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TECHNICAL REPORT 88-37E

GRIMSEL TEST SITE

ENGINEERING GEOLOGICAL INVESTIGATIONS FOR THE INTERPRETATION OF ROCK STRESS MEASUREMENTS AND FRACTURE FLOW TESTS

V. Bräuer
B. Kilger
A. Pahl

APRIL 1989

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

GRIMSEL TEST SITE / SWITZERLAND
A JOINT RESEARCH PROGRAM BY

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

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FOREWORD

Concepts 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.

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 Versuchsstollen umfasst insbesondere

- den Aufbau von Know-how in der Planung, Ausführung und Interpretation von Untergrundversuchen in verschiedenen Experimentierbereichen und
- den Erwerb praktischer Erfahrung in der Entwicklung, Erprobung und dem Einsatz von Testapparaturen und Messverfahren.

Das Felslabor (FLG) wird durch die Nagra betrieben. Die verschiedenen Untersuchungen werden aufgrund eines deutsch-schweizerischen Zusammenarbeitsvertrages 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).

Eine Uebersicht des FLG und die Zusammenfassungen der Untersuchungsprogramme sind mit Status August 1985 im NTB 85-47 enthalten.

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).

Un aperçu du laboratoire souterrain et un résumé des programmes de recherches apparaissent dans le rapport NTB 85-47 d'août 1985.

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

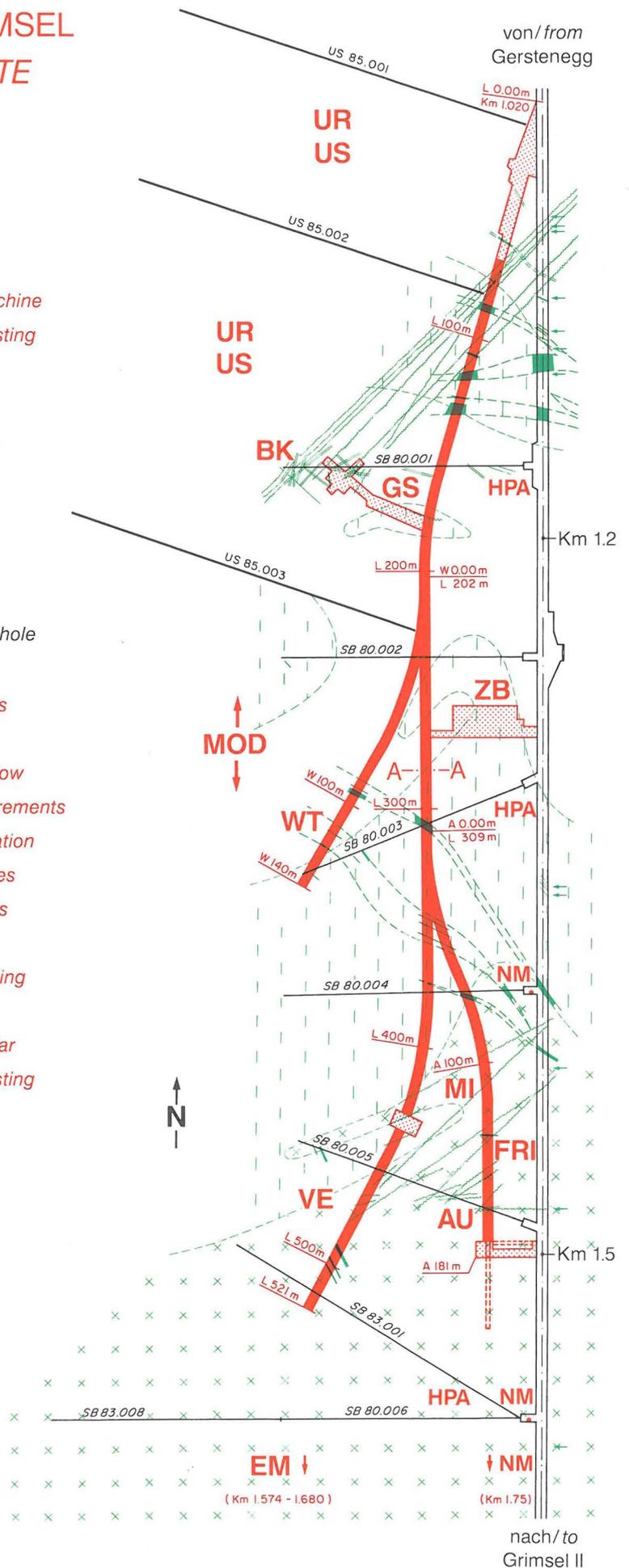
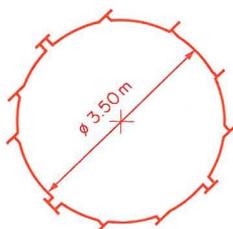
FLG FELSLABOR GRIMSEL
GTS GRIMSEL TEST SITE

Situation



- Zugangsstollen/Access tunnel
- Fräsvortrieb/by tunnel boring machine
- Sprengvortrieb/excavated by blasting
- Zentraler Aaregranit ZAGR
Central Aaregranite CAGR
- Biotitreicher ZAGR
CAGR with high content of biotite
- Grimsel-Granodiorit
Grimsel-Granodiorite
- Scherzone/Shear zone
- Lamprophyr/Lamprophyre
- Wasserzutritt/Water inflow
- Sondierbohrung/Exploratory borehole
- US Bohrung/US borehole
- ZB Zentraler Bereich/Central facilities
- AU Auflockerung/Excavation effects
- BK Bohrlochkranz/Fracture system flow
- EM El.magn. HF-Messungen/-measurements
- FRI Klufftzone/Fracture zone investigation
- GS Gebirgsspannungen/Rock stresses
- HPA Hydr. Parameter/Hydr. parameters
- MI Migration/Migration
- MOD Hydrodyn. Modellierung/H. modeling
- NM Neigungsmesser/Tiltmeters
- UR Untertageradar/Underground radar
- US Seismik/Underground seismic testing
- VE Ventilationstest/Ventilation test
- WT Wärmeversuch/Heat test

A — A Schnitt/Section



SUMMARY

This report describes the basic geological work carried out within the BGR projects "Rock Stress Measurements" (GS - Gebirgsspannungen) and "Fracture System Flow Test" (BK - Bohrlochkranzversuch) at the Grimsel Rock Laboratory/Switzerland. A short introduction into the geology of the Grimsel area is followed by the description of the engineering geological investigations and the evaluation methods applied. The structural geological data resulting formed the basis of the subsequent overall engineering geological evaluation and the tectonic analysis. The relationships between the stress field and the joint system (GS area) on the one hand and the results of the flow tests (BK area) on the other are particularly important.

Evaluation of the geological data shows structural tectonic and hence rock mechanical and rock hydraulic differences between closely neighbouring rock sections. For this reason this report includes descriptions of the joint system within the area investigated as well as the rock mechanical and rock hydraulic aspects.

The engineering geological analysis of both test areas then enables a prognosis to be made of rock stresses and rock hydraulic properties in the full rock area investigated by the BGR. In this manner transferability to other areas is justified.

ZUSAMMENFASSUNG

Im vorliegenden Bericht werden die grundlegenden geologischen Arbeiten für die BGR-Forschungsvorhaben "Gebirgsspannungen" (GS) und "Bohrlochkranzversuch" (BK) im Felslabor Grimsel/Schweiz beschrieben. Nach einer kurzen Einführung in die Geologie des Grimselgebietes folgt die Beschreibung der ingenieurgeologischen Untersuchungen und der angewandten Auswertemethoden. Die erarbeiteten strukturgeologischen Daten bilden die Voraussetzung für die anschließende ingenieurgeologische Gesamtauswertung und die tektonische Analyse. Besondere Bedeutung fällt dabei den Zusammenhängen zwischen Spannungsfeld und Trennflächengefüge (GS-Bereich) einerseits und den Ergebnissen der Durchströmungsversuche (BK-Bereich) andererseits zu.

Die Auswertung der geologischen Daten zeigt strukturelle tektonische und somit felsmechanische und felshydraulische Unterschiede zwischen eng benachbarten Gesteinsbereichen. Deshalb wird die Trennflächensystematik innerhalb der untersuchten Bereiche im Zusammenhang mit felsmechanischen und felshydraulischen Aspekten behandelt.

Die ingenieurgeologische Analyse beider Versuchsbereiche läßt schließlich eine Prognose der Gebirgsspannungen und der felshydraulischen Verhältnisse im gesamten, von der BGR untersuchten Gebirgsbereich zu. Eine Übertragbarkeit auf weitergefaßte Gebiete wird somit ermöglicht.

RESUME

Le présent rapport décrit les travaux géologiques fondamentaux menés dans le cadre des projets du BGR relatifs aux "contraintes dans un massif rocheux" (GS - Gebirgsspannungen) et aux "écoulements dans un système de fractures" (BK - Bohrlochkranzversuch), réalisés au laboratoire souterrain du Grimsel en Suisse. Une brève introduction à la géologie de la région du Grimsel est suivie par la description des investigations faites dans le domaine de la géologie technique et des méthodes d'évaluation utilisées. Les données résultantes relatives à la structure géologique constituent la base des évaluations globales subséquentes dans la domaine de la géologie technique et des analyses tectoniques. Les relations entre le champ de contraintes et le système de joints (domaine GS) d'une part et les résultats des essais de circulation (domaine BK) d'autre part, sont particulièrement importants.

L'analyse des données géologiques montre des différences dans les structures tectoniques et par conséquent aussi sur le plan géomécanique et géohydraulique entre des zones rocheuses très voisines. C'est pourquoi le système de joints de la zone étudiée est traité en relation avec les aspects géomécaniques et géohydrauliques.

L'analyse géotechnique des deux zones d'essais permet finalement de pronostiquer les contraintes dans les roches et les conditions hydrauliques dans toute la zone étudiée par le BGR. Une transposition à d'autres régions devient ainsi possible.

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1. INTRODUCTION

Within a joint German-Swiss project involving the National Cooperative for the Storage of Radioactive Waste (NAGRA), the Federal Institute for Geosciences and Natural Resources (BGR) and the Research Centre for Environmental Sciences (GSF) a comprehensive series of tests was carried out at the Grimsel Rock Laboratory (Switzerland) to study the rock mechanical, hydrogeological, geochemical and geophysical properties of crystalline rock formations. Under the terms of an order granted by the Federal Ministry for Research and Technology (BMFT) the BGR undertook in-situ measurements within the "Rock Stress Measurements" (GS) and the "Fracture System Flow Test" (BK) research projects to test and further develop equipment and to determine the state of stress and establish rock hydraulic processes in virgin, in part jointed rock masses.

The studies were proposed by PAHL et al. (1986) and integrated into a further engineering geological framework. This report describes the geological work, methods, results and analyses undertaken by the BGR.

2. GEOLOGY OF THE GRIMSEL TEST SITE

The Grimsel Test Site is located at a depth of between 400 and 450 m beneath the Juchlistock in the southern section of the Central Aar Massif (Figure 1).

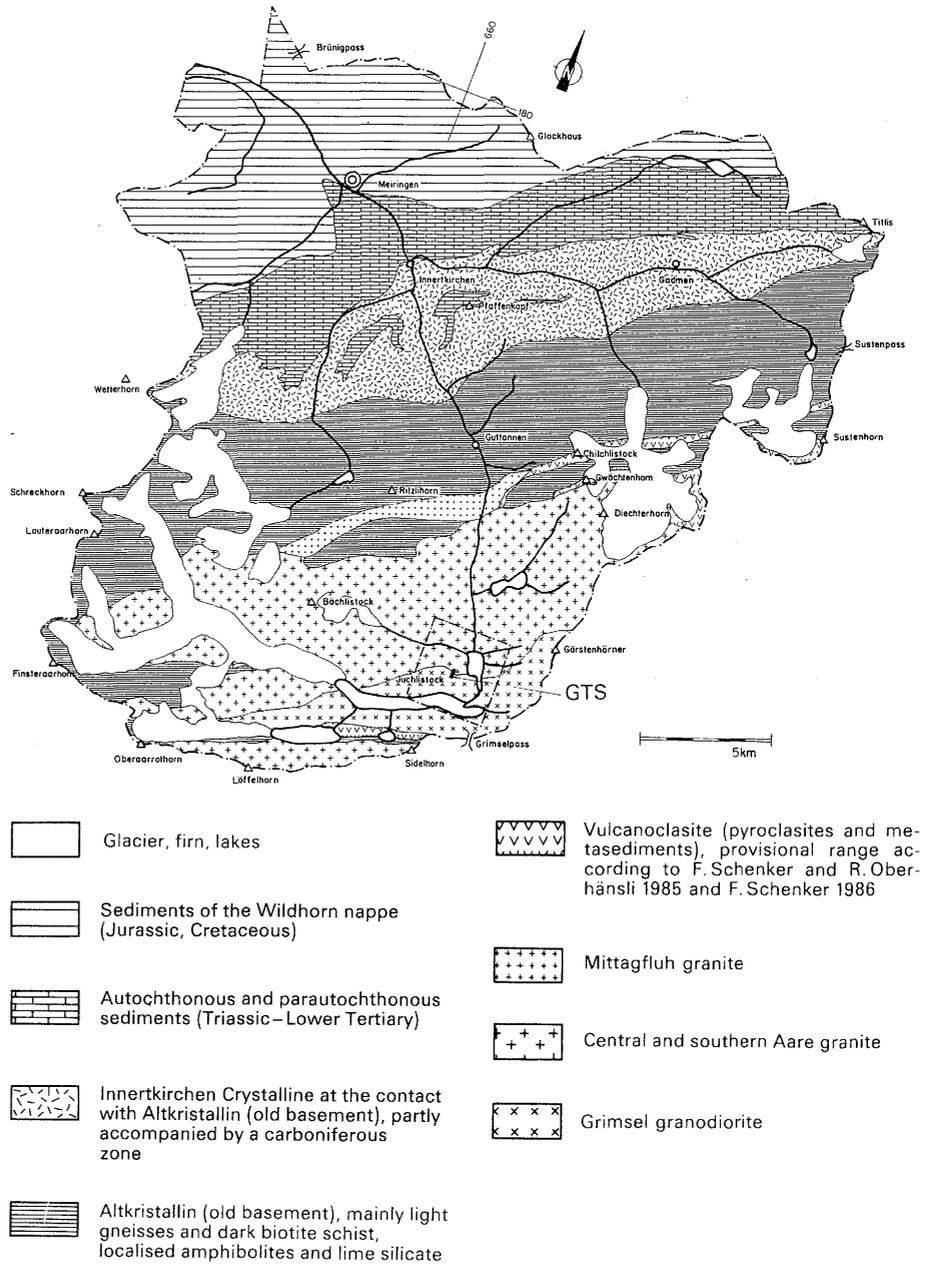


Fig. 1: Geologic overview of the Grimsel area (MÜLLER, 1988)

This predominantly granitic rock massif has Central Aare granite (ZAGr) exposures in its northern and Grimsel granodiorite (GrGr) exposures in its southern sectors (Figure 2). Age determinations indicate a Variscan intrusion age of between 290 - 300 million years. Numerous veins, usually lamprophyres, cut the rock mass, often in clusters.

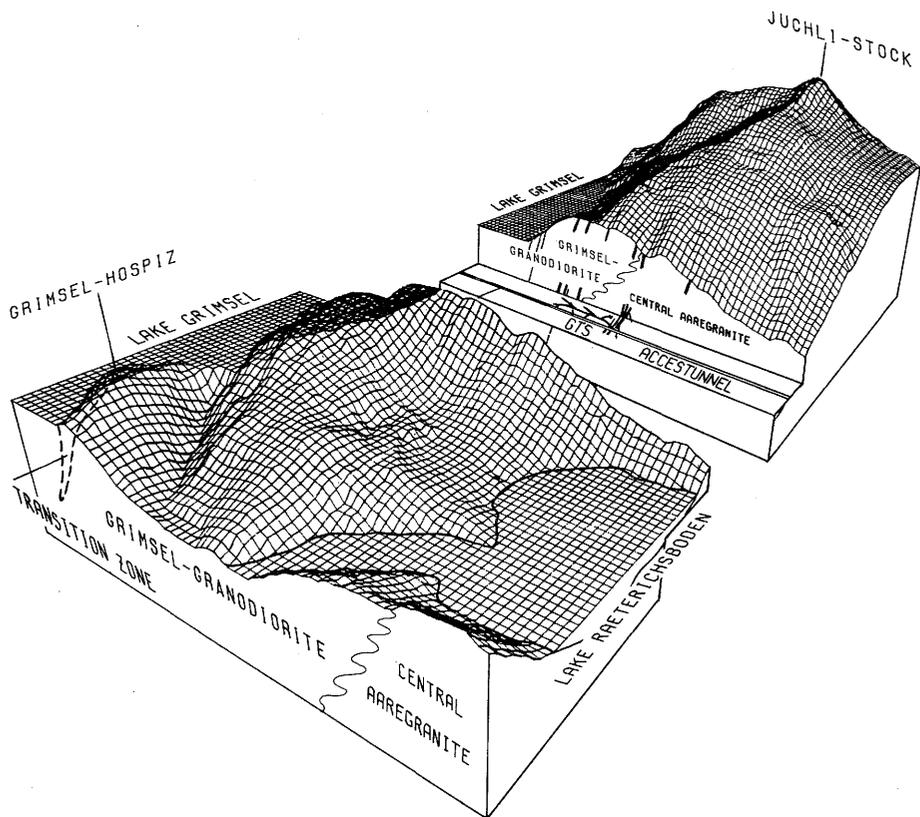


Fig. 2: Geologic cross section of the Juchlistock with the Grimsel test site

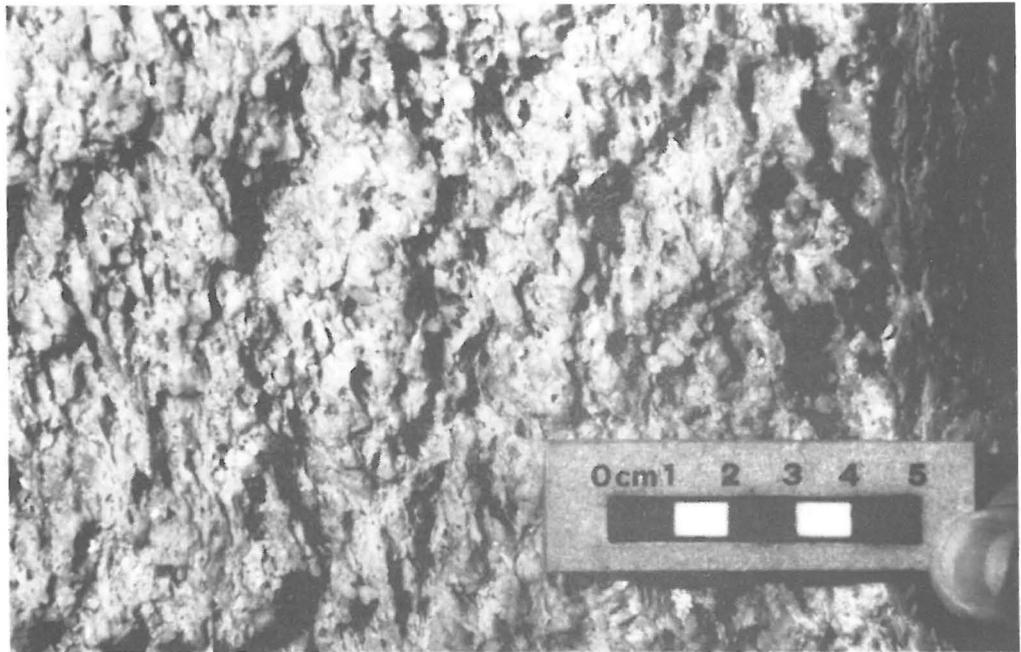


Fig. 3: Hydrothermal alteration of ZAGr in the Grimsel test site



Fig. 4: Tension joint in the Grimsel test site

In the Aar Massif the alpidic orogeny led to strong deformations with the creation of schistose structures, shear and fault zones, with in part intensely jointed rock mass partitions. Individual shear planes and brittle structure systems can be differentiated statistically. Typical for the Grimsel area are subhorizontal joints of alpidic origin surrounded by a hydrothermally altered area (Figure 3 and 4). The studies as undertaken by the BGR took place exclusively in Central Aare granite, which is for the most part uniform in character and generally has a slight to definite lamellar structure. For a more detailed description of the regional geological situation in the Grimsel area see NTB 87-14.

In addition the data was to bring to light the possible relationship between joint systems and stress directions and values. Also, the recording and interpretation of the rock mass structures in the area of the fracture system flow test (BK) represented a prerequisite for the deciding the location of the boreholes and the determination of injection and measuring systems during the rock hydraulic investigations. The actual test area and configuration is as shown in Figure 5.

