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Äspö Hard Rock Laboratory

Rock stress measurements at the Äspö HRL

Hydraulic fracturing in boreholes KA2599G01 and KF0093A01

Gerd Klee
Fritz Rummel

MeSy

January 2002

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel +46 8 459 84 00
Fax +46 8 661 57 19

Äspö Hard Rock
Laboratory

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Author	Date
Klee, Rummel	01-12-18
Checked by	Date
Christer Andersson, Rolf Christiansson, Thomas Wallroth	02-01-10
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Summary

During October, 9th to 12th, 2001 a total of 12 hydraulic and hydrofrac / hydraulic injection tests were conducted in the almost vertical borehole no. KA2599G01 and the horizontal borehole no. KF0093A01 in order to determine the in - situ stress regime at a depth of about 455 m below surface in the Äspö Hard Rock Laboratory, Sweden. The in - situ tests were carried out by using the MeSy hydrofrac and impression packer unit PERFRAC II within the 96 mm diameter boreholes.

The hydrofrac tests yield distinct characteristic hydrofrac pressure data (e.g. clear breakdown pressure P_c, refrac pressure P_r, and shut-in pressure P_{si}), the impression packer tests showed that mainly steeply inclined fractures with similar orientation were initiated. Therefore, the stress analysis was carried out on the basis of the classical *Hubbert and Willis (1957)* concept by neglecting the ambient pore pressure for the low permeable rock. The results are summarized by the following mean stresses at the corresponding depth:

borehole no.	depth below surface TVD (m)	S_v* (MPa)	S_v (MPa)	S_h (MPa)	S_H (MPa)
KA2599G01	455.7 ± 8.8	12.1 ± 0.2		11.0 ± 0.9	21.8 ± 2.9
KF0093A01	450	11.9	19.5 ± 1.1	11.0 ± 1.2	

where S_h and S_H are the minimum and maximum horizontal principal stresses, S_v is the measured vertical stress, and S_v* is the vertical stress calculated for a mean density of the overburden rock of 2.7 g/cm^3. The significant discrepancy between the measured and calculated vertical stress requires further discussions under consideration of the influence of existing tunnels and shafts on the in-situ stresses.

The direction of the maximum horizontal stress S_H in relation to magnetic north was consistently determined as N 119° ± 8° in borehole no. KA2599G01 and N 115° ± 8° in borehole no. KF0093A01.

The analysis of the pressure pulse tests conducted prior to the hydrofrac tests yield an average hydraulic conductivity of (1.9 ± 1.2) · 10^{-10} m/s, which characterizes the tight granitic rock.

Sammanfattning

Den 9 till 12 oktober 2001 genomfördes totalt 12 stycken hydrauliska spräckningar och injektionsförsök i det nästan vertikala borrhålet KA2599G01 och i det horisontella borrhålet KA0093A01. Syftet var att bestämma bergspänningarna in situ på ett djup av cirka 455 m under havsytan i Äspölaboratoriet. Vid mätningarna i borrhålen med en diameter på 96 mm användes MeSy:s manschettsystem PERFRAC II.

Mätningarna gav distinkta och karakteristiska hydrauliska spräckdata och avtrycksmanschetten visade att i huvudsak brantstående sprickor med likartad strykning initierades. Analysen kunde därför genomföras enligt Hubbert and Willis (1957) princip genom att bortse från protrycket i det lågpermeabla berget. En sammanställning av medelspänningarna redovisas i tabellen nedan

Borrhålets ID	Djup underhavsytan (m)	S_v* (MPa)	S_v (MPa)	S_h (MPa)	S_H (MPa)
KA2599G01	455,7 ± 8,8	12,1 ± 0,2		11,0 ± 0,9	21,8 ± 2,9
KF0093A01	450	11,9	19,5 ± 1,1	11,0 ± 1.2	

där S_h och S_H är de minsta respektive största horisontella huvudspänningarna, S_v motsvarar den uppmätta vertikalspänningen och S_v* motsvarar en beräknad vertikalspänning där en medeldensitet på bergmassan motsvarande 2,7 g/cm^3 använts. Den påfallande skillnaden mellan den uppmätta och beräknade vertikalspänningen tarvar vidare diskussioner där hänsyn bör tas till befintliga tunnlars och schakts påverkan på in situ spänningarna.

Riktningen på den största horisontella huvudspänningen S_H i förhållande till magnetiskt norr bestämdes till N 119° ± 8° i borrhål KA2599G01 och N 115° ± 8° i borrhål KF0093A01.

Analyserna av tryckpulstesterna genomförda innan varje hydrauliskt test gav en genomsnittlig hydraulisk konduktivitet på (1,9 ± 1,2) · 10^{-10} m/s vilket är karakteristiskt för en homogen granitisk bergmassa.

Content

APPENDIX

A1: Records from in-situ hydrofrac - tests together with evaluation of characteristic pressure data, borehole no. KA2599G01
A2: Records from in-situ hydrofrac - tests together with evaluation of characteristic pressure data, borehole no. KF0093A01

B1: Fracture traces on the impression packer sleeve, borehole no. KA2599G01
B2: Fracture traces on the impression packer sleeve, borehole no. KF0093A01

C1: Analysis of pressure pulse tests, borehole no. KA2599G01
C2: Analysis of pressure pulse tests, borehole no. KF0093A01

1 Introduction

Since 1989, extensive rock stress measurements by using the overcoring and hydraulic fracturing methods have been carried out at the location of the Äspö Hard Rock Laboratory (HRL) in south-eastern Sweden (*Lundholm*, *1999*). Recently, the AECL-Doorstopper - and the Swedpower Triaxial Cell techniques were applied in a horizontal and an almost vertical borehole at about 450 m depth below surface. In order to compare the test results and to evaluate the applicability of different stress testing methods, a series of hydraulic fracturing tests was carried out in the same boreholes. The results of the in-situ tests are presented in the present report.

2 Borehole Characteristics

The Äspö HRL (app. N 57°26', E 16°39'40") is located on the island of Äspö, about 25 km north of Oskarshamn, in the south-eastern part of Sweden (Figure 2-1). The laboratory is situated close to the Oscarshamn Nuclear Power Station (OKG) and the Central Interim Storage Facility for Spent Nuclear Fuel (CLAB). The underground part of the Äspö HRL consists of a 3.6 km long tunnel system down to 460 m depth below ground surface.

The hydrofrac tests were conducted in two inclined boreholes which were core-drilled in HQ-size (96 mm diameter): borehole no. KA2599G01 was drilled from the -343 m level with an inclination of 10° (with respect to vertical) towards N 310° (related to geographic North). The borehole has a length of 131 m and reaches the -472 m level. Borehole no. KF0093A01 was drilled nearly horizontal (inclination: 2° upward) at the -451 m level. The bearing of the borehole is N 300° (related to geographic North), the length is 30 m. Relevant technical borehole information are summarized in Table 2-1. The borehole locations and the borehole trajectories within the Äspö HRL are shown in Figure 2-2. The closest distance between the boreholes is approximately 4.8 m.

Tabel 2-1. Technical data of borehole nos. KA2599G01 and KF0093A01.

location	Äspö HRL (app. N 57°26', E 16°39'40"), about 25 km north of Oskarshamn, south-eastern part of Sweden.	
borehole no.	KA2599G01	KF0093A01
borehole length	130.96 m	30.00 m
borehole diameter	96 mm	96 mm
inclination *(with respect to vertical)*	10°	92°
azimuth *(North over East)*	N 303° to N 296°	N 298°
coordinates *(Äspö-96 system)*		
start point	N 7303.00 E 2043.00	N 7297.50 E 1997.00
final depth	N 7324.79 E 2017.03	N 7320.47 E 2016.27
altitude		
start point	-343.50 m	-451.00 m
final depth	-470 m	-449.05 m
borehole fluid	water (artesian flow)	-
cored section	0 - 130.96 m	0 - 30.0 m
core diameter	63.5 mm	63.5 mm
lithology	granite	granite

Figure 2-1. Location of the Äspö HRL.

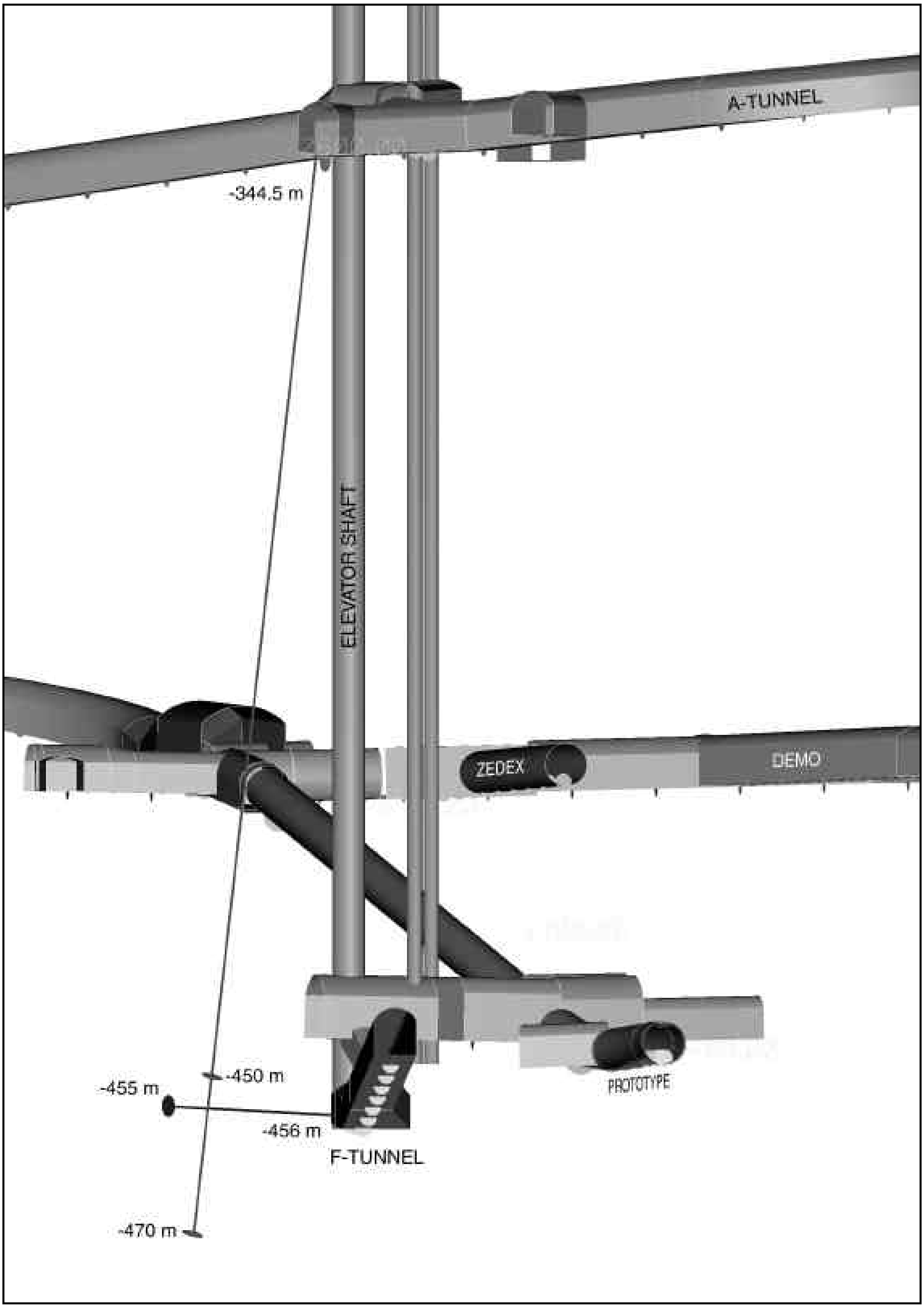

Figure 2-2. *Location of borehole no. KA2599G01 (nearly vertical) and KF0093A01 (horizontal) in the Äspö HRL (view from the west). The circles denote the depth of overcoring stress measurements.*

3 Test Equipment and Test Procedure

3.1 In-Situ Test Equipment

The hydraulic / hydraulic fracturing tests in the 96 mm diameter boreholes in the Äspö HRL were carried out by using the MeSy straddle packer assembly PERFRAC II equipped with nylon - reinforced packer elements (S & K, type TK 80 - V - 1300, OD : 81 mm). The sealing length of each packer element is about 1.0 m, the length of the test interval between the two packers was about 0.6 m.

For the case of the hydrofrac tests in the "vertical" borehole no. KA2599G01, the tool was moved within the borehole on a seven conductor borehole logging cable with the electric-driven winch system MKW-500. A schematic view of the system is given in Figure 3-1, a photo of the winch - system in the Äspö HRL is presented in Figure 3-2.

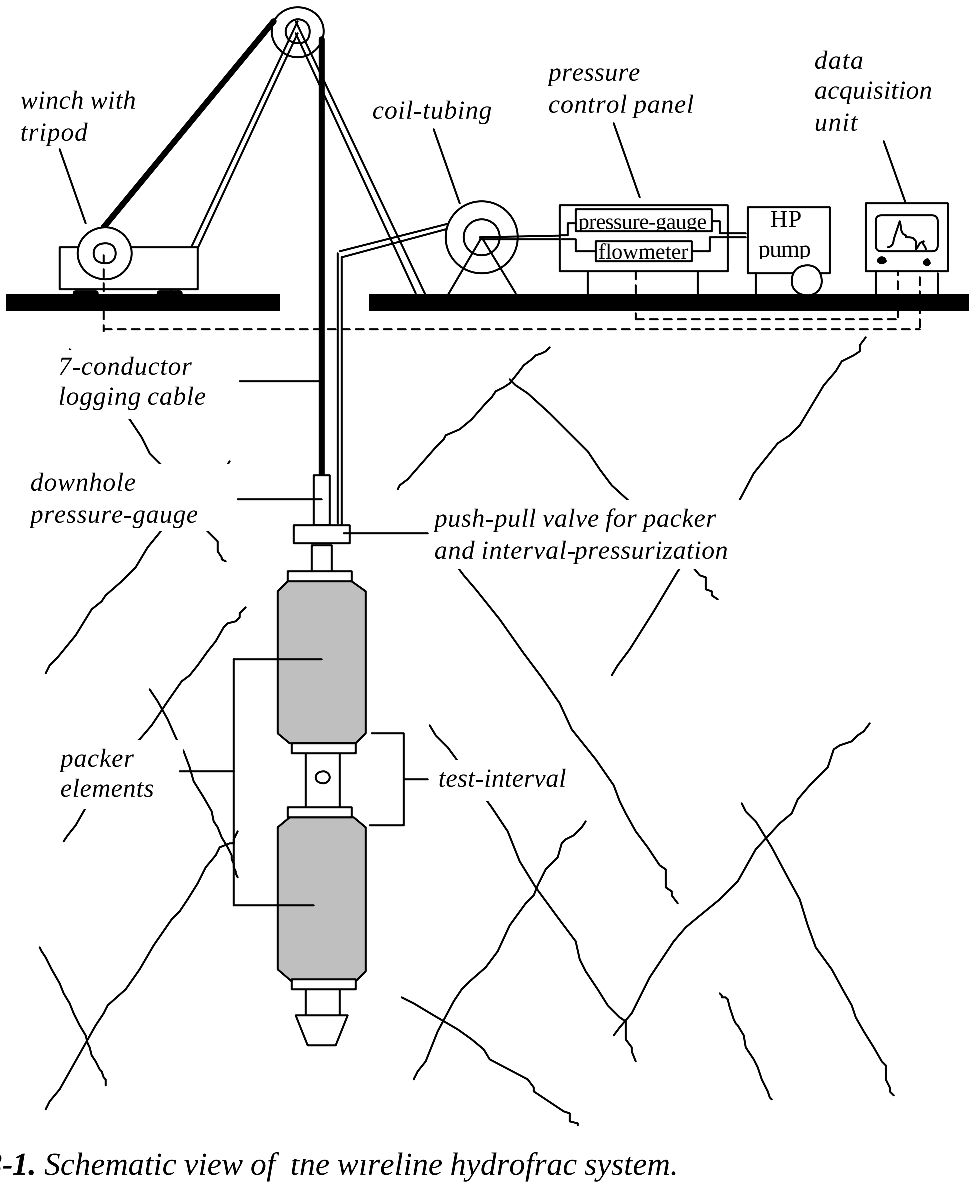

Figure 3-1. *Schematic view of the wireline hydrofrac system.*

The packer elements were pressurized via a high pressure stainless steel coil tubing (OD 10 mm, ID 8 mm, maximum operating pressure 60 MPa) which was clamped to the logging cable at 30 m intervals. A push - pull valve mounted on top of the packer assembly allows to switch from packer pressurization to injection into the test interval, and the reverse, simply by controlling the tension of the logging cable.

