Holford Gas Storage Project

HYDRAULIC / HYDROFRAC TESTING
FOR PERMEABILIY AND IN-SITU STRESS DETERMINATION

Final Report
Volume I: In-Situ Tests

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Content

Abbreviations

dP	:	differential pressure [MPa]
g	:	gravitational acceleration [m/s^2]
k	:	hydraulic conductivity [m/s]
K	:	permeability [Darcy = 10^{-12} m^2]
L	:	length of test interval [m]
P	:	measured downhole injection pressure [MPa]
P_a	:	asymptotic pressure [MPa]
P_c	:	breakdown pressure (fracture initiation) [MPa]
P_{co}	:	in - situ hydraulic tensile strength [MPa]
P_p	:	pore pressure [MPa]
P_r	:	refrac pressure (fracture re - opening) [MPa]
P_{si}	:	shut - in pressure [MPa]
Q	:	injection flow - rate [l/min]
r	:	borehole radius [m]
S_h	:	minimum horizontal principal stress [MPa]
S_H	:	maximum horizontal principal stress [MPa]
S_v	:	vertical principal stress [MPa]
t	:	time [s]
V	:	injected volume [l]
z	:	depth [m]
α	:	dip of fracture (with respect to horizontal) [deg]
β	:	dip direction (north over east) [deg]
θ	:	fracture strike direction (north over east) [deg]
ρ	:	rock density [g/cm^3]
ρ_{fluid}	:	fluid density [g/cm^3]
η	:	viscosity of injection fluid [Pa·s]

Summary

During 31.7. to 2.8.2006, a total of 13 hydraulic- and hydrofrac tests were conducted in borehole H 405 between 488.5 m and 724 m depth in order to determine the rock mass permeability and to derive the in - situ stress regime at the Holford gas storage cavern site, Cheshire, UK. The in - situ tests in the 6-7/32 inch open-hole borehole sections were carried out by using the MeSy wireline approach, where the hydrofrac and impression packer tools equipped with TAM 5-½ inch packer elements were moved within the borehole via a 7-conductor wireline.

The test procedure at each test section consisted of an initial pressure - pulse test for permeability determination, the frac tests to initiate a hydraulic fracture, several fracture opening- and extension cycles, and a final step-rate test. The injection rate varied between 1 and app. 6 l/min. The injection fluid was saturated brine with a density of 1.2 g/cm^3.

The initial pressure pulse tests yield a near-wellbore permeability of 0.9 - 8.7 µDarcy (10^{-18} m^2) for the rock salt and 0.6 - 13.1 µDarcy for the marl formation. The values characterize the low permeable rock.

The hydrofrac tests demonstrate breakdown (fracture initiation) events at 11 test sections with breakdown pressure values between 24.7 - 36.4 MPa (two frac attempts were abandoned to prevent a packer damage at rather high injection pressure). Apparent fracture re-opening occurred at 15.7 - 24.8 MPa. Thus, the in-situ hydraulic tensile strength is 9.2 ± 3.2 MPa for the marl and 7.6 ± 0.5 MPa for the rock salt. After several fracture extension cycles, the shut-in pressure (fracture closure) are rather distinct and vary between 15.9 - 20.4 MPa. The low P_{si} - value at 660 m depth corresponds to the vertical stress S_v calculated for a mean overburden rock mass density of 2.49 g/cm^3 to 458 m depth and 2.21 g/cm^3 for the rock salt:

$$S_v \text{ [MPa]} = 11.2 + 0.0217 \cdot (z \text{ [m]} - 458).$$

All other P_{si} - values are 2.1 - 4.9 MPa larger than the vertical stress S_v.

Impression packer tests to determine the spatial orientation of induced fractures were conducted at 6 test sections in marl and at one test section in salt rock. All tests yield distinct vertical (axial) fracture traces with an average strike direction of NNW - SSE.

Since the derived minimum horizontal stresses S_h do not differ for the marl and rock salt and the data do not show a depth dependence below 600 m depth, the results may be summarized by:

S_h [MPa] = 16.8 ± 0.1 between 488.5 - 515 m depth and
S_h [MPa] = 19.4 ± 0.6 MPa between 604.5 - 724 m depth.

The maximum horizontal stress S_H was determined for the marl sections only with:

S_H [MPa] = 31.2 MPa at 488.5 and
S_H [MPa] = 35.0 ± 2.0 MPa between 604.5 - 724 m depth.

However, it has to be expressively mentioned, that due to the uncertainties of the refrac pressure, the estimation of the maximum horizontal stress has to be considered with care.

The results suggest a direction of the maximum horizontal stress S_H as N 165° ± 29°, in agreement with existing stress orientation data for the UK.

1. Introduction / Objective

Underground gas storage caverns were planned near Northwich / Cheshire in the Triassic Northwich Halite Formation at a depth of about 600 m below the Byley mudstones. For the cavern design and its operation both, permeability and stress data are required. Following a first project meeting on Geomechanical Borehole Testing at the University of Clausthal / Germany during 29./30.3.06, it was decided to carry out 8 extended permeability tests of 1 hour duration (7 tests in the Marl section, 1 test in the Salt section) and 12 hydrofrac tests (7 tests in the Marl section, 5 tests in the Salt formation including, permeability tests of about 10 minutes duration). The tests should be carried out in the cased section of the 6-7/32 inch diameter pilot hole of borehole H 405. According to this information MeSy submitted the proposal no. 03511.05A for hydraulic /hydrofrac testing for permeability and in-situ stress determination. For quality control of the in-situ stress data, it was also agreed to conduct hydrofrac related laboratory tests on the core material from both the Marl and the Salt formations which includes elasticity data, density, fracture toughness and laboratory hydrofrac tests under confining pressure.

Although drilling was considerably delayed, the MeSy in-situ test program could be started on 31.7.06 and could successfully be completed on 2.8.06. The present report is the Final Report volume I for the in-situ test campaign. The results of the laboratory tests and the quality control will be given in the Final Report volume II.

2. Location

The Holford cavern site at Byley is about 30 km south of Manchester and about 3 km north of the town Middlewich or about 6 km SE of the town of Northwich in Cheshire (Fig. 2.1). The Holford Gas Storage Project drilling site is given in Figure 2.2.

Figure 2.1	**Location of the Holford gas storage project site.**

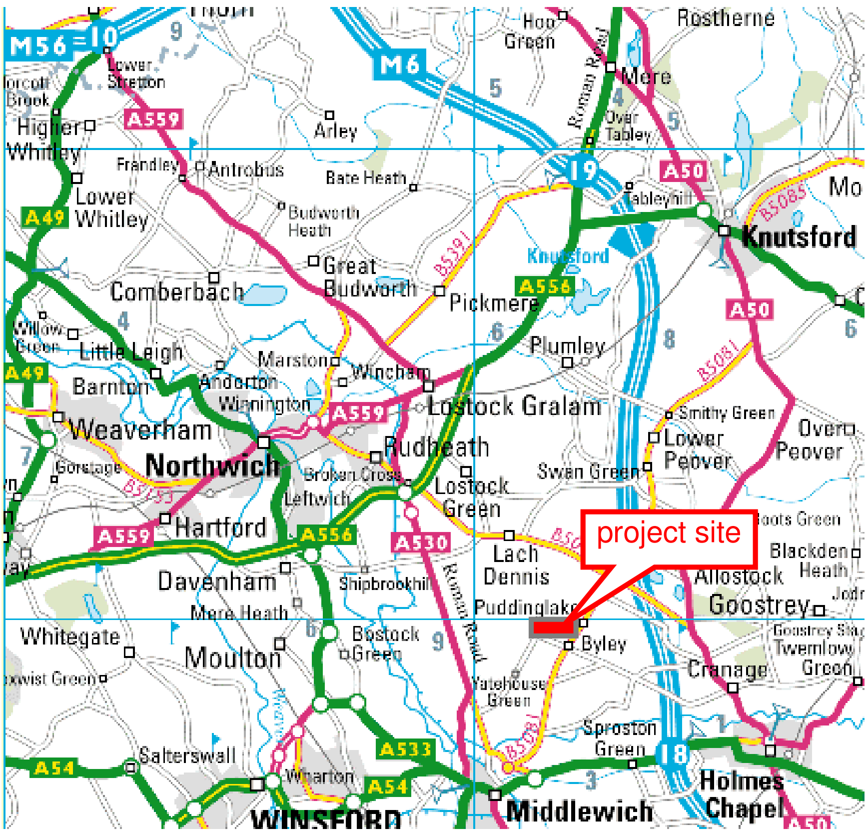
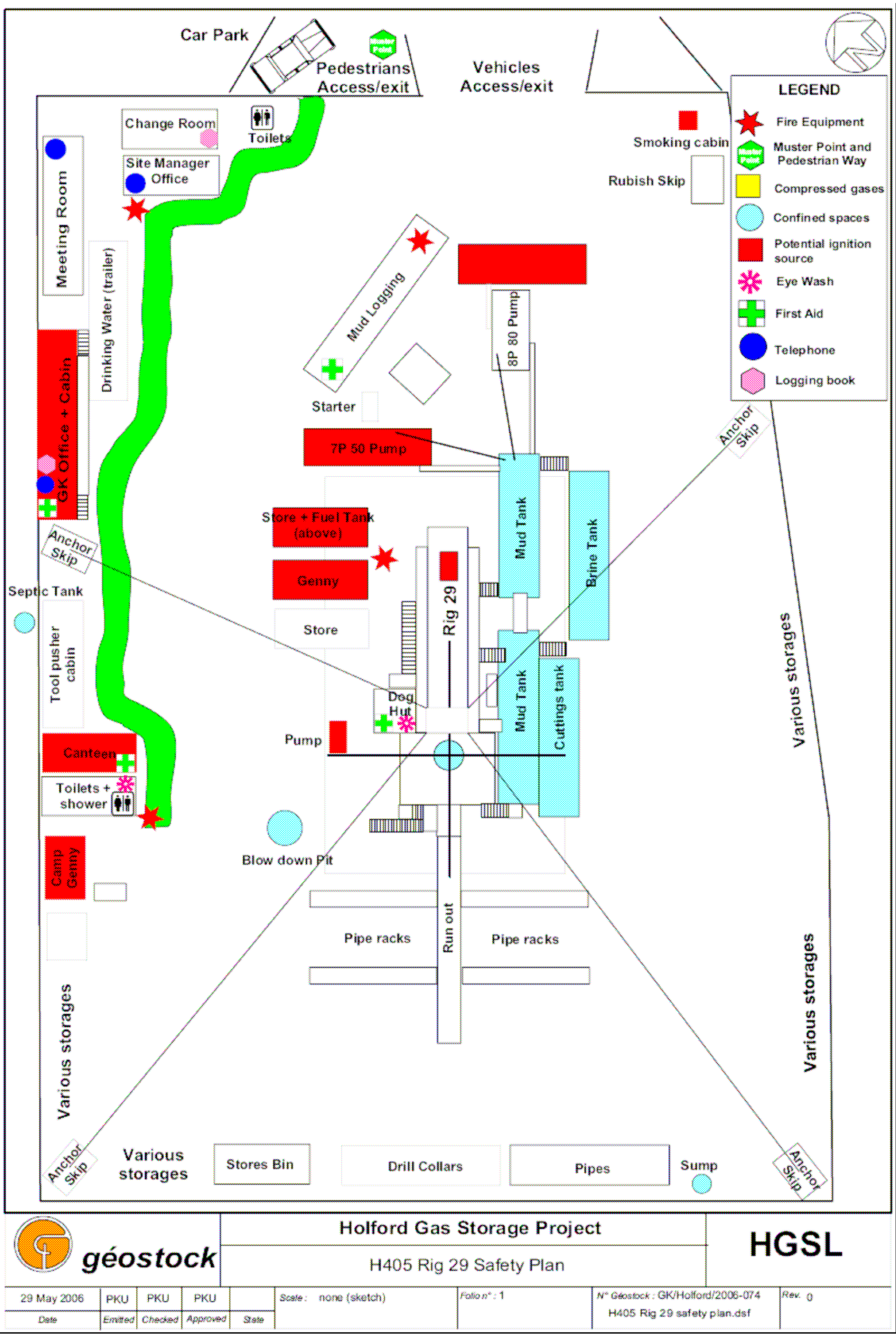


