboratory-size samples is small and thus represents a small-scale rock volume phenomenon (Pahl et al. 1989).
- Differences in sample size and shape.

A more detailed synthesis of rock mechanical properties for the rock types surrounding the GTS is beyond the scope of this report.
Tab. 3.4: Rock mechanical properties reported for the GTS

<table>
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</thead>
<tbody>
<tr>
<td>Young's modulus [GPa]</td>
<td></td>
<td>GrGr</td>
<td>GrGr</td>
<td>CAGr</td>
<td>GrGr</td>
<td>MBD</td>
<td>CAGr</td>
<td>CAGr</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>22 – 30.5</td>
<td></td>
<td>53.3 ± 11.0</td>
<td>47.3 ± 15.4</td>
<td>42.4 ± 8.5</td>
<td>25.8</td>
<td>35 – 45</td>
<td></td>
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<tr>
<td>Young's modulus [GPa]</td>
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<td>par</td>
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<td>Young's modulus [GPa]</td>
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<td>66 – 68</td>
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</tr>
<tr>
<td>Anisotropy in Young's mod.</td>
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<td>0.4 – 1</td>
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<td></td>
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</tr>
<tr>
<td>Poisson's ratio</td>
<td></td>
<td>uni</td>
<td></td>
<td>0.37 ± 0.12</td>
<td>0.33 ± 0.15</td>
<td>0.33 ± 0.17</td>
<td>0.23</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>par</td>
<td></td>
<td>0.18 – 0.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>per</td>
<td></td>
<td>0.16 – 0.17</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Internal cohesion [MPa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>21.1</td>
<td></td>
</tr>
<tr>
<td>Internal angle of friction [°]</td>
<td></td>
<td></td>
<td></td>
<td>33</td>
<td>30 ± 2</td>
<td>32.5 ± 3.5</td>
<td>53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeability [m²]</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>5 e-17</td>
<td></td>
</tr>
<tr>
<td>Permeability [m²]</td>
<td></td>
<td>par</td>
<td></td>
<td>5.95e-19 – 8.38e-19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeability [m²]</td>
<td></td>
<td>per</td>
<td></td>
<td>1.70e-19 – 4.14e-19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porosity [%]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt; 1.0</td>
<td>0.4 – 1.0</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2730</td>
<td>2660 ± 23.8</td>
</tr>
<tr>
<td>Vp (mean) [km/s]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2706 ± 13.6</td>
<td>2909 ± 31.0</td>
</tr>
<tr>
<td>Vs (mean) [km/s]</td>
<td></td>
<td>3.35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear modulus [GPa]</td>
<td></td>
<td>par</td>
<td></td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear modulus [GPa]</td>
<td></td>
<td>per</td>
<td></td>
<td>28 – 29</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk modulus [GPa]</td>
<td></td>
<td>par</td>
<td></td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk modulus [GPa]</td>
<td></td>
<td>per</td>
<td></td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dir. denotes orientation of the measured parameter with respect to foliation, either parallel (par) or perpendicular (per). Vp: P-wave velocity, Vs: S-wave velocity, CAGr: Central Aar Granite, GrGr: Grimsel Granodiorite, MBD: Metabasic dykes.
4 Structural geological description

4.1 Introduction

Deformation features are ubiquitous in the rock volume surrounding the GTS. Detailed characterisation of deformation features allows a comprehensive understanding of the mechanical discontinuities present in the rock volume and, therefore, a better assessment of the long-term evolution of the latter. Further, heterogeneities within the rock volume, such as foliation, strongly influence the mechanical properties, which in turn affect the interpretation of investigations such as overcoring stress relief experiments or hydraulic fracturing tests.

Structural geological work has been performed since the start of the GTS (Geotest AG 1981, Keusen et al. 1989, Bossart and Mazurek 1991, Martel and Peterson 1991, Möri 2009). Most prominently, the structural geological framework of the GTS is reported in Keusen et al. (1989). The observed brittle structures are subdivided based on their orientation into 12 different groups (S₁, S₂, S₃, S₄, S₅, S₆, L, K₁, K₂, K₃, K₄, ZK), where S stands for foliation (‘Schieferung’), L for lamprophyre (metabasic dykes), K for joint (‘Kluft’) and ZK for Alpine tension gash (‘Zerrkluft’). However, as already indicated by Keusen et al. (1989), it is not clear whether all groups occur, as overlaps of 10 to 20° are often observed between the groups. Further, the grouping is based solely on orientation and does not include kinematic indicators. Here, the structures at the GTS (brittle and ductile regime deformation structures) are summarised and interpreted based on the regional kinematic model presented by Herwegh et al. (2017) and Wehrens et al. (2017, see Chapter 2).

The features are described chronologically based on mapping performed in 2014–2015 in conjunction with literature data. More details on the structures are found in Schneeberger et al. (2016). The following terminology is employed for the various deformation features (Tab. 4.1), regardless of the time of formation. Further, the differences between the brittle structures are shown schematically in Fig. 4.1 and in Fig. 4.2 with photographs from the GTS.

![Fig. 4.1: Schematic representation of brittle deformation features occurring in the GTS](image-url)
Tab. 4.1: Structural terminology used in this report based on Schultz and Fossen (2008)

<table>
<thead>
<tr>
<th>Regime</th>
<th>Label</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brittle</td>
<td>Fracture</td>
<td>A sharp structural discontinuity having a local reduction in strength and/or stiffness and an associated increase in fluid conductivity between the opposing pair of surfaces.</td>
</tr>
<tr>
<td></td>
<td>Joint</td>
<td>A sharp structural discontinuity having field evidence for predominantly opening displacements between the opposing walls.</td>
</tr>
<tr>
<td></td>
<td>Fault</td>
<td>A sharp structural discontinuity defined by slip planes (surfaces of discontinuous shear displacement) and related structures including fault core and damage zones that formed at any stage in the evolution of the structure.</td>
</tr>
<tr>
<td></td>
<td>Micro-fracture</td>
<td>A sharp structural discontinuity having a local reduction in strength and/or stiffness between the opposing pair of surfaces, without indication of the underlying kinematics and identified on the microscopic scale.</td>
</tr>
<tr>
<td></td>
<td>Fault zone</td>
<td>A set of relatively closely spaced faults having similar orientation.</td>
</tr>
<tr>
<td></td>
<td>Cataclasite</td>
<td>Brittle fault rock with cohesion.</td>
</tr>
<tr>
<td></td>
<td>Fault gouge</td>
<td>Fault zone formed by cataclasis with loss of cohesion.</td>
</tr>
<tr>
<td></td>
<td>Vein</td>
<td>Former brittle fracture filled with secondary minerals.</td>
</tr>
<tr>
<td></td>
<td>Alpine tension gash</td>
<td>Structural discontinuity formed by predominantly opening movements and remaining open, allowing incomplete filling with secondary minerals such as quartz.</td>
</tr>
<tr>
<td>Ductile</td>
<td>Ductile shear zone</td>
<td>A tabular structural discontinuity having a continuous change in strength or stiffness across a relatively narrow zone of shearing; shear and volumetric strains are relatively continuous across the zone, and large or continuous (linked) slip surfaces are rare or absent.</td>
</tr>
<tr>
<td></td>
<td>Foliation</td>
<td>Planar fabric formed by mineral alignment.</td>
</tr>
</tbody>
</table>

4.2 Magmatic structures

Structures related to the emplacement of magmatic bodies are present around the GTS. However, Alpine deformation strongly overprinted the rock volume and thus magmatic structures are largely hidden by later Alpine structures. Magmatic deformation can be recognised in the least deformed parts of the CAGr in the WT drift and around the central facility.

Magmatic structures in the GTS have been described in detail by Zarco Ambrosio (2011). Magmatic foliation is marked by the shape-preferred orientation of large K-feldspar and plagioclase grains and by a planar arrangement of lentoid-shaped mafic enclaves. The magmatic foliation has an average orientation of 145/80 (dip azimuth/dip, Schneeberger et al. 2016). Anisotropy of magnetic susceptibility measurements show orientations parallel to the magmatic foliation (pers. communication Jan Franěk, January 2019). Other magmatic structures are magmatic shear zones, which are localised zones of increased strain. Magmatic ductile shear zones are recognised based on the variation in orientation of the magmatic foliation.
Fig. 4.2: Graphical summary of mappable structures in the GTS (modified after Schneeberger et al. 2016)

Ductile fabrics are shown separately for the CAGr and the GrGr as they have slightly different appearances.
4.3 Alpine structures

The following section is subdivided into pervasive and localised deformation features related to deformation resulting from the Alpine orogenesis.

4.3.1 Pervasive Alpine deformation

Alpine solid-state foliation is ubiquitous in the granitoids surrounding the GTS, resulting in a gneissic appearance of the granitoids. It is marked by an alignment of biotite, white mica and shape-preferred orientation of recrystallised quartz (e.g. Wehrens 2015). The foliation appears stronger in the GrGr than in the CAGr (Fig. 4.2), which is due to the higher biotite content in the GrGr in conjunction with a southward increasing strain in the 'Haslital' (e.g. Choukroune and Gapais 1983, Rolland et al. 2009, Steck 1968, Wehrens et al. 2017). The Alpine foliation is oriented sub-parallel to the magmatic foliation (i.e. ca. 150°/72).

4.3.2 Localised Alpine deformation

Two types of localised deformation features occur within the rock volume, structures originating from ductile regime deformation and structures resulting from retrograde brittle regime deformation (Fig. 4.2). Numerous ductile features were subsequently reactivated under brittle regime deformation.

4.3.2.1 Ductile shear zones

Localised ductile regime deformation is expressed by the occurrence of ductile shear zones, where shear zone describes a high strain zone. Alpine ductile shear zones occur as discrete narrow (mm to cm) shear zones, and as asymmetric shear zones with macroscopically visible strain gradient. The macroscopic strain gradient is expressed by a reduction in grain size (dark appearance), an increase in foliation intensity and, if present, an elongation of quartz aggregates (Fig. 4.2). Chemical mass transfer during deformation resulted in enrichment in sheet silicates within the ductile shear zones (Tab. 3.1, Wehrens et al. 2016).

Discrete ductile shear zones are more prominent within the CAGr than in the GrGr and probably have a brittle precursor structure (Mancktelow and Pennacchioni 2005, Wehrens 2015). This is evidenced by the typical low width to length ratio of the discrete ductile shear zones (Schneeberger et al. 2016). In the case of ductile shear zones with a macroscopically visible strain gradient (Fig. 4.2), the origin can be manifold (localisation from a homogeneous state, localisation along pre-existing mechanical anisotropies as lithological contacts or brittle precursors).

In the GTS, ductile shear zones occur in three distinct orientations: NE-SW, E-W, and NW-SE striking (Fig. 4.3). Most ductile shear zones are steeply south dipping. Observed orientations are comparable with reported orientations on a regional scale (e.g. Herwegh et al. 2017, Rolland et al. 2009, Wehrens et al. 2017). NE-SW striking ductile shear zones are part of fault set 1 (see Chapter 3). They are located within the Haslital Group granitoids. E-W and NW-SE striking ductile shear zones are part of fault set 2. E-W ductile shear zones are seldom observed in the GTS (Enclosure 2), but are prominent on a regional scale, e.g. Grimsel Pass shear zone (Herwegh et al. 2017, Wehrens et al. 2017). NW-SE striking ductile shear zones in the GTS are predominantly located within metabasic dykes.
A total of 65 ductile shear zones were mapped along the 517 m of the main (L) tunnel in the GTS, resulting in an average frequency of ca. 120 features per km (Fig. 4.4). This frequency is comparable to the frequency observed in the nearby GasTransit tunnel¹ (ca. 100 features per km, Wehrens 2015), but higher than the frequency observed at the surface (ca. 24 ductile shear zones per km) or in the tunnel linking the Handegg with the Gerstenegg (KWO Liselotte tunnel², ca. 41 features per km). The lower value at the surface could result from differences in outcrop conditions, whereas the lower value in the KWO Liselotte tunnel could reflect the strain gradient increasing towards the south, which could also explain the slightly lower value of the GasTransit tunnel, as the measured tunnel segments extend further to the north than the GTS.

Fig. 4.3: Lower-hemisphere pole diagram with the measured poles of ductile shear zones in the GTS (a) and the corresponding contours (b)
The contours are colour-coded to enhance readability.

Fig. 4.4: Frequency of ductile shear zones grouped by their strike direction at the surface and in the GTS
Surface perimeter as in Fig. 2.4.

¹ Measured in N-S direction between the points 155'677 and 161'197 (CH1903 north coordinates)
² Measured in N-S direction between the points 160'281 and 163'091 (CH1903 north coordinates)
4.3.2.2 Brittle regime

Ductile features were overprinted by brittle features with decreasing temperature and pressure conditions (see PTt path in Chapter 3, Fig. 2.4). Observed brittle features include faults, fault zones, fault cores filled with fault gouge, cataclasites, veins (quartz- or epidote-filled), and Alpine tension gashes (Fig. 4.2, Schneeberger et al. 2017).

Fault cores filled with fault gouge are formed by grinding down (cataclasis) of mylonitic material with only minor mineralogical changes. Neo-formation of clay minerals was only sporadically observed (Bossart and Mazurek 1991, Kralik et al. 1992, Mäder and Ekberg 2006, Wehrens 2015).

Dilation related to brittle reactivation of former ductile shear zones induces an increase in porosity (e.g. Egli et al. 2018, Keusen et al. 1989, Bossart and Mazurek 1991). Bossart and Mazurek (1991) quantified the increase in porosity for the Migration shear zone (AU096). Fig. 4.5 shows a compilation of pictures, most importantly UV light pictures of resin-injected thin sections (Tanaka et al. 2014). The resin was injected into a borehole, which was subsequently overcored. The porosity in ductile shear zones is even lower than in the protolith (Fig. 4.5), but brittle features such as fault gouge are characterised by a higher porosity. As the porosity is estimated from injected resin, the values represent connected porosity and the permeability is therefore increased compared to the unfractured rock matrix.

Fig. 4.5: Macroscopic, microscopic and UV light images of deformation features (modified after Schneeberger et al. 2018)

Cross polarised and UV light thin section images show the same detail of the thin section.
Brittle faults are ubiquitous at the GTS but are of limited lateral extent as they can rarely be correlated between neighbouring galleries. They occur along pre-existing structures (e.g. quartz veins, ductile shear zones, metabasic dykes) or within unfractured rock matrix. All faults are steeply dipping (with varying dip azimuth).

Some of the observed joints might result from tunnel construction resulting in an excavation damaged zone (EDZ, for details see section 8.4.2).

Microfractures are reported from different locations at the GTS: near boreholes and tunnels as excavation damaged zones (Schild et al. 2001, Frieg and Blaser 2012), rims of fault gouge cores (Bossart and Mazurek 1991). In the Connected Porosity experiment (CP), microfractures were analysed in detail. It was observed that mica cleavage cracks, intergranular cracks within quartz polycrystals and intergranular cracks in feldspars formed along cleavage planes are the most abundant forms of microfractures (Möri et al. 2003, Schild et al 2001).

### 4.4 Conceptualisation of faults

Structural features observed at the GTS are of different ages (Fig. 4.6). Primary structures are related to the emplacement of the magmas forming magmatic foliation and magmatic shear zones. The intrusion of metabasic dykes into these magmatic hosts formed a major rheological contrast that governs further strain localisation. Alpine deformation is expressed by pervasive foliation and localised ductile deformation depicted by high strain zones. Further, brittle deformation is related to uplift and cooling of the massif and reactivation is concentrated along rheological anisotropies such as the rims of metabasic dykes or former ductile shear zones. Fig. 4.7 is a summary of a typical fault zone occurring within the GTS.

<table>
<thead>
<tr>
<th>Time</th>
<th>Process</th>
<th>Structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Ma</td>
<td>Brittle overprint of former ductile shear zones (cataclasism)</td>
<td>Brittle regime</td>
</tr>
<tr>
<td>3 Ma</td>
<td>Uplift and exhumation decreasing temperature</td>
<td>Fractures (faults + joints)</td>
</tr>
<tr>
<td>7 Ma</td>
<td>Brittle deformation of K-feldspars and plagioclase</td>
<td>Fault core with gouge</td>
</tr>
<tr>
<td>13 Ma</td>
<td>Ductile deformation of sheet silicate and quartz (dynamic recrystallization)</td>
<td>Biotite-coated fractures</td>
</tr>
<tr>
<td></td>
<td>Solid-state deformation in response to Alpine orogeny</td>
<td>Cataclasites</td>
</tr>
<tr>
<td>25 Ma</td>
<td>Greenschist facies metamorphism</td>
<td>Foliation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Streching lineations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Porphyroclasts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ductile shear zones</td>
</tr>
</tbody>
</table>

Fig. 4.6: Simplified deformational history of the rock volume surrounding the GTS (modified after Frick et al. 1992 and Wehrens 2015)
The unfractured rock matrix is marked by magmatic and Alpine foliation. Ductile shear zones localised in granitoid rocks as well as within the metabasic dykes are often precursor structures for subsequent brittle reactivation. Brittle reactivation is expressed by a fault core with gouge and by a damaged zone consisting of faults and increased microfracturing.

**Fig. 4.7:** Conceptual model of an asymmetric fault zone at the GTS with a single fault core

Inferring common values to describe the structure network such as frequency, thickness or aperture is complicated by the fact that the distribution over the GTS is not homogeneous. Certain areas are characterised by a strong ductile overprint and subsequent brittle reactivation, whereas others are far less deformed. Nevertheless, Tab. 4.2 represents an attempt to define the aforementioned parameters for the GTS. In general, brittle deformation tends to reactivate rheological contrast (i.e. ductile shear zones or metabasic dykes). This localisation of brittle deformation, which governs the permeability distribution, allows a tentative extrapolation of the brittle deformation along the precursor structure even though the brittle reactivation is heterogeneous.

Tab. 4.2: Fracture network characteristics for the entire GTS.

<table>
<thead>
<tr>
<th>Features</th>
<th>Spacing</th>
<th>Thickness</th>
<th>Length</th>
<th>Open apertures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[features per m]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ductile shear zones</td>
<td>clustered</td>
<td>cm – m</td>
<td>up to km</td>
<td>-</td>
</tr>
<tr>
<td>Metabasic dykes</td>
<td>clustered</td>
<td>m</td>
<td>up to km</td>
<td>-</td>
</tr>
<tr>
<td>Brittle fault core with gouge</td>
<td></td>
<td>cm</td>
<td>m</td>
<td>0.001 – 0.005 mm**</td>
</tr>
<tr>
<td>Faults – background rock domain</td>
<td>0 – 3*</td>
<td>mm</td>
<td>m</td>
<td>µm</td>
</tr>
<tr>
<td>Strongly faulted domains</td>
<td>&gt; 20*</td>
<td>mm</td>
<td>m</td>
<td></td>
</tr>
</tbody>
</table>

* Krietsch et al. (2018); ** Frick et al. (1992)
Within the framework of the GAM (gas migration in shear zones) experiment, a conceptual description of a typical fault zone across various scales was undertaken. This structural model is shown in Fig. 4.8. On the GTS scale, fault zones are typically described as planar features. On the outcrop (or tunnel mapping) scale, the fault zone is described as a fault zone composed of multiple fault cores filled with fault gouge that form an anastomosing network. One single fault core reveals an interconnected network of flow channels of various apertures, embedded in a layer of more or less homogeneous fault gouge material in the thin section description (Marschall and Lunati 2006).

Fig. 4.8: Descriptive structural model of the GAM shear zone on different scales (Marshall and Lunati 2006)
4.5 Structures at the surface above the GTS and the 3D geometry of major structures

Structural geological 3D models often serve as the basis for various geo-informed models, such as hydrodynamic transport models. The GTS was used to validate the 3D models based on surface mapping (Schneeberger et al. 2017). Structures mapped in the underground do not directly correlate with structures mapped at the surface due to a large difference in observable feature frequency (Schneeberger et al. 2017). Outcrop conditions in the GTS allow identification of each structure, whereas at the surface only major structures are mappable. Therefore, major structures were extrapolated from the surface to depth and not interpolated between the GTS and the surface in a recent effort to obtain a 3D structural model (Schneeberger et al. 2017). Although this approach means ignoring the data on smaller features, it represents the usual approach, where the data are extrapolated from the surface to depth.

Three different extrapolation techniques were compared in order to take advantage of the GTS dataset to validate the extrapolation of surface features to depth using different workflows: extrapolation based on field measurements, extrapolation based on Delaunay triangulation (Delaunay 1934) and extrapolation based on the ribbon tool, a Move™ (Midland Valley) internal extrapolation technique. All three extrapolation approaches were used to build a 3D model of the major structures in the Juchlistock (Fig. 4.9 and 4.10).

In order to compare the three approaches, a 'best-estimate' model was defined and used as the basis for a statistical approach using the Bayes theorem ('maximum a posteriori'). The statistical modelling defined the likelihood of a specific connection between a certain surface structure and a certain underground structure. Based on trace lengths from the surface, it is assumed that the surface structures connect down to the GTS. Based on the assumption that major structures do not cross, a probability distribution function was obtained for every surface structure. Each individual surface point was linearly connected with the 'maximum a posteriori' value in the GTS. This resulted in a 3D structural model. The three extrapolation techniques could then be compared based on the deviation from the 3D structural model. The comparison highlighted that classical field work resulted in a close fit with the statistical interpolation ('maximum a posteriori' model, Fig. 4.9), which confirms the statistical approach, but also highlights the importance of classical field work as a basis for the development of 3D structural models.

The 3D structural model obtained resembles the model proposed by Keusen et al. (1989), as the major available information is the dip value of a specific structure. However, the level of detail in features is increased compared to that given in Keusen (1989).
Fig. 4.9: Comparison of extrapolation techniques and statistical interpolation (modified after Schneeberger et al. 2017)
Based on the 'maximum a posteriori' model, the surface structures were linearly connected with the underground structures resulting in a 3D visualisation of the major structures crosscutting the entire rock volume surrounding the GTS (Fig. 4.10).

Fig. 4.10: 3D visualisation of the 'most probable' interpolation model showing structures connecting the surface and the GTS
5 In-situ stress measurement

5.1 Introduction

Characterisation and monitoring of the present-day stress field is important for a thorough description of a specific site and forecasting its long-term tectonic evolution.

Information on the stress state in the GTS is available on a regional scale from several sources: the world stress map, orientation of exfoliation jointing, and stress measurements performed by KWO in two vertical boreholes. On the local scale, information about the stress field is obtained from GTS-scale experiments such as the excavation damaged zone (EDZ) investigations, the tunnel levelling campaign, the tilt meter experiment (NM), and from borehole-based stress measurements (e.g. In-situ Stimulation and Circulation project).

5.2 Regional stress information

5.2.1 World stress map

The world stress map is a compilation of diverse estimates of stress (Heidbach et al. 2016), obtained from earthquake focal mechanism analyses and from borehole investigations. In the Central Alps of Switzerland, a general NW-SE trending maximum horizontal stress is inferred (Fig. 5.1).
Fig. 5.1: Stress map showing the orientation of maximum horizontal compressional stress (modified after Heidbach et al. 2016)

Magenta rectangle marks the Grimsel area. Data depth range 0–40 km, Projection: Mercator

5.2.2 Topographically controlled stress changes – exfoliation joints

Exfoliation joints form in response to exhumation. In the Grimsel area, numerous Pleistocene exfoliation joints are reported (Ziegler et al. 2013). Plumose structures formed in response to joint propagation are sometimes preserved on joint planes. The plumose axis is considered to approximate the orientation of the main principal compressive stress ($\sigma_1$, Ziegler et al. 2014a). Under this assumption, mapped plumose axes can be used for reconstruction of the stress orientation during exfoliation joint formation (Pleistocene). Ziegler et al. (2014b) inferred a strongly compressive stress field in the uppermost 45 m of rock with $\sigma_1$ perpendicular to the valley axis for the Grimsel area. Numerical modelling was used to reconstruct the in-situ stress conditions, resulting in the observed exfoliation joint pattern. The observed orientations of $\sigma_1$ could not be achieved with a purely gravitational load model, and a far-field tectonic stress component was required. Pure gravitational loading resulted in tensile stresses in the uppermost 100 m of rock volume in the valley floor. The orientation of the plumose axes could be matched with an additional NW-directed far-field stress component. The NW-directed stress field corresponds to the general structural trends observed in the Grimsel area (Wehrens 2015, Ziegler 2013). Therefore, the near-surface stress field is most likely characterised by a combination of gravitational loading and NW-directed tectonic stress.
### 5.2.3 KWO stress measurements

In the course of the expansion of subsurface hydropower constructions belonging to KWO, three different stress measurement campaigns were performed. Two were based on the hydraulic fracturing method: a deep vertical borehole was drilled near the Kessiturm and a second borehole near Handegg (Fig. 1.1). A third measurement campaign was performed with an overcoring technique in a niche of the Grimsel II hydropower plant. Tab. 5.1 gives an overview of the resulting stress tensors obtained by KWO.

<table>
<thead>
<tr>
<th>Location</th>
<th>Overburden [m]</th>
<th>$S_v$ [MPa]</th>
<th>$S_h$ [MPa]</th>
<th>$S_H$ [MPa]</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kessiturm</td>
<td>320–570</td>
<td>8.7–15.5</td>
<td>7.8–22.3</td>
<td>9.5–37.3</td>
<td>WNW-ESE</td>
</tr>
<tr>
<td>Handegg I</td>
<td>40–80</td>
<td>1.1–2.0</td>
<td>7.4–9.0</td>
<td>14.2–17.3</td>
<td>W-E</td>
</tr>
<tr>
<td>Grimsel II</td>
<td>265</td>
<td>7.0</td>
<td>-</td>
<td>ca. 20</td>
<td>NNW-SSE</td>
</tr>
</tbody>
</table>

#### 5.2.3.1 Kessiturm

As a part of the extension of the hydropower unit Grimsel 3, a 610 m deep vertical borehole was drilled near the Kessiturm, south of Lake Grimsel (CH1903 coordinates: 667170/157440). The stress field was characterised with 7 hydro-fracture stress measurements (HFSM) between 320 and 569 m depth. The induced fractures strike ESE-WNW with an average strike of 105° (Gruner and Ziegler 2011). The estimated maximum horizontal stress is WNW-ESE with a magnitude of 9.5 to 37.3 MPa (Gruner and Ziegler 2011). The minimum horizontal stress trends NNE-SSW.

#### 5.2.3.2 Handegg I

HFSM in the borehole Handegg I have shown that the maximum horizontal stress is oriented W-E with a magnitude of 14.2 – 17.3 MPa; the minimum horizontal stress is perpendicular (N-S striking) with a magnitude of 7.4 – 9.0 MPa (Rummel and Klee 2009). The vertical stress is very small (1.1 – 2.0 MPa) due to the small overburden (40 – 80 m). With such a small overburden, the topography strongly influences the stress field and the stress field is therefore mostly representative for the local conditions, limiting any larger scale comparison.

#### 5.2.3.3 Grimsel II

Based on overcoring data obtained in a cavern about 260 m below ground in the KWO tunnel system (Illies and Greiner 1976), a maximum horizontal stress orientation of roughly SSE-NNW was inferred. The magnitude of the maximum horizontal stress was approximately 20 MPa and the vertical stress (based on overburden) about 7 MPa. The inferred stress field is quite different from the estimates from Kessiturm and Handegg I and may reflect differences in the measurement method or the influence of nearby excavations.
5.3 Local (GTS) stress information

5.3.1 Excavation damaged zone\(^2\) (formerly termed the excavation disturbed zone)

Mechanical excavation of tunnels leads to stress relief reactions in the rock volume, which may cause the formation of a damaged zone. In the GTS, the Excavation Damaged Zone experiment (EDZ) was performed in the WT drift (cf. map, Fig. 1.2), where tunnel wall damage was most extensive. It therefore represented an extreme example of the excavation damaged zone in the TBM (tunnel-boring machine) tunnels rather than a typical value (cm-sized) for the GTS (Frieg and Blaser 2012). The excavation damaged zone was examined based on several purpose-drilled boreholes. Intensive hydraulic characterisation showed that borehole test intervals in unfractured rock matrix less than 1 m away from the tunnel have higher permeability values than expected from the known background unfractured rock matrix in the GTS. No measurements were available between 1 and 2 m but this increase in transmissivity was not observed in borehole test intervals 2 m away from the tunnel (Frieg and Blaser 2012). This confirms the existence of an excavation damaged zone of approximately 0.4 to 1.5 m around the WT tunnel at this location (Frieg and Blaser 2012). More generally, the EDZ is expected to be cm scale in TBM sections of the GTS and somewhat greater around drill and blast excavations (ca. 1 m; see for example GMT, section 8.4.2).