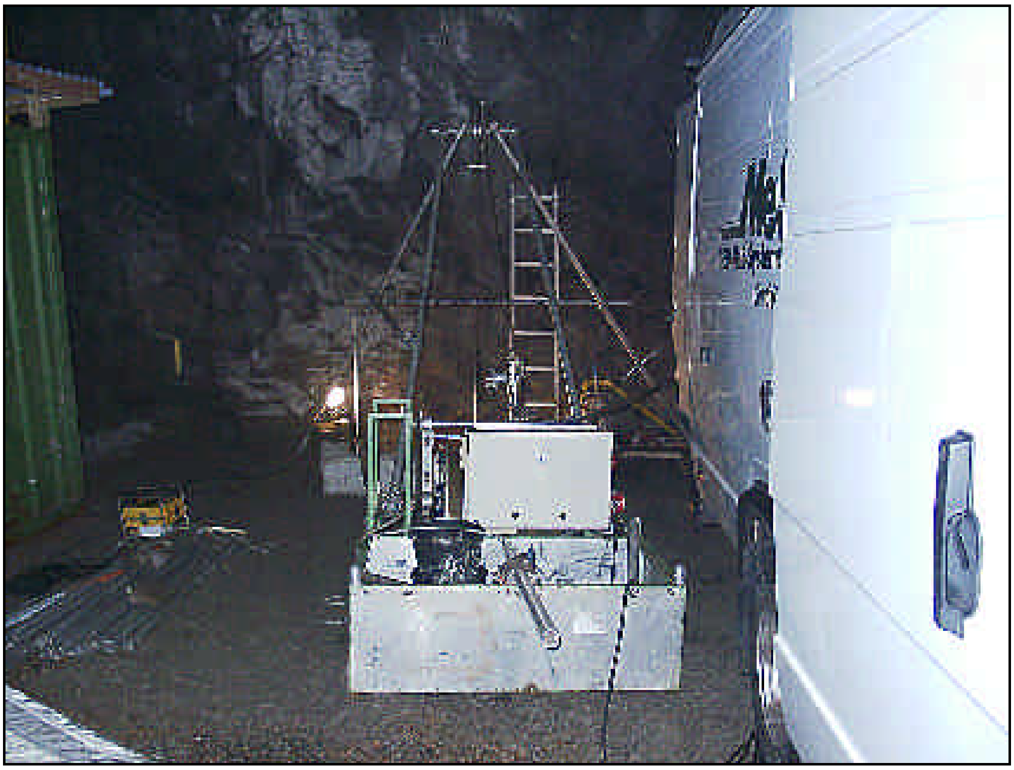

Figure 3-2. *Photo of the winch system MKW-500 at the location of borehole no. KA2599G01.*

For the case of the hydrofrac tests in the horizontal borehole no. KF0093A01, the tool was moved within the borehole with a 16 mm OD / 11 mm ID steel tubing, which also served as hydraulic line to the test interval.

For pressurization of both, packer elements and the test interval an electric driven three - plunger pump (SPECK, type HP 400 / 2 - 12) with a maximum working pressure of 40 MPa and a maximum injection rate of 12 lpm was used. The injection fluid was water (mixed with Uranin as tracer).

Packer - and interval pressure were measured uphole and downhole with high precision electric pressure transducers (KELLER, type PA-23, 0 - 40 MPa). Pressure values and the injection flow rate (UNIMESS turbine type flow - meter, QPT 01, 1.2 - 10 lpm) were recorded by a digital data acquisition system (SILVI, 8 channels, 16 bit resolution, sampling rate: 5 Hz) and by an analogue paper strip-chart recorder (BBC, type SE-400, 4 channels).

The impression packer tool to measure the orientation of induced or stimulated fractures consisted of a single packer element (S & K, type TK 80 - V - 1300, OD : 81 mm) with a soft rubber sleeve, in conjunction with a magnetic single shot device (EW, type RW). The packer preserves the imprint from the borehole wall and from the fracture traces when it is pressurized to a pressure level higher than the fracture re - opening pressure for a time of app. 10 minutes.

3.2 Testing Procedure

The in - situ tests in the Äspö HRL were carried out during 9.-12.10.2001. Short overviews of the major activities during the test phase were given in the daily operation reports (SKB Daily Logs). The test-sections in the two boreholes were selected on the basis of a core-inspection prior to testing. Since the conduction of only five tests in the deepest parts of each borehole was planned, test-sections without visible fractures and joints were selected in order to induce new fractures.

A typical test record illustrating the test procedure is shown in Figure 3-3 for the test at 123.5 m depth in borehole no. KA2599G01. Each test consisted of the following pumping operations after inflating the packer elements to a differential (above hydrostatic) pressure of about 15 MPa:

– rapid pressurization of the test interval to a differential pressure of about 3 - 6 MPa and subsequent monitoring of the pressure decline for app. 5 minutes (P - test in Figure 3-3);

– 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 in interval pressure occurs or a constant injection pressure is reached (Frac - test in Figure 3-3); 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 5 lpm (increasing order) until constant injection pressure is reached (Refrac - test in Figure 3-3); 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 test in Figure 3-3);

– release of the interval pressure and fluid recovery;

– packer deflation and movement to the next test section.

The impression packer tests consisted of an inflation of the single packer element to a pressure app. 20% above the fracture re-opening pressure for a period of about 15 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 (Figure 3-4). The film disc of the single - shot unit was developed documenting the orientation of the reference mark with respect to magnetic North.

In summary, the test conduction in the two boreholes was a routine operation which produced 12 hydraulic / hydrofrac - and 12 impression packer test results from the test sections within a period of 4 days.

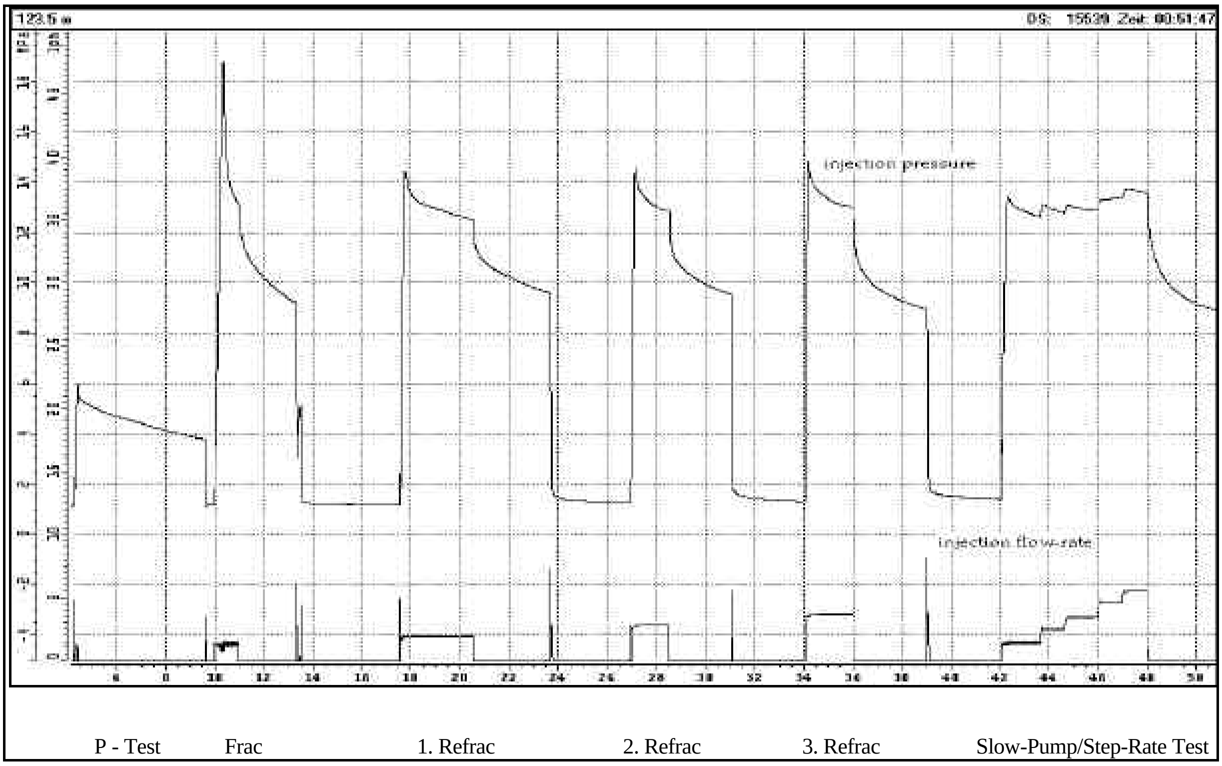

Figure 3-3. *Downhole pressure and surface flow-rate record of the hydrofrac tests at 123.5 m measured depth (MD) in borehole no. KA2599G01.*

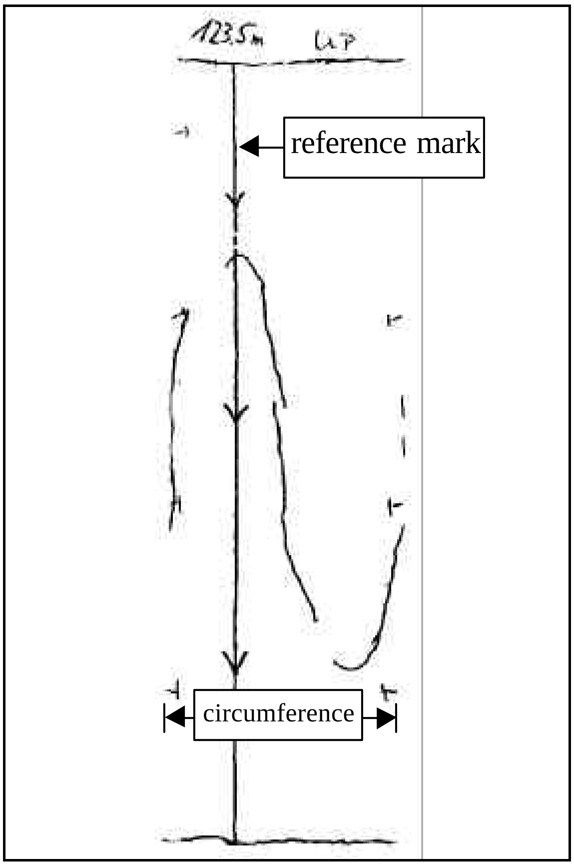

Figure 3-4. *Fracture traces of the impression packer test at 123.5 m MD in borehole no. KA2599G01. The circumference of the packer is app. 280 mm, the length is app. 1000 mm.*

4 Data Analysis

The stress determination from the in - situ hydrofrac / hydraulic injection tests generally requires the following test data:

– breakdown pressures P_c (fracture initiation)

– refrac pressures P_r (fracture re - opening)

– shut - in pressures P_{si}

– determination of the spatial orientation of induced or stimulated fractures.

The pressure values breakdown pressure P_c, refrac or re - opening pressure P_r, and shut - in pressure P_{si} are identified by the following analysis procedure:

– The breakdown pressure P_c is defined as the maximum pressure observed during the frac - cycle (first pressurization). P_c is determined from a detailed pressure P vs. time t plot.

– The determination of the refrac pressure P_r is based on the analysis of the stiffness (dP/dV) during the pressurization of the test interval. Fracture opening is correlated with a significant deviation of the stiffness from linearity.

– The shut - in pressure P_{si} is determined by the following three step procedure:

  A plot of pressure P vs. injection flow - rate Q allows to determine the exact pressure value at which the hydraulic flow terminates (Q = 0). Therefore, the P vs. Q plot yields an upper - limit estimate of the shut - in pressure.

  A Muskat - type plot of the logarithm of the difference between the pressure P and an asymptotic pressure level Pa vs. time t yields the lower - limit of the shut - in pressure, assuming that the linear part of the plot characterizes radial flow, i.e. the stimulated fracture is nearly closed.

  Within these two limits the shut - in pressure, which corresponds to the acting stress across the fracture plane, marks the transition from a rapid linear pressure drop (observed immediately after shut - in) to the beginning of a diffusion - dominated slow pressure decrease. The transition can be determined by the tangent to the linear pressure decrease in a detailed P vs. time t plot.

– The slow pump / step rate tests were analyzed similar to classical Lugeon - tests using the steady - state P - Q data pairs determined from a detailed pressure P and flow - rate Q vs. time t - plot.

– The fracture orientation data (strike deviation θ, fracture dip α and dip direction β) are obtained from the observed fracture traces and the single shot information. The orientation of the fracture traces with respect to the reference mark on the magnetic single shot compass unit (which is related to magnetic North) is determined under consideration of the geometrical borehole data and the magnetic declination (angle between magnetic and geographic North).