Figure 2.2	Holford gas storage project, drilling site H 405.



3. Borehole Characteristics

Drilling of borehole H 405 started early June 2006. The hole was deepened to about 480 m and then cased wit 18-5/8" OD / 17-¾" ID (451 mm) diameter casing with the casing shoe at 478.6 m depth (12.7.06). Then, the pilot hole was core-drilled in 6-7/32 inches diameter from 486 m (17.7.06) to final depth of 747.5 m (30.7.06). The hole inclination in the cored section was about 2 degrees from vertical. Drilling was conducted by the BDF (rig 29). During MeSy's testing (31.7. to 2.8.06) the hole was filled with brine with a density of about 1.3 g/cm^3. The top of the Northwich Halite formation was found at 458 m below ground level. At 713 m the hole penetrated into the Triassic Bollin Mudstone formation. The salt formation consisted partly of 98 % Halite, with Clay stone beds or patches and Anhydrite veins between. The mean rock salt density can be estimated as 2.21 g/cm^3, the density of the over-lying Marl formation can be estimated as 2.49 g/cm^3. The most relevant borehole data are summarized in Table 3.1.

Table 3.1 **Technical borehole data.**

location	Byley, Cheshire, UK
borehole denotation	H 405 (Holford 405)
geographical coordinates	N 53°13'17", W 2°26'17"
altitude (a.m.s.l.)	37.5 m
final borehole depth, b.g.l.	747.5 m
borehole diameter, inch (mm)	6-7/32 (158)
casing shoe depth, m	478.5
casing OD, inches	18-5/8
casing ID, mm	451
core diameter, mm	100
brine density, g/cm^3	≈ 1.3
geology	Byley Mudstone formation to 458 m Northwich Halite formation to 713 m below Bollin Mudstone formation
drilling contractor	BDF (rig 29)

4. Test Equipment, Test Procedures, Test Analysis

4.1 Test Equipment

The hydraulic / hydrofrac stress testing in borehole H 405 was conducted by the MeSy wireline testing technique using a logging winch to move the double straddle packer sonde within the borehole. The hydraulic connection between the surface pump and the downhole sonde consisted of a stainless steel coil tubing with a diameter of 10 mm OD / 8 mm ID. The system has a stiffness of about 10^{-11} m^3/Pa, which permitted accurate permeability testing. A schematic view of the test set-up is given in Figure 4.1. The test equipment used is listed as follows:

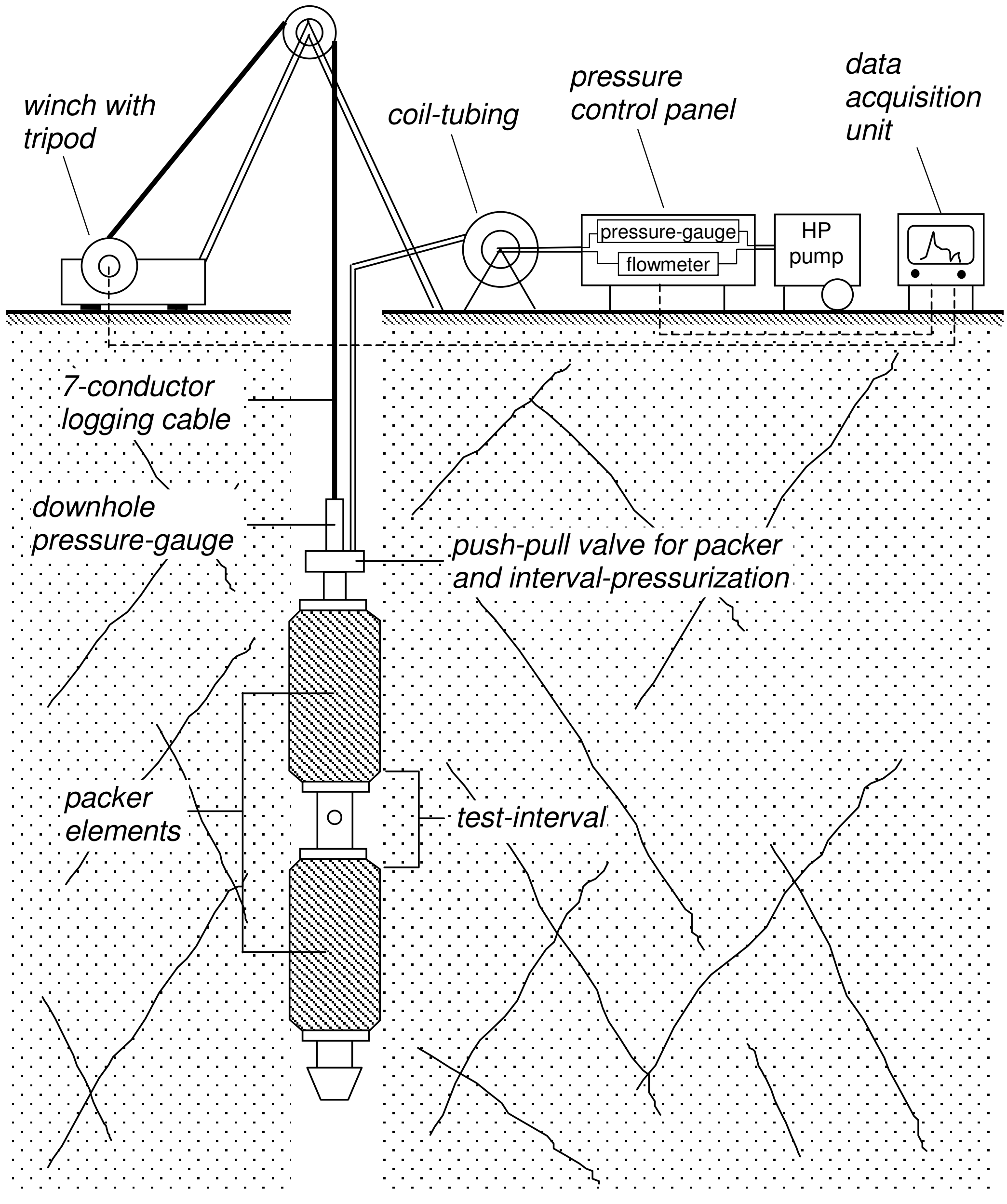
Downhole:

- 900 m stainless steel tubing OD 10 mm / ID 8 mm,
- double straddle packer sonde PERFRAC-140 equipped with 2 TAM packer elements of 5-½ inch diameter, sealing length: 1 m, test interval length: 1 m,
- 7 conductor logging cable type Rochester 7-H-314 A, OD 8.2 mm, GO type cable head OD 1-½ inch,
- pressure transducer type Keller PA-23, 40 MPa and resistance type thermometer,
- impression packer unit PERFRAC 140 equipped with 1 TAM packer element of 5-½ inch diameter and a magnetic single shot compass unit type Eastman-Whipstock RG.

Surface

- MeSy cable winch unit MKW-2000 (diesel-driven) on trailer incl. tripod,
- coil tubing drum, diameter 1.3 m,
- frequency controlled servo-electric high pressure pump type Speck HP 400/2-12 lpm, 3 x 380 VAC, 8 kW,
- pressure control unit with 1 pressure transducer, type Keller PA-23, manometers, and flow-meter type Unimess QPT-04, 0-10 l/min,
- digital data acquisition unit Delphin (24 bit, up to 100 Hz),
- MeSy field truck and van.

