GRIMSEL TEST SITE
ROCK STRESS INVESTIGATIONS

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Federal Institute for Geosciences and Natural Resources, Hannover, Federal Republic of Germany

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GRIMSEL TEST SITE / SWITZERLAND
A JOINT RESEARCH PROGRAM BY

- NAGRA – National Cooperative for the Storage of Radioactive Waste, Baden, Switzerland
- BGR – Federal Institute for Geosciences and Natural Resources, Hannover, Federal Republic of Germany
- GSF – Research Centre for Environmental Sciences, Munich, Federal Republic of Germany
FOREWORD

Concepts which foresee the disposal of radioactive waste in geological formations lay great weight on acquiring knowledge of the proposed host rock and the surrounding rock strata. For this reason, Nagra has, since May 1984, been operating the Grimsel Test Site which is situated at a depth of 450 m in the crystalline formation of the Aar Massif. The general objectives of the research being carried out in this system of test tunnels include, in particular

- the build-up of know-how in planning, performing and interpreting underground experiments in different scientific fields and

- the acquisition of practical experience in developing, testing and applying test equipment and measuring techniques.

The Test Site (GTS) is operated by Nagra. On the basis of a German-Swiss cooperation agreement, the various experiments are carried out by Nagra, the Federal Institute for Geoscience and Natural Resources (BGR) and the Research Centre for Environmental Sciences (GSF); the latter two bodies are supported in this venture by the German Federal Ministry for Research and Technology (BMFT).

NTB 85-47 gives an overview of the GTS and a review of the status of the investigation programme as at August 1985.

This report was produced in accordance with the cooperation agreement between the three partners mentioned previously. The authors have presented their own opinions and conclusions, which do not necessarily coincide with those of Nagra, BGR or GSF.
VORWORT

Bei Konzepten, die die Endlagerung radioaktiver Abfälle in geologischen Formationen vorsehen, ist die Kenntnis des Wirtgesteins und der angrenzenden Gesteinsschichten von grundlegender Bedeutung. Die Nagra betreibt deshalb seit Mai 1984 das Felslabor Grimsel in 450 m Tiefe im Kristallin des Aarmassivs. Die generelle Zielsetzung für die Arbeiten in diesem System von Versuchsstellen umfasst insbesondere

- den Aufbau von Know-how in der Planung, Ausführung und Interpretation von Untergrundversuchen in verschiedenen Experimentierbereichen und


Das Felslabor (FLG) wird durch die Nagra betrieben. Die verschiedenen Untersuchungen werden aufgrund eines deutsch-schweizerischen Zusammenarbeitvertrages durch die Nagra, die Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) und die Gesellschaft für Strahlen- und Umweltforschung (GSF) durchgeführt, beide gefördert vom Deutschen Bundesministerium für Forschung und Technologie (BMFT).


Der vorliegende Bericht wurde im Rahmen der Zusammenarbeit zwischen den drei Partnern erstellt. Die Autoren haben ihre eigenen Ansichten und Schlussfolgerungen dargelegt. Diese müssen nicht unbedingt mit denjenigen der Nagra, BGR oder GSF übereinstimmen.
AVANT-PROPOS

La connaissance de la roche d'accueil et des couches rocheuses avoisinantes est d'importance fondamentale pour l'élaboration de concepts prévoyant le stockage de déchets radioactifs dans des formations géologiques. C'est pour cela que la Cédra exploite depuis mai 1984 le laboratoire souterrain du Grimsel à 450 m de profondeur dans le cristallin du massif de l'Aar. Les objectifs généraux des travaux menés dans ce complexe de galeries d'essais comprennent notamment:

- la constitution d'un savoir-faire dans la préparation, l'exécution et l'interprétation d'essais souterrains dans divers domaines et
- l'acquisition d'expérience pratique dans le développement, la mise à l'épreuve et l'engagement d'appareillages d'essais et de techniques de mesure.

Le laboratoire souterrain est exploité par la Cédra. Les différentes recherches sont réalisées dans le cadre d'un accord de collaboration germano-suisse par la Cédra, la "Bundesanstalt für Geowissenschaften und Rohstoffe" (BGR) et la "Gesellschaft für Strahlen- und Umweltforschung" (GSF), ces deux dernières instances étant soutenues par le Ministère allemand pour la recherche et la technologie (BMFT).


Le présent rapport a été élaboré dans le cadre de la collaboration entre les trois partenaires. Les auteurs ont présenté leurs vues et conclusions personnelles. Celles-ci ne doivent pas forcément correspondre à celles de la Cédra, de la BGR et de la GSF.
GRIMSEL-GEBIET
Blick nach Westen

1 Felslabor
2 Juchlistock
3 Räterichsbodensee
4 Grimselsee
5 Rhonetal

GRIMSEL AREA
View looking West

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

On the research project "Rock Stress Measurements" the BGR has developed and tested several methods for use in boreholes at a depth of 200 m.

Indirect stress measurements using overcoring methods with BGR-probes and CSIR-triaxial cells as well as direct stress measurements using the hydraulic-fracturing method were made. To determine in-situ rock deformation behavior, borehole deformation tests, using a BGR-dilatometer, were performed. Two types of the BGR-probe were applied: a four-component-probe to determine horizontal stresses and a five-component-probe to determine a quasi three-dimensional stress field. For the first time, a computer for data processing was installed in the borehole together with the BGR-probe. Laboratory tests on hollow cylinders were made to study the stress-deformation behavior. To validate and to interpret the measurement results, some test methods were modelled using the finite-element method.

The dilatometer-tests yielded high values of Young's modulus, whereas laboratory tests showed lower values with a distinct deformation anisotropy. Stress measurements with the BGR-probe yielded horizontal stresses higher than the theoretical overburden pressure. These results are comparable to the results of the hydraulic fracturing tests, whereas stresses obtained with CSIR-triaxial cells are lower.

The detailed geological mapping of the borehole indicated relationships between stress and geology. With regard to borehole depth, different zones of rock structure, joint frequency, joint orientation, and orientation of microfissures as well as stress magnitude, stress direction, and degree of deformation anisotropy could be distinguished.
ZUSAMMENFASSUNG

Im Projekt "Gebirgsspannungen" wurden Meßverfahren für den Einsatz in Bohrungen bis 200 m Tiefe weiterentwickelt und getestet.


Durch eine detaillierte geologische Aufnahme der Versuchsbohrung wurden darüber hinaus Zusammenhänge zwischen Gebirgsspannungen und geologischer Struktur nachgewiesen. Dabei konnten bezüglich der Bohrlochtiefe verschiedene Bereiche hinsichtlich Klufthäufigkeit, Kluftrichtung und Mikrorißorientierung sowie Spannungsniveau, Orientierung der maximalen Horizontalspannung und Grad der Verformungsanisotropie identifiziert werden.
RESUME

Dans le cadre de son projet "contraintes dans un massif rocheux", le BGR a poursuivi le développement de techniques de mesures et les a mis à l'épreuve pour un engagement dans des forages jusqu'à une profondeur de 200 m.

Les mesures de contraintes ont été réalisées par la méthode de détente du trou de forage, par le procédé de surforage de BGR avec dilatomètres et cellules triaxiales CSIR, ainsi que par la technique de fracturation hydraulique. Pour étudier le comportement à la déformation du massif rocheux, on a fait des essais d'épanouissement du trou de forage à l'aide d'un dilatomètre BGR. Deux types d'indicateurs d'épanouissement du trou de forage ont été utilisés: une sonde à quatre composantes pour déterminer les contraintes horizontales et une sonde à cinq composantes pour une détermination quasi-spaciale du champ des contraintes. On a utilisé à cette occasion, pour la première fois dans un trou de forage, un système de saisie des données digitalisé. Des essais en laboratoire ont par ailleurs été réalisés pour étudier le comportement à la déformation d'échantillons cylindriques creux et les contraintes résultantes. Dans le cadre d'études théoriques, on a simulé quelques essais à l'aide de la méthode des éléments finis, afin de valider et interpréter des résultats de mesures.

Les mesures par dilatomètre ont livré des valeurs élevées de rigidités du massif montagneux, alors que des valeurs plus modestes, avec anisotropie marquée, ont été déterminées en laboratoire. Les mesures de contraintes, faites à l'aide du procédé de surforage BGR, ont donné des contraintes horizontales dans le massif rocheux supérieures aux valeurs théoriques résultant de la charge gravitative. Les résultats des essais de fracturation hydraulique s'intègrent bien dans l'image d'ensemble du champ des contraintes alors que l'utilisation de sondes triaxiales CSIR donne des contraintes relativement plus faibles.

Un levé géologique détaillé du trou de forage a montré des relations entre les contraintes dans le massif rocheux et la structure géologique. On a pu identifier, en fonction de la profondeur dans le forage, différentes zones relatives à la concentration des diaclases, la direction des diaclases, l'orientation des microfissures ainsi que pour le niveau des contraintes, l'orientation des contraintes horizontales maximales et le degré de déformation anisotropique.
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1. INTRODUCTION

In the planning and design of underground openings it is necessary, in particular in the inspection of possible location sites for final disposal facilities for radioactive wastes, to prepare a comprehensive engineering geological and geotechnical expertise of the host rock mass. In order to study the rock mechanical, hydrogeological, geochemical and geophysical properties of crystalline rock formations a number of comprehensive studies are being undertaken at the Grimsel Test Site (GTS) (Figure 1). Under the terms of a German/Swiss cooperation agreement between the Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (NAGRA - National Cooperative for the Storage of Radioactive Waste), the Gesellschaft für Strahlen- und Umweltforschung (GSF - Research Centre for Environmental Sciences) and the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR - Federal Institute for Geosciences and Natural Resources) the BGR, acting on behalf of the German Federal Ministry for Research and Technology (BMFT), Bonn, undertook the research project "Rock Stresses (GS)". This project covered the development and modification of measuring equipment and methods, the testing of this equipment with regard to its utilization in deep boreholes and the determination of stress states in virgin rock and rock mechanical and engineering geological investigations to evaluate and interpret the stress measurements.

In order to measure the stresses in hard rock masses various methods and equipment are available. The BGR developed some of these methods previously and employed them in the construction of underground openings. In the case of borehole tests these consisted mainly of overcoring
Fig. 1: 3D overview of the Grimsel Test Site and test areas of phase 1 (LIEB 1985)

tests using the BGR borehole stress release method for indirect stress measurements and accompanying borehole dilation tests using the BGR method to assess rock deformation behaviour.

These well known methods have, however, only been infrequently employed in deep boreholes, i.e. deeper than 100 metres. Within the terms of the "Rock Stress" research project the intention was then to study whether or not the measuring methods mentioned in the preceding are suitable for larger borehole depths.
During the first test phase, extending from May 1984 to December 1984, work consisted of developing and designing several overcoring probes (BGR type) and a dilatometer probe (BGR type) and the execution of corresponding tests in a borehole to a maximum depth of 170 m. For control purposes several CSIR triaxial cells (Interfels type) were also employed up to a maximum borehole depth of 110 m in parallel to the BGR overcoring probes. In the second phase in 1985 the hydraulic fracturing method was also employed to allow direct determination of rock stresses. The hydrofrac measurements were carried out to provide the data gained in the overcoring method with critical discussion and comparison results using a method differing from first principles. Whereas the overcoring method with measurement of deformation represents an indirect method the hydrofrac method, involving hydraulic creation and repeated opening of fractures, represents a method providing direct measurement of rock mass stresses.

This report comprises the description of the measuring equipment and test methods developed and employed in the project together with the presentation of some typical measurement results. In addition, details are given on the evaluation of the data and determination of rock mass stresses and rock mass coefficient values. The results gained using the various methods are compared with one another and assessed. In order to allow interpretation of some of the measurements the results of concurrent finite element calculations are also included. As a check on the stress tests carried out in-situ with dilatometers the hollow cylindrical cores recovered from the overcoring tests were subjected to biaxial tests in the laboratory, the results of which are also included. The engineering geological work encompasses the presentation of detailed geological data logged in the vicinity of the GS boreholes and the comparison of the results of the stress measurements with studies of the rock mass structure (joint structure and microstructure).
2. GEOLOGICAL DESCRIPTION OF TEST LOCATION

The Grimsel Test Site (GTS) has a regional geological location within the Aare Massif. The tunnel system of the rock laboratory exposes Central Aare granite (ZAGr) and Grimsel granodiorite (GrGr). Dark lamprophyre veins of tens of centimetres to several metres in thickness cut through these two deep rock types (Figure 2).

The ZAGr is for the most part light, fine to medium grained, massive to clearly parallel textured. Signs of tectonic influence during younger phases of the variscian and alpidic orogeny are evident in the zones of pronounced texturization and strong schistosity. Of unequivocal alpidic age are the mineralized, approximately horizontal fissures. Their location is usually associated with apophyses of the lamprophyre and its contacts to the host rock.

The GrGr is darker in appearance. This rock, in part coarse grained and porphyritic, has clear and pronounced parallel texture extending to schistosity. The GrGr is generally held to be the somewhat older, more basic southern marginal facies of the ZAGr.

The cavern of the rock stress (GS) and the fracture system flow test (BK) is located in the Central Aare granite. It was geologically mapped between the end of 1983 (walls) and early 1984 (bottom) (App. 1). This detailed mapping, with special emphasis placed on the detection of joints, provided the basis for the subsequent geological work, for example drilling of test boreholes, recovering oriented cores and the statistical logging and analysis of the joints detected.
Glacier, firm, lakes

Vulcanoclastite (pyroclastites and metasediments), provisional range according to F. Schenker and R. Oberhansli 1985 and F. Schenker 1986

Sediments of the Wildhorn nappe (Jurassic, Cretaceous)

Mittagfluh granite

Autochthonous and parautochthonous sediments (Triassic-Lower Tertiary)

Central and southern Aare granite

Innertkirchen Crystalline at the contact with Altkristallin (old basement), partly accompanied by a carboniferous zone

Grimsel granodiorite

Altkristallin (old basement), mainly light gneisses and dark biotite schist, localised amphibolites and lime silicate

Fig. 2: Geological overview of the Grimsel Test Site (MÜLLER 1988)
Fig. 3: Joint statistics of bottom in the GS and BK areas - overall view
(Total number: 150; lower hemisphere projection; contour lines: 1, 3 and 7 %)

In the cavern at the GS test section the typical light form of the ZAGr is accompanied by a biotite-rich, darker variety (see App. 1).