5 Results of in-situ Hydrofrac - Tests

5.1 Borehole No. KA2599G01

A total of six hydrofrac / hydraulic injection - and impression packer tests were carried out in borehole no. KA2599G01 between 105.5 m and 123.5 m measured depth MD (corresponding depth below surface TVD under consideration of the borehole trajectory: 446.9 m - 464.5 m). The graphical test record analysis is given in APPENDIX A1. The derived characteristic pressure data P_c, P_r, P_{si}, and the resulting in - situ tensile strength $P_{co} = P_c - P_r$ are summarized in Table 5-1 and are graphically shown as a function of depth in Figure 5-1. The data are listed and shown as downhole pressure values. The results of the impression packer tests conducted to derive the spatial orientation of induced or stimulated fractures are listed in Table 5-2 and are shown graphically as a pole-plot in Figure 5-2. Copies of the fracture traces are shown in APPENDIX B1. Table 5-2 also contains remarks regarding the fracture orientation with respect to the borehole axis.

Table 5-1. Breakdown pressure P_c, refrac - pressure P_r, in-situ hydraulic tensile strength $P_{\infty} = P_c - P_r$, and shut-in pressure P_{si} derived from hydrofrac tests in borehole no. KA2599G01 (depth is related to the center of the 0.6 m long test interval.

* *stimulation of a pre-existing fracture*

measured depth MD (m)	depth below surface TVD (m)	P_c (MPa)	P_r (MPa)	P_{co} (MPa)	P_{si} (MPa)
105.5	446.9	17.3	13.1	4.2	10.6
108.0	449.4	15.0	11.2	3.8	10.3
112.7	454.0	13.1	9.3	3.8	10.0
116.2	457.4	18.0	12.5	5.5	12.2
119.3	460.5	-*	8.8	-*	11.7
123.5	464.5	18.8	12.8	6.0	11.4

Table 5-2. Orientation of induced or stimulated fractures derived from impression packer testing in borehole no. KA2599G01. q**: strike direction (North over East),** b**: dip direction (North over East),** a **: dip (with respect to horizontal).**

<>mean value

MD (m)	TVD (m)	fracture trace	θ (deg)	β (deg)	α (deg)	remark
105.5	446.9	A	129	219	89	axial
108.0	449.4	A	125	215	89	axial
112.7	454.0	A	106	16	88	axial
116.2	457.4	A	115	25	89	axial
119.3	460.5	A B	112 124 <118>	22 214	73 82 <78>	inclined inclined
123.5	464.5	A	118	28	80	inclined

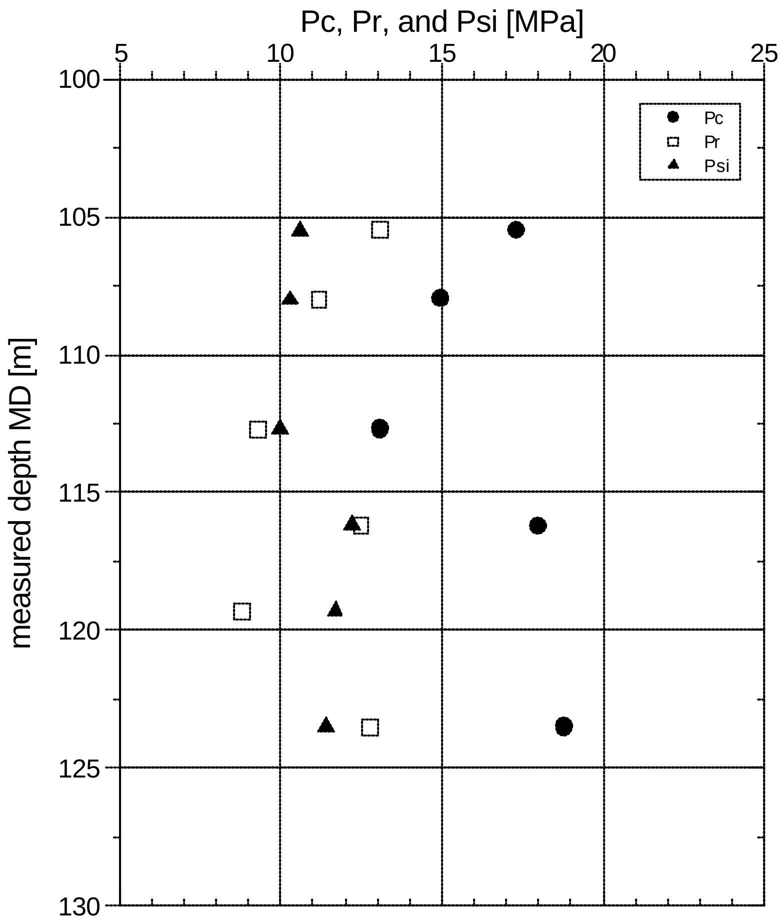

Figure 5-1. *Breakdown pressure P_c, refrac - pressure P_r, and shut-in pressure P_{si} derived from hydrofrac tests in borehole no. KA2599G01.*

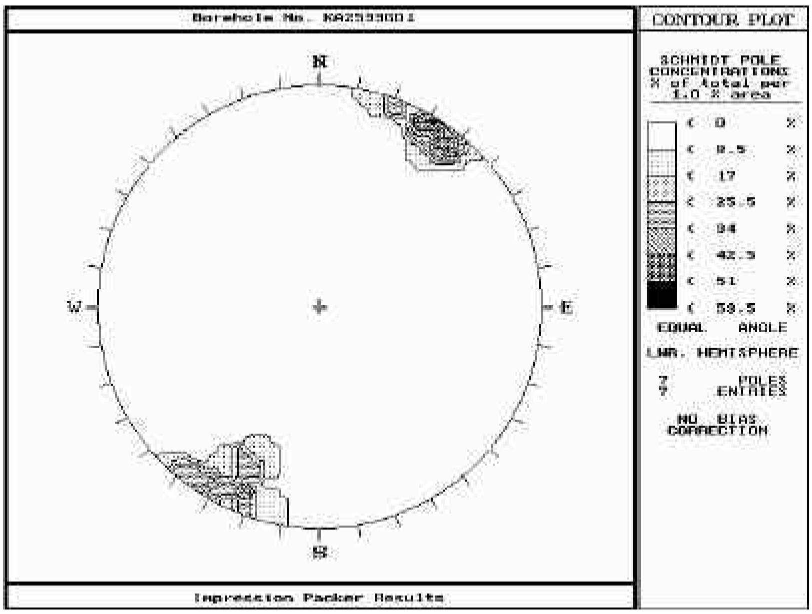

Figure 5-2. *Orientation of induced or stimulated fractures derived from impression packer testing in borehole no. KA2599G01.*

Since the impression packer tests showed that mainly unambiguous sub-vertical (axial) fractures with a consistent orientation of WNW - ESE were induced (only at 119.3 m MD a pre-existing fracture was stimulated), the stress estimation was conducted on the basis of the "classical" *Hubbert and Willis (1957)* approach with the following simplified assumptions:

- the overburden stress S_v is a principal stress;
- the rock is homogenous and isotropic;
- the fracturing fluid does not penetrate into the rock prior to fracture initiation;
- the induced vertical fracture is oriented perpendicular with respect to the minimum horizontal stress S_h.

This results in the following simple relations:

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

$$P_{si} = S_h$$

$$P_{co} = P_c - P_r$$

with P_c : breakdown pressure at frac initiation
P_r : fracture re-opening pressure
P_{si} : shut-in pressure
P_{co} : in-situ hydrofrac tensile strength
P_p : pore pressure
$S_{h,H}$: minimum and maximum horizontal principal stress

Neglecting the ambient pore - pressure P_p in crystalline rocks with low permeability, the resulting principal stresses S_h and S_H are listed in Table 5-3 and are graphically shown in Figure 5-3. The vertical stress S_v* was calculated for a mean overburden rock mass density of 2.7 g/cm^3. Since the stress data do not show a distinct depth dependence within the short depth interval of only 18 m, the results can be summarized by the following mean stresses at the corresponding mean depth:

mean depth MD (m)	depth below surface TVD (m)	S_v* (MPa)	S_h (MPa)	S_H (MPa)
114.5 ± 9.0	455.7 ± 8.8	12.1 ± 0.2	11.0 ± 0.9	21.8 ± 2.9

The acting maximum horizontal principal stress S_H is oriented N 119° ± 8° (WNW - ESE).

Table 5-3. Results of the stress evaluation for borehole no. KA2599G01 (S_v*: vertical stress calculated for a mean overburden rock mass density of 2.7 g/cm^3, S_h: minimum horizontal stress, S_H: maximum horizontal stress, q_{SH}: strike direction of S_H).

measured depth MD (m)	depth below surface TVD (m)	S_v* (MPa)	S_h (MPa)	S_H (MPa)	θ_{SH} N over E (deg)
105.5	446.9	11.8	10.6	18.7	129
108.0	449.4	11.9	10.3	19.7	125
112.7	454.0	12.0	10.0	20.7	106
116.2	457.4	12.1	12.2	24.1	115
119.3	460.5	12.2	11.7	26.3	118
123.5	464.5	12.3	11.4	21.4	118

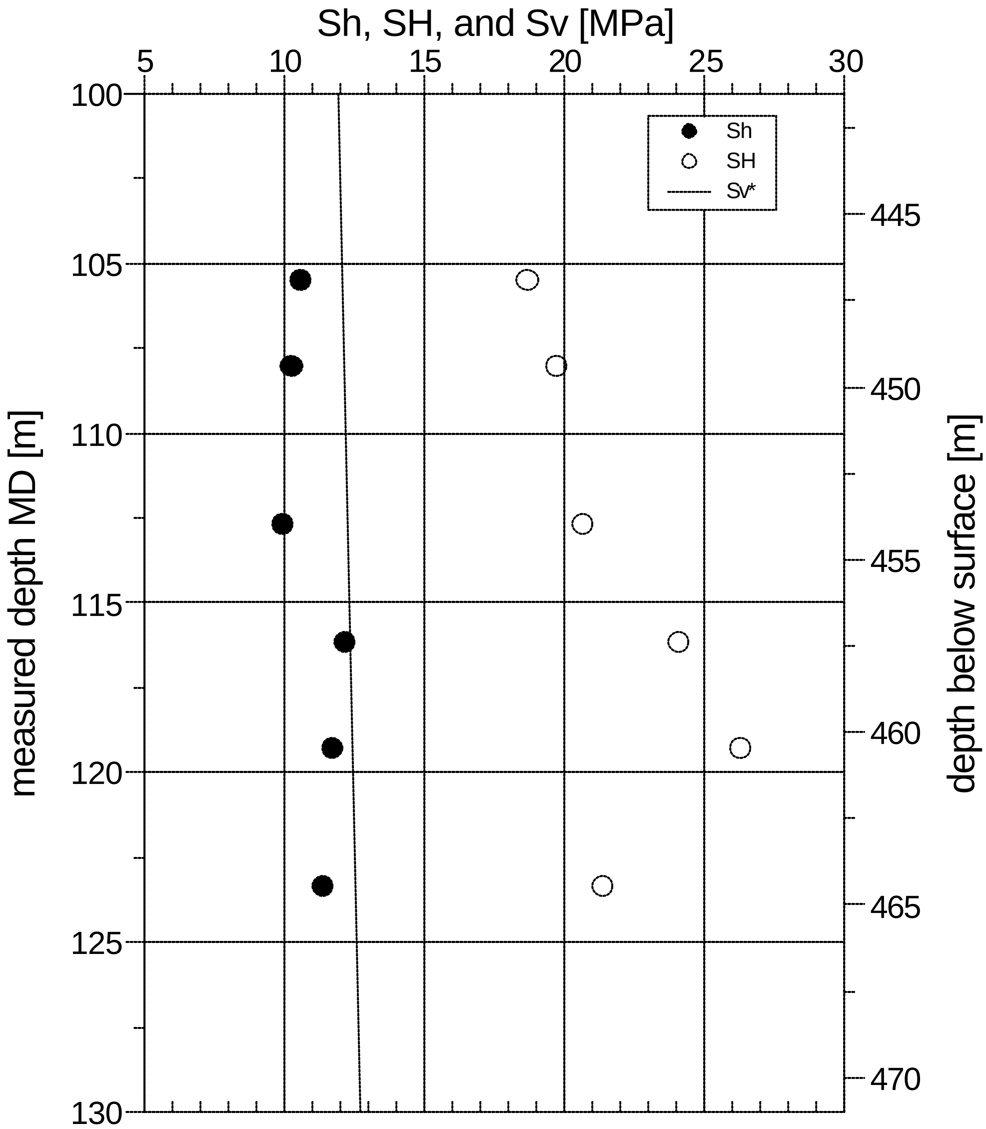

Figure 5-3. *Principle stresses for borehole no. KA2599G01.*

5.2 Borehole No. KF0093A01

Six hydrofrac- and impression packer tests were conducted in the horizontal borehole no. KF0093A01 between 21.5 m and 32.0 m depth. The graphical test record analysis is given in APPENDIX A2. The derived characteristic pressure data P_c, P_r, P_{si}, and the resulting in - situ tensile strength $P_{co} = P_c - P_r$ are summarized in Table 5-4 and are graphically shown as a function of depth in Figure 5-4. The results of the impression packer tests conducted to derive the spatial orientation of induced or stimulated fractures are listed in Table 5-5 and are shown graphically in Figure 5-5. Copies of the fracture traces are shown in APPENDIX B2.

Table 5-4. Breakdown pressure P_c, refrac - pressure P_r, in-situ hydraulic tensile strength $P_{\infty} = P_c - P_r$, and shut-in pressure P_{si} derived from hydrofrac tests in borehole no. KF0093A01 (depth is related to the center of the 0.6 m long test interval.