Figure 4.1	Schematic view of the wireline packer testing system



4.2 Test Procedures

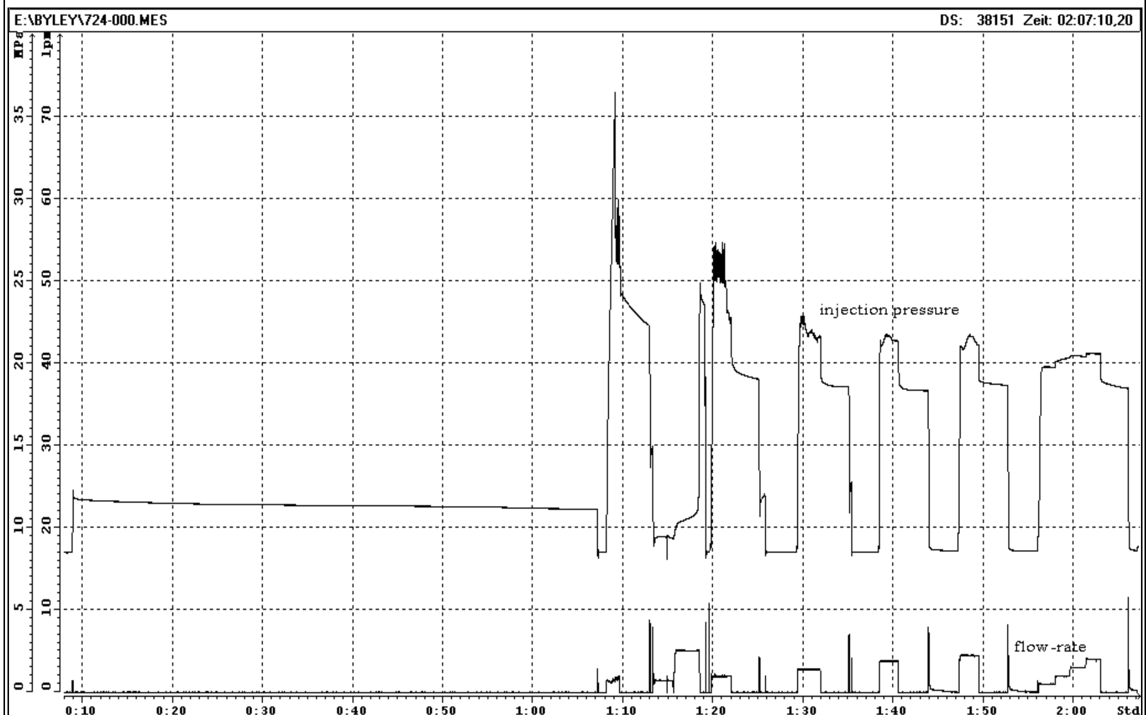
The in-situ tests in borehole H 405 were carried out during 31.7. to 2.8.06. A summary of the activities is given in Table 4.1 (details were already given in the Daily Operation Reports No. 1. to 3). A typical test record illustrating the test procedure is shown in Figure 4.2. Each test consisted of the following test cycles after inflating the packer elements to a differential pressure of about 10 MPa:

- rapid pressurization of the test interval to a differential pressure of about 2 to 4 MPa and subsequent monitoring of the pressure decline for app. 10 to 60 minutes (P-test in Fig. 4.2);
- release of the interval pressure and fluid recovery:
- pressurization of the test interval with an injection rate of 1 to 2 lpm until a drop interval pressure occurs or a constant injection pressure is reached (Frac (F) - test in Fig. 4.2); termination of injection and shut-in for about 3 minutes;
- release of the interval pressure and fluid recovery;
- re-pressurization of the test interval with injection rates of 2 to 6 lpm (increasing order) until constant injection pressure is reached (Refrac (RF) - test in Fig. 4.2); termination of injection and shut-in for about 3 minutes;
- release of the interval pressure and fluid recovery;
- several repetitions of the refrac-cycle until reproducible shut-in pressures are observed;
- stepwise increase of the injection flow-rate and observation of the corresponding injection pressure (Slow-Pump / Step Rate (SP/SR) - test Fig. 4.2);
- release of the interval pressure and fluid recovery;
- packer deflation and movement to the next test section;

Impression packer tests at the different test sections consisted of an inflation of the single packer element to a pressure app. 20 % above the fracture re-opening pressure of a period of about 10 minutes. After tool recovery to surface the impression and the position of a reference mark were transferred on a plastic cover sheet wrapped around the packer (Fig. 4.3). The film disc of the single - shot unit was developed documenting the orientation of the reference mark with respect to magnetic North.

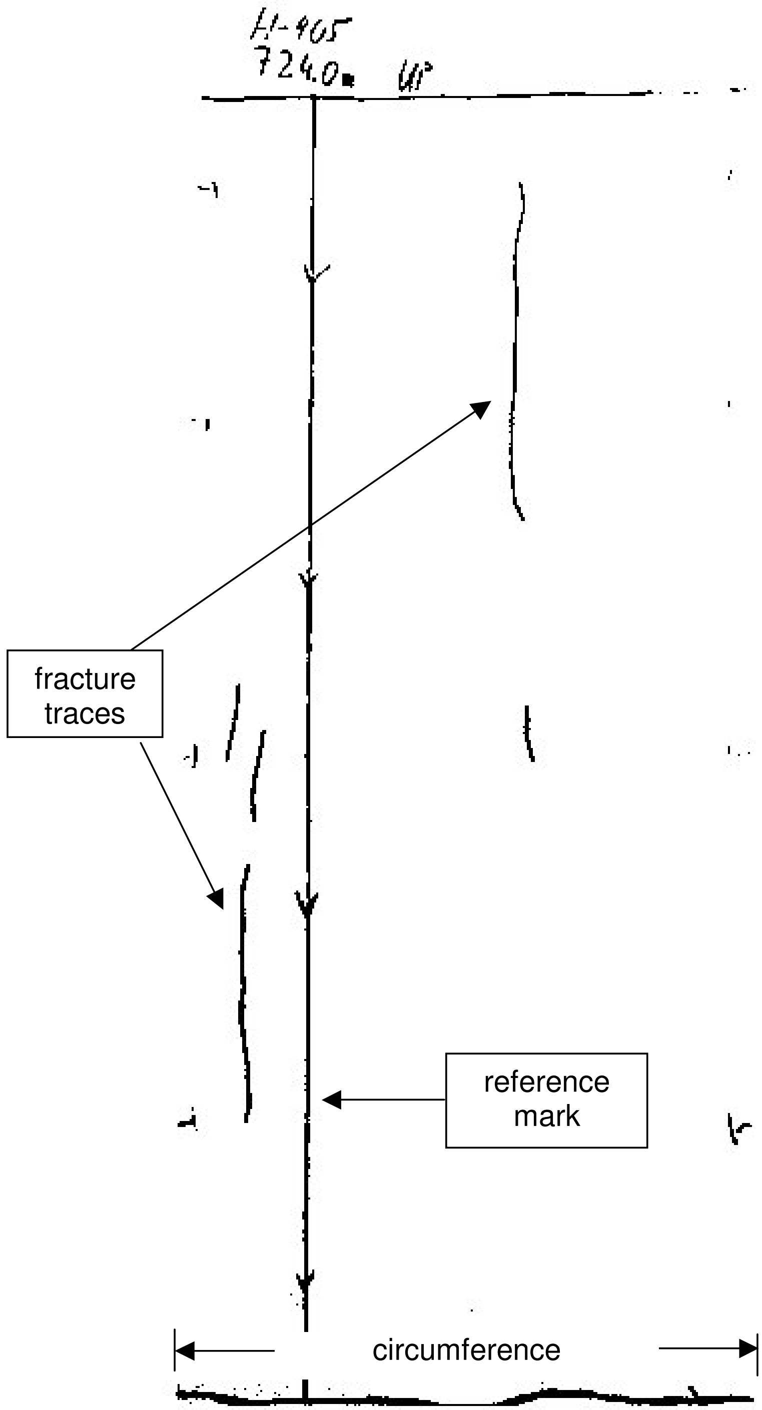
Table 4.1	Test Operation Summary
Date	Activity
June/July	preparation of test equipment and stand-by for casing completion in borehole H 405,
28.7.06	mobilization of test equipment and 4 engineers from Bochum to Rotterdam for ferry to Hull,
29.7.06	continue mobilization from Hull to Holford Gas Storage project site at Byley,
30.7.06	safety instruction, discussion of test program and time schedule, stand-by until 31.7.06 for logging completion,
31.7.06	test sections selection with Geostock, set-up of winch system and packer sonde, dummy run to 740 m depth, first-trip down of packer sonde with problems to enter 6-7/32" open-hole section due to clay particles on the packer pressure release valve (19.00), trip-down to 724 m (22.00),
1.8.06	conduction of 13 tests at 724 m, 717.5 m, 700 m, 677 m, 673.5 m, 660 m, 675 m, 648 m, 637 m, 625 m, 604.5 m, 515 m, 488.5 m, POOH at 0.00,
2.8.06	conduction of 7 impression packer tests at 604.5 m, 625 m, 637 m, 675 m, 717.5 m, 724 m, 488.5 m, POOH (20.40), rig-down equipment and loading (22.30),
3./4.8.06	demobilization of equipment and personnel from Holford project site to Bochum via Hull/Rotterdam, departure Byley 3.8.06, 8.00, arrival Bochum 4.8.06, 12.00,
5./6.8.06	unloading and post-preparation of equipment.