The joint statistics of the bottom mapped in the two sections, GS and BK, bring to light definite differences in the direction and frequency distribution of joints and shear planes. The dark, biotite-rich ZAGr in the GS section displays a relatively uniform picture with regard to the spatial location of the joints, whereas in the BK section, in exclusively light ZAGr, several joint systems are present (Figures 3 and 4).
Fig. 4: Joint statistics of bottom in the GS and BK areas - separate plots (lower hemisphere projection)
The structure of the joint planes of the GS and BK cavern also shows that the planes in the GS section tend to be continuous, whereas in the BK section wedging out and transitions to other joints are apparent; this is presumed to be due to different mechanical behaviour under tectonic stress, caused by the differing petrographic characteristics and existing joint planes.

The boreholes in the BK section encountered a much larger number of joints. In particular in the close proximity of shear zones, which are divided in several shear planes with slickensides, a large number of open joints are present along which the not inconsiderable circulation of water takes place.

Chapter 5 contains a separate description of the geological work performed and the rock mass structure.
3. **EQUIPMENT AND TEST DESCRIPTION**

The test methods employed at the Grimsel Test Site are shown schematically in Figure 5.

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<td>Stress direction</td>
<td></td>
</tr>
<tr>
<td><strong>Compensation method:</strong></td>
<td></td>
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<tr>
<td>- BGR rock mechanical laboratory with ROBERTSON cell</td>
<td>Modulus of elasticity</td>
<td>Hollow cylinder</td>
</tr>
<tr>
<td></td>
<td>Modulus of deformation</td>
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<td>Degree of anisotropy</td>
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<td>Stresses</td>
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Fig. 5: Methods employed at the Grimsel Test Site for measuring rock stresses

3.1 **Overcoring tests with BGR probes**

3.1.1 **Measuring equipment and data acquisition**

The procedure for indirect stress measurement consists of measuring the stress release deformations which arise when overcoring a pilot borehole and converting this data into a value for the rock stress. The stress release deformations are measured, in the case of the BGR overcoring method described here, as diameter changes and also as axial borehole margin deformations.
Two different types of the BGR overcoring probe, in the following known as the BGR probe, were developed for use at the Grimsel Test Site (GTS):

- BGR probe (Figure 6) with 4 radially arranged displacement transducers (referred to in the following as the BGR-2D probe)
- BGR probe (Figure 7) with 4 radially arranged displacement transducers and an additional measuring system for detecting axial borehole release (referred to as the BGR-3D probe).

The basis of the two BGR probes is a stainless steel body, inductive differential transducers (LVDTs), adjustable rubber packers for holding the probe in the pilot borehole, connections for attaching weights when running the probes in and terminals for data and installation cables.
The 4 radial transducers are located in the stainless steel body at an axial offset of approximately 1.5 cm and with a radial offset of 45° to each other. The measuring resolution is 0.001 mm over a measurement range of 45 - 48 mm and enables changes in diameter to be determined (initial diameter of pilot borehole = 46 mm). The measured data is transmitted via a data cable, which runs inside the drill string, via a custom-built water tight circulation head to the data receiving and recording equipment. During overcoring this allows registration of the measured values either manually or using a pen recorder. The data is stored on disks using a portable microcomputer designed for field use and can be mathematically and graphically evaluated at a later date.

A further development of the BGR-2D probe, which only allows radial pilot borehole stress release to be measured and hence allows the determination of only rock stresses in a plane perpendicular to the axis of the borehole, is the
BGR-3D probe (although strictly speaking the term 3D probe only applies when the axis of the borehole coincides with that of a principal stress direction). This model comprises the basic model as described in the preceding with the addition of an LVDT transducer in an axial direction, which detects the axial deformation of the overcored pilot borehole. In addition to this, when installing the probe in a pilot borehole a special mechanism allows two measuring tags to be detached and fixed to the wall of the borehole. Any axial pilot borehole deformations occurring during overcoring are then measured in that the axial transducer registers distance changes with respect to the measuring tags.

The acquisition of data from the BGR-3D probe is via a data cable as described in the preceding. In addition, an attachment was also developed for digital data recording downhole without the need for a wire connection. This is shown in Figure 8 and consists of the data acquisition system GEOCOM 16 K, Type A with a central processor, an analog input converter, a data store, an interface to the control unit, a power supply unit (PSU) and a stainless steel housing ($\phi = 33.7$ mm, watertight up to 20 bar).
The single card central processor controls data recording, conversion, management and storage of the data and transmission of the data to a surface computer.

The BGR probes are evaluated as follows compared with triaxial cells (e.g. CSIR, CSIRO and LULEA triaxial cells):

**Advantages:**

- total probe reusable
- measurement takes place during overcoring due to basic design principles
- probes measure integrally over entire diameter or measurement section, the influence of different crystal deformations is therefore negligible
- underwater use
- no gluing necessary
- installation on data cable relatively fast
- downhole digital data acquisition possible
- interpretation of results relatively straightforward

**Disadvantages:**

- measurements can be affected by core discing
- at present only four radial and one axial direction of measurement possible, consequently determination of full stress tensor in one test run not possible.

The computer section and the battery section are coupled with the BGR-3D probe and installed as a single unit in the borehole. When the overcoring procedure has been completed and after retrieving the probe the data stored in the computer section is transmitted to a standard computer via a special interface using a special utility program.
3.1.2 Test description

The BGR overcoring method for undertaking stress measurements in vertical boreholes consists of the stages shown in sequence in Figure 9. These stages may be described as follows:
- drill core borehole of diameter = 146 mm down to the planned measurement level

- smooth the face of the borehole using a smoothing bit; subsequently drill the pilot borehole of diameter \( \phi = 46 \text{ mm} \), of minimum length \( L = 1.00 \text{ m} \) (2D probe) or \( L = 3.50 \text{ m} \) (3D probe with computer and battery section)

- drill a cone of maximum diameter 72 mm using a special cone drill bit

- install the BGR probe with data cable through the drill string and corer, whereby threading the probe into the pilot borehole is greatly simplified by a centralizing pipe in the corer and the bevelled cone edges

- proceed with overcoring and any deformation of the pilot borehole during overcoring is measured simultaneously

- the BGR probe and data line are retrieved through the drill string, the hollow core is recovered and the drilling of the borehole continued.

In order to determine the orientation of the probe and the various directions of measurement in the pilot borehole several alternatives are feasible: The installation of the probe on a tubing would allow direct orientation at borehole entrance, but would involve time consuming tubing string adjustments and, moreover, insufficient torsional rigidity of the string at greater depths could lead to considerable margins of error due to stem twist. The method of orientation chosen represents a simple but efficient and robust solution to this problem. In the BGR overcoring method using the 2D probe a piece of blackboard chalk sets a characteristic mark corresponding to a certain measurement direction on the wall of the pilot borehole as the probe is set in place. After the probe has been
retrieved and the overcored core recovered this can be evaluated by correlating it with the overall core orientation of the borehole. When employing the 3D probe the core and the probe are retrieved together allowing orientation to be derived.

The overcoring tests carried out in the GS test section showed in the majority of cases that the BGR overcoring method is well-suited technically to employment at greater depths. The test procedure was only impeded in a small number of cases by geological or technical problems. Thus, for example, in the vicinity of fault zones and intensely jointed sections core fractures were unavoidable, leading to test abort in order to avoid damaging the probe. In addition in isolated cases the data cable and the cable connection to the probes developed leaks, due to mechanical damage when installing or retrieving the probe.

3.2 Borehole dilation tests with the BGR dilatometer

3.2.1 Measuring equipment and data acquisition

The BGR dilatometer is used in borehole dilation tests to assess the load-deformation behaviour of the rock mass. The borehole section to be tested is stressed by increasing the pressure in the dilatometer in steps up to the specified maximum and measuring the diameter change of the borehole at the same time. The borehole diameter changes are recorded as functions of loading and unloading and plotted as curves, such that the rock mechanical coefficients, for example the moduli of elasticity and deformation, can be derived.

The main components of the dilatometer (see Figure 10) are the steel base, the high pressure expansion section (φ 84 mm x 800 mm length), inductive differential
transformation transducers (LVDTs), hydraulic and data
cable connections, tubing connector and oil drain
container.

The high pressure expansion section has walls approximately
4 mm thick and is stretched over the cylindrical base.
Special seals between the cylindrical base and the tube
ensure pressure tight ends. The internals of the probe
consist of three LVDT transducers with an approximate 4.5
cm axial offset and a circumferential 60° offset. The
transducers are located radially across the cylindrical
base and work with steel disks laminated into the tube such
that the resulting data is for the most part unaffected by
deformations of the tube.

The maximum operating pressure of the dilatometer is
approximately 450 bar. The measurement range of the
transducers is 10 mm, the measurement resolution 0.001 mm.
The hydraulic oil pressure in the dilatometer is generated
with a hand pump and indicated on a manometer. The pump
and the probe are connected by an hydraulic line.

Fig. 10: BGR dilatometer and measuring equipment
The data from the individual transducers are transmitted along a data line to the receiving equipment (Digital Extensotest D20) via a measurement point converter. The borehole diameter changes measured are indicated directly and registered manually. The storage and evaluation of the data is done, as in the BGR overcoring tests, using a portable microcomputer.

3.2.2 Test description

The procedure for executing dilatometer tests using the BGR method is described in the following working steps:

- Prepare a core borehole of $\phi = 146$ mm (required for the overcoring tests) down to the test depth

- If necessary smooth the end face of the borehole using a smoothing drill bit

- Prepare a centered, precision test hole of $\phi = 86$ mm and length approximately 2 metres, using centralizing gear

- Assess the test section using the cores recovered for the eventuality of joints and fault zones and on this basis specify the horizon to be measured

- Install the dilatometer together with the hydraulic line on an oriented, torsionally rigid string and determine the measurement directions at the borehole entrance via the string
Perform the tests, e.g. generate an initial hydraulic pressure of approximately 10 bar in order to ensure uniform settling of the pressure tube along the wall of the borehole, execute a reference measurement and then commence the stress and release cycles of 10 bar to 50 bar, 100 bar, 200 bar, 300 bar and maximum 400 bar respectively.

In special cases the data density may be raised by varying the direction of the measurements by turning the dilatometer through 30° whilst remaining at the same measurement horizon.

A further alternative is to raise the pressure of the dilatometer to generate a crack in the wall of the borehole by exceeding the local rock stress and tensile strength.

Retrieve the dilatometer after draining the hydraulic oil into the catch tank below the probe in order to avoid the unit sticking as a result of the oil's own weight.

The dilatometer tests were fairly simple from a technical point of view. Only in one case was the setting of the probe within the test borehole hindered due to knotting of the pressure line, the test had to be aborted. For the subsequent dilatometer tests the design of the probe was changed slightly with the lower end of the pipe being fixed.
3.3. **Overcoring tests with CSIR triaxial cells**

Overcoring tests using the CSIR triaxial cells followed the same basic principles as those for the BGR probes. The main difference between the two procedures is in the measurement of the stress release deformations. CSIR triaxial cells are fitted with strain gauges at various orientations which are cemented to the borehole wall and which measure the change in strain in either tangential or axial directions (see LEEMAN, 1968).

The CSIR triaxial cell (Interfels type) consists of the following components:

- Head unit for pneumatic coupling of setting and orientation string
- Measuring block (same as CSIR triaxial cells) with 3 extendable rosettes each of which has 4 strain gauges with 45° offsets
- Distributor for cement
- Cement reservoir
- Compressed air driven piston for expending the cement
- Cone and centralizing section for proper setting of the probe in the pilot borehole
- Two component synthetic cement for underwater use.

In the case of CSIR triaxial cells the pilot borehole deformation is only measured before (reference) and after (final) the actual overcoring, by coupling the setting tool to the probe head. The measured values are displayed digitally on the measuring unit (Model DMD 20 Hottinger-Baldwin) which has twelve channels and a measuring point selector switch. The display is digital, recording manual. Just as in the preceding example the data can also be stored or evaluated using a microcomputer.
The CSIR-triaxial cell as used in the GTS is evaluated as follows:

**Advantages:**
- high number of strain gauges
- determination of full stress tensor possible in on run
- adhesion of probe or strain gauge can reduce risk of core discing in measurement section

**Disadvantages:**
- point measurement
- parts of probe only usable once
- adhesion problems in underwater application
- no measurement during overcoring
- depth of installation restricted by adhesive hardening time
- measurements affected by single large crystals and microfissures in borehole wall.

Special details when performing tests using CSIR triaxial cells in the GS test section were:

- Preparation of a core borehole of $\phi = 146$ mm

- Drill a central pilot borehole from the borehole base ($\phi = 37$ mm, length approximately 1.2 m)

- Assess the test zone on basis of data taken from the core recovered from the pilot borehole and specify the measuring horizon accordingly

- Flush the borehole to remove mud in the section to be tested
- Set probe oriented with measuring cables and compressed air lines on a setting and orientation string

- Cement strain gauges to wall of borehole using a special two component underwater cement (setting time minimum 12 hours)

- Perform the reference measurement, detach and retrieve the setting string, overcore the probe with the corer and drillbit ($\phi = 146$ mm)

- Retrieve the core around the cemented probe, connect the setting string to the probe and perform several measurements to determine stress release deformation.

In order to ensure as near identical conditions with respect to temperature and wetness for the reference measurement and the final measurement the recovered overcore is immersed together with the probe in a water-filled tank.

The use of the CSIR triaxial cell was limited as far as test depth is concerned by the time span of maximum of 1 hour between mixing and initial setting of the cement. This time is taken up at a maximum applications depth of approximately 110 m by the setting work and string manoeuvres.

With respect to the technical side of the test procedure the overcoring tests with the triaxial cells were not always trouble-free. In several cases the measuring rosettes or individual strain gauges malfunctioned after setting. In addition some rosettes had an orientation of measurement points which did not accord with the works specification conventions. It was necessary to undertake a renewed calibration of the measurement directions.
3.4 Hydraulic fracturing tests with MESY frac apparatus

The hydrofrac apparatus manufactured by the MESY company of Bochum and used at Grimsel corresponds in its basic design to the apparatus developed by RUMMEL (1978). This apparatus has the following main components:

- Frac apparatus with guide rod, injection tube, 2 packers, cable head with integrated pressure sensor, switchover valve, support wire with integrated data cable, high pressure line and several clamps for connecting support wire and pressure line
- Imprint packer.