3.1 GS test area (rock stress measurements)

The cavern in which the GS and BK tests are located was geologically mapped at the end of 1983 (walls) and early 1984 (bottom) (Enclosures 1-3). This detailed mapping, specially adapted to record joints, formed the basis for the subsequent geological work, for example drilling the test boreholes, recording the oriented cores, the statistical data acquisition and the analysis of the joints detected.

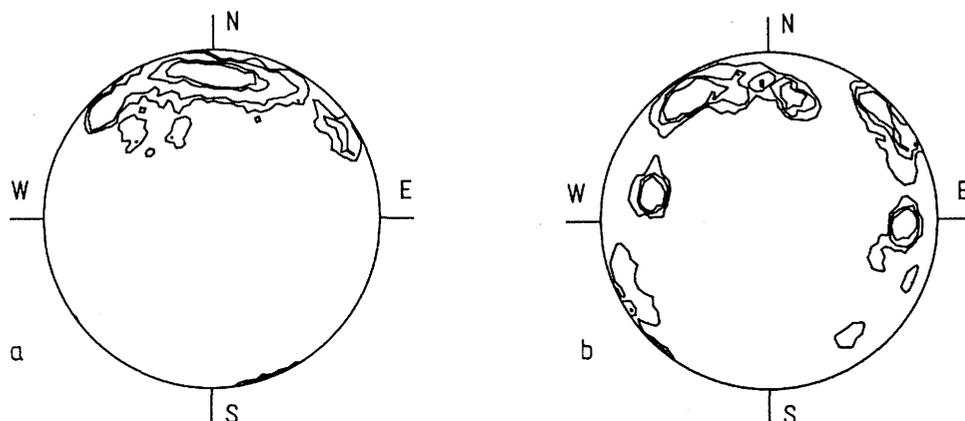


Fig. 6: Joint statistics of the bottom in the GS and BK areas (lower hemisphere projection)

- a) Bottom GS - test area, 71 joints
(contour lines: 1, 3, 7, 11 and 15 %)
- b) Bottom BK - test area, 79 joints
(contour lines: 1, 3, 7 and 11 %)

The spatial location values measured were recorded individually and plotted as lower hemisphere projections on Schmidt net diagrams. The contour lines of joint density are drawn showing various percentage gradations. The orientation of the joints recorded at the bottom of the GS and BK cavern is shown in Figure 6.

The joint statistics of the GS and BK areas combined shows characteristic differences in the direction and frequency distribution of the joints. The dark, biotite-richer Central Aare granite in the GS area is relatively uniform in the spatial location of joints, whereas in the BK area, in a relatively light rock, several different orientations of planes are apparent. The joints present at the bottom of the cavern (Enclosure 1) also shows that the joints in the GS area tend to be continuous, whereas in the BK area transitions to other joints are detectable. Furthermore, the rock mechanical and rock hydraulic properties are affected in the farther sections of the BK test area by a shear zone and lamprophyre veins (see also Chapter 6).

3.1.1. GS boreholes

Trials for the testing and further development of methods to measure rock stresses using the overcoring method were undertaken in vertical borehole GS 84.041 A, depth 200 m. Future studies of final 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 test 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 with low numbers of joints. In addition a short horizontal borehole (GS 84.042 A) enabled pretrials of equipment without water pressure prior to use in the deeper borehole.

The position of the GS boreholes within the test area is shown in Figure 5. In total 211.24 m of oriented, recovered core was geologically recorded. Vertical borehole GS 84.041A was drilled to 171.17 m with a diameter of 146 mm and from there to total depth (TD) 191.29 m, with a diameter of 86 mm to allow for subsequent hydro-frac tests. Horizontal borehole GS 84.042A was drilled through to TD at 19.95 m at a diameter of 146 mm.

Borehole	Diameter mm	Depth m	Az/inclin. degree	Coordinates			Drill time
				y	x	z	
GS 84.041A	146/86	191.29	000 -90	197.31	444.59	1729.73	17.06-31.12.84
GS 84.042A	146	19.95	205 + 5	195.28	443.68	1730.96	13.07-26.11.84

Table 1: Summary of GS test boreholes

3.1.2 Geological data recording (GS)

In recording the geological data of all cores studied at the Grimsel Rock Laboratory the method proposed by NAGRA has proven itself well. For this reason, and for reasons of uniformity, data recording 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 the triaxial probe into borehole GS 84.041A.

The section of borehole GS 84.041A (Enclosure 4) shows, as do the cavern bottom in the GS area (Enclosure 1) and horizontal borehole GS 84.042A (Enclosure 5), the biotite rich, dark and in part schistose variety of the Central Aare granite during the first few metres. With increasing depth this rock changes over into the lighter, more compact form.

The rock, particularly in section 40 - 100 m of borehole GS 84.041A, is compact and without any open fractures. Noticeable here are many quartz-epidote veins which cut through the granite without transitions and without visibly affecting the host rock.

At around 100 m (borehole GS 84.041A) an open fracture was encountered of alpidic origin, typical for the Grimsel area. The primary fracture minerals are quartz as idiomorphic crystals (up to max. 2 mm) and sandy

chlorite. Similarly formed subhorizontal fractures are also present at numerous points in the laboratory area. They are characterized in all cases by a margin of hydrothermally altered granite (see also Figure 4).

The creation of these joints may have many causes:

- lifting and hence relief of the massif,
- increasing brittleness of the granite,
- the frac effect of hydrothermal solutions, e.g. at lamprophyre offshoots.

Strongly fractured areas with clearly open, but non mineralized, fractures were encountered between 127 and 131 m and between 137.50 and 144 m.

A biotite/chlorite schistose zone with adjacent lamprophyres was encountered at 181.26 m. The schistose zone caused major core losses during drilling. This area and the enclosed lamprophyre can be correlated with a similarly formed zone in the front section of the laboratory tunnel (around metre 130) and a corresponding zone in the northern BK area (see also figures 22 and 23).

Borehole GS 84.041 A had to be stopped because of break-outs at a TD of 191.29 m because the plans for subsequent hydrofrac tests meant no casing or injection support was possible (the planned TD was approximately 200 m).

The overall plot of the joints measured in borehole GS 84.041A shows two clear maxima. The open fractures, whose total of 73 is comparatively low compared to boreholes in the BK area, have a maximum in a direction approximately ENE/WSW. Closed joints contrast by striking mainly in a WNW/ESE direction (Figure 7, overall plot in centre).

Slickensides were only encountered in the upper section of the borehole, but could not be oriented due to strong core breakage.

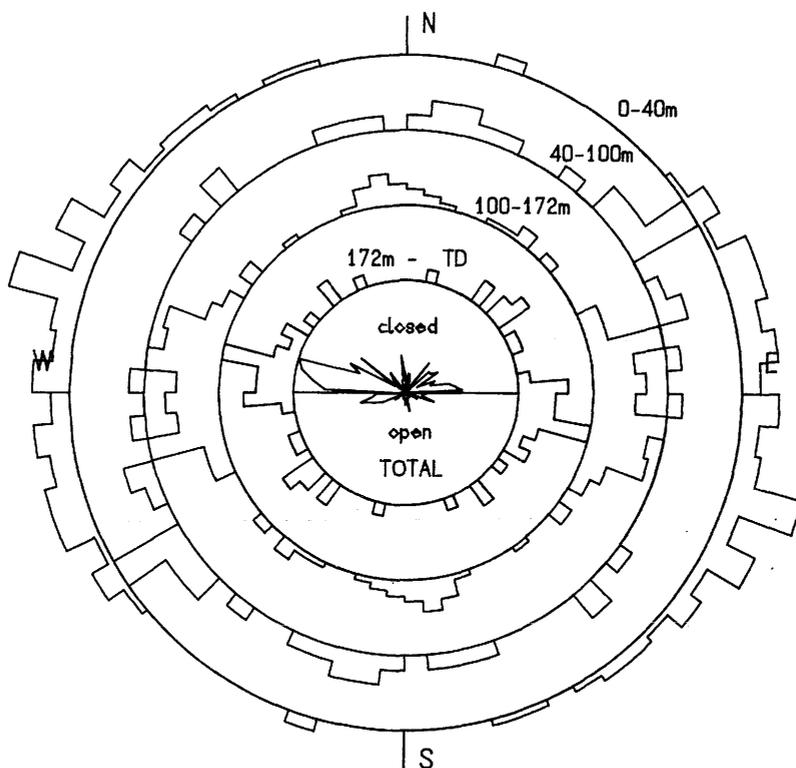


Figure 7: Joint statistics of borehole GS 84.041A
 Centre: Open and closed joints
 Outer rosettes: Different sections of depth

Borehole GS 84.042A was drilled perpendicularly to GS 84.041A with an inclination of 5° and an azimuth of 205° . In the upper part, to around 4 m, biotite-rich granite was drilled, as was the case in the vertical borehole. This changes to a slightly lighter rock to TD 19.95 m (Enclosure 5). The joint statistics show an open joint

(possibly as a result of blasting) 0.24 m deep from the face and a maximum in the direction of the joints as for GS 84.041A. In addition a subordinate maximum of approximate strike direction WNW/ESE is also present. No significant changes in the direction of joints and their frequency are apparent in GS 84.042A.

3.1.3 Evaluation methods (GS)

Software developed specifically for this purpose at the BGR was used for the further evaluation of the geological structures recorded on polyfilm (see also mathematical geological joint model, Chapter 3.2.3). This software enables, amongst other things, the conversion of the values derived from the core of the apparent angle of inclination and azimuth of planes and linears with respect to the borehole axis into values suitable for further processing. The statistical evaluation of the large volume of data makes the use of comprehensive evaluation and plotting software necessary. For plotting joint polar points and the contour lines of frequency density on a Schmidt net diagram the general "GELI" software (FORTRAN) was modified. "CLODAT" software (FORTRAN) as supplied by the University of Hannover and based on cluster analysis was used for the specific evaluation of slickenside planes and lineation. It was implemented in an expanded version on a VAX mainframe computer.

3.2 BK test area (fracture system flow test)

The test site for the fracture system flow test had the layout as shown in Figure 5 after completion of drilling.

Geological studies in the area of the fracture system flow test include mapping of the test cavern, processing of cores in the manner described in Chapter 3.1.2, exact investigation of joints and slickensides with tectonic evaluation of the joint systems and changes to the rock matrix. One objective is to prepare and test methods for presenting and assessing rock hydraulic and rock mechanical properties. The evaluation of rock hydraulic test data on the basis of joint statistics and the geological assessment of joint openings and joint length is also a contribution towards determining flow paths in rock masses. In addition the data provides the basis for models, numerical calculations and the transferability of results to neighbouring or other rock masses or hard rock areas.

3.2.1 BK boreholes

The original test arrangement planned for the fracture system flow test was modified after drilling the central borehole (BK 85.004) to better match the test to the rock mass structures encountered and hence the predicted rock hydraulic properties. The geological evaluation of the then drilled boreholes (BK 85.005, 85.006 etc.) determined, together with previously existing boreholes, the direction of subsequent drilling. The resulting layout (one shallow angled and one vertically angled fan of boreholes) provides a large number of alternatives for injection and measuring configurations at hydraulically representative points within the rock mass.

The central borehole was ultimately extended to a TD of approximately 138 m (BK 86.001) in order to penetrate a predicted thick lamprophyre zone, as was indeed the case

(see also Figs. 22 und 23). In this way the backlying rock area could be included in the hydraulic tests.

A total of 582.93 metres was drilled in the BK area and cored throughout. All boreholes have a diameter of 86 mm.

Borehole	Dia. mm	Depth m	Az/Inclin. Degrees	Coordinates			Drilltime
				y	x	z	
BK 85.004	86	49.01	311 - 35	414.04	222.68	1730.17	07.01-21.01.85
BK 85.005	86	43.50	311 - 35	415.34	214.97	1730.16	21.01-04.02.85
BK 85.006	86	46.40	311 - 35	425.42	219.45	1730.14	05.02-20.02.85
BK 85.007	86	47.74	311 - 60	415.53	221.45	1729.79	12.04-24.04.85
BK 85.008	86	48.87	356 - 35	427.78	221.76	1730.10	01.05-13.05.85
BK 85.009	86	49.50	311 - 35	414.02	209.56	1730.15	15.05-29.05.85
BK 85.010	86	43.84	041 - 35	429.22	222.69	1730.08	31.05-12.06.85
BK 85.011	86	47.00	000 - 90	417.04	220.09	1729.81	13.06-08.07.85
BK 86.001	86	89.26	311 - 35	295.86	295.87	1652.05	14.04-02.05.86
BK 86.002	86	49.26	221 - 35	414.44	206.31	1730.07	12.05-23.05.86
BK 86.003	86	68.22	266 - 35	413.41	207.16	1730.08	26.05-12.06.86

Table 2: Summary of main drilling data (BK boreholes)

The boreholes produced the following findings:

Borehole BK 85.004 (49.01 m, Encl. 6, BK central borehole):

The exposed granite displays initially medium jointing, which increases with depth. At around 4 m depth a fault zone was encountered with a water flow of around 3 l/min, and farther on a large number of joints was accompanied by several hydrothermally altered zones. Previous geophysical investigations (BGR, 1986) indicated intense fracturing at larger depths, leading ultimately to the borehole being extended (see also borehole BK 86.001).

Borehole BK 85.005 (43.50 m, Encl. 7):

The rock shows frequent changes between lighter and darker zones. The sections around 5, 15 and 40 m are

intensely jointed, hydrothermally altered zones are encountered at around 41 m.

Borehole BK 85.006 (46.40 m, Encl. 8):

From 0 to approximately 30 m depth the borehole penetrates light, medium jointed Aare granite. After this the rock becomes slightly darker and from around 40 m onwards shows strong hydrothermal alteration. From approximately 25 m depth the jointing becomes very pronounced. At 19.85 m depth the borehole had to be stabilized with 50 kg cement because major borehole breakouts threatened drilling progress.

Borehole BK 85.007 (47.74 m, Encl. 9):

To around 25 m depth the borehole penetrates very massive, low jointed granite, and subsequently several hydrothermally altered zones and intense jointing. Near the borehole TD massive dark rock material reappears.

Borehole BK 85.008 (48.87 m, Encl. 10):

The top approximately 15 m of the borehole penetrates light, slightly jointed granite, after this more intense jointing with mylonitization and stronger hydrothermal alteration is visible. Between around 30 and 40 m the borehole penetrates a lamprophyre system which is also encountered in boreholes BK 85.010, 86.001, GS 84.041A and in the laboratory tunnel at around metre 130.

Borehole BK 85.009 (49.50 m, Encl. 11):

Over its initial 13 metres the borehole penetrates light, slightly jointed granite, this is followed by in part mylonitized and hydrothermally altered zones with more frequent jointing. In the last 15 m of the borehole very strong hydrothermal changes are apparent in the rock matrix.

Borehole GK 85.010 (43.84 m, Encl. 12):

The upper 30 m of the borehole penetrate light granite with the number of joints increasing with depth. After around 15 m mylonitizations and hydrothermal changes are apparent. Between around 30 and 40 m the borehole penetrates the previously described lamprophyre zone, this is followed by strong hydrothermally altered granite.

Borehole BK 85.011 (47.00 m, Encl. 13):

The entire borehole penetrates very massive hard granite. Only at around 5 and around 35 m were isolated joints encountered.

Borehole BK 86.001 (89.49 m, Encl. 6):

This borehole is the extension of borehole BK 85.004 (BK central borehole). It encounters a thick lamprophyre system between around 88 and 128 m (total depth together with borehole BK 85.004). This system is identical with that encountered previously in preceding boreholes, in the laboratory tunnel at around 130 m and in borehole GS 84.041A. The contact zones to the host granite are in part intensely altered by hydrothermal processes. Slickenside planes are frequent, and numerous in the lamprophyre. The last metre of the borehole again encounters relatively unjointed granite. Taking the geophysical studies (BGR 1986) as a basis it is surmised that there follow strongly disturbed rock zones and more lamprophyre veins.

Borehole BK 86.002 (49.26 m, Encl. 14):

This borehole showed almost throughout its entire length massive low jointed and lamellar structured granite. At depths around 10 m and around 20 m thin (only a few cm thick) biotite-slate bands are encountered. At around 35 m an alpine joint was encountered of approximately 10 cm opening width surrounded by slightly hydrothermally altered rock zones. Slickenside planes are rare.

Borehole BK 86.003 (68.22 m, Encl. 15):

In the first 50 m this borehole penetrates slightly jointed, lighter granite. An alpine joint with margin formation is penetrated at 22.85 m and a thin biotite slate band at 28.30 m. In depth section 50.60 - 54.20 m a biotite slate band is encountered with numerous slickensides. The subsequent granite zones (54.40 - 67.75 m) are characterized by strong hydrothermal changes. Intense jointing and fracturing predominate from 64 m onwards, where a strong hydraulic interconnection to the system of borehole US 85.003 (which does not belong to the BGR test area) was detected. The final metre of the borehole again penetrates massive, aplitic light granite.

3.2.2 Geological data recording (BK)

The BK cavern was mapped to a scale of 1:100 (Enclosures 1-3) as described in chapter 3.1.2. The recording of the cores on a 1:1 scale on polyfilm was improved with respect to the recording of slickenside planes and directions of lineation. In addition to joints the recording method also takes into account the structure of the rock and possible changes to the rock matrix. In the processing of the cores the BGR also developed a system for the hydraulic weighting of open fractures (see also chapter 4.2).

3.2.3 Evaluation methods (BK)

The BK test is targetted towards the investigation of the rock hydraulic properties of the rock mass. For this reason structural geological data are the primary basis for the test evaluation.

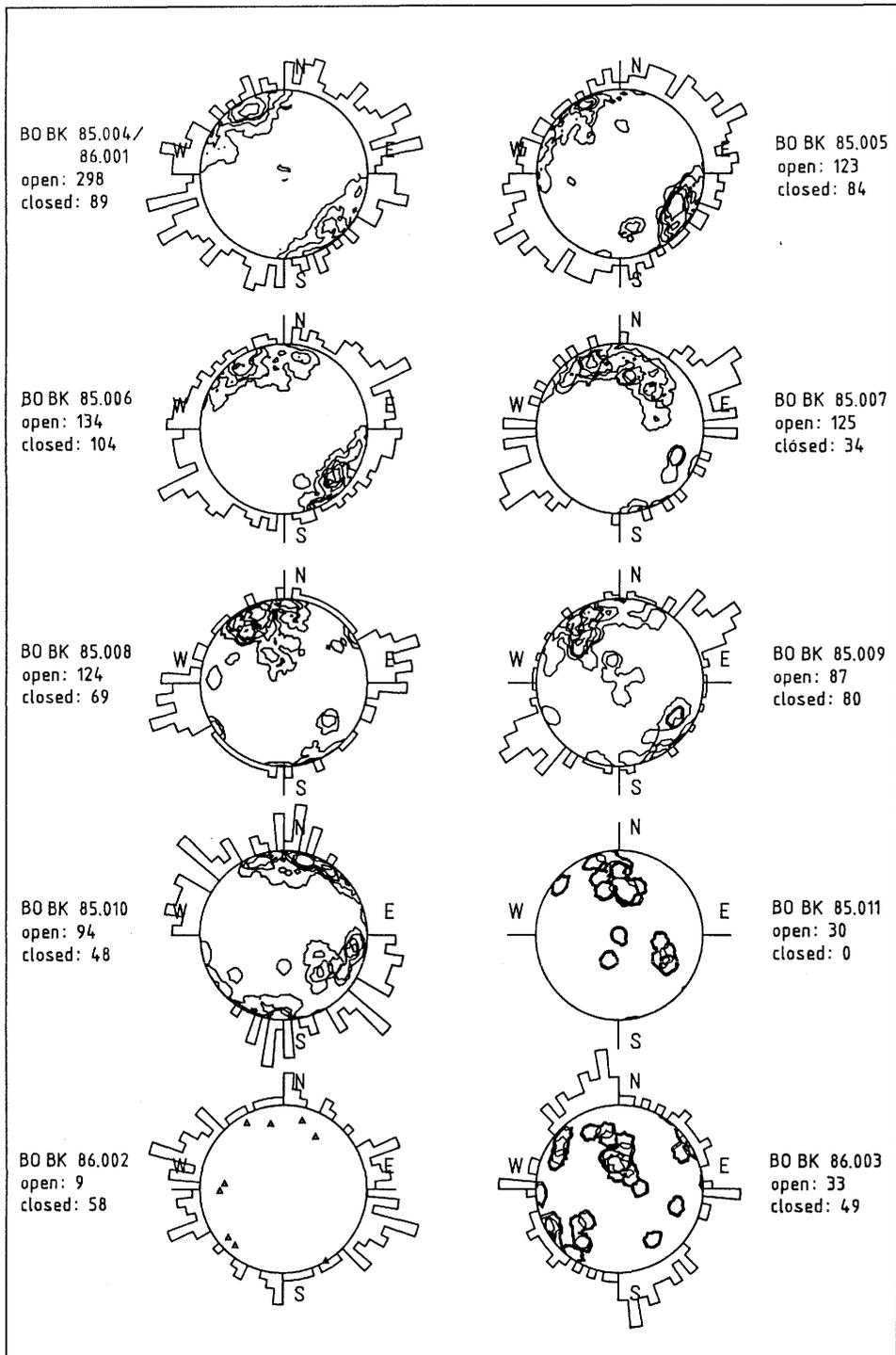


Figure 8: Joint statistics of BK boreholes
 External: Closed joints (strike directions)
 Internal: Open joints (lower hemisphere projection with 1, 3, 5, 7 and 10 % contour lines).