Figure 4.2	**Downhole injection pressure and surface flow-rate record of the hydrofrac test at 724.0 m depth**



P-Test F 1.RF 2.RF 3.RF 4.RF SP/SR-Test

Figure 4.3	Fracture traces of the impression packer test at 724.0 m depth. The circumference of the packer is approximately 465 mm, the length is approximately 1000 mm.



4.3 Data Analysis

4.3.1 Pressure Pulse Tests

Rock permeability can be derived from so-called pressure-pulse tests where the pressure in the test interval between the packers is instantaneously increased to a differential dP, then the hydraulic system is shut-in, and the subsequent pressure fall-off is observed over an adequate time (10 min, 1 hour).

For the case of a pressurized borehole of radius R and radial fluid flow into the rock formation around the borehole, the diffusion equation can be written in the form:

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r} - \frac{1}{\lambda}\frac{\partial p}{\partial t} = 0$$

where p is the fluid pressure within the rock at distance r and time t, and λ is the diffusivity which is related to the rock permeability K, the fluid viscosity η and the formation storage capacity S. A solution of the problem is presented in the classical approach suggested by Cooper et al. (1967) for the analysis of conventional slug tests. For the analysis of pulse tests with a hydraulic system of high stiffness, MeSy has developed the software code PERM which allows matching numerically calculated pressure-fall-off curves with the observed pressure decline curves. The matching is carried out by using an inversion technique (master curve method) for model calculations with a variety of input values for hydraulic transmissivities and storage coefficients. The results are given as the average of all models which satisfy the linear error regression analysis standard. The results are then presented as permeability K or as hydraulic conductivity k:

$$k = K \cdot \frac{\rho \cdot g}{\eta}$$

where ρ is the fluid density and η is the fluid viscosity.

4.3.2 Hydrofrac Tests

The stress evaluation by hydraulic fracturing is based on the Kirsch solution (Kirsch 1898) for the stress distribution around a cylindrical hole subjected to far-field stresses S. In the case where the borehole is vertical and parallel to the overburden stress S_v, and vertical fractures are induced, the classical Hubbert and Willis approach (1957) can be used which relates the measured characteristic pressure values P_c (breakdown pressure at frac initiation), the refrac pressure P_r for fracture re-opening, during the refrac cycles, and the shut-in pressure P_{si} at fracture closure with the two principal horizontal stresses S_h and S_H ($S_h < S_H$):

$$P_c = 3 \cdot S_h - S_H + P_{co} - P_p$$
$$P_{si} = S_h$$
$$P_{co} = P_c - P_r$$
$$P_r = 3 \cdot S_h - S_H - P_p$$

where P_{co} is the in-situ hydraulic tensile rock strength and P_p is the formation pore pressure. The vertical stress S_v can be taken as

$$S_v = g \cdot \int_0^z \rho \cdot dz$$

where ρ is the density of the overburden rock.

In the case of a salt formation the value of P_p can be neglected. Thus, the horizontal principal stresses can easily be determined using the measured characteristic pressure values P_c, P_r and P_{si}. These values are derived from the test records of the different hydrofrac test cycles by an extensive analysis using the MeSy interactive graphical program package GEOCALC in the following manner:

- P_c is defined as the maximum pressure observed from the first frac cycle, and is determined from a detailed P versus t plot.

- P_r is determined by the consideration of the change of the system stiffness dP/dV during the re-pressurization of the test interval. Fracture opening is correlated with a significant deviation of the hydraulic stiffness from linearity.

- P_{si} values are determined by the following three-step procedure:
  - A plot P versus injection flow-rate Q allows to determine the exact pressure value at the moment Q = O (shut-in). Therefore, the P versus Q plot yields an upper limit estimate for P_{si}.
  - A Muskat-type plot of the logarithm of the difference between the pressure P and an asymptotic pressure level P_a versus time t yields the lower limit of the P_{si} - value, assuming that the linear part of the plot characterizes radial flow, i.e. the stimulated fracture is nearly closed.

- Within the 2 limits of the shut-in pressure, the realistic estimate for the acting normal stress across the fracture plane corresponds to the pressure acting during transition from a rapid linear pressure drop to a diffusion-dominated pressure decrease in a detailed P vs. t plot (tangent method).

- The final step-rate test again yields a reliable P_{si} at shut-in after a larger quantity of fluid has been injected into the stimulated fracture.

5. Test Results

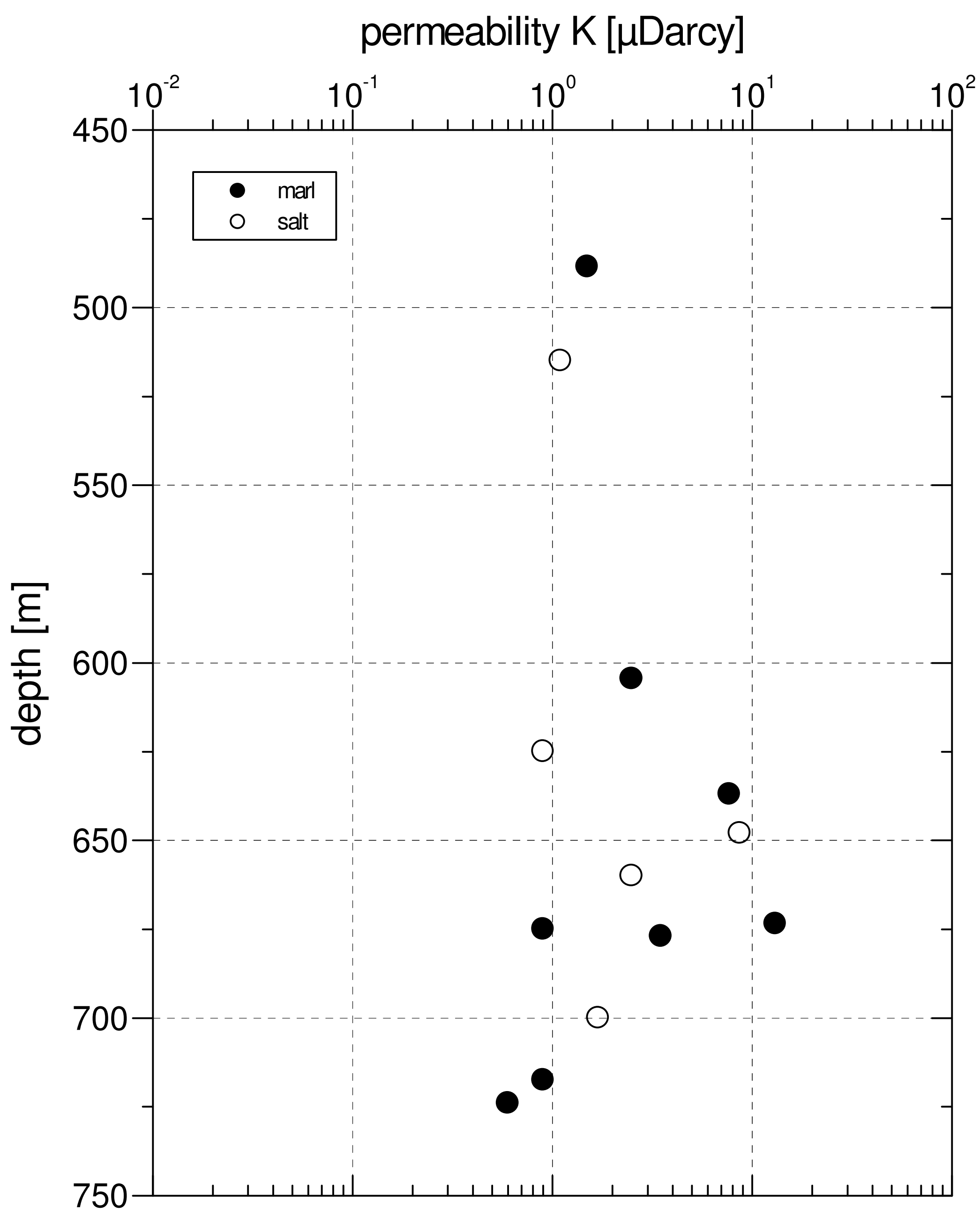
5.1 Results of Pressure Pulse Tests

The test records of the pressure pulse tests are given in the overview plots in Appendix A, the analysis of the tests is presented in Appendix B. The test results are summarized in Table 5.1 as permeability data K (in µDarcy = 10^{-18} m^2) and as hydraulic conductivity k. The data are shown in Figure 5.1 as a function of depth.

Although some of the tests exhibited a minor pressure increase during the shut-in phase (tests at 488.5 m, 604.5 m, 675 m, 677 m, 717.5 m) and two tests showed a stepwise pressure decrease (625 m, 637 m), the analysis yield reliable permeability values of 0.9 - 8.7 µDarcy within the salt sections and 0.6 - 13.1 µDarcy for the marl sections. In particular, the test sections at 604.5 m and 677 m depth with vertical fractures visible in the core material, gave no indication of open fractures with higher permeability.