5.3.2 Levelling measurements

High precision levelling measurements were performed in the late 1980s and repeated as part of the LASMO project in 2014. The levelling measurements were performed at 9 observation points in the GTS and diverse observation points in the KWO main access tunnel (Fig. 5.2). They used the point 10.2 as a reference point (Fig. 5.2).

The height variations for the southern observation points correlate with the height changes of Lake Grimsel (Schneefuss et al. 1989). An increase of ca. 20 m in lake level leads to a subsidence (max. 3 mm) of the observation points (Fig. 5.3). The northern observation points (labelled 1.8, 2.3, Fig. 5.2) seem to behave in a different manner to the southern ones (Fig. 5.3) in the levelling campaigns carried out in the 1980s, whereas they show similar behaviour for the levelling campaign in 2014. The accuracy in the 2014 levelling campaign is reported as ± 0.4 mm. The magnitude of the response to lake level changes decreases with increasing distance from the lake. A non-uniform response of the observation points to the lake level changes was observed in the measurements performed in the 1980s. This might indicate that the observation points are somehow decoupled from each other. This decoupling is probably the result of large deformation structures crosscutting the rock volume between certain observation points (Schneefuss et al. 1989). The large deformation structures result in crustal blocks of less deformed rock volume separated by the structures (Herwegh et al. 2017).

\(^2\) We refer to the former Excavation Disturbed Zone and now label it the Excavation Damaged Zone in agreement with the internationally accepted terminology for a damaged zone.
Fig. 5.2: GTS situation plan with observation points during the levelling campaign

Fig. 5.3: Height variation of reference points as a function of time and elevation level changes of Lake Grimsel

Note that the time axis (x-axis) is not linear. The reference points are shown in Fig. 5.2.

In general, an apparent subsidence of the observation points, which was observed in the measurements in the 1980s (Schneefuss et al. 1989), is confirmed by the measurements of 2014. It has to be noted that the measurement (15.04.1985) used as the zero point was performed at a relatively low Grimsel Lake level (1862.2 m a.s.l.). In combination with the fact that the reference point was chosen to be the farthest away from Lake Grimsel, this yields an apparent subsidence of all observation points closer to Lake Grimsel.

5.3.3 Tilt meter experiment

In addition to the height levelling, inclination measurements were carried out at the GTS in order to characterise the movements of the rock volume (Schneefuss et al. 1989). In the GTS, six boreholes (NM boreholes, Fig. 5.4) were equipped with high precision tilt meters (Flach and Noell 1989).
All inclination measurement stations showed responses to changes in the Lake Grimsel level (Fig. 5.4). An increase in the lake volume (from roughly 2 to $9 \times 10^7$ m$^3$) leads to a southward inclination of the tilt meters. The magnitude of the response in the tilt meters to lake level changes decreases with increasing distance away from the lake. Water level changes in Lake Rätrichsboden also influenced the rock volume. The northernmost station showed movement towards the centre of Lake Rätrichsboden. As was observed in the levelling campaigns, the response of the tilt meters did not uniformly correlate to changes in the level of the lakes. This non-uniform response probably results from the decoupling of crustal blocks by large deformation structures, similar to observations by Herwegh et al. (2017). The observations from the tilt meter experiment corroborate the findings of the levelling campaigns.

Fig. 5.4: Response of tilt meter 3 to lake level changes (modified after Flach and Noell 1989)  
The y axis in the upper plot shows the tilt in [ms]. The y axis of the lower plot shows the lake level change relative to the beginning of the measuring campaign.

In addition to the decoupling and the strong effect of lake level changes, other perturbations were identified. The tilt meters reacted to earth tides and to an annual meteorological wave that is induced by air pressure changes. These effects are discussed further in Chapter 8.
5.3.4 Borehole-based rock stress state estimations

5.3.4.1 Rock stress investigations experiment

In the early stages of the GTS investigations, rock stress ('Gebirgsspannung' 'GS') was characterised by a series of in-situ stress measurements performed along a 197 m long vertical borehole located near the BK cavern in the GS drift (borehole GS 84.041A, Enclosure 1). The measurements used an overcoring technique and the maximum and minimum horizontal stresses were estimated as a function of depth along the borehole (Fig. 5.5). The overcoring stress measurements assumed a linear-elastic rock behaviour (Pahl et al. 1986, Pahl et al. 1989).

![Fig. 5.5: Horizontal stress estimations made in borehole GS 84.041A showing stress heterogeneity (modified after Pahl et al. 1989)](image)

The left column summarises geological domains: I: granite with pronounced planar texture, partly foliation (ca. 2 fracture/m), II: compact granite with horizontal fissure at around 100 m (ca. 0.5 fracture/m), III: mostly compact granite with numerous closed joints and two intensely fractured zones with open fissures between 121 – 131 m and 137.5 – 144 m (ca. 1.7 fracture/m), IV: granite, cataclasite, damaged zone from metabasic dyke (MBD, ca. 1.9 fracture/m).

In the middle column, the circles represent the maximum horizontal stress, while the triangles represent the minimum horizontal stress axis. E refers to the Young's modulus and ν to the Poisson's ratio.
Three distinct zones were observed (Fig. 5.5). (i) Down to a depth of 40 m below the tunnel, the minimum horizontal stresses increased from 15 to 32 MPa and the maximum horizontal stress increased from 25 to 40 MPa (typically oriented E). (ii) Between 40 and 100 m borehole depth below the tunnel, the minimum horizontal stresses are ~27 MPa and the maximum horizontal stresses ~40 MPa; the maximum horizontal stresses are S to SE oriented. (iii) In the section from 100 m to the borehole end, the minimum horizontal stresses were about 16 MPa and the maximum horizontal stresses between 25 and 35 MPa, E to SE oriented (Fig. 5.5). The variation of both the stress orientation and the stress magnitudes correlate with changes in the macrofracture frequency and orientation (Pahl et al. 1989). Furthermore, the investigated volume contains numerous metabasic dykes and brittle reactivated former ductile shear zones. Major structures are known to influence the in-situ stress conditions (see Krietsch et al. 2018).

5.3.4.2 Excavation Damaged Zone (EDZ) experiment

Within the framework of the Excavation Damaged Zone experiment (EDZ, Frieg and Blaser 2012), the undisturbed in-situ stress at the GTS was estimated. The stress field was derived from numerical modelling (calculating back the effects of the tunnels and of the topography) and crosschecked against stress measurements performed as part of the Gas Migration Test (GMT) using the borehole slotting technique (Bock 1993, Wohnlich 1995). Two different numerical models were used to fit the data. The numerical modelling was performed on a regional scale, including 9 large-scale faults that are located between 500 m and 2500 m along the KWO main access tunnel. The model assumed linear-elastic behaviour of the rock volume and Mohr-Coulomb behaviour for the discrete features. The models used the following properties: Young's modulus (E) of 40 GPa, and Poisson's ratio of 0.33 based on Keusen et al. (1989). The water load from the two adjacent lakes was ignored.

The first model was based solely on gravitational loading of the rock volume and the resulting stresses. However, the measured stress in the GMT experiment could not be fitted. The second model included an additional far-field stress component, which was chosen to strike NE-SW with a magnitude of 0 MPa at 2000 m altitude, increasing to 50 MPa at 3 km below sea level. Modelling results revealed that the NE-SW and NW-SE striking fault zones (considering the assumptions of the model) did not significantly influence the regional stress field. However, local-scale stress modelling showed the importance of the fault zones in decoupling single crustal blocks and stress orientation variation in the fault near field.

The resulting undisturbed stress field at the GTS under the assumption of a far-field tectonic stress component is characterised by a NE-SW plunging maximum principal stress axis (Tab. 5.2).
Tab. 5.2: Principal stress axes reported at the GTS

Values are inferred from numerical modelling including a far-field tectonic stress (Frieg and Blaser 2012) and from borehole-based stress estimation (Krietsch et al. 2018).

<table>
<thead>
<tr>
<th></th>
<th>σ₁</th>
<th>σ₂</th>
<th>σ₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frieg and Blaser (2012)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnitude [MPa]</td>
<td>24.7 – 30.0</td>
<td>11.4 – 11.6</td>
<td>7.0 – 9.7</td>
</tr>
<tr>
<td>Plunge azimuth [°]</td>
<td>121 – 129</td>
<td>019 – 030</td>
<td>235 – 250</td>
</tr>
<tr>
<td>Plunge [°]</td>
<td>12 – 20</td>
<td>29 – 30</td>
<td>47 – 57</td>
</tr>
<tr>
<td>Krietsch et al. (2018)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnitude [MPa]</td>
<td>13.1</td>
<td>8.2</td>
<td>6.5</td>
</tr>
<tr>
<td>Plunge azimuth [°]</td>
<td>134</td>
<td>0.26</td>
<td>235</td>
</tr>
<tr>
<td>Plunge [°]</td>
<td>14</td>
<td>50</td>
<td>36</td>
</tr>
<tr>
<td>Krietsch et al. (2018)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnitude [MPa]</td>
<td>13.1</td>
<td>9.2</td>
<td>8.7</td>
</tr>
<tr>
<td>Plunge azimuth [°]</td>
<td>105</td>
<td>259</td>
<td>004</td>
</tr>
<tr>
<td>Plunge [°]</td>
<td>39</td>
<td>48</td>
<td>13</td>
</tr>
</tbody>
</table>

For details about the stress estimation of Krietsch et al. (2018) see section 5.3.4.3 below.

5.3.4.3 In-situ Stimulation & Circulation (ISC) experiment

As part of the In-situ Stimulation & Circulation experiment (ISC, Fig. 1.2), in-situ stress measurements were performed in three dedicated boreholes (Krietsch et al. 2017). The boreholes were oriented according to the stress field suggested by Konietzky and Marschall (1997). In total, 6 hydraulic fracturing (HF) and 3 overcoring tests were conducted.

Micro-seismic events associated with the hydraulic fracturing tests are on average located on an E-W striking plane, indicating on average a N-S striking σ₃ (assuming the hydro-fractures are oriented perpendicular to σ₃). The magnitude estimated from instantaneous shut-in pressures is between 8 and 10 MPa. P-wave polarisation analysis of the seismic events related to the hydro-fractures suggests thrust and normal faulting mechanisms (Gischig et al. 2018). The elastic properties of the tested rock volume are required to invert the overcoring measurements and infer the stress field. Two different sets of mechanical properties were assumed by Krietsch et al. (2018), which leads to two different interpretations of the stress field (Tab. 5.2). Assuming isotropic behaviour (E = 20.4 to 25.7 GPa, ν = 0.24 – 0.27), the stress field is characterised by σ₃ plunging SW with a magnitude in the range of 4.8 to 7.4 MPa. However, this orientation of σ₃ is not compatible with the orientation of the HF tests. Therefore, a second set of rock mechanical properties were used with a Young’s modulus anisotropy (E_max/E_min) of 2. As a result, the plunge of σ₁ rotates from SW to E.
Such a large Young's modulus anisotropy is supported by on-site measurements (Bouffier et al. 2016) and by laboratory work (Nejati 2018). However it is large compared to modulus ratios compiled by Worotnicki (1993) for crystalline environments, where the maximum $E_{\text{max}}/E_{\text{min}}$ ratio is 1.3.

The orientations of $\sigma_2$ and $\sigma_3$ are less well constrained, as the difference in magnitude is small and the magnitude depends strongly on the absolute magnitude of the Young's modulus (E) (Krietsch et al. 2018). The overcoring test results interpreted with a strong anisotropy coincide with the results obtained from the hydraulic fracturing tests.

One of the three boreholes cuts a major fault zone (Fig. 5.6, ISC-SBH 15.004). Hydro-fracturing (HF) indicates a progressive reduction of the magnitude of $\sigma_3$ from 8.0 MPa to 2.8 MPa approaching the fault zone (Krietsch et al. 2018). This reduction is corroborated by the overcoring tests. Consequently, Krietsch et al. (2018) proposed two different stress fields for the ISC domain, an unperturbed and a perturbed stress field. The unperturbed stress field is valid away from the major fault zone and is characterised by eastward plunging $\sigma_1$, whereas the perturbed stress field is characterised by SE-plunging $\sigma_1$. The nature of the stress heterogeneity is uncertain. Two mechanisms could potentially contribute. The magnitude changes correlate with an increase in fracture frequency along the borehole and potential slip along the fault zone would perturb the stress field (Krietsch et al. 2018).
5.3.4.4 **Comparison of different stress tensors**

Three different stress tensors have been suggested for the GTS (Fig. 5.7). Three stress measurement campaigns were performed at different locations in the GTS, and thus under variable overburden (Fig. 5.8). The varying overburden implies a different vertical stress (lithostatic pressure) and influences both the magnitude and the orientation of the principal stress axes. In general, $\sigma_1$ plunges towards SE with a higher magnitude than $\sigma_2$ and $\sigma_3$, which have a similar magnitude. Further $\sigma_2$ and $\sigma_3$ are located on a NW-dipping plane, although their exact orientation is poorly constrained.

![Lower hemisphere equal area stereographic projection of the principal stress axes](image)

**Fig. 5.7:** Lower hemisphere equal area stereographic projection of the principal stress axes

According to Krietsch et al. (2018), the orientation of the principal stress axes varies because the strain measurements are performed closer to a fault zone. This strong influence of fault zones on the stress field is corroborated by the levelling measurements and by the tilt meter experiment. In the tilt meter experiment, differences in the response to level changes in Lake Grimsel are observed between stations separated by a major fault zone. Moreover, the orientation of the principal stress axes is also influenced by the degree of anisotropy in the Young's modulus (Krietsch et al. 2018).

The perturbed stress field of Krietsch et al. (2018) and the stress field suggested by Konietzky and Marschall (1997) are comparable. The major difference is in the magnitude of the principal stresses. As inferred from modelling by Krietsch et al. (2018), the Young's modulus has a strong effect on the magnitude of the principal stresses. This could account for the higher magnitudes obtained by Konietzky and Marschall (1997) compared to those reported by Krietsch et al. (2018). However, it has to be noted that the two stress measurements were performed in different rock types (CAGr and GrGr).

While a more profound description of the stress field is beyond the scope of this report, the comparability of the stress field estimations by Konietzky and Marschall (1997) and by Krietsch et al. (2018) may indicate that these stress fields might be representative of the in-situ stress field for the rock volume surrounding the GTS.
In general, given the complexity involved in performing stress measurements (e.g. Evans and Engelder 1989, Martin and Christiansson 1992, Martin 2007, Krietsch et al. 2017) and potential variability due to overburden, rock properties and structures, the estimated stress fields require careful use and any results derived from them need to consider the uncertainty associated with the stress field.

Fig. 5.8: GTS map with isohypses showing the vertical overburden

Red lines show oblique distance between the GTS and the topography as projected on a horizontal plane. The contour distance is 5 m.
6  Water-conducting features at the GTS

Groundwater flow at the GTS occurs within the rock matrix and within discrete water-conducting features (WCFs). WCFs are associated with a range of geological structures: fault zones, brittle reactivated former ductile shear zones and faults associated with metabasic dykes. Within larger, more complex structures, brittle deformation, associated dilation and the distribution of fault gouge (fault-filling material) influence the location of the water flow paths.

The unfractured rock matrix and the different geological structures associated with WCFs are discussed in the following sections.

6.1  Rock matrix

The rock matrix at the GTS shows a connected porosity made up of four different pore types: grain boundary pores, sheet silicate pores, solution pores and micro-fractures (Möri et al. 2003). Matrix porosity has been studied in detail in the Connected Porosity (CP), Pore Space Geometry (PSG) and Long-Term Diffusion (LTD) experiments. Other relevant information comes from studies of two-phase flow in the tunnel near field and tracer transport (VE (ventilation), ZPM (two-phase flow in the matrix of crystalline rocks)). More generally, hydraulic testing in unfractured intervals across a range of experiments has contributed to the characterisation of the hydraulic conductivity of the matrix.

Autoradiographs4 (e.g. Fig. 6.1) from the PSG experiment illustrate that flow and transport paths are associated with grain margins and are, in effect, controlled by the micro-scale network of cracks and microfractures within the matrix. Controls on overall matrix permeability could therefore include grain size and mineralogy, degree of cleavage/tectonic deformation, proximity to macro-scale fracturing and stress state.

Fig. 6.1: 1200 dpi autoradiograph of a Grimsel Granodiorite sample (5× actual size)

Concentrations of radionuclides used as tracers are shown as grey scale. Black areas highlight high concentrations of radionuclides (courtesy Marja Siittari-Kauppi Helsinki University).

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4 Radionuclides used as tracers are visualised with the grey scale corresponding to the activity.
In the following, information about the hydraulic conductivity of the unfractured rock matrix gained from multiple experiments is summarised. Tab. 6.1 provides a list of matrix properties from the various investigations at the GTS.

The granite matrix at the GTS is considered to have a hydraulic conductivity between $10^{-12}$ and $10^{-11}$ m/s, with undisturbed porosity below 1% (Schild et al. 2001). Core testing from the GAM experiment (Marschall and Lunati 2006) in the Grimsel Granodiorite shows some dependence of both permeability and porosity on stress (Fig. 6.2), although this may reflect some damage (micro-cracking) from the drilling process.

A collaborative benchmarking study (David et al. 2018a,b) on the permeability of Grimsel Granodiorite cores at a common effective confining pressure (5 MPa) was performed as part of the ISC project. The average gas permeability was $1.1 \times 10^{-18}$ m$^2$ (standard deviation of $0.6 \times 10^{-18}$ m$^2$) after discarding outliers (4 out of 39). The gas permeability was higher along foliation that normal to it. David et al. (2018a) also found that the liquid permeability was typically a factor of 2 lower than the gas permeability.

David et al. (2018b) present porosity measurements, microstructure characterisation (BIB-SEM and µCT) and statistical modelling of the pore network. The porosity of the plug varied from 0.2 – 1.8% with a mean value of 0.8%, which suggests that at least some of the porosity relates to the sampling effects discussed by Möri (2009). A weak correlation of permeability with porosity was found in the study. In addition, some participants in the study investigated pressure-dependence in the 1–30 MPa range and modelled this with an exponential law.

Field tests away from major features set an upper bound on the hydraulic conductivity of the unfractured matrix. Gimmi et al. (1997) report that "from borehole injection tests in granodiorite at the GTS, saturated hydraulic conductivity was estimated between $3.8 \times 10^{-12}$ and $2.2 \times 10^{-10}$ m/s". Kull et al. (1993) performed ventilation tests in the VE drift, where they measured the water inflow into the drift and the hydraulic gradient between two observation boreholes under varying climatic conditions. They concluded that the large-scale hydraulic conductivity in granodiorite was in the order of $10^{-11}$ m/s. Bossart et al. (in Frieg and Vomvoris 1994) compared the results of evaporation measurements with those of ventilation tests during a desaturation experiment. They derived hydraulic conductivity values of $3.9 \times 10^{-11}$ m/s (ventilation tests) and $2.1 \times 10^{-11}$ m/s (evaporation tests) assuming steady-state conditions and a fully saturated rock matrix.

Hydraulic testing and analyses at the FEBEX site (Martinez-Landa and Carrera 2005) showed a range of estimated hydraulic conductivity from $10^{-12}$ to $10^{-10}$ m/s, although for numerical
modelling minor fractures were lumped together with the matrix using values below $10^{-11}$ m/s. Hydraulic screening tests at the LTD site in a matrix interval indicated a low conductivity of $\sim 2 \times 10^{-12}$ m/s. Pulse tests performed in the matrix at the GAM site resulted in a hydraulic conductivity between $10^{-12}$ to $8 \times 10^{-11}$ m/s.

Tab. 6.1: Rock matrix properties from GTS investigations

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Unit</th>
<th>Central value</th>
<th>Range</th>
<th>Comment</th>
</tr>
</thead>
</table>
| Permeability              | $k$    | m²   | $5 \times 10^{-19}$ | $10^{-19} - 10^{-18}$ | Marschall and Lunati (2006): Lab $\sim 6 - 65 \times 10^{-19}$, Packer tests 4 - 200 $\times 10^{-19}$  
  Finsterle and Pruess (1993): $6.8 \times 10^{-19}$  
  Marschall and Lunati (2006): $2.4 - 7.5 \times 10^{-19}$ (lower gas $k$ stress $\sim 10$ MPa)  
  David et al. (2018a): mean $1.1 \times 10^{-18}$ m² with standard deviation $0.6 \times 10^{-18}$ m²  
  Wenning et al. (2018): $1 - 8 \times 10^{-19}$ along foliation, $0.5 - 4 \times 10^{-19}$ perpendicular to foliation  
  Marschall and Lunati (2006): $0.03, 0.6 \times 10^{-19}$ mylonitic core |
| Hydraulic Conductivity    | $K$    | m/s  | $5 \times 10^{-12}$ | $10^{-13} - 10^{-11}$ | Martinez-Landa and Carrera, 2005: $10^{-12}$ and $10^{-11}$  
  Schild et al. 2001: $5.6 \times 10^{-13}$ and $4.9 \times 10^{-12}$  
  Kull et al. 1993: $3 \times 10^{-11}$ |
| Porosity                  | $\phi$ | -    | 0.65%          | 0.1 – 1.5%      | Reference value (Soler presentation 2011)  
  Marschall and Lunati (2006): 0.5 – 1.5%  
  Finsterle and Pruess (1993): 1%  
  Schild et al. 2001: 0.4 to 0.6% |
| Specific storage          | $S_s$  | m⁻¹  | $5 \times 10^{-7}$ |               | Marschall and Lunati (2006): Low sensitivity, best estimate $10^{-7}$  
  LTD interference $10^{-7} - 10^{-6}$ (fully saturated Lanyon and Blechschmidt 2008) |
| Diffusivity               | $\eta$ | m²/s | $10^{-5}$      |               | LTD interference $10^{-7} - 10^{-6}$ estimate $5 \times 10^{-6}$ |
| Entry pressure (Vg)       | $P_0$  | kPa  | 1000           | 400 – 3000    | Marschall and Lunati (2006): Lab 400 – 800, GTPT 1500 – 3000  
  Lanyon and Senger (2008): 500 kPa to match observed pressure (LTD) |
| Pore size distribution index | $n$   | -    | 1.88           | 1.4 – 2.4     | Marschall and Lunati (2006): Lab test $n=1.4$, field assumed $n=2.4$ |
| Residual water saturation | $S_w$  | -    | 0.1            |               | Finsterle and Pruess (1993): 0.1 |
Permeability and seismic velocity anisotropy across a ductile–brittle fault zone were investigated as part of the ISC project (Amann et al. 2018). For a 0.6 m long core crossing an entire fault zone, Wenning et al. (2018) report permeability values of $1 - 8 \times 10^{-19}$ and $0.5 - 4 \times 10^{-19}$ m$^2$ along and perpendicular to foliation, respectively (Tab. 6.1) for the unfractured fault rock.

The anisotropic low permeability of the rock matrix at the GTS is well established from field and laboratory testing. Variability in permeability is largely due to variability in the pore network (typically associated with mineralogy, see Chapter 3), but is also associated with excavation-induced and sample disturbance (micro-cracking) and applied stress.

### 6.2 Faults and fault networks in the northern part of the GTS

With the CAGr exposed in the northern part and the GrGr in the southern part, the lithology of the GTS rock volume varies (Schneeberger et al. 2016). Therefore, the hydraulic regimes are discussed separately for the northern and southern part of the GTS by providing a summary of the corresponding experiments (Fig. 6.3).

In the northern part of the GTS, flow in faults and fault networks has been characterised in the FEBEX and BK areas. Key results from different projects are summarised below.
Fig. 6.3: Concept for the influence of geological controls on water-conducting features at the GTS
6.2.1 US/BK area

The US/BK area was investigated by BGR (Bundesanstalt für Geowissenschaften und Rohstoffe) over a 20-year period starting in 1984. The Effective Field Parameter (EFP, Himmelsbach et al. 2003) experiment in GTS Phase V summarised the comprehensive investigation of the fracture system around the US/BK area (Fig. 6.4). Investigations included trace mapping and core characterisation, together with hydraulic and tracer tests performed in 20 boreholes. Fractures in the US/BK area were mapped, and geostatistical models were developed to describe fracture orientation and length (Himmelsbach et al. 2003).

Fig. 6.4: Fracture orientation in the US/BK area after weighting and correction for geometric bias

all fractures (N=6448), open fractures (N=2705), source: Himmelsbach et al. (2003).

pdf: probability distribution function, m: mean values, s: standard deviation
The results from hydraulic and tracer testing in this area showed that most of the boreholes are in good hydraulic communication with each other due to the well-developed fault system in this part of the GTS. Packer testing in the area indicated multiple high permeability intervals with interval transmissivity in the range of $10^{-9}$ to $10^{-5}$ m$^2$/s. The transmissivity variation (derived from multiple double packer tests) is exemplified by the BK 85.005 borehole illustrated in Figure 6.5. The interval length was normally 1.1 m and tests were performed every metre along the borehole with a small overlap.

A series of longer crosshole pump tests were performed in conjunction with tracer tests between multiple boreholes. The mean transmissivities from both double packer and crosshole tests were similar with $\sim2\times10^{-7}$ m$^2$/s, but transmissivity in the faulted zone in the central region was around an order of magnitude higher.

A deterministic flow model of the region was also developed and used to interpret multiple crosshole and tracer tests. The main features in the final model are shown in Fig. 6.6. The orientation of the deterministic features corresponds with the main fracture orientations derived from the geostatistical model. Stochastic models of the fracture network suggested multiple permeable fracture clusters together with isolated clusters of fractures which did not have any hydraulic connection.

![Fig. 6.5: Interval transmissivity variation along BK 85.005 from double packer tests](image)

Source: Himmelsbach et al. (2003).

The position of BK 85.005 is shown in Enclosure 1.
6.2.2 FEBEX area

A significant effort was made to characterise and model groundwater flow at the FEBEX site under both undisturbed conditions and after Engineered Barrier System (EBS) emplacement (Martinez-Landa and Carrera, 2005, 2006, Alonso et al. 2005). Extensive hydraulic testing in existing and new boreholes was performed as part of the FEBEX project. Tests included pressure build-up, pulse tests and longer production/injection tests. The tests are documented in Guimerà et al. (1998). Larger scale hydraulic tests were performed in boreholes US 85.001, US 85.002, FBX 95.001, and FBX 95.002 (Fig. 6.7). The extensive hydraulic testing together with monitoring of the response to excavation was used to identify the most important hydraulic structures and their connectivity.

The major hydraulic feature that intersects the FEBEX drift is associated with the metabasic dyke (Fig. 6.7). Martinez-Landa and Carrera (2005, 2006) suggest that the hydraulic conductivity of the background rock volume (matrix and small fractures) is $\sim 10^{-11}$ m/s, while locally features such as Fr-7 (metabasic dyke channel, see Fig. 6.7) are many orders of magnitude more permeable. Small-scale tests showed a transmissivity range from $10^{-12}$ to over $10^{-7}$ m$^2$/s, with a mode of $\sim 10^{-11}$ m$^2$/s representing the background rock volume. Transmissivity estimates for the identified flowing structures from crosshole tests (Martinez-Landa and Carrera, 2006) varied from $10^{-10}$ to $3\times 10^{-8}$ m$^2$/s, with one feature (Fr-7, a highly conductive channel associated with the metabasic dyke margin) showing a transmissivity $\sim 10^{-5}$ m$^2$/s.

In 2005, two boreholes (FUN 05.001, FUN 05.002) were drilled parallel to the FEBEX drift at distances of 30 and 60 cm, to investigate geochemical gradients and bentonite colloid concentrations in the near field (Buil et al. 2010). Fracture transmissivity was typically very low: $10^{-12} – 10^{-11}$ m$^2$/s with the exception of interval FU1-1 intersecting a fault with a transmissivity of $6 – 8 \times 10^{-10}$ m$^2$/s near the end of the drift (known as the "September" fracture). This feature may be related to the fault zone containing Fr-5 intersected by boreholes J5 and B23 (Fig. 6.7). Inflows
to the FEBEX drift were measured during and after excavation using a variety of methods. The total was estimated at 7.8 ml/min (Alonso et al. 2005, Martinez-Landa and Carrera 2005), approximately half of which came from 6 identified inflow points.

Fig. 6.7: Borehole geometry and packer locations a) prior to tunnel excavation (Guimerà et al. 1998) and b) during the FEBEX experiment (Martinez-Landa and Carrera 2006)

Fr indicates fault zones; B, F, G, I, J, K label boreholes.