The joints detected in the BK boreholes are summarized in Figure 8. Some orientation maxima are already apparent, which indicate differences between the boreholes. The tectonic and rock hydraulic sections and the joint statistics are described in Chapter 5 and 6.

The number of mapped joints made the development of a mathematical-geological joint model necessary. A major fraction of the joints recorded previously in the BK boreholes (approximately 2500) were evaluated with the aid of this model. Detailed knowledge of the structural geology and the use of the model made it possible to predict hydraulic test results in test areas, and also to differentiate between tectonic sections (see also figures 22 and 23).

In the program the first step is the calculation of the actual joint orientation in space by acquisition and storage of the joint data. The next step in data processing in the form of individual joints or averaged joint groups enables the joints to be plotted as plan, section, 3-D and spatially oriented lower hemisphere projections (joint statistics). The extrapolation of joints between any of the boreholes (Figure 11) enables joints to be redetected at different points in space and statements to be made concerning the spatial extension of various joint systems. And finally, the calculation of joint intersections enables improved assessment of water flow paths in rock masses and is an important factor in future test predictions (Figure 13). The software interfaces to a comprehensive packet of routines for graphic presentation which provide in part spatial plots of areas considered.

4. ENGINEERING GEOLOGICAL OVERALL EVALUATION

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 lamellar structure 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 schistosity planes 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.

The slickenside planes, which were recorded separately from the joints and schistosity planes, are numerous predominantly in the area of the fracture system flow test (Figure 15). In the southern BK area slickensides are detected in substantially lower numbers than in the north.

This agrees well with the fact that here substantially denser and more massive granite blocks are predominant. In general there is a clear increase in the number of slickensides observable in the contact zones between granite and lamprophyres.

Evaluation of the geological data shows structural tectonic and hence rock mechanical and rock hydraulic differences between closely neighbouring rock sections. For this reason this report includes descriptions of the joint systems within the area investigated as well as the rock mechanical and rock hydraulic aspects.

4.1 Rock mechanical aspects

Structure diagrams provide evidence of the layout of joints and the density (joint frequency) in preferentially occurring spatial locations. In the case of clear maxima it is possible to differentiate between joint systems of different orientation. The allocation of obviously genetically related joint systems enables details of principle stress directions to be given in the analysis of the tectonic stress pattern.

The parallel studies undertaken into rock structure and stress field in borehole GS 84.041A were aimed at spotlighting relationships between joint structure and measured stresses. Together with the planned studies into the microstructure of the rock it is intended to be in a position to transfer the knowledge and results gained on to broader areas to clarify the regional stress field. In addition this also opens up the possibility of transferring the investigative methods applied here to other, not necessarily only crystalline, areas.

Borehole GS 84.041A of apparent geological homogeneity may be divided into 4 sections (Figure 9):

- Section I: 0- 40 m: Granite with pronounced lamellar structure, in part schistose.
- Section II: 40-100 m: Compact granite with horizontal fissure 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-TD: Granite, kakiritized, within (191.29 m) influence zone of lamprophyre-schistose zone.

Figure 7 makes the differences in joint distribution clear. The total number of joints (272) is given whereby in the non-symmetrical fracture rosette the number of closed joints (199) is given at top and the number of open joints (73) is given at bottom. In the external joint array the direction of the joints is detailed for the 4 sections (0-40 m, 40-100 m, 100-172 m and 172 m - TD). In Section 0-40 m and in the two lowermost sections the direction maximum is at approximately ESE/WNW. In the 60 m section between 40 and 100 m no clear direction maximum of the joints is recognizable. Noticeable, also, is that in this section only 28 joints were recorded (Figure 9).

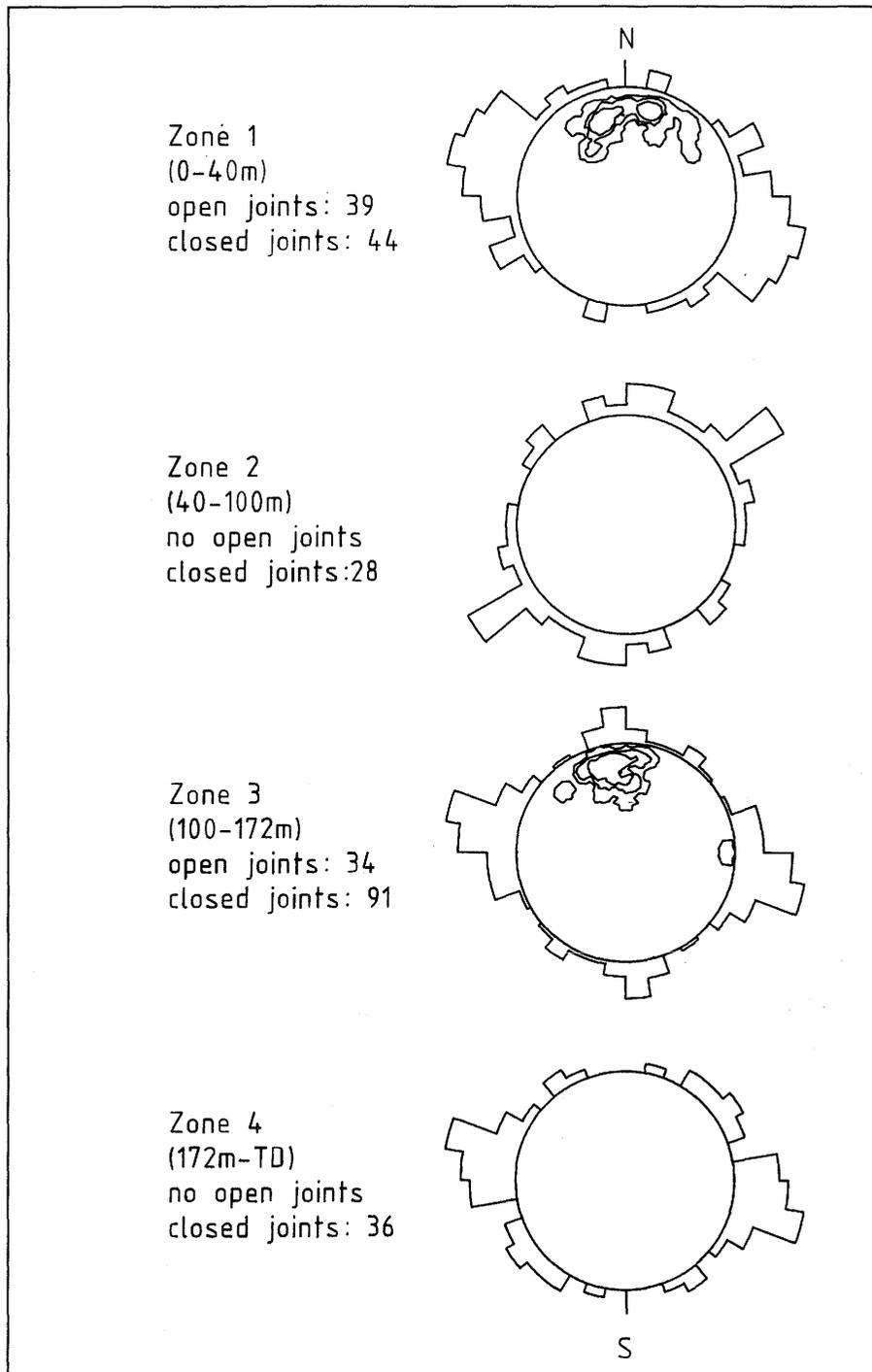


Figure 9: Joint statistics of the 4 sections in borehole GS 84.041A

External: Closed joints (direction of strike)

Internal: Open joints with 2, 6 and 12 % - contour lines (lower hemisphere projection)

Borehole GS 84.041A has a heterogeneous structure which is reflected in the results of the stress measurements. Figure 10 shows the joints and also the stress directions as measured 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.

Also, the stress values measured, which are otherwise on average around 30 MPa, climb in this section to an average of 40 MPa (Figure 10). Some form of influence of the geological structure on the main stress direction and on the stress values is obvious. In the area of the compact granite the high horizontal stress is not reduced by the opening up of fissures as is the case in the sections having numerous joints.

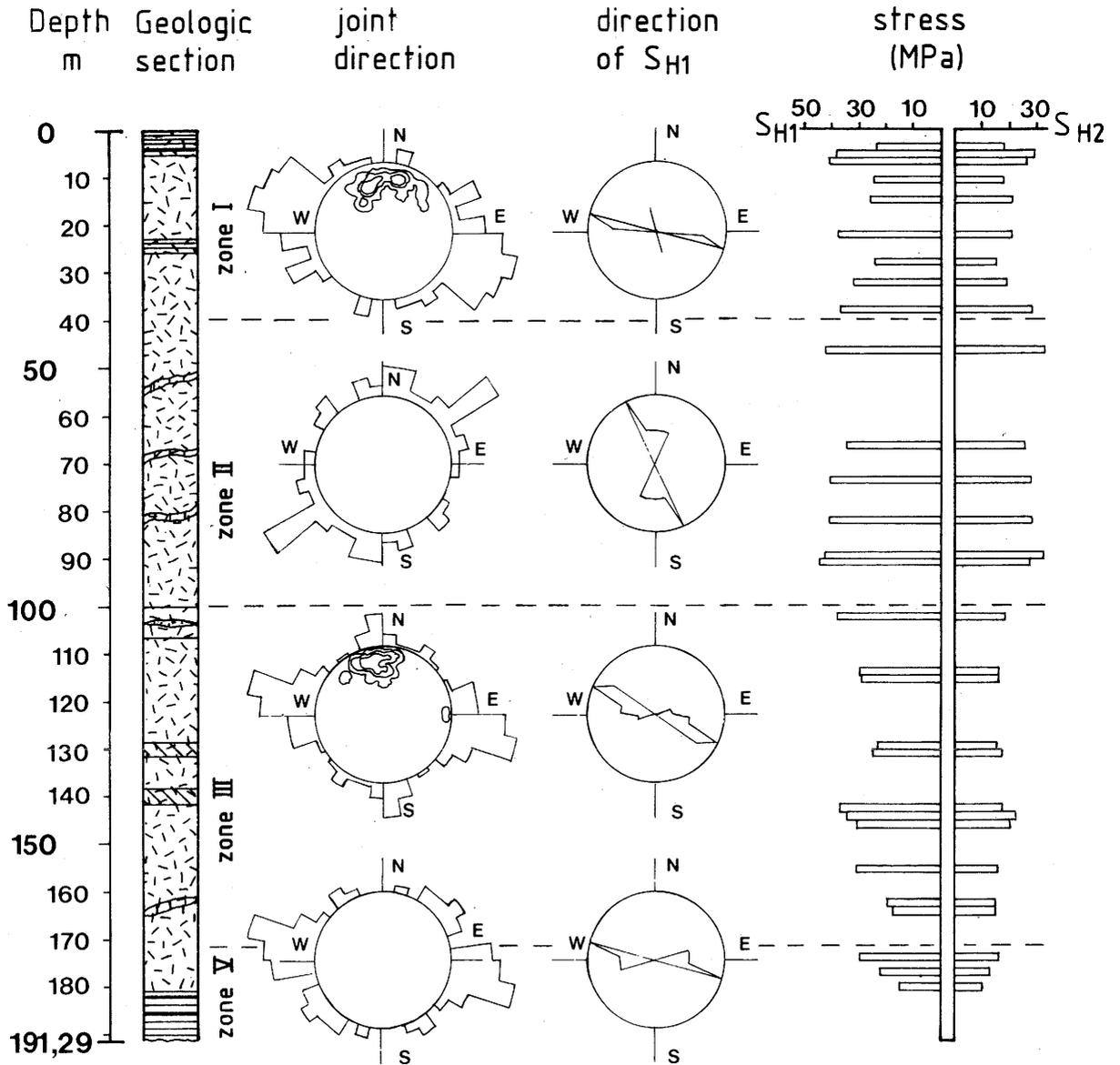


Figure 10: Joint structure of borehole GS 84.041A/relationships between geological structure, horizontal stress direction and stress values
 External: Strike direction of closed joints
 Internal: Lower hemisphere projection of open joints with contour lines

4.2 Rock hydraulic aspects

The majority of water movements in crystalline rocks run along fissures. In the presence of a good rock matrix which is not influenced by hydrothermal or tectonic processes or open joints, this is probably in excess of 99 %. The spatial extension of fissures (extrapolation) and the degree of their interlinking is, from an hydraulic viewpoint, of great importance for the water conductance and their preferential orientation in space. Rock hydraulic statements are therefore based primarily on joint statistics.

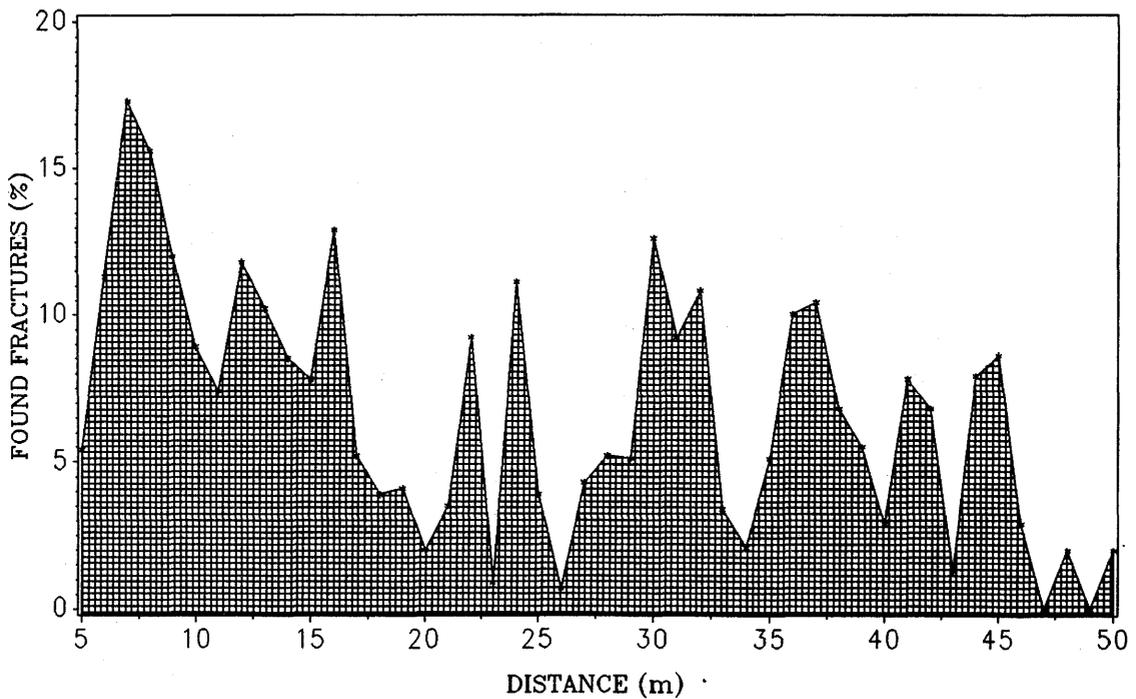


Figure 11: Extrapolation of joints in the BK test area
 Criteria: Azimuth and angle of dip $\pm 10^\circ$
 Section of borehole ± 1.0 m

An exact extrapolation of joints in rock masses (e.g. from one borehole to another) is strictly speaking not possible because joints rarely represent mathematically exact planes but rather usually exhibit slight curvature or stepping. Extrapolation in a geological sense therefore requires the acceptance of certain "tolerances" in the fundamental criteria (e.g. azimuth/dip or metering of the boreholes). Experience at the Grimsel Rock Laboratory has shown that a tolerance of 5 - 10° for the azimuth and dip and of 50 - 100 cm in the metering represent acceptable values in the rock types studied.

The result of the extrapolation of joints under the criteria stated was that the number of joints recognizable from borehole to borehole does not decrease uniformly with increasing distance. A significant cut off was detected at around 18 m oblique distance and a renewed growth at around 30 - 40 m (Figure 11). Naturally the geometry of the boreholes plays a certain role here, referring to Figure 15 does however show that all oblique distances are numerous in the BK test configuration.

Figure 12 shows the orientation of the joints in the BK area with an extrapolatability exceeding 30 m.

Joints which penetrate the rock mass still further (oblique distance 30 m and more) correlate in a spatial orientation with systems S1 and S2 in the Grimsel area. This observation is also be confirmed by surface exposures. The orientation maxima of the open joints are less well represented.

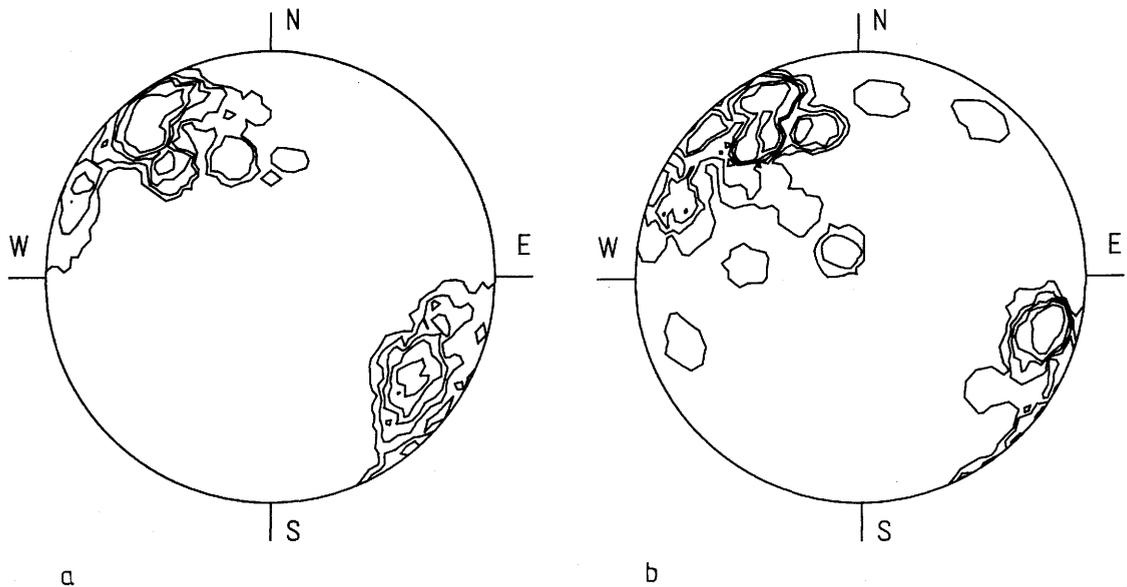


Figure 12: Orientation of joints in the BK test area with a possible extrapolation of more than 30 m; contour lines: 1, 3, 5, 7 and 10 % in lower hemisphere projection
 a) Open joints (103)
 b) Closed joints (53)

With regard to rock hydraulic and flow mechanical consideration it is critical to weight joints according to their hydraulic efficiency. A classification has to be based on not only the average width of opening of a joint but also according to the lining and roughness of the inner surfaces. This was achieved as follows (whereby the following weighting scale is not mathematically exact but should be understood as "greater" or "lesser"):

- W 1: Just visible with the naked eye (better with magnifying glass or binocular). Core not broken along joint. Joint almost completely filled (e.g. with chlorite or quartz). The question of "open" or "closed" cannot be answered unequivocally. Contact matrix massive and unchanged.
- W 2: Visible without magnifying glass. Core broken in places along joint. Joint inner surface incompletely lined with minerals. Contact matrix massive and unchanged.
- W 5: Well visible to the naked eye. Core broken up along joint surface. Joint filling only patchy or completely absent. Contact matrix slightly changed by mechanical or chemical processes (joint width up to 0.5 mm).
- W 10: Core broken, contact matrix with secondary jointing or margins in mm range (joint width up to 1 mm).
- W 20: Several joints, cannot be visibly distinguished. Contact matrix with changes, dissolution or recrystallization of individual components. Alteration zone in cm range (joint width > 1 mm).
- W 50 and larger: Sum of several joints. Contact matrix in part intensely changed or mechanically stressed. Alteration zone in dm range (joint width sum in cm range).