[a)] *no clear brakdown*
[b)] *increase of shut-in pressure during the injection cycles*

measured depth MD (m)	P_c (MPa)	P_r (MPa)	P_{co} (MPa)	P_{si} (MPa)
21.5	22.4 - 23.5 [a)]	15.3	7.1 - 8.2	18.6
24.0	21.4	16.0	5.4	13.4
26.0	21.8	14.3	7.5	11.6
28.0	20.3	16.6	3.7	12.4
30.0	15.1	11.2	3.9	10.3 [b)]
32.0	16.5	10.9 - 11.5	5.0 - 5.6	9.8

Table 5-5. Orientation of induced or stimulated fractures derived from impression packer testing in borehole no. KF0093A01. q: strike direction (North over East), b: dip direction (North over East), a : dip (with respect to horizontal).

measured depth MD (m)	fracture trace	θ (deg)	β (deg)	α (deg)	remark
21.5	A B	77 136	167 46	28 6	inclined, no fracture tip detected axial single trace
24.0	A	122	32	26	axial, doubtful (only short pieces of the fracture trace visible)
26.0	A	103	193	87	inclined
28.0	A	119	29	72	axial
30.0	A	118	208	89	axial
32.0	A	119	29	73	axial

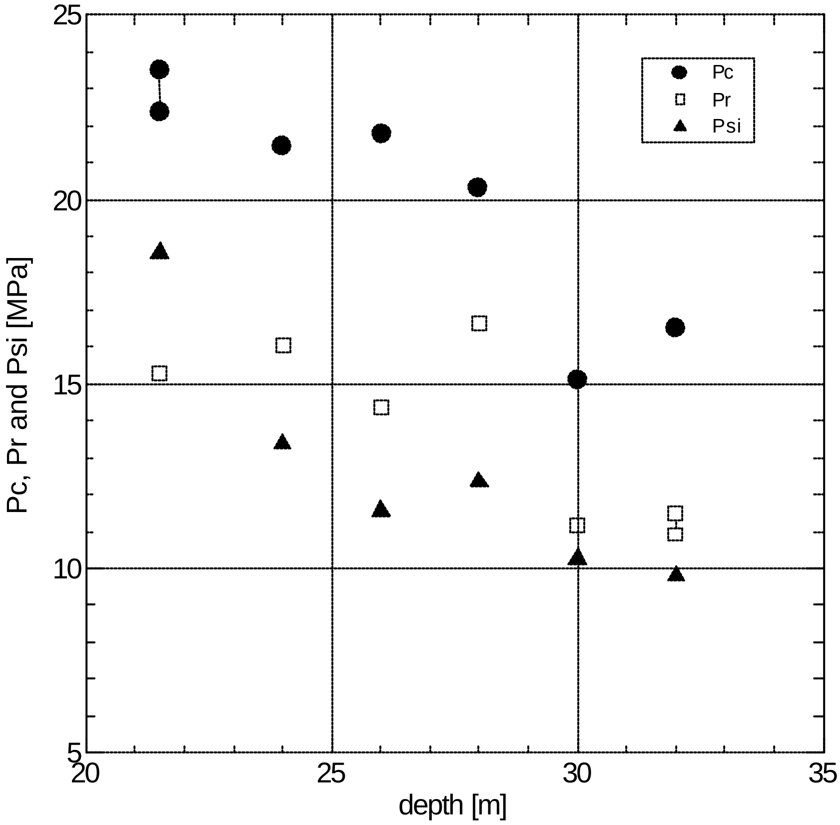

Figure 5-4. *Breakdown pressure P_c, refrac - pressure P_r, and shut-in pressure P_{si} derived from hydrofrac tests in borehole no. KF0093A01.*

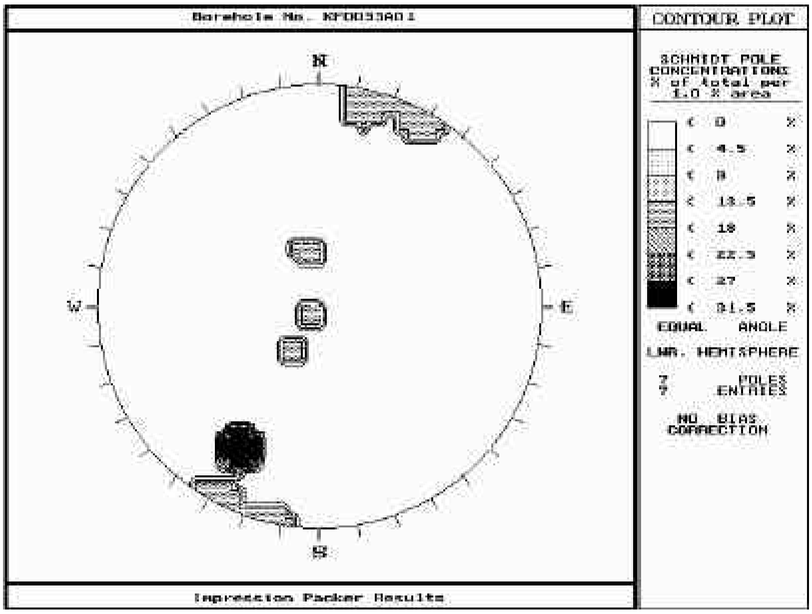

Figure 5-5. *Orientation of induced or stimulated fractures derived from impression packer testing in borehole no. KF0093A01.*

The results of the stress estimation for borehole no. KF0093A01 is presented in Table 5-6 and is shown graphically in Figure 5-6. The evaluation of the in-situ stresses is based on the following interpretation of the test data:

– Under consideration of the direction of the maximum horizontal stress derived in the vertical borehole (θ_{SH} = N 119° ± 8°), the horizontal borehole is orientated parallel to the direction of the maximum horizontal stress S_H. For the particular case of $S_h < S_v$, axial vertical fractures will be initiated. Neglecting the ambient pore pressure in rocks with low permeability, the *Hubbert and Willis (1957)* -concept then yields:

$$S_h = P_{si}$$

$$S_v = 3 \cdot P_{si} - P_r$$

However, although breakdown (fracture initiation) events were observed during all tests, the impression packer tests showed axial, steeply inclined fractures only for the test sections between 26.0 m and 32.0 m depth.

– At 21.5 m and 24.0 m depth, sub-horizontal fractures were detected by the impression packer tests (but doubtful at 24.0 m). In this case, the shut-in pressure, which corresponds to the normal stress acting across the fracture plane, can be used to determine the vertical stress ($P_{si} = S_v$)

The results of the calculations can be summarized by the following mean stresses at a depth of 450 m below surface (the vertical stress S_v* was calculated for a mean overburden rock mass density of 2.7 g/cm^3)::

mean depth below surface (m)	S_v* (MPa)	S_h (MPa)	S_v (MPa)
450	11.9	11.0 ± 1.2	19.5 ± 1.1

The acting maximum horizontal principal stress S_H is oriented N 115° ± 8° (WNW - ESE).

Table 5-6. Results of the stress evaluation for borehole no. KF0093A01 (S_v*: vertical stress calculated for a mean overburden rock mass density of 2.7 g/cm^3, S_h: minimum horizontal stress, S_v: measured vertical stress, q_{SH}: strike direction of the maximum horizontal stress S_H).

<> mean value
( ) neglected due to the doubtful impression packer test result

measured depth MD (m)	S_v* (MPa)	S_h (MPa)	S_v (MPa)	θ_{SH} N over E (deg)
21.5	11.9		18.6	
24.0	11.9		(13.4)	
26.0	11.9	11.6	20.5	103
28.0	11.9	12.4	20.6	119
30.0	11.9	10.3	19.7	118
32.0	11.9	9.8	17.9 - 18.5 <18.2>	119

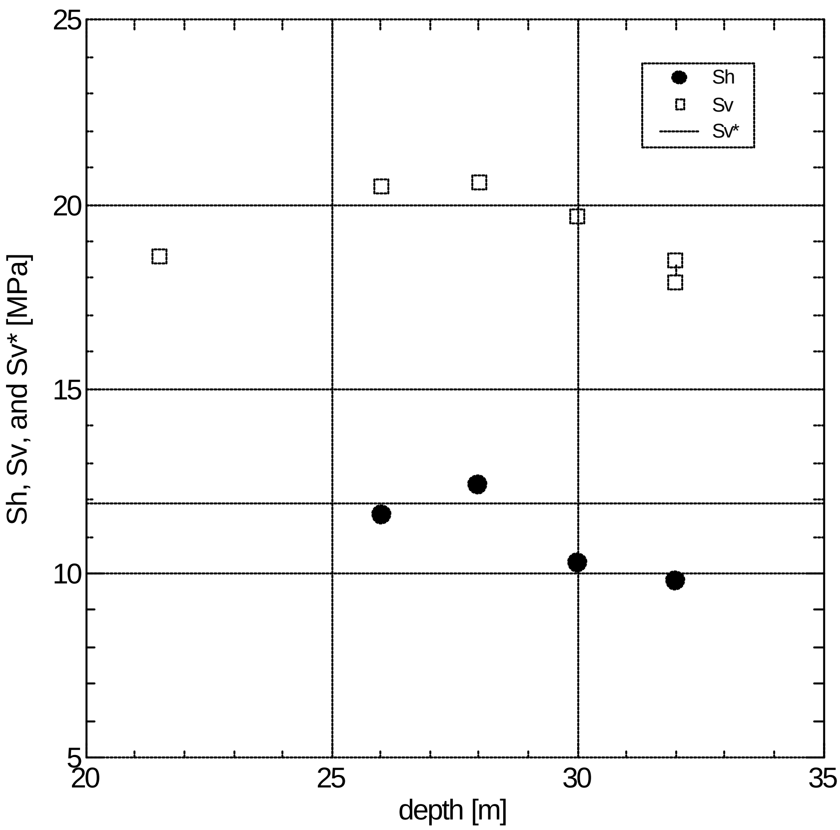

Figure 5-6. *Principle stresses for borehole no. KF0093A01.*

6 Analysis of Pressure Pulse Tests and Results

Prior to the hydrofrac / hydraulic injection tests, short pressure pulse tests were carried out to test the suitability of the test interval for the subsequent fracturing test and to determine the in-situ rock mass permeability in the vicinity of the borehole wall. The analysis of the tests is based on the classical method suggested by *Cooper et al. (1967)* for slug - tests. For the special case of the wireline packer - system (high system stiffness dP/dV) MeSy has developed the software code PERM, where theoretical and measured pressure decline curves are matched for a variety of input parameters such as storage coefficient and permeability by using an inversion procedure (master curve method). The result of the calculations are presented as the mean of all successful models, which satisfy the linear error regression analysis standard.

The analysis of the pressure pulse tests is given in APPENDIX C1 and C2. The results are summarized in Table 6.1. The hydraulic conductivity K was estimated from the permeability k by:

$$K = \frac{k \cdot \rho_{water} \cdot g}{\eta}$$

where K : conductivity (m/s)
k : permeability (1 Darcy = 10^{-12} m^2)
ρ_{water} : water density (1000 kg/m^3)
g : gravitational acceleration (9.81 m/s^2)
η : water viscosity (1 cPoise = 10^{-3} Pa·s)

Table 6-1. Results of pressure pulse tests in borehole no. KA2599G01 and KF0093A01.

borehole no.	measured depth MD (m)	permeability k (µDarcy = 10^{-18} m^2)	conductivity K (m/s)
KA2599G01	105.5	8	$7.8 \cdot 10^{-11}$
	108.0	23	$2.3 \cdot 10^{-10}$
	112.7	9	$8.5 \cdot 10^{-11}$
	116.2	42	$4.2 \cdot 10^{-10}$
	119.3	11	$1.1 \cdot 10^{-10}$
	123.5	40	$4.0 \cdot 10^{-10}$
KF0093A01	21.5	24	$2.4 \cdot 10^{-10}$
	24.0	11	$1.1 \cdot 10^{-10}$
	26.0	14	$1.4 \cdot 10^{-10}$
	28.0	12	$1.2 \cdot 10^{-10}$
	30.0	9	$8.8 \cdot 10^{-11}$
	32.0	26	$2.6 \cdot 10^{-10}$

7 Summary of Results

– In order to compare the results of different stress testing methods, a series of hydrofrac / hydraulic injection tests was conducted in the almost vertical borehole no. KA2599G01 and the horizontal borehole no. KF0093A01 in the Äspö Hard Rock Laboratory, Sweden, between 447 m and 465 m depth below surface. Based on the results of previous stress measurements, the horizontal borehole is oriented approximately parallel to the expected direction of the maximum horizontal stress. The in-situ tests in the 96 mm diameter boreholes were conducted with the MeSy hydrofrac straddle packer - and impression packer tool PERFRAC II which was equipped with 81 mm diameter packer elements.

– The hydrofrac / hydraulic injection tests in borehole no. KA2599G01 demonstrated clear breakdown events with breakdown pressure values ranging from 13.1 MPa to 18.8 MPa at five out of six test sections. The refrac - pressure values varied between 8.8 MPa and 13.1 MPa, the distinct shut - in pressure values varied between 10.0 MPa and 12.2 MPa. The six tests conducted in the horizontal borehole no. KF0093A01 exhibited breakdown events with breakdown pressure values ranging from 15.1 MPa to 23.5 MPa. . The refrac - pressure values varied between 10.9 MPa and 16.6 MPa, the shut - in pressure values varied between 9.8 MPa and 18.6 MPa. Thus, the tests in both boreholes yield a mean in-situ hydraulic tensile strength of 5.2 ± 1.5 MPa for the granitic rock mass.

– Since the impression packer tests carried out in both boreholes showed that in most test sections distinct steeply inclined fractures with a consistent WNW - ESE orientation were induced, the evaluation of the in-situ stresses was therefore conducted on the basis of the classical *Hubbert and Willis (1957)* approach under consideration of the borehole orientation with respect to the orientation of the principle stresses. The results can summarized by the following mean stresses at the corresponding depth (Figure 7-1):

borehole no.	depth below surface TVD (m)	S_v* (MPa)	S_v (MPa)	S_h (MPa)	S_H (MPa)
KA2599G01	455.7 ± 8.8	12.1 ± 0.2		11.0 ± 0.9	21.8 ± 2.9
KF0093A01	450	11.9	19.5 ± 1.1	11.0 ± 1.2	

where S_h and S_H are the minimum and maximum horizontal principal stresses, S_v is the measured vertical stress, and S_v* is the vertical stress calculated for a mean density of the overburden rock of 2.7 g/cm^3.

– While the tests in the two boreholes yield consistent magnitudes for the minimum horizontal stress S_h, a significant discrepancy between the measured vertical stress S_v and calculated vertical stress S_v* is observed. At present, this observation cannot be further explained without detailed consideration of the influence of the existing underground excavation system with tunnels, shafts and niches on the in-situ stresses.

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– The hydrofrac stress measurements in both boreholes yield consistently a WNW - ESE orientation of the maximum horizontal stress S_H (N 119° ± 8° in borehole no. KA2599G01 and N 115° ± 8° in borehole no. KF0093A01).

– The analysis of the pressure pulse tests conducted prior to the hydrofrac tests yield an average hydraulic conductivity of $(1.9 \pm 1.2) \cdot 10^{-10}$ m/s (average permeability of 19 ± 12 µDarcy). The values characterizes the tight granitic rock.