6.2.3 C-FRS

Following the investigation of the BK area, the C-FRS project in the GTS investigation Phase VI characterised the fracture network in the northern part of the BK area (Fig. 6.2, CRIEPI 2010). Characterisation included 7 constant head withdrawal, 1 constant head injection, and 1 pulse injection tests. The various tests aimed at characterising the hydraulic behaviour of the investigated rock volume. Most constant head withdrawal and constant head injection tests were analysed with the straight-line analysis method (CRIEPI 2010). The pulse injection test was analysed with a type curve method. Additionally, the recovery phase following the constant head withdrawal test was analysed based on the Agarwal time.

The transmissivity values estimated for tested fractured intervals in borehole C-FRS 09.002 vary by about 2 orders of magnitude and range from $3 \times 10^{-9}$ to $6 \times 10^{-7}$ m$^2$/s. Transmissivity values obtained for the investigated fault zone in C-FRS 09.001 only spread within 1 order of magnitude between $2 \times 10^{-6}$ m$^2$/s and $3 \times 10^{-5}$ m$^2$/s. All measured intervals in C-FRS 09.001 show good connectivity with the other fractured intervals in the investigated volume. The connectivity is evidenced by the pressure responses observed within the monitoring borehole test intervals.

In a second experimental step, resin was injected into the fault zone from neighbouring boreholes and larger diameter cores were drilled (CRIEPI 2013, Tanaka et al. 2014). Based on the characterisation of the resin distribution in the two studied fault zones, two flow path types were discriminated: main channels along the fault zones and fault networks branching off the main channels.

Pressure recovery analysis performed on the fifth constant head withdrawal pressure recovery phase (HWS 5) in C-FRS 09.001 shows an IARF (infinite acting radial flow) period and yields a transmissivity of $4 \times 10^{-6}$ m$^2$/s, which agrees well with the transmissivity obtained for the constant head withdrawal period.
6.3 Faults and fault networks in the southern part of the GTS

In the southern part of the GTS, flow is dominated by a series of well-defined planar fault zones localised within former ductile shear zones (VE, MI, HPF, GAM; the fault zones have been labelled by the first experiment performed in the zone). Flow is typically associated with brittle reactivation at one of the margins of the ductile shear zone. Locally, transmissivity values derived from small-scale pulse tests vary strongly within these structures and range from matrix-like values \(<10^{-10}\) to over \(10^{-5}\) m\(^2\)/s. Nevertheless, at larger scale these features represent major WCFs.

6.3.1 MI shear zone

The true thickness of this ductile shear zone is about 1–2 m and it extends over 4 m of the tunnel wall from AU95–AU99 (Fig. 6.8, Möri and Blechschmidt 2006). The main shear plane at the northern contact shows a high degree of brittle deformation overprinting the older ductile features. The main water-conducting feature is associated with the brittle fracturing in the form of a braided structure of 3 fault cores with gouge. Seven distinct inflow points have openings of up to 10 mm in width and continuous water inflow into the tunnel.

On excavation of the shear zone (1983), a relatively high inflow rate was encountered on the shear zone trace at AU96 (Hoehn et al. 1990). The inflow is the largest of the entire southern part of the GTS (higher inflows are encountered in the BK area in the northern part of the GTS). Discharge at the “Kalotte” inflow on the shear zone plane was measured from November 1983 for a period of about 8 months, when it was observed to decline approximately logarithmically from 0.45 l/min to 0.21 l/min. In 1987, the total outflow was estimated at 0.5 l/min (Hoehn et al. 1990), while in May 1996 Meier (in Smith et al. 2001) states that inflow had slowly decreased during the previous 10 years and was approximately 400 ml/min. In 2005, a new flow channel in the roof developed (perhaps due to removal of fault gouge) during tunnel cleaning prior to the sealing performed within the CFM project.

Hydraulic testing in the MI zone has shown significant small-scale variability, with pulse test transmissivity varying from below \(10^{-10}\) to more than \(10^{-5}\) m\(^2\)/s, while at large scale (>10 m) the transmissivity is estimated to be \(~10^{-6}\) m\(^2\)/s. The MI shear zone intersects four tunnels at the GTS but only the intersection at AU96 produces significant flow:

- AU tunnel: intersection at AU96 associated with significant flow;
- VE tunnel: intersection at VT420 shows no water inflow points or wet locations, inflow less than 1 ml/min (Smith et al. 2001);
- KWO main access tunnel: inflow less than 1 ml/min (Smith et al. 2001);
- KWO cable tunnel: no significant inflow recorded.

Hydraulic heterogeneity within the MI shear zone around AU96 was investigated in the MI and CRR projects by Meier et al. (1998) and Jodar et al. (2002) using hydrotesting at multiple scales (pulse tests and crosshole tests) and inverse geostatistical models. The transmissivity field estimated from a range of geostatistical models developed in CRR is shown in Fig. 6.9. The realisation shown in Fig. 6.9 corresponds to a model with relatively elongated horizontal channels and barriers and was selected as the best fit for the collected hydrotest data. Horizontal channels would agree with a thrust-related deformation and the most permeable structures being oriented parallel to \(\sigma_2\) (Sibson 1996).
Fig. 6.8: Detailed geological mapping of the MI shear zone expression on the AU tunnel surface with surface packer locations (red circles) indicating inflow points (Schlickenrieder et al. 2017)
The Excavation Project (EP, Alexander et al. 2003) involved overcoreing of a resin-injected tracer dipole within the MI shear zone. Two adjacent large-diameter overcore boreholes (368 mm) were drilled in the plane of the shear zone and a very detailed laboratory characterisation programme was performed. Small-scale investigations during EP using microscopy, resin impregnation, and autoradiography showed a range of flow path morphologies including channels, micro-scale networks, cracks and splay features (see description of pore space in section 3.5). This small-scale characterisation of the flow structures within the shear zone emphasises the interaction of fault morphology and fault gouge filling material in determining the flowing (advective) porosity within the fault cores. The distribution of fault gouge in particular is a key control on the flow channels within the shear zones as the open channels within the fault core are the main water conduits, with the fault gouge acting as a barrier to flow.

Fig. 6.10 illustrates the conceptual model of fault architecture suggested by Frick et al. (1992) for the MI shear zone. Highlighted is the fault core with fault gouge (black area in Fig. 6.10). Within the fault gouge, open channels (high reflectance of UV-sensitive resin in inlet figure in Fig. 6.10) provide first-order water flow paths, whereas the fine-grained fault gouge material acts as a barrier to flow.
Fig. 6.10: Simplified representation of the Migration shear zone with a thin section image of resin-injected fault core with gouge under UV light (modified after Frick et al. 1992)

The thin section image inlet shows the distribution of UV-sensitive resin. The resin was injected prior to overcoring and thus represents the in-situ connected porosity.
6.3.2 GAM shear zone

The GAM shear zone was investigated using similar techniques to those developed by Meier et al. (1998) for the MI shear zone. With a large-scale transmissivity of \( \sim 10^9 \) m\(^2\)/s, the shear zone is less transmissive than the above-mentioned MI shear zone at AU96. However, Fig. 6.11 shows that a similar pattern of sub-horizontal channels was interpreted from the crosshole testing.

Fig. 6.11: Preferential hydraulic connections obtained by the analysis of storativity data from individual injection tests (from Ramajo et al. 1999)

The figures represent the shear zone plane with the intersection of the multiple boreholes shown as dots. The boreholes used for injection are highlighted in red. The various hydraulic connections inferred from the four injection tests are shown in green.

6.3.3 VE shear zone

The VE shear zone has been extensively studied in a series of experiments (VE, GMT, HPF and LCS). The inflow to the VE tunnel from the shear zone was measured in a Ventilation Experiment (Vomvoris and Frieg 1992) at 26.4 l/day (1.1 l/hr), which is similar to the estimated total inflow to the VE tunnel of 28.8 l/day (Voborny et al. 1991). Vomvoris and Frieg (1992) proposed a shear zone transmissivity of \( 2 \times 10^9 \) m\(^2\)/s based on a water balance analysis of the ventilation test, while inverse models suggested a slightly lower transmissivity of \( 0.9 \times 10^9 \) m\(^2\)/s. Hydraulic testing in the shear zone and surrounding background rock volume during the GMT project again illustrated the heterogeneous nature of the shear zone and fault system, but also showed a strong influence of the excavation, mainly on the unfractured rock volume (Fig. 6.12).
6.3.4 ISC

The In-situ Stimulation and Circulation (ISC) experiment was located at the southern end of the GTS around the small cavern at the end of the AU tunnel. The focus of the ISC experiment was a decametre-scale in-situ hydraulic stimulation experiment (Amann et al. 2018) to investigate hydromechanical processes related to the creation of a heat exchange fracture network in crystalline rock.

As part of the site characterisation work, prior to hydro-fracturing and in-situ stimulation, 15 boreholes were drilled, including two injection boreholes, nine boreholes monitoring for strain, pressure and temperature and four boreholes for geophysical monitoring in an investigation volume of about 20×20×20 m³ (Doetsch et al. 2018).

Discontinuities were logged in core and borehole image logs and integrated into a structural model containing six large-scale structures (4 NE-SW striking fault zones and 2 E-W striking fault zones associated with metabasic dykes) and five rock domains of varying fracture intensity as shown in Fig. 6.13. Given that these structures and rock domains mutually intersect, the volume of interest is relatively complex (Fig. 6.13).

Pulse tests were performed in the boreholes to derive the local transmissivity distribution. The derived transmissivity ranged from 10⁻¹⁴ to over 10⁻⁵ m²/s. The relationship between fracture intensity and local transmissivity was found to be complex and was synthesised using a classification scheme including host rock, wall damage zones, linking damage zones and reactivated ductile shear zones (pers. comm. B. Brixel). They suggest that high transmissivity tension fractures observed within the damage zone of the E-W striking fault zones are associated with a higher transmissivity (pers. comm. B. Brixel). Also, single faults in the rock volume were less permeable than single faults in the former ductile shear zones.
Fig. 6.13: Structural model of the ISC volume a) plan view of tunnels, boreholes and main structures, b) hydrostructural model (pers. comm. B. Brixel)
Seven constant rate crosshole tests (ranging from 5 to 670 ml/min) were performed for periods between 0.2 and 60 hours. Injection pressure was maintained well below the estimated minimum jacking pressure. The local transmissivity of the injection intervals ranged from $10^{-8}$ to over $5 \times 10^{-6}$ m²/s. The measured pressure responses were analysed using the Theis solution, fractional flow dimension and dual porosity models. They suggest that fast (high diffusivity) responses may be associated with the wall damage zones (pers. comm. B. Brixel), while overall a "sub-radial" (flow dimension < 2, Barker 1988) pattern of pressure diffusion was observed. However the influence of individual high transmissivity features was important. They also observed that fractures developed within the S3 (EW-striking) faults are much more interconnected than in the S1 (NE-SW-striking) faults as the majority of crosshole responses were monitored in the S3 faults.

The results of additional hydraulic testing, tracer testing and fluid logging at the ISC site are presented in Jalali et al. (2018). The complete dataset from the ISC experiment has been made available on ETH Zürich's Research Collection website (Krietsch et al. 2018).

### 6.4 Summary of faults and fault networks at the GTS

The hydrogeological characterisation of the entire GTS based on multiple experimental programmes can be conceptualised in a hydraulic model for the entire GTS, with a northern part (CAGr-dominated) and a southern part (GrGr-dominated).

In the northern part of the GTS, large-scale flow structures are related to major brittle fault zones, while locally smaller-scale faults provide a connected fault network at the US/BK, FEBEX and C-FRS sites. The transmissivity is dependent on scale and ranges from $\sim 10^{-11}$ to $10^{-4}$ m²/s for small-scale tests on individual structures, whereas larger structures are characterised by a reduced range ($\sim 10^{-8}$ to $2 \times 10^{-7}$ m²/s, Tab. 6.2).

<table>
<thead>
<tr>
<th>Site</th>
<th>Feature</th>
<th>Properties</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>US/BK</td>
<td>Large-scale fault clusters</td>
<td>~2x10^{-7} m²/s</td>
<td>Himmelsbach et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>Individual faults</td>
<td>Transmissivity range 10^{-8} to 10^{-5} m²/s</td>
<td></td>
</tr>
<tr>
<td>FEBEX</td>
<td>Large-scale flow structures</td>
<td>Transmissivity ~10^{-8} m²/s</td>
<td>Martinez-Landa and Carrera (2005, 2006)</td>
</tr>
<tr>
<td></td>
<td>Small-scale flow structures</td>
<td>Transmissivity range 10^{-10} to 3x10^{-8} m²/s (~10^{-5} m²/s for channel associated with metabasic dyke)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Background rock (matrix + low transmissivity faults)</td>
<td>$K_{eff} &lt; 10^{-11}$ m/s</td>
<td></td>
</tr>
<tr>
<td>C-FRS</td>
<td>Individual fault</td>
<td>Transmissivity range 10^{-9} to 10^{-5} m²/s</td>
<td>CRIEPI (2010)</td>
</tr>
</tbody>
</table>
Characterisation of multiple fault zones in the southern part of the GTS shows a consistent pattern whereby:

- Elevated permeability values are associated with fault cores filled with gouge material, arranged in anastomosing packets at the rheological contrasts of the former ductile shear zones or metabasic dykes.
- Highly heterogeneous small-scale properties are related to local-scale fault architecture and the distribution of fault gouge in fault cores.
- Flow is concentrated in channels within the faults. Channels are separated by low transmissivity barriers. There is some evidence that both channels and barriers are sub-horizontal.
- The larger-scale transmissivity varies from $10^{-10}$ to $10^{-6}$ m$^2$/s, but flow is highly heterogeneous with large parts of the water-conducting features of the fault zone showing no significant connected permeability (Tab. 6.3).

Results from the investigations performed as part of the ISC experiment at the southern end of the GTS are thought to be more representative of complex regions related to the intersection of such large-scale structures.

Tab. 6.3: Transmissivity of fault zones in the southern part of the GTS

<table>
<thead>
<tr>
<th>Feature</th>
<th>Transmissivity [m$^2$/s]</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>MI shear zone</td>
<td>$&lt;10^{-10}$–$10^{-5}$</td>
<td>Blechschmidt et al. (2018)</td>
</tr>
<tr>
<td>GAM shear zone</td>
<td>$10^{-11}$–$3\times10^{-8}$</td>
<td>Marschall and Lunati (2006)</td>
</tr>
<tr>
<td>VE shear zone</td>
<td>$10^{-12}$–$10^{-6}$</td>
<td>Vomvoris and Frieg (1992)</td>
</tr>
<tr>
<td>HPF shear zone</td>
<td>$7\times10^{-10}$ –$2\times10^{-8}$</td>
<td>Pers. Comm. U. Mäder (NTB in preparation)</td>
</tr>
<tr>
<td>ISC shear zones</td>
<td>$10^{-11}$–$10^{-6}$ mean $10^{-8}$</td>
<td>B. Brixel pers. communication</td>
</tr>
<tr>
<td>ISC host rock</td>
<td>$10^{-14}$–$10^{-7}$ mean $10^{-11}$</td>
<td>B. Brixel pers. communication</td>
</tr>
</tbody>
</table>

5 The term shear zone is used for reasons of continuity in the literature. In accordance with the structural description provided in this report, the features are fault zones because the retrograde brittle deformation increased the hydraulic conductivity.
Possible explanations for the observed differences between the northern and southern flow regimes include varying deformational styles between the two rock types (Fig. 6.3). The northern part (CAGr-dominated) is characterised by relatively simple and small-scale brittle faults that form an interconnected network, whereas the southern part (GrGr-dominated) is structurally characterised by complex fault architectures with multiple fault cores filled with gouge localised along former ductile shear zones. The difference in structural style provides a possible explanation for the observed difference in hydraulic behaviour.

This difference in structural style could be related to small but significant variations in the rock types. The CAGr is characterised by a relatively higher amount of K-feldspar and lower amount of sheet silicate than the GrGr. This could yield a more brittle behaviour of the CAGr under similar deformation conditions than the GrGr (Mazurek 2000). Further, a southward strain gradient is postulated on the larger scale (Choukroune and Gapais 1983, Wehrens et al. 2017). This strain increases towards the south and also promotes strain localisation and thus development of rather complex structures (as for example the MI shear zone or the GAM shear zone).  

6.5 Metabasic dyke-related water flow paths

Channelled flow has been observed at the margins of the metabasic dykes (previously referred to as "lamprophyres", Schneeberger et al. 2018). Martel and Peterson (1991) comment that "Flow along the metabasic dykes probably would be concentrated along their edges where deformation of the dyke and the adjacent granite is great. Flow could be particularly high along the Alpine tension fissures that extend from the dyke. The micaceous material in the metabasic dykes (see section 3.3.3) probably causes permeability across the metabasic dykes to be quite low. However, some flow across the dykes could occur along foliation planes or where the dykes are discontinuous."

In the VE tunnel, Vomvoris and Frieg (1992) found that, although measured fluxes were relatively high at the metabasic dyke – granitic matrix contact, the overall flow from the dykes was comparable to that of the unfractured granitic rock matrix (Tab. 6.4). At the FEBEX site, one of the significant WCFs is associated with a metabasic dyke that intersects the tunnel at TM60. Martinez-Landa and Carrera (2006) comment that while the dyke itself is of low permeability, the contact planes are conductive. Lanyon and Blechschmidt (2008) suggest that hydraulic interference between the CFM and LTD experiments was due to flow paths associated with the MI shear zone and a metabasic dyke that intersects the AU tunnel at AU73. The influence of the metabasic dykes on water flow was confirmed by water inflow mapping performed throughout the GTS within the framework of the LASMO project (Schneeberger et al. 2018).

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6 In the far south of the GTS, the results from the ISC experiment illustrate the complexity associated with the intersection of such structures.
Tab. 6.4: Transmissivity of metabasic dykes (lamprophyres) at the GTS

<table>
<thead>
<tr>
<th>Feature</th>
<th>Transmissivity range (m²/s)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabasic dyke (FEBEX TM60)</td>
<td>Large-scale 1 – 4×10⁻¹⁰</td>
<td>Martinez-Landa and Carrera (2006)</td>
</tr>
<tr>
<td></td>
<td>Locally channel at contact ~10⁻⁵</td>
<td></td>
</tr>
<tr>
<td>Lamprophyre/shear zone intersection</td>
<td>~10⁻⁹</td>
<td>Lanyon and Blechschmidt (2008)</td>
</tr>
<tr>
<td>CFM 06.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metabasic dyke at VE460</td>
<td></td>
<td>Frieg and Vomvoris (1994)</td>
</tr>
<tr>
<td>Highly deformed metabasic dyke at</td>
<td>2×10⁻¹¹ – 5×10⁻⁸</td>
<td>Mäder and Frieg (in press)</td>
</tr>
<tr>
<td>AU126 (HPF)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.5.1 Alpine tension fractures or gashes

These typically decimetre-metre scale sub-horizontal features are highly transmissive with open apertures of many centimetres (equivalent to local transmissivity ~1 m²/s and above). They are often associated with the margins of metabasic dykes (Martel and Peterson 1991) or of faults (e.g. Bossart and Mazurek 1991, Schneeberger et al. 2016). While these features have in the past acted as conduits for hydrothermal fluids, they now provide only very local connectivity and act as "storage" associated with flow paths formed of less transmissive brittle faults.

6.6 Water transport mechanisms

On the larger scale, groundwater flow around the GTS is dominated by the hydraulic head gradients induced by the rugged topography (section 2.7) and the occurrence of faults. Major fault zones and fault intersections connect today’s topography with the GTS (section 4.5) and thus provide water flow paths for the recharge (Schneeberger et al. 2018, see section 7.3 for isotopic determination of the meteoric origin of the groundwater at the GTS). Locally, the various tunnels of KWO and the GTS tunnels provide sinks for flow that is then controlled by, and drained along, the tunnels (see Fig. 2.9). Detailed water inflow mapping corroborates the structural control on flow paths (Schneeberger et al. 2018). Further, the comparison of the structural inventory and distribution of structures along the GTS with the mapped inflow points has highlighted the importance of fault-fault and fault-dyke intersections for groundwater flow.

On the tunnel-scale, ventilation in the tunnels creates an unsaturated zone in the low permeability rock volume, resulting in isolated wet spots and inflows where permeability is sufficient to maintain wet conditions (Mazurek 2000, Schneeberger et al. 2018). In winter, the dry air in the tunnels results in extension of the unsaturated zone. The draining yields a diminished number of water inflow points compared to summer. The influence of the ventilation on the number of water inflows has been assessed by mapping of water inflows in the GTS tunnel (Schneeberger et al. 2018).

The unsaturated zone was also observed in hydraulic head measurements (e.g. Frieg and Blaser 2012). Very low hydraulic pressures are associated with the unsaturated zone or where the water is under tension.
Generally, in the GTS, measured hydraulic head is influenced by the distance and hydraulic connection to the tunnels or open boreholes (Fig. 6.14).

The highest pressures measured at the GTS are ~ 4.6 MPa at the end of the ADUS borehole ~100 m from the main GTS tunnels. At one point, the ADUS borehole was allowed to crossflow over its entire length (197 m), resulting in significant recharge from the water-conducting features, caused by the high hydraulic head gradient between the end of the borehole and the area around the central GTS. This recharge was carried by the network of water-conducting features associated with transmissive fault zones and metabasic dykes. These water-conducting features are heterogeneous (channelled) but provide a relatively large-scale connected flow system.

Small variations in hydraulic head relate to variations in the lake levels around the GTS and to earth-tide responses as discussed in Chapter 8.

### 6.7 Sorption capacity

The process of ion exchange and adsorption along flow paths is a major retardation mechanism for trace components (e.g. radionuclides) in addition to any solubility-limiting solids, or the diffusion of aqueous species into the unfractured rock matrix (Mäder and Ekberg 2006). It has been extensively studied as part of the Migration (MI) experiment and, to some extent, in the Hyperalkaline Plume in Fractured Rock (HPF) experiment at the GTS. Sorption in the unfractured matrix has been extensively studied in the LTD experiment.

In the Migration (MI) experiment, laboratory-based batch sorption experiments were performed to study the sorption of $^{131}$I, $^{82}$Br, $^{85}$Sr, $^{22}$Na, and $^{137}$Cs on different grain size fractions (Aksoyoglu et al. 1991). Experiments with $^{85}$Sr and $^{22}$Na were conducted with particle size < 250 µm. Conditions close to in-situ conditions at the GTS were used during the experiments as Eh and pH conditions have strong effects on the sorption phenomena. The mylonite used in the experiments was sampled at the GTS at AU126. Exchangeable cations were determined after the sorption experiments by flushing the rock samples with a silver-thiourea complex. First tests were carried out with the conservative anions ($^{82}$Br and $^{131}$I). The conservative behaviour was confirmed and, in general, no retention for anions larger than the measurement uncertainty could be demonstrated (Aksoyoglu et al. 1991). Tests with $^{85}$Sr and $^{22}$Na have shown that their sorption behaviour is...
independent of the rock/water ratio with a sorption coefficient $R_d^{(^{85}\text{Sr})} = 66.9 \pm 3.8 \text{ ml/g}$ and $R_d^{(^{22}\text{Na})} = 2.3 \pm 0.1 \text{ ml/g}$. Sorption of $^{137}\text{Cs}$ was found to be non-linear with respect to initial concentration and reversible, with a sorption coefficient varying between 21 and 3800 ml/g (Aksoyoglu et al. 1991).

In addition to the sorption coefficient, the cation exchange capacity of various rock types and associated structures were determined. Cation exchange capacity determined for the mylonites in the AU126 shear zone and in the AU96 shear zone are comparable, however with differences in the selectivity coefficient for K and Ca ($K > Ca$ for AU126 and $Ca > K$ for AU96, Bradbury 1989, Mäder and Ekberg 2006). The selectivities determined for a fault core with gouge material from AU126 are very similar to the selectivities determined for the mylonite (ductile shear zone) with, however, a ca. 2.5 times larger cation exchange capacity for the fault core with gouge material, which can be explained by the increased specific surface area (Tab. 6.5, Tab. 6.6). Tab. 6.6 summarises the cation exchange properties for AU126 for three rock domains (unfractured matrix, ductile shear zone, and fault core with gouge), showing the composition of the sorbed cations per 100 g of rock.

Tab. 6.5: Surface measurements in three samples from the Grimsel Granodiorite with varying deformation grade

Source: Mäder and Ekberg 2006

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Granite</th>
<th>Mylonite</th>
<th>Fault gouge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface, external (BET)</td>
<td>m$^2$/g</td>
<td>0.5 – 1.3</td>
<td>0.6 – 1.5</td>
<td>0.7 – 1.6</td>
</tr>
<tr>
<td>Surface, total (EGME)</td>
<td>m$^2$/g</td>
<td>5</td>
<td>11</td>
<td>10</td>
</tr>
</tbody>
</table>

Tab. 6.6: Compositions of Ni-en$^8$ extracts of prototype rock units

Data refer to a solid:liquid ratio of 1:4 (Mäder and Ekberg 2006)

<table>
<thead>
<tr>
<th>Rock unit</th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Sr</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfractured granite matrix</td>
<td>0.11</td>
<td>0.27</td>
<td>0.1</td>
<td>0.03</td>
<td>0.001</td>
<td>0.51</td>
</tr>
<tr>
<td>Ductile shear zone</td>
<td>0.05</td>
<td>0.31</td>
<td>0.14</td>
<td>0.04</td>
<td>0.001</td>
<td>0.54</td>
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<tr>
<td>Fault core with fault gouge</td>
<td>0.05</td>
<td>0.17</td>
<td>0.85</td>
<td>0.04</td>
<td>0.001</td>
<td>1.12</td>
</tr>
</tbody>
</table>

$^7$ Rd refers to sorption coefficient, which is defined as the ratio of the concentration of sorbent on the solid phase at equilibrium over the concentration of sorbent in the solution at equilibrium (Aksoyoglu et al. 1991).

$^8$ Ni-en refers to nickelethylenediamine, which is a high selectivity complex.
7 Groundwater at the GTS

7.1 Introduction

This chapter compiles the description of the composition of the undisturbed groundwater (fracture water and porewater) at the GTS. This is a pre-requisite for many smaller-scale experiments (baseline composition and its variation). The chapter is subdivided into two parts. First, porewater sampled in an unfractured rock matrix interval is described, then fracture water sampled within borehole test intervals is characterised.

7.2 Matrix porewater composition

Within the time frame considered for the safety analysis of a repository for radioactive waste, the exchange between unfractured rock matrix porewater and the underground facility could potentially be significant. Of interest are, for example, retardation of radionuclide transport by rock matrix diffusion (Martin et al. 2015), or porewater as an archive of changing boundary conditions during past climate change (Waber and Smellie 2008). Therefore, a characterisation of the in-situ rock matrix porewater is part of a typical site characterisation programme (e.g. Berglund and Lindborg 2017, Martin et al. 2015).

7.2.1 Matrix porewater chemistry

Out-diffusion experiments on rock samples in water as performed by Eichinger (2009) provide indirect information about the porewater chemical composition. The chemical composition of conservative elements such as chloride can be inferred from the stable experimental solution composition and rock porosity (Eichinger 2009). The analysis of out-diffusion curves (time evolution) allows back-calculation of effective diffusion coefficients and estimation of the porewater composition for the conservative components. Water-rock interactions during the out-diffusion experiments potentially alter non-conservative species and, therefore, their composition in the porewater is not directly measurable.

The chloride concentrations calculated for 9 borehole core samples from the southern part of the GTS (LCS 07.001) are in the range of 76 to 437 [mg/kg$_{H_2O}$] with a median value of 311 [mg/kg$_{H_2O}$] (Fig. 7.1). In contrast, very low Cl concentrations were observed in an adjacent fracture water sample (Fig. 7.1). Core samples were taken along a profile away from a shallow dipping fault. The chloride content increases with increasing distance from the fault. The entire section tested is part of a larger shear zone with multiple water-conducting brittle features, and thus these chloride values obtained for matrix porewater are a minimum value for what might be present elsewhere. There is a clear trend towards even higher chloride values with increasing distance from water-conducting features. However, the constraints are insufficient to attempt a modelling interpretation.
Fig. 7.1: Chloride profile across a water-conducting fault (dashed) in the LCS area (modified after Eichinger 2009)

7.2.2 Stable water isotopic composition of porewater

The stable water isotopic composition of the porewater is characterised by $\delta^{18}$O values between -7.91 ± 1.13 and -9.1 ± 0.85 ‰ VSMOW and $\delta^2$H values ranging from -77.2 ± 7.1 to -89.4 ± 12.4 ‰ VSMOW (Fig. 7.2, Eichinger 2009). Porewater is isotopically heavier than present-day fracture water at the GTS (Fig. 7.2, Eichinger 2009, Schneeberger 2017). The shift towards elevated $\delta^{18}$O – $\delta^2$H values on the $\delta^{18}$O – $\delta^2$H plot indicates a different source for the water component than the infiltrating meteoric water observed for groundwater.