Bearing in mind the hydraulic weighting of joints and with knowledge of their statistical extension (extrapolation) in rock it is possible to determine intersection lines with spatial orientation and longitudinal extension.

Figure 13 shows an example of some intersection elements in the area south west of the test cavern postulated using the mathematical geological joint model and then confirmed in injection tests. Using the method described it is possible to establish a model representing a relatively true picture of the hydraulic structures.

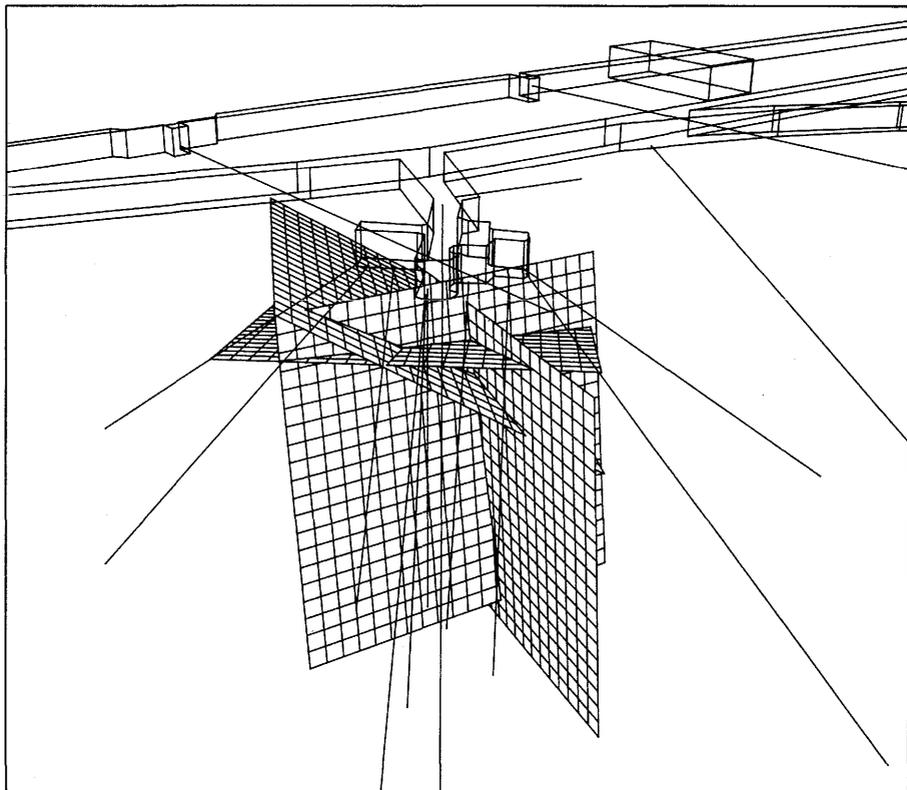


Figure 13: Example of intersection of joints in mathematical geological joint model.

The joint linings, joint minerals and their influence on the water conductance are factors which had been previously neglected in modelling. It would, however, be useful to include these in the hydraulic weighting.

Similarly, the rock matrix should be weighted under rock hydraulic considerations because in zones of hydrothermal change dissolution and recrystallization processes have usually resulted in an increase in pore volume and hence hydraulic conductance (see also Figure 3).

The rock hydraulic statements are then confirmed using the previously performed test evaluations, as follows:

In Central Aare granite continuous hydraulic networks of joints exist which are sometimes traceable over tens of metres through the rock mass. The differing hydraulic potentials, which were measured at some points in the rock laboratory, especially in the BK zone, show that these hydraulic joint networks stop up superordinate (usually tectonically influenced) structures. In this manner rock hydraulic sections are created which are for the most part independent of one another.

Figure 14 shows the water level as measured in various sections of the BK zone (long-term measurements of the hydrostatic potential, converted to m above sea level). In this manner, the different geological/tectonic sections (Figs. 22 and 23) as described in chapters 5 and 6 also become visible hydraulically. The lamprophyres are made visible in the form of in part vertical walls, whereas the areas in between each have a relatively uniform hydraulic level due to the presence of joint systems with hydraulic networking.

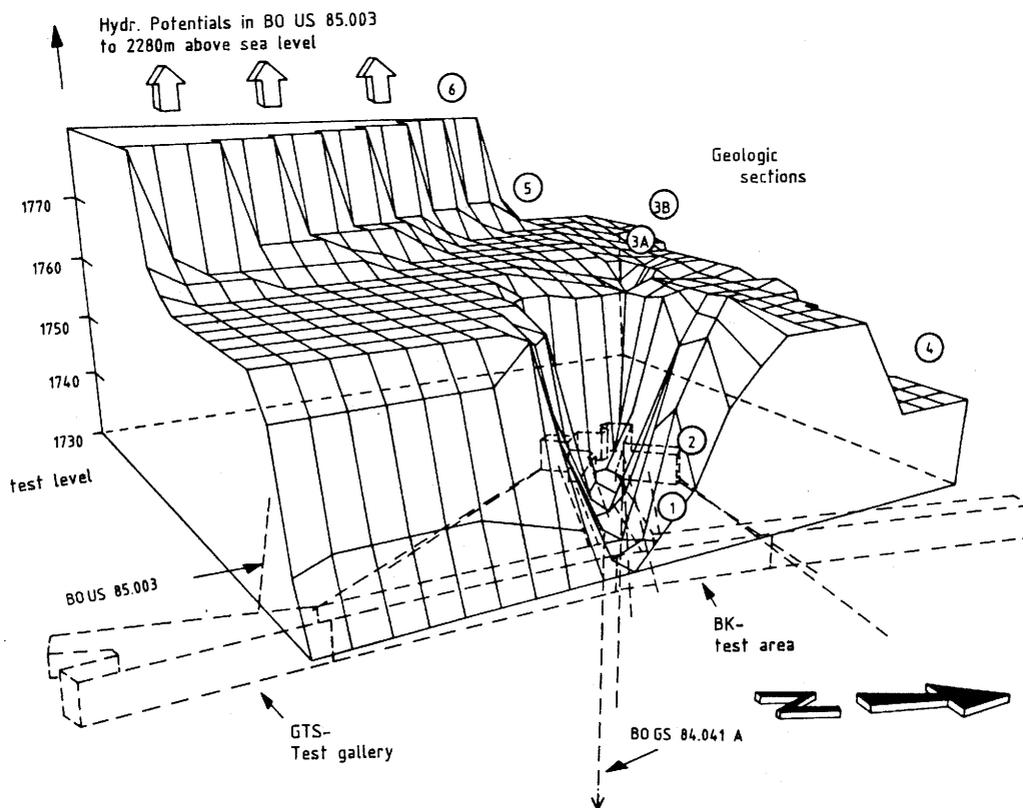


Figure 14: Hydraulic sections at the GS and BK test location (hydraulic potential as water levels).

5. TECTONIC ANALYSIS

The studies of fractures by the BGR in the Grimsel Rock Laboratory indicate a close relationship between tectonics and geological structure on the one hand and rock mechanical and rock hydraulic properties of the rock mass on the other.

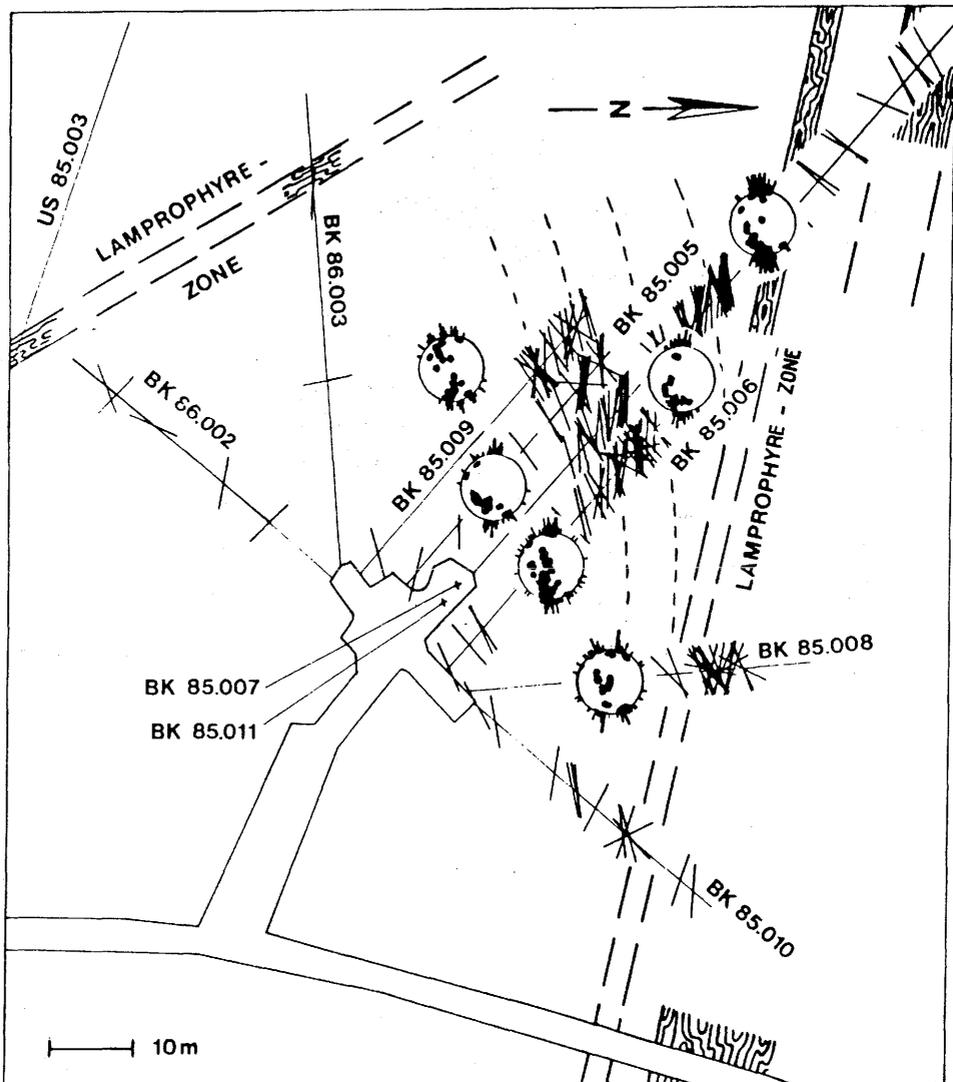


Figure 15: Distribution of slickensides in the BK test area with hemispherical projections for individual borehole sections (1 % contour lines filled black). Curvature of the slickensides indicated with shading.

This means that the fracture mechanical behaviour of the rock mass, which is reflected in the extent of joints, schistosity planes and slickensides and in the occurrence of hydrothermally altered zones, represents the key to the analysis of the stress field and the flow properties.

In order to clarify these relationships detailed studies of in particular the numerous slickensides with the associated lineations was undertaken in the area of the BK test.

In the analysis of the shear surfaces there is a noticeable concentration in clusters and borehole sections. Figure 15 shows the irregular distribution of slickensides within the BK test field with diagrams of frequency distribution of slickenside linears (hemispherical projection, internal) and the directions of strike (external). Apparent here is a slight curvature of the surfaces from borehole BK 85.008 to BK 85.006, 004 and 005 in the direction of BK 85.009 (see also Figure 22).

The contour line plots of the polar projections of slickensides in a Schmidt net show maxima in a NE/SW to E/W direction (Figure 16). Tectonic movements in this section of the rock mass took place along these, in part already present, shear planes. These "pre-existing fracture planes" in the rock mass are also exploited by the present stress field (main thrust direction from ESE).

These more recent movements in the Grimsel area and in the area of the Aar and Gotthard Massif have been proven using precision levelling (ECKHARD et al., 1983). Such zones of movement are also clearly visible in a smaller area at the surface of the Central Aare granite (LABHART, 1977).

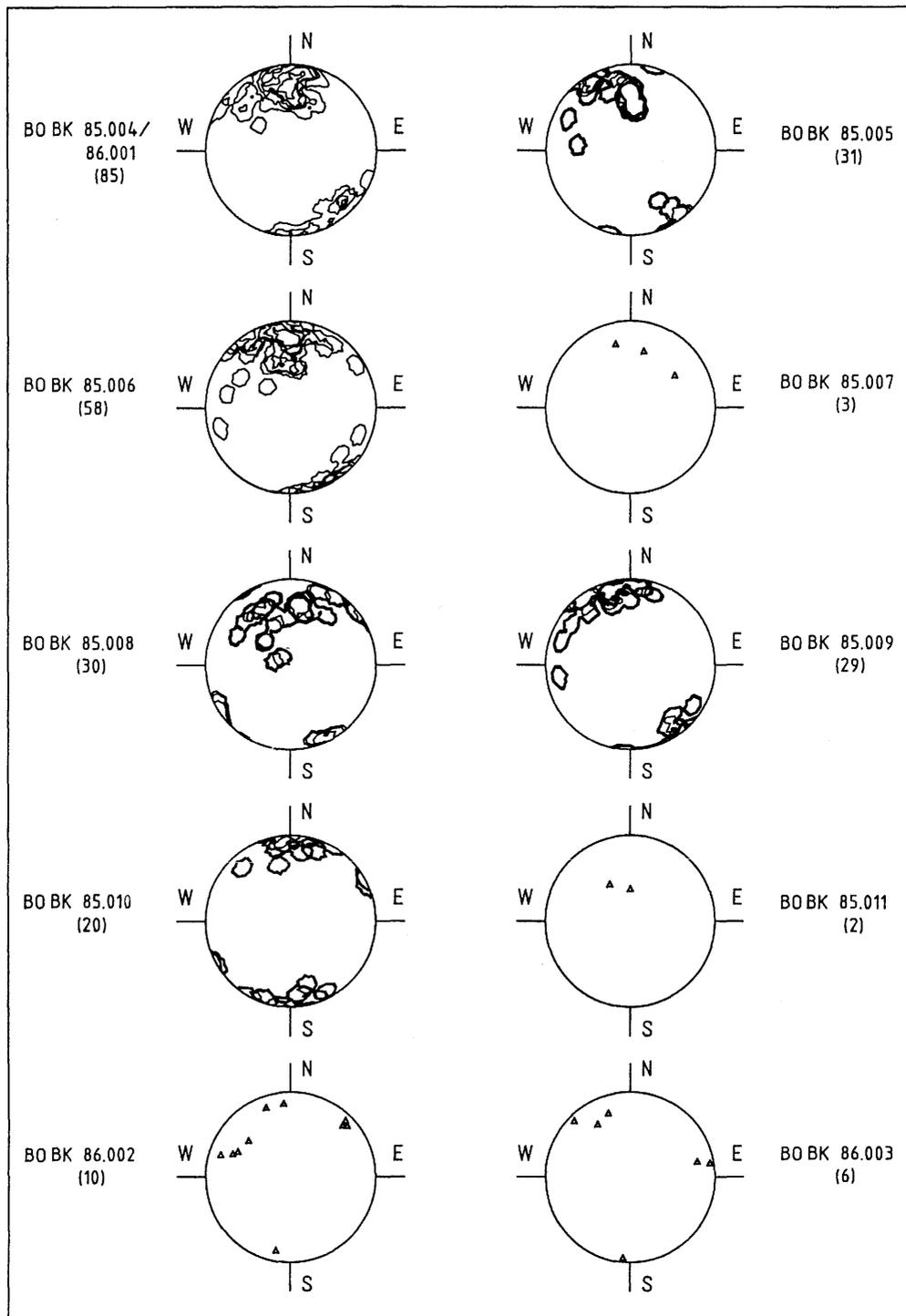


Figure 16: Orientation of slickensides in the BK boreholes (polar projection in the lower hemisphere with 1, 5, 10, 15 and 20 % contour lines).

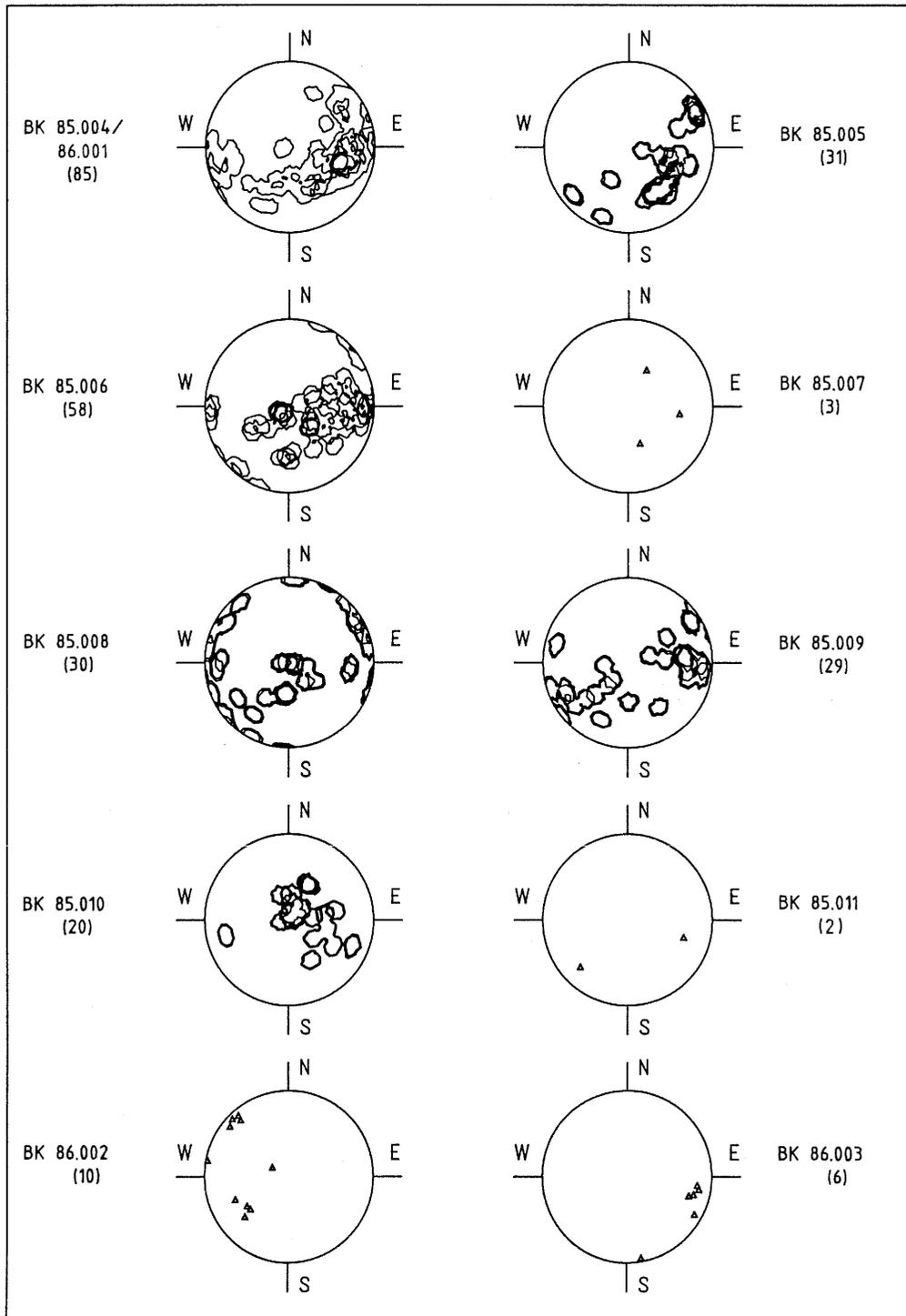


Figure 17: Directions of linears on slickenside planes in BK boreholes (lower hemisphere projection 1, 5, 10, 15 and 20 % contour lines)

The evaluation of the structure diagrams of slickenside linears must be seen in conjunction with the spatial plot of movement planes. In this the relationship between the direction of the linears and the slickenside planes on which they occur provide important information. The plot of these lines for the individual BK boreholes shows a great circle distribution (Figure 17) for boreholes BK 85.004/005/006 and 009, i.e. the majority of the poles can be allocated to the great circle of a certain shear surface.

Using computer software, based on vector analysis and specially developed for the investigation of linears (WALLBRECHER 1986), it is possible to undertake a more exact analysis of the linear direction. In this method points are allocated into clusters (Figure 18). In addition it is possible to see whether a great circle distribution of the poles is present, i.e. the great circle and the location of the slickenside can be specified upon which the majority of the tectonic movements took place. In Figure 18 the poles allocated to a cluster with a minimum point density of 0.5 % result in the high probability of 64.7 % of a great circle with a spatial location of 154/63 (azimuth of dip/angle of dip).