As used at the Grimsel Test Site the following components were modified or supplemented the basic design:

- Instead of one, two pressure lines were used for pressuring the packers and the injection section. In previous trials considerable difficulties had been experienced with the standard switchover valve at the head of the frac apparatus. The use of two pressure lines saw modifications including a special connector on the head of the frac probe and a manually operated switchover valve at the pump.

- Special distance pieces and centering elements were made of synthetic material in order to provide better adaptation to the actual local borehole configuration. The transition of the borehole from φ 146 mm to φ 86 mm in GS 84.041 A at around 171 m resulted in the frac apparatus jamming and attempts at threading it into the φ = 86 mm hole proving impossible.

The following units were used by the BGR when operating the frac apparatus and performing the test:
- Pump unit (pressure max. 790 bar, pump volume 11.9 l/min.), switchable between low pressure for permeability tests or high pressure for frac tests. In addition this unit was used to drive a winch for lowering or retrieving the frac apparatus or the imprint packer on a wireline.

- Hydraulically controlled winch with depth indicator with decimeter resolution, and continuous adjustment of lower and retrieval rates.

- Precision manometer and pressure sensor at pump outlet for controlling packer pressure.

- Multi-channel recorder for analog recording of data values (injection pressure, packer pressure, water volume).

- Single shot device (in connection with imprint packer) for registering imprint packer orientation at time of fracture logging.

Fig. 11 shows an overview of the equipment and units described.

Original plans foresaw 10 - 15 frac tests in a depth range of approximately 170 to 210 m in BOGS 84.041 A. However, during drilling of the exploration borehole a heavily faulted schistose zone with a lamprophyre was encountered and drilling was terminated at a total depth of 191 m in order to prevent deeper areas being affected by borehole collapse. The available test section of around 20 m length was reduced to 10 m by the fault zone as described in the preceding, such that whilst maintaining sufficient separation between the individual measurement horizons only 4 hydrofrac tests could be performed.
Fig. 11: Schematic of hydraulic fracturing apparatus

At each test level the following tests were carried out:

- Simple pressure surge test at an injection pressure of approximately 50 bar and recording of pressure fall over 5-10 minutes to determine permeability of the rock matrix or the permeability of open joints in the test section.

- Generation of a fracture by increasing packer pressure to around 200-250 bar with subsequent increase of injection pressure at full pump output.

- Repeated reopening of the crack.
- Periodic pressure surge test with phased injection pressure increases from, e.g. 60 - 75, 90, 105, 120 bar; the pressure drop resulting provides data for determining or checking the shut in pressure.

- Fracture logging with an imprint packer together with a single shot device.

3.5 **Mechanical fracturing test using BGR frac apparatus**

A mechanical frac apparatus (MF-probe, BGR system) was developed to determine rock stresses and their directions for use in downhole situations. The plan foresaw the development of a probe fitted with two curved rigid plates to allow a non-rotation symmetrical stress condition to be induced in the borehole wall, which would allowfracing in a preselected orientation.

Using the MF-probe it was planned to determine stresses and also study rock deformation behaviour by measuring borehole deformation for defined loads, as with a dilatometer.

The overall configuration of the apparatus is shown in Fig. 12, and comprises following components:

- MF-probe with high pressure line, support and data cable
- setting unit, motor, compass, electronic orientation module, setting arms
- probe electronics with data amplifier for pressure gauges and LVDTs, probe computer and PSU (power supply unit)
Fig. 12: Configuration of mechanical frac probe

1. Mechanical frac probe
2. Electronic unit
3. Motor unit with compass
4. Pump and pressure gauge
5. Winch with electric motor
6. Digital measurement unit
7. Microcomputer
8. Printer
9. Recorder
- borehole winch with electronic motor drive, depth
gauge, automatic cable guide and collector for
connecting data cable with data acquisition unit
- digital data acquisition unit configured for MF-probe,
data transmission, analog and digital measured data
acquisition and storage
- manual pump (Lukas) for hydraulic pressure generation,
  max. 1500 bar
- external microcomputer with printer for data output
- line plotter for analog data recording.

Fig. 13 shows the MF-probe with setting unit and electronic
unit. Fig. 14 shows the digital data acquisition module.

In principle the MF-probe functions by pressing two semi-
circular rigid plates onto the borehole wall (borehole
diameter $\phi 146$ mm). The plates are forced apart by an
expansion tube. Pressure is exerted within the expansion
tube by hydraulics, and recorded in the probe by the
pressure sensor. Changes in distance caused by the pressure
change between the two plates are recorded by four LVDTs.
The measured values are digitized in the probe and
transmitted to the data acquisition module.
Fig. 13: MF-probe with setting unit and electronic unit

Fig. 14: Digital data acquisition module
3.6 Laboratory tests on the ROBERTSON biaxial cell

In order to determine rock stresses by compensation and also the determination of rock-mechanical characteristic values, the BGR installed laboratory test equipment to study the deformation behaviour of hollow-cylindrical specimens during pressure loading and unloading. The specimens stem from overcoring tests and therefore provide for the most part identical material for a comparison of in-situ and laboratory measurements.

The objective of the laboratory investigations was to check the results of the dilatometer tests executed in-situ and determine an specific elasticity modulus for each overcoring test to facilitate the final evaluation. In some cases the compensation of release deformation measured in-situ permitted a direct estimate of rock stress levels. It proved possible during the evaluation of the overcoring test results to compensate for any anisotropy of deformation present by taking values of degree and orientation of the anisotropy into account.

The laboratory test equipment is listed below, and illustrated in Figures 15 and 16:

- biaxial cell (Robertson)
- hydraulic unit for generating and regulating the confining pressure (max. pressure = 300 bar) in the biaxial cell
- data logger for test regulation and control and data acquisition
- pressure sensor with integrated data amplifier
- BGR -2D probe with 4 LVDTs for measuring hollow cylinder deformations
- data amplifier with digital display and precision manometer for manual data acquisition
- 4 x-y plotters for continuous analog data recording
- microcomputer with peripherals (screen, printer, plotter, disk drive) for storing and displaying measured values
- calibration unit for adjusting data amplifier
- hollow cylindrical aluminium specimen for test purposes.

Fig. 15: Biaxial cell with test specimen, BGR-2D probe and calibration unit
Biaxial loading and unloading tests were carried out on all specimens recovered from borehole GS 84.041 A during overcoring tests having a minimum length of 35 cm. The sectional dimensions for all specimens were uniform: outer diameter 123 mm and internal diameter 46 mm. A probe orientation of $\gamma_3$ was chosen for the laboratory work, corresponding to the probe orientation used in the overcoring tests. Angle $\gamma_3$ (positive defined as counter clockwise) is the angle between GS/BK tunnel axis and measurement direction c (see Figure 17).

The load on the specimen varied from test to test depending upon the release values measured in-situ. To take account of the facts, that a) it was not possible to simulate the generally non-isotropic horizontal stress state of the rock in the laboratory and b) the biaxial cell was limited to the generation of uniform stress states, lower and upper pressure levels were selected. The deformations caused by these pressure levels in the pilot borehole are considered to correspond approximately with the minimum and maximum
in-situ measured release values, analogous to a compensation. In general a pressure increase rate of $\dot{p} = 2$ MPa/min was chosen.

![Diagram](image)

Fig. 17: Transducer orientation in biaxial test

The pronounced non-linearity of the load-deformation plots in the lower stress range meant a direct comparison of all test results was not possible, bearing in mind the different lower pressure levels. For this reason, and where necessary, a third pressure level was set at $p = 25$ MPa.

Further laboratory tests were undertaken on hollow cylindrical test specimens which were recovered directly from an overcoring test, but originate from adjacent borehole sections. These test specimens were tested at a pressure of $p = 25$ MPa and a stress increase rate of $\dot{p} = 2$ MPa/min.
4. RESULTS AND TEST EVALUATION

During the first two phases of the rock stress test the following tests were carried out in the vertical borehole:

- 29 overcoring tests using BGR probes (of which 4 with 3D probe)
- 10 overcoring tests with CSIR triaxial cells
- 7 dilatometer measurements
- 4 hydrofrac measurements

In a departure from the original planned total depth of around 200 m the above equipment was only used down to a depth of about 170 m. This was due to the fact that in the second phase of the test program the hydraulic fracturing measurements required a smaller borehole diameter of 86 mm as opposed to 146 mm.

4.1 Measurements taken using the BGR overcoring method

4.1.1 Result of measurements

The diameter changes in the pilot borehole measured using the BGR overcoring method were stored to disk and drawn on a plotter.

The graph in Figure 18 is an example taken in test GS24-BS14 of diameter changes in the pilot borehole in 4 measuring directions as a function of overcoring depth. The curves show an overall elastic rock reaction as being typical for overcoring tests in granite. Thus, after the phase with unchanging diameter (reference measurement) a phase commences characterized by relatively minor
convergence of the pilot borehole with negative diameter changes. This convergence must be due to stress redistribution and to an increase in the radial stresses in the vicinity of the pilot borehole which result from the overcoring. This phase is followed by the stress release phase proper, i.e. the overcoring bit reaches the level of the transducers and, in the process of cutting the rock mass, removes the rock pressure acting on the pilot borehole, and results in the increase of borehole diameter. When overcoring is continued sufficiently far for the most part constant deformation values set in. The difference between these final values and the initial values are then further processed.

Fig. 18: Stress release deformations in overcoring test GS24-BS14
Figure 19 is a plot of the pilot borehole deformations measured in overcoring test GS51-BS32 using the BGR-3D probe in 4 radial and 1 axial directions. The plot of the axial stress release indicates that relatively minor deformations took place. The changes plotted are plausible with the axial (vertical) stress release leading to positive axial deformations while the radial (horizontal) stress release results in fact in negative axial deformations due to lateral contraction, (equivalent to shortening of the core) and the two effects superimposing one another. Because of the slight axial deformations the scattering of the measured values makes itself apparent as a pronounced oscillation in the curve.

Numerical model calculations to provide a basis for qualitative checking of plots and their interpretation are described in Section 6.1.

Fig. 19: Stress release deformations in overcoring test GS51-BS32.
The measured results as illustrated in the examples indicate that a major advantage of the BGR overcoring method is found in the deformations due to stress release being measured directly during the overcoring process and as such representing a continuous monitoring of test progress. As a result any abnormal deformation behaviour of the pilot borehole is recognizable immediately (e.g. due to core fracture or fissure opening with possible subsequent damage to the probe). In addition, changes to the initial position of the probe can be corrected with respect to the reference measurement at commencement of the overcoring process. And finally it is possible to identify measurement errors in the system (e.g. due to creep currents in the data lines) and to take these into account when interpreting the raw data).

4.1.2 Evaluation of data assuming isotropic rock mass behaviour

The diameter changes $\Delta D$ registered during overcoring of the pilot borehole allow the horizontal rock mass stresses (perpendicular to the vertical axis of the borehole) to be derived. In the evaluation the rock mass is considered to be as shown in Figure 20, i.e. a circular hole on an infinite plane.

To determine the principal stresses and their directions at least three measurement directions are necessary such that per test a total of 4 combinations of the 4 measurement directions as shown in Figure 20 can be drawn on in the evaluation.
According to OBERT/DUVALL (1967) the maximum and minimum horizontal stresses $S_{H1}$ and $S_{H2}$ perpendicular to the axis of the borehole can be calculated according to equation (1):

$$S_{H1,2} = \frac{E}{4 \cdot (1-\nu^2)} \left( 2A + \sqrt{B^2 + C^2} + 2 \cdot \nu \cdot \varepsilon_z \right)$$

where

$$A = \frac{1}{2D} \left( \Delta D_a + \Delta D_c \right),$$

$$B = \frac{1}{2D} \left( \Delta D_a - \Delta D_c \right)$$

and

$$C = \frac{1}{D} \left[ \Delta D_b - \frac{1}{2} \cdot (\Delta D_a + \Delta D_c) \right]$$
In equation (2) D represents the diameter of the pilot borehole. Variables $\Delta D_a$, $\Delta D_b$ and $\Delta D_c$ represent diameter changes in three measurement directions $\theta_a$, $\theta_b$, and $\theta_c$ with a $45^\circ$ offset measured counter clockwise. The combination of in each case three measurement directions produced four stress ellipses per test as follows:

- $a = 1$, $\theta_a = 0^\circ$, $b = 2$, $\theta_b = 45^\circ$, $c = 3$, $\theta_c = 90^\circ$,
- $a = 2$, $\theta_a = 45^\circ$, $b = 3$, $\theta_b = 90^\circ$, $c = 4$, $\theta_c = 135^\circ$,
- $a = 3$, $\theta_a = 90^\circ$, $b = 4$, $\theta_b = 135^\circ$, $c = 1$, $\theta_c = 180^\circ$,
- $a = 4$, $\theta_a = 135^\circ$, $b = 4$, $\theta_b = 180^\circ$, $c = 2$, $\theta_c = 225^\circ$

In equation (1) in addition to the radial deformation the axial deformation $\varepsilon_z$ is also entered. Assuming plane deformation conditions $\varepsilon_z$ is assumed to have a value of $\varepsilon_z = 0$ when evaluating measurement results from the 2D probe.

Angle $\alpha$ between the direction of the principal stress $S_{H1}$ and the local coordinate system is calculated using

$$\alpha = \arctan \frac{C}{B}$$

(3)

In the case of the 3D probe, which has an additional axial measurement direction, equation (4) below allows calculation of the influence of the axial stress release on the principal radial stresses $S_{H1}$ and $S_{H2}$:

$$\varepsilon_z = \frac{\Delta z}{l_0}$$

(4)

where

$\Delta z =$ axial deformation

$l_0 =$ original length (16.5 cm)
In addition the following equation allows the vertical stress $S_V$ to be derived:

$$S_V = E \cdot \varepsilon_z + \nu \cdot (S_{H1} + S_{H2}) \tag{5}$$

In equation (5) $S_{H1}$ and $S_{H2}$, compressive stresses, and $\varepsilon_z$, expansion, are defined as being positive.

Fig. 21: Horizontal stress ellipses for overcoring test GS40-BS22
The consistency of the measured values can be judged by comparing the results from a combination of various measurement directions. Fig. 21 shows an example of the horizontal stress ellipses for test GS40-BS22. The size and direction of the ellipses resulting from the test show excellent agreement in this case. As such further evaluation is generally possible by considering a single ellipse of size and orientation corresponding to the mean of the four individual ellipses of a test. Fig. 22 illustrates a typical stress ellipse derived in this way from test GS40-BS22.