There is the possibility that matrix porewater preserves chemical and isotopic signatures that are much older than present-day groundwater. The interpretation of such remnant older signatures potentially provides constraints on long-term effective transport parameters (e.g. diffusion), as was shown for case studies in the Swedish and Finnish site investigation programme (e.g. Waber and Smellie 2008).
Fig. 7.2: Stable water isotopic composition of porewater and fracture water at the GTS and rain water at the Grimsel pass

Data source: GTS porewater (Eichinger 2009), GTS fracture water (Schneeberger 2017), Grimsel rain water (IAEA/WMO 2018).

7.3 Fracture water

7.3.1 Introduction to fracture water

Fracture water (groundwater s.l.) composition has been reported for the GTS since the early exploration in 1980 up to the compilation of this report. The available fracture water data were collected within the framework of specific experiments (e.g. MI and LASMO), and from overarching early studies by Keusen et al. (1989; pre-1990) and Keppler (1996; 1992-1993). Limited geochemical data, but including tritium measurements, are available from the pre-construction characterisation (Geotest AG 1981; 1980). Data from the Migration experiment are mostly from the southern part of the GTS (AU drift), whereas the most recent data from the LASMO project cover the entire GTS. A summary of relevant investigations is given in Tab. 7.1., and selected details are discussed in the following sections.
Tab. 7.1: Major Nagra and GSF reports with contributions to the geochemistry of fracture water at the GTS

GSF: Forschungszentrum für Umwelt and Gesundheit GmbH

<table>
<thead>
<tr>
<th>Report</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTB 81-07</td>
<td>Sondierbohrungen Juchlistock – Grimsel</td>
<td>Geotest AG</td>
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<td>Exploration drillings Juchlistock - Grimsel</td>
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<td>NTB 84-46</td>
<td>Bestimmung des Sorptionskoeffizienten von Uran (VI) an Grimsel und Böttsteingranit</td>
<td>Wernli, B., Bajo, C., Bischoff, K.</td>
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<td></td>
<td>Determination of the sorption coefficients of uranium (VI) on Grimsel and Böttstein granite</td>
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<tr>
<td>NTB 87-08</td>
<td>Natural analogue studies in crystalline rock: the influence of water-bearing fractures on radionuclide immobilisation in a granitic rock repository</td>
<td>Alexander, W.R., MacKenzie, A.B., Scott, R.D., McKinley, I.G.</td>
</tr>
<tr>
<td>NTB 87-14</td>
<td>Grimsel Test Site: Geology</td>
<td>Keusen, H.R., Ganguin, J., Schuler, P., Buletti, M.</td>
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<tr>
<td>NTB 88-23</td>
<td>Laboratory investigations in support of the Migration Experiment</td>
<td>Bradbury, M.H. (ed.)</td>
</tr>
<tr>
<td>NTB 89-15</td>
<td>Hydrogeological characterisation of the Migration experimental area at the Grimsel Test Site</td>
<td>Hoehn, E., Fierz, T., Thorne, P.</td>
</tr>
<tr>
<td>NTB 90-01</td>
<td>Grimsel colloid exercise: an international intercomparison exercise on the sampling and characterisation of fracture water colloids</td>
<td>Deguidere, C., Longworth, G., Moulin, B., Vilks, P.</td>
</tr>
<tr>
<td>NTB 90-15</td>
<td>Uranium migration in crystalline rock: capillary solution transport in the granite of the Grimsel Test Site, Switzerland</td>
<td>Bärtschi, P., Alexander, W.R., Dollinger, H.</td>
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<tr>
<td>NTB 91-06</td>
<td>Batch sorption experiments with iodine, bromine, strontium, sodium and caesium on grimsel mylonite</td>
<td>Aksoyoglu, S., Bajo, C., Mantovani, M.</td>
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<tr>
<td>NTB 91-30</td>
<td>Hydrochemische Synthese Nordschweiz: Buntsandstein-, Perm- und Kristallin-Aquifere</td>
<td>Schmassmann, H., Kullin, M., Schneemann, K.</td>
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<tr>
<td></td>
<td>Hydrochemical synthesis</td>
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</tr>
<tr>
<td></td>
<td>Northern Switzerland: Buntsandstein, Perm and crystalline aquifers</td>
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</tr>
</tbody>
</table>
### 7.3.2 Chemical composition of fracture water

Fracture water data at the GTS stem mostly from the Migration (MI) experiment, with high density data from one particular fault zone (Migration shear zone AU96, Fig. 7.3) and from the LASMO project with a lower sampling density, but with samples over the entire GTS (Fig. 7.3). Samples in the LASMO project were taken from 14 borehole test intervals from six previously drilled boreholes within the GTS covering different structural and lithological features (Fig. 7.3). Boreholes US 85.001, US 85.002 and SB 80.001 are located within the CAGr, whereas boreholes VE 13.001, VE 88.003 and HP 98.007 are located within the GrGr (Schneeberger et al. 2016). Test intervals were isolated by multi-packer systems; US 85.001 and US 85.002 were instrumented in 1996, SB 80.001 and VE 88.003 in 1994, VE 13.001 in 2013, and HP 98.007 in 2000. Multiple test intervals in the same borehole are labelled with increasing numbers from the deepest interval (i1) towards the borehole mouth. Test interval lengths vary from 0.4 to 60.5 m (Tab. A.1).

#### Table: List of Reports

<table>
<thead>
<tr>
<th>Report</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSF 4/96</td>
<td>Hydrogeologische, hydrochemische und isotopenhydrologische Untersuchungen an den Oberflächen- und Kluftwässern im Grimselgebiet, Schweiz</td>
<td>Keppler, A.</td>
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<td>NTB 03-01</td>
<td>The CRR final project report series I: Description of the field phase - methodologies and raw data</td>
<td>Möri, A. (ed.)</td>
</tr>
<tr>
<td>NTB 08-11</td>
<td>Hyperalkaline plume in fractured rock (HPF) project: final report of field experiments, laboratory experiments, summary and conclusions</td>
<td>Mäder, U.K., Frieg, B.</td>
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<tr>
<td>NAB 06-08</td>
<td>GTS/HPF project: Geochemical evolution of porewater in the granitic shear zone AU126 during 3 years of interaction with a hyperalkaline fluid, and its interpretation</td>
<td>Mäder, U.K., Ekberg, C.</td>
</tr>
</tbody>
</table>

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**Fig. 7.3:** GTS overview map with major boreholes and highlighted (red) boreholes used for fracture water sampling
Generally, fracture water in the GTS is described as poorly mineralised with total dissolved solid (TDS) concentrations of 48.4 and 81.4 mg/l and with alkaline pH values of around 9 ± 1 (Schneeberger 2017). Water temperatures recorded during the different sampling campaigns of LASMO and in the various test intervals vary between 11.6 and 15.5°C. Water temperature in the CAGr is on average lower (12.4 ± 0.6°C) than water sampled within the GrGr (13.5 ± 0.9°C, Schneeberger 2017).

Fracture water investigations from the Migration (MI) experiment yielded an ionic strength of about 10^{-3} M and a pH value of ca. 9.6 (Bradbury 1989). According to Jäckli (1970), the overall water type is Na-Ca-TIC-F-(SO4). The groundwater analyses carried out within LASMO experiment confirmed the groundwater type. The range in chemical composition for the fracture water analysed in the LASMO project is reported in the Appendix (Tab. A.2 and A.3).

Eh measurements (-248 to 186 mV Ag/AgCl) performed as part of LASMO vary between different sampling rounds in individual boreholes, but not in a systematic way (Schneeberger 2017). These Eh values are comparable to the Eh values measured in the CFM experiment (Blechschmidt et al. 2016). This variation may result from analytical difficulties, as the concentrations of redox-sensitive elements (e.g. Fe_{tot}, Mn_{tot}) are low in most of the measured fracture water. Except for interval US 85.001i3 and the first two LASMO sampling campaigns (April and August 2014) in SB 80.001i1, reducing conditions were measured in all samples (Tab. A.2 and A.3). Reducing conditions are confirmed by the smell of H2S during one sampling in VE 88.003i3 and US 85.002i4, and by sampling in the MaCoTe experiment (pers. communication N. Giroud).

The chemical composition of the fracture water is stable over time and lacks any indication of seasonal variation (Degueldre et al. 1989, Keppler 1996, Schneeberger 2017). The absence of seasonal variation indicates that the observed chemical composition results from water-rock interactions occurring during transport of the fracture water from the surface (recharge) to the GTS (sink).

Within the framework of the LASMO project, groundwater was sampled in the northern CAGr as well as in the southern GrGr (Fig. 7.3). Based on the following considerations (illustrated in Fig. 7.4), two types of fracture water can be defined (type A and type B), where waters sampled within the CAGr typically belong to type A, while waters sampled within the GrGr typically resemble type B. It is important to note that the two types show a gradual transition.

The Na+ concentration is plotted against the Cl- concentration (Fig. 7.4a) because Cl- is considered as a conservative element (e.g. Nordstrom et al. 1989). The Cl- concentration is clearly distinguishable between type A and type B waters (Fig. 7.4). In type A water, Cl- concentrations are low (< 0.2 mmol/l) and correspond closely to the meteoric input water (Tab. A.2, A.3). Na+ correlates linearly with Cl- in the type B waters with a slope close to one. This suggests a coupled evolution such as in the case of in-diffusion of porewater with elevated Cl- and Na+ concentrations. The weak linear relationship observed between Ca²⁺ and TIC (Fig. 7.4b) indicates a common evolution such as in the case of a mutual solubility control by calcite. The Ca²⁺ against Na⁺ plot shows a lower Na/Ca ratio for the type A waters (Fig. 7.4c). Lower TIC in type B waters yields lower partial pressures of CO₂ in type B water than in type A water (Tab. A.4). Furthermore, the pH values differ, ranging from 8.53 to 9.61 in type A waters and 8.85 to 9.79 in type B waters (Schneeberger 2017).

Geochemical modelling revealed that fracture water in the GTS is saturated with respect to quartz and calcite (Frick et al. 1992, Keppler 1996, Mäder and Ekberg 2006, Schneeberger 2017). In contrast, it is undersaturated with respect to plagioclase, K-feldspar and fluorite (Tab. A.4). Fracture water is characterised by a CO₂ partial pressure distinctly below atmospheric partial
pressure (Degueldre et al. 1989, Keppler 1996, McKinley et al. 1988, Schneeberger 2017). Accordingly, the fracture water is unstable in contact with air, causing the pH value to decrease to about 7.8 after sampling due to in-diffusion of CO$_2$ (McKinley et al. 1988).

In summary, type A water is characterised by relatively low Cl$^-$ concentration, low pH value, low Na/Ca ratios, and a higher P(CO$_2$) compared to type B. Fracture water from SB80.001i1 located in the CAGr is typical for type A water. Fracture water from VE 13.001i2 located in the GrGr is typical for type B water.

![Fig. 7.4](image)

**Fig. 7.4:** Selected ion-ion plots showing differences in chemical composition for GTS fracture water (Schneeberger 2017)

Endmembers of fracture water types (A and B) are indicated. Type A water is displayed as diamonds, type B water as rectangles. a) Na/Cl plot showing differentiation between type A and B waters. b) Ca/total inorganic carbon plot showing a weak linear correlation caused by calcite precipitation/dissolution. c) Ca/Na plot showing the fracture water evolution caused by the hydrolysis of plagioclase and precipitation of calcite. d) Mg and K/Cl plot showing the absence of correlation between the alkalis and Cl, which is evidence for non-sheet silicate origin of the Cl in the fracture water.
7.3.3 Stable water isotopic composition of fracture water

$\delta^{18}\text{O}$ and $\delta^{2}\text{H}$ values for atmospheric precipitation show a spread between multiple samples and strong seasonal dependence (Fig. 7.5, Schotterer et al. 2010). In contrast, $\delta^{18}\text{O}$ and $\delta^{2}\text{H}$ values of the fracture water at the GTS show no seasonal variation (Frick et al. 1992, Keppler 1996, Schneeberger 2017). For the borehole test intervals sampled in the LASMO project, the average $\delta^{18}\text{O}$ and $\delta^{2}\text{H}$ values are reported per interval in the Appendix (Tab. A.5, Schneeberger 2017). Attenuation of the seasonal variation, as observed in the fracture water at the GTS (Schneeberger 2017), is reported for the unsaturated zone in crystalline environments, as mixing of infiltration water can occur (Clark and Fritz 1997). Exfoliation joints that occur within the uppermost 200 m may be part of the unsaturated zone, as they occur in diverse orientations and form an interconnected network of joints and thus potential flow paths (Chapter 4, Ziegler et al. 2013).

$\delta^{18}\text{O}$ and $\delta^{2}\text{H}$ values for the fracture water at the GTS are comparable with values for the local atmospheric precipitation (Fig. 7.5, Keppler 1996, Schneeberger 2018). The mean $\delta^{18}\text{O}$ and $\delta^{2}\text{H}$ values for the atmospheric precipitation data from 1993 to 2014 ($\delta^{18}\text{O} = -12.86$, $\delta^{2}\text{H} = -92.40$) are statistically not significantly different from the measured mean values for the fracture water data ($\delta^{18}\text{O} = -12.94$, $\delta^{2}\text{H} = -91.69$, Tab. A.5).

All fracture water samples plot along the local Grimsel meteoric water line (LMWL, Fig. 7.5, Frick et al. 1992, Keppler 1996, Schneeberger 2017). The LMWL was defined based on rainwater samples taken between 1993 and 2010 at the Grimsel pass weather station (SMA – ‘Schweizerische Meteorologische Anstalt‘; Schotterer et al. 2010).

Fig. 7.5: Average $\delta^{18}\text{O}$ and $\delta^{2}\text{H}$ values for GTS fracture water compared to atmospheric precipitation (Grimsel) and Keppler’s fracture water data (Keppler 1996). Close-up for GTS fracture water (Schneeberger 2017)

Envelope of atmospheric precipitation data (1993 to 2014) taken from IAEA/WMO (2018). Values are compared to the local meteoric water line (LMWL, Schotterer et al. 2010) and the global meteoric water line (GMWL) which is defined as: $\delta^{2}\text{H} = 8 \delta^{18}\text{O} + 10$ (Craig 1961).
LMWL: \[ \delta^2\text{H} = 8.082 \times \delta^{18}\text{O} + 12.751 \] (Schotterer et al. 2010) (1)

The LMWL and the GMWL (global meteoric water line, Craig 1961) fit closely, however the LMWL is shifted towards lower \( \delta^{18}\text{O} \) values (Fig. 7.5).

All the aforementioned arguments indicate that fracture waters at the GTS are of meteoric origin.

The deuterium (D) excess for GTS fracture water is similar to the mean of the local atmospheric precipitation between 1993 and 2014 (D excess: 11.7 ± 2.9; IAEA/WMO 2018). This indicates a meteoric origin from the same atmospheric precipitation source for all GTS fracture waters. The D excess being slightly above 10 indicates relatively dry air conditions during fractionation (Schotterer 2000). Further, the comparability of the D excesses is evidence for restricted mixing between the meteoric input water with non-meteoric water sources such as porewater.

A more detailed picture of the fracture waters was possible with the samples from the LASMO project. The northern GTS fracture water samples (US 85.002, SB 80.001) differ systematically from the southern fracture waters (VE 13.001, VE 88.003, HPF 98.007). The northern fracture waters are isotopically heavier (\( \delta^{18}\text{O} = -12.65, \delta^2\text{H} = -89.28 \)) than the southern ones (Fig. 7.5, \( \delta^{18}\text{O} = -12.85, \delta^2\text{H} = -91.18 \)). Consistent differences over two years of sampling in the LASMO project indicate that no mixing occurs between the two flow fields (Schneeberger 2017). Isotopic groundwater data reported by Keppler (1996) confirm this difference. As detailed below (section 7.3.8), the isotopic data corroborates the grouping inferred from the chemical composition with the isotopically heavier northern water corresponding to the type A water from a chemical composition point of view.

A possible explanation for the observed difference in mean \( \delta^{18}\text{O} \) values (0.2 ‰) is a difference of ca. 100 m in recharge altitude, which results using the empirical relationship between \( \delta^{18}\text{O} \) and a recharge altitude of 0.2‰/100 m (Schotterer 2010).

### 7.3.4 Tritium concentrations in fracture water

Tritium (\(^3\text{H}, t_{1/2} = 12.32\text{ a}\)) is a useful indicator of average residence time for young fracture waters (e.g. Morgenstern et al. 2010, Keppler 1996). Most \(^3\text{H}\) originates from hydrogen bomb testing. Atmospheric concentrations started to increase sharply during the 1950s, peaked in 1963 (ca. 5000 TU in the northern hemisphere, 1 TU = 0.119 Bq/l) and decreased thereafter. Since about 2005, rain water (northern hemisphere) has higher TU values than "bomb" water recharged in 1980, due to decay (Morgenstern et al. 2010), rendering the method increasingly difficult to apply (atmospheric precipitation from the last 1–2 decades of bomb pulse becomes indistinguishable from pre-bomb recharge). At the SMA stations Grimsel and Guttannen, annual mean tritium in atmospheric precipitation decreased from 42.6–54.2 TU (1982) to 15.4–18.1 TU (1992) (plotted in Keppler 1996), and to 10–12 TU (2000–2010). In 2010, regular measurements were discontinued by the Swiss Federal Office for the Environment. Pre-bomb atmospheric background is estimated at ca. 5 TU (possibly somewhat higher at the elevation of the GTS), and thus decay of such recharge towards lower values may also serve as a residence time constraint given today's measurement accuracy and detection limits. There may be an in-situ tritium production from U/Th decay series in some rocks, leading to local variations, but at low levels. Artefacts relate to contamination with drilling water and hydraulic testing, isotope exchange with air humidity, evaporation effects, and uncertain in-situ production, among others.

Tritium concentration measurements on fracture waters, seepages, surface and spring waters at the GTS and surroundings were performed in several characterisation campaigns and within experiment-specific projects (Appendix 3, Tab. A.6), as well as during one PhD thesis (Keppler
However, no overarching data synthesis has been attempted so far. An overall interpretation is hampered by the fact that most borehole sampling intervals tap into multiple water-bearing features (mixing waters), that borehole testing may have affected some measurements, and that no extended time series have been collected systematically at selected locations. Early data are subject to higher detection limits and are generally more affected by sampling artefacts and other sources of contamination.

Linking the campaigns detailed in Appendix 3 provides some interesting (partial) time series for three locations (Tab. 7.2): SB 80.001 ("SB1" before GTS excavation) located in the northern part, crossing the BK area, EM 85.012 located 135 m south of the GTS, and HF 84.031, approximately 175 m south of the GTS (Fig. 7.3).

Tab. 7.2: Time series of tritium concentrations for selected boreholes (extract from Tab. A.6)

<table>
<thead>
<tr>
<th>Sampling time</th>
<th>SB 80.001</th>
<th>EM 85.012</th>
<th>HF 84.031</th>
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<tr>
<td>Distance along KWO main access tunnel</td>
<td>1170 m</td>
<td>1625 m</td>
<td>1675 m</td>
</tr>
<tr>
<td></td>
<td>TU</td>
<td>TU</td>
<td>TU</td>
</tr>
<tr>
<td>1980&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.8 ± 2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/1982&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.3 ± 0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/1983&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.1 ± 0.6</td>
<td></td>
<td></td>
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<tr>
<td>10 and 11/1983&lt;sup&gt;b&lt;/sup&gt;</td>
<td>&lt;1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8/1985&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td>19.9 ± 2.4</td>
<td></td>
</tr>
<tr>
<td>07/1986&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td>20.1 ± 3.0</td>
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</tr>
<tr>
<td>6/1986&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td>20.3 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>1992–1993&lt;sup&gt;d&lt;/sup&gt;</td>
<td>4.8 ± 0.1</td>
<td>25.5 → 18.6 (1.5 a)</td>
<td>9.4 → 13.9 (1.5 a)</td>
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<td>01/2016&lt;sup&gt;e&lt;/sup&gt;</td>
<td>3.1 ± 0.6</td>
<td>5.1 ± 0.8</td>
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<td>12/2017&lt;sup&gt;e&lt;/sup&gt;</td>
<td>2.5 ± 0.3</td>
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SB 80.001 (SB1 in Geotest AG 1981; likely mislabelled in Keppler 1996 as SB 80.000) is the only borehole within the GTS area apart from ADUS 96.001 that may carry bomb-pulse tritium. The highest levels of 7.8 TU (Tab. 7.2) were found during site exploration in 1980 before the GTS was excavated in 1983, but this value could not be confirmed by later measurements and hence remains uncertain. Structures and observed inflows (Geotest AG 1981) suggest dominant contributions from borehole depths beyond 80 m that more or less coincide with the deep end that was packed off after GTS construction, extending from the NW side of the BK cavern, and that was sampled again in 1992–1993, 2016 and 2017. Without these zero-measurements in 1982/83, data would follow an approximate decay trend over approximately 3 half-lives. Keppler (1996) suggested that his value of 4.8 TU may have been affected by testing water used in other parts of the BK cavern, and this surface water would have had some 14–21 TU at that time. These multiple uncertainties preclude a rigorous interpretation. It is noted that this part of the BK cavern is an area of high groundwater inflow from multiple faults that significantly contributes to total inflow into the GTS.
The other two data sets with interpretable trends in tritium concentration evolution relate to two borehole locations 135–175 m south of the GTS, at EM 85.012 (1625 m) and HF 84.031 (1675 m along the KWO main access tunnel; Tab. 7.2). The former displayed a decreasing trend from 25.5 to 18.6 TU from May 1992 to November 1993 (Keppler 1996), and a measurement of 5.1 ± 0.8 TU in 2016. The decrease observed from May 1992 to November 1993 (1.5 years) is faster than tritium decay and suggests that the bomb maximum input has already passed this sampling location. The drop to 5.1 TU after slightly less than two half-lives can be approximately explained by decay. Keppler (1996) deduced an average residence time of 5 years for EM 85.012 based on simple piston-flow models with a discretised input function (recharge). HF 84.031 shows an increase in tritium concentrations from 9.4 to 13.9 TU during the same 1.5 years of quarterly sampling (May 1992 – November 1993), which opposes the trend observed in EM 85.012. Keppler (1996) deduced an average residence time of 36.5 years for this situation, again based on piston-flow modelling.

In 2016, the 197 m long ADUS 96.001 borehole yielded a low mixed tritium concentration of 2.3 TU, and current efforts to isolate and test shorter packed-off intervals suggest that small variations in tritium activities exist from borehole section to section; however it is noteworthy that cross-flow occurred within the borehole as it was sealed by a single end packer. Interpretation in terms of residence times is not possible with single-point data at these low levels but indicates that effective mixing along recharge pathways is absent, and that the bomb component had decayed to levels well below present-day recharge. It is uncertain if these low levels represent the arrival of bomb tritium or the fading of the plume that had already passed the ADUS 96.001 level. ADUS 96.001 represents the only borehole within the GTS footprint that carries bomb tritium with certainty, carefully sampled and confirmed by multiple measurements, but without a sufficiently long time series for a detailed interpretation.

Low levels of tritium concentration, near 1 TU, have been measured at many locations; these show local scatter, but are near the detection limit and have never been interpreted to reflect any admixture of a bomb-age component, but rather are assumed to reflect contamination from testing, interaction with atmosphere in the case of seepages, and potentially irregularly distributed in-situ production in this granitoid environment with elevated U/Th contents.

The overall conclusion is therefore that the available tritium data – while largely not systematically and repeatedly measured – suggest that average residence times in most water-conducting fault zones exceed 60 years, corresponding to vertical linear average fracture water velocities < 6.7 m/a at 400 m overburden. This lower limit may be even lower when considering that the top and more transmissive 100–200 m is characterised by much shorter travel times (due to the presence of exfoliation joints, Chapter 4). There are selected water-conducting fault zones or loci of fault intersections where tritium may have arrived even before construction of the GTS. One of those (ADUS 96.001) is located within the GTS footprint, and 4 more (2 associated with boreholes, 2 with seepage zones) are located south of the GTS at 1550–1800 m along the KWO main access tunnel, but where the overburden is still 300–450 m. The data set from SB 80.001 (at the BK area) is contradictory and inconclusive. The dynamics of the systems are not well constrained, but it is reasonably certain that, in 1992–1993, opposite trends were observed in two boreholes (at 1625 m and 1675 m along the KWO main access tunnel), regularly decreasing tritium in one (bomb pulse already passed through) and increasing in the other (bomb maximum still to arrive), with inferred average residence times of 5 and 36.5 years, respectively. The observed range in average residence time agrees well with the reported range in transmissivity values reported in Chapter 6.
7.3.5 Constraints from $^{36}$Cl and $^{14}$C analyses

In addition to the aforementioned tritium sampling and dating attempts, miscellaneous attempts have been made to use different dating methods appropriate for relatively young groundwaters. Frick et al. (1992) noted that attempts with $^{14}$C dating failed due to low dissolved carbon contents and irregular but generally high contents of modern carbon (despite mostly tritium-free waters). Dating with $^{39}$Ar ($t_\text{v}=269$ a) also failed because of a high apparent proportion (140%) of modern atmospheric composition interpreted to be due to elevated nucleogenic production of $^{39}$Ar in the granitoids.

Keppler (1996) went to great effort in analysing and understanding the $^{14}$C system, focusing on data series sampled in 1992–1993 from boreholes EM 85.012 (bomb tritium-bearing) and US 85.002 (tritium-free). Attempts using dissolved inorganic carbon (DIC) resulted in a large scatter in the data series, modelled average residence times with large uncertainties, and generally implausible results with modelled residence times between 200 ± 200 and 6900 ± 200 years. More promising were procedures using the low levels of dissolved organic carbon (DOC), whereby fulvic acids were extracted and concentrated from sampled volumes ranging from 600 to 1500 l. Different separation procedures were tested, and those thought to be most reliable yielded close to 100% modern DOC for US 85.002, and 120–127% modern DOC for EM 85.012, implying an anthropogenic contribution from bomb testing for the latter. Applying a piston-flow model, and a variable input function for bomb-$^{14}$C recharge (1959–1992), resulted in mean residence times of 220 ± 180 a for the tritium-free borehole and 13 ± 3 a for EM 85.012, for which a residence time of 5 years was derived for the tritium data series. The origin of the DOC (humic and fulvic acids) was inferred to be the moss-type and locally peat-type sparse vegetation in the recharge area of the Juchlistock.

Additionally, some attempts using $^{36}$Cl were made by Keppler (1996). The waters are too young for dating based on decay of $^{36}$Cl ($t_\text{v}=3.01\cdot10^5$ a), but the relatively short thermo-nuclear pulse generated during bomb testing from 1953–1977 (maximum at 1958–1959) may be used as an indicator, similar to tritium concentration. There is also an atmospheric production (pre-bomb and post-bomb input) and an underground production depending on $^{238}$U and $^{232}$Th contents in the rocks. Background values not (or only minimally) affected by bomb $^{36}$Cl or in-situ production were measured in repeat samples at EM 85.012 in 1986, 1991, 1992 and 1993, suggesting that (1) no significant production from rocks was present, and (2) that the bomb pulse had already passed this location, given the relatively short average residence time of 5 years derived from tritium concentration (above). Piston-flow modelling with a constructed recharge input for $^{36}$Cl from 1953–1977 yielded a maximum average residence time of 18 ± 5 years, distinctly longer than the value of 5 years deduced from tritium concentration. Location US 85.002 showed no elevated tritium (pre-bomb water) but elevated $^{36}$Cl values in 1991, 1992, and 1993, distinctly above pre-bomb recharge. It is concluded that there must be an elevated production from rocks at this location because bomb input cannot be present in these older waters (based on pre-bomb $^{3}$H).

While most dating methods for obtaining mean residence times other than $^{3}$H proved difficult or non-constraining for the older tritium-free waters ($^{39}$Ar, $^{36}$Cl, $^{14}$C$_\text{DIC}$), the $^{14}$C system using DOC resulted in two residence times (220 ± 180 a for US 85.002; 13 ± 3 a for EM 85.012) that are comparable and hence consistent with the tritium data series from the same locations (> 60 a and 5 a, respectively).