In clusters with tighter specifications (minimum point density 1.4 %) there is a 54.1 % probability of a second great circle with a spatial location of 151/46. The other clusters with higher minimum point densities do not produce any interesting new information but reinforce the basic statement made above that the majority of tectonic movements with horizontal and oblique linears took place on NE/SW to ENE/WSW striking slickenside planes.

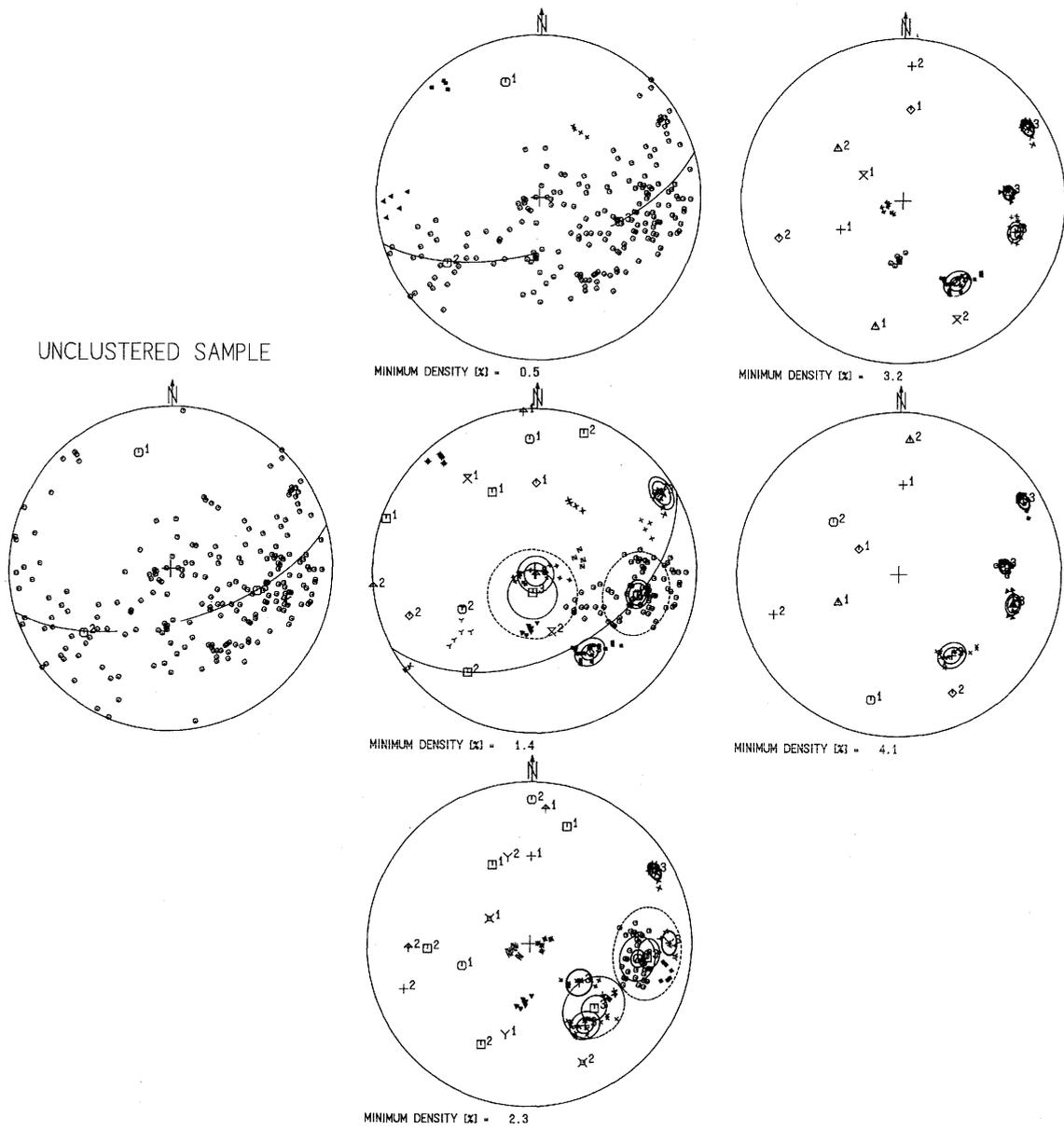


Figure 18: Directions of linears on slickenside planes in BK area (cluster plot with main vectors)

The principle of the mechanism of movement in the Grimsel area for the ESE main thrust direction measured is shown in Figure 19. The conjugated sinistral shear component is under-represented in the test field (shaded), since the approximately NW/SE striking shear planes which would be used are not, or hardly, present.

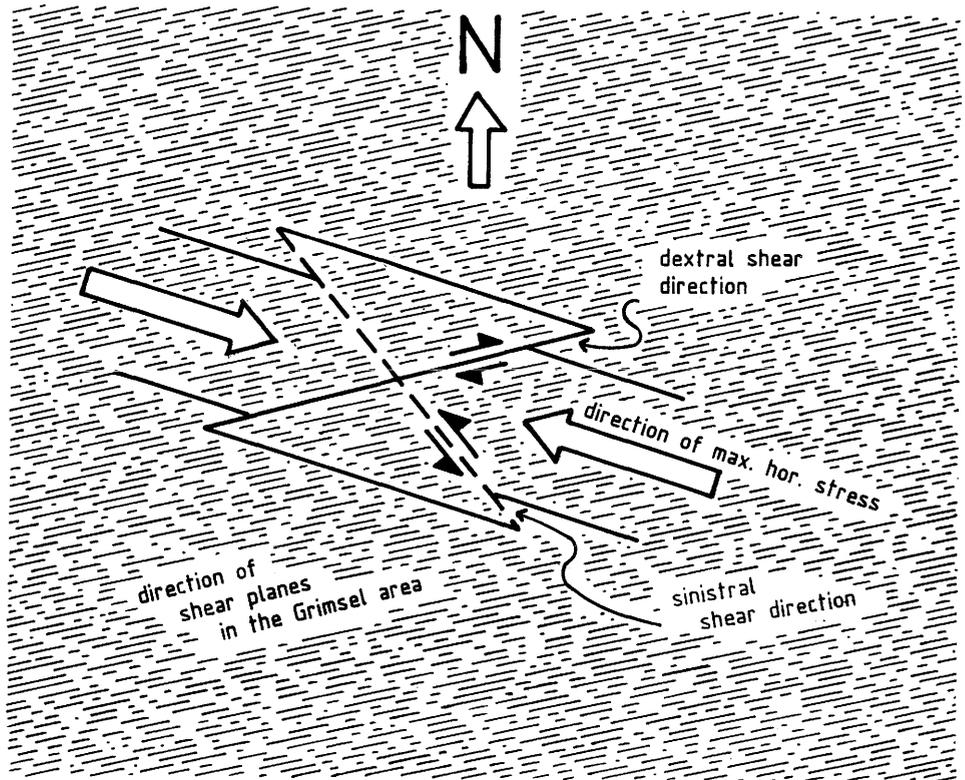


Figure 19: Conjugated shear planes in Grimsel area for main thrust direction from ESE (principle diagram)

The tectonic processes which result in the creation of open and therefore rock hydraulically relevant joints stand in a direct relationship with the shear movements. In the case of a tectonic stressing of the rock mass in the direction shown of ESE/WWN and a dextral shear movement along a slickenside plane striking approximately ENE/WSW one may expect open "feather joints" with an approximate E/W direction of strike (Figure 20). Such joints, which occur frequently in the GS and BK test area (see also Figure 6 and 8) are usually not traceable over longer distances but gain their rock hydraulic importance more due to intense networking. In the area studied shear planes rarely occur alone but tend to be found in adjacent groups, often cutting across one another which frequently leads to an extensive networking of the associated feather joints (Figure 21).

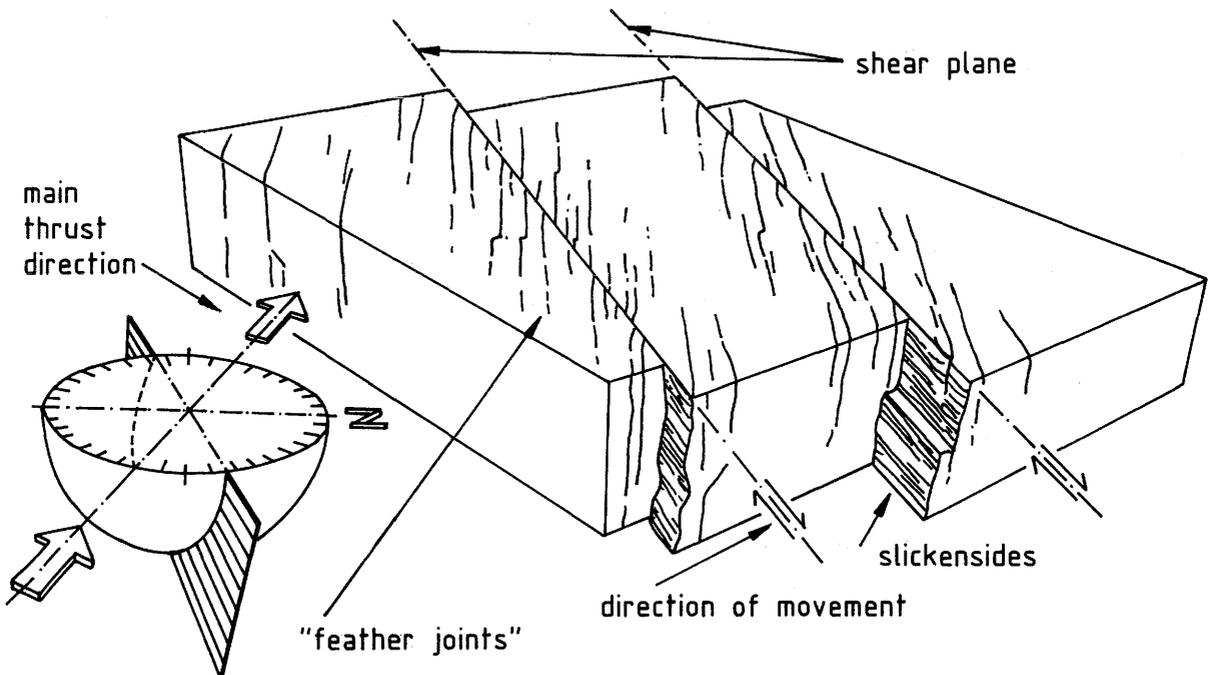


Figure 20: Principle of "feather joints" resulting from 2 shear planes

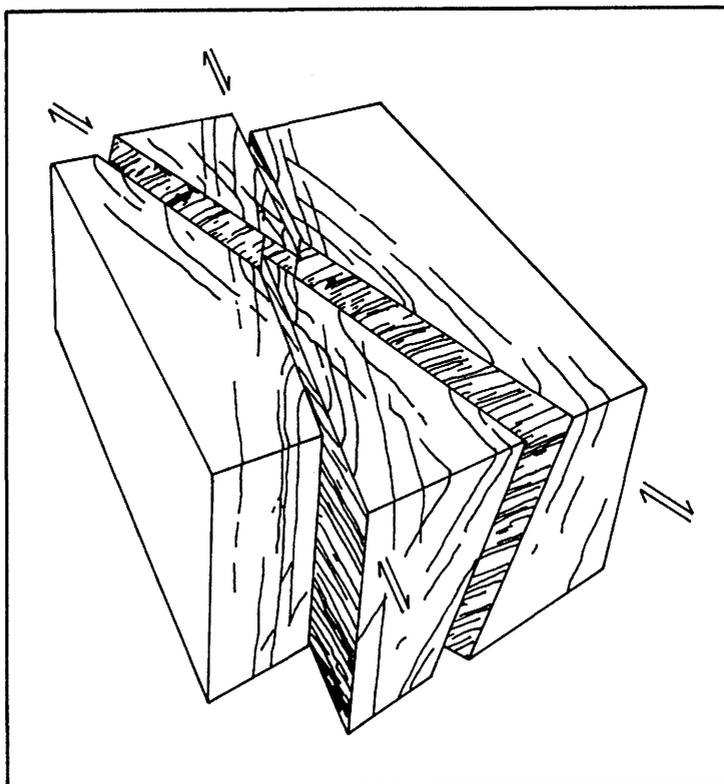


Figure 21: Example of 2 slickenside planes with dextral movement; reactivation of shear planes with intense networking of feather joints.

Just as in the area of borehole GS 84.041A (see also Chapter 4.1) different geological sections are recognizable in the BK test field. These sections are brought to light in the joint statistics and can be correlated with the sections present in the GS area (see also Figures 22 and 23).

BK section 1 comprises the test cavern itself together with those rock sections which reach approximately 10 metres to the west, north and downwards. This section corresponds with GS section I (Figure 23). The granite here has a strongly pronounced lamellar structure and is relatively intensely jointed.

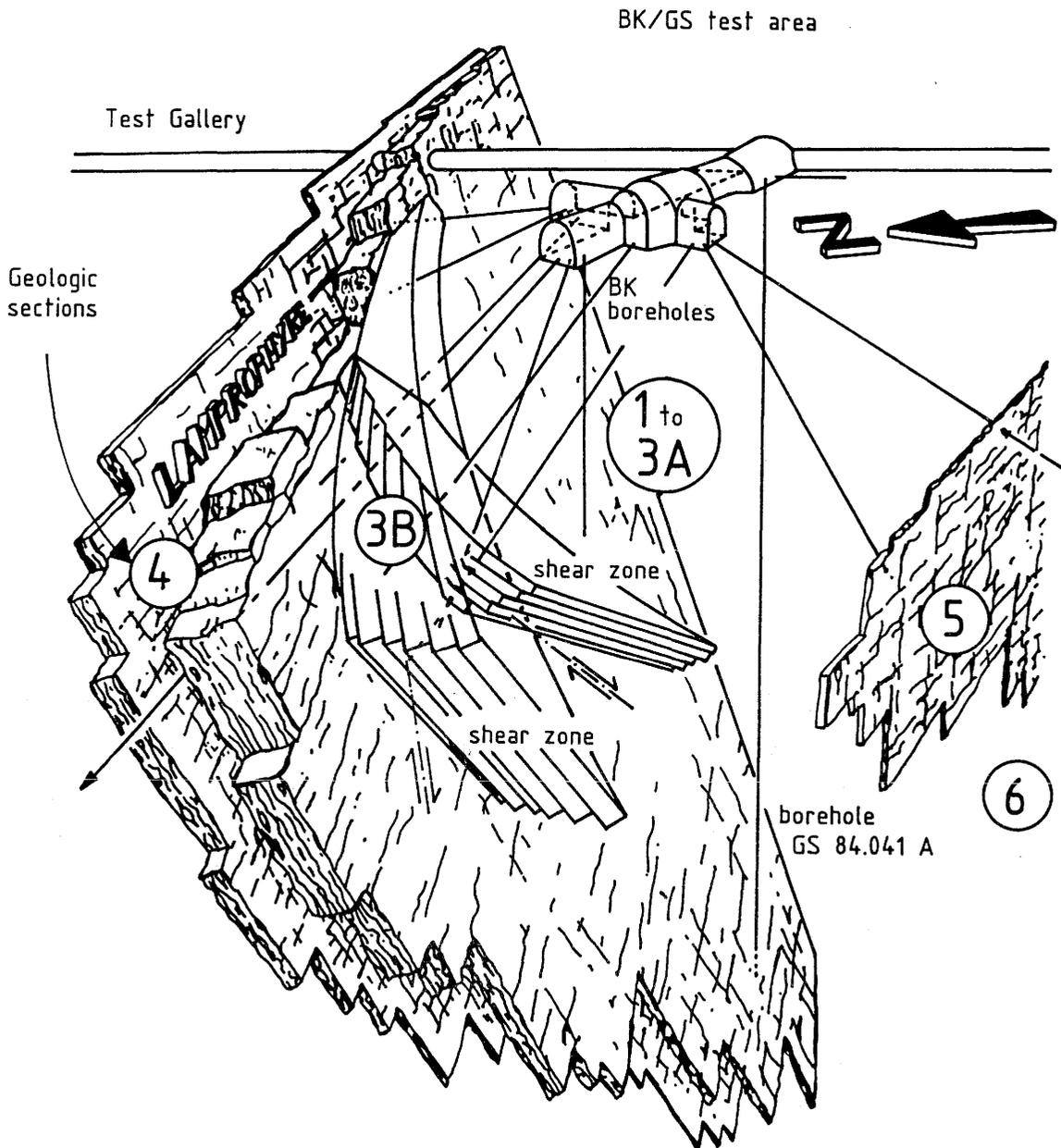


Figure 22: Lamprophyres, shear zones and geological sections in the GS and BK area.

Some open joints drain into the test cavern and result in the relief of the hydrostatic rock pressure in the direction of the cavern down to a depth of approximately 10 m (see also Figure 14).

BK section 2 shows a compact granite with relatively minor jointing in which, however, several hydraulically relevant joint systems are present (not shown in Figure 22). This section is exposed in boreholes BK 85.007 and 85.011 approximately 10 - 30 m below the cavern and corresponds with GS section II, although at this point stretching between 40 - 100 m depth (Figure 23). The rock mass sections south of the cavern (boreholes BK 86.002 and 86.003) also belong to this section. The hydraulic potential after heading the laboratory tunnel is about 28 m (2.8 bar) more than the test level at this point (Figure 14).

BK section 3 seen hydraulically represents a unit with a current potential of approximately 30 m (3 bar) above test level. Because of the strong increase in the number of shear planes in the direction of the lamprophyre this section is divided into subsection (3a) subject to lower rock mechanical stress and subsection (3b) with strong shearing and subject to hydrothermal alteration. This section covers the area north and west of the test cavern adjacent to sections 1 and 2 (Figures 22 and 23). The corresponding GS section (III) also shows several shear zones (Figure 23).

BK section 4 is formed by a thick lamprophyre zone which lies adjacent to the previously specified sections to the west, north and downwards (Figures 22 and 23). The lamprophyre veins alternate with strongly hydrothermally

altered granite blocks. Borehole GS 84.041A encounters this lamprophyre in GS section IV, as does the laboratory tunnel at around metre 130.

The hydraulic potential here is only approximately 10-15 m (1-1.5 bar) above the test level which indicates that this system is drained (primarily via the granite/lamprophyre contact).

BK sections 5 and 6 (not shown in Figure 23) are located to the south of the test field and are only exposed in the last metre of borehole BK 86.003 and also by borehole US 85.003 (not part of the BGR test field). BK section 5 consists of a relatively thin biotite-slate zone with numerous slickensides and small folds. BK section 6 consists, similar to sections 1 and 3, of jointed granite with relatively numerous, interconnected open joints.

The hydraulic potential here is up to 430 m (43 bar) above the test level (Figure 14), which corresponds approximately to the overburden of the laboratory.

Consideration of other sections exposed in the tunnel system of the rock laboratory and on the surface of the Juchlistock demonstrate that the relationships presented in Figures 20 - 24 apply to both the GS/BK test field as well as to the adjacent areas. The individual blocks or sections appear to cut into the Juchlistock either as slices or wedges, whereby these can be only a few metres or up to 100 m in thickness.

6. ROCK MECHANICAL AND ROCK HYDRAULIC RELATIONSHIPS BETWEEN THE TEST SITES GS AND BK

In the preceding chapter it was shown that the two test sites, GS and BK, can be subdivided into geological/tectonic sections which are characterized mainly by the form and spatial location of the joint planes.

These special geological relationships are determinants for both the value and direction of rock stresses as well as for the extent and main direction of the rock permeability. In order to be able to transfer bilaterally the named rock parameters between the GS and BK test sites, or to prognose the same, sections have to be specified which are geologically comparable. Figure 23 gives a schematic impression of this whereby the numbering of the sections is chosen such that the Roman numerals (GS) correspond to the Arabic (BK) (Sections 5 and 6 (BK) do not enter into this consideration since they are extra to the sections exposed in GS area). The following sections can be named which differ from one another both rock mechanically and hydraulically. Figure 22 shows the relationship schematically and spatially, figure 23 is a longitudinal section through the two test sites, GS and BK, parallel to the axis of the cavern.