A) Mean values

B) Regression

Fig. 22: Horizontal stress ellipse for GS40-BS22
(1: mean, r: after regression calculation)

Alternatively the four stress release curves measured per test were evaluated such that, after regression calculation using the Gaussian least square method, a single ellipse of deformation resulted. Taking the principal axes $\Delta D_H$ and $\Delta D_h$ of the ellipses, $S_{H1}$ and $S_{H2}$ can be calculated by entering into the equations as follows:
\[ S_{H1} = \frac{E}{8 \cdot D \cdot (1 - \nu^2)} (3 \cdot \Delta D_H + \Delta D_h) \]  

(6a)

and

\[ S_{H2} = \frac{E}{8 \cdot D \cdot (1 - \nu^2)} (3 \cdot \Delta D_h + \Delta D_H) \]  

(6b)

The direction of \( S_{H1} \) corresponds with the direction of the larger principal axis of the measured deformation ellipse. Fig. 22 shows a typical plot of the stress ellipse, calculated using equation (6) for test GS40-BS22. It can be seen that the ellipses resulting from the two methods described have only minor differences with respect to size and direction. This applies to the majority of the overcoring tests, such that in general for each test one ellipse can be derived from the arithmetic mean of four ellipses.

The following characteristic material values were used in the evaluation of equation (1):

\[ E = 40\,000 \, \text{MPa}, \quad \nu = 0.25 \]

The modulus of elasticity \( E \) was determined in the dilatometer tests (see Section 4.2).

The results of the horizontal stress measurements made using the BGR overcoring method in borehole GS 84.041 A are summarized in Figure 23. It can clearly be seen that the maximum stresses are approximately 25 - 40 MPa and the minimum horizontal stresses between 15 and 30 MPa. We have then that the horizontal stresses are substantially higher than the depth-related overburden pressure. In several sections of the borehole there are higher stresses which deviate from the above, and also sections with divergent stress directions; the sections concerned are below the
laboratory tunnel down to 40 m, below that down to 100 m and then to approximately 170 m. These sections are also characterized by the horizontal stresses being in different directions; also shown in Figure 23 as the azimuth (angle between north and direction of $S_{H1}$, positive defined as counter clockwise direction). Fig. 23 serves as the basis for comparing the joint system and the rock stresses described in Section 5.3.

Fig. 23: Size and direction of horizontal stresses obtained from BGR overcoring tests assuming isotropic rock mass behaviour ($E = 40$ GPa, $v = 0.25$)
4.1.3 **Evaluation assuming anisotropic rock behaviour**

In the case of anisotropic rock behaviour, e.g. caused by rocks shears or microfissuring, the evaluation of laboratory tests using the BGR method is possible by applying the model, as illustrated in Figure 24, of an infinite plate with a central hole and transverse anisotropic material properties.

![Fig. 24: Infinite plate with hole and transverse anisotropic material properties](image)

Assuming the borehole axis runs parallel to the plane of isotropy and that said borehole axis corresponds to one of the principal stress directions then, based on BERRY & FAIRHURST (1966) and RAHN (1981), the maximum and minimum horizontal rock stresses $S_{H1}$ and $S_{H2}$ and $\alpha$, the angle between the direction of strike of the isotropic plane and the direction of $S_{H1}$ (positive defined in counter clockwise direction as per Figure 24), are as follows:
\[
S_{H1,2} = \frac{1}{2} \cdot \frac{A' \cdot t_3 - B' \cdot t_2}{t_1 \cdot t_3 - t_2 \cdot t_1} + \frac{1}{2} \cdot \sqrt{Q_1^2 + Q_2^2}
\]  

(7)

\[\tan 2 \alpha = \frac{Q_1}{Q_2}\]  

(8)

with

\[Q_1 = \frac{C}{t_4}\]  

(9a)

\[Q_2 = \frac{A' \cdot t_2 - B' \cdot t_1}{t_2 \cdot t_2 - t_1 \cdot t_3}\]  

(9b)

\[A' = \frac{D_A}{D} - T_{13} \cdot \varepsilon_z\]  

(10a)

\[B' = \frac{D_B}{D} - T_{23} \cdot \varepsilon_z\]  

(10b)

\[C = \frac{D_C}{D}\]  

(10c)

\[D_A = U_1 \cdot \sin^2 (\theta_3 - \theta_1) + U_2 \cdot \sin^2 (\theta_1 - \theta_3) + U_3 \cdot \sin^2 (\theta_2 - \theta_4)\]  

(11a)

\[D_B = U_1 \cdot (\sin^2 \theta_2 - \sin^2 \theta_3) + U_2 \cdot (\sin^2 \theta_3 - \sin^2 \theta_1) + U_3 \cdot (\sin^2 \theta_1 - \sin^2 \theta_2)\]  

(11b)

\[D_C = U_1 \cdot (\cos^2 \theta_3 - \cos^2 \theta_2) + U_2 \cdot (\cos^2 \theta_2 - \cos^2 \theta_3) + U_3 \cdot (\cos^2 \theta_1 - \cos^2 \theta_2)\]  

(11c)

\[D_D = \sin^2 (\theta_3 - \theta_2) + \sin^2 (\theta_2 - \theta_1) + \sin^2 (\theta_1 - \theta_3)\]  

(11d)

and material-dependent terms

\[T_{13} = -\frac{1}{2} (\nu_1 + \nu_2)\]  

(12a)

\[T_{23} = -\frac{1}{2} (\nu_1 - \nu_2)\]  

(12b)

\[t_1 = \frac{s (1 + c^2 - d^2)}{(1 - c + d)^2}\]  

(12c)

\[t_2 = \frac{2 \cdot s \cdot c}{(1-c+d)^2}\]  

(12d)

\[t_3 = \frac{2 \cdot s \cdot (1+d)}{(1-c + d)^2}\]  

(12e)

\[t_4 = \frac{2 \cdot s \cdot (1-d)}{(1-c + d)^2}\]  

(12f)
\[ c = \frac{2 \cdot (k_1 - 1)}{k_1 + 1 + \sqrt{2} \cdot \sqrt{k_1 + k_2}} \]  \hspace{1cm} (12g)

\[ d = \frac{k_1 + 1 - \sqrt{2} \cdot \sqrt{k_1 + k_2}}{k_1 + 1 + \sqrt{2} \cdot \sqrt{k_1 + k_2}} \]  \hspace{1cm} (12h)

\[ k_1 = \frac{c_{11}}{c_{22}} \]  \hspace{1cm} (12i)

\[ k_2 = \frac{c_{66} + c_{12}}{c_{22}} \]  \hspace{1cm} (12k)

\[ s = c_{22} \]  \hspace{1cm} (12l)

and the coefficients of the flexibility matrix

\[ c_{11} = \frac{1 - \nu_1^2}{E_1} \]  \hspace{1cm} (13a)

\[ c_{12} = -\frac{\nu_2 \cdot (1 + \nu_1)}{E_1} \]  \hspace{1cm} (13b)

\[ c_{22} = \frac{E_1 - \nu_2 \cdot E_2}{E_1 \cdot E_2} \]  \hspace{1cm} (13c)

\[ c_{66} = \frac{1}{2G_{12}} \]  \hspace{1cm} (13d)

and the normalized diameter deformations

\( U_i = \Delta D_i (\theta_i)/D \)  \hspace{1cm} (14)

and the axial deformation \( \epsilon_z \) as per equation (4).
The elasticity coefficients of the transverse anisotropic material are \( E_1 \) and \( v_1 \) (in the plane of isotropy), \( E_2 \) and \( v_2 \) (normal to the plane of isotropy) and shear modulus \( G_{12} \), which according to BECKER & HOOKER (1967) can be approximated using

\[
\frac{1}{G_{12}} = \frac{1}{E_1} + \frac{1}{E_2}
\]

The diameter deformations measured \( \Delta D_i \) can be combined analogously to Section 4.1.2 such that in each case three adjacent measurement directions, e.g. \( \theta_1 = 0^\circ \), \( \theta_2 = 45^\circ \) and \( \theta_3 = 90^\circ \) (\( \theta_1 \) = angle between angle of strike of plane of isotropy and measurement direction \( i \), positive defined in counter clockwise direction as per Figure 24), can be taken into account. In this way it is again possible for four horizontal stress ellipses to be constructed per test and summarized into a mean ellipse.

The evaluation of the BGR overcoring tests was carried out using Poisson's ratio values \( v_1 = v_2 = 0.25 \). To determine \( E_1 \) and \( E_2 \) the rigidity values established in the biaxial compensation tests in the lab on the hollow specimens, and summarized in Table 1, were used (see Section 2.6), and which varied from test to test. The shear modulus \( G_{12} \) was also calculated using \( E_1 \) and \( E_2 \) as per equation (15).

The horizontal stresses and their orientations determined in this way are displayed in Figure 25 as functions of borehole depth. It is apparent that, compared with the evaluation assuming isotropic rock behaviour (see Figure 23), stress values are lower. The maximum horizontal stresses are between 13 and 36 MPa, the minimum stresses between 8 and 24 MPa. Working analogously to Figure 23, various depth ranges can be differentiated having
different stress components. Thus, e.g., the largest stresses with $S_{H1} = 32$ MPa and $S_{H2} = 22$ MPa are found in the range from approx. 40 m to approx. 100 m borehole depth.

Fig. 25: Size and direction of horizontal stresses from BGR overcoring tests for anisotropic rock behaviour ($E_1$ or $E_2$ variable, $\nu_1 = \nu_2 = 0.25$)
The azimuth of $S_{H1}$ (angle between north and direction of $S_{H1}$, positive defined in clockwise direction) shows a similar pattern dependent upon the depth of the borehole as in Figure 23. Major deviations only occur in the section between 70 and 100 m.

4.1.4 **Vertical rock stresses**

In some of the coring tests the values were also measured for the vertical rock stress component $S_v$ (assumptions: isotropic behaviour, $E = 40$ GPa, $v = 0.25$):

- **BOGS 84.042** (borehole depth 19.2 m): $S_v = 10.7$ MPa,
- **BOGS 84.041 A** (borehole depth 159.2 m): $S_v = 13.9$ MPa,
- **BOGS 84.041 A** (borehole depth 167.5 m): $S_v = 11.5$ MPa.

These values correspond approximately with the rock pressure due to weight of overlying rock.

4.2 **Dilatometer measurements**

The radial deformations caused by loading and unloading and measured in the borehole dilation test using the BGR dilatometer were stored to disk and then plotted.

Figure 26 shows an example of the load-deformation diagram for test GS29-DI6. In this graph the load-deformation curves show a for the most part uniform pattern and an almost linear gradient for all pressure stages indicating a linear-elastic rock behaviour. The unloading stage is characterized by a weak hysteresis loop.
In some cases, in a departure from the standard test procedure, the dilatometer pressure was raised until fracture formation in the wall of the borehole, allowing comparison of the fracture orientation to the principal stress orientation as derived from the overcoring tests.

In connection with the overcoring tests using the BGR method boreholes GS84.041 A and GS84.042 A were drilled at diameter \( \phi = 146 \text{ mm} \). For the dilatometer measurements a pilot borehole of \( \phi = 86 \text{ mm} \) was drilled centrally from the
Fig. 27: Load-deformation plot of dilatometer test GS46-DI9

borehole end face allowing subsequent overcoring to $\phi = 146$ mm. The hollow cylindrical cores produced in this fashion allow firstly geological data to be acquired and secondly a direct investigation of the rock mass stressed in the dilatometer tests and study of fractures on the outer side of the hollow cylinder.

Figure 27 illustrates the non-linear increase in borehole deformation resulting from fracturing and fracture opening. Figure 28 is an example of the geological survey data including details of core orientation and the line of the fractures in test GS29-DI6. As in all other cases fracture lines are present in the wall of the borehole running in approximately the same direction as the borehole axis.
Fig. 28: Fracture line and fracture orientation in dilatometer test GS29-DI6

The values and orientation of the fracture are also shown in Figure 28. The visible fracture lines are first drawn as idealized straight lines parallel to the axis of the borehole and their direction is then derived from the core data and the continuation of the orientation line of the core.
If fracture line pairs are not exactly at 180° to one another then the plane of the fracture is shifted in parallel to align with the centre of the borehole allowing definite orientation data to be recorded.

The evaluation of the dilatometer tests can then be undertaken as shown in Figure 29 using an infinite plate with a hole under internal pressure assuming plane strain conditions.

![Figure 29: Infinite plate with hole under internal pressure](image)

In this manner isotropic rock mass deformation behaviour may be assumed and a deformation modulus (from the loading stage) and a modulus of elasticity (from the unloading stage according to equation (16)) may be derived:

\[
E = (1 + \nu) \cdot \frac{D}{\Delta D} \cdot p_i
\]  

(16)
In equation (16) D represents the diameter of the test borehole, $\Delta D$ the change in diameter and $p_i$ the internal pressure applied by the dilatometer.

As shown in Figure 29, a total of 3 measurement directions are available, each set at 60° to the other, such that it is possible to detect transverse anisotropic deformation behaviour assuming that the borehole axis is on the plane of isotropy.

In general the various measurement directions display only minor differences such that, at least for the plane of measurement, an assumption of isotropic deformation behaviour is justified. The moduli obtained from loading and unloading do not indicate any pronounced dependency on the load and only differ slightly from one another. The assumption of linear-elastic rock mass behaviour is therefore pertinent on the whole.

Figure 30 is a graph showing the results of all dilatometer measurements carried out in BOGS 84.041 (A). In the individual tests the values for the modulus of elasticity vary on average between around 35 and 45 GPa. At greater depth the average is between around 40 and 42 GPa. Overall the value for the modulus of elasticity assumed of $E = 40$ GPa and used in the evaluation of the stress measurements is confirmed by the results. The modulus of elasticity can be checked for the individual results using data gained in laboratory tests on the hollow cylinders recovered from the overcoring tests (see Section 4.5).

Assuming isotropic homogeneous material properties any fracture generated in a dilatometer test will theoretically run vertically to the minimum stress within the plane of measurement under consideration. With respect to the vertical borehole GS 84.041 A this fracture orientation may be taken to be equal to the direction of maximum horizontal stress.
Fig. 30: Review of the modulus of elasticity from the dilatometer tests
Figure 31 shows plots of the directions of maximum horizontal stress as derived for selected depth ranges using the overcoring test according to the BGR method (BS) and the dilatometer tests (DI). The agreement is excellent for each individual level studied.