7.3.6 Inorganic colloids in the fracture water

For the migration of radionuclides, the concentration of colloids in the fracture water is significant, as they could reduce the effect of retardation mechanisms such as sorption and matrix
diffusion (Degueldre et al. 1990). Therefore, the colloid concentration has been determined several times in water from the GTS (e.g. Degueldre et al. 1990, Schäfer et al. 2012, Schlickenrieder et al. 2017). According to Smith et al. (2001), the colloid population was:

- $10^{14}$ colloids per l with > 10 nm diameter
- $10^{12}$ colloids per l with > 50 nm diameter
- $10^7$ colloids per l with > 450 nm diameter

The colloids in the fracture water are mainly formed by amorphous silica with small amounts of illite/muscovite, biotite, calcium silicates, and organic particles (Degueldre et al. 1990, Smith et al. 2001). Under in-situ conditions, the colloids are negatively charged (Degueldre et al. 1990).

### 7.3.7 Microbes in the fracture water

The following section describing microbial populations in the fracture water at the GTS is based on Konno et al. (2013). Microbial studies were performed along 4 sub-horizontal boreholes (JGP 09.002, US 85.002, ADUS 96.001 and LCS 08.002; Enclosure 1). The total reported cell concentrations were $4.9 \pm 5.1 \times 10^3$ cells/ml for ADUS 96.001, $7.5 \pm 3.5 \times 10^3$ cells/ml for US 85.002, $2.9 \pm 1.4 \times 10^4$ cells/ml for JGP 09.002, and $3.0 \pm 0.9 \times 10^4$ cells/ml for LCS 08.002.

Boreholes of different drilling ages (US 85.002 in 1985, ADUS 96.001 in 1996, LCS 08.002 in 2008 and JGP 09.002 in 2009) were used to assess the differences between microbial populations colonising stably under borehole conditions and those that flourish due to drilling-induced disturbance. Microbial cells were more abundant in the more recently drilled boreholes. Phylogroups closely related to β-Proteobacteria were only abundant in the 1- to 2-year old boreholes (Fig. 7.6). In contrast, bacterial candidate division GTS and Nitrospirae were ubiquitous in all investigated boreholes and thus represent the stably colonising microbial populations under borehole conditions at the GTS.

The measured total cell numbers were found to be comparable with studies performed in deep aquifers in the Fennoscandian Shield (Hallbeck and Pedersen 2008), Olkiluoto (Pedersen et al. 2008) and deep granitic fracture water from Colorado (Sahl et al. 2008).

![Fig. 7.6: Bacteria populations in fracture water at the GTS (modified after Konno et al. 2013)](image-url)
7.3.8 Summary of observations for fracture water

The detailed investigation of the fracture water across the GTS has highlighted the presence of two types of water, type A and type B. The discrimination between the types is based on the chemical composition (pH, Na/Ca ratio, and Cl concentration), the temperature, the stable isotopic water composition (northern and southern type) and the tritium concentration. Despite all the differences, both types of fracture water are of meteoric origin.

In the LASMO project (Schneeberger 2017) it was attempted to link the observed differences in chemical composition of the fracture water with the mineralogical composition of the borehole test interval. However, it was not possible to establish such a link, as illustrated by the following two observations. First, test intervals US 85.002i4 and US 85.002i5 show similar fracture water chemical compositions and transmissivity values (Tab. A.1), although they drain rocks with a different mineralogical composition. US 85.002i4 is characterised by the presence of metabasic dykes containing mainly plagioclase and biotite, whereas US 85.002i5 is characterised by faults in a ductile shear zone of granitic mineralogical composition. Second, the chemical composition of fracture water in HP 98.007i2 and HP 98.007i3 is comparable, although the structural permeable feature is different. In HP 98.007i2, flow is controlled by the presence of a fault core with gouge, whereas faults along a former ductile shear zone control water inflow to HP 98.007i3.

As detailed above, the transition between type A and type B waters is gradual (Fig. 7.4). Therefore, similar water-rock interactions should occur along the flow path of type A and type B waters. In the LASMO project (Schneeberger 2017), element mass balance calculations (inverse modelling) were performed in analogy to those presented by Garrels and MacKenzie (1967) to compare type A and type B waters.

Inverse modelling was performed using Na\(^+\), K\(^+\), Ca\(^{2+}\), Al\(^{3+}\), F\(^-\), Cl\(^-\), SO\(_4^{2-}\), TIC and Si as observables and the mass transfer (i.e. dissolution or precipitation) of Ca-albite (local plagioclase), quartz, calcite, fluorite, kaolinite, CO\(_2\)(g), pyrite, NaCl\(_{(s)}\) and either dissolution of muscovite (increase in K\(^+\) concentration) or precipitation of K-montmorillonite (decrease in K\(^+\) concentration, Schneeberger 2017) as unknown parameters that should be estimated. Plagioclase composition was adapted to the local composition (Schneeberger et al. 2016). For all other phases, the pure end-member compositions were used. No major Cl-bearing mineral is known to occur in the rock volume around the GTS (Keusen et al. 1989, Schneeberger et al. 2016). Therefore, in the model Cl\(^-\) is added by the dissolution of a generic NaCl phase, serving as a proxy for the potential uptake of Cl\(^-\) from another water source such as rock matrix porewater.

Inverse modelling for type A water (Tab. 7.3) showed that the fracture water composition sampled in the GTS is achieved by dissolution of Ca-albite, fluorite, calcite, pyrite and NaCl\(_{(s)}\) halite in conjunction with the precipitation of quartz, kaolinite, and K-montmorillonite (Tab. 7.3). Inverse modelling for type B water differs only slightly, as calcite is not dissolved, but precipitated (Tab. 7.3). Comparison of the inverse models with saturation indices revealed that all suggested reactions are thermodynamically plausible considering the saturation index of every single mineral (Tab. A.4).

The different amount of dissolution of NaCl\(_{(s)}\) obtained from the inverse models agrees with the difference in Cl\(^-\) concentrations observed for the two water types (Fig. 7.4a). Based on the lack of correlation between Cl\(^-\) and K\(^+\), as well as between Cl\(^-\) or Mg\(^{2+}\) concentrations (Fig. 7.4), sheet silicates can be excluded as a potential Cl\(^-\) source. Therefore, the assumption that Cl\(^-\) is added by in-diffusion of rock matrix porewater is confirmed (section 7.2.1). Moderately mineralised rock matrix porewater (Cl\(^-\) ≈ 330–440 mg/kgH\(_2\)O) is known to occur within the GrGr in the GTS (section 7.2, Eichinger 2009). A porewater contribution of about 1/120 is inferred for type B water based on the reported Cl\(^-\) concentrations. Such a low contribution only slightly alters the stable isotopic
composition of the fracture water, and hence it is consistent with the observation that rock matrix
porewater plots away from the LMWL in the $\delta^{18}$O – $\delta^{2}$H plot (Fig. 7.2, Eichinger 2009).

Tab. 7.3: Phase mole transfer inferred from inverse modelling for type A and type B waters
Positive values indicate dissolution, negative precipitation.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Units</th>
<th>Type A water SB 80.001i1</th>
<th>Type B water VE 13.001i2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite</td>
<td>mmol/l</td>
<td>-0.1154</td>
<td>-0.2293</td>
</tr>
<tr>
<td>Ca-albite</td>
<td>mmol/l</td>
<td>0.2574</td>
<td>0.4502</td>
</tr>
<tr>
<td>Pyrite</td>
<td>mmol/l</td>
<td>0.0319</td>
<td>0.0204</td>
</tr>
<tr>
<td>CO$_2$(g)</td>
<td>mmol/l</td>
<td>-0.0218</td>
<td>-0.0070</td>
</tr>
<tr>
<td>Calcite</td>
<td>mmol/l</td>
<td>0.04983</td>
<td>-0.0800</td>
</tr>
<tr>
<td>Quartz</td>
<td>mmol/l</td>
<td>-0.3531</td>
<td>-0.7443</td>
</tr>
<tr>
<td>Fluorite</td>
<td>mmol/l</td>
<td>0.0958</td>
<td>0.1478</td>
</tr>
<tr>
<td>NaCl$_{(s)}$</td>
<td>mmol/l</td>
<td>0.0000</td>
<td>0.0820</td>
</tr>
<tr>
<td>K-montmorillonite</td>
<td>mmol/l</td>
<td>-0.0141</td>
<td>-0.0019</td>
</tr>
</tbody>
</table>

Similar dissolution/precipitation patterns for type A water and type B water are proposed, except
for precipitation of calcite needed in the case of type B water. Thus, the gradual transition inferred
from the chemical composition (Fig. 7.4) is confirmed by the similarity of the inverse models.
Furthermore, type B fracture water seems to be an evolved type A fracture water.

In summary, the geochemical evolution of the fracture water seems to be governed by the progress
of the proposed water-rock interactions, which are controlled by the residence time. Residence
time estimations were performed in numerous borehole test intervals, but only very little informa-
tion was gained on fracture water occurring within the GTS. Nevertheless, the two water samples
with detectable tritium concentration show the smallest Na/Ca ratios, which serves as a proxy for
the evolution and thus supports the evolution hypothesis.

Additional information on residence time can be gained from the interplay between flow path
length and flow velocity. The flow path length is primarily controlled by the structure along which
the water was sampled. However, the unsaturated zone in the uppermost rock volume inhibits a
direct correlation to the flow path length (Schneeberger 2017). Nevertheless, the increased
vertical overburden in the southern part positively influences the flow path length and thus the
flow paths tend to be longer in the southern part.

The flow velocity is controlled inter alia by the permeability of the rock volume. The comprehen-
sive hydraulic characterisation carried out in the GTS allowed a distinction between a typical
northern flow regime and a typical southern flow regime. The flow regimes are host rock-
dependent, which happens to correlate with the overburden. The distinction further shows that the
northern part tends to be characterised by higher large-scale transmissivity values.

The evidence presented supports the hypothesis that the fracture water composition is a product
of the progress of water-rock interaction, which is mainly governed by residence time. The
observed pattern is corroborated by information about the hydraulic flow regime.
8 Perturbations to the baseline conditions

Perturbations to the baseline conditions at any site are likely to be ubiquitous. Only a thorough baseline characterisation of the host rock allows accurate identification of perturbations. Perturbation characterisation is part of the long-term safety assessment of a repository site, as perturbations are likely to occur and thus need to be defined in terms of magnitude and source. The GTS offers the opportunity for a long-term baseline characterisation after excavation of the tunnels. In contrast, the original condition prior to tunnel excavation is mostly unknown. The GTS thus allows the accurate definition of a perturbation catalogue. This catalogue serves as input to conceptual models for the potential perturbations of a potential repository site. The natural background with the presence of the tunnels is perturbed at the GTS by both natural events and processes such as earthquakes, earth tides and meteorological phenomena, and by anthropogenic events and processes such as ventilation, nearby drilling or hydrotesting. In the following, major perturbations are evaluated for their potential impact on the GTS together with examples from a range of experiments.

8.1 Natural perturbations

8.1.1 Natural earthquakes

Earthquake activity in Switzerland is routinely monitored by the Swiss Seismological Service (SED), documented in annual reports, and downloadable from their website (http://seismo.ethz.ch/en/home/ or http://arclink.ethz.ch/webinterface/). The SED has a permanently installed station at the GTS.

Two different systems with varying sensitivity are used by the SED. The high-sensitivity Swiss Digital Seismic Network (SBSNet) is able to detect slight vibrations and the Swiss Strong Motion Network (SSMNet), which records undistorted signals from very strong earthquakes.

Earthquakes within the area of interest (Fig. 8.1) typically occur at a depth between 1.2 and 13.4 km, with a median value of 5.6 km below surface. The magnitude ranges from -0.6 to 3.2, with a median value of 0.7. Earthquakes influence the rock volume surrounding the GTS and have been detected, for example, during micro-seismic surveys of the influence of lake level changes on the rock volume (Kinali et al. 2018).

Background monitoring of seismic events was important for the hydro-fracturing and hydraulic stimulation experiments performed in the ISC project (Jalali et al. 2018). However, a thorough characterisation of the perturbations to the baseline conditions induced by earthquakes around the GTS has not been performed.
Fig. 8.1: Map with earthquakes recorded between January 2013 and May 2018
Data source: arclink.ethz.ch/webinterface, accessed on May 7, 2018
The position of the GTS is indicated by a red-coloured dot.

8.1.2 Earth tides
The sun and the moon induce a periodical deformation of the solid earth (known as earth tides, Melchior 1983) with semidiurnal and diurnal amplitude peaks (Fig. 8.2). At the GTS, earth tide activities were observed in the tilt meter experiment (Fig. 8.2) as well as in hydraulic pressures measured in packed-off test intervals in almost all fully saturated borehole intervals where extended monitoring has occurred (Fig. 8.3, ADUS 96.001 borehole, see Fig. 7.3 for location). The variation of the hydraulic pressure in response to earth tides is typically within the range of 5 – 15 mbar (e.g. Frick et al. 1992), which corresponds to < 1 % of the background hydraulic pressure.
Fig. 8.2: Daily oscillation in response to earth tides observed in the tilt meter experiment (modified after Frick et al. 1992)

Fig. 8.3: Hydraulic pressure in ADUS 96.001 (Fig. 7.3) showing the influence of earth tides during a 1 month period (Fisch et al. 2019)

8.1.3 Meteorological data

Meteorological and climatic impacts might affect the regional and near-field repository environment. Their identification and monitoring are therefore an integral part of a thorough site description. Rock volume tilting was studied within the framework of neotectonic investigations
(Tilt meter experiment at the GTS) (Flach and Noell 1989). In the performed measurements, the response of the rock volume to an annual air pressure change was identified (Flach and Noell 1989). The annual variation is inferred from similar linear movement recordings on various tilt meters after filtering out other variations such as lake level changes (Flach and Noell 1989, Fig. 8.4). So far, no further detailed investigations of impact and relationship to meteorological data have been performed at the GTS.

Fig. 8.4: Movements recorded on tilt meters (three stations) during three selected periods in response to annual air pressure variations (modified after Flach and Noell 1989)

The observed movements are the result of the analysis of the aperiodic movements after subtraction of all known perturbations such as lake level changes and earth tides. The arrows show the maximum deviation of the tilt meters.

The position of the three stations is shown in Fig. 5.4.

### 8.2 Lake level changes

The influence of lake level changes was identified in the tilt meter experiment, but also in experiments related to the hydraulic environment (e.g. Keusen et al. 1989, Schlickenrieder et al. 2017). Lake level changes are a consequence of the hydropower exploitation of the lakes, as well as of natural effects such as strong atmospheric precipitation or glacier melting.

In the CFM experiment, detailed investigation of the hydraulic head variation has shown that changes in the level of Lake Grimsel are depicted in the hydraulic heads of selected borehole test intervals. About 4 – 5% of the lake level variation is transferred to the hydraulic heads at GTS level (Figs. 8.5 and 8.6, Schlickenrieder et al. 2017). Moreover, the influence of the earth tides on the hydraulic heads could be assessed. The induced variation has a peak-peak amplitude of 0.1 m hydraulic head or ~10 kPa (Schlickenrieder et al. 2017).
Water flow modelling for the GTS (e.g. Correa et al. 1994) typically used the levels of Lake Grimsel and Lake Rätrichsboden as boundary conditions. Lake level changes show a clear annual pattern, with high lake levels in the second half of the year and low lake levels in early summer. This pattern results from KWO's water management to control snow melt in the forthcoming season.
8.3 Anthropogenic far-field perturbations

KWO activities related to the operation of the hydropower plant result in a range of perturbations. The management of the turbines, for instance, is visible in the micro-seismic survey campaign (Kinali et al. 2018). Most of the activities are not regular. However, Nagra is generally informed about planned larger activities such as drilling or blasting of new drifts and caverns. A regularly observed perturbation is related to movement of heavier trucks along the main access tunnel, which leads to vibrations and noise, especially in micro-seismicity studies.

8.4 Anthropogenic near-field perturbations

8.4.1 Ventilation

The GTS is subject to constant air ventilation to ensure healthy working conditions (ca. 3000 l/min). Air is taken from the outside and pumped through the tunnel system. The relative humidity of the air changes with the seasons (Fig. 8.7). These changes influence the near field of the tunnel. The ventilation results in a drying front within the rock volume where the rock cannot provide sufficient water to balance evaporation. The annual variation in relative humidity results in variations in the depth of the drying front and in hydraulic head variations close to the tunnel as seen in borehole intervals within the rock matrix (Fig. 8.7). On a larger scale, it is observable in the number of water discharges in the tunnel system that decrease in winter compared to summer (Keusen et al. 1989, Schneeberger et al. 2018).

Fig. 8.7: Correlation between hydraulic pressure and ventilation at the Colloid Formation and Migration (CFM) site (Schlickenrieder et al. 2017)

Two-phase flow in the unsaturated zone has been studied extensively at the GTS (e.g. ZPM Zweiphasenfluss in der Gesteinsmatrix (two-phase flow in the rock matrix) experiment), as discussed in Kull and Miehe (1995) and Marschall et al. (1999).
8.4.2 BDZ and EDZ

Observations of the Borehole Disturbed Zone (BDZ) in intact rock have shown a pattern with increased porosity extending a few mm from the borehole wall. In-situ resin impregnation measurements (Möri 2009) in the Grimsel Granodiorite in the southern part of the laboratory showed a zone of 0-2 mm depth with higher porosity (0.59 vol.%), while mean porosity values from deeper in the rock matrix were significantly smaller (0.22 to 0.39 vol.%) and showed no dependence on the distance to the borehole. Soler et al. (2013) demonstrate that such a BDZ is required to match observations from the LTD Monopole #1 in-situ diffusion experiment. This is consistent with calculations that macroscopic failure is not expected at the GTS given the expected rock strength and stress field. A deeper BDZ (Möri et al. 2003) was observed in a borehole close to the excavation wall, perhaps due to the Excavation Damaged Zone or to greater disturbance during coring caused by excavation-induced stresses.

The extent of the EDZ at the GTS varies with excavation method (TBM, drill & blast) and tectonic fracturing (intact, shear zone, fractured zone).

TBM tunnels in intact rock generally show only a very minor EDZ limited to a few mm (~ grain size). SEM/EDX investigations for the FEBEX tunnel showed disturbance to the matrix extending 1-3 mm with crushed quartz grains and some fractures extending to depths of a few mm from the wall surface. A more extensive region of disturbance (10 to 15 mm) was associated with a metabasic dyke.

One zone in the WT tunnel showed a ~10 m zone of spalling (WT 76-86 m) which terminated at a metabasic dyke. This zone was investigated in the EDZ experiment (Frieg & Blaser 2012). Within this zone, unloading fractures were identified up to 20 cm from the tunnel wall, while pre-existing and possibly stress-disturbed fractures were observed up to 1 m from the tunnel wall. It is possible that the tunnel orientation together with stress concentrations related to the dyke caused this localised damage.

In more fractured zones there is the possibility of disturbance of natural fractures and structurally controlled failure along pre-existing fracture planes. Investigations in the EDZ experiment showed potentially reactivated transmissive fractures to about 1 m from the tunnel wall. A large breakout zone in the roof of the AU tunnel is associated with the GAM shear zone. Such structures are also associated with perturbations of the stress field (Krietsch et al. 2018).

Drill & blast excavations (e.g. GMT, BK area) show induced fracturing near the tunnel wall extending up to about 0.5 m in relatively intact rock (Marschall et al. 1999), but structurally induced failures have been observed, for example, in the upper part of the silo at the GMT where the VE shear zone cuts across the excavation.

Fig. 8.8 shows conceptual models of the EDZ in the different experiments at the GTS, together with an "envelope" for the EdZ (Excavation disturbed Zone). At the GTS, the most important excavation-induced disturbance relates to the development of a partially saturated zone around the tunnels due to ventilation and, especially in winter, low relative humidity within the tunnels. Kull and Miehe (1995) suggest partial saturation to at least 2 m into the rock during ventilation tests at the GTS, but the depth of the partially saturated zone is dependent on the ventilation, relative humidity and the local rock permeability, two-phase flow properties and hydraulic head (i.e. the ability of the rock to replace water lost by evaporation at the tunnel wall). Because the extent of the partially saturated zone varies around the laboratory, care must be taken to characterise the saturation state when performing experiments close to the tunnels.

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9 Measurements were not available between 1 and 2 m from the tunnel wall.
Fig. 8.8: Conceptual model of the Excavation Damaged Zone (EDZ) and Excavation disturbed Zone (EdZ) at different locations around the GTS

Tab. 8.1: Summary of the EDZ around excavations at the GTS

<table>
<thead>
<tr>
<th>Method</th>
<th>Rock mass</th>
<th>Site</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBM</td>
<td>Intact</td>
<td>FEBEX</td>
<td>Minor damage extending ~1-3 mm from tunnel wall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WT/EDZ</td>
<td>Higher stress zones may lead to local breakouts together with induced and reactivated fracturing</td>
</tr>
<tr>
<td></td>
<td>Fractured</td>
<td>AU/GAM, WT/EDZ</td>
<td>Possible disturbance and structurally controlled failure on critically oriented fracture planes</td>
</tr>
<tr>
<td>Drill &amp; blast</td>
<td>Intact</td>
<td>GMT</td>
<td>Increased permeability to ~1 m from tunnel wall</td>
</tr>
<tr>
<td></td>
<td>Fractured</td>
<td>GMT, BK</td>
<td>Induced fracturing and structurally controlled failure on critically oriented fracture planes</td>
</tr>
</tbody>
</table>
8.4.3 Experimental activities

Activity related to running experiments can influence the rock volume in a manner that perturbs nearby experiments (Figs. 8.9 and 8.10). For example, hydro-testing performed in 2016, 2017, and 2018 in the ADUS 96.001 borehole was measured in the neighbouring GAST experiment, but the pressure signal was also detected in the Colloid Formation and Migration (CFM) experiment. In part this reflects the sensitivity of the pore pressure measurements (~0.25 kPa) and differential pressure measurements (~0.001 kPa), which when combined with stable baseline conditions and well characterised responses to natural perturbations allow the detection of small pressure responses to laboratory activities.

Excavation or drilling work performed in the GTS can also influence the rock volume. However, this work is not regular and the timing is well constrained.

Fig. 8.9: GTS map showing the location of the GAST experiment and the ADUS 96.001 borehole
Fig. 8.10: Crosshole pressure response in the GAST experiment to hydro-testing in the ADUS 96.001 borehole (Fisch et al. 2019)

The upper diagram shows the pressure evolution in the ADUS borehole as a consequence of the hydraulic testing campaign. The different pressure drops in varying test intervals correlate with pressure changes in the SVP 88.006 borehole, whereas other close-by boreholes appear to be unaffected by the pressure variations.
9 Experiments at the GTS

The development of the GTS is linked to the experiments performed over more than 3 decades, with a shift from site characterisation-specific experiments to the engineered barrier system and finally to experiments designed to develop and test monitoring systems and study rock-independent processes such as corrosion of canister materials (see section 1.2). In Tab. 9.1, 9.2 and 9.3, an overview is given of experiments that have been performed, or are currently running, at the GTS. The key references should enable the interested reader to obtain more details on a specific experiment. Further details on the experiments are given in Appendix 4.

Tab. 9.1: Alphabetical overview of selected completed experiments at the GTS

<table>
<thead>
<tr>
<th>Experiment name (short)</th>
<th>Experiment name (long)</th>
<th>Key objectives for RD&amp;D</th>
<th>Experiment runtime</th>
<th>Key reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTS Phases I - II</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic High-Frequency Measurements</td>
<td>Developing non-destructive measurements of the rock volume around tunnels and boreholes</td>
<td>1984–1990</td>
<td>NTB 87-13</td>
</tr>
<tr>
<td>FRI</td>
<td>Fracture Zone Investigation</td>
<td>Increasing knowledge about the effects of fractures on a radioactive waste repository</td>
<td>1984–1990</td>
<td>NTB 90-49</td>
</tr>
<tr>
<td>HPA</td>
<td>Hydraulische Potentiale Hydraulic Potential</td>
<td>Determining the hydraulic potential around the GTS and developing suitable techniques for it</td>
<td>1984–1990</td>
<td>NTB 89-01</td>
</tr>
<tr>
<td>MI</td>
<td>Migration Experiment</td>
<td>Acquiring fundamental chemical and physical knowledge of transport of nuclides in fractures</td>
<td>1984–1996</td>
<td>NTB 00-09</td>
</tr>
<tr>
<td>MOD</td>
<td>Hydrodynamic Modelling</td>
<td>Developing and testing new numerical tools and techniques to support interpretation of hydrological in-situ experiments</td>
<td>1984–1993</td>
<td>NTB 91-03</td>
</tr>
<tr>
<td>Experiment name (short)</td>
<td>Experiment name (long)</td>
<td>Key objectives for RD&amp;D</td>
<td>Experiment runtime</td>
<td>Key reference</td>
</tr>
<tr>
<td>------------------------</td>
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</tr>
<tr>
<td>NFH</td>
<td>Near-field Hydraulics</td>
<td>Investigating the influence of boreholes and tunnels on hydraulic parameters in the near field</td>
<td>1984–1990</td>
<td>NTB 94-04</td>
</tr>
<tr>
<td>NM</td>
<td>Neigungsmessungen Tilt meters</td>
<td>Demonstration of neotectonic measurements by tilt meters</td>
<td>1984–1990</td>
<td>NTB 89-11</td>
</tr>
<tr>
<td>SVP</td>
<td>Stollenvorfeld-prognose Prediction ahead of tunnel face</td>
<td>Gaining knowledge about rock volume prior to drilling a tunnel</td>
<td>1984–1990</td>
<td>NTB 90-07</td>
</tr>
<tr>
<td>VE</td>
<td>Ventilation Test</td>
<td>Measuring large-scale (metres) permeability of the rock matrix</td>
<td>1984–1990</td>
<td>NTB 91-02E</td>
</tr>
<tr>
<td>WT</td>
<td>Wärmetest Heater Test</td>
<td>Providing information on the reaction of the bedrock to heat influx</td>
<td>1984–1990</td>
<td>NTB 88-40E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GTS Phase III</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UZ</td>
<td>Unsaturated Zone</td>
<td>Acquiring knowledge about the unsaturated zone near the underground facility</td>
<td>1990–1993</td>
<td>NTB 93-10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GTS Phase IV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOS</td>
<td>Borehole Sealing</td>
<td>Developing borehole seals with irregular borehole shapes</td>
<td>1994–1996</td>
<td>NTB 07-01</td>
</tr>
<tr>
<td>CP</td>
<td>Connected Porosity</td>
<td>Investigating the connected porosity in the unfractured rock matrix</td>
<td>1994–1996</td>
<td>NTB 00-08</td>
</tr>
<tr>
<td>EDZ</td>
<td>Excavation Damaged Zone (formely called Excavation disturbed Zone)</td>
<td>Studying the effects of the damaged zone around excavations on diverse parameters</td>
<td>1994–1996</td>
<td>NTB 98-01</td>
</tr>
<tr>
<td>EP</td>
<td>Excavation Project</td>
<td>Investigate potential methods for immobilising a rock volume prior to overcoring</td>
<td>1994-1996</td>
<td>NTB 00-06</td>
</tr>
<tr>
<td>Experiment name (short)</td>
<td>Experiment name (long)</td>
<td>Key objectives for RD&amp;D</td>
<td>Experiment runtime</td>
<td>Key reference</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------------</td>
<td>-------------------------</td>
<td>--------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>RRP</td>
<td>Radionuclide Retardation Project</td>
<td>Increasing knowledge about retardation processes of radionuclides</td>
<td>1994–1996</td>
<td>NTB 00-07</td>
</tr>
<tr>
<td>TOM</td>
<td>Further development of seismic tomography</td>
<td>Evaluating and testing underground seismic sources and improving analysis methods in terms of stability, quality and resolution</td>
<td>1994–1996</td>
<td>NTB 97-05</td>
</tr>
</tbody>
</table>

Tab. 9.2: Selected completed experiments dedicated to the Engineered Barrier System (GTS Phase V)