GS II/BK 2 is in compact granite. Here a relatively uniform and high rock stress is predicted (approximately 40 MPa from SSE/NNW direction, Figure 10). Only very few joint planes are present such that permeability is almost exclusively due to pore-aquifer properties and the low rock permeability of the granite matrix (coefficient of permeability = 1×10^{-11} to 1×10^{-12} m/s) (see also rock hydraulic sections of the individual BK

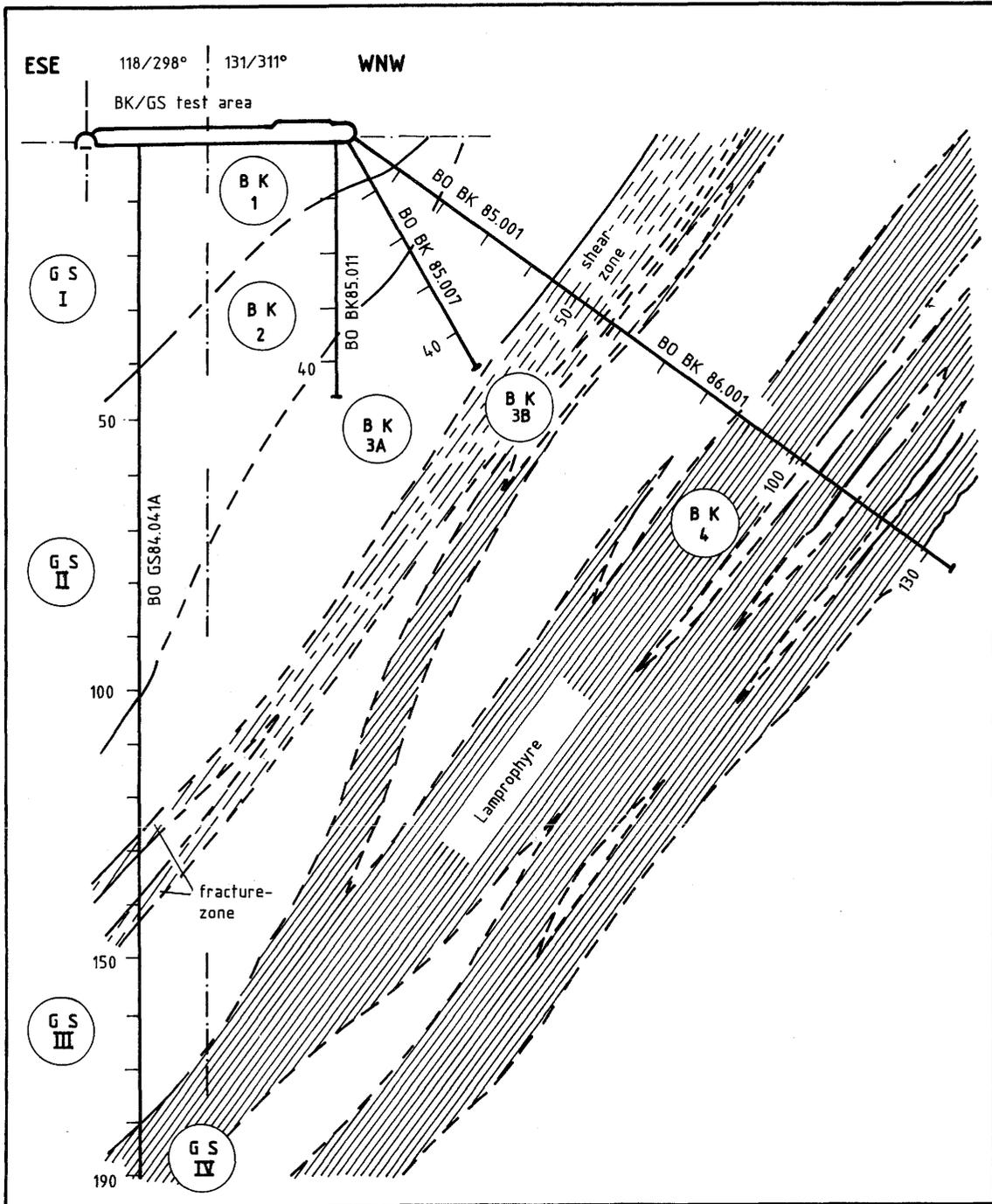


Figure 23: Longitudinal section through the GS/BK test field with geological sections

boreholes, BGR, 1985 and 1986). The direction of the maximum permeability in the compact granite runs along the orientation of the schistose structure (Figure 20, shaded area).

GS I/GS III/BK 1/ BK 3 A/BK 3 B consist of relatively intensely jointed granite which is strongly fractured in the fault zones (GS III, Figure 23) and at the contact to the adjacent lamprophyre (BK 3 B).

The shear movements as described in the preceding chapter along pre-existing shear planes have lead to a partial compensation of rock stresses such that lower values of around 30 MPa predominate. The direction of the major horizontal stress has also changed to approximately ESE/WNW. The maximum permeability in this homogeneous area is determined by the presence of numerous and often hydraulically linked open joints whose mechanism of origin is also described in the preceding (Figures 20 and 24). The transmissivity is approximately 1×10^{-7} m/s in areas which closely packed jointing (see also rock hydraulic sections of BK boreholes, BGR 1985 and 1986), the direction of planes with the greatest transmissivity is predicted to be at around 100° (strike) based on the preferential joint orientation (Figure 24).

In the geological section described here, and as mentioned previously, a zone of intense shearing (numerous slickensides) is observable. In this zone the rock stress values decrease and rock permeability values increase. The importance of hydrothermally altered areas has been pointed out in the preceding.

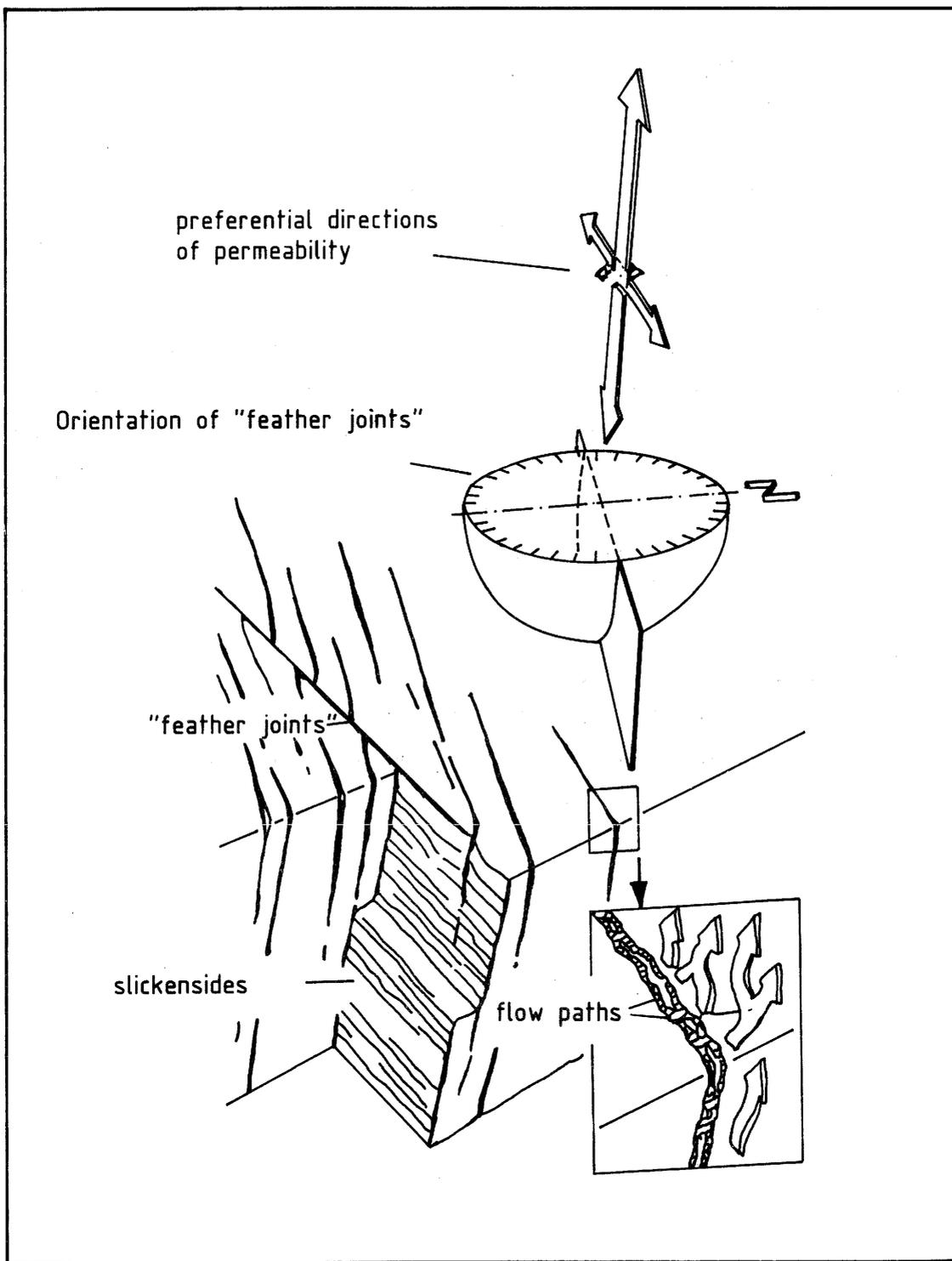


Figure 24: Hydraulic efficiency of feather joints (preferential directions of permeability)

GS IV/BK 4 is characterized by a lamprophyre vein and a shear zone. Upon the close examination the lamprophyre (kersantite) consists exclusively of sheared and mylonitized material, slickensides are so common that they can hardly be separated optically and because of intense disintegration of the cores can not be recorded with orientation. Because of the low rock strength of the kersantite material open joints are not present. Other areas are mylonitized and contain clay minerals. The rock permeability within the lamprophyre is even less in a horizontal direction than in the matrix of compact granite due to the high clay proportion on the shear planes. The transmissivity is barely detectable (less than 1×10^{-12} m/s). The permeability increases sharply parallel to the planes and reaches particularly high values at the lamprophyre/granite contact. The relatively low horizontal stress values found in the GS borehole when approaching the lamprophyre should also be expected in the continuation of this section.

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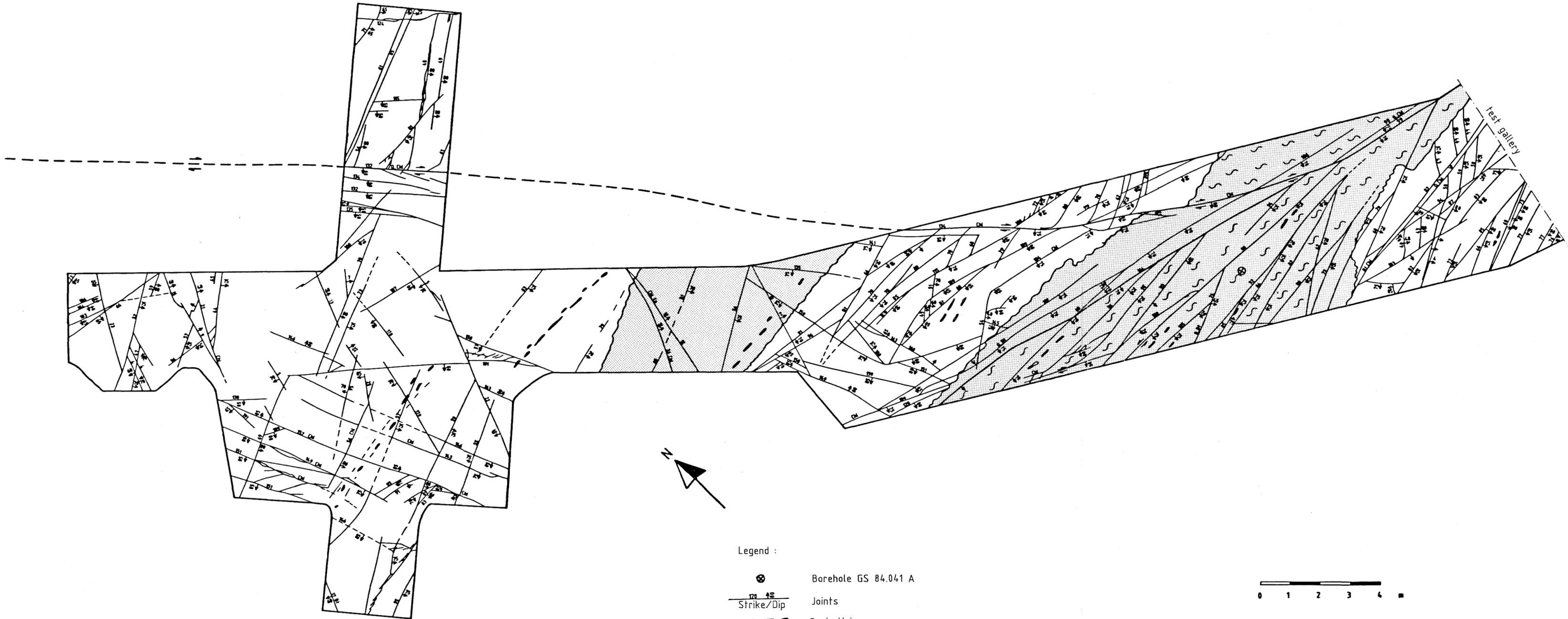
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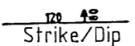
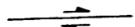
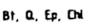
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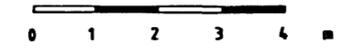
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- Legend :
-  Borehole GS 84.041 A
 -  Joints
 -  Basic Veins
 -  Quartz Veins
 -  Fault
 -  Dark Central Aaregranite
 -  Minerals
Biotite, Quartz, Epidote, Chlorite
 -  Zone of tectonic deformation



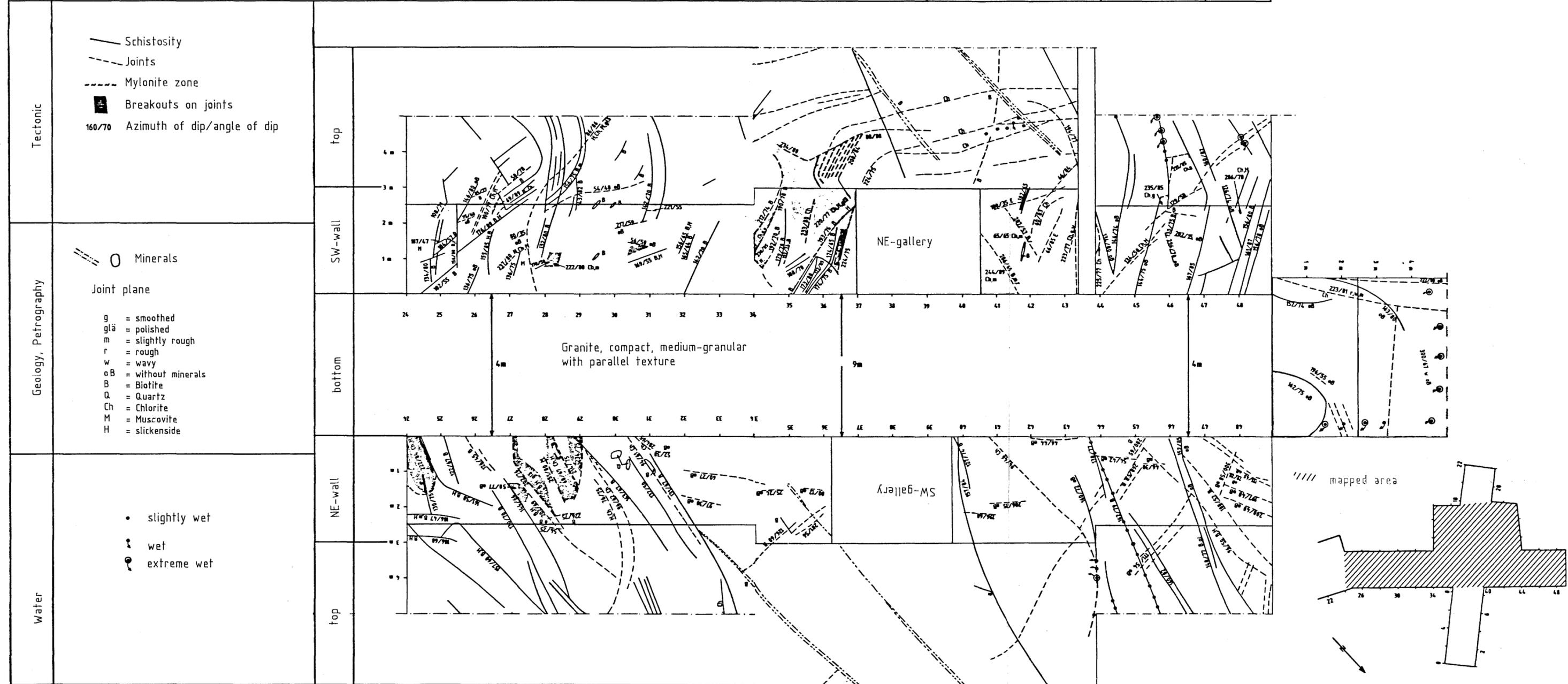
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GEOLOGIC MAP OF THE GS/BK CAVERN (BOTTOM)

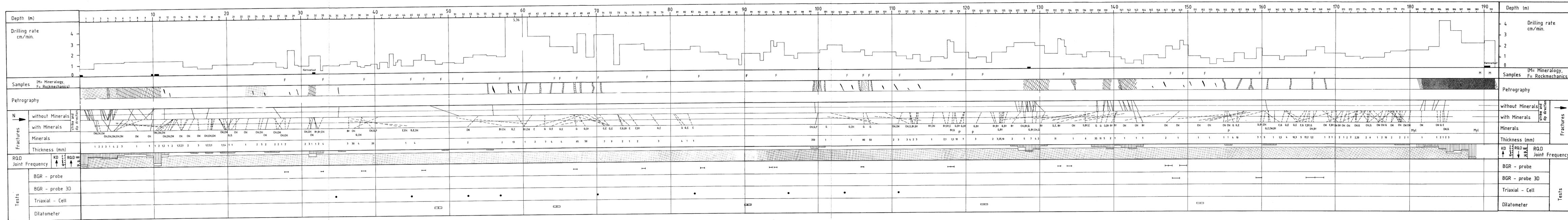
GRIMSEL TEST SITE DAT: ENCLOSURE 1

Orientation	Metre	24	25	30	35	40	45	49
	Gallery axis	295.01°		311.53°, 1%				
	Status of blasting	24.10.83			26.10.83		28.10.83	1.11.83



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 GEOLOGIC MAP OF THE GS/BK CAVERN (A)
 GRIMSEL TEST SITE DAT: ENCLOSURE 2



LEGEND

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

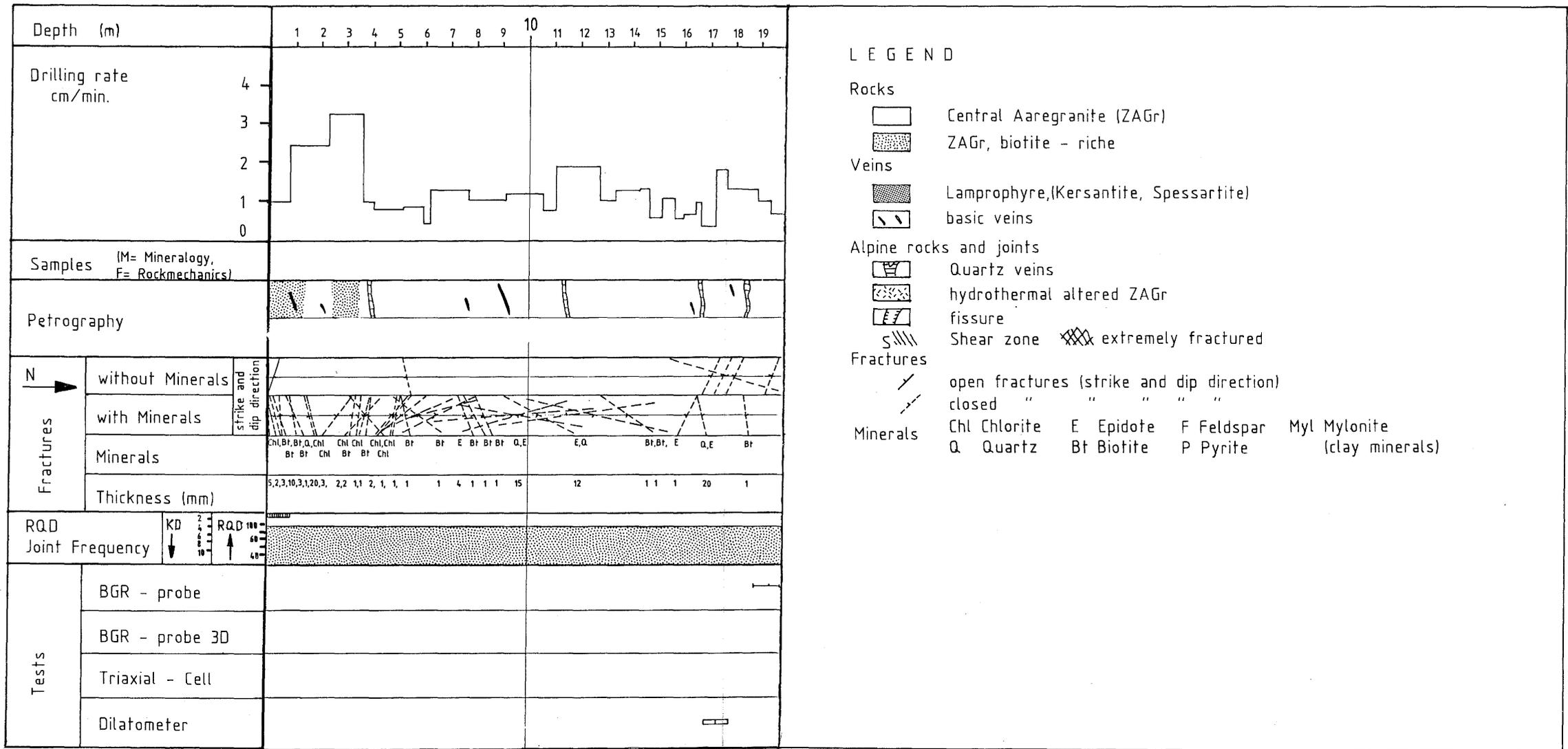
- Chl Chlorite
- E Epidote
- F Feldspar
- Q Quartz
- Bt Biotite
- P Pyrite
- Myl Mylonite (clay minerals)