Table 5.1	Result of pressure pulse tests in borehole H405				
test no.	depth m	lithology	permeability K µDarcy = 10^{-18} m^2	conductivity k m/s	remark
13	488.5	marl	1.5 ± 0	$1.8 \cdot 10^{-11}$	pressure drop during the first 17 min. analyzed
12	515.0	salt	1.1 ± 0.1	$(1.4 \pm 0.1) \cdot 10^{-11}$	
11	604.5	marl	2.5 ± 0.1	$(3.0 \pm 0.1) \cdot 10^{-11}$	pressure drop during the first 10 min. analyzed
10	625.0	salt	0.9 ± 0 *(1.5 ± 0)*	$1.0 \cdot 10^{-11}$ *$1.8 \cdot 10^{-11}$*	pressure drop during the whole test for the first 13 min. only
9	637.0	marl	7.7 ± 0.2 *(9.8 ± 0.2)*	$(9.3 \pm 0.2) \cdot 10^{-11}$ *$1.2 \cdot 10^{-10}$*	pressure drop during the whole test for the first 9 min. only
8	648.0	salt	8.7 ± 0.3	$1.0 \cdot 10^{-10}$	
6	660.0	salt	2.5 ± 0.1	$(3.0 \pm 0.1) \cdot 10^{-11}$	
5	673.5	marl	13.1 ± 0.1	$1.6 \cdot 10^{-10}$	
7	675.0	marl	0.9 ± 0	$1.1 \cdot 10^{-11}$	pressure drop during the first 50 min. analyzed
4	677.0	marl	3.5 ± 0.1	$(4.2 \pm 0.2) \cdot 10^{-11}$	pressure drop during the first 2 min. analyzed
3	700.0	salt	1.7 ± 0	$2.0 \cdot 10^{-11}$	
2	717.5	marl	0.9 ± 0	$1.1 \cdot 10^{-11}$	pressure drop during the first 19.4 min. analyzed
1	724.0	marl	0.6 ± 0	$(6.7 \pm 0.2) \cdot 10^{-12}$	

Figure 5.1	Hydraulic permeability derived from pressure pulse tests in borehole H 405



5.2 Hydrofrac Test Data and Stress Estimation

A total of 13 hydrofrac tests and 7 impression packer tests were conducted in borehole H 405 between 488.5 m and 724.0 m depth. Overview - plots of the test records together with remarks about the test conduction and the data analysis are given in Appendix A, whereas copies of the fracture traces observed during impression packer testing are given in Appendix C. The derived characteristic hydrofrac pressure data (breakdown pressure P_c at fracture initiation, fracture re-opening pressure P_r, shut-in pressure P_{si}, and the resulting in - situ tensile strength $P_{co} = P_c - P_r$) as well as the results of the impression packer tests (fracture strike direction θ, dip direction β, dip α) are summarized in Table 5.2 and are shown graphically in Figures 5.2 to 5.6. The pressure data are listed as downhole values, and fracture orientation data are given with respect to magnetic north. Table 5.2 also contains information on the injected and recovered fluid volumes.

The 13 hydrofrac tests resulted in 11 distinct breakdown events, while the tests at 673.5 m and 677 m depth were abandoned at injection pressures of 37.5 MPa and 39.1 MPa to prevent a damage of the packer elements.

At most of the test sections, the refrac pressure was difficult to identify. Fracture opening often is characterized by a first decrease of the system stiffness at low pressure, followed by a pressure increase at a lower stiffness or by a continuous decrease of the stiffness during pressurization. Furthermore, subsequent refrac cycles yield decreasing fracture re-opening pressure values, indicating that the fracture was not fully closed at the borehole wall.

Nevertheless, the resulting in-situ tensile strength amounts to $P_{co} = 9.2 \pm 3.2$ MPa for the marl and $P_{co} = 7.6 \pm 0.5$ MPa for the salt formation. The high P_{co} - values characterize rather "intact" rock (a detailed discussion of the hydraulic tensile strength will be presented in the Final Report volume II: hydrofrac relevant laboratory tests on the core material).

In contrary to the fracture re-opening pressure, all the tests yield distinct and reliable shut-in pressure values, which are determined from the last injection cycles. Since the fracture has extended in length during the successive injection cycles, the shut-in pressure exhibited some decrease before corresponding ultimately to the far-field stress conditions. However, a significant decrease of the shut-in pressure was observed during the test at 660 m depth, indicating a rotation of the stimulated fracture into the horizontal plane (P_{si} corresponds to the vertical stress S_v). Apart from the test at 660 m depth, the shut-in pressure values do not correspond to the vertical stress calculated for a mean overburden rock mass density of 2.49 g/cm^3 to 458 m depth and 2.21 g/cm^3 within the salt formation.

The spatial orientation of the initiated fractures by impression packer tests were determined for the 6 complete tests in the marl formation and for one test in the salt. In all tests, the imprints of the fracture traces are rather distinct. The test analysis yield mainly vertical (axial) double traces with a fracture strike direction between NW - SE to NNE - SSW. It is interesting to note that the test in salt at 625 m depth confirmed the results of the other tests in the marl formation (with the exception that only axial single traces were observed).

Table 5.2 **Results of hydraulic fracturing tests in borehole H 405 (V_i: injected fluid volume, V_r: recovered fluid volume, P_c: breakdown - pressure, P_r : refrac - pressure, P_{co} : hydraulic tensile strength, P_{si} : shut - in pressure, θ : fracture strike direction (North over East), β : dip direction (North over East), α : dip (with respect to horizontal).**

test no.	depth m	litho-logy	V_i l	V_r l	P_c MPa	P_r MPa	P_{co} MPa	P_{si} MPa	frac trace	θ deg.	β deg.	α deg.	remark
13	488.5	marl	49.3	13.3	25.1	18.9	6.2	16.7	A B	146 17	56 / 236 287	90 64	axial double trace, distinct inclined fracture without tips, not unambiguous
12	515.0	salt	56.8	20.4	24.7	15.7 - 17.95 <16.8>	6.75 - 9.0 <7.9>	16.8					no impression packer test conducted
11	604.5	marl	53.6	4.6	30.7	(19.0) - 23.5	7.2	19.0	A	159	69 / 249	90	axial double trace, distinct decrease of P_{si} from 22.8 to 20.0 MPa between 1.RF and 2. RF
10	625.0	salt	38.6	13.8	27.8-28.1	20.0	7.8 - 8.1 <7.95>	18.6	A	33-50	123-140 / 303-320	90	axial single trace, distinct
									B	179	89 / 269	90	short axial single trace, distinct
9	637.0	marl	38.6	6.1	27.5	(16.8) - 20.5	7.0	19.6	A	154	64 / 244	90	axial double trace, distinct
8	648.0	salt	36.6	7.3	26.1	18.1 - 19.9 <19.0>	6.2 - 8.0 <7.1>	20.2					no impression packer test conducted
6	660.0	salt	36.9	5.5	(21.7) / 27.7	18.8 - 22.8 <20.8>	4.9 - 8.9 <6.9>	15.9					no impression packer test conducted decrease of P_{si} from 21 to 15.9 MPa between 2.RF and 4.RF

Table 5.2	Results of hydraulic fracturing tests in borehole H 405 (V_i: injected fluid volume, V_r: recovered fluid volume, P_c: breakdown - pressure, P_r : refrac - pressure, P_{co} : hydraulic tensile strength, P_{si} : shut - in pressure, θ : fracture strike direction (North over East), β : dip direction (North over East), α : dip (with respect to horizontal).												
test no.	depth m	litho-logy	V_i l	V_r l	P_c MPa	P_r MPa	P_{co} MPa	P_{si} MPa	frac trace	θ deg.	β deg.	α deg.	remark
5	673.5	marl			> 39.1								no fracture initiation achieved
7	675.0	marl	48.5	4.3	36.2	23.3	12.9	18.95	A B	121 69	31 / 211 159 / 339	90 90	axial double trace, distinct axial single trace, distinct decrease of P_{si} from 24.4 to 18.95 MPa between 1.RF and 2.RF
4	677.0	marl			>37.55								no fracture initiation achieved
3	700.0	salt	46.3	26.1	27.9	(17.0) - 19.85	8.05	20.4					no impression packer test conducted
2	717.5	marl	54.7	20.9	30.9	22.4	8.5	19.3	A	13	103 / 283	90	axial double trace, distinct
1	724.0	marl	49.0	4.8	36.4	21.2 - 24.8 <23.0>	11.6 - 15.2 <13.4>	19.1	A	26	116 / 296	90	axial double trace, distinct
	mean *mean*	*marl* *salt*					*9.2 ± 3.2* *7.6 ± 0.5*						

< > : mean value

Figure 5.2	Breakdown - pressure P_c derived from hydrofrac tests in borehole H 405.