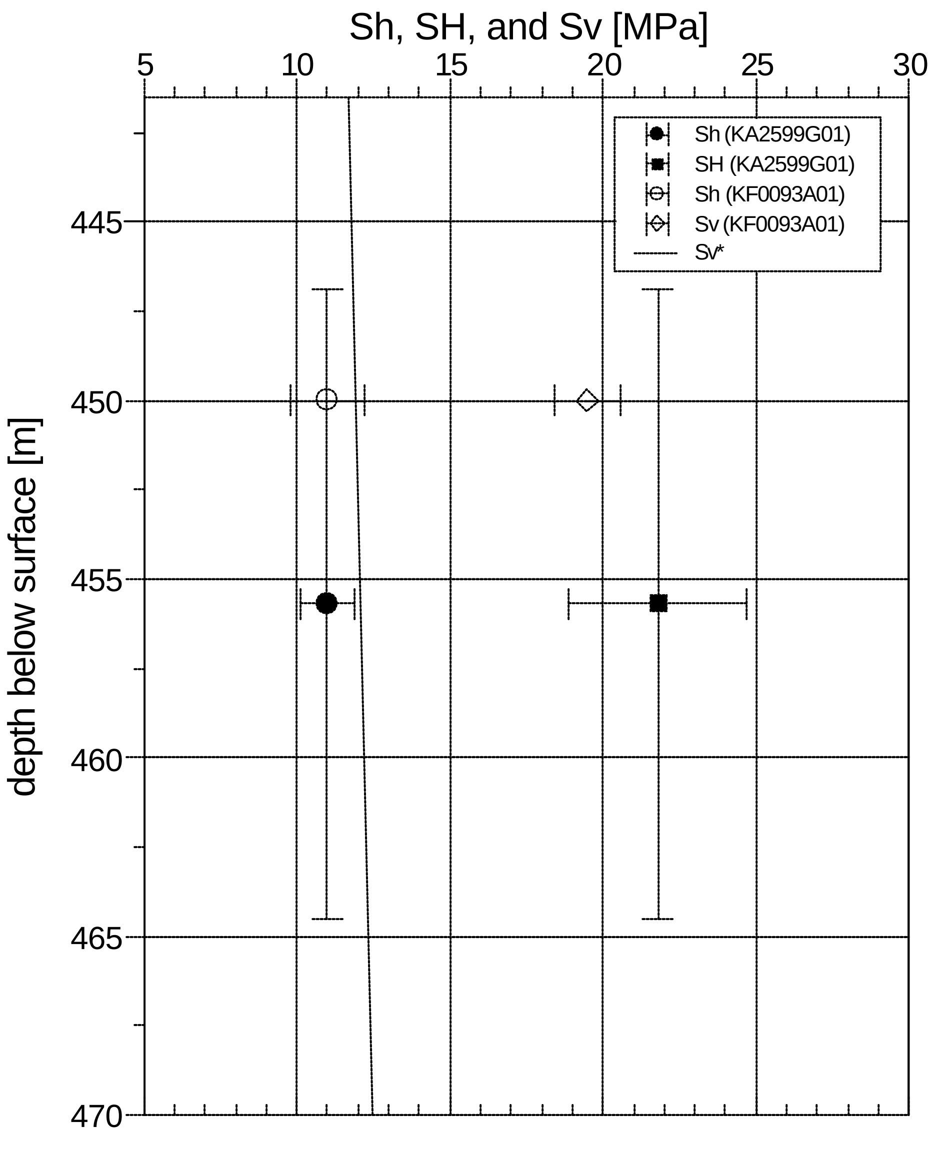

Figure 7-1. *Principle stresses derived from hydrofrac testing in borehole nos. KA2599G01 and KF0093A01 in relation to the vertical stress S_v calculated for a mean overburden rock mass density of 2.7 g/cm^3. The bars represents the average stress values with standard deviation for the corresponding depth interval.*

Acknowledgement

We acknowledge the possibility to carry out the in - situ hydraulic and hydrofrac stress measurements in the Äspö HRL. We are particularly grateful to Christer Andersson, Rolf Christiansson, and Lars Andersson (SKB) for contract discussions, logistic preparations of the field tests and technical support during the in-situ test conduction.

We also like to thank Thomas Wallroth (Bergab) for the discussion of preliminary results of the tests.

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Hubbert M K, Willis D K, 1957. Mechanics of Hydraulic Fracturing. Trans AIME; 210: 153-163.

Lundholm B, 1999. State of Stress at Äspö, Sweden. Proc. of the 2nd Euroconference on WSM - Deformation and Stress in the Earth's Crust, 22-26.09.1999, Äspö HRL, Sweden.

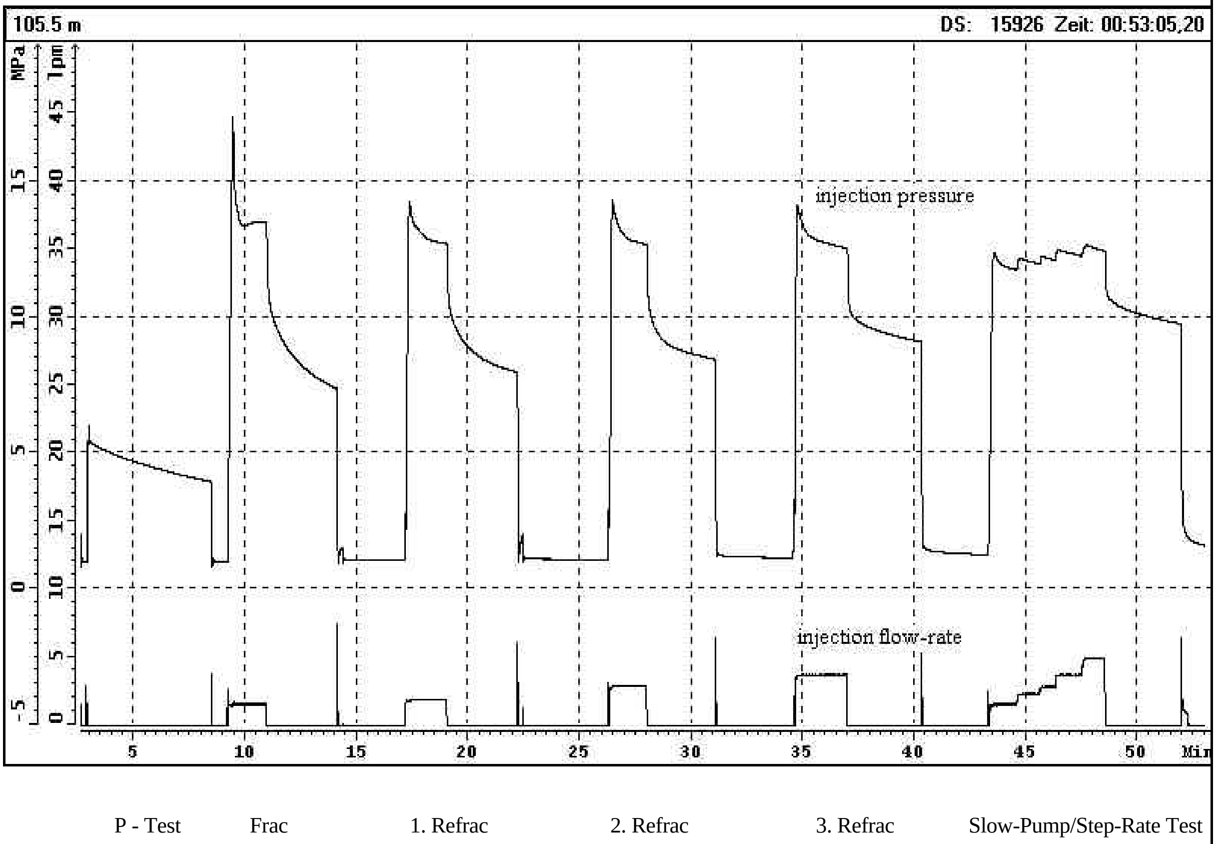
APPENDIX A1

Records from in-situ hydrofrac tests together with evaluation of characteristic pressure data

borehole no. KA2599G01

Test at 105.5 M MD / 446.9 M TVD

Test at 105.5 m MD : Overview - Plot



<u>Test Summary</u>

P - Test : pressure decrease: 1.4 MPa in 5 min. 24 sec.

Frac - Cycle : injection-rate Q_i= 1.6 lpm, injected volume V_i = 2.8 l, back-flow volume V_r = 0.1 l
clear fracture initiation (breakdown event)

1. Refrac - Cycle : Q_i = 1.9 lpm, V_i = 3.4 l, V_r = 0.2 l

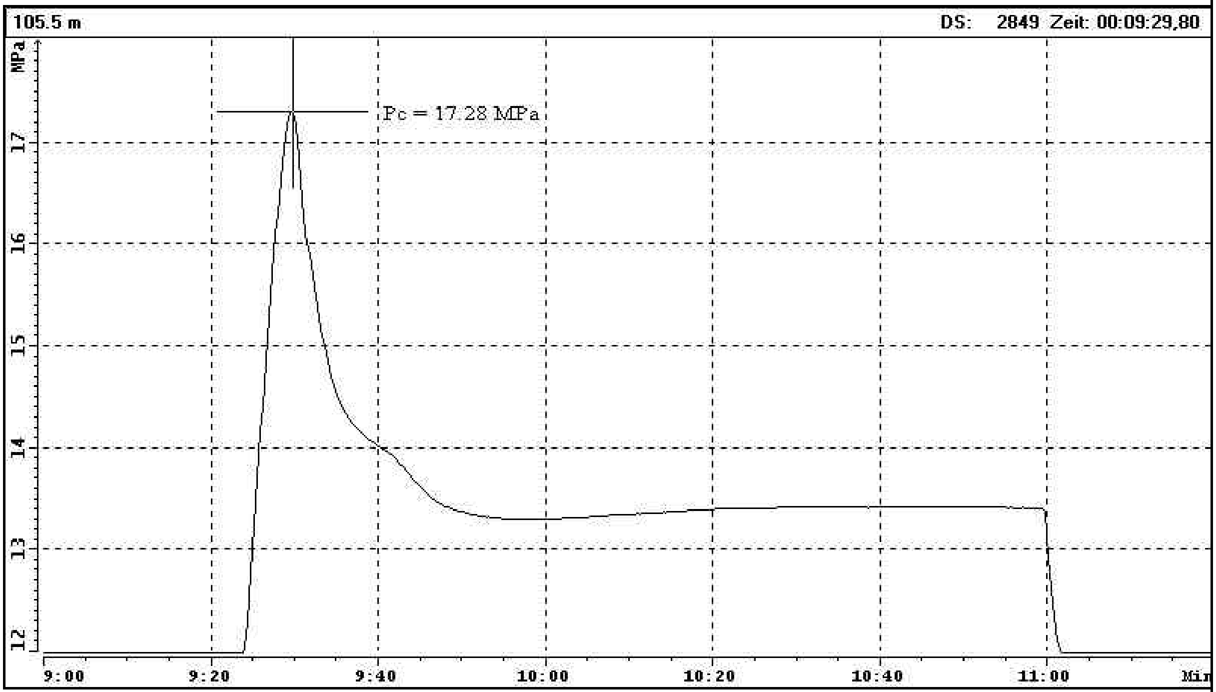
2. Refrac - Cycle : Q_i = 2.9 lpm, V_i = 4.8 l, V_r = 0.2 l

3. Refrac - Cycle : Q_i = 3.7 lpm, V_i = 8.7 l, V_r = 0.2 l

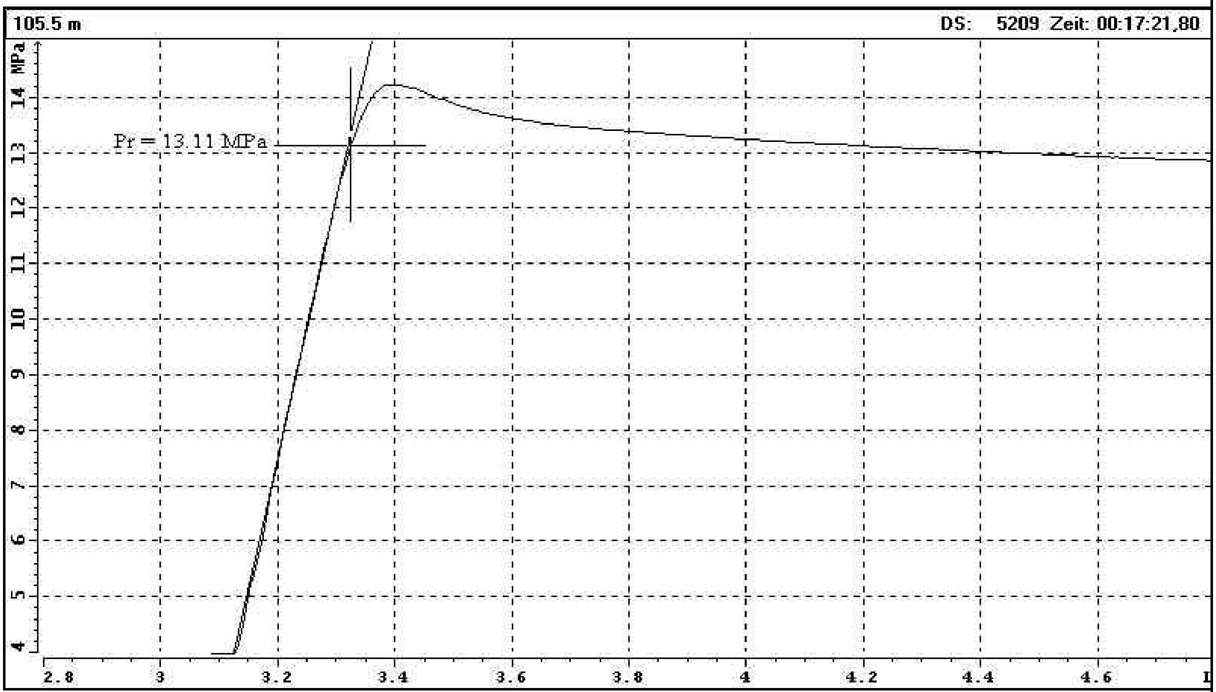
Step-Rate Test : Q_i = 1.5-5.0 lpm, V_i = 15.7 l, V_r = 0.5 l

total injected volume = 35.4 l, recovered volume = 1.2 l (3.4 %)