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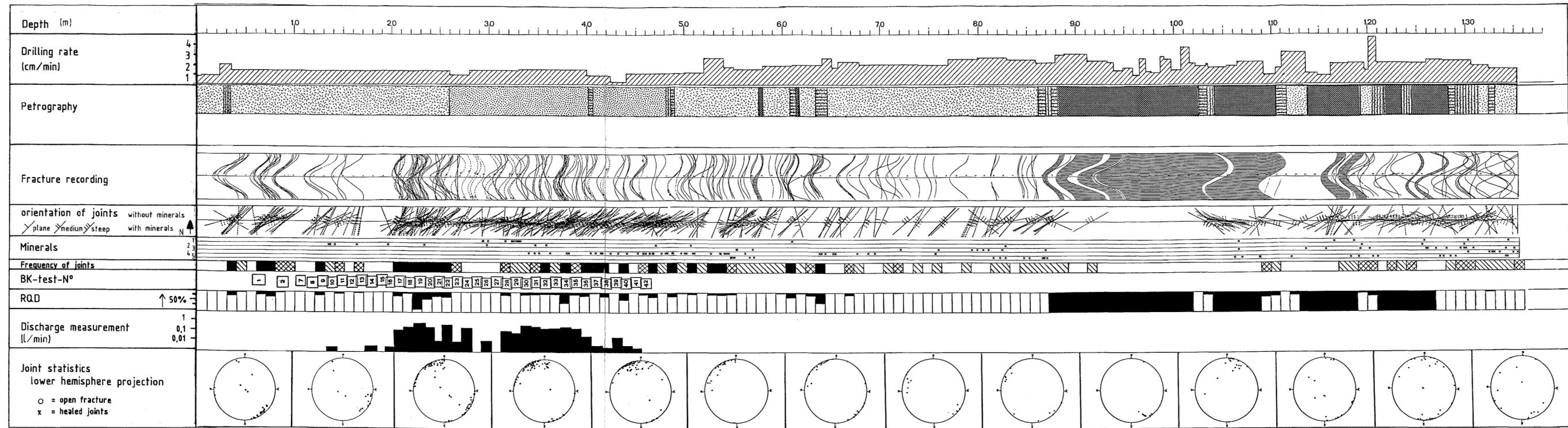
GEOLOGY OF BOREHOLE GS 84.041 A

GRIMSEL TEST SITE DAT: ENCLOSURE 4



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NAGRA TECHNICAL REPORT NTB 88-37E
 GEOLOGY OF BOREHOLE GS 84.042 A
 GRIMSEL TEST SITE DAT.: ENCLOSURE 5



LEGEND

PETROGRAPHY:

- CENTRAL AAREGRANITE (LIGHT)
- CENTRAL AAREGRANITE (DARK)
- LAMPROPHYRE (KERSANTITE)
- BASIC VEINS
- APLITE
- ALPINE ROCKS**
- QUARTZ - VEINS
- HYDROTHERMAL ALTERATION
- MYLONITE

- MINERALS:**
- 1 = QUARTZ
 - 2 = EPIDOTE
 - 3 = BIOTITE
 - 4 = CHLORITE
 - 5 = FELDSPAR, CALCITE,
 - 6 = OTHER MINERALS

JOINT FREQUENCY:

- NO OPEN FRACTURES/METRE
- 1-2 " " "
- 3-4 " " "
- 5 AND MORE " "

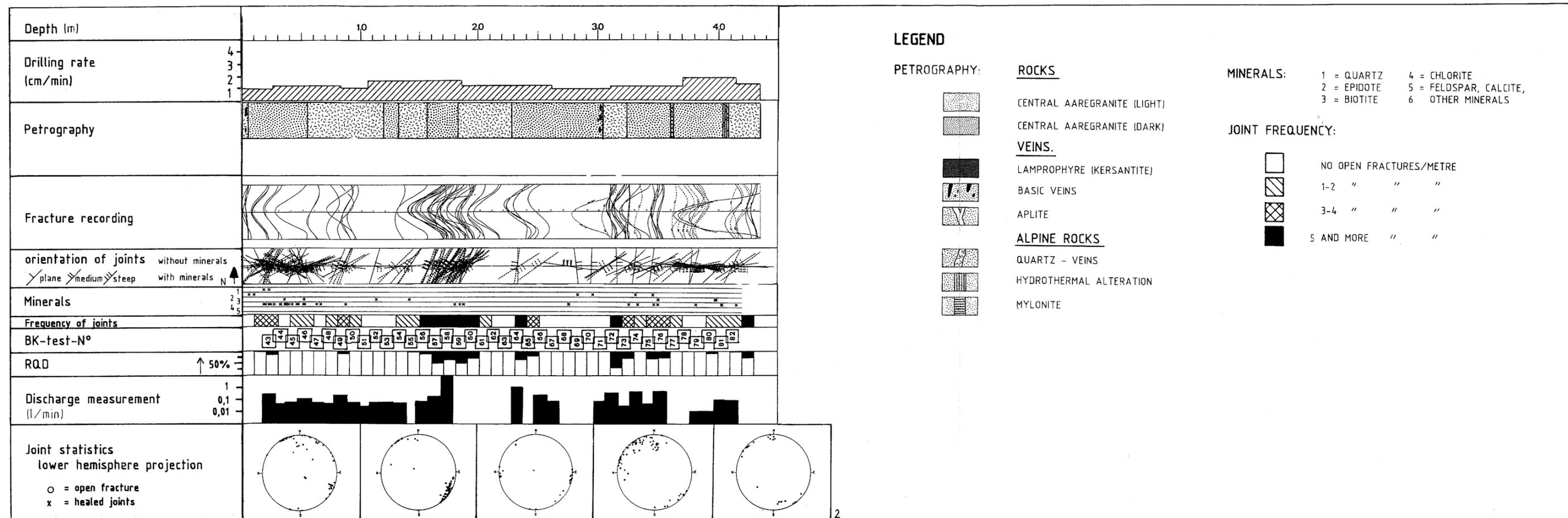
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NAGRA TECHNICAL REPORT NTB 88-37E

GEOLOGY OF BOREHOLE BK 85.004/86.001

GRIMSEL TEST SITE DAT: ENCLOSURE 6

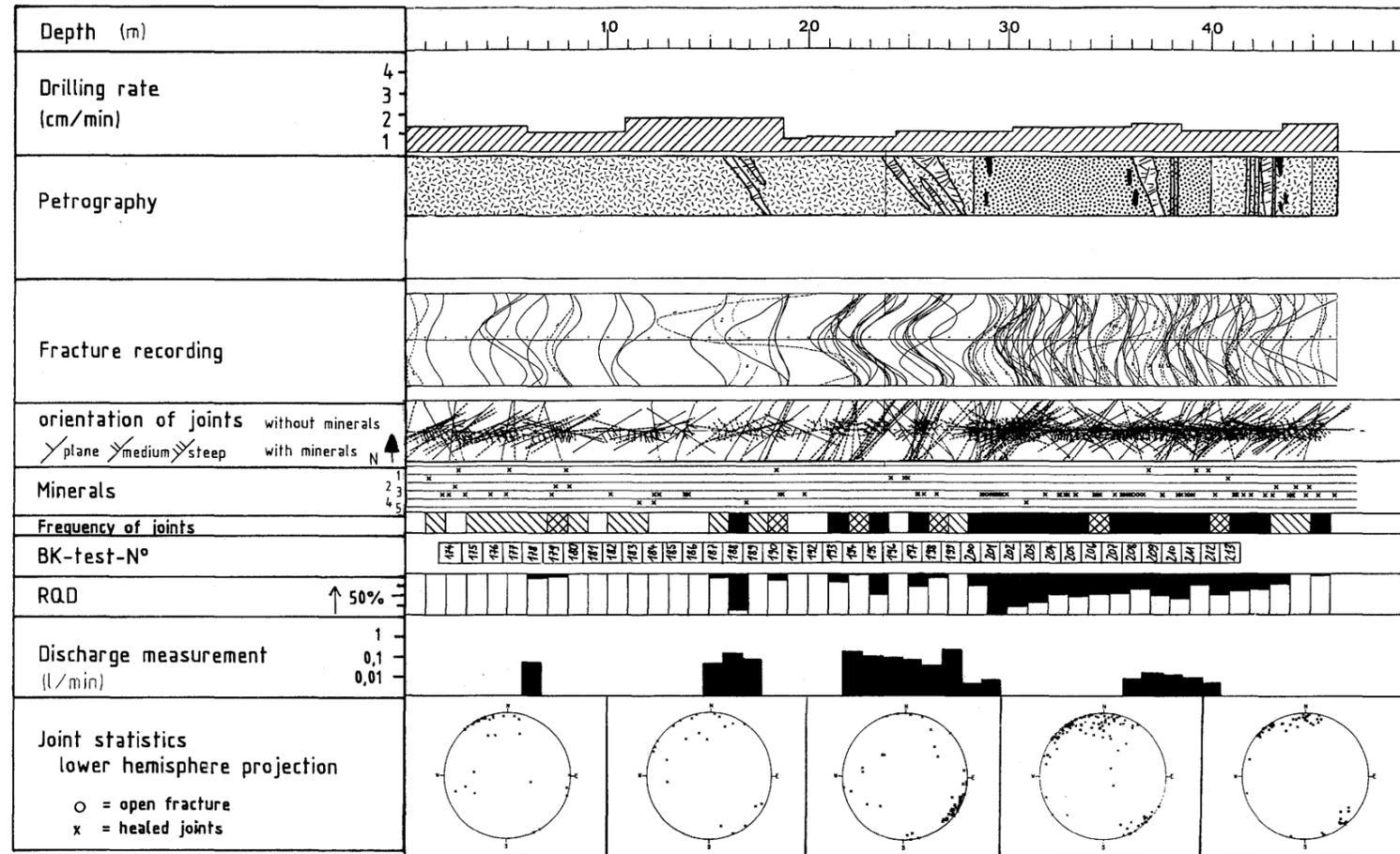


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GEOLOGY OF BOREHOLE BK 85.005

GRIMSEL TEST SITE DAT: ENCLOSURE 7



LEGEND

PETROGRAPHY:

- CENTRAL AAREGRANITE (LIGHT)
- CENTRAL AAREGRANITE (DARK)
- LAMPROPHYRE (KERSANTITE)
- BASIC VEINS
- APLITE
- ALPINE ROCKS**
- QUARTZ - VEINS
- HYDROTHERMAL ALTERATION
- MYLONITE

MINERALS:

- 1 = QUARTZ
- 2 = EPIDOTE
- 3 = BIOTITE
- 4 = CHLORITE
- 5 = FELDSPAR, CALCITE,
- 6 = OTHER MINERALS

JOINT FREQUENCY:

- NO OPEN FRACTURES/METRE
- 1-2 " " "
- 3-4 " " "
- 5 AND MORE " " "

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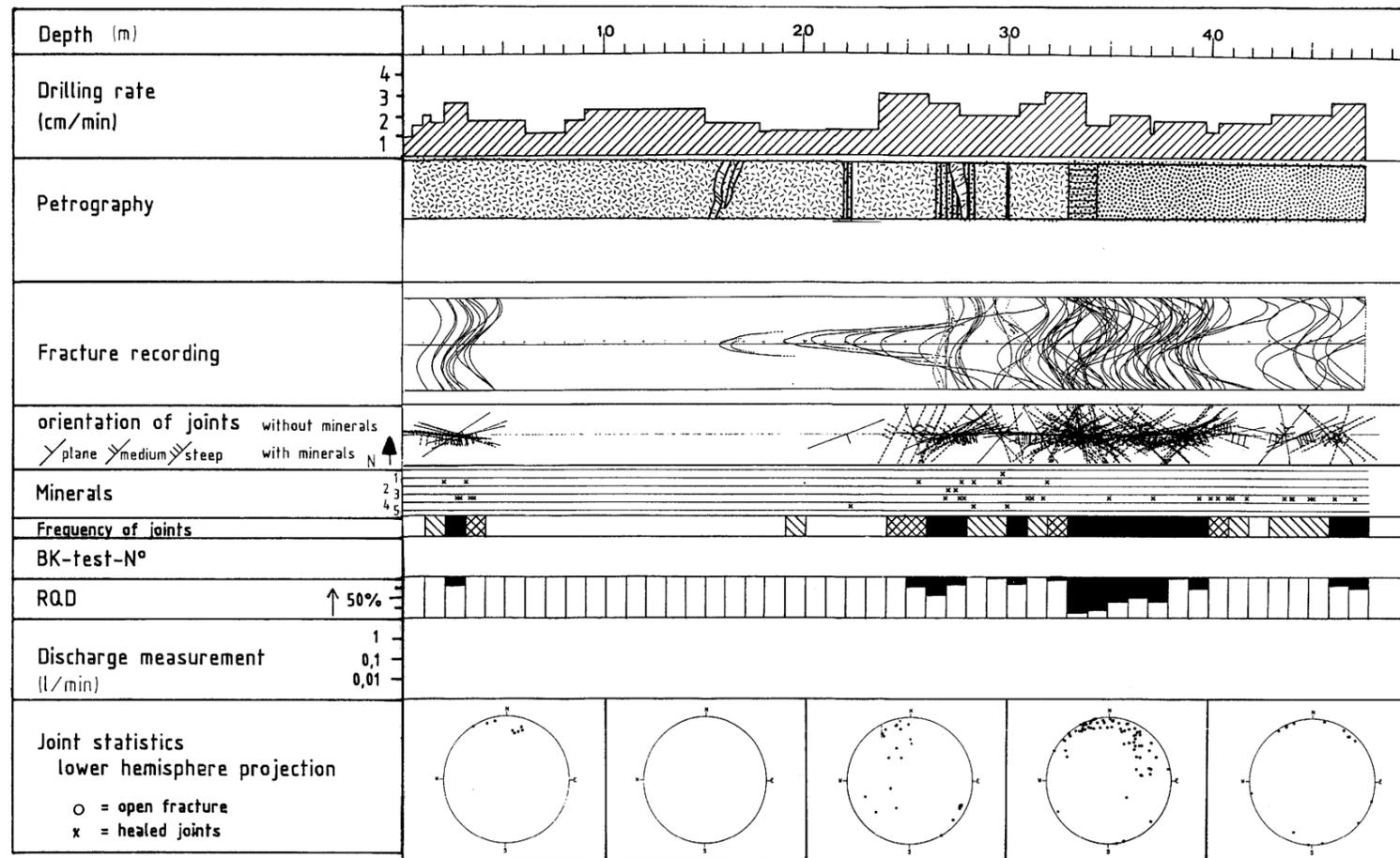
TECHNICAL REPORT NTB 88-37E

GEOLOGY OF BOREHOLE BK 85.006

GRIMSEL TEST SITE

DAT:

ENCLOSURE 8



LEGEND

PETROGRAPHY

- CENTRAL AAREGRANITE (LIGHT)
- CENTRAL AAREGRANITE (DARK)
- LAMPROPHYRE (KERSANTITE)
- BASIC VEINS
- APLITE
- ALPINE ROCKS
- QUARTZ - VEINS
- HYDROTHERMAL ALTERATION
- MYLONITE

ROCKS

VEINS

ALPINE ROCKS

MINERALS:

- 1 = QUARTZ
- 2 = EPIDOTE
- 3 = BIOTITE
- 4 = CHLORITE
- 5 = FELDSPAR, CALCITE,
- 6 = OTHER MINERALS

JOINT FREQUENCY:

- NO OPEN FRACTURES/METRE
- 1-2 " " "
- 3-4 " " "
- 5 AND MORE " "

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NAGRA

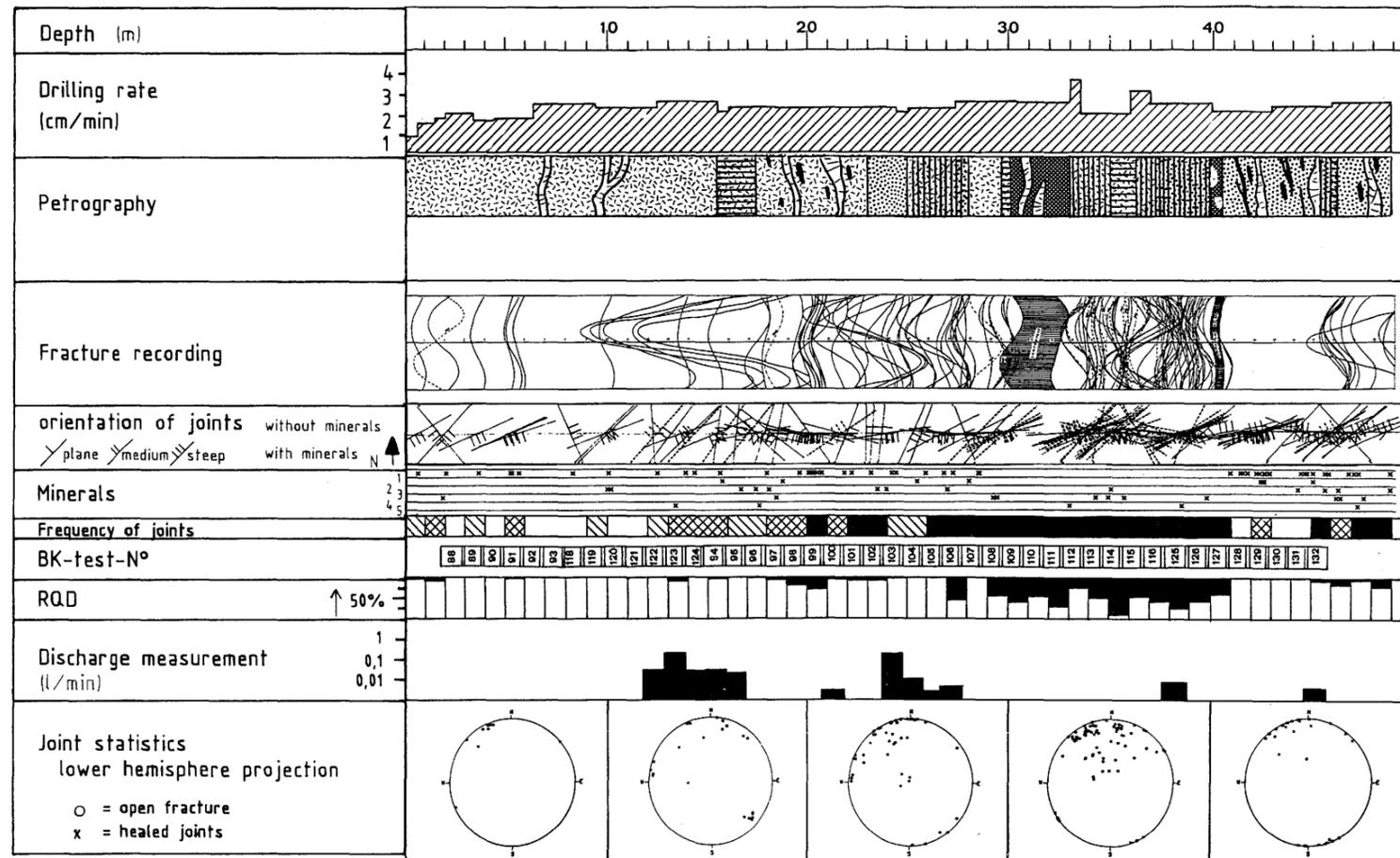
TECHNICAL REPORT NTB 88-37E

GEOLOGY OF BOREHOLE BK 85.007

GRIMSEL TEST SITE

DAT:

ENCLOSURE 9



LEGEND

PETROGRAPHY:

- CENTRAL AAREGRANITE (LIGHT)
- CENTRAL AAREGRANITE (DARK)
- LAMPROPHYRE (KERSANTITE)
- BASIC VEINS
- APLITE
- ALPINE ROCKS**
- QUARTZ - VEINS
- HYDROTHERMAL ALTERATION
- MYLONITE