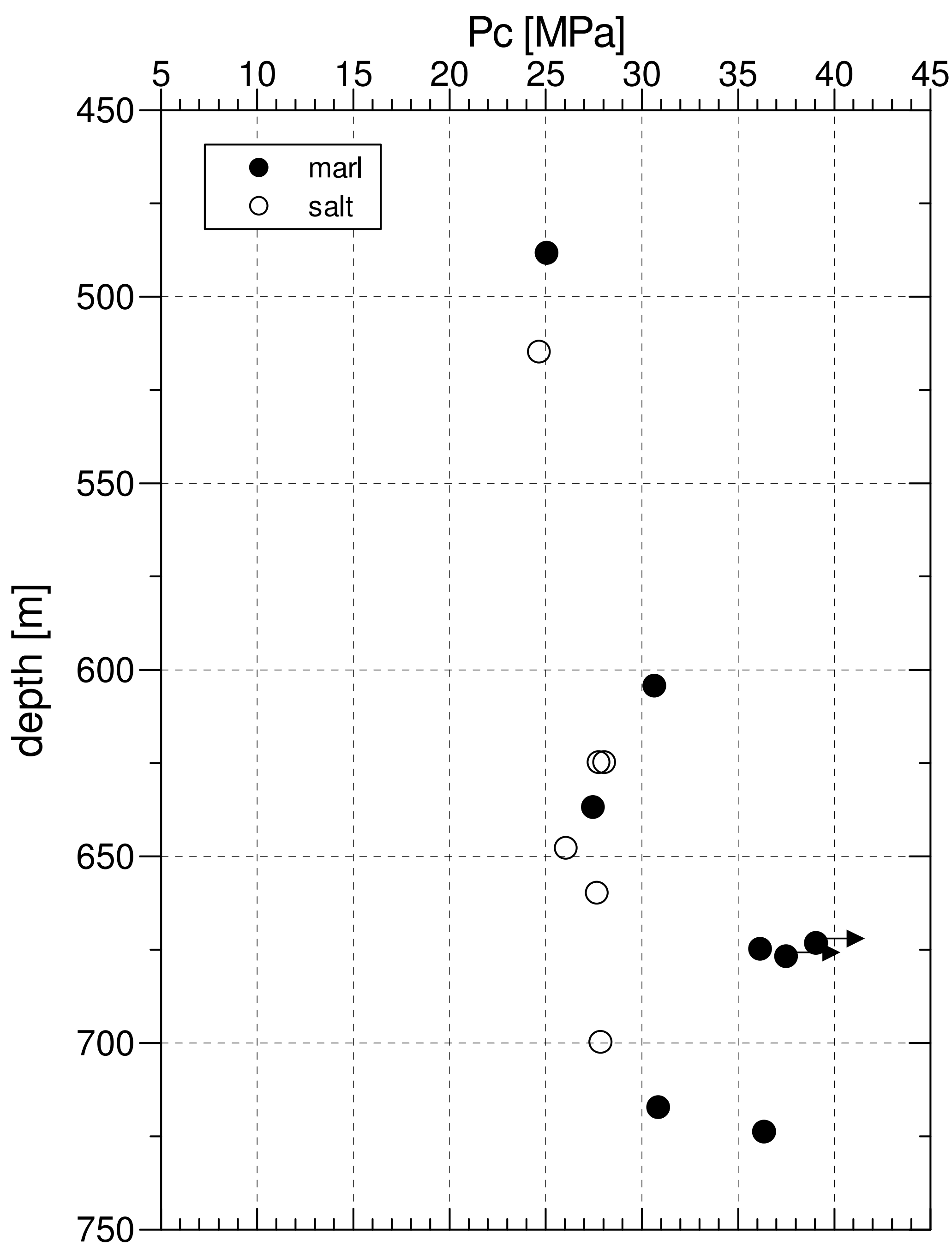


Figure 5.3	Refrac - pressure P_r derived from hydrofrac tests in borehole H 405.

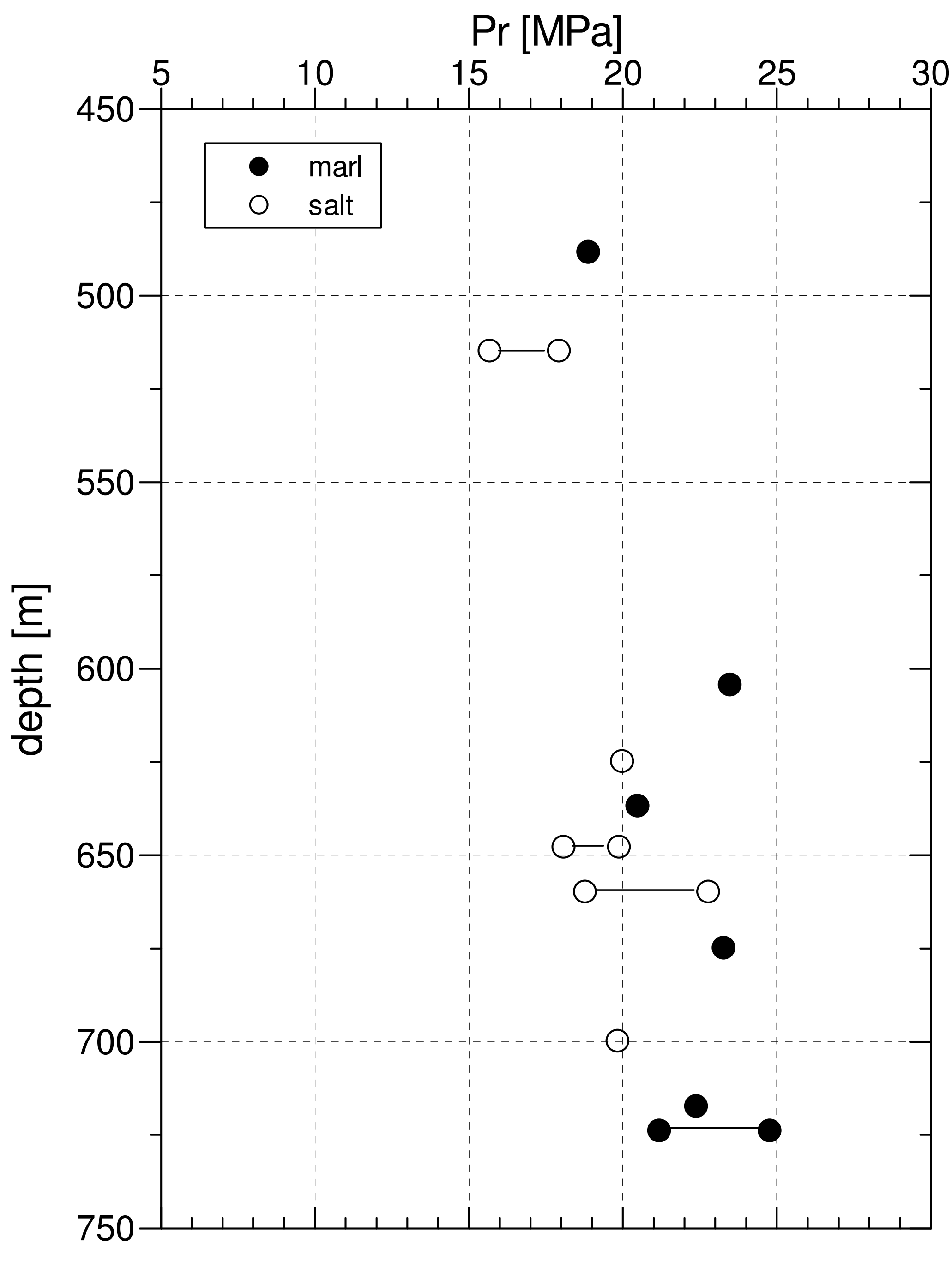


Figure 5.4	Shut-in - pressure P_{si} derived from hydrofrac tests in borehole H 405.

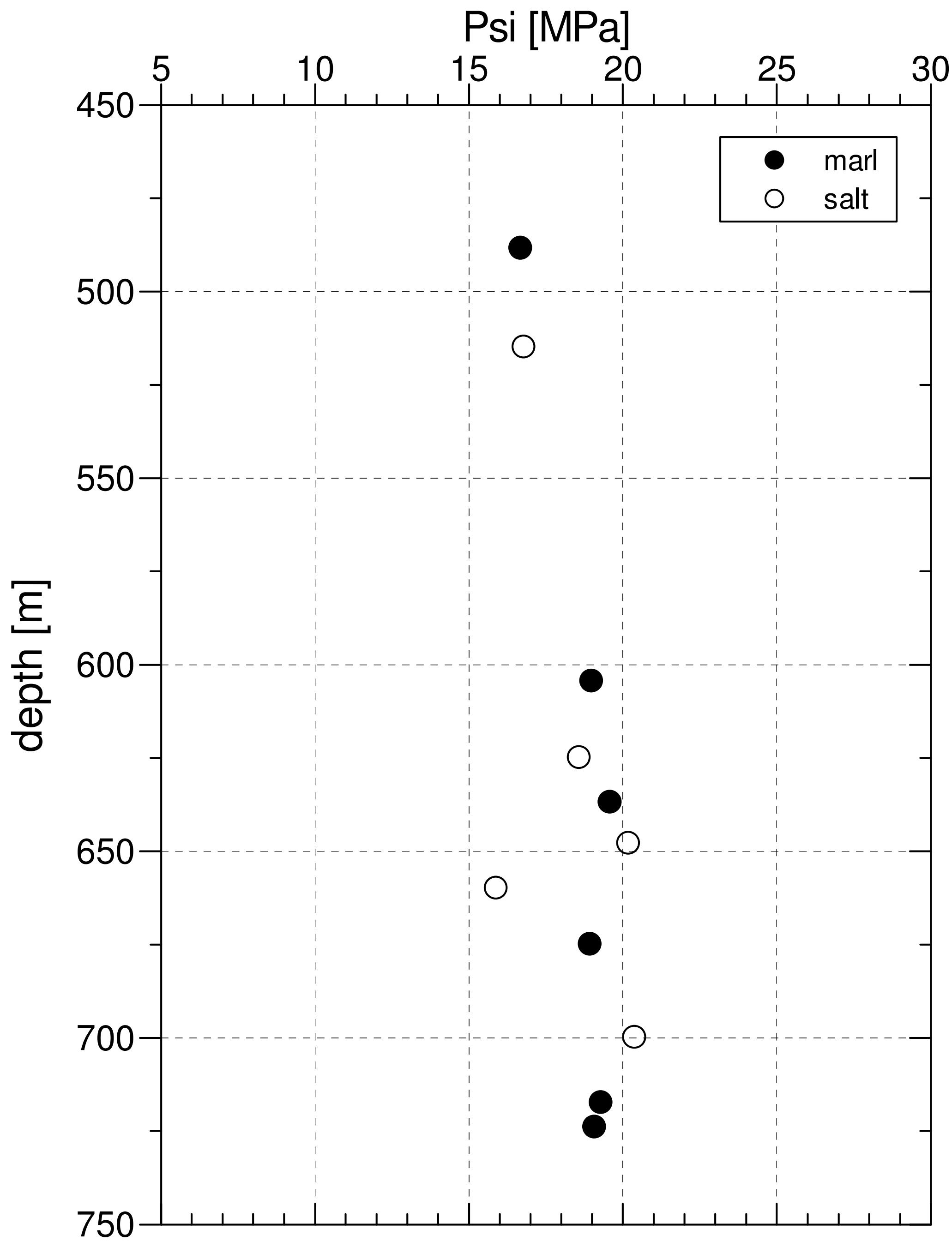


Figure 5.5	Orientation of initiated fractures derived from impression packer tests in borehole H 405.