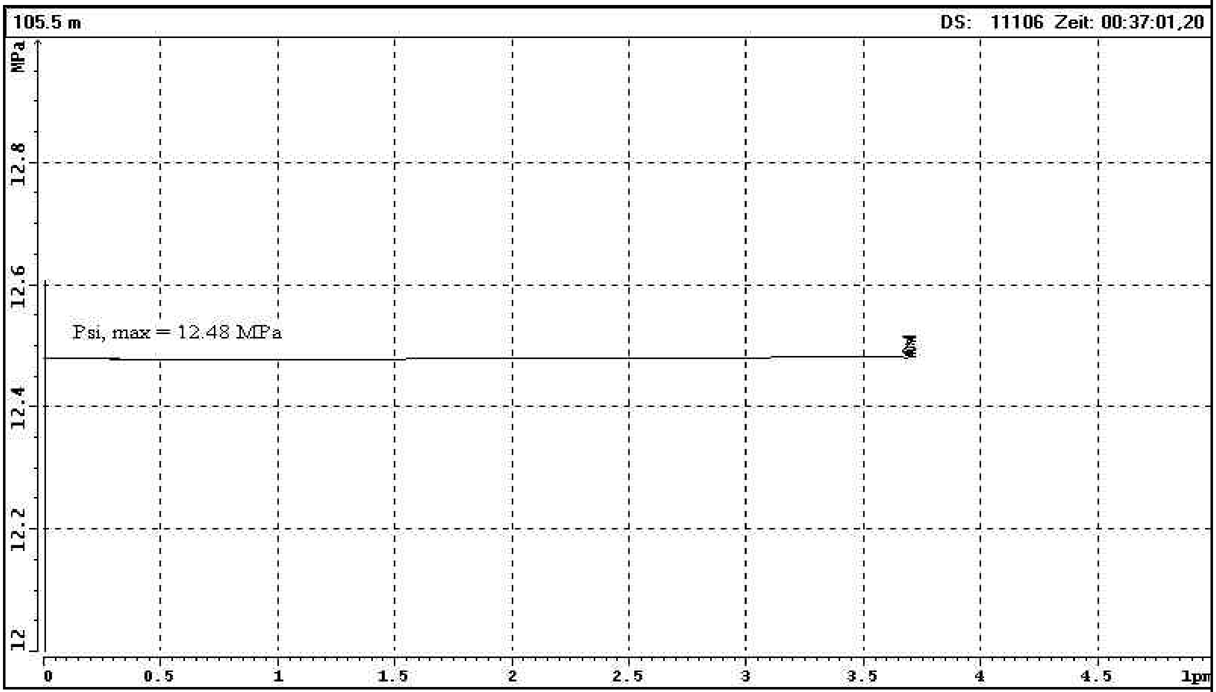
Test at 105.5 m MD: Estimation of P_c (Frac - Cycle)



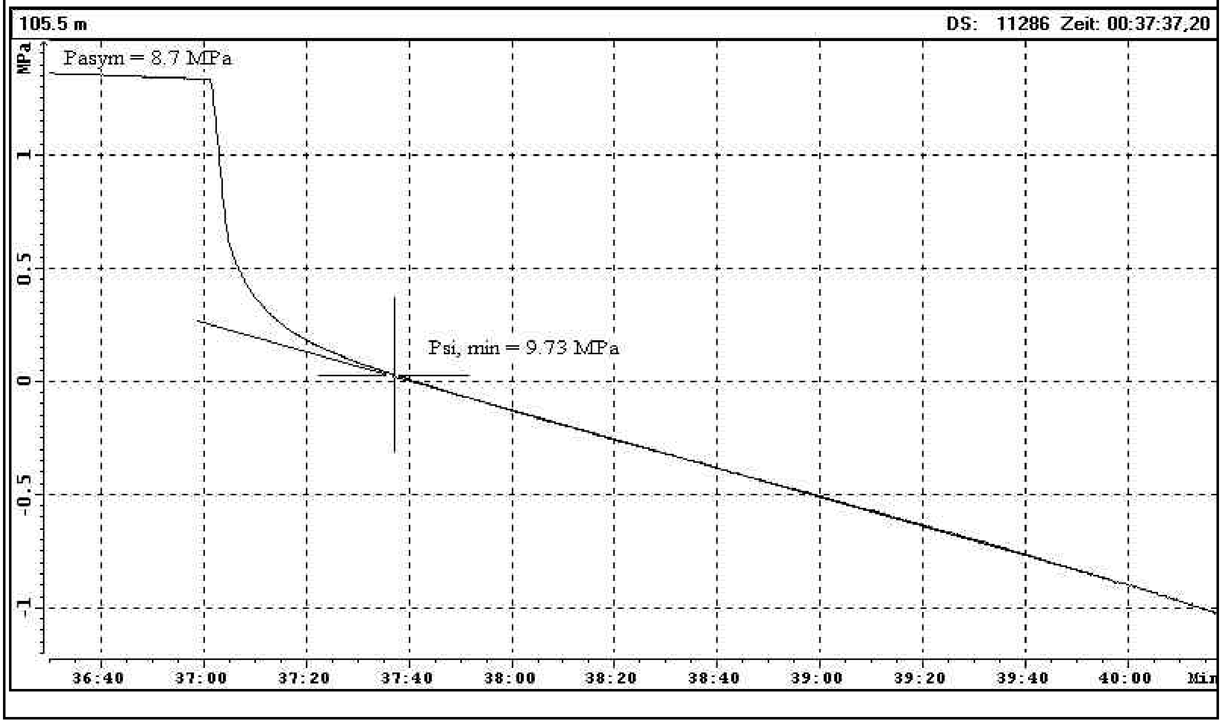
Test at 105.5 m MD: Estimation of P_r (1. Refrac - Cycle)



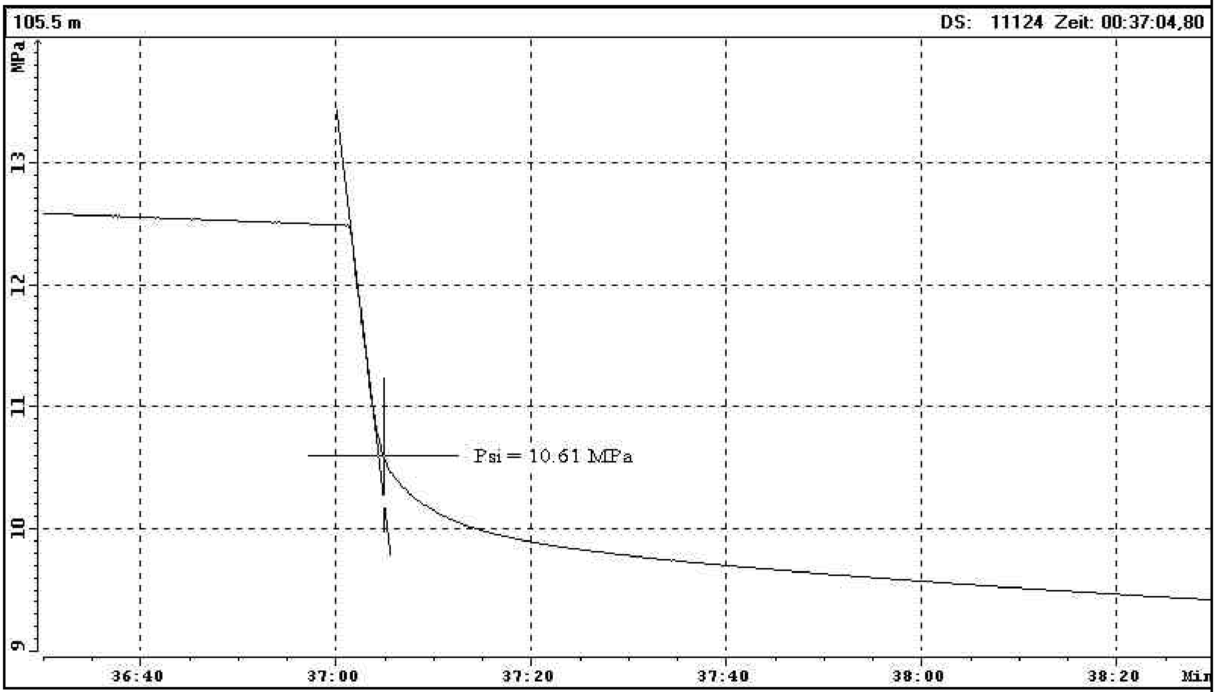
Test at 105.5 m MD: Estimation of $P_{si, max}$ (3. Refrac - Cycle)



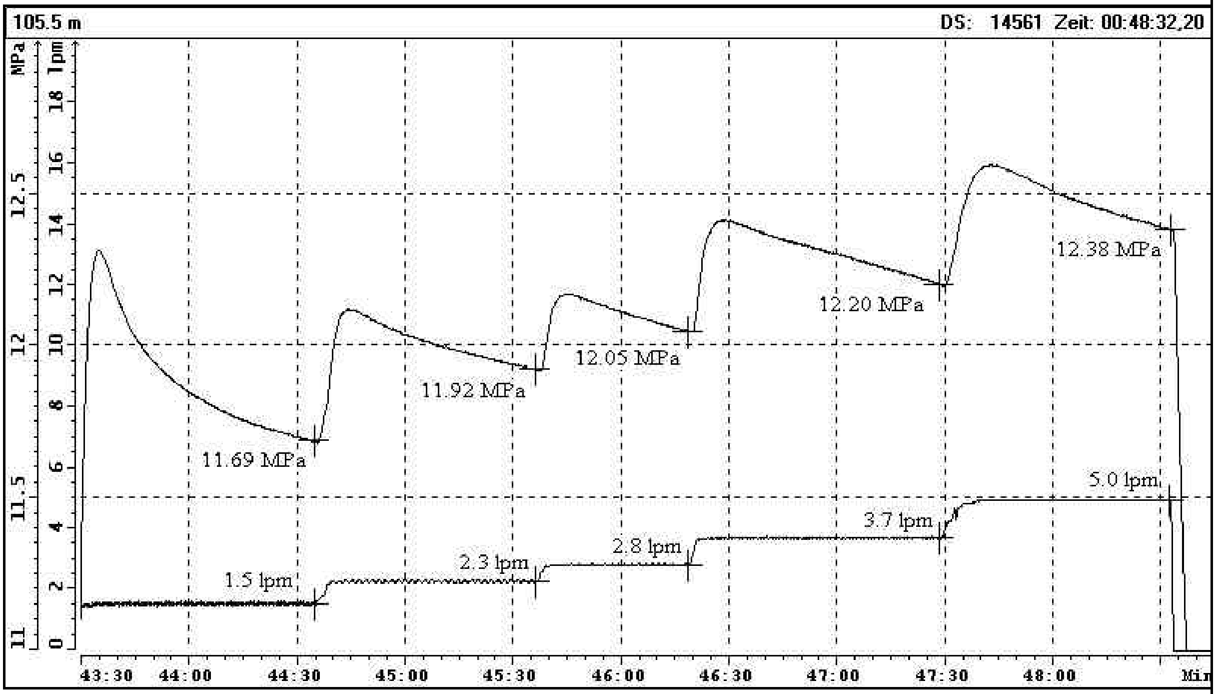
Test at 105.5 m MD: Estimation of $P_{si, min}$ (3. Refrac - Cycle)



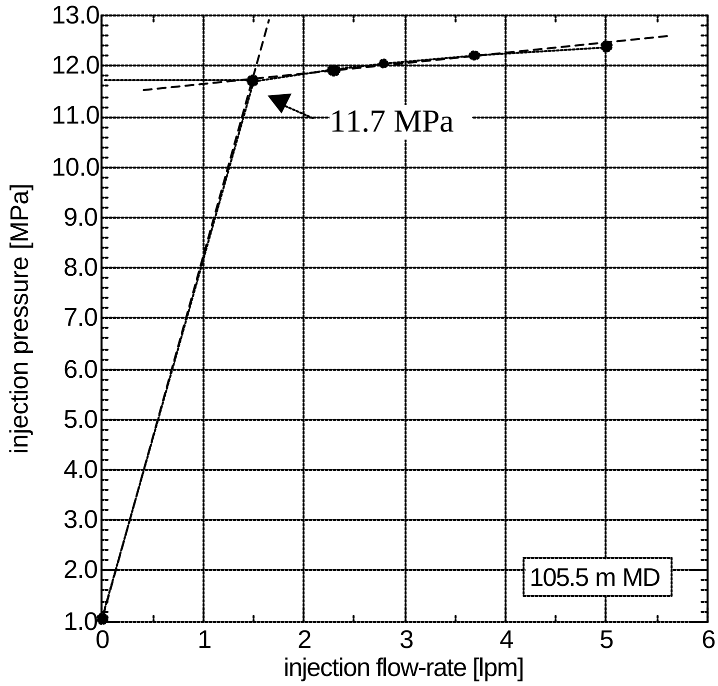
Test at 105.5 m MD: Estimation of P_{si} (3. Refrac - Cycle)



Test at 105.5 m MD: Analysis of Slow - Pump / Step - Rate - Test

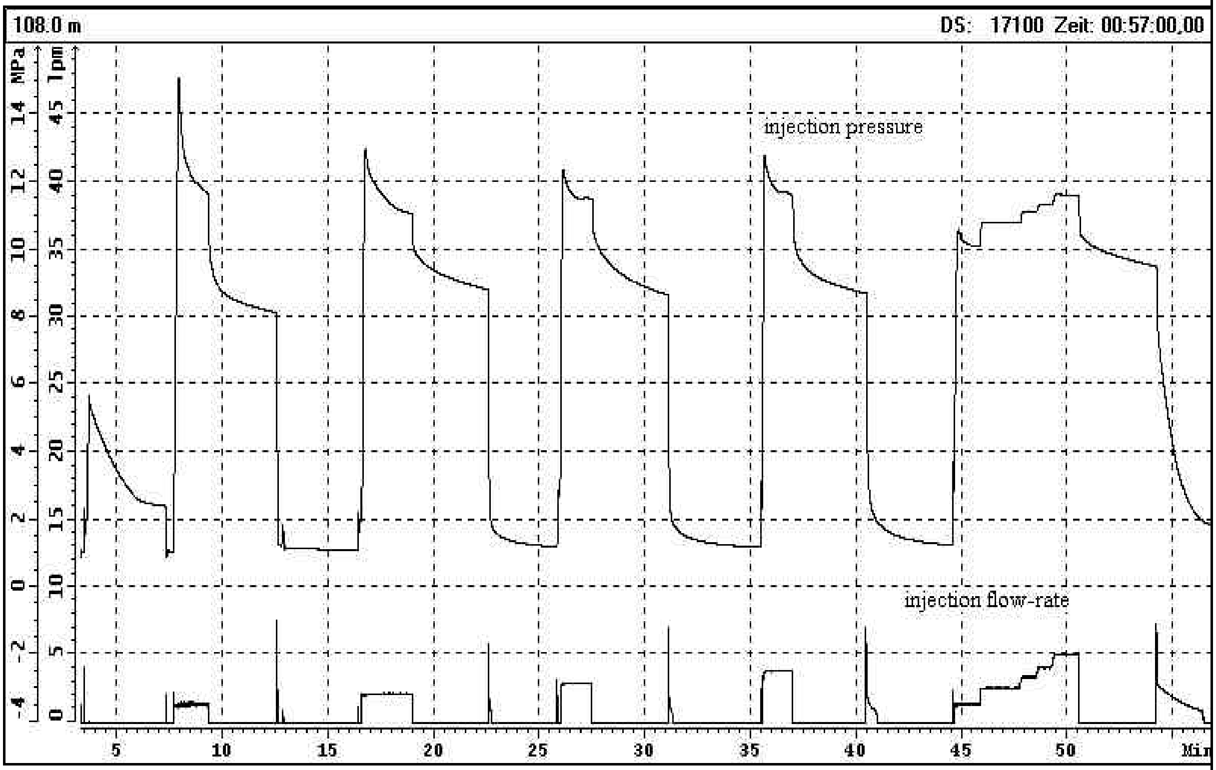


Test at 105.5 m MD: Examination of P_{si} (Step - Rate - Test)



Test at 108.0 M MD / 449.4 M TVD

Test at 108.0 m MD : Overview - Plot



P - Test   Frac   1. Refrac   2. Refrac   3. Refrac   Slow-Pump/Step-Rate Test

<u>Test Summary</u>

P - Test : pressure decrease: 2.9 MPa in 3 min. 34 sec.