Fig. 31: Fracture orientation in dilatometer tests and direction of maximum horizontal stress
4.3 **Overcoring tests using CSIR triaxial cells**

In total 10 overcoring tests using triaxial cells were carried out in BOGS 84.041 A at depths of around 23 m to a maximum of around 111 m. One test had to be aborted following damage to the probe head preventing registration of the strain gauge values. In another test the stress release deformations were found to be mainly negative indicating a triaxial tensile stress state, and hence abnormal stresses.

In general the remainder of the tests indicated that qualitatively perfect measurement results are only achievable in isolated cases. In two more tests several strain gauges malfunctioned such that it was impossible to log complete stress data.

No graphic plots of the data has been undertaken since the measurement of the stress release deformations with the triaxial cells took place only twice, once prior to the overcoring (reference measurement) and next after recovery of the overcore.

The rock mass stresses may be derived from the deformations measured by the CSIR triaxial cell by using a model of a hollow cylinder of infinite extension under triaxial stress.

A total of 12 strain gauges are located on the triaxial cell, fitted on 3 measuring rosettes set at 120° to one another around the circumference whereby each rosette has 4 strain gauges set at 45° to one another. The general equation of elasticity as in equation (17) may then be used to calculate the full rock stress tensor:
\[ \varepsilon = A \cdot \sigma \]

where

\[ \sigma = (\sigma_x', \sigma_y', \sigma_z', \tau_{xy}', \tau_{yz}', \tau_{zx}') \]

where \( \varepsilon \) represents the matrix of the strains measured and \( A \) the flexibility matrix whose components are dependent on the elastic indices \( E \) and \( v \) as well as on the spatial orientation of the strain gauges in the borehole. Figure 32 shows an example of the arrangement of the rosettes MR1, MR2 and MR3.

Fig. 32: Orientation of triaxial cell and measuring rosettes
The strain gauges are arranged on the individual measuring rosettes as shown in the example in Figure 33, rosette MR1 (seen from the origin).

\[ \begin{align*}
\omega_A &= 90^\circ \\
\omega_B &= 0^\circ \\
\omega_C &= 135^\circ \\
\omega_D &= 45^\circ
\end{align*} \]

Fig. 33: Arrangement of strain gauges on rosette MR1

Using, for example, the equations as stated by GARTUNG et al. (1981), the individual components of flexibility matrix \( \mathbf{A} \) can be derived as functions of \( E, v, \theta \) and \( \omega \). The matrix comprises components \( A_{i,k} \) (\( i = 1.6 \) and \( k = 1.12 \)), in which coefficient \( k \) is the strain gauge under consideration, and coefficient \( i \) represents the stress component according to equation (18). To calculate stress matrix \( \sigma \) flexibility matrix \( \mathbf{A} \) is inverted and multiplied by strain matrix \( \varepsilon \).

In a similar method to that used in the evaluation of the overcoring tests using the BGR probes the evaluation here is carried out assuming uniform material properties (modulus of elasticity \( E = 40 \) GPa, Poisson's ratio \( v = 0.25 \)). For the evaluation the measured values were used as acquired; for those measurement directions where the strain gauges were defective the stress release deformation was taken in a first approximation to approach zero.
Figure 34 is a diagram of the principal stress directions in a polar projection (lower hemisphere). No clear trend is recognizable with respect to the direction of principal stresses, however, 5 of 8 value triples indicate an orientation of the largest principal stress in a direction approaching the vertical (± 30°) (Section I).

Leaving the principal stress components out of the consideration, it is possible to isolate two sections with stress directions of virtually horizontal orientation (± 15°) and azimuth values of 160° – 210° (Section III) and 260° – 330° (Section II).

Fig. 34: Principal stress directions from the overcoring tests using CSIR triaxial cells
In Figure 35 the minimum and maximum horizontal rock stresses and their directions are plotted to allow direct comparison of the results from the overcoring tests using triaxial cells with those using the BGR overcoring method. The expression

\[ S_{H1,2} = \frac{1}{2} \cdot (\sigma_x + \sigma_y) \pm \frac{1}{2} \cdot \sqrt{(\sigma_x - \sigma_y)^2 + 4 \tau_{xy}^2} \]  

(19)

allows these factors to be calculated from the perpendicular stress components \( \sigma_x \) and \( \sigma_y \) and the shear stress component \( \tau_{xy} \). The direction of the maximum horizontal stress \( S_{H1} \) (defined as positive in a counter clockwise direction) can be derived from components for \( \sigma_x > \sigma_y \) using

\[ \tan 2\alpha = \frac{2 \tau_{xy}}{\sigma_x - \sigma_y} \]  

(20)

The results show that the maximum horizontal stresses are between around 10 and 20 MPa. The minimum horizontal stresses have values of less than approximately 13 MPa and in isolated cases are even negative (tensile stress). It is then clear that the stresses determined using CSIR triaxial cells are substantially lower than those values measured using the BGR overcoring tests.
Fig. 35: Size and direction of horizontal stresses measured in overcoring tests using CSIR triaxial cells

4.4 Hydrofrac measurements

In general the determination of the initial frac pressure $P_C$ at the instant of fracture generation was followed by measuring of the refrac pressure $P_R$ and the shut in pressure $P_{Si}$ in several repeat phases. Figure 36 shows the injection pressure over time diagram with fracture generation and several subsequent refrac tests in test no. GS55-HY4. The diagram shows that both $P_R$ and $P_{Si}$ values clearly fall compared with the initially measured values.
after repeated fracture reopening and propagation, and finally drop to an almost constant value. This effect is considered to be due to the original vertical orientation of the fracture plane changing its spatial orientation and possibly approaching the horizontal, which indicates vertical stresses which are lower than the horizontal stresses.

The qualitative pattern of the pressure-time curves illustrated in Figure 28 concurs with those curves measured in for example HAIMSON & RUMMEL (1982).

![Pressure-time plot for frac test GS55-HY4](image)

**Fig. 36:** Pressure-time plot for frac test GS55-HY4

Figure 37 shows the fracture imprint of test GS53-HY2 as an example. The diagram clearly shows 2 almost vertical and sharply pronounced fracture lines were created which, near the bottom of the borehole section, run into a joint which probably opened up during the frac test.
Fig. 37: Fracture imprint and orientation in test GS53-HY2

The rock stresses can be derived from the frac pressures $P_c$, refrac pressures $P_R$ and shut-in pressures $P_{si}$ measured during the frac tests after FAIRHURST (1964) based on the following assumptions:
- an elastic, isotropic, homogeneous and impermeable rock mass

- borehole runs parallel to the principal stress direction

- fracture propagates normally to smallest principal stress

- the frac pressure $P_C$ compensates for tangential stress at the borehole wall and the hydraulic tensile strength $T$ of the rock mass.

Assuming a vertical borehole and a stress constellation of $S_V < S_{H1} < S_{H2}$ (i.e. vertical stress $S_V$ is smaller than the minimum and maximum horizontal stresses $S_{H1}$ and $S_{H2}$) the fracture should be created with a horizontal orientation. However, since the packer pressure generates an additional radial stress and hence represents an additional vertical stress in the study zone, a vertical fracture will be initially created which develops into a horizontal fracture with increasing distance from the borehole.

The following equations then apply:

$$P_{si,1} = S_{H2}$$

$$S_{H1} = 3P_{si,1} - P_C + T - P_o$$

$$T = P_C - P_R$$

$$P_{si,2} = S_V$$

where

- $P_{si,1}$ = shut-in pressure immediately after frac generation
- $P_{si,2}$ = shut-in pressure after frac propagation at greater vicinity from borehole
- $T$ = hydraulic tensile strength of rock mass
- $P_o$ = pore and fracture water pressure
- $P_C$ = frac pressure
- $P_R$ = refrac pressure
Using equation (21) the minimum and maximum horizontal stresses $S_{H1}$ and $S_{H2}$ result as shown in Figure 38 together with the results from the overcoring test using the BGR method (BS) in the test section from 140 to 180 m in GS84.041 A.

![Diagram of horizontal stresses and orientation of max. horiz. stresses](image)

**Fig. 38:** Size and direction of horizontal stresses measured in the hydrofrac tests

It is apparent that the minimum horizontal stress determined in hydrofrac test GS55-HY4 fits extremely well into the overall picture. The associated maximum horizontal stress is higher than those values measured using the BS method in neighbouring areas but is in good agreement with the values determined in the test section from 145 to 160 m.
In addition it is also clear that the minimum and maximum horizontal stresses decrease with increasing depth. This phenomenon is considered to be due to increasing proximity to the fault zone, which starts at around 181 m, this fault zone affects the stress field locally and the stress components decrease as a result.

The orientation of the maximum horizontal stress can be determined by replacing the fracture line pairs identified with the imprint packer by idealized straight lines (see Figure 37). These straight lines can be allocated using the orientation lines of the imprint packer and membrane as aids together with a superimposed compass. If the fracture lines are not exactly opposed, i.e. the axis of the borehole is not exactly in the fracture plane then the fracture plane is shifted in parallel until the plane of the fracture and the axis of the borehole correlate and allow definite direction determination.

Figure 38 also shows the direction of the maximum horizontal stresses (= fracture orientation) for tests GS53-HY2 to GS55-HY4. The orientation (approximately E/W) fits in well with the overall picture of the results from the BS tests in the section from 145 to 170 m.
4.5 **Mechanical frac tests**

The MF-probe was tested in the Grimsel Test Site (GTS) at the end of 1986. The tests consisted of several pretests in horizontal borehole BOGS 84.042 A with a borehole depth of approx. 0.5 - 5.0 m and horizontal or vertical plate orientation. In a departure from the system configuration described in Section 3.5 the probe was installed on a pipe string and oriented.

The objective of the pretests was initially to check the designed probe pressure in the expansion membrane of max. 150 MPa. Initial difficulties due to insufficient probe specifications, which led to large axial deformation of the probe mandrel, were overcome after some modifications and a maximum pressure of 160 MPa was reached. The generation of a fissure in the borehole wall was not detected.

![Graph showing borehole deformations](image)

**Fig. 39: Borehole deformations in test GS74-MF9**
Figure 39 shows the examples of the distance changes $s$ measured in test GS74-MF9 between the plates as functions of the probe pressure $p$, with $p_{\text{max}} = 160$ MPa for the four LVDTs. All load-deformation curves have a uniform pattern. The initial deformation behaviour shows large movements for comparably low probe pressure as the plates move outwards up to value of $\Delta s = 3.5 \pm 4$ mm. The plates then establish contact with the borehole wall and gradually form a tight pad-rock contact. The next stage of the curve is non-linear, as is the final unloading stage. The lower stress section has a comparably low gradient. This is due to the as yet incomplete contact between the plates and the borehole wall; in this stage the plates go through an initial deformation phase and only then as the pressure increases is the borehole itself expanded.

A comparison of the gradient of the measured curves with the values calculated for $E = 40$ GPa in Section 6.2, indicates that in the upper stress range the agreement is good.

The calculation results described in Section 6.2 allow the conclusion that the probe pressure generated during the tests would lead to the generation of a fracture. This fracture generation should then theoretically produce an overproportional elongation of the borehole and correspondingly large displacements $\Delta s$. The data plots do not point to such deformation behaviour, i.e. the measurement results do not evidence any fracture generation. Some design modifications to the MF-probe are planned so that in the future such measured evidence should be available.
4.6 Laboratory tests on hollow cylindrical test specimens

The test specimen deformations resulting from the biaxial tests were measured as diameter changes in the pilot borehole in four measurement directions, A, B, C and D, and plotted in the load-deformation diagrams. The stress then corresponds to the confining pressure in the biaxial cell. As an example of this the load-deformation curves determined in biaxial test GS51-BS32 are plotted in Figure 40.

Fig. 40: Load-deformation curves in biaxial test GS51-BS32
In general it may be stated that:
- the deformations occurring in the tests are virtually fully reversible
- in the lower stress range a non-linear deformation behaviour occurs with comparably large diameter changes
- overall a sometimes pronounced anisotropic deformation behaviour is detectable.

\[ E_S = 2 \cdot \frac{D_a^2 \cdot D_i}{D_a^2 - D_i^2} \cdot \frac{P_R}{\Delta D} \]  
(22)
with

\[ E_s = \text{elasticity modulus as secant of unloading cycle (MPa)} \]
\[ D_a = \text{external borehole diameter (123 mm)} \]
\[ D_i = \text{borehole diameter internal (46 mm)} \]
\[ P_R = \text{confining pressure (MPa)} \]
\[ \Delta D = \text{change in borehole diameter (mm)} \]

It must be emphasized that in contrast to the evaluation of dilatometer measurements the Poisson's ratio is not entered into the determination of \( E \) due to plane stress conditions.

Fig. 42: Secant moduli \( E_s \) from biaxial tests
As illustrated in Figure 42, for a total of 29 test specimens subjected to a load/unload cycle from 25 or 30 MPa, the minimum secant moduli $E_2$ are between around 28 and 35 GPa and the maximum secant moduli $E_1$ between around 34 and 42 GPa. To facilitate evaluation the principal axis of the deformation ellipses were determined for the test specimen deformations measured, and then converted using equation (22). The values of the secant moduli do not provide any unequivocal indications of dependence upon sampling depth.

![Graph showing azimuth of maximum deformation](image)

**Fig. 43:** Azimuth of the larger principal deformation axis
In Figure 43 the azimuth of the larger principal deformation axis is plotted versus the sampling depth of the test specimen. In the sector between 20 and 70 m the orientation of the principal axis is between N and NW. From 70 - 100 m the azimuth is between N and NNE, and gradually swings round to N and NW as the sampling depth increases. A similar trend was also found with respect to the orientation of the maximum horizontal stress (see Section 4.1).

Fig. 44: Degree of anisotropy $\mu$ for $E_s$
If the degree of anisotropy $m = a/b$ ($a =$ larger principal deformation axis, $b =$ smaller principal deformation axis) is calculated for each test then it is possible to differentiate between three ranges of sampling depth of test specimens, as shown in Figure 44. In the range up to around 70 m the value of $m$ is maximum 1.34, in the range from approximately 70 - 140 m the value of $m$ is between 1.12 and 1.25. In the range from approximately 145 m to 170 m the values of $m$ is relatively large, between 1.30 and 1.40.