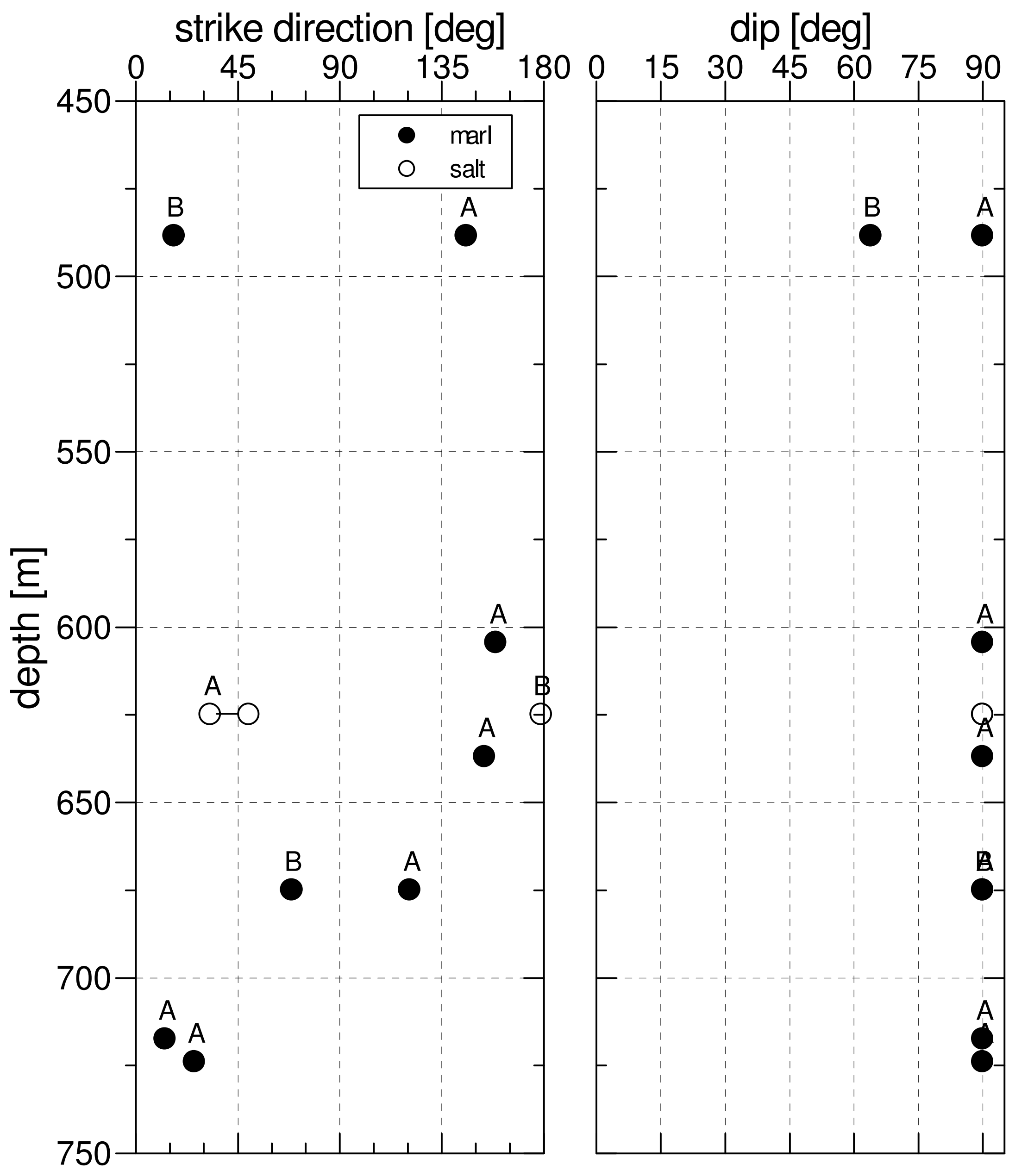
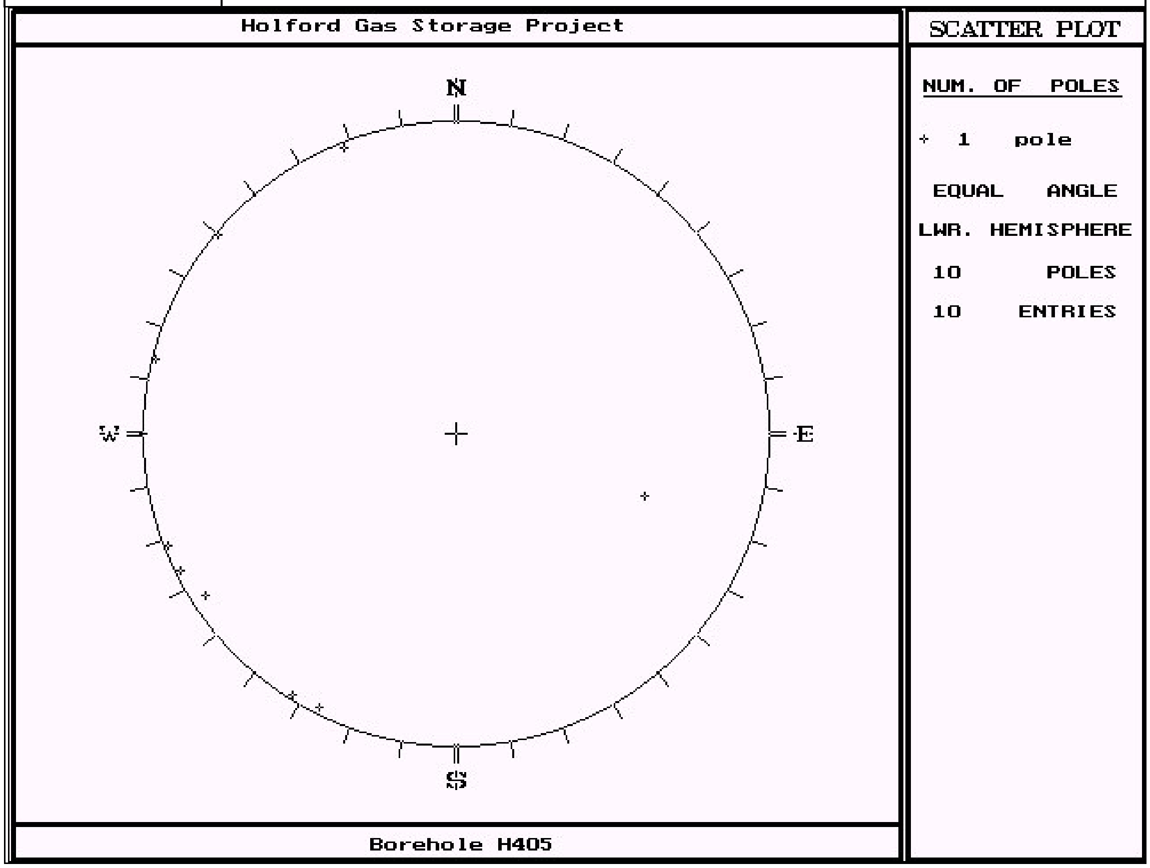


Figure 5.6	**Orientation of initiated fractures derived from impression packer tests in borehole H 405.**



Thus, the stress estimation was carried out on the basis of the Hubbert and Willis (1957) concept (chap. 4.3.2). The results of the calculations are summarized in Table 5.3 and are shown graphically in Figure 5.7. It has to be noted that the Bredehoeft et al. (1976) approach to determine the maximum horizontal stress

$$S_H = 3 \cdot S_h - P_r$$

was used and the pore pressure was neglected. The justification for this assumption is the low permeability of the rock. On the other hand, the resulting values of S_H has to be considered with care (and therefore are printed in Italic in Tab. 5.3) due to the reliability of the refrac pressure in case of fluid penetration into the fracture prior to fracture opening (although the Hubbert and Willis approach is widely used, this subject is still controversially discussed (Ito et al., 1999, Rutquist et al., 2000)). In addition, the resulting high horizontal stress anisotropy is difficult to understand, particular for the salt formation.

Nevertheless, the results do not differ for the marl and rock salt formation and do not show a significant depth dependence below app. 600 m. Therefore, the resulting horizontal stresses may be summarized by the following mean values:

depth range m	S_h MPa	S_H MPa ***only for marl***
488.5 - 515	16.8 ± 0.1	31.2
604.5 - 724	19.4 ± 0.6	35.0 ± 2.0

The results yield a direction of the maximum horizontal stress S_H of N 165° ± 29° (NNW - SSE).

The vertical stress S_v was calculated for an average overburden rock mass density of 2.49 g/cm^3 to 458 m depth and 2.21 g/cm^3 for the rock salt below:

$$S_v \text{ [MPa]} = 11.2 + 0.0217 \cdot (z \text{ [m]} - 458).$$

where z is the depth in meter.