<table>
<thead>
<tr>
<th>Experiment name (short)</th>
<th>Experiment name (long)</th>
<th>Key objectives for RD&amp;D</th>
<th>Experiment runtime</th>
<th>Key reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRR</td>
<td>Colloid and Radionuclide Retardation</td>
<td>Improving understanding of in-situ retardation of colloid-associated radionuclides</td>
<td>1997–2002</td>
<td>NTB 03-01, 03-02, 03-03</td>
</tr>
<tr>
<td>CTN</td>
<td>Tunnel Near-Field Programme</td>
<td>Performance assessment bases on tunnel near-field investigations</td>
<td>1997–2002</td>
<td>NTB 99-07</td>
</tr>
<tr>
<td>EFP</td>
<td>Effective Field Parameters</td>
<td>Examining methods for rock characterisation and development of a structural model</td>
<td>1997–2002</td>
<td>NTB 03-13</td>
</tr>
<tr>
<td>FOM</td>
<td>Fibre Optic Monitoring</td>
<td>Testing fibre optic sensing systems of DBE technology in an engineered barrier system</td>
<td>1997–2002</td>
<td></td>
</tr>
<tr>
<td>FEBEX</td>
<td>Full-scaled High-Level Waste Engineered Barriers Experiment</td>
<td>Demonstrating the feasibility of the Spanish disposal concept and developing methodologies to assess thermo-hydro-mechanical and thermo-hydro-geochemical behaviour of the engineered barrier system</td>
<td>1994–2015</td>
<td>NTB 15-04, 17-01</td>
</tr>
<tr>
<td>Experiment name (short)</td>
<td>Experiment name (long)</td>
<td>Key objectives for RD&amp;D</td>
<td>Experiment runtime</td>
<td>Key reference</td>
</tr>
<tr>
<td>-------------------------</td>
<td>------------------------</td>
<td>-------------------------</td>
<td>--------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>GAM</td>
<td>Gas Migration in shear zones</td>
<td>Visualising channelling in shear zones on the laboratory and field scale</td>
<td>1997–2002</td>
<td>NTB 03-11</td>
</tr>
<tr>
<td>GMT</td>
<td>Gas Migration in EBS and Geosphere</td>
<td>Evaluating models of gas migration through the engineered barriers and into the geosphere</td>
<td>1997–2002</td>
<td>Senger et al. 2007</td>
</tr>
<tr>
<td>HPF</td>
<td>Hyperalkaline Plume in Fractured Rock</td>
<td>Assessing potential perturbations of a HPF on a repository host rock under in-situ conditions</td>
<td>1997–2008</td>
<td>NTB 08-11</td>
</tr>
<tr>
<td>PSG</td>
<td>Pore Space Geometry</td>
<td>Studying pore space on in-situ resin-injected samples and visualising connected porosity</td>
<td>1997–2002</td>
<td>NTB 05-03</td>
</tr>
<tr>
<td>CIM</td>
<td>In-Situ Migration of Carbon-14 and Iodine in Cement</td>
<td>Studying the retardation of migration of weakly sorbing radionuclides in aged cement</td>
<td>2018–ongoing</td>
<td>-</td>
</tr>
<tr>
<td>CFM</td>
<td>Colloid Formation and Migration project</td>
<td>Colloid formation and migration, colloid-associated radionuclide transport, bentonite erosion, fracture water/porewater mixing zone</td>
<td>2004–ongoing</td>
<td>NTB 15-03</td>
</tr>
<tr>
<td>C-FRS</td>
<td>CRIEPI's Fractured Rock Studies</td>
<td>Demonstration and testing of newly developed technology for fracture characterisation and tracer use</td>
<td>2006 – 2012</td>
<td>Tanaka et al. (2014)</td>
</tr>
<tr>
<td>FORGE Mock-up</td>
<td>Lab-scale Gas Test (see below)</td>
<td>Mock-up version of GAST</td>
<td>2009 – 2015</td>
<td>NAB 15-08, 12-62</td>
</tr>
<tr>
<td>GAST</td>
<td>Gas Permeable Seal Test</td>
<td>Gas-permeable plugs and seals to increase the gas transport capacity of backfilled underground structures without compromising the radionuclide retention capacity of the EBS</td>
<td>2010–ongoing</td>
<td>NAB 12-59</td>
</tr>
</tbody>
</table>

Tab. 9.3: Selected experiments dedicated to monitoring, demonstration, technology development and engineering (GTS Phase VI)
<table>
<thead>
<tr>
<th><strong>Experiment name</strong> (short)</th>
<th><strong>Experiment name</strong> (long)</th>
<th><strong>Key objectives for RD&amp;D</strong></th>
<th><strong>Experiment runtime</strong></th>
<th><strong>Key reference</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>HotBENT</td>
<td>High Temperature Buffers</td>
<td>Increasing the database and understanding of buffer/host rock performance under high T and demonstration on realistic scales and conditions</td>
<td>2018– ongoing</td>
<td>-</td>
</tr>
<tr>
<td>ISC</td>
<td>In-situ Stimulation and Circulation</td>
<td>Improving knowledge about geomechanical processes during hydraulic stimulation</td>
<td>2014 – 2018</td>
<td>Amann et al. (2018)</td>
</tr>
<tr>
<td>LASMO</td>
<td>Large-scale Monitoring</td>
<td>Monitoring of large-scale geological processes resulting from glacial unloading</td>
<td>2013 – 2018</td>
<td>NTB 19-01</td>
</tr>
<tr>
<td>LCS</td>
<td>Long-term Cement Studies</td>
<td>Studies related to cement leaching and hyperalkaline plume production, emphasis on in-situ field experiments with more realistic boundary conditions and longer timescales</td>
<td>2003 – 2016</td>
<td>NAB 10-05, 12-60</td>
</tr>
<tr>
<td>LTD</td>
<td>Long-term Diffusion project</td>
<td>Long-term, large-scale experiment examining in-situ matrix diffusion and pore space visualisation</td>
<td>2004 – ongoing</td>
<td>NAB 15-35</td>
</tr>
<tr>
<td>MaCoTe</td>
<td>Material Corrosion Test</td>
<td>Study of in-situ corrosion of candidate canister materials embedded in bentonite</td>
<td>2015 – ongoing</td>
<td>running</td>
</tr>
<tr>
<td>NF-Pro</td>
<td>Near-Field Processes</td>
<td>Optimising single-hole granite probe design and the interpretation of time domain reflectometry measurements</td>
<td>2005 – 2008</td>
<td>NTB 15-04</td>
</tr>
<tr>
<td>TEM (ESDRED)</td>
<td>Test and Evaluation of Monitoring Techniques</td>
<td>Testing alternative or complementary monitoring techniques</td>
<td>2006 – ongoing</td>
<td>running</td>
</tr>
</tbody>
</table>
10 Concluding remarks

Geoscientific knowledge for the GTS

The geoscientific knowledge documented in this report represents a summary and condensation of the geoscientific data acquired during multiple experiments over more than three decades of underground research. Detailed information for all chapters in this report is available in the reports on the specific experiments (see compilation provided in Chapter 9).

In very succinct form, the information for the GTS can be summarised as follows:

- The rock volume surrounding the GTS is composed of relatively homogeneous lithologies changing from north to south. Superimposed, however, are fault structures that appear simple on the kilometre scale, but on a cm to mm scale the complexity increases strongly. This is best illustrated in the structural description of the Migration shear zone (Möri and Blechschmidt 2006). The long-lasting deformation history resulted in a ductile deformation forming a pervasive foliation and localised ductile shear zones, which are often subsequently overprinted by a retrograde brittle deformation (i.e. cataclasis). This yields brittle faults and fault cores filled with gouge in former ductile shear zones.

- The stress field at the GTS is strongly influenced by the ubiquitous deformation structures crosscutting the rock volume, defining blocks that are separated by fault cores with gouge. Different stress state measurement campaigns performed at the GTS yield varying stress tensors. However, on average $\sigma_1$ plunges sub-horizontally towards the ESE. $\sigma_2$ and $\sigma_3$ are less well constrained as the difference in their magnitudes is small, but they are located on a NW dipping plane.

- The hydraulic regime at the GTS is dominated by the occurrence of brittle faults. The unfractured rock matrix is characterised by very low permeability ($10^{-19} – 10^{-18}$ m$^2$). The hydraulic behaviour of faults can be subdivided into two types. (i) In the northern part of the GTS, retrograde brittle deformation is more pervasive than in the southern part, leading to an interconnected fault network. (ii) In the southern part of the GTS, the hydraulic regime is dominated by fault zones with complex deformation history and a frequent occurrence of fault gouge (acting as a barrier to flow, Bossart and Mazurek 1991); this leads to highly channelised water flow (open channels) within quasi-planar fault zones. Fault intersections are preferentially associated with flowing features, but typically result in complex flow paths (e.g. ISC).

- Fracture water at the GTS is of meteoric origin and percolates driven by hydraulic gradients strongly influenced by the rugged topography and the presence of the GTS from today’s surface towards the GTS. During percolation, the chemical composition is altered by water-rock interactions, which are mainly dissolution of plagioclase and fluorite as well as precipitation of quartz and kaolinite. The mean residence time of the fracture water varies depending on the permeability of the water-conducting features. However, it is typically $> 50$ years, and several indicators suggest that there are 'fast' and 'slow' pathways with residence times as short as 5 years. Rock matrix porewater is moderately mineralised with chloride. Porewater and fracture water interact via diffusion into the walls of the faults, yielding an increased chloride concentration in the fracture water and reducing chloride content in the matrix close to flowing fractures.

- The virgin state of the rock volume around the GTS is perturbed by the presence of the laboratory. Major perturbations are due to ventilation, the tunnel layout, drilling, and hydro-testing. Further, natural phenomena such as earthquakes, earth tides and annual relative humidity changes further alter the state of the rock volume.
The GTS in the context of generic and site-specific URLs:

The GTS, and underground research laboratories (URLs) in general, have been an integral part of radioactive waste management strategies in many countries around the globe. According to their objectives, URLs are located in geological formations that are considered to be suitable for the construction of deep geological disposal facilities, such as granite, salt, clay/shale, volcanic tuff, etc. at relevant depths below the surface.

Projects in URLs are very important with respect to building up scientific understanding and gathering the full spectrum of data required to analyse the potential behaviour of repository components and systems on large (1:1) scales, over long time spans and under as realistic (repository-relevant) boundary conditions as possible. They are characterised by a wide spectrum of research, development and engineering/demonstration projects and complementary small-scale laboratory-based experiments and natural analogues.

Specific areas where the GTS and URLs in general have extended the knowledge base (Blechschmidt and Vomvoris 2017) can be summarised as:

- developing appropriate tools and techniques for testing, characterising and observing repository systems underground,
- identifying key properties for characterising geological environments at realistic depths and scales and under natural or perturbed conditions,
- upscaling of processes and parameters from laboratory scale to repository scale,
- transferability (applicability/limitations) of results from generic URLs to other locations or even different geological host environments,
- functioning of components of the engineered barrier system and of the repository system under realistic conditions and how they can be further optimised, and
- suitability of construction and excavation methods to meet the rigorous repository requirements.

Looking more closely at long-term safety, URL investigations have contributed significantly to the aspects of radionuclide mobility and radionuclide retardation. The understanding gained with respect to advection, dispersion, matrix diffusion and colloid migration has been important for the reduction of uncertainties and for confidence-building. The current level of understanding has been achieved mainly through upscaling experiments, studies of coupled phenomena in the engineered barrier system and host rock, and the testing, further development, calibration and validation of conceptual and numerical models of relevant processes for radionuclide transport. Although methods and conceptualisations are transferable to other situations, the transferability (applicability/limitations) of the results from URL programmes to repository siting regions or even different geological host environments needs to be further evaluated and considered (Blechschmidt and Vomvoris 2017).

In terms of repository construction and operation, invaluable experience has been gained under real site conditions for the excavation and construction of a repository. Concepts for the emplacement of the waste and of the engineered barriers have been tested and refined in a realistic setting (e.g. FEBEX, GAST, EDZ). Lessons have also been learned concerning repository monitoring during both the operational and post-closure phases without affecting the long-term safety; further work is needed to design robust and long-lasting monitoring techniques.
Acknowledgments

The work summarised here is derived from three decades of investigations performed by scientists from around the world at the Grimsel Test Site. More than two dozen organisations and research institutes from twelve countries and the European Union have participated in the six phases of the research programme. Everyone who has worked at GTS is gratefully acknowledged.

The operation of the GTS has been supported by many local organisations but, from the beginning, KWO has been one of the most important and highly reliable local partners, guaranteeing the safe operation of the Test Site, also when faced with the occasional technical and logistical challenges.
References


Herwegh, M., Berger, A., Baumberger, R., Wehrens, P., & Kissling, E. (2017). Large-Scale Crustal-Block-Extrusion During Late Alpine Collision. Scientific Reports, 7. https://doi.org/10.1038/s41598-017-00440-0.


IAEA (2001). The use of scientific and technical results obtained from underground research laboratory investigations for the geological disposal of radioactive waste. IAEA/TECDOC-1243.


Appendix 1: Mindmap showing the thematic link between chapters and GTS experiments (blue see Tab. 9.1)
Appendix 2  Fracture water sampling related to the LASMO project

Appendix 2.1  Methods

The sampled borehole test intervals are connected by polyamide or steel tubes with the tunnel instrumentation for water sampling and hydraulic testing. Test intervals along the selected boreholes were classified based on available geological information (Geotest AG 1981, Mäder and Ekberg 2006, Vomvoris et al. 1992). The classification aimed at the distinction of mineralogical differences along water-conducting features that potentially result in differences in fracture water chemical composition. The first criterion was the occurrence of metabasic dykes, CAGr or GrGr. If no metabasic dyke was identified within the test interval then the test interval was classified based on the occurrence of fault gouge, ductile shear zone and/or brittle fracture. In this classification, the amount of fault gouge may be underestimated, because specific drilling techniques are required to retrieve fault gouge in drill core samples. Only borehole HP 98.007 was drilled accordingly (Mäder and Ekberg 2008).

Appendix 2.1.1  Fracture water sampling

Fracture water was sampled from hard polyamide or stainless-steel flow lines installed during emplacement of the packers to delimit the test intervals. Interval pressures were monitored with pressure gauges mounted on the outflow lines.

Samples were taken with a 50 ml syringe directly on the outflow valve from the sampled test interval in order to prevent air contamination. Samples for cations, anions, and stable water isotopes were filtered with a 45 µm CE filter into a 30 ml or 125 ml polypropylene (PP) bottle. Cation samples were acidified with HNO₃ to prevent precipitation. Samples for total inorganic/organic carbon (TIC/TOC) were taken unfiltered in a PS bottle.

Appendix 2.1.2  Chemical and isotope analyses

On-site measurements included temperature, pH, Eh, and electrical conductivity (EC). All these parameters were measured in-line during sampling of each test interval with electrodes mounted in a flow-through chain (Mäder and Ekberg 2006, Mäder et al. 2006) to avoid atmospheric contamination with respect to pH and Eh measurements.

Chemical analyses of samples taken were performed at the Institute for Geological Sciences, University of Bern. Major anions and cations (F⁻, Cl⁻, Br⁻, NO₃⁻, SO₄²⁻, Na⁺, NH₄⁺, Ca²⁺, K⁺, Sr²⁺, Mg²⁺) were analysed by ion chromatography (Metrohm 850 Professional IC). The detection limit is 0.016 mg/l for anions and 0.1 mg/l for cations, with an analytical uncertainty of ± 5%. Concentrations of K⁺, Mg²⁺ and Sr²⁺, which were close to or below the detection limit by IC techniques, were re-analysed along with trace elements (Al³⁺, Si, Mnₜₒₜ, Feₜₒₜ) using inductively coupled plasma optical emission spectrometry (ICP-OES, Varian 720-ES). Detection limits of this technique are 1 µg/l for Sr²⁺ and Feₜₒₜ, and 5 µg/l for K⁺, Mg²⁺, Al³⁺, Si, and Mnₜₒₜ, with an analytical uncertainty of ± 5–10% depending on element concentration and sample matrix. Concentrations of Si were additionally determined by colorimetric techniques using a spectrophotometer (Varian UV/VIS Cary 50) in order to avoid any colloidal Si. The detection limit for Si is 0.005 mg/l, with an analytical uncertainty of ± 5%. Li⁺ concentration was measured via graphite furnace atomic absorption spectroscopy (GFAAS) with a detection limit of 1.25 µg/l and an analytical uncertainty of ± 5%. Total inorganic and organic carbon concentrations were determined using a TIC/TOC analyser (Analytic Jena multi N/C 2100S) with a detection limit of 0.1 mg/l for total carbon and an analytical uncertainty of ± 5%. The amount of total organic carbon...
was deduced from the difference between total carbon and total inorganic carbon. Stable water isotopic compositions were analysed by cavity ring down spectroscopy (Picarro) and are reported relative to VSMOW (Vienna Standard Mean Ocean Water) as $\delta^{18}$O, $\delta^2$H. Analytical uncertainty ($2\sigma$) is 0.1‰ VSMOW for $\delta^{18}$O and 1.5 ‰ VSMOW for $\delta^2$H. Samples for tritium were analysed by Hydroisotop GmbH via liquid scintillation spectroscopy after electrolytic enrichment, with a detection limit of 0.6 TU.

Appendix 2.1.3 Geochemical modelling

Geochemical model calculations were conducted using the software PhreeqC (Parkhurst and Appelo 2013) with the thermodynamic database Wateq4F (Ball and Nordstom 1991 updated version 2005-08-23). Initial modelling included speciation and saturation index calculations for quality control and to correct for sampling artefacts such as in gassing of atmospheric CO$_2$. Saturation indexes were calculated based on field pH measurements and carbon was integrated from the measured TIC concentration after correction for potential in gassing of CO$_2$. The correction was calculated by numerically removing or adding CO$_2$ until the pH measured in the field was obtained.

Element mass-balance calculations (inverse modelling) were done using the software NETPATH (Plummer et al. 1994) to identify major water-rock interactions that may occur from infiltration of atmospheric precipitation into the fracture water sampled at depth.

Appendix 2.2 Laboratory data groundwater composition
Tab. A.1: Physical parameters describing sampled test intervals and their fracture water

<table>
<thead>
<tr>
<th>Test interval</th>
<th>Rock type</th>
<th>Geology</th>
<th>Interval length [m]</th>
<th>Interval diameter [m]</th>
<th>Samples number of samples</th>
<th>EC [μ S/cm]</th>
<th>Flow rate [ml/min]</th>
<th>Transmissivity [m²/s]</th>
<th>Overburden [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>US 85.001i2</td>
<td>CAGr</td>
<td>BF</td>
<td>9.5</td>
<td>0.101</td>
<td>6</td>
<td>69.3-74.7</td>
<td>n.m.</td>
<td>1.50E-09</td>
<td>418</td>
</tr>
<tr>
<td>US 85.001i3</td>
<td>CAGr</td>
<td>DS</td>
<td>60.5</td>
<td>0.101</td>
<td>4</td>
<td>67.9-74.7</td>
<td>n.m.</td>
<td>2.40E-10</td>
<td>447</td>
</tr>
<tr>
<td>US 85.002i1</td>
<td>CAGr</td>
<td>DS</td>
<td>36.3</td>
<td>0.101</td>
<td>2</td>
<td>71.7-78.2</td>
<td>9.4</td>
<td>7.40E-10</td>
<td>515</td>
</tr>
<tr>
<td>US 85.002i2</td>
<td>CAGr</td>
<td>DS</td>
<td>2</td>
<td>0.101</td>
<td>6</td>
<td>62.1-70.0</td>
<td>186</td>
<td>1.70E-08</td>
<td>500</td>
</tr>
<tr>
<td>US 85.002i3</td>
<td>CAGr</td>
<td>MD</td>
<td>20</td>
<td>0.101</td>
<td>6</td>
<td>63.2-67.0</td>
<td>16.5</td>
<td>7.00E-09</td>
<td>489</td>
</tr>
<tr>
<td>US 85.002i4</td>
<td>CAGr</td>
<td>MD</td>
<td>29</td>
<td>0.101</td>
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<td>61.5-65.5</td>
<td>162</td>
<td>6.00E-08</td>
<td>461</td>
</tr>
<tr>
<td>US 85.002i5</td>
<td>CAGr</td>
<td>DS</td>
<td>5</td>
<td>0.101</td>
<td>6</td>
<td>59.4-62.2</td>
<td>31</td>
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<td>440</td>
</tr>
<tr>
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<td>DS</td>
<td>40</td>
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<td>DS</td>
<td>28</td>
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<td>DS</td>
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<td>0.086</td>
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<td>n.m.</td>
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<td>MD</td>
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<td>0.086</td>
<td>6</td>
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<td>DS</td>
<td>5</td>
<td>0.086</td>
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<td>63.1-70.9</td>
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<td>FG</td>
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<td>US 85.001i3</td>
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<td>US 85.002i2</td>
<td>US 85.002i3</td>
<td>US 85.002i4</td>
<td>US 85.002i5</td>
<td>US 85.002i6</td>
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<td>-------------</td>
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<tr>
<td>Eh (Ag/AgCl)</td>
<td>mV</td>
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<td>93 to 186</td>
<td>-176</td>
<td>-238 to -81</td>
<td>-234 to -115</td>
<td>-248 to -17</td>
<td>-235 to -19</td>
<td>-233 to 2</td>
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<td>21.1-21.4</td>
<td>n.m</td>
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<td>6.6-7.7</td>
<td>13.8-20.1</td>
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<td>K⁺ mg/l</td>
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<td>0.16-0.86</td>
<td>0.16</td>
<td>0.36-0.48</td>
<td>0.14-0.16</td>
<td>0.12-1.73</td>
<td>0.22-0.34</td>
<td>0.11-0.18</td>
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<td>&lt;0.1</td>
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<tr>
<td>Mg²⁺ mg/l</td>
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<td>0.023-0.035</td>
<td>0.023</td>
<td>0.024-0.026</td>
<td>0.023-0.024</td>
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<td>0.016-0.018</td>
<td>0.012-0.016</td>
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<tr>
<td>Sr²⁺ mg/l</td>
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<td>0.11-0.12</td>
<td>0.21</td>
<td>0.18-0.20</td>
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<td>0.22-0.25</td>
<td>0.18-0.20</td>
<td>0.17-0.18</td>
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<td>0.023</td>
<td>0.06-0.16</td>
<td>0.007-0.009</td>
<td>&lt;0.005-0.011</td>
<td>0.006-0.041</td>
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<td>Mn₂+ mg/l</td>
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<td>&lt;0.005-0.026</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
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<tr>
<td>Al³⁺ mg/l</td>
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<td>&lt;0.001-0.022</td>
<td>0.041</td>
<td>0.012-0.18</td>
<td>&lt;0.001-0.006</td>
<td>&lt;0.001-0.013</td>
<td>&lt;0.001-0.004</td>
<td>0.005-0.017</td>
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<tr>
<td>F⁻ mg/l</td>
<td></td>
<td>5.76-5.92</td>
<td>6.08-6.20</td>
<td>5.54</td>
<td>4.53-4.96</td>
<td>4.24-4.44</td>
<td>4.17-4.31</td>
<td>3.86-4.00</td>
<td>4.73-4.96</td>
</tr>
<tr>
<td>Cl⁻ meq/l</td>
<td></td>
<td>0.83-0.87</td>
<td>0.69-0.79</td>
<td>0.44</td>
<td>0.34-0.36</td>
<td>0.31-0.32</td>
<td>0.33-0.44</td>
<td>0.27-0.31</td>
<td>0.33-0.66</td>
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<tr>
<td>Br⁻ mg/l</td>
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<td>&lt;0.016</td>
<td>&lt;0.016</td>
<td>&lt;0.016</td>
<td>&lt;0.016</td>
<td>&lt;0.016</td>
<td>&lt;0.016</td>
<td>&lt;0.016</td>
<td>&lt;0.016</td>
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<tr>
<td>SO₄²⁻ mg/l</td>
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<td>6.79-7.30</td>
<td>7.12-7.27</td>
<td>8.67</td>
<td>5.52-6.48</td>
<td>6.35-6.58</td>
<td>5.98-6.76</td>
<td>6.17-7.10</td>
<td>7.34-7.77</td>
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<tr>
<td>NO₃⁻ mg/l</td>
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<td>0.032-0.764</td>
<td>0.020-0.061</td>
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<td>0.024-0.043</td>
<td>0.031-0.045</td>
<td>0.017-0.041</td>
<td>0.026-0.042</td>
<td>0.018-0.053</td>
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<tr>
<td>Tot. Alk. meq/l</td>
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<td>0.51-0.73</td>
<td>0.49-0.76</td>
<td>0.63</td>
<td>0.50-0.81</td>
<td>0.52-0.87</td>
<td>0.50-0.85</td>
<td>0.49-0.83</td>
<td>0.50-0.69</td>
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<tr>
<td>TIC mg/l</td>
<td></td>
<td>5.58-6.81</td>
<td>6.45-6.72</td>
<td>5.97</td>
<td>4.51-5.86</td>
<td>4.81-6.34</td>
<td>4.74-6.09</td>
<td>4.70-6.04</td>
<td>4.33-5.10</td>
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<tr>
<td>Si mg/l</td>
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<td>3.28-3.87</td>
<td>3.66-4.28</td>
<td>4.82</td>
<td>4.67-5.19</td>
<td>4.35-5.08</td>
<td>4.35-5.04</td>
<td>4.30-4.59</td>
<td>4.39-5.02</td>
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<tr>
<td>TDS mg/l</td>
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<td>63.7-70.6</td>
<td>75.8-81.4</td>
<td>66.3</td>
<td>53.9-60.3</td>
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<td>54.6-60.6</td>
<td>53.0-59.5</td>
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Tab. A.3: Ranges in composition of the southern fracture water of the GTS and for a surface water sample ("Totensee")

The intervals are listed from N to S (n.m. = not measured).