![secant moduli $E_1$ and $E_2$ (GPa)](image)

**Fig. 45:** Secant moduli $E_D$ from biaxial tests
Alternatively, the evaluation of the biaxial tests as per Figure 41 can be carried out in that the secant modulus $E_D$ is determined for the third-points of an unloading cycle. Referring to Figure 45 the values for $E_{D1}$ and $E_{D2}$ using equation (22) have generally higher values, of between approx. 39 and 47 GPa ($E_{D2}$) and between approx. 42 and 53 GPa ($E_{D1}$), compared to the evaluation as described above. This is due to the influence of the relatively large test specimen deformations in the lower stress range being for the most part neglected. The values for $E_{D1}$ and $E_{D2}$ can, e.g. after ODA (1988), be taken as rigidity values for the intact rock matrix, i.e. not affected by fractures or microfissuring.

If the degree of anisotropy $m$ is determined for $E_{D1}$ and $E_{D2}$, see Figure 46, the values are comparably lower than those of the evaluation method described above. This shows clearly that the anisotropic deformation behaviour of the test specimen is related to the non-linear deformation behaviour in the lower stress range, caused by, e.g., the rock texture or the opening or closing of oriented microfissures.

It is again possible to differentiate between various depth ranges of test specimen origin. For example the section from approx. 70 - 120 m has a degree of anisotropy of max. $m = 1.10$, and is relatively low. The azimuth of the principal deformation axis is for the most part unaffected by the method of evaluation.

The elasticity moduli necessary to evaluate the overcoring tests (see also Section 4.1) were calculated as secant moduli $E_{S1}$ and $E_{S2}$ similarly to a compensation test under variable stress (see Section 3.6). They are listed in Table 1 together with the respective test specimen designation, the mean sampling depth, the load levels, the orientation of the plane of isotropy (strike direction $\gamma_{iso}$, with
respect to north, positive defined as counter clockwise) and the probe orientation ($\gamma_3$ as angle between tunnel axis and measurement direction $C$, positive defined as counter clockwise).

![Degree of anisotropy](image)

Fig. 46: Degree of anisotropy $m$ for $E_D$
Tab. 1: Elasticity moduli $E_{S1}$ and $E_{S2}$ from biaxial laboratory tests

The smallest value $E_{S2}$ was calculated for the lower pressure level, the largest value $E_{S1}$ from the highest pressure level.

For a comparison of the results gained in the laboratory with some in-situ results see Section 4.7.
4.7 **Comparison of laboratory and in-situ test results**

Results of some in-situ tests have in part been compared directly with one another (see Figure 31 and Figure 38). In addition some of the results gained in overcoring tests using the BGR method and in dilatometer tests have also been compared with lab results.

![Graph showing SH1 and degree of deformation anisotropy as function of borehole depth.](https://via.placeholder.com/150)

**Fig. 47: Amount of SH1 and degree of deformation anisotropy as function of borehole depth.**

Figure 47 shows the values of the maximum horizontal stresses \( S_{H1} \) as determined in the BGR overcoring tests versus the borehole depth (see also Figure 23) together with the corresponding adjustment curve (unbroken line) calculated as spline function. The plot also includes the
degree of deformation anisotropy, again as a function of borehole depth. The laboratory values of m were determined using test specimens drilled out in the various overcoring tests. Here again an adjustment curve (dashed line) has also been calculated.

There is good correlation between the two compensating curves. For example, in the high stress section (approx. 70 - 100 m) there is a relatively low degree of anisotropy, whereas in contrast the section of very low stresses (approx. 130 - 170 m) has a comparatively high value for m.

Fig. 48: Modulus of elasticity of the rock determined in dilatometer measurements and laboratory tests
Figure 48 shows the elasticity modulus of the rock as a function of borehole depth, determined using fundamentally different processes at approximately similar stresses of approximately 25 - 30 MPa: in-situ tests used borehole deformation tests with the BGR dilatometer, in the laboratory using biaxial tests on hollow cylindrical test specimens (see also Figures 42 and 45).

It is clear from the above that the values determined in the dilatometer tests are on average 40 GPa, and are generally larger than the values measured in the laboratory. In addition it is also clear that the deformation anisotropy occurring in-situ is generally relatively low and, when assessing the rock mass macro-behaviour, can be taken as negligible. In contrast to this, the test specimens studied in the laboratory display a marked deformation anisotropy with differing values for $E_1$ and $E_2$. Possible reasons for this anisotropy and the comparably low modulus of elasticity $E_2$ are described in Section 4.6.

The deviations determined between the values of rigidity found in-situ and in the lab show that the value for the elasticity modulus determined in the dilatometer tests is the more characteristic of the rock mass' macro deformation behaviour. In contrast, the elasticity modulus values determined in the lab on test specimens describe a locally limited rock behaviour. The pronounced non-linear, anisotropic deformation behaviour of the test specimens shows that this modulus of elasticity is stress-dependent and in part often considerably lower. It can only be applied when dealing with special questions, in particular concerning the evaluation of overcoring test.
5. **ROCK MASS STRUCTURE AND STRESS FIELD**

5.1 **Logging methods and evaluation**

Tests for proving and further development of methods to measure rock stresses using the overcoring method were undertaken in vertical borehole GS 84.041A, depth 200 m. Future studies of ultimate storage locations will probably require, for the most part, vertical deep boreholes. In addition, the measurement probes require testing in a water-filled vertical borehole at depths below tunnel level. Furthermore, a vertical arrangement should provide additional data on understanding the overall geology in the GS-BK area. The area between the fault zone located at the end of borehole SB 80.001 and the laboratory tunnel was selected as borehole location, in that it offered excellent preconditions for infrastructural links with the BK tests as well as the promise of good overcoring results from a rock area previously unworked and with low numbers of joints. In addition a short horizontal borehole (GS 84.042A) enabled pretests of equipment without water pressure prior to use in the deeper borehole.

In logging the geological data of all cores studied at the Grimsel Test Site (GTS) the method proposed by NAGRA has proven itself well. For this reason, and for reasons of uniformity, data logging on the cores from the 2 GS test boreholes was carried out using this method, and it was also further developed. Precondition for data evaluation is a careful orienting of the cores. In the method used the core is marked with a pin before retrieval. An additional basis for fixing the spatial orientation of the core was provided by oriented installation of CSIR triaxial cells into borehole GS 84.041A.
In total 211.24 m of oriented, recovered core was geologically logged. Vertical borehole GS 84.041A was drilled to 171.17 m with a diameter of 146 mm and from there to total depth 191.29 m, with a diameter of 86 mm to allow for subsequent hydrofrac tests. Horizontal borehole GS 84.042A was drilled through to total depth at 19.95 m at a diameter of 146 mm (Table 2).

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Dia. mm</th>
<th>Depth m</th>
<th>Az/incl. degree</th>
<th>Coordinates y</th>
<th>x</th>
<th>z</th>
<th>Drill time</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS 84.041A</td>
<td>146/86</td>
<td>191.29</td>
<td>000 -90</td>
<td>197.31</td>
<td>444.59</td>
<td>1729.73</td>
<td>17.06.-13.12.84</td>
</tr>
<tr>
<td>GS 84.042A</td>
<td>146</td>
<td>19.95</td>
<td>205 +5</td>
<td>195.28</td>
<td>443.68</td>
<td>1730.96</td>
<td>13.07.-26.11.84</td>
</tr>
</tbody>
</table>

Table 2: Summary of GS test boreholes

The subsequent evaluation of the core data was carried out using the ORKAN software package (spatial orientation of joint planes by azimuth and dip). This software development has the objective of converting the data determined from the core of the apparent azimuth and apparent angle of dip of joint planes.

Both values, i.e. apparent azimuth of dip and apparent angle of dip are first drawn from the logging data of the core which assumes a theoretical vertical orientation of the borehole axis. If the actual borehole orientation deviates from the theoretical orientation then the spatial location of the joint plane determined from the core changes.
This requires in turn that a new dip line has to be determined, which can then be drawn on as the characteristic coefficient to describe joint orientation. The conversion of the apparent orientation of a joint plane into the actual orientation, i.e. the determination of the actual dip line of a joint plane, as described by its azimuth of dip and angle of dip is achieved with the aid of the ORKAN software package. Using vector analysis the actual values for the dip azimuth and the angle of dip of the joint plane are calculated from the data of the apparent values and the borehole orientation. The program is written in FORTRAN and BASIC and can run on a microcomputer at test location.

5.2 Geological description BOGS 84.041A

The profiles of boreholes GS 84.041 A and GS 84.042 A display within their first few metres the biotite-rich dark and in part schistose variety of the ZAGr as found in the base of the cavern in the GS section. With increasing depth this changes into a lighter more compact form (see Figure 49 for a schematic of borehole GS 84.041A and App. 2 for more details).

The section between drill metre 40 and drill metre 100 exposes particularly compact ZAGr in GS 84.041A and no open joints are apparent. Noteworthy here are the many quartz epidote veins which cut through the granite without transitions and without visibly influencing the host rock.
ZAGr, biotite-rich with shear-zone

ZAGr, light, partly porphyritic

ZAGr, biotite-rich, definite lamellar structure

ZAGr, light with quartz-epidote veins, definite lamellar structure

ZAGr, hydrothermally altered with open subhorizontal fracture

ZAGr, dark, strongly fractured

ZAGr, light, strongly fractured

ZAGr, light and dark with quartz-epidote veins partly definite lamellar structure

Lamprophyre with shear-zones

Fig. 49: Schematic geological section of borehole GS 84.041A (for details see App. 2)
At around 100 metres depth an open fracture was encountered of alpidic origin and typical for the Grimsel area. Noticeable joint minerals are quartz as idiomorphic crystals (up to maximum 2 mm) and sandy chlorite. Similarly formed, more or less horizontal joints are found in the laboratory area in many locations. They are always characterized by a margin of hydrothermally altered granite.

The origin of these fractures could have many causes:

- lifting and resultant stress release of the massif
- increasing brittleness of the granite
- frac effect of the hydrothermal solutions, e.g. at apophyses of lamprophyres.

Strongly fractured sections with clearly open, but non-mineralized joints, were encountered between 127 to 131 m and 137.5 m to 144 m.

At 181.26 m a biotite/chlorite schistose zone with subsequent lamprophyre was encountered. The schistose zone resulted in high core losses. This section and the following lamprophyre can be correlated with regard to spatial location with a similar zone in the front section of the laboratory tunnel (around tunnel metre 130).

Borehole GS 84.041A had to be aborted because of the high breakout rate in the schistose at total depth 191.29 m, because the subsequent hydrofrac tests planned did not include any casing or injection alternatives.
5.3 Joint statistics and rock stresses

5.3.1 Objectives

The geological investigations undertaken in the GS test section provided the data basis for test configuration, the location of the boreholes and the interpretation of measurement results. They also represented the data basis for determining locations for overcoring tests in the measurement of rock stresses.

The parallel investigations into the rock mass structure and stress field in borehole GS 84.041 A were undertaken to spotlight connections between the joint system and the stresses measured. Together with the studies of the microstructure it was intended to prove the transferability of know-how and results to other sections enabling clarification of the regional stress field. This also opens the possibility of being able to transfer the investigative methods used here to other, not only crystalline, rock areas.

5.3.2 Joint systems in the Grimsel area

The structural studies in the Grimsel massif resulted in the designation of numerous joint systems which also represent different ages of origin. The tectonic analyses indicated that the Central Aare granite together with the Grimsel granodiorite was subject at different times to stresses from different directions. The resultant deformations and faulting commenced during the herzynian orogeny and continued in the alpidic mountain forming period.
The rock mass of the Grimsel area, having in part clear parallel texture and cut by joint systems, should then be regarded as the product of tectonic processes over a number of phases.

When considering the joints and planes of schistosity in the Central Aare granite it is apparent that they often occur in clusters, i.e. in joint families which are characterized in each case by very similar spatial orientation and similar joint filling materials. The majority of the joints have a very steep angle of dip (often more than 80°).

The statistical evaluation of the joints produced the orientation maxima of the shear surface systems S1-S3 previously known in the Grimsel area, whereby S1 and S2 could often not be differentiated spatially. It was also possible to confirm the clustering in some other joint systems (BRÄUER et al. 1989).

5.3.3 Joint statistics of borehole GS 84.041A

The diagram showing all measured joints in borehole GS 84.041 A has 2 clear maxima. The maximum of the open fractures, 73 in number and low compared to boreholes in the BK zone, lies approximately in an ENE/WSW direction (Figure 50, contour lines). The closed fractures strike mainly in a WNW/ESE direction (Figure 50, shown as outer fracture rosette). Slickensides were only encountered in the upper regions of the borehole, but could not be logged with orientation because of high core breakage. Based on experience also gained in the neighbouring BK test area, the vertical alignment of the GS borehole provides a sufficient base for a statistical evaluation of the location and frequency of joints.
Fig. 50: Joint statistics of borehole GS 84.041A
(open fractures (73); lower hemisphere projection, contour lines: 0.5, 2, 6 and 12 %; closed fractures (199): outer rosette)

5.3.4 **Direction of maximum horizontal stress**

In the diagram showing the direction of the maximum horizontal stress ($S_{H1}$) the results are taken from a total of 29 stress measurements. The statistical evaluation of all measurements shows 2 direction maxima: WNW/ESE and NNW/SSE (Figure 51, overall diagram as symmetrical joint rosette).
5.3.5 Joint system and stress direction

It is difficult to recognize any direct relationship between the direction of the joint systems and the direction of maximum stresses when considering borehole GS 84.041A overall.

The apparently geologically homogeneous borehole can, however, be subdivided into 4 depth sections following close analysis of the joint statistics and the results of the stress measurements (see Figure 52):

- Section I: 0 - 40 m: Granite with pronounced parallel texture, in part schistose
- Section II: 40 - 100 m: Compact granite with horizontal joint at around 100 m.

- Section III: 100 - 172 m: For the most part compact granite with numerous closed joints and two intensely fractured zones with open fissures between 127 - 131 m and 137.50 - 144 m.

- Section IV: 172 m - TD: Granite, kakkirited, within influence zone of lamprophyre-schistose zone.

(191.29 m)

Considering each section individually spotlights interesting relationships between the results of the stress measurements (direction $S_{H1}$) and the direction and frequency distribution of the joints (Figures 52 and 53).