Frac - Cycle : injection-rate Q_i= 1.4 lpm, injected volume V_i = 2.2 l, back-flow volume V_r = 0.2 l
clear fracture initiation (breakdown event)

1. Refrac - Cycle : Q_i = 2.1 lpm, V_i = 5.1 l, V_r = 0.3 l

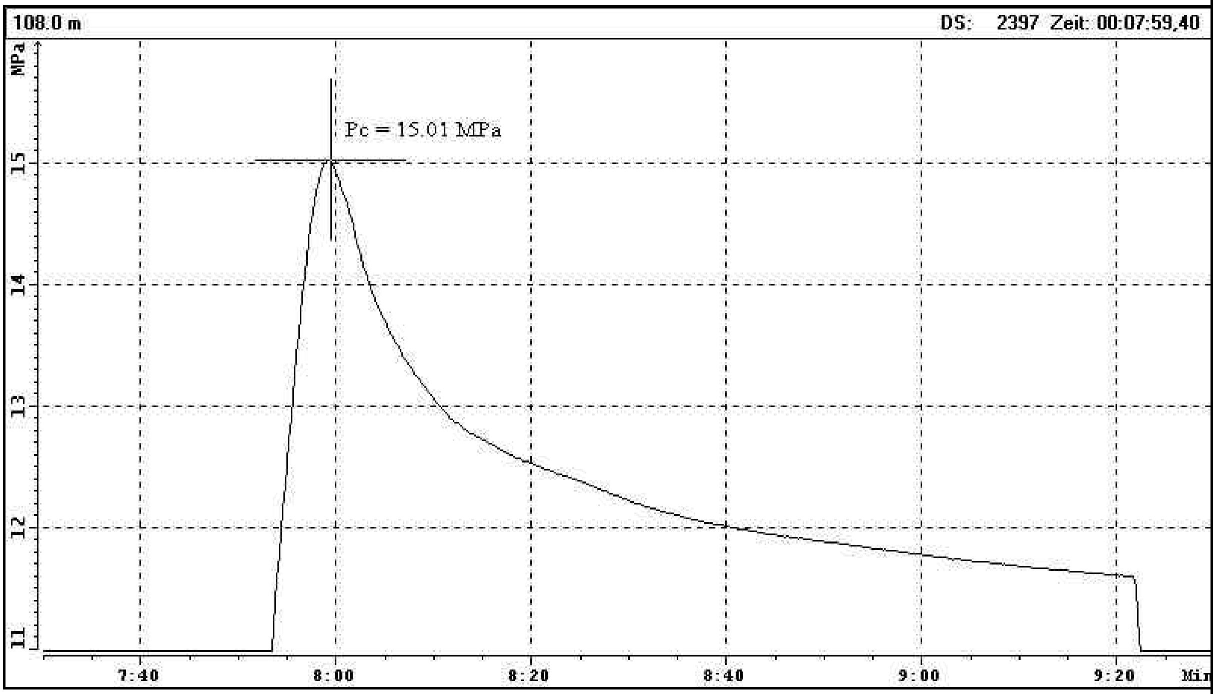
2. Refrac - Cycle : Q_i = 2.9 lpm, V_i = 4.3 l, V_r = 0.4 l

3. Refrac - Cycle : Q_i = 3.9 lpm, V_i = 5.5 l, V_r = 0.8 l

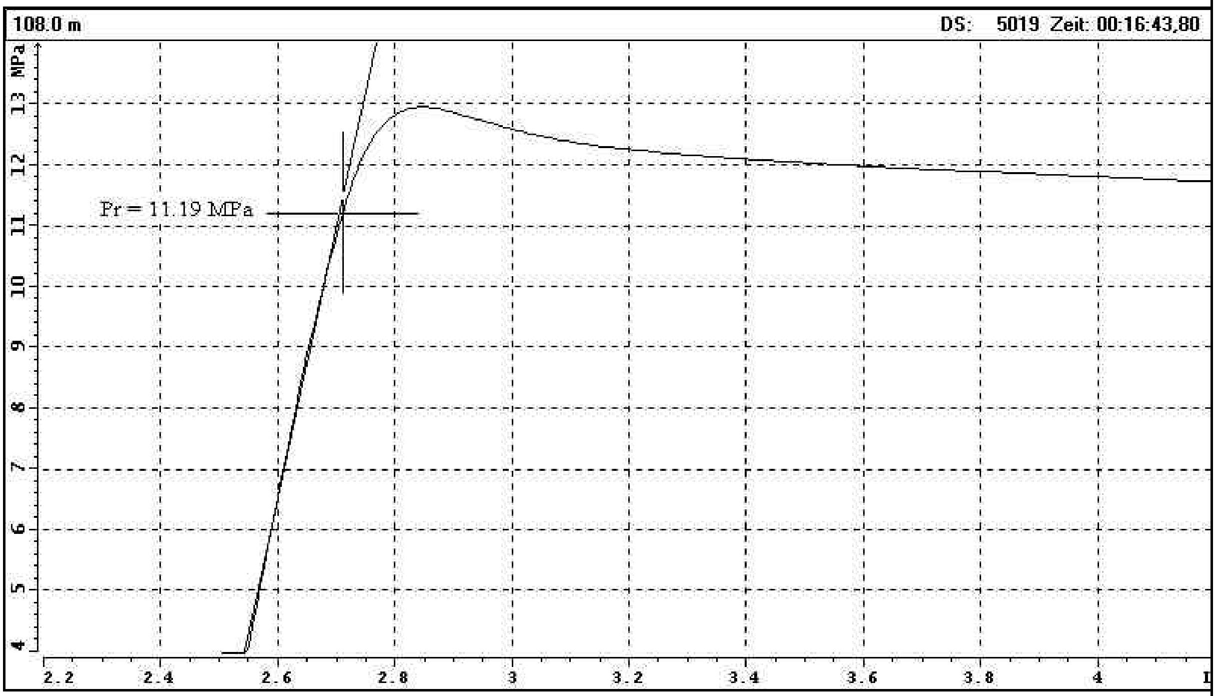
Step-Rate Test : Q_i = 1.4-5.0 lpm, V_i = 18.3 l, V_r = 3.8 l

total injected volume = 35.4 l, recovered volume = 5.5 l (15.5 %)

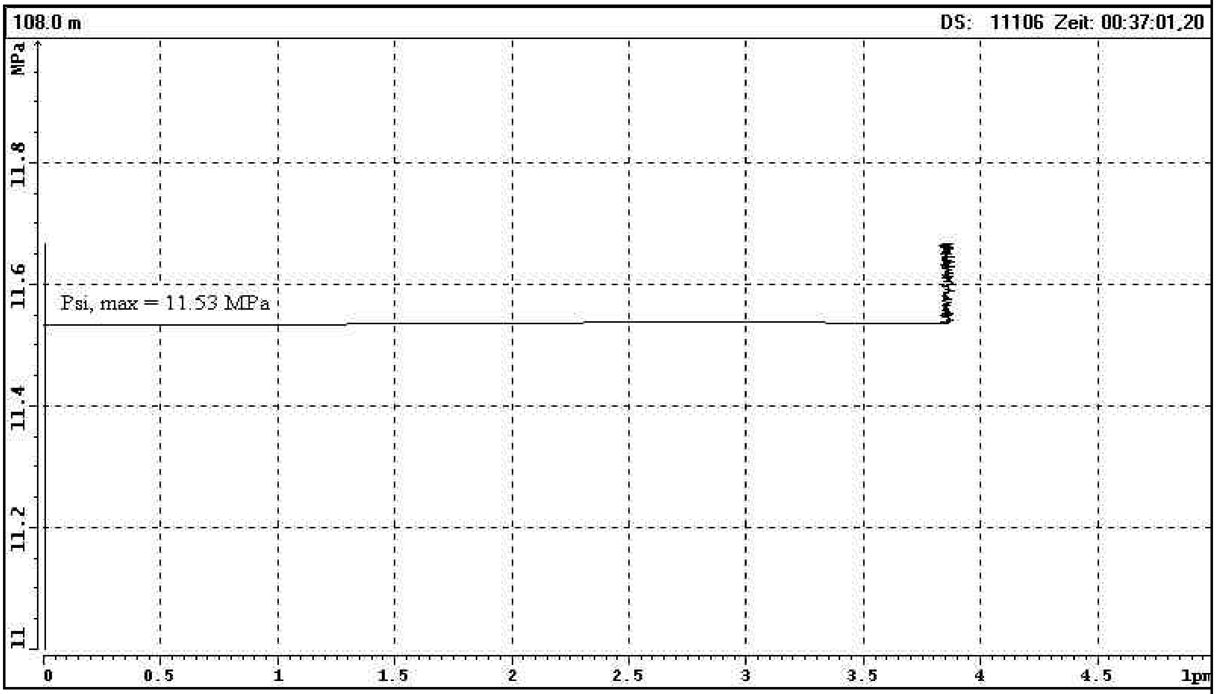
Test at 108.0 m MD: Estimation of P_c (Frac - Cycle)



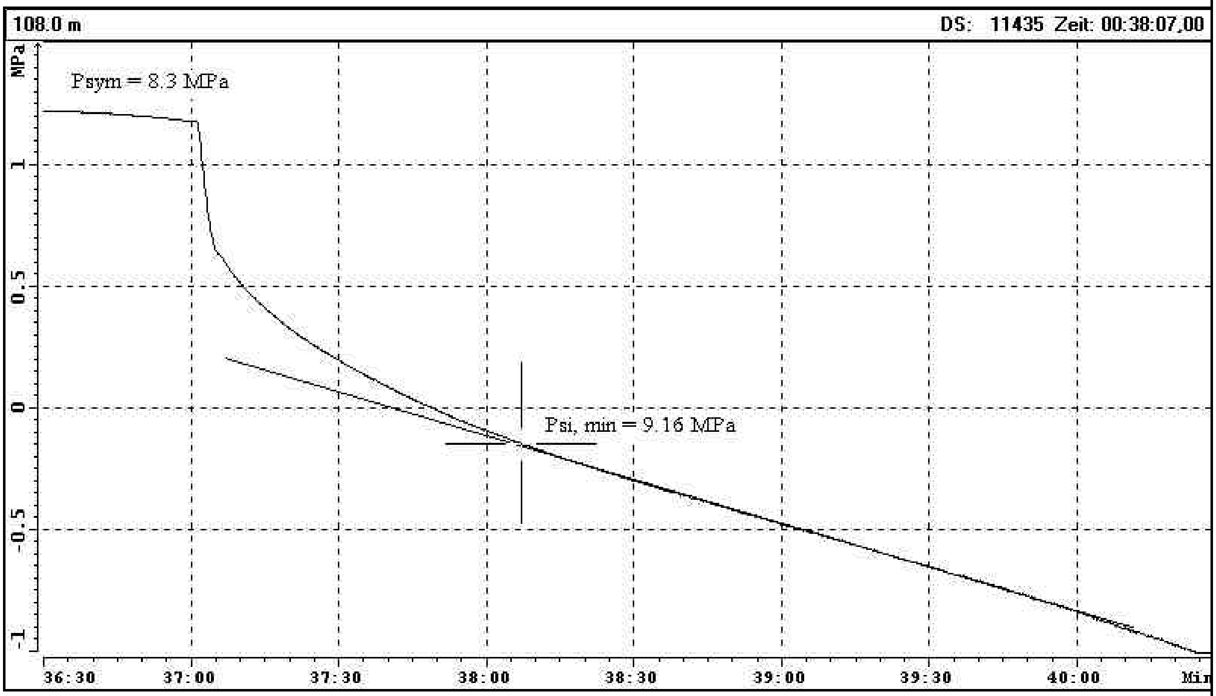
Test at 108.0 m MD: Estimation of P_r (1. Refrac - Cycle)



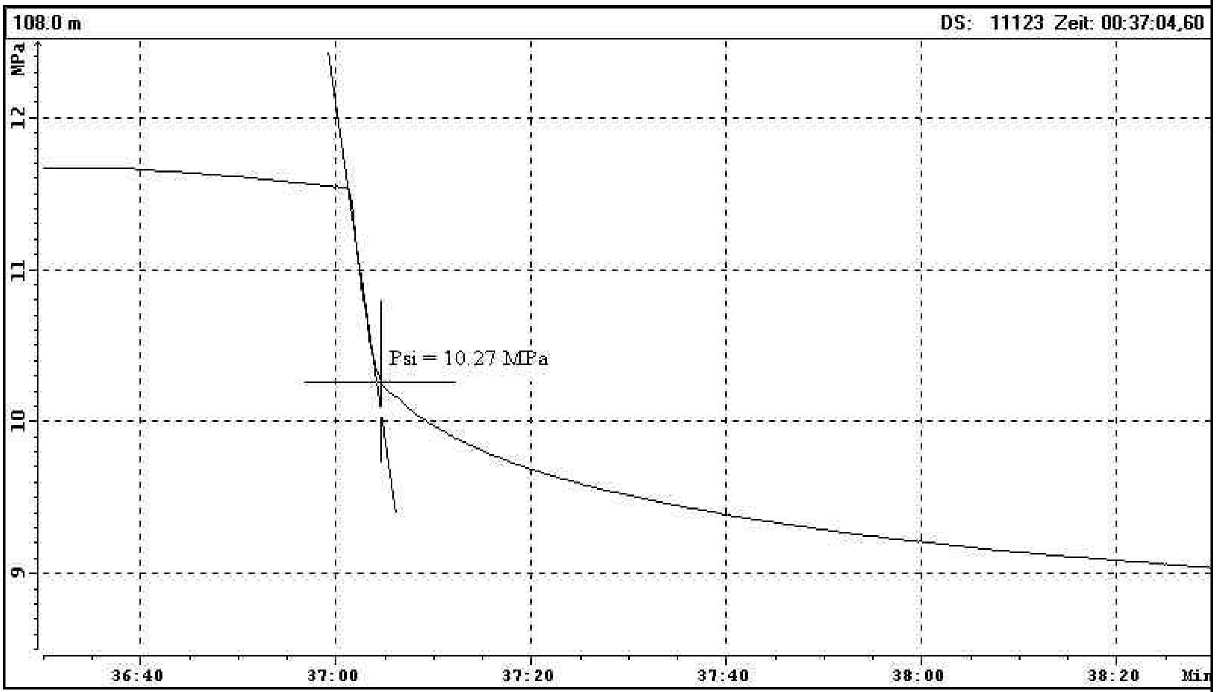
Test at 108.0 m MD: Estimation of $P_{si, max}$ (3. Refrac - Cycle)