<table>
<thead>
<tr>
<th>Entity</th>
<th>Units</th>
<th>VE 13.001i2</th>
<th>VE 88.003i2</th>
<th>VE 88.003i3</th>
<th>HP 98.007i2</th>
<th>HP 98.007i3</th>
<th>Totensee</th>
</tr>
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<td>13.2-14.6</td>
<td>13.2-15.5</td>
<td>12.2-15.0</td>
<td>11.9-13.8</td>
<td>12.1-13.6</td>
<td>12.5</td>
</tr>
<tr>
<td>Eh (Ag/AgCl)</td>
<td>mV</td>
<td>-92 to -16</td>
<td>-198 to 62</td>
<td>-238 to -91</td>
<td>-203 to -56</td>
<td>-180 to -65</td>
<td>23</td>
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<tr>
<td>Li⁺</td>
<td>µg/l</td>
<td>42.8-43.8</td>
<td>28.1-35.5</td>
<td>31.1-32.1</td>
<td>32.0-39.0</td>
<td>33.0-36.4</td>
<td>n.m.</td>
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<td>Na⁺</td>
<td>mg/l</td>
<td>12.51-12.70</td>
<td>11.05-11.83</td>
<td>11.14-11.83</td>
<td>11.71-12.01</td>
<td>11.78-11.95</td>
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<tr>
<td>K⁺</td>
<td>mg/l</td>
<td>0.28-0.34</td>
<td>0.44-0.57</td>
<td>0.30-0.38</td>
<td>0.37-2.35</td>
<td>0.39-0.52</td>
<td>0.38</td>
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<tr>
<td>NH₄⁺</td>
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<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
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<td>Mg²⁺</td>
<td>mg/l</td>
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<td>0.018-0.022</td>
<td>0.025-0.036</td>
<td>0.016-0.019</td>
<td>0.016-0.018</td>
<td>0.086</td>
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<td>Ca²⁺</td>
<td>mg/l</td>
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<td>5.45-6.41</td>
<td>5.58-6.76</td>
<td>4.89-5.90</td>
<td>4.29-5.18</td>
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<td>5.00-5.21</td>
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<td>0.017-0.047</td>
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<td>US 85.001i3</td>
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<td>US 85.002i3</td>
<td>US 85.002i4</td>
<td>US 85.002i5</td>
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<tr>
<td>pH</td>
<td>7.3 to 8.1</td>
<td>6.6 to 6.8</td>
<td>9.1</td>
<td>9.1 to 9.4</td>
<td>8.5 to 9.4</td>
<td>8.8 to 9.4</td>
<td>8.9 to 9.4</td>
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<td>Calcite</td>
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<td>-2.8 to -2.6</td>
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<td>-2.7</td>
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<td>-4.7 to -4.4</td>
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<td>-0.6 to 1.5</td>
<td>1.8</td>
<td>0.7 to 1.7</td>
<td>-0.2 to 1.8</td>
<td>0.6 to 1.8</td>
<td>0.8 to 1.9</td>
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<td>Fluorite</td>
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<td>-0.3 to -0.2</td>
<td>-0.1</td>
<td>-0.4 to -0.3</td>
<td>-0.3 to -0.2</td>
<td>-0.4 to -0.4</td>
<td>-0.5 to -0.4</td>
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<td>-1.4</td>
<td>-2.8 to -2.1</td>
<td>-4.0 to -3.7</td>
<td>-3.6 to -2.4</td>
<td>-3.7</td>
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<td>-0.1 to 0.8</td>
<td>-0.9 to -0.1</td>
<td>-0.6 to 1.0</td>
<td>-0.3</td>
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<td>Muscovite</td>
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<td>2.4 to 3.4</td>
<td>0.8 to 1.4</td>
<td>1.3 to 3</td>
<td>1.4</td>
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<td>-0.0 to 0.0</td>
<td>0.1</td>
<td>-0.0 to 0.0</td>
<td>-0.0 to 0.1</td>
<td>-0.1 to 0.0</td>
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Tab. A.4: continued for southern borehole intervals

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<tr>
<th>Borehole interval</th>
<th>HP 98.007i3</th>
<th>HP 98.007i2</th>
<th>VE 88.003i3</th>
<th>VE 88.03i2</th>
<th>VE 13.001i2</th>
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<td>9.0 to 9.8</td>
<td>8.9 to 9.8</td>
<td>9.2 to 9.4</td>
<td>9.0 to 9.8</td>
<td>9.2 to 9.6</td>
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<td>Calcite</td>
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<td>-0.1 to 0.0</td>
<td>-0.4 to 0.1</td>
<td>-0.3 to 0.0</td>
</tr>
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<td>Log P(CO₂)</td>
<td>-5.8 to -4.7</td>
<td>-5.7 to -4.5</td>
<td>-5.2 to -4.9</td>
<td>-5.8 to -4.8</td>
<td>-5.5 to -5.0</td>
</tr>
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<td>Adularia</td>
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<td>-2.3 to -1.5</td>
<td>-3.4 to -3.1</td>
<td>-2.7 to -2.3</td>
<td>-2.1 to -1.6</td>
</tr>
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<td>Albite</td>
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<td>-3.4 to -2.9</td>
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<td>-3.0 to -2.5</td>
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<td>-4.6 to -4.2</td>
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<td>-5.3 to -4.9</td>
<td>-4.0 to -3.2</td>
</tr>
<tr>
<td>Fe(OH)₃(a)</td>
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<td>0.2 to 0.8</td>
<td>0.6 to 1.9</td>
<td>0.4 to 1.5</td>
<td>1.2 to 2</td>
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<td>-0.6 to -0.4</td>
<td>-0.3 to -0.2</td>
</tr>
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<td>-4.6 to -3.8</td>
<td>-3.8 to -2.7</td>
<td>-2.4 to 1.0</td>
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<td>Muscovite</td>
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<td>2.9 to 4.6</td>
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<td>-0.2 to -0.0</td>
<td>-0.1 to 0.0</td>
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Tab. A.5: Compilation of the average $\delta^{18}$O and $\delta^2$H values and measured $^3$H concentrations

Atmospheric precipitation data from IAEA/WMO (2018, Grimsel Pass), n.m.: not measured

<table>
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<th>Sample ID</th>
<th>Sampling date</th>
<th>$\delta^{18}$O Mean</th>
<th>$\delta^{18}$O St.dev</th>
<th>$\delta^2$H Mean</th>
<th>$\delta^2$H St.dev</th>
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<tr>
<td>US 85.001i2</td>
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<td>0.42</td>
<td>-90.08</td>
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<td>US 85.001i3</td>
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<td>0.05</td>
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<td>US 85.002i1</td>
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<td>0.07</td>
<td>-88.45</td>
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<td>Precipitation mean 2013</td>
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</table>
Appendix 3  Detailed description of groundwater age dating records at the GTS

This Appendix presents a detailed account of isotopic studies and measurements of $^3$H, $^{36}$Cl and $^{14}$C in fracture waters assembled over the entire history of the GTS investigations. Much of the data are contained in reports that are difficult to access and are therefore summarised here, with Tab. A.6 containing all measurements that we are aware of. In some cases, only average values are available, with some details no longer traceable to original data.

The only $^3$H measurements performed before construction of the GTS were within the framework of site characterisation when 6 horizontal boreholes of ca. 100 m length were drilled in 1980 from the KWO main access tunnel (excavated in 1974) across the footprint of the future GTS (Geotest AG 1981). Detection limits varied (0.3–3.8 TU), and one value from SB1 (SB 80.001) showed a distinctly elevated value of 7.8 TU ($\pm 2.2$). A value of 2.2 TU ($\pm 0.5$; SB 80.004) was thought to be not well constrained, and all others were below detection. The conclusion was, therefore, that boreholes largely yielded recharge water of pre-bomb age in the region of the GTS, with one exception. Values of 58.7 TU were found from fault seepages at tunnel location 2074 m (near/below Lake Grimsel). Lakes Rätrichsboden (35.5 TU) and Grimsel (39.2 TU) contained values typical for atmospheric precipitation at that time, with some seasonal influence also from glacial melt water.

Follow-up analyses (Nagra 1985) attempted to monitor/verify the elevated $^3$H values found in SB 80.001 (7.8 TU) and also in SB 80.004 (2.2 TU). Four samples from SB 80.001 from May 1982 to November 1983 showed two low values of 0.3 and 1.1 TU, and two below a detection limit of 1.5 TU (Tab. A.6). SB 80.004 indicated no tritium concentration above a detection limit of 0.5 TU in 1982. Later reports dismissed the initial high value in SB 80.001 before construction and stated that all SB 80.00x boreholes were free of tritium (e.g. Frick et al. 1992).

Site characterisation during and after construction of the GTS in 1983 is largely compiled in Keusen et al. (1989), where some geochemical data as well as tritium measurements are included (Tab. 7 in Keusen et al. 1989). More details on geochemical data and tritium measurements are provided in NIB 87-72, the complementary report to NTB 87-14 (Keusen et al. 1989). Frick et al. (1992) summarise the MI Experiment (1985–1990) and include some geochemical data and tritium concentrations throughout the GTS, which are referenced to Kralik (private communication in 1991). In particular, Frick et al. (1992) present a N-S profile with 24 tritium concentrations along the KWO main tunnel (Fig. A.1). For the entire profile, distinctly elevated values (20 TU, no sampling date given) are shown for one location only (2 measurements), which refers to a tunnel position of ca. 1630 m (ca. 130 m south of the GTS). Most other values are below 1 TU, whereas only a few are in the range of 1.5–4 TU (no tabulated data, no borehole associations). At the MI location, undisturbed values of 0.6–0.9 TU ($\pm 0.6$) were sampled in 1983, 1984 and 1991, whereas values of 2–4 TU (1986 and 1988) were inferred to be contaminated by drilling water or injection water from borehole testing. This is because drilling for the MI campaign (1986/1987) was done with low-conductivity surface water originating from the Trübtensee, a lake at 2300 m altitude near the Grimsel Pass, which was likely characterised by substantial tritium concentrations at that time.
Keppler (1996) reports results from a thorough sampling and analysis campaign performed during 1992–1993 on fracture waters (boreholes and seepages), as well as on surface and spring waters collected at the GTS and the KWO access tunnel with the focus on flow regimes and geochemical characterisation. The campaign included tritium, $^{14}$C and selected $^{36}$Cl analyses for age dating and constraining average residence times. Sampling for tritium (and other parameters) was done quarterly, 8 times between May 1992 and November 1993. Unfortunately, no tabulated values are given, and only average concentrations are reported. However, the temporal evolution is discussed for a few specific locations. Surface and spring waters, representing a proxy for recharge, range from $14\pm21$ TU, except for two springs yielding concentrations of 64 TU (spring at Spittelamm-bach), and 40 TU (spring at Chessibidmerbach), respectively. Elevated tritium concentrations in seepages from fault zones were observed in the northern part of the KWO main access tunnel, where the overburden is below 200 m and recent recharge prevails (up to ca. 700 m along the tunnel), and towards the south (> 1900 m along the KWO main access tunnel), where the overburden is lower and an influence from Lake Grimsel also leads to elevated values. The region below the Juchlistock hosting the GTS (1000–1500 m along the KWO main access tunnel), with an overburden of $>300–520$ m, yielded no tritium concentrations above 1.6 TU, except for one value of $4.8\pm0.1$ TU measured in a sample from the SB 80.000 borehole (this should most likely be SB 80.001), corresponding to a packed-off deep section of the SB 80.001 borehole drilled before construction of the GTS (see above). An interesting section is between 1600–1800 m along the KWO main access tunnel, where the overburden is 460–340 m. Despite this overburden, consistently elevated tritium concentrations were found in boreholes HF 84.031 (1582 m, $11.7\pm0.2$ TU), and EM 85.012 (1625 m, $21.7\pm2.3$ TU), as well as in two fault seepages at 1698 m (23.8 TU) and 1755 m (16.7 TU).

Keppler (1996) declared the GTS region as free of bomb tritium (notably below pre-bomb background), with variations near detection (0.6 to 1.6 TU) being due to minor artefacts as discussed above, and the elevated value of 4.8 TU in the old SB 80.001 borehole being potentially affected by the use of surface water in the adjacent BK area. Systematic temporal evolutions were recorded for boreholes HF 84.031 and EM 85.012. The former showed a gradual increase from 9.4 to 13.9 TU, whereas a gradual decrease from 25.4 to 18.6 TU (1.75-year period, 8 quarterly measurements) was observed for the latter. Other fracture waters with observed tritium concentrations decreased during this period by 10–15% in accordance with radioactive decay. From these observations, it can be inferred that the maximum bomb input had already passed EM 85.012, but was still arriving at HF 84.013.
Based on $^3$H analyses (Fig. A.2), Keppler (1996) applied a piston-flow model to estimate average residence times with an input function (recharge) discretised annually for the time period 1953–1992 and adjusted to the GTS latitude and altitude for times before local monthly measurements started in 1972 at Guttannen and the Grimsel Pass. The results yield residence times > 40 years for the low values in the GTS region, 5 years for EM 85.012, 4.5–9 years for faults at 1698 and 1755 m (KWO main access tunnel), and 36.5 years for HF 84.031. Short mean residence times (4.5 to 12.5 years) were also obtained for fracture waters towards the northern end, and below Lake Grimsel towards the south. In summary, $^3$H analyses indicate residence times of > 40 years for water-conducting faults in the region of large overburden (including the GTS), except for some faults south of the GTS, at 1550–1800 m along the KWO main access tunnel, where tritiated water was measured in all tested faults, corresponding to residence times of 4.5–36.5 years.

![Fig. A.2: N-S cross-section along the KWO main access tunnel showing the overburden and the tritium concentrations measured by Keppler (1996)](image)

The FEBEX experimental site was developed in 1995/1996 to install a large-scale long-term heater test with bentonite, including drilling of dedicated boreholes for groundwater sampling and monitoring. Sampling campaigns performed in 2000 and 2003 (pers. comm. Antonio Garralón Lafuente) showed tritium concentrations below a detection limit of 0.67 TU, and only one concentration detected at 0.55 TU. The FEBEX site was therefore considered as being free of tritium.

No systematic sampling campaigns for tritium analysis or other geochemical/isotopic parameters were made after the Keppler campaign (1992–1993). Thus, the most recent $^3$H analyses were carried out in the LASMO Project and started in 2014. Sampling was performed for specific intervals of existing multi-packer systems of previously drilled boreholes (designated with "i" and a number, increasing from borehole end towards the tunnel). During the January 2016 sampling campaign, samples for the analysis of tritium were taken from 15 test intervals (Tab. A.6) within the GTS area. From the SB 80.001(i1) interval, only one sample showed a measurable tritium activity (3.1 TU), whereas all other samples yield activities at or below detection limit (< 0.6 TU). This suggested that, 23 years after the last systematic tritium sampling campaign (Keppler 1996), fracture waters sampled from the GTS (except for one) have residence times > 60 years. Additionally, borehole EM 85.012 (open borehole with free outflow for several years) was also sampled and yielded a tritium concentration of 5.1 ± 0.8 TU, compared to 25.4 TU in 1992 (see
details above). The Handegg river and Lake Grimsel were also sampled and resulted in concentrations of $7.5 \pm 0.9$ and $7.0 \pm 1.1$ TU, respectively. A somewhat reduced sampling programme was carried out in December 2017 covering some of the same borehole intervals (Tab. A.6) and a sample from Lake Grimsel yielding a concentration of $5.8 \pm 0.3$ TU. One analysis failed and was re-sampled in June 2018 along with an additional borehole interval (Tab. A.6). These measurements confirmed low tritium levels of $0.1-0.4$ TU, except for SB 80.001 where tritium concentrations of $2.5 \pm 0.3$ TU were measured (compared to $3.1$ TU nearly 2 years earlier, see above).

Borehole ADUS 96.001, drilled in 1996, is sub-horizontal and extends 197 m towards WNW in the southern part of the GTS (Fig. 7.3). It was packed-off near the tunnel and, with 4.8 MPa, it showed one of the highest mixed hydraulic heads of the entire GTS. Further, it is characterised by a high outflow rate, a large storage capacity and it intersects numerous fault zones. This large test interval was sampled in April 2016 and yielded a tritium concentration of $2.3 \pm 0.4$ TU (Tab. A.6). Hydraulic testing was started in 2017 and successively deeper intervals were isolated, tested and also sampled for tritium analysis. Three intervals sampled between July and October 2017 were all tritium-bearing at levels of $1.9 \pm 0.2$, $2.2 \pm 0.3$ and $2.8 \pm 0.3$ TU. Two deeper intervals up to 125 m were sampled between September and December 2017, resulting in tritium concentrations of $1.9 \pm 0.3$ and $1.8 \pm 0.3$ TU, whereas the deep end to 197 m yielded a tritium concentration of $1.6 \pm 0.3$ TU. Hydraulic heads increased with increasing distance from the tunnel, and it can be assumed that deeper intervals were feeding shallower intervals during the 10 years when only a packer near the tunnel was installed. It is therefore also unclear if all the tested intervals truly represent conditions of the packed-off sections without effects from the previous history of mixing. In this context, it should be noted that sealing of ADUS 96.001 with a single end packer resulted in a crossflow, where the borehole was essentially producing from the end interval for a significant period of time.

In general, the tritium sampling campaign carried out within the framework of LASMO confirmed the findings reported by Keppler (1996).

Tab. A.6: Compiled tritium concentrations for the GTS

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<th>SB 80.002</th>
<th>SB 80.003</th>
<th>SB 80.004</th>
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*a* Geotest AG (1981)

*b* Nagra (1998)

*c* Keusen et al. (1989) – Auxiliary report (NIB 87-42/AN 86-252)

*d* Keusen et al. (1989) – Auxiliary report (NIB 87-42/AN 87-141)

*e* Keusen et al. (1989) – Auxiliary report (NIB 87-42/AN 87-020)

*f* Keppler (1996)

*g* Schneeberger (2017), UniBERN & LASMO project

*h* IAEA/WMO (2018) – input function discretised for 1 year-period

*TS* refers to transformer station, RäBo refers to Lake Rätrichsboden, Kalotte and Pinkel are surface water inflows along the Migration shear zone at AU96.
Appendix 4  Short introduction to experiments carried out at the GTS

In this Appendix, the experiments presented in the table in Chapter 9 are described in further detail. They are sorted alphabetically per investigation phase at the GTS. The interested reader is referred to the key references indicated in the table for further details on a specific project (Tab. 9.1).

Auflockerungszone (AU) – Excavation Effects

Aims and objectives
Knowledge of the rock strata surrounding an underground facility is of the utmost importance for the long-term safety of a deep geological repository site. The AU experiment aimed at characterising the effects of excavation on the rock hosting an underground facility.

Project organisation
The project was a collaboration between Germany and Switzerland between 1984 and 1990.

Results / conclusions
Monitoring of the stress changes in the rock as a result of excavation was successful. However, the prediction or quantification of the parameters influencing the Excavation Damaged Zone was not achieved (NTB 85-46).

Bohrlochkranzversuch (BK) – Fracture System Flow

Aims and objectives
For the long-term safety assessment of a deep geological repository, it is key to characterise the fracture pattern in the rock volume. The permeability of the rock volume also has to be determined. The project aimed at the characterisation of the fracture pattern and assessment of the influence of the fractures on the in-situ flow field.

Project organisation
The BK experiment was run by German and Swiss organisations between 1984 and 1990. The BK cavern branching off the main tunnel at L180 was excavated for the project and named accordingly.

Results / conclusions
Detailed geological mapping in the BK area allowed the identification of major structure orientations (NE-SW, E-W, NW-SE). The resulting fracture statistics could be mathematically extrapolated in space by adding an uncertainty of 5–10° in dip and dip azimuth along the planes. The fracture statistics served as the basis for the evaluation of the subsequently performed hydraulic tests, and as prediction tools. In total, 99% of the rock volume is composed of unfractured rock matrix, but water flow is focused along fractures. Large-scale tectonic structures decouple blocks with smaller-scale fracture networks that were identified as water conducting and traceable over tens of metres.
Electromagnetic high-frequency measurements (EM)

Aims and objectives
The EM project was dedicated to the non-destructive investigation of the rock volume surrounding single boreholes or tunnels. The project aimed at testing existing technologies and further developing investigation technologies.

Project organisation
The EM project was part of the larger cooperation between German and Swiss organisations between 1984 and 1990.

Fracture zone investigation (FRI)

Aims and objectives
The project was dedicated to determining the fundamental nature of the propagation of seismic waves in fractured media and to relating the seismological parameters to hydrological parameters.

Project organisation
The FRI experiment was run between 1987 and 1989 by US and Swiss organisations.

Results / conclusions
The experiment used high frequency 1000 to 10,000 Hz signals in a crosshole configuration at scales of several tens of metres. The investigation area (i.e. AU126) is crossed by a dominant fracture zone, which was the target of the investigations. In-situ geomechanical and hydrological tests were carried out to determine the mechanical stiffness and conductivity of fractures. Laboratory work indicates that the level of saturation of the rock medium has a dominant effect on P- and S-wave velocities and amplitudes. The results indicate that both P-waves and S-waves can be used to map the location of fractures, both natural and induced from mining activity. Additionally, it appeared that, for frequencies approaching several kilohertz, attenuation measurements are more useful than velocity measurements. At lower frequencies, the opposite seems to be true. Furthermore, open fractures which are hydrologically conductive are more visible to seismic waves than non-conductive fractures.

Gebirgsspannung (GS) – Rock Stress measurement

Aims and objectives
The experiment aimed at testing and developing new techniques for measuring the in-situ stress field in crystalline rock. The GS experiment gave the name to the GS drift around L180 in the main GTS tunnel.

Project organisation
The Rock Stress measurement experiment was carried out by German and Swiss organisations between 1984 and 1990. It was run in parallel with the BK experiment.

Results / conclusions
Within the framework of the GS experiment, both direct (i.e. hydraulic fracturing) and indirect (i.e. overcoring) techniques were used to characterise the in-situ stress field. Further, borehole deformation was used to determine major rock mechanical properties such as Young's modulus. Detailed geological mapping of the cores and the area in the vicinity complemented the stress measurements. The dilatometer tests yielded relatively high values for Young's modulus between 35 and 45 GPa.
Different stress quantification techniques produced similar results, indicating a maximum horizontal stress between 25 and 40 MPa, with a minimum horizontal stress ranging from 15 to 30 MPa. Detailed geological mapping revealed a strong relationship between the acquired stress data and the structures, showing that the occurrence of large-scale fault zones or metabasic dykes influences the stress field.

**Hydraulic potential (HPA)**

*Aims and objectives*

One of the general objectives of the GTS is to increase know-how in planning, conducting and interpreting underground tests and also to foster the level of practical experience in the operation of test equipment. With respect to hydrogeological investigations, the aim was specifically to build confidence in routine tasks planned for the hydrological investigation of potential repository sites. The HPA project was designed to develop and apply hydrological test systems and testing techniques.

*Project organisation*

The HPA project was run between 1984 and 1990 by Swiss organisations.

*Results / conclusions*

The hydrogeological investigations in an underground environment were successfully tested and are now standard techniques that are frequently used. Specifically, the development of a multi-packer system was developed in the HPA experiment.

**Migration Experiment (MI)**

*Aims and objectives*

The experiment aimed at the acquisition of fundamental physical and chemical knowledge on the transport of radionuclides in fractured media. In more detail, the experiment was designed to develop new technologies for site characterisation, to study the hydrology and geochemistry of fractured rock, and to achieve a thorough characterisation of a single water-conducting feature based on laboratory, field and modelling work, as well as the testing of models for radionuclide transport.

*Project organisation*

The MI experiment is located in the radiation-controlled zone and was started in 1984 and run till 1996. It was a collaboration between Japanese and Swiss organisations and was carried out during different operational phases of the GTS; and CFM experiment is currently running as a follow-up experiment.

*Results / conclusions*

In order to support the development of transport models, a detailed geological, geochemical and hydrogeochemical characterisation of the MI shear zone (the studied water-conducting feature) was carried out. Natural decay-series isotope profiles across the MI shear zone provided evidence of connected, diffusion-accessible porosity extending for some centimetres into the unfractured rock matrix. Laboratory work was carried out to identify suitable sorbing tracers. Three sorbing radionuclides were selected for the transport test: weakly sorbing sodium, moderately sorbing strontium and more strongly sorbing caesium.
Overall, the MI experiment has demonstrated that the methodology for the characterisation of water-conducting features, the simplification of this characterisation for modelling purposes, the adaptation of laboratory data to field conditions, the selection of transport-relevant processes and the numerical solution of the governing equations are applicable to solute transport modelling in a fractured crystalline rock volume.

**Hydrodynamic modelling (MOD)**

**Aims and objectives**
The MOD project investigated an adequate strategy for hydrodynamic modelling of fracture water flow in a fractured rock body such as that surrounding the GTS. Specifically, the project aimed at the development and testing of new numerical tools and techniques related to mesh generation, pre- and post-processing and at the determination of appropriate calibration and validation procedures and criteria. Further, the project was designed to support the interpretation of hydrological in-situ experiments in the GTS test programme and to clarify some fundamental questions concerning the modelling of hydrodynamic effects in fractured rock around underground constructions.

**Project organisation**
The MOD was run by German and Swiss organisations between 1984 and 1993.

**Results / conclusions**
Hybrid modelling (porous medium with a small number of discrete 2D fracture zones) following a hierarchical model structure is a useful method for characterising water flow through fractured media on the regional scale as well as on the local scale. Hydraulic heads calculated on a regional scale showed only a weak sensitivity to variations in transmissivity values. Hybrid modelling further provides a basis for future hydrodynamic modelling of the near field of a rock laboratory or water repository. A calibration method was proposed and successfully applied to a local model. The experience gained with the MOD experiment shows that such modelling requires an iterative procedure with checking and updating the various model assumption in each step.

**Near-field Hydraulics (NFH)**

**Aims and objectives**
The NFH experiment was designed to study the effects of man-made excavations such as boreholes or tunnels on the hydraulic flow field in the area surrounding an excavation.

**Project organisation**
The NFH project was run by German and Swiss organisations between 1984 and 1990.

**Results / conclusions**
In underground structures, the possibility of permanently altering the saturation conditions in the rock pore space exists. In low porosity rocks such as those surrounding the GTS, the saturation conditions gradually change from saturated to partially saturated due to the excavation. In contrast to water flow, the possibility for gas flow is only achieved in partially water-saturated conditions. The desaturation of the tunnel near field is a reversible process as long as the repository produces no gas.
Neigungsmessung (NM) – Tilt meter measurements

Aims and objectives
The NM experiment was designed to measure neotectonic movements in the rock volume surrounding the GTS using high-precision tilt meters installed in designated boreholes.

Project organisation
The NM project was part of a larger German-Swiss investigation run between 1984 and 1990.

Results / conclusions
Between 1985 and 1989, the deflections from the vertical were observed at 6 different measurement stations at the GTS. The periodic range observed include earth tides and aperiodic tectonic movements. The earth tide analysis gave differing amplitude factors and phase shifts at the different measurement devices. This could be due to large-scale inhomogeneities between the stations, such as large fault zones decoupling single crustal blocks. Detailed investigations of the effect of the lakes in the vicinity showed that the Lake Grimsel has a limited influence on the rock volume at the GTS. Further, an annual perturbation could be observed and correlated with an annual air pressure variation. The aperiodic analysis indicates subsidence in the vicinity of the reservoirs (Lakes Grimsel and Rätrichsboden).

Stollenvorfeldprognose (SVP) - Prediction ahead of tunnel face

Aims and objectives
The SVP project was dedicated to investigating the potential of geophysical remote sensing methods to predict discontinuities ahead of the tunnel face. This was attempted to provide a more complete knowledge of the rock volume for safe tunnel construction.

Project organisation
The SVP project was part of the German-Swiss collaboration between 1984 and 1990.

Results / conclusions
The SVP project was based on seismic methods rather than electro-magnetic (radar) due to the shallow penetration depth of the latter in electrically conductive rocks. Reflection seismic experiments showed that seismics could provide information on disturbances nearly perpendicular to the tunnel, cavities around the investigated segment of tunnel, and fractured zones and quasi-planar rock interfaces running parallel to the tunnel.

Underground seismics (US)

Aims and objectives
The US experiment was designed to test radar deflection equipment allowing a comprehensive interpretation of the geometry of structures at a specific site. Further, the radar measurements were used as the basis for a geological model of the study site.

Project organisation
The US experiment was carried out by Swedish, German and Swiss organisations between 1984 and 1990.
**Results / conclusions**

The tested equipment proved to be capable of routine investigations. Single-hole reflection measurements had an infiltration depth of ca. 150 m radially around the borehole, with a resolution of ca. 2 – 3 m. Using the system in a crosshole configuration, infiltration depth is increased to 200 m. Based on single- and crosshole radar data, the main geological features in the study area could be determined as being metabasic dykes. However, fractured zones do not show a strong signal in the reflectometers due to the moderate electrical conductivity of the intact granite and to the irregular shape of the zones themselves. Moreover, the perpendicular orientation of most features with respect to the borehole is more difficult to reproduce with the radar measurements than an orientation parallel to the borehole.

**Underground radar (UR)**

**Aims and objectives**

The UR experiment aimed at the prediction of groundwater flow and nuclide transport in a previously unexplored volume of the Stripa granite.

**Project organisation**

The UR experiment was carried out by a Swedish company under contract with Nagra between 1984 and 1990 in the Stripa URL.

**Results / conclusions**

Borehole radar investigations comprised single-hole reflection measurements with three centre frequencies of 22, 45 and 60 MHz. The obtained radar range between boreholes was approximately 100 m for lower frequency (22 MHz) and about 60 m for centre frequency (45 MHz).

The radar investigations resulted in a three-dimensional description of the structure at the study site. A generalised model combined three major zones, four minor zones and a circular feature. The zones are strongly heterogeneous, containing zones of increased faulting. They appear to be rather planar, at least at site-scale.

**Ventilation test (VE)**

**Aims and objectives**

The test was dedicated to the measurement of large-scale (metre-scale) hydraulic conductivity of the rock matrix.

**Project organisation**

The VE experiment was performed between 1984 and 1990. It was carried out by German and Swiss organisations. It was performed in the VE drift, south of the VE cavern.

**Results / conclusions**

Macropermeability along a 70 m long drift was found to be $k = 10^{-18}$ m$^2$ or $K = 10^{-11}$ m s$^{-1}$. The drift is mainly composed of unfractured rock matrix with only a limited number of major structures such as metabasic dykes or brittle fault zones. Detailed structural geological mapping of the tunnel surface in combination with hydraulic testing revealed that the influence of structures on the macropermeability depends on their extent. Structures locally increase the permeability within their area of influence, that is their lateral extent. The experiment has demonstrated that the collected in-situ data allow an accurate definition of the macropermeability.
Wärmetest (WT) – Heater test

Aims and objectives
The WT experiment tested the reaction of the rock volume to a heat influx. The heat influx was designed as an analogue to the heat production of radioactive waste shortly after emplacement. Furthermore, a numerical model was developed and tested for the thermo-mechanical processes in the vicinity of the heat source.

Project organisation
The WT experiment was performed in the WT drift between 1984 and 1990 by German and Swiss organisations.

Results / conclusions
The WT experiment has demonstrated that the influence of a heat source in the crystalline rock volume is limited both in space and time. The thermally induced mechanical response does not reach a repository-relevant scale. The overall deformation related to the expansion is small and the resulting stress is below 10 MPa. Further, no increased seismicity was observed during the experiment period. Observed changes in the hydraulic regime, mainly in the passive outflow rates, were localised and temporally short. The modelling of the results has proved to be relatively uncomplicated.