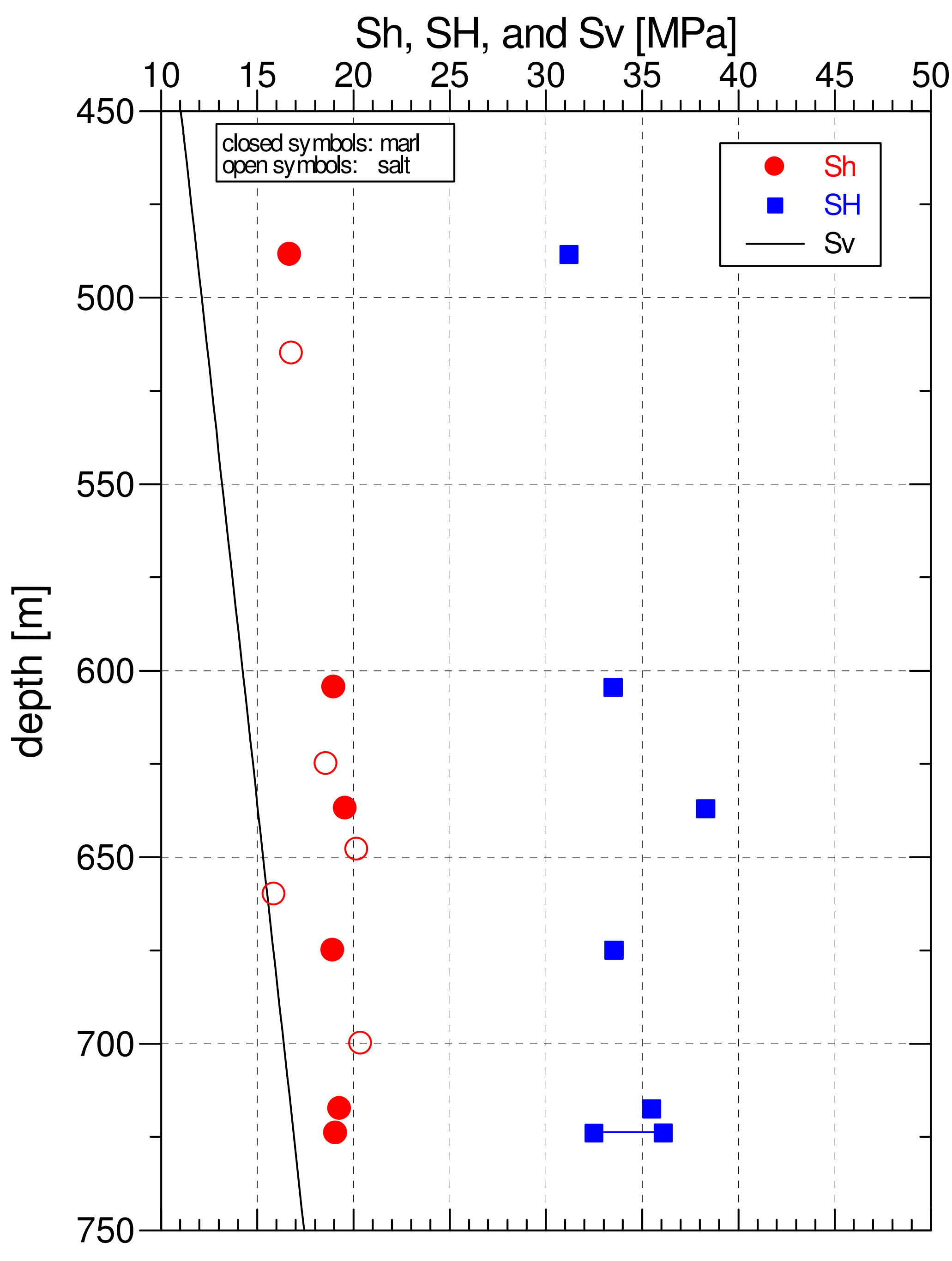
The shut-in pressure of the test at 660 m depth, which indicates a rotation of the stimulated fracture into the horizontal plane, is in close agreement with the estimation of the vertical stress S_v.

Table 5.3 **Result of stress evaluation using the Hubbert and Willis (1957) approach for borehole H 405. The vertical stress S_v was calculated for an average overburden rock mass density of 2.49 g/cm^3 to 458 m depth and 2.21 g/cm^3 within the salt formation below. θ_{SH} denote the strike direction of the maximum horizontal stress S_H.**

test no.	depth m	lithology	S_v MPa	S_h MPa	S_H MPa	θ_{SH} deg.
13	488.5	marl	11.8	16.7	*31.2*	N 146
12	515.0	salt	12.4	16.8	*32.45-34.7* *<33.6>*	
11	604.5	marl	14.4	19.0	*33.5*	N 159
10	625.0	salt	14.8	18.6	*35.8*	N 179 (N 33-50)
9	637.0	marl	15.0	19.6	*38.3*	N 154
8	648.0	salt	15.3	20.2	*40.7 - 42.5* *<41.6>*	
6	660.0	salt	15.6	15.9 **= S_v**		
7	675.0	marl	15.9	18.95	*33.55*	N 121
3	700.0	salt	16.4	20.4	*41.35*	
2	717.5	marl	16.8	19.3	*35.5*	N 13
1	724.0	marl	17.0	19.1	*32.5 - 36.1* *<34.3>*	N 25
						N 165 ± 29

< > mean value

Figure 5.7	Principal stresses for borehole H 405. The maximum horizontal stress S_H is only plotted for the marl formation



5.3 Summary and Discussion of Results

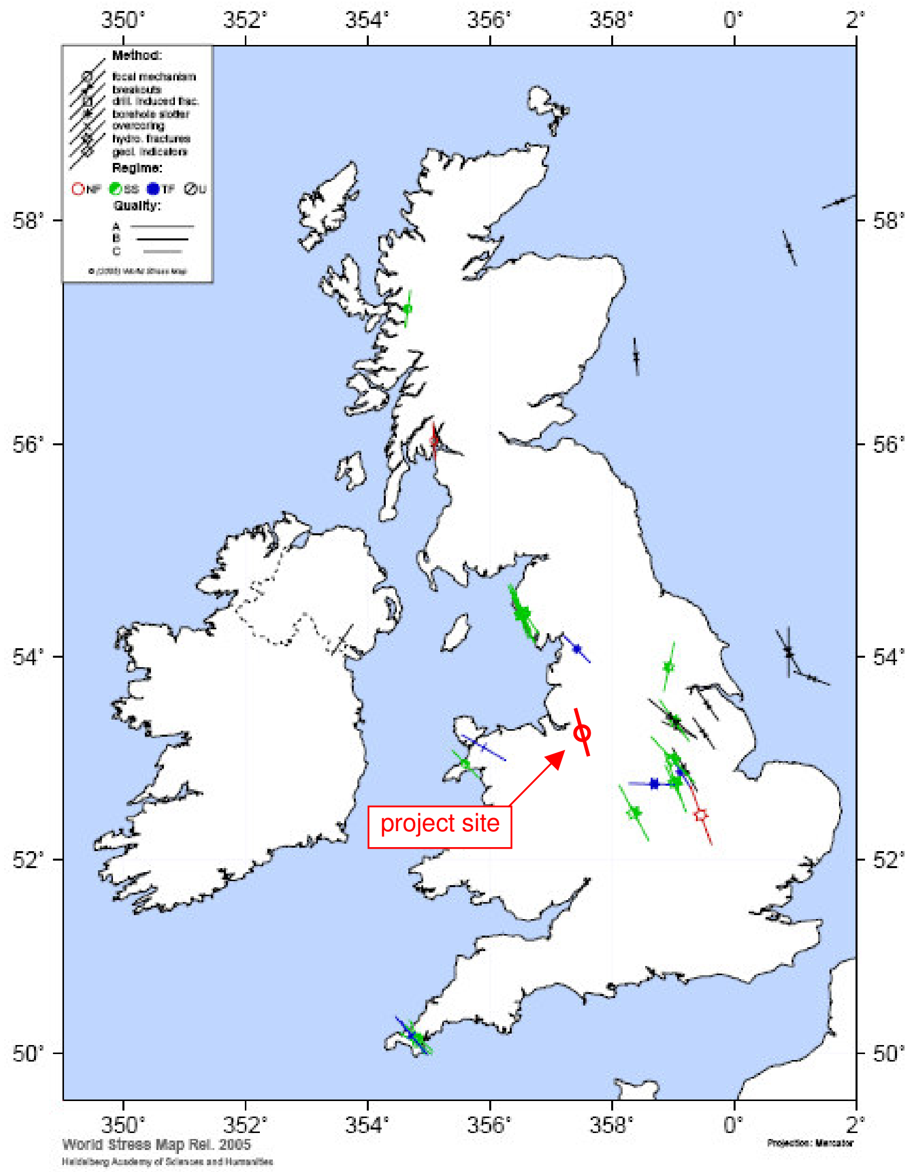
A total of 13 hydraulic permeability and hydrofrac stress measurements were conducted in the un-cased section of borehole H 405 between 488.5 m and 724 m depth.

The initial pressure pulse tests yield a near-wellbore rock permeability of 0.9 - 8.7 µDarcy (10^{-18} m^2) for the rock salt and 0.6 - 13.1 µDarcy for the marl. The values characterizes the low permeable rock mass. In particular the test results at 604.5 m and 677 m depth, where vertical fractures are observed in the rock core material, gave no hint of borehole sections with higher permeability.

During hydro-fracturing, breakdown of the marl - and salt formation required fluid pressures between 24.7 MPa and 36.4 MPa. The distinct fracture closure (shut-in) allows to estimate the minimum horizontal stress S_h, which is 2.1 - 4.9 MPa larger than the vertical stress S_v calculated for a mean overburden rock mass density of 2.49 g/cm^3 to 458 m depth and 2.21 g/cm^3 for the rock salt. Similar high minimum horizontal stresses were observed also in other layered salt formations in the UK, while stress measurements in a salt dome in Northwestern-Germany suggest lithostatic stress conditions (Rummel et al., 1996).

Due to the uncertainties of the refrac pressure, the estimated maximum horizontal stress S_H has to be considered with care. However, the consistent orientation of induced fractures of N 165° ± 29° (the scatter is mainly induced by the two tests at 717.5 m and 724 m depth with a NNE - SSW orientation of the initiated fractures) suggest anisotropic horizontal stresses and a NNW - S SE direction of S_H. The tectonic compression direction is in agreement with existing stress data for the UK as shown in Figure 5.8.

Figure 5.8	Orientation of the maximum horizontal stress S_H in Great Britain and Ireland (Reinecker et al., 2005).



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7. Acknowledgement

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