The heterogeneous rock mass structure encountered in the GS test borehole is also reflected in the results of the stress measurements. Figure 53 also shows the stress directions as determined in the overcoring tests. The internal array reflects the direction of the maximum horizontal stress from 29 measurements. A clear maximum is recognizable running approximately ESE/WNW. Bearing in mind the different sections as depicted in the joint statistics the stress directions measured also show an anisotropy. In the section between 40 and 100 m the direction of the maximum horizontal stress shifts from the previously mentioned maximum to a secondary maximum in a direction of approximately NNW/SSE.
Fig. 52: Joint statistics for borehole GS 84.041 A
(External: closed fractures (strike direction)
Internal: open fractures in lower hemisphere projection; contour lines 2, 6 and 12 %)
Individually each section can be described as follows:

**Section I:**

Figure 53 shows, for section 0 - 40 m the direction of the maximum horizontal stress ($S_{H1}$), the maximum of which lies approximately along WNW/ESE. This maximum is apparent in both the dominant direction of the closed fractures and also that of the open fractures (Figure 52).

**Section II:**

In the section between 40 - 100 m (Fig. 53) the direction of $S_{H1}$ is between around NNW/SSE and N/S. The ZAGr is very compact at this depth and only two open fractures were detected. The number of closed joints is also very low. The joints here are mainly healed by quartz and epidote, without any clear direction maximum (external joint rosette) (Fig. 52).

**Section III:**

The section between 100 - 172 m is comparable with respect to stress direction and spatial location of joints with Section I (0 - 40 m). The maximum of the joints is also in that direction. The open fractures are concentrated between depths 127 - 131 m and 137.5 - 144 m (see also Figure 49 and App. 2).

**Section IV:**

The lower regions of the borehole (172 m - total depth) are, below 180 m, clearly influenced by the lamprophyre shear zone. Figure 52. shows the joint statistics for this section. Open joints are secondary here. The maximum of the joints is, as in section III (100 - 172 m), in a line lying WNW/ESE. The orientation of the maximum horizontal stress $S_{H1}$ was determined in this depth section by hydrofrac measurements and has the approximate direction of WNW/ESE - E/W (Figure 53).
Fig. 53: Borehole GS 84.014 A, direction of $S_{H1}$; separate plots of various sections

The section between 40 - 100 m on the GS test borehole shows significant differences to the borehole overall, not only with respect to joint distribution and stress directions but also with respect to the stress values measured. The values for $S_{H1}$, which are on average 30 MPa, increase in Section II to around 40 MPa and more. It is thought that the low number of joints, in particular the absence of open joints in this section, has resulted in not only a rotation of the horizontal stress direction but also explains the higher stress values measured (for summarizing diagram see Figure 54).
Fig. 54: Joint system of borehole GS 84.041 A; 
relationship between geological structure, 
maximum horizontal stress direction and stress 
values  
(External: Direction of strike of closed joints, 
internal: Polar projection of open joints)

The drop in the stress values in the lower section of the 
borehole is also noteworthy. These values, measured using 
the hydraulic fracturing method, allow one to draw the 
conclusion that the incompetent lamprophyre schistose zone 
leads to a reduction in the stress values for depths of 
180 m and lower.
5.3.6 Joint frequency and horizontal stress values

The results of the stress measurements may be subjected to a differentiated analysis within a geological structural investigation. This applies not only to the relationships mentioned in the preceding between joint system and stress direction, but is also valid for the reciprocity between the joint frequency and the stress values measured. As measure for the frequency of joints use is made of the "joint coefficient" which is adapted from the term "fracture coefficient" (fractures per metre) (after STINI). In this both open and closed joints and shear planes are counted.

Fig. 55: "Joint coefficient" and horizontal stress in borehole GS 84.041 A

- Joint coefficient
- Horizontal stress
Figure 55 shows an obvious relationship in a comparison of stress value and joint coefficient. As the number of joints per drilled metre increases so is there a definite drop in the horizontal stress value. This is made clearer in Figure 56, in which the horizontal stress components and the joint coefficient values determined for that particular depth are compared. The two lower stress components of 10 and 15 MPa are considered to be the stress reductions resulting from decreasing distance to the lamprophyre-shear zone commencing at around 180 m (Figure 57).

If one considers the results and know-how gained within the stress relationships of the GS exploratory borehole overall then, with suitable interpretation, statements can be made with regard to those borehole sections in which no stress
measurements were carried out (Figure 58). In addition, a closer analysis of the results of the stress measurements taken together with a detailed engineering geological analysis provides a basis for undertaking the bigger step of transferring the methods employed to other boreholes and homogeneous zones.
5.3.7 **Profile description and joint statistics of BOGS 84.042A**

Borehole GS 84.042 A was drilled at right angles to GS 84.041 A with an dip of 5° and an azimuth of 205°. In the first section, to around 4 m, drilling encountered biotite-rich ZAGr, similar to the vertical borehole. By total depth, 19.95 m, this had changed to a somewhat lighter granite (App. 3).

![Joint statistics of borehole GS 84.042 A](image)

**Fig. 59:** Joint statistics of borehole GS 84.042 A  
(Total number: 45; lower hemisphere projection,  
contour lines: 1, 4, 6 and 8 %)

The joint statistics detected only one open fracture (possibly due to blasting) and maxima for the other joints as found in GS 84.041 A (Figure 59).
5.4 **Investigations of the microstructure**

5.4.1 **Objectives and methods**

Parallel to the macro analysis of joints investigations were also carried out into the microstructure of the Central Aare granite. The objective of these investigations was to correlate the results of the stress measurements with measurements of formation and orientation of microfissures.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Depth (m)</th>
<th>Number of thin sections</th>
<th>Number of recorded fissures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>horizontal</td>
<td>vertical</td>
</tr>
<tr>
<td>DS 10</td>
<td>27.83</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>DS 11</td>
<td>33.13</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>DBS 12</td>
<td>38.82</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>DS 13</td>
<td>47.46</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>DS 14</td>
<td>67.43</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>DS 15</td>
<td>76.62</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>DBS 16</td>
<td>84.70</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>DBS 18</td>
<td>94.75</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>DS 19</td>
<td>107.17</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>DBS 21</td>
<td>118.41</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>DS 23</td>
<td>133.40</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>DS 27</td>
<td>146.38</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>DBS 28</td>
<td>159.62</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>DS 30</td>
<td>167.64</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Thin sections of borehole GS 84.041 A

(DBS = thin sections, vertical and horizontal
DS = additional thin sections, horizontal)
To determine the spatial orientation of microfissures thin rock sections were studied on a universal stage and magnifications of 160 - 200 (see Table 3). Three mutually perpendicular thin rock sections were taken from a sample in turn taken from an oriented core in order to cover the whole directional spectrum of the microfissures (Figure 60).

Fig. 60: Direction of the oriented thin sections
(Left: core ø 123 mm with the borehole ø 46 mm and oriented rock sample; right: direction of thin sections in the oriented rock sample)
In the course of the measurements it was found that the main proportion of the fractures had steep angles (75° - 90°) such that the horizontal thin sections provided the best results. From a technical viewpoint as well the evaluation was concentrated on the thin sections lying in a horizontal plane. The spatial values of the microfissures detected in the 2 vertical thin sections had to be recalculated by rotating within the coordinate system.

5.4.2 Results of thin section studies

The intense tectonic stress on the ZAGr during its geological history is also apparent in its microstructure. The quartz filling in particular shows intense undulatory extinction whereas in the feldspars fractured deformation was often determinable. Therefore the evaluation of the microstructure was based mainly on the measurements of open and closed microfissures in feldspars (alkali feldspar and plagioclase) and on many fluid inclusion trails in the quartz. In total around 600 microfissures at 14 different depths were determined three-dimensionally during the report period.

The overall evaluation of the thin sections shows a definite maximum in the near vertical microfissures in an E/W to ESE/WNW direction (Fig 61). This maximum compares to the frequency distribution of the joints measured in the cores. In addition a maximum in an SE/NW to SSE/NNW direction was determined. There was no joint plane maximum in this orientation detectable in the cores from the GS borehole. Seen overall, however, there is a relationship apparent with the horizontal stress directions measured.
Fig. 61: Direction of microfissures
(Internal: polar point projection in lower hemisphere, External: strike direction)

Consideration of the various depth sections produces a differentiated picture. Fig 62 shows contour lines (lower hemisphere projection) and external joint rosette for the microfissure orientation, whereas the internal results are shown as depth-related stress measurements with spread margin. It is apparent that the direction of the maximum horizontal stress frequently coincides with the direction of microfissuring (clear exception: at depth 47.46 m).

In most cases the microfissures were fluid inclusion trails in relatively large quartz grains. These fissures, which could not have originated from core release during overcoring are seen as an indication of a tectonic stress. In addition it is noticeable that there are clear direction differences between closed (including fluid inclusion trails) and definitely open microfissures.
Fig. 62: Directions of microfissures in different sections of depth in borehole GS 84.041A; Strike direction (outer rosette) and spatial direction (contour lines in lower hemisphere projection); Internal: direction of maximum horizontal stress with spread margin.
Fig. 63: Directions of microfissures in a granite sample of borehole GS 84.041A; (Depth: 67.4 m; contour lines: total; External: open fissures; Internal: closed fissures)

Figure 63 shows an example of microfissure directions at a drill depth of approximately 67.4 m. The closed fissures (external joint rosette) have a maximum in a direction of SSE/NNW, whereas the orientation of the open fissures (internal joint array) is along ESE/WNW.

These two maxima are also apparent in the summary diagrams in Figure 64, in this case the strike direction refers to the usually steep fissures. The fluid inclusion trails have a clear maximum at 110° and a subordinate maximum at 140/150°. The maximum of the open fissures on the other hand is around 140/170°.
The remaining closed fissures, mainly healed over with epidote, have no preferential directions. The measured fissures occur in alkali feldspar and quartz grains with a ratio of around 50:50 respectively, whereas other minerals, for example plagioclase, titanite and mica are definitely under represented (Figure 65).
5.5 **Sonic televiewer logging (SABIS) in borehole GS 84.041 A**

(SABIS = Scanning Acoustic Borehole Imaging System)

In accordance with the order dated 6 June 1985 the BGR ran a log in borehole GS 84.041 A from depth 37 m (bottom of casing) to depth 171.17 m (171.17 to total depth 191.29 m, caliper 86 mm) using the sonic televiewer of the Westfälische Berggewerkschaftskasse (WBK), Bochum.

Objectives here were:

1. Direct comparison with geological core data
2. Detection and measuring of any borehole breakouts
3. Detection of fractures generated in the preceding dilatometer tests.

In preparation for this survey the approximately 5 m long probe was run down to total depth and then retrieved at a constant rate for the survey. During raising the scanning head at the bottom end of the probe rotates and records signals reflected by the borehole wall. Different wall properties produce differences in the logging. Parallel to this north is fixed, allowing determination of actual spatial location of the data measured.

The reflection values and the amplitude values are displayed directly on a colour monitor, recorded on magnetic tape and also plotted on a scale 1:10. The engineer in the test vehicle supervises the entire survey and two technicians are available for the installation and performance of the survey.
The execution of the SABIS survey in borehole GS 84.014 A ran smoothly. Although the test vehicle could not be located directly at the borehole (at 3.5 m diameter the tunnel was too small) the installation of the retrieval wire was possible using a pulley system.

The scientific questions could not be clarified in all points. The ultrasonic probe only registered sections greater than 1 to 1.5 mm in thickness. For this reason the fractures generated in the dilatometer tests were not detected. (It may be assumed that the fractures generated are reduced to thicknesses of less than 1 mm by the lithostatic pressure.) Also, throughout the entire length of borehole no significant breakouts were registered.

The thicker joints (in excess of approximately 1.5 mm) are well recognizable in the survey by their spatial characteristics. In most cases it is indeed possible to differentiate between open and closed fissures on the basis of the reflection and amplitude changes of the sonic waves. This differentiation is not possible when the core is poor, or in the case of core loss. The survey of the borehole wall using the SABIS probe therefore represents a useful supplement to the geological core data. The logging of the borehole wall can, however, in the case of clean and flushed boreholes, also be carried out using a downhole video probe.

In the SABIS survey the registering of north also provides data for post-orientation of the core sections. This is particularly important in sections in which core orientation is questionable or absent. In the case of borehole 84.014 A the location of the core orientation was confirmed by the SABIS survey.
In contrast to a video probe it was difficult to recognize sections with pronounced parallel texture or the rock fabric (e.g. large alkali feldspar crystals in the matrix). Similarly no data on joint filling is available. In contrast sections with higher porosity could usually be clearly differentiated from the denser sections.

Summarizing, table 4 below shows the advantages and disadvantages of a survey using a sonic televiewer system.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Suitable for greater depths (currently down to 5000 m)</td>
<td>- joints of less than 1.5 mm not detected</td>
</tr>
<tr>
<td>- Post core orientation possible</td>
<td>- joint filling not determinable</td>
</tr>
<tr>
<td>- Data from sections with core losses</td>
<td>- rock fabric, texture only poorly recognizable</td>
</tr>
<tr>
<td>- Recognition of porous sections</td>
<td>- survey currently only possible in boreholes greater than cal 90 mm</td>
</tr>
<tr>
<td>- Determination possible of spatial location of joint planes</td>
<td>- survey not recommendable in boreholes with irregular caliper</td>
</tr>
<tr>
<td>- Recognition of borehole breakouts (at great depths) to determine rock stress direction</td>
<td>- personnel requirement: 3 (1 engineer, 2 technicians)</td>
</tr>
<tr>
<td>- Suitable for inclined boreholes</td>
<td>- Only slightly effected by drilling fluid</td>
</tr>
</tbody>
</table>

Table 4: Assessment of SABIS survey in BOGS 84.014 A
6. **FINITE-ELEMENT STUDIES**

In order to design measuring equipment, interpret measurement results and assess the influence of individual test conditions and rock variables on those measurement results, theoretical investigations are necessary. To this end numerical calculations were carried out using the Finite-Element Method (FEM) on the ADINA software package (Automatic Dynamic Incremental Nonlinear Analysis). For details of this package (version 1984) see ADINA user's manual (1984).

6.1 **BGR overcoring method**

The following constellation of questions was considered in the many finite-element studies of the BGR overcoring method:

- influence of overcore diameter
- influence of borehole diameter \( \phi \) 146 mm and cone on stress distribution in the zone of the pilot borehole and on radial and axial stress release deformations
- influence of Poisson's ratio on the deformation behaviour of the pilot borehole during overcoring
- checking assumption of plane strain condition (EVZ) for the evaluation of the tests carried out with the BGR-2D probe
- qualitative check of the stress release deformation method, in particular for those values measured in an axial direction

The FEM calculations were carried out using the model illustrated in Figure 67, 180 rotational-symmetric, isoparametric 8-node elements and 646 nodes. The calculations were based on the following assumptions:
- ideal elastic, isotropic, homogenic rock behaviour
- rotational symmetry with respect to geometry and loading

Assessment of the calculation results assumed following points and distances in the FE model (Figure 67):

- point B as reference point for the BGR-2D probe (radial measurement only), approx. 13 cm distant from the borehole front φ 146 mm
- point E approx. 32 cm distant from borehole front φ 146 mm compared with point B
- distance A-D is reference distance with l₀ = 16 cm for axial measurement length of BGR-3D probe
- distance C-D is l₀ = 2 cm compared with distance A-D.