 Unsaturated zone (UZ)

Aims and objectives
The UZ experiment was dedicated to studying the effects of ventilation on the rock volume surrounding an underground tunnel. The unsaturated zone surrounding the tunnel was described by point measurements of water content and water potential.

Project organisation
The UZ experiment was conducted by Swiss organisations during investigation Phase III at the GTS between 1991 and 1993.

Results / conclusions
The formation of an unsaturated zone surrounding the GTS was observed during previous experiments. The unsaturated zone has strong effects on the hydraulic conditions in the near field of the GTS. The ventilation of a tunnel has a strong influence on the water fluxes in the neighbouring rock volume to the GTS. Therefore, the macropermeability tends to be overestimated. The changes induced by the ventilation proved to be reversible.

Borehole sealing (BOS)

Aims and objectives
The BOS experiment was designed to test sealing in boreholes up to 500 m deep, to seal non-cylindrical boreholes, to achieve sealing with a hydraulic conductivity below $10^{-11}$ to $10^{-12}$ ms$^{-1}$ and to assure quality control during routine work.

Project organisation
The BOS project was run between 1994 and 1996 by organisations from France and Switzerland.
Results / conclusions
The sealing of the borehole was performed by injection of highly compacted bentonite pellets or granular bentonite. The bentonite pellets were emplaced using a modified core barrel, while the granular bentonite with a particle size between 4 and 10 mm was emplaced by pneumatic injection. The techniques employed were developed and constructed after a detailed literature study. Both techniques were used successfully in the GTS. The resulting sealing had hydraulic conductivity values below the values of surrounding intact granite (ca. $3-6 \times 10^{-12}$ ms$^{-1}$). Also, no evidence for enhanced conductivity along the sealing trace was observed. Both techniques have advantages and disadvantages. While the modified core barrel requires no additional specialists on site, but can be performed by the drilling crew, the pneumatic injection is advantageous in cases where very long sections have to be sealed.

Connected porosity (CP)
Aims and objectives
The CP project was initiated to characterise the connectivity of in-situ matrix porosity, to quantify the influence of sample preparation on total porosity, and to assess the influence of the obtained results on transport models used for performance assessment purposes.

Project organisation
The CP project was run between 1994 and 1996 as a Japanese-Swiss joint project dedicated to the study of radionuclide retardation processes in fractured crystalline rock.

Results / conclusions
Matrix porosity is a key parameter for the evaluation of various scenarios in the estimation of radionuclide retardation in the geosphere. The project revealed that the structural and mineralogical heterogeneity in the less deformed rock matrix of the Grimsel Granodiorite is significant and strongly influences the prevailing porosity. Four different pore types were distinguished: grain boundary pores, sheet silicate pores, solution pores and micro-fractures. All pores form a connected network, which was accessible by resin during the experiment. Comparison of newly developed pore quantification techniques with standard measurement techniques indicates that standard techniques tend to overestimate in-situ porosity by a factor of 2 to 2.5. The assessment of the influence of the aforementioned results on the performance assessment of retardation processes revealed that the retardation processes are relatively insensitive to the magnitude of the porosity and pore diffusion coefficient in the rock matrix. However, the depth of connected pores has a strong influence. Connected porosity in the two rock types studied could be identified up to several metres into the rock matrix.

Excavation Damaged Zone experiment (EDZ)
Aims and objectives
The EDZ experiment aimed at the description of the potentially occurring damaged zone in the vicinity of the GTS tunnels. The damaged zone formed as a result of the excavation and subsequent stress relief fracturing. Special focus was placed on the hydraulic regime and the mechanical properties of the EDZ.

Project organisation
The EDZ experiment was run between 1994 and 1996 within the framework of the near-field programme in investigation Phase IV. The project was run by French, Spanish, Japanese, Swedish, US, other European and Swiss partners and was carried out in the WT tunnel.
Results / conclusions
Detailed geological mapping was carried out in the WT tunnel to confirm the study site. In-situ stress measurements using the borehole slotter technique were performed and further used as a basis for the numerical modelling of the virgin in-situ stress field. The results from the borehole slotter measurements could not be explained by pure gravitational loading and a far-field tectonic stress striking NE-SW was added in order to reproduce the strain measurements. A small increase in stress as well as the frequency of micro-fractures in the vicinity of the tunnel potentially relate to the occurrence of a plastic zone. The displacement field and the geomechanical behaviour of the rock volume surrounding the WT tunnel are strongly influenced by the existence of mechanical discontinuities formed by ductile shear zones or brittle fault zones. Shear deformation of up to 10 mm along the tunnel walls was inferred from local 2D numerical modelling.

A hydraulic testing campaign revealed increased hydraulic conductivity within the first 2 m away from the tunnel wall. This corroborates the existence of an EDZ. Increased macroscopic fracture frequency, however, was only observed within the first 20 cm away from tunnel wall.

Based on the evidence gathered in the field, a new methodology for estimating axial flow in the near field after closure and resaturation of the tunnel was developed.

Excavation project (EP)
Aims and objectives
The EP experiment aimed at enhancing the understanding of radionuclide transport in fractured rock. The experiment was designed as a follow-up project of the MI experiment, specifically dedicated to determining the locations and processes resulting in radionuclide retardation. The EP project involved injection of a radionuclide "cocktail" (\(^{238}\)U, \(^{235}\)U, \(^{234}\)U, \(^{237}\)Np, \(^{99}\)Tc, \(^{152}\)Eu, \(^{60}\)Co, \(^{75}\)Se, \(^{113}\)Sn, and stable Mo) of safety-relevant radiotracers into a water-conducting fault zone.

Project organisation
The EP experiment was run between 1990 and 1996 as part of a larger Japanese-Swiss project dedicated to the study of radionuclide retardation processes in fractured crystalline rock.

Results / conclusions
The radiotracer "cocktail" was successfully injected into the water-conducting zone by a dipole between two boreholes 2 m apart cutting the same water-conducting zone. However, the injection occurred in an acidified form and therefore little information of direct relevance about the geochemical processes of radionuclide retardation can be gleaned from their in-situ behaviour. After completion of the radiotracer test, the experimental setup was stabilised by resin injection and subsequently overcored. The water flow path was observed as strongly channelised, where the open tube-like channels are dominated by advective flow.

Development of seismic tomography (TOM)
Aims and objectives
The TOM project had two components: evaluating and testing underground seismic sources for use over large measuring distances and improvement of analysis in terms of stability, quality and resolution.
Project organisation
The TOM project was designed as a follow-up project of the US experiment. It was run in the GTS between 1994 and 1996 by UK and Swiss organisations.

Results / conclusions
Various seismic sources were tested at the GTS. Of the tested sources, small explosive charges were found to have the most favourable energy and frequency characteristics. Seismic sources were located both in water-filled boreholes (sparker, two piezo-electric sources, explosives) and at the tunnel wall (accelerated weight drop, mini-vibrator, bolt gun, buffalo gun, explosives). At the GTS, the target distance of approx. 1000 m was reached with explosive charges of around 50 g or more. The project was also partially dedicated to the improvement of analysis techniques and three inversion techniques were tested and developed. Several problems occurred in the first inversion taking into account the heterogeneity of the rock, however the encountered artefacts could be overcome.

Colloid and Radionuclide Retardation (CRR)

Aims and objectives
The CRR is dedicated to improving the understanding of the in-situ retardation of colloid-associated, safety-relevant actinides and fission products in the vicinity of the Engineered Barrier System.

Project organisation
The CRR project was run between 1997 and 2002 by organisations from France, Spain, Germany, Japan, the USA and Switzerland.

Results / conclusions
The central component of the CRR was a series of dipole tracer tests that were carried out in the same water-conducting fault zone as the MI and the EP experiments. The tracers consisted of uranine, bentonite colloids, homologue elements for the tri- and tetravalent actinides, and finally a tracer cocktail containing isotopes of Am, Np, Pu, U, Tc, Th, Cs, Sr and I. The natural colloid background in the Grimsel groundwater showed an average colloid diameter of around 200 nm and a stable colloid concentration around 5 \( \mu \text{gL}^{-1} \). In the absence of bentonite colloids, a clearly lower recovery was found for the homologue elements and for the final tracer cocktail.

Effective Field Parameters (EFP)

Aims and objectives
Predictive models of groundwater flow and solute transport are indispensable for long-term safety analyses of a deep geological repository. The EFP project aimed at the examination of different techniques for characterising the rock volume, the development of a structural model, checking numerical models for calculation of the temporal and spatial distribution of tracer concentration on a large-scale, and validating the developed model using in-situ data from large-scale tracer experiments at the GTS.

Project organisation
The EFP project was initiated by Germany following the large-scale investigations performed by Germany and Switzerland between 1984 and 1990. The EFP was run between 1997 and 2002.
Results / conclusions

Generally, the EFP experiment has shown that only a combined modelling strategy considering deterministic and stochastic distribution of effective parameters and a corresponding numerical code will allow large-scale predictive modelling to be performed. Effective parameters, which were evaluated from the small and intermediate scale, should be upscaled to the spatial variance and correlation length for the large-scale modelling. Non-linear adsorption and desorption dynamics combined with chemical reactions may become important in the near-field, whereas, in the far-field, the matrix diffusion and the K_d concept will ensure a sufficient prediction feasibility due to the generally low concentration levels.

Gas Migration (GAM)

Aims and objectives
The GAM experiment was dedicated to the development and testing of laboratory and field equipment for tracer experiments. Innovative technologies such as Laser Scanning Confocal Microscopy, X-Ray tomography, flow visualisation in artificial fractures, nuclear magnetic resonance measurements or neutron radiography were employed. The upscaling methodologies and derivation of effective parameters was another issue of interest.

Project organisation
The GAM project was run in the GTS between 1997 and 2001 by organisations from France, Spain, the USA and Switzerland.

Results / conclusions
The investigations comprised theoretical studies on solute transport in a non-uniform flow field and assessment of the impact of the micro-structures on solute and gas transport. Related to the theoretical studies was the numerical interpretation of the combined solute and gas tracer tests, which revealed the great potential of such data sets with regard to model discrimination. Initial investigations of transport processes in a single heterogeneous shear zone were planned on a 1 to 10 m scale, however, the unexpectedly low pore volume of the flow paths caused major problems. Generally, shear zones in the studied area are described as continuous, planar structures ranging over hundreds of metres. Detailed mapping of the fault core revealed that the experimental shear zone is formed by multiple sub-parallel fault cores with metre to decametre extents. The fault cores are composed of interconnected flow channels within a fine-grained gouge matrix. This heterogeneous structure of the fault zone was confirmed by hydraulic testing.

Gas migration in EBS and Geosphere (GMT)

Aims and objectives
In repositories for low- and intermediate-level waste, large quantities of gas are expected to be produced by corrosion and microbial degradation of metallic material. The GMT project aims at increasing the understanding of the interaction between the generated gas and the engineered barrier system and the geosphere. In detail, the GMT experiment considers the events where excess gas pressure could cause high stresses on the concrete silo and other EBS components, gas pressure could push contaminated water out of the waste packages into the geosphere, and escaping gas could transport volatile radionuclides through the EBS into the geosphere.

Project organisation
The GMT project was conducted between 1998 and 2004 by organisations from Japan, Germany, France and Switzerland.
Initial conclusions
Some initial conclusions can be drawn from the dismantling of the experiment: the buffer seems to be visually unaltered, uniform bentonite content indicates no segregation after emplacement, mineralogical content was consistent with that emplaced, no dominant water flow direction was observed, no lateral variability in density, porosity or water content was seen in the geophysical logs, directional logging did not show any high-porosity channels, dry density typically increased indicating some small additional compaction after emplacement, and the concrete silo and vent showed no evidence of damage or alteration.

Full-scaled Engineered Barrier System Experiment (FEBEX)
Aims and objectives
The FEBEX experiment was dedicated to demonstrating the feasibility of the Spanish disposal concept. As part of this demonstration, new methodologies were developed for assessing the thermo-hydro-mechanical as well as the thermo-hydro-geochemical behaviour of the Engineered Barrier System.

Project organisation
The FEBEX experiment, extended as FEBEXe and FEBEX-DP, was carried out between 1994 and 2015. The FEBEX experiments were multi-partner projects including organisations from France, Spain, Finland, Germany, Sweden, Japan, South Korea, the USA, the Czech Republic, the UK, and Switzerland.

Results / conclusions
The FEBEX experiment has demonstrated the feasibility of the Spanish repository concept. Further, the Engineered Barrier System (EBS) has performed as expected. The bentonite buffer reached a homogeneous saturation, which indicates that joints related to the buffer emplacement have been quickly sealed. The buffer showed a relatively uniform axisymmetric thermal, saturation and stress response that was controlled by the distance to the heater. Changes in the mineralogy and the porewater within the buffer were observed and could be related to interaction with the geosphere. THM modelling was carried out throughout the experiment and evolved as a product of newly obtained data. The evolution of the buffer could be modelled accurately as the major processes such as buffer saturation were identified prior to the emplacement.

Hyperalkaline Plume in Fractured rock (HPF)
Aims and objectives
Cement is a major component of the Engineered Barrier System (EBS) in low- and intermediate-level waste repositories. The interaction between the hyperalkaline solutions derived from the degradation of the cement with the host rock could alter the physical and chemical properties of the latter.

The project aimed at demonstrating the types of geochemical interactions and their coupling with the hydraulic processes to be expected during the interaction of a hyperalkaline solution postulated to occur in a cementitious environment in a situation relevant for a deep repository for low- and intermediate-level radioactive waste.
Project organisation
The HPF experiment was carried out by French, Japanese, Swedish, Finnish, US, and Swiss organisations between 1997 and 2008. The experiment was carried out along the HPF shear zone, which is located in the rear end of the AU tunnel (AU126).

Results / conclusions
The HPF experiment has shown that the hyperalkaline solutions derived from the degradation of cement are very reactive and cause significant dissolution and precipitation that influence the local flow field. Major induced geochemical reactions are surface complexation, dissolution of primary silicate minerals such as quartz and plagioclase and the precipitation of secondary phases, namely Ca-Si-hydrates. A trend towards self-healing of the cement was observed. The geochemical reactions mentioned lead to a reduction of the transmissivity and a focusing of the flow field within the shear zone, confirming the observations made during hydraulic testing. Further, an asymmetric flow field was observed in the shear zone. Results obtained in the field are comparable to results from the laboratory and enhance confidence in predictive reactive transport models.

Tunnel Near-field Programme (CTN)
Aims and objectives
The CTN projects aimed at compiling the effects of the tunnel on the rock volume surrounding an underground facility. More specifically, what is the role of the near-field in the performance assessment, what are the key elements dominating the near field, how to establish quantitative models for gas migration and for axial flow along sealed tunnels?

Project organisation
The CTN project was a summary of diverse smaller projects (TPF, ZPK, ZPM) carried out at the GTS between 1997 and 2002. The projects were run by German and Swiss partners.

Results / conclusions
The tunnel near field represents the transition from the repository installations to the geosphere. Within crystalline rock, stress redistribution around the repository will induce long-term changes of the near field such as excavation-related fractures and reversible changes in the hydraulic conditions of the near-field rock volume. After closure of the repository, the near field will be characterised by two-phase flow. Desaturation of the tunnel near field was observed as a reversible effect, absent of hysteresis effects. Significant desaturation may be expected within the first metre around the tunnel. The resaturation time of the near field determines when radionuclide transport to the biosphere starts.

Pore Space Geometry (PSG)
Aims and objectives
The PSG project aimed at characterising the rock porosity in-situ by resin injection labelled with $^{14}$C. The labelling of the resin should be investigated and developed further.

Project organisation
The PSG experiment was run between 2003 and 2010 by Finnish, French, Swedish and Swiss organisations.
Results / Conclusions
The potential role of the geosphere as a safety barrier is relatively well known. However, little is known about the changes in the rock properties induced by sampling and decompression. The PSG experiment conducted at the GTS has shown that non-conservative errors in calculated transport properties for crystalline rocks deviate from laboratory values by a factor of approx. two to three. The injected resin was successfully tested, however drying of the resin in-situ was more challenging than expected. The resin penetrated 2 to 5 cm into the rock matrix around the injection interval and indicated a connected porosity; the inferred porosity shows a decreasing trend in the first 5 cm.

Long-term Cement Studies (LCS)
Aims and objectives
The overall goal of the LCS project is to increase the understanding of cement leachate interaction effects in the repository near field and geosphere so that modelling can make confident, robust, safety-relevant assessments of future system behaviour.

In more detail, the project is dedicated to (i) closing the circle of laboratory work – in-situ experiments – modelling – natural analogue studies, leading to improved system understanding of the implications of cement leachate interactions in a repository, (ii) providing a firm basis for reactive transport modelling and demonstrating the ability to reconcile and predict the relevant processes, (iii) performing a long-term in-situ demonstration experiment under realistic boundary conditions, possibly with a solid source for the cement leachates, (iv) supporting the aforementioned objectives with focused laboratory experiments, (v) improving mechanistic understanding to the point where all participating organisations can address their own site-specific and design-specific issues.

Project organisation
The LCS project was run by French, Japanese, Swedish, Finnish and Swiss organisations between 2003 and 2016. It was set up as follow-up project of the HPF project. The aforementioned aims were defined based on results obtained from the HPF experiment.

The project was split into three phases: Phase 1 focused on the selection of reliable equipment and the development of feasible concepts for long-term monitoring, Phase 2 aimed at monitoring the behaviour of high-pH plumes over several years, and Phase 3 was dedicated to improve the understanding of the hydraulic field and to overcoring the in-situ experiments.

Long-term Diffusion project (LTD)
Aims and objectives
The LTD project is dedicated to the long-term, large-scale examination of in-situ matrix diffusion of radionuclides and the visualisation of the pore space. More specifically, its aim is (i) to define the degree of realism of the matrix diffusion and the flow-wetted surface parameters employed in current performance assessment calculations, (ii) to demonstrate the in-situ radionuclide retardation in the matrix of crystalline rock volume, (iii) to verify in-situ the long-term and large-scale diffusion concepts for radionuclides, (iv) to verify the conceptualisation of existing transport codes, (v) to compare field and laboratory data, (vi) to fully characterise the spatial distribution of porosity in the rock matrix and its link with the mineralogy and, finally, (vii) to identify the flow-wetted surfaces to better define the spatial distribution of mass transfer coefficients controlling transport of radionuclide from the fracture to the rock matrix.
Project organisation
The LTD project is currently running and started in 2004. It is a joint project between Japanese, Finnish, Czech and Swiss organisations. The project is subdivided into three phases, Phase I (2004–2008), Phase II (2009–2013), and Phase III (2014–2018).

Results / conclusions
Preliminary results from Phase I showed that transport distances in the rock matrix were 20 cm for HTO, 10 cm for $^{22}$Na$^+$ and 1 cm for $^{134}$Cs$^+$. In order to match the observations with the different sorption models, a borehole damaged zone of around 1–2 mm had to be taken into account. The occurrence of the borehole damaged zone confirms previous observations in the Pore Space Geometry (PSG) experiment and the Connected Porosity (CP) experiment at the GTS.

Colloid Formation and Migration experiment (CFM)

Aims and objectives
The Colloid Formation and Migration (CFM) project is designed to study bentonite colloids and colloid-associated radionuclide transport and to examine the colloid formation process under close to repository-like conditions at relatively low hydraulic gradients and flow velocities.

In more detail, the project aims (i) to examine colloid generation rates and mechanisms at the Engineered Barrier System (EBS) – rock volume boundary under in-situ conditions, (ii) to evaluate the long-distance migration behaviour of EBS-derived colloids in a water-conducting feature in a repository-relevant flow system, (iii) to study the long-term geochemical behaviour of radionuclides at the EBS – rock matrix interface, (iv) to examine the reversibility of radionuclide uptake onto colloids, (v) to gain experience in long-term monitoring of radionuclide/colloid propagation near a repository, (vi) to apply the results to improve repository PA, and (vii) to contribute to the optimisation of EBS design.

Project organisation
The CFM project started in 2004 and activities are planned until 2023.

The CFM project has benefitted from numerous contributions from various countries (Japan, USA, Germany, France, South Korea, Finland, Sweden, UK, and Switzerland) since its start.

The CFM project is subdivided into three phases: phase 1 (2004–2008), phase 2 (2008–2013) and phase 3 (2013–2018). Phase 1 was dedicated to site characterisation and site preparation, laboratory work on colloid generation, transport, stability, radionuclide association and the comparison of different bentonite materials. Phase 2 was focused, between 2009 and 2011, on the completion of site characterisation and preparation, the finalisation of the experiment design, laboratory and mock-up studies, field tests to characterise the source zone and considerations of colloid migration. From 2012 on, the project emphasised the long-term emplacement of a bentonite source tagged with nuclides (Am, Pu, Cs, Tc, Ca, Se, Np, and U) in a borehole and a migration experiment with near- and far-field monitoring, followed by overcoring and detailed analyses of the source.

Test and Evaluation of Monitoring techniques (TEM/ESDRED)

Aims and objectives
The permanent closure of a deep geological repository will be accompanied by observations in the vicinity. The TEM/ESDRED project is dedicated to testing and developing techniques for the long-term monitoring of the pilot facility in a future repository. More specifically, the project
aims at investigating the efficiency of an existing wireless magneto-inductive transmission technique and evaluating seismic tomography as a non-intrusive monitoring technique.

The experiment is designed as a shotcrete plug sealing off a bentonite section containing the magneto-inductive source. In the current experimental setup, the monitoring concept encompasses three completely separate systems to measure and compile data relating to total pressure, pore pressure, and water content in and around the plug and bentonite section: (i) A conventional system with sensors connected to the data acquisition unit via cables, (ii) a wireless system using the magneto-inductive technique to transmit data, and (iii) non-intrusive seismic tomography which employs 6 boreholes positioned at a certain distance around the low-pH shotcrete plug.

Project organisation
The TEM/ESDRED project has been running since 2009 at the GTS with Spanish, French, British and Swiss partners.

Criepi’s Fractured Rock Studies (C-FRS)
Aims and objectives
The C-FRS project aimed at demonstrating newly acquired techniques for fracture characterisation and tracer testing. High-resolution borehole camera images, analysis of dissolved radon, various tracers, and borehole-to-borehole acoustic tomography were tested.

Project organisation
In 2007, a Japanese organisation charged Nagra with the C-FRS project running until 2012.

Results / conclusions
The first challenge was to identify a suitable test site at the GTS and to characterise it. A site in the BK cavern was chosen. Purposely drilled boreholes were logged with a high-resolution camera. Based on the acquired images, the position and orientation of the target fault zone could be reliably assessed. Radon was analysed multiple times in fracture water to demonstrate the use of radon for fracture characterisation. Several tracer tests were also conducted to characterise the fault zone at depth. Using high viscosity fluid, information about the flow dimension and aperture of the fractures was obtained. Borehole-to-borehole tomography was used to further characterise the fault zone.

Gas Permeable Seal Test (GAST)
Aims and objectives
The GAST experiment aims at developing and testing gas-permeable plugs and seals in order to increase the gas transport capacity of backfilled underground structures without compromising the radionuclide retention capacity of the EBS. Gases are produced in a repository by corrosion and microbial activity.

In more detail, the project aims at (i) the demonstration of the effective functioning of gas-permeable seals at realistic scale and with realistic boundary conditions, (ii) the validation, if required, and improvement of current conceptual models for the resaturation and gas invasion processes into S/B (sand/bentonite) seals, and (iii) the determination of upscaled gas/water permeability values of S/B seals. Secondary objectives are: (i) the evaluation of in-situ emplacement techniques and the necessary QA measures to be applied, and (ii) the development of non-destructive monitoring systems and, in particular, tomographic survey methods.
**Project organisation**
The GAST project is a collaboration between organisations from South Korea, France, Canada and Switzerland. The project started in 2010 and is ongoing. The project is subdivided into 4 phases, (i) detailed planning, (ii) site instrumentation and emplacement, (iii) supporting modelling and laboratory programme, and (iv) dismantling. Phase I was completed in mid-2011. Phases II and III are running and Phase IV is in planning. The experimental site was chosen at the rear end of the WT tunnel.

**Lab-scale gas test (FORGE)**

**Aims and objectives**
The formation and accumulation of a free gas phase in the backfilled underground structures of a L/ILW repository has several aspects that are considered in the safety analysis. FORGE aimed at studying the backfill material in terms of increasing the gas permeability without compromising the radionuclide retardation capability. The mock-up experiment was designed to simulate the interface between porous mortar backfill and sand/bentonite plugs or seals. The main goals were providing experimental data on the water saturation process and gas invasion at an intermediate scale, obtaining samples from the mortar - bentonite interface, testing QA procedures for later full-scale experiments (GAST), demonstrating the functioning of gas-permeable seals on a decametre scale, and providing improved model parameters for full-scale modelling.

**Project organisation**
The FORGE/mock-up experiment was conducted by organisations from Japan and Switzerland at the GTS between 2009 and 2013.

**Results**
First results showed that the bentonite ring around the sand/bentonite body was able to prevent water flow along the steel vessel. Furthermore, it was observed that water saturation was complete, but that the permeability was too low to allow for a gas breakthrough even after gas injection.

**Large-scale Monitoring (LASMO)**

**Aims and objectives**
LASMO was designed to study and monitor perturbations to the host medium of a future repository site. Several known anthropogenic perturbations were used for monitoring technique development and analysis of the impact on the host media. A large-scale geological model served as the basis for constraining water flow and stress field. Stress measurements in specially oriented boreholes were used to infer the in-situ stress field. Fault zones were equipped with displacement measuring devices. Fracture water composition was monitored on a long timescale and on a short timescale, correlating with major perturbations such as Lake Rätichsboden drainage. A microseismic survey was conducted during most of the experimental time and new algorithms were developed to detect events in a high noise environment.

**Project organisation**
The LASMO project was conducted by organisations from the UK, the Czech Republic and Switzerland between 2013 and 2018.
Material Corrosion Test (MaCoTe)

Aims and objectives
The Material Corrosion Test consists of non-heated and heated experiments to study in-situ corrosion of candidate canister materials embedded in bentonite. The tests aim to confirm the long-term anaerobic corrosion rate of the candidate material under repository-relevant conditions and to provide experimental evidence of the inhibiting effect of the bentonite buffer (two different dry densities tested) on microbial activity and microbially influenced corrosion.

Project organisation
The project is a collaboration between organisations from Canada, Japan, the UK, the Czech Republic and Switzerland. The project was started in 2013 and is currently running.

The project is based on the emplacement and subsequent corrosion of metal coupons placed in a bentonite matrix in modules. Each module consists of metal coupons composed of carbon steel, wrought copper, stainless steel, electro-deposited copper, or cold spray copper. The specimens are embedded in MX-80 bentonite. Two different density values of the bentonite are tested: 1.25 and 1.5 Mg/m³.

The project plan foresees removing modules after varying corrosion periods in order to better constrain the corrosion rates. Samples are removed after 1, 3, 4, 5, 7 and 10 years of emplacement. Two modules, one per density, are removed conjointly.

Corrosion rates of samples will be determined by the weight loss method and the mineral alterations at the interfaces will be analysed using available analytical methods. Microbial populations both in the bentonite and the borehole water will be analysed using advanced cell counting and DNA mapping techniques.

In-situ Stimulation and Circulation (ISC)

Aims and objectives
The ISC project aims at bridging the gap between laboratory experiments and enhanced geothermal power plants. The ISC project is split into three phases: pre-stimulation phase, stimulation phase and post-stimulation phase.

The pre-stimulation phase is dedicated to the (i) installation of a seismic survey, (ii) in-situ stress measurements, (iii) borehole drilling, (iv) site characterisation by borehole logging, hydraulic and thermal tests and geophysical imaging, (v) installation of a monitoring system comprising FBG (Faser-Bragg-Grating) sensors, stress cells, tilt meters, hydraulic packers, VWP (vibrating wire piezometer) sensors and distributed sensors.

The stimulation phase is designed to (i) inject fluid into an existing water-conducting feature, (ii) perform multiple pressure-step injection through different packer intervals, (iii) monitor fault displacement, flow rates, injection pressures, acoustic emissions in the tunnel, and hydraulic pressure, temperature, stress, strain and tilt meters in monitoring boreholes.

The post-stimulation phase aims at characterising the changes in the hydraulic field and geophysical properties in the test volume induced by the stimulation phase.

Project organisation
The ISC project was implemented in 2015 at the GTS by the ETHZ (Switzerland). Nagra operates as a contractor and the host of the experiment. The main project phase ended in 2017, and long-term monitoring, smaller tests and reporting are ongoing.