MINERALS:

- 1 = QUARTZ
- 2 = EPIDOTE
- 3 = BIOTITE
- 4 = CHLORITE
- 5 = FELDSPAR, CALCITE,
- 6 = OTHER MINERALS

JOINT FREQUENCY:

- NO OPEN FRACTURES/METRE
- 1-2 " " "
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- 5 AND MORE " "

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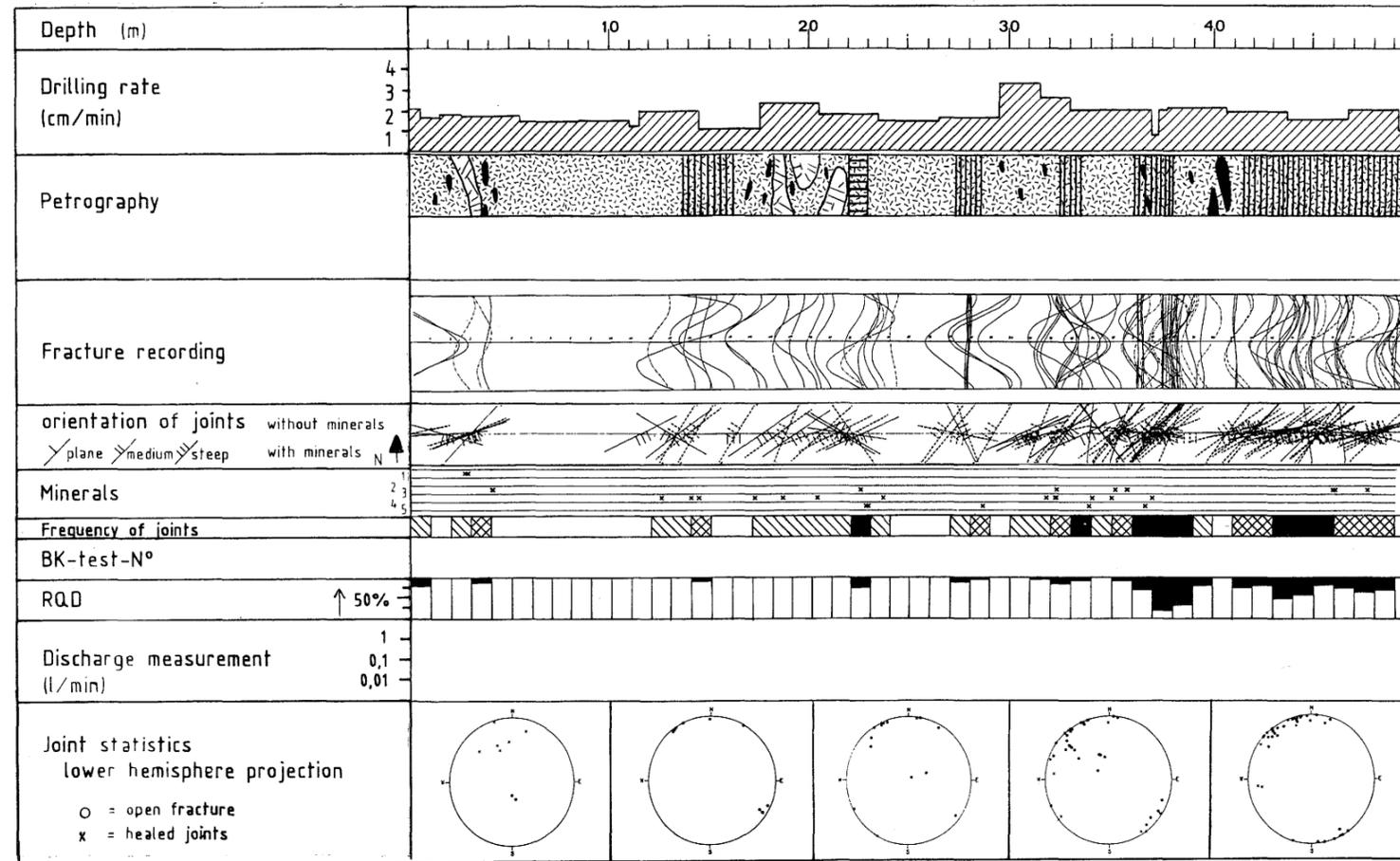
TECHNICAL REPORT NTB 88-37E

GEOLOGY OF BOREHOLE BK 85.008

GRIMSEL TEST SITE

DAT:

ENCLOSURE 10



LEGEND

PETROGRAPHY:

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- CENTRAL AAREGRANITE (DARK)
- LAMPROPHYRE (KERSANTITE)
- BASIC VEINS
- APLITE
- QUARTZ - VEINS
- HYDROTHERMAL ALTERATION
- MYLONITE

ROCKS

VEINS.

- LAMPROPHYRE (KERSANTITE)
- BASIC VEINS
- APLITE

ALPINE ROCKS

- QUARTZ - VEINS
- HYDROTHERMAL ALTERATION
- MYLONITE

MINERALS:

- 1 = QUARTZ
- 2 = EPIDOTE
- 3 = BIOTITE
- 4 = CHLORITE
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JOINT FREQUENCY:

- NO OPEN FRACTURES/METRE
- 1-2 " " "
- 3-4 " " "
- 5 AND MORE " " "

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NAGRA

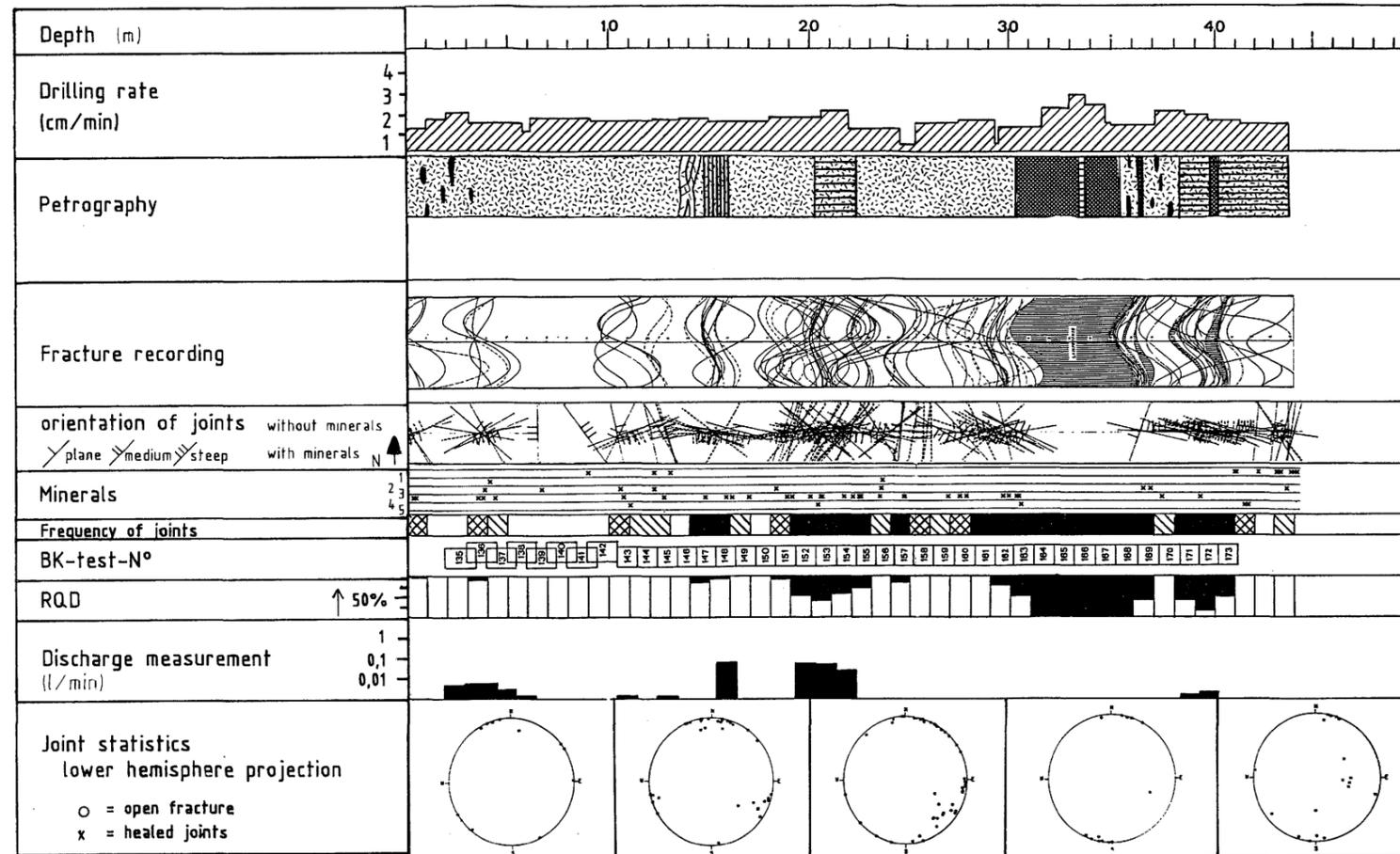
TECHNICAL REPORT NTB 88-37E

GEOLOGY OF BOREHOLE BK 85.009

GRIMSEL TEST SITE

DAT:

ENCLOSURE 11



LEGEND

PETROGRAPHY:

- CENTRAL AAREGRANITE (LIGHT)
- CENTRAL AAREGRANITE (DARK)
- LAMPROPHYRE (KERSANTITE)
- BASIC VEINS
- APLITE
- ALPINE ROCKS
- QUARTZ - VEINS
- HYDROTHERMAL ALTERATION
- MYLONITE

MINERALS:

- 1 = QUARTZ
- 2 = EPIDOTE
- 3 = BIOTITE
- 4 = CHLORITE
- 5 = FELDSPAR, CALCITE,
- 6 OTHER MINERALS

JOINT FREQUENCY:

- NO OPEN FRACTURES/METRE
- 1-2 " " "
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NAGRA

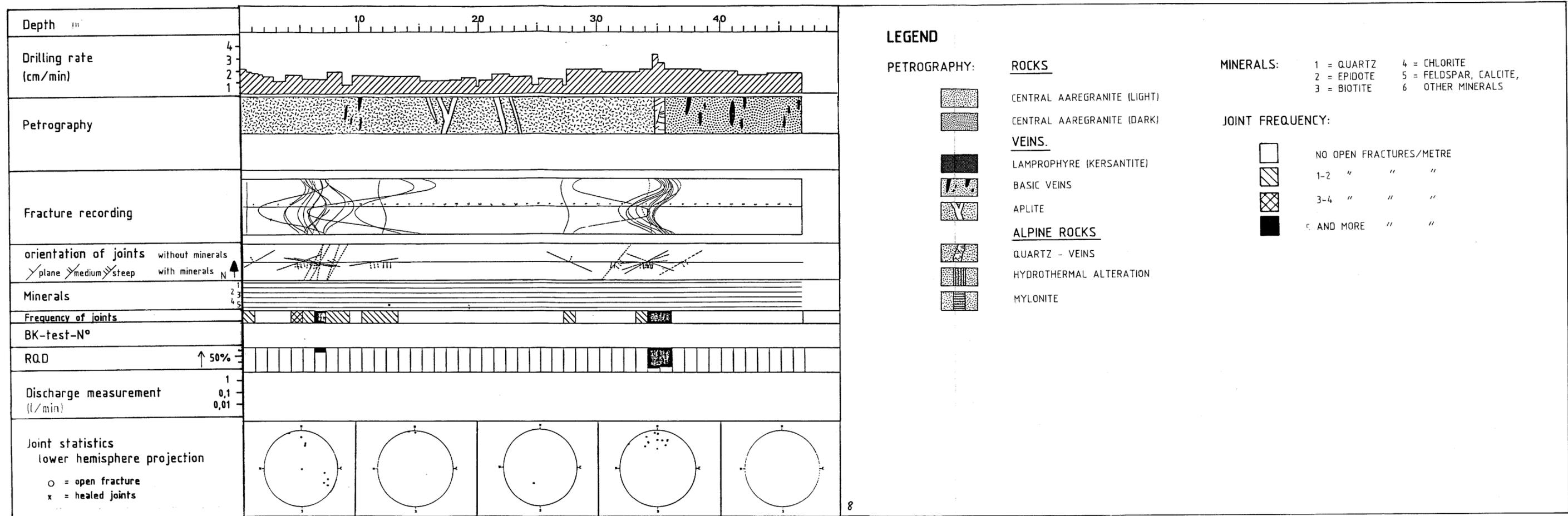
TECHNICAL REPORT NTB 88-37E

GEOLOGY OF BOREHOLE BK 85.010

GRIMSEL TEST SITE

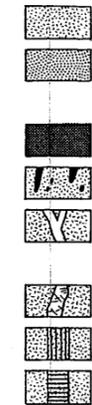
DAT:

ENCLOSURE 12



LEGEND

PETROGRAPHY:



ROCKS

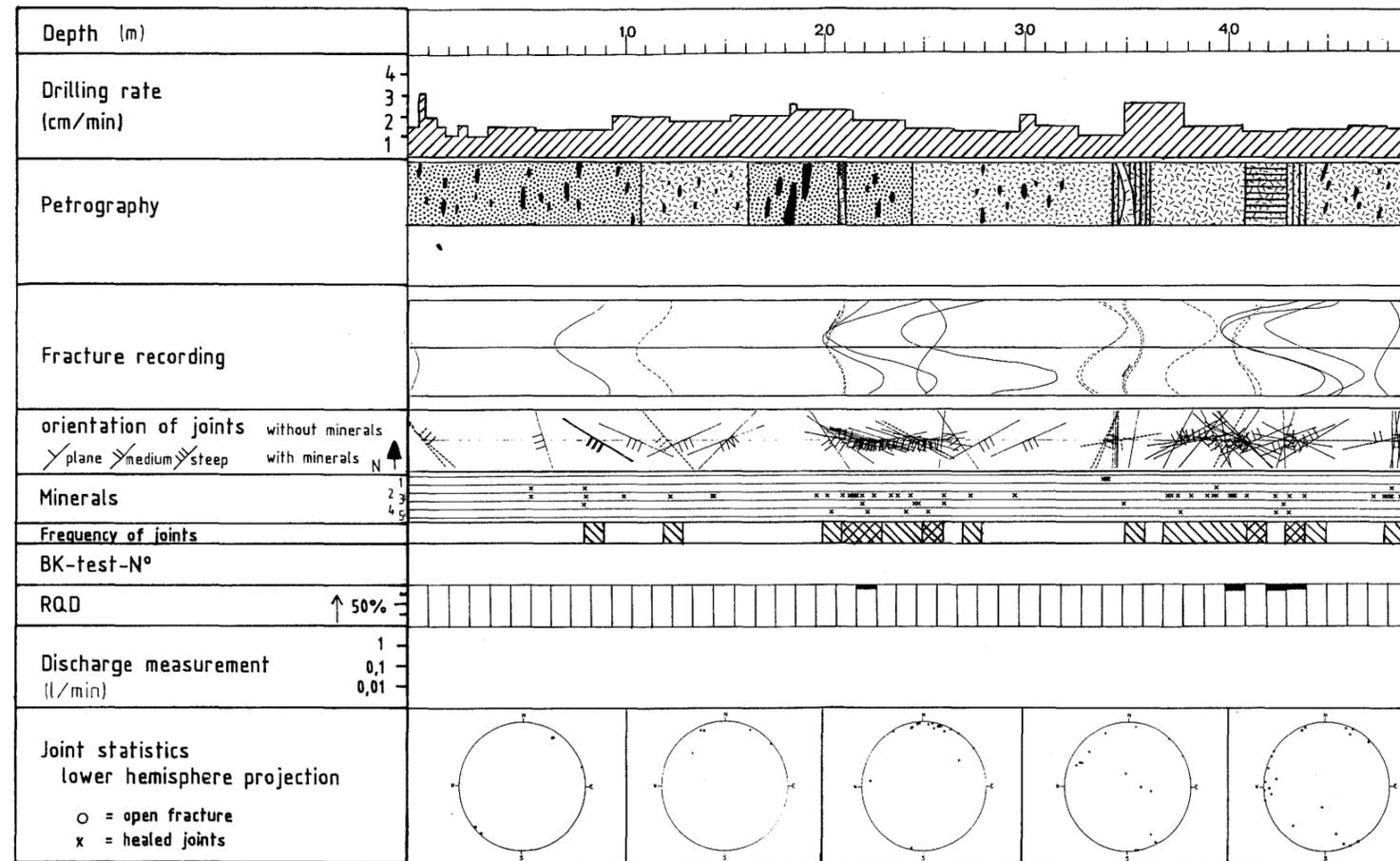
- CENTRAL AAREGRANITE (LIGHT)
- CENTRAL AAREGRANITE (DARK)
- VEINS:**
- LAMPROPHYRE (KERSANTITE)
- BASIC VEINS
- APLITE
- ALPINE ROCKS**
- QUARTZ - VEINS
- HYDROTHERMAL ALTERATION
- MYLONITE

MINERALS:

- 1 = QUARTZ
- 2 = EPIDOTE
- 3 = BIOTITE
- 4 = CHLORITE
- 5 = FELDSPAR, CALCITE,
- 6 = OTHER MINERALS

JOINT FREQUENCY:

- NO OPEN FRACTURES/METRE
- ▨ 1-2 " " "
- ▩ 3-4 " " "
- 5 AND MORE " " "



LEGEND

PETROGRAPHY:

- CENTRAL AAREGRANITE (LIGHT)
- CENTRAL AAREGRANITE (DARK)
- LAMPROPHYRE (KERSANTITE)
- BASIC VEINS
- APLITE
- ALPINE ROCKS
- QUARTZ - VEINS
- HYDROTHERMAL ALTERATION
- MYLONITE

ROCKS

VEINS.

- LAMPROPHYRE (KERSANTITE)
- BASIC VEINS
- APLITE

ALPINE ROCKS

- QUARTZ - VEINS
- HYDROTHERMAL ALTERATION
- MYLONITE

MINERALS:

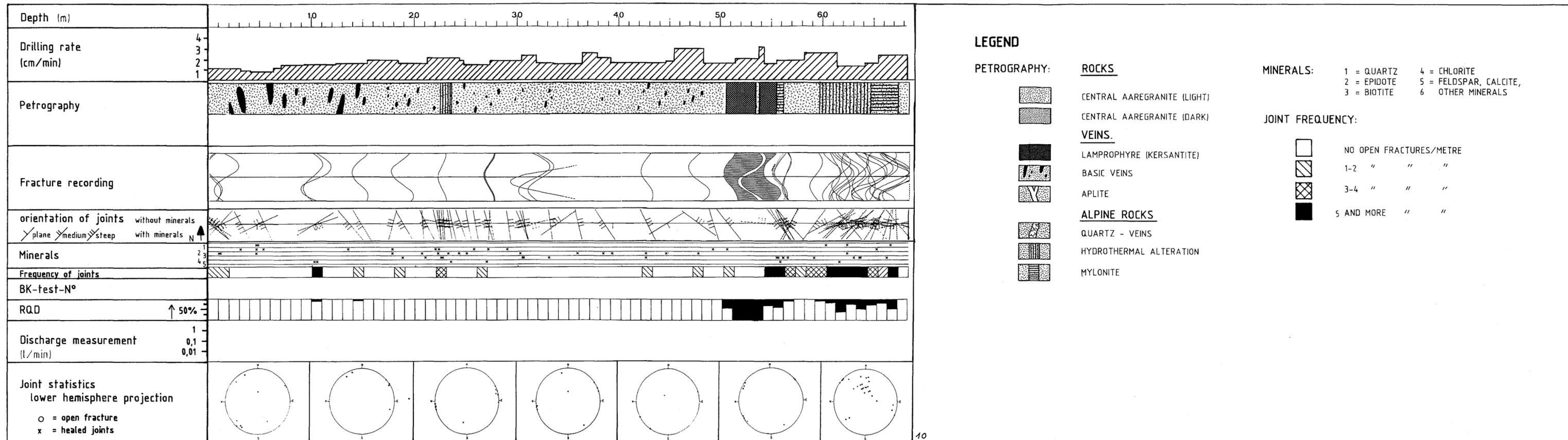
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- 2 = EPIDOTE
- 3 = BIOTITE
- 4 = CHLORITE
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- 6 OTHER MINERALS

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- 3-4 " " "
- 5 AND MORE " " "

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 GEOLOGY OF BOREHOLE BK 86.002
 GRIMSEL TEST SITE DAT.: ENCLOSURE 14



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GEOLOGY OF BOREHOLE BK 86.003

GRIMSEL TEST SITE

DAT:

ENCLOSURE 15