Fig. 67: FE model 180/646 for simulation of BGR overcoring test
Simulation of the overcoring process involves application of the ADINA implemented "element death option", in which at preset points in time marked elements of the FE model can be eliminated, and hence made mechanically ineffective. This allows the time dependent processes of the overcoring tests to be considered as the borehole front drilling progresses.

Fig. 68: Principal stress distribution during overcoring progress (\( p_R = 30 \) MPa, \( p_V = 10 \) MPa)
Figure 68 shows the distribution of the principal stresses during a well advanced overcoring test. In this the overcoring front has reached the position of point B. The pronounced stress redistribution, marked by a substantial change in principal stress values and directions, produces a temporary increase of stresses in the overcore front zone. The effect finally leads to convergence of the pilot borehole followed by the actual stress release of the overcored section (see also Section 4.1.1).

![Diagram showing stress distribution and overcoring diameter variation](image)

**Fig. 69: Variation of overcoring diameter**

The variation of the overcoring diameter \( D_{UB} \) is shown in Figure 69, where \( D_{UB} = 2.7 \times D_{PB} \), \( D_{UB} = 2.1 \times D_{PB} \) and \( D_{UB} = 1.6 \times D_{PB} \) \((D_{PB} = \text{pilot borehole diameter})\). I.e. the theoretical release deformation display only slight deviations when considered as functions of the normalized overcoring time \( t/t_0 \). In this case as \( D_{UB} \) decreases the
stress release deformation $\Delta D$ also decreases slightly. This reduction is due to numerical effects, since the FE structure in the pilot borehole zone becomes relatively coarse as the overcore diameter decreases. Analysis of the overcoring process using closed solutions shows that for ideal elastic rock behaviour there is no dependence between the stress release deformation and the overcore diameter (HEUSERMANN, 1984).

Fig. 70: Pilot borehole deformation at points B and E

In order to provide a quantitative check of the pilot borehole diameter changes determined for point B, a comparison is made with the values calculated at point E, which is still further from the $\phi$ 146 mm borehole front. Figure 70 shows that the stress release deformation in point B is around 3 % higher than that in point A. This slight deviation is caused by the concentration of stress in the area of the borehole front $\phi$ 146 mm.
The setting depth of the BGR-2D probe, i.e. the separation between the transducer to the borehole front φ 146 mm, is therefore sufficiently large.

Fig. 71: Axial pilot borehole deformation

In addition to the radial, the axial deformation measurement, as carried out with the BGR-3D probe, has also to be checked with respect to its distance from borehole front φ 146 mm. Figure 71 shows the theoretical axial borehole deformation $\varepsilon_z$ during the overcoring process plotted over the normalized overcoring time $t/t_0$. The initial distortion was calculated for distance A-D with $l_0 = 16$ cm. This distance corresponds approximately to the initial measurement length of the 3D probe with $l_0 = 16.5$ cm. Distance A-D with $l_0 = 2$ cm is drawn on as a comparison as it is not affected by the borehole front
\( \phi \) 146 mm. The axial stress release deformations remaining after the overcoring process have only a relatively small difference according to Figure 71: the values calculated for distance A-D are around 10 % lower than for distance C-D. As a consequence, the measurement values determined using the 3D probe have to be corrected by a factor of approx. +10 %.

The evaluation of indirect rock stress measurements using the overcoring method requires not only determination of the modulus of the elasticity \( E \), but also knowledge of Poisson's ratio \( \nu \). To this end a parameter study was carried out into the influence of \( \nu \). The initial stress state was taken as rock pressure \( p_R = 30 \) MPa (horizontal) and \( p_V = 10 \) MPa (vertical). It was shown that \( \nu \) has only a minor influence on changes in the pilot borehole diameter because of the small size of the vertical stress \( p_V \) compared with the horizontal stress \( p_R \).

\[ \begin{align*}
E &= 40 \ \text{GPa} \\
p_R &= 30 \ \text{MPa} \\
p_V &= 10 \ \text{MPa}
\end{align*} \]

![Fig. 72: Variation of \( \nu \)](image-url)
In contrast to this, the plot in Figure 72 of axial pilot borehole deformation \( z \) for distance C-D, shows that because of the higher horizontal stress \( p_R \) the remaining stress release deformation \( \Delta z \) after overcoring is considerably influenced by \( \nu \). For \( \nu = 0.0 \) a positive release deformation takes place, whereas for \( \nu = 0.25 \) and \( \nu = 0.50 \) the lateral contraction of the overcored pilot borehole is, as result of \( p_R \), larger than the vertical stress release deformation due to \( p \), and hence the \( \epsilon_z \) values are negative.

![Graph showing axial deformation](image)

**Fig. 73: Variation of horizontal stress state**

To check the assumption of the plane strain conditions where \( \epsilon_Z = 0 \) for the evaluation of the stress measurements carried out with the BGR-2D probe, the axial borehole deformation \( \epsilon_z \) was calculated taking the horizontal stress state as variable. Figure 73 shows then, that e.g. for \( p_V/p_R = 10/30 \) MPa, a slight negative axial deformation occurs after overcoring, whereas for \( p_V/p_R = 10/20 \) MPa, \( \epsilon_z \) returns to approximately that of the initial value. Thus in the stress constellation determined for BOGS 84.041 A, which has comparatively high horizontal and low vertical stresses, the influence of \( \epsilon_Z \) may be taken as negligible.
Comparing the axial release deformation determined in the FE calculations with the values measured (see Figure 19) produces good overall agreement. Thus, e.g., the overcoring process displays initial dilation, followed by a compressive phase and finally, at the end of the overcoring process, again a dilation of the pilot borehole in an axial direction.

6.2 Mechanical frac probe

The objective of the new development of a mechanical frac probe (BGR type) was to determine rock stresses and their directions by generating fractures in boreholes. In so doing the direction of the fracture was to be set by probe orientation. In the dilatometer or hydrofrac tests the induced fractures have in principle an orientation which is dependent upon the direction of the minimum rock stress due to the constant load, $p_i$, in the direction of the borehole circumference. In the case of the mechanical frac probe it was planned to achieve non rotation-symmetric loading of the rock by employing two rigid plates to produce a local preselected overstressing to create the fractures. In the process several fractures of different orientation are targeted in one measurement horizon; the amounts and directions of which provide the means to derive any rock stresses effective at right angles to the borehole axis.

For design details of the mechanical frac probe see Section 3.5. In the course of equipment development and testing the following questions were considered:

- design of the probe
- interpretation of borehole deformation to be measured during tests
- prognosis of stresses induced via probe in the borehole zone.
Figure 74 illustrates the FE discretisation of the probe in a borehole zone of 70 x 70 cm in a section normal to the borehole axis. For reasons of symmetry only one quarter of the section is modelled. The plane FE model encompasses 324 isoparametric two-dimensional 8-node elements, and a total of 1426 node points. The calculations are carried out for plane strain conditions assuming an ideal elastic, isotropic and homogenic continuum. In addition the calculations use material constants for steel \((E_{st}, \nu_{st})\) and granite \((E_{g}, \nu_{g})\).
The first point to be checked was the deformation path predicted between the plates as a function of probe pressure. The gap $\Delta s$ between the two plates increased with pressure stages $p_i = 50, 100$ and $150$ MPa in a linear fashion up to max. $0.38$ mm. Similarly to the implementation of a Goodman probe (see HEUZE & AMADEI, 1985), the elasticity modulus of the rock can be determined from this. The measured and theoretical deformation values are compared in Section 4.5.

The use of the mechanical frac probe to measure rock stresses requires knowledge of the size and distribution of the isometric stressing caused by the rigid plates on the borehole wall. For example the borehole wall is subject to different values of principal compressive stresses (radial) and principal tensile stresses (tangential). The generation of fractures, the orientation of which is dependent only on the orientation of the probe, and not the direction of the rock stresses, is at least theoretically possible.

Fig. 75: Tangential stress in section A-A due to probe pressure
In order to generate radial fractures it is necessary to overcome not only the rock strength but also the tangential rock pressure stress effective at the borehole: hence the development of the induced tangential tensile stress is of special interest. Figures 75 and 76 show the development of the tangential stress caused by the probe pressure in two sections.

Section A-A (normal to the direction of movement of the rigid plates in the plane of the gap between the two plates) shows, for an internal probe pressure of $p_i = 100$ MPa, high tangential tensile stresses at the borehole wall of up to approx. 190 MPa, which fall rapidly with increasing radius (Figure 75). In contrast section B-B (Figure 76) shows only very minor tangential tensile stresses of approx. 5 MPa. These values indicate the theoretical possibility of preferred fracture generation in section A-A.
7. CONCLUSIONS

In the development and testing of various methods for measuring rock stresses the methods listed below were employed at the Grimsel Test Site in vertical borehole BOGS 84.014 A down to a depth of approximately 180 m:

- Overcoring using BGR 2D and 3D probes
- Borehole dilation tests using the BGR dilatometer
- Overcoring using CSIR triaxial cells (Interfels type)
- Hydrofrac test using the MESY Frac apparatus.

The use of the BGR probe produces measurement results which are relatively uniform. With respect to providing comprehensive control of test progress and comprehensive acquisition of measurement values it was found that measurements made during overcoring were extremely advantageous. In principle the use of this method is possible in boreholes down to 400 m depth with the probe suspended on a data line. With respect to the computer probe used for the first time for data registration it is probably suitable for overcoring tests at still greater depths.

The use of the BGR dilatometer for assessing rock mass deformations was only impeded in one case by technical problems. The use of the BGR dilatometer would therefore appear possible at depths of several hundred metres.

Measurements carried out with the CSIR triaxial cells show that perfect cementing of the probe underwater is very difficult and the use of the cement when installing on an orienting string allows maximum installation depths of around only 120 m. The results also indicate that data acquisition with this device is insufficient because measurements are only possible prior to and after, but not during, the overcoring itself.
The evaluation of the measurements performed with the BGR probes show a for the most part uniform picture. Maximum horizontal stresses are indicated of between approx. 25 and 40 MPa and minimal horizontal stresses of between 15 and 30 MPa. In so doing several sections may be designated having different stress levels and different orientation of the maximum horizontal stresses.

The dilatometer measurements show moduli of elasticity of between approximately 35 and 45 GPa at various test depths.

The evaluation of the stress measurements using the CSIR triaxial cells shows that the values have a substantial spread. Comparison with the stresses measured using the BGR method (BS) in the overcoring tests shows that the measurements with the triaxial cells produce substantially lower stress values.

The logging and calibration of the fractures generated in the frac test display excellent agreement with the direction of the maximum horizontal stresses as determined during BS tests in the neighbouring rock sections.

The horizontal stresses measured in the hydrofrac tests between the borehole depths of approximately 170 to 180 m fit in well with the overall picture of the stress field. Simultaneously it is clear that the stress contributions are substantially influenced by a marked fault zone. The direction of the maximum horizontal stresses also shows excellent agreement with the results of other test methods.

The comparison of detailed geological studies and the results of the stress measurements bring to light relationships between rock structure and stress field. Both the rock stress component as well as the orientation of the largest horizontal stress show dependency upon the frequency of joints and joint direction. This is particularly apparent in the sections above and below an
alpidic, i.e. geologically recent, fracture. The stress field is also influenced by differing petrography (lamprophyre veins) and rock mass continuity (shear zones).

The microstructural study also shows relationships between the microfissure orientation and the direction of the maximum horizontal stress. These results provide the means of estimating rock stress conditions in areas where measurement results are absent.

The results of the measurements together with the geological survey data allow stress measurements to be assessed in a manner important with respect to future planning as well as the transferability of measurement results. The determination of point stress measurements should only be carried out in association with detailed geological logging. This allows the number of measurements to be reduced to a minimum whilst providing a great deal of information.

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REFERENCES


GLOSSARY OF ABBREVIATIONS

App.: Appendix
BGR: Bundesanstalt für Geowissenschaften und Rohstoffe
     (Federal Institute for Geosciences and Natural Resources), Hannover
BK: Fracture system flow test
BMFT: Bundesministerium für Forschung und Technologie, Bonn
      (Federal Ministry for Research and Technology)
BO: Borehole
BS: BGR overcoring probe
CSIR: Council for Scientific and Industrial Research, South Africa
DBS: Thin section taken from overcored probes
DI: Dilatometer
DMS: Strain gauge
DS: Thin section
DTW: Differential transformation transducer (LVDT)
EVZ: Plane strain condition
FE: Finite-Element
FEM: Finite-Element Method
Fig.: Figure
GrGr: Grimsel Granodiorit
GS: Rock stresses
GSF: Gesellschaft für Strahlen- und Umweltforschung mbH,
     Institut für Tieflagerung, Braunschweig
     (Research Centre for Environmental Sciences)
GTS: Grimsel Test Site
HY: Hydraulic Fracturing (Hydrofrac)
MESY: Befeld Meßsysteme, Bochum
MF: Mechanical frac-probe
MR: Measurement direction / measuring rosettes
N,S,E,W: North, South, East, West
NAGRA: Nationale Genossenschaft für die Lagerung radioaktiver
       Abfälle, Baden
       (National Cooperative for the Storage of Radioactive Waste)
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Samples (Ms: Mineralogy, Fr: Rockmechanics)

Petrography

Fractures

without Minerals

with Minerals

Minerals

Thickness (mm)

RQD
Joint Frequency

Tests

BGR - probe
BGR - probe 3D
Triaxial - Cell
Dilatometer

Rocks

Central Aaregranite (ZAGr)
ZAGr, biotite - riche

Veins

Lamprophyre (Kersantite, Spessartite)
basic veins

Alpine rocks and joints

Quartz veins
hydrothermal altered ZAGr
fissure
Shear zone extremely fractured

Fractures

open fractures (strike and dip direction)
closed

Minerals

Chl Chlorite E Epidote F Feldspar Myl Mylonite Q Quartz Bt Biotite P Pyrite (clay minerals)

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GRIMSEL TEST SITE

ENCLOSURE 3