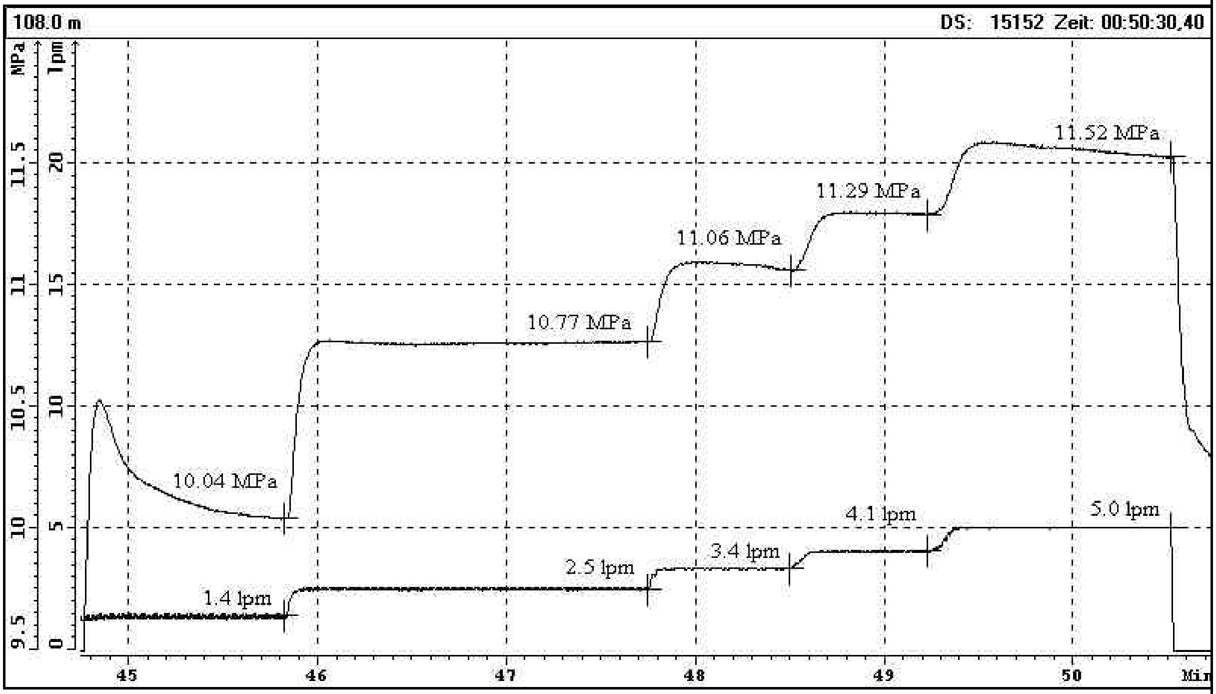
Test at 108.0 m MD: Estimation of $P_{si, min}$ (3. Refrac - Cycle)



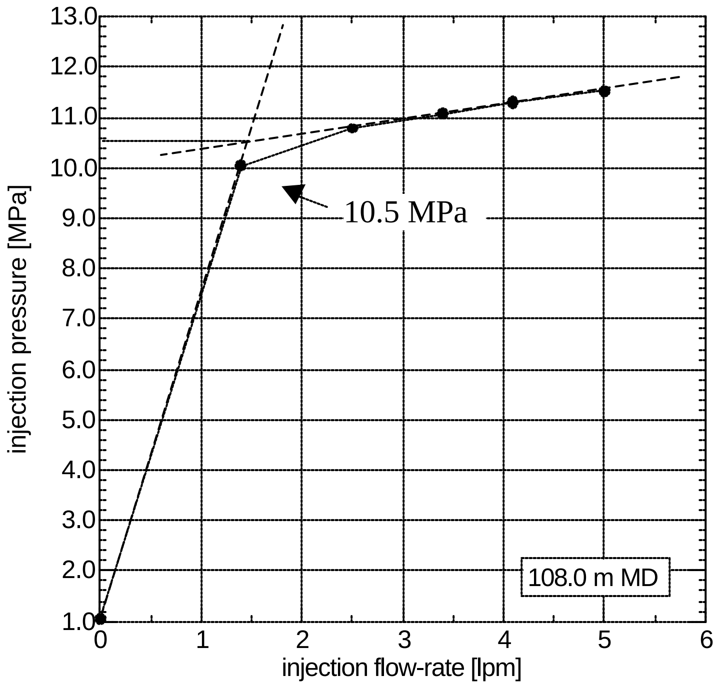
Test at 108.0 m MD: Estimation of P_{si} (3. Refrac - Cycle)



7.1.1 Test at 108.0 m MD: Analysis of Slow - Pump / Step - Rate - Test

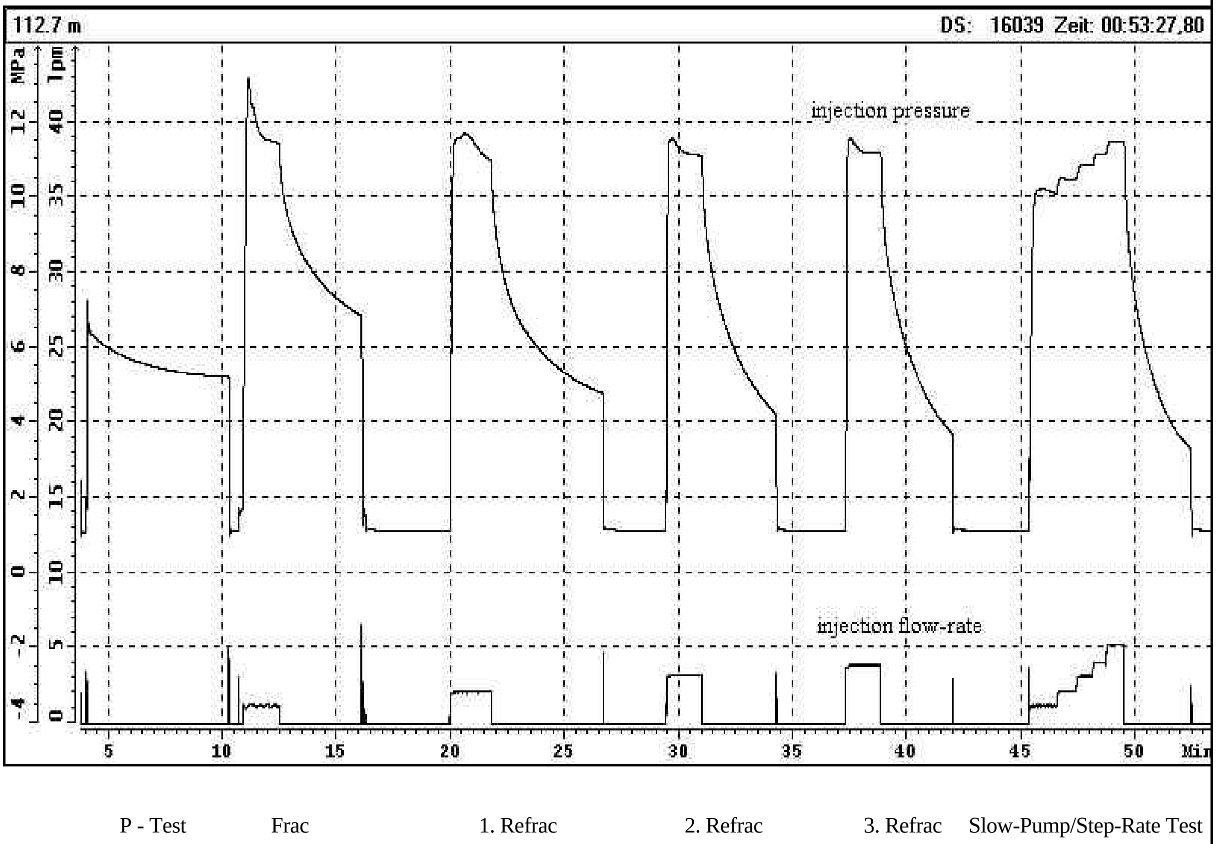


Test at 108.0 m MD: Examination of P_{si} (Step - Rate - Test)



Test at 112.7 M MD / 454.0 M TVD

Test at 112.7 m MD : Overview - Plot



<u>Test Summary</u>

P - Test : pressure decrease: 1.2 MPa in 6 min. 4 sec.

Frac - Cycle : injection-rate Q_i= 1.2 lpm, injected volume V_i = 1.9 l, back-flow volume V_r = 0.1 l
fracture initiation (breakdown event) observed

1. Refrac - Cycle : Q_i = 2.1 lpm, V_i = 3.8 l, V_r = 0.1 l

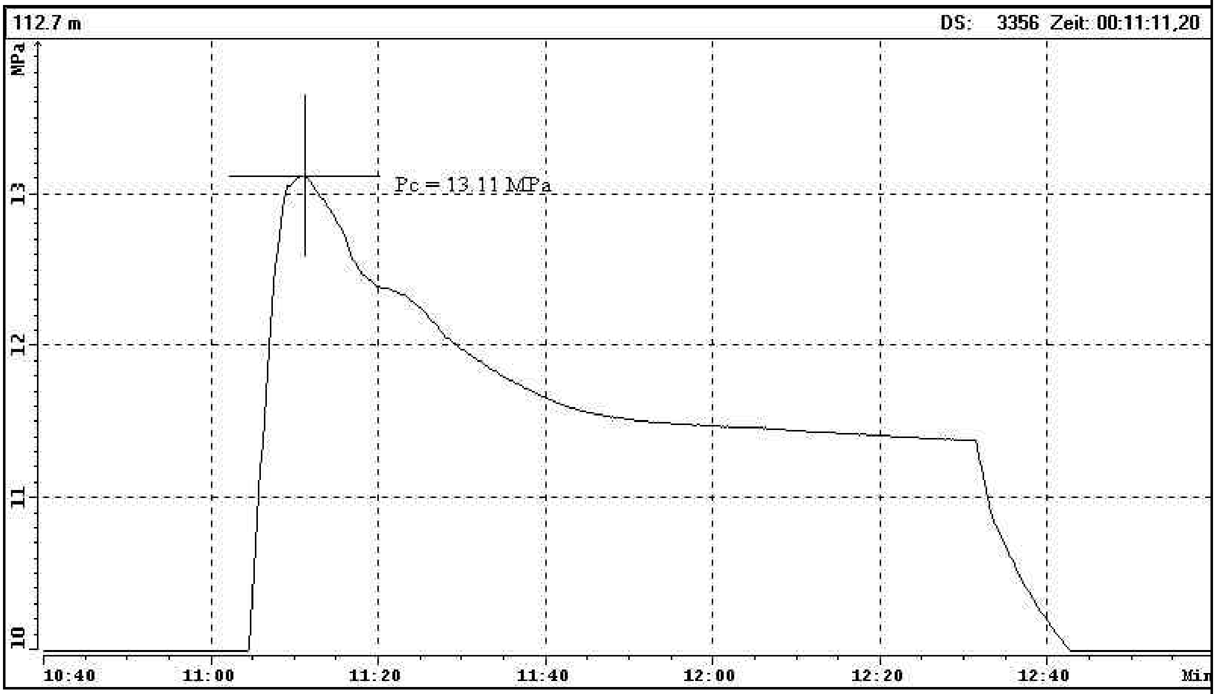
2. Refrac - Cycle : Q_i = 3.2 lpm, V_i = 5.0 l, V_r = 0.1 l

3. Refrac - Cycle : Q_i = 3.9 lpm, V_i = 5.9 l, V_r = 0.1 l

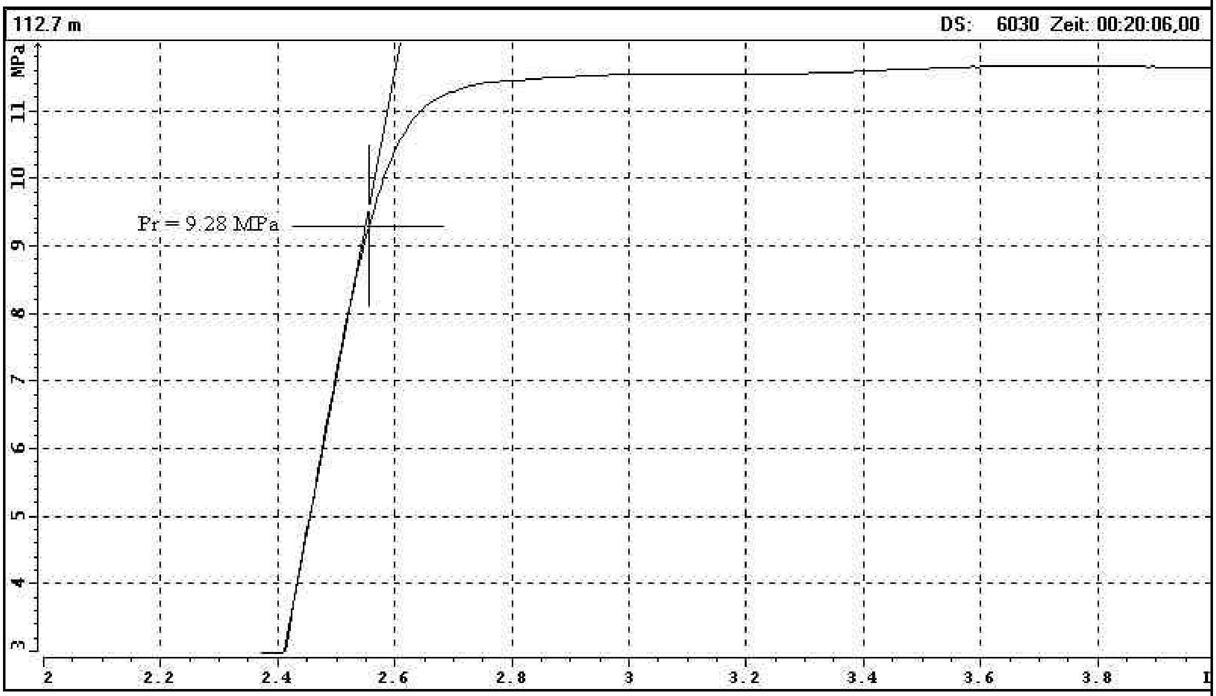
Step-Rate Test : Q_i = 1.1-5.2 lpm, V_i = 12.1 l, V_r = 0.1 l

total injected volume = 28.7 l, recovered volume = 0.5 l (1.7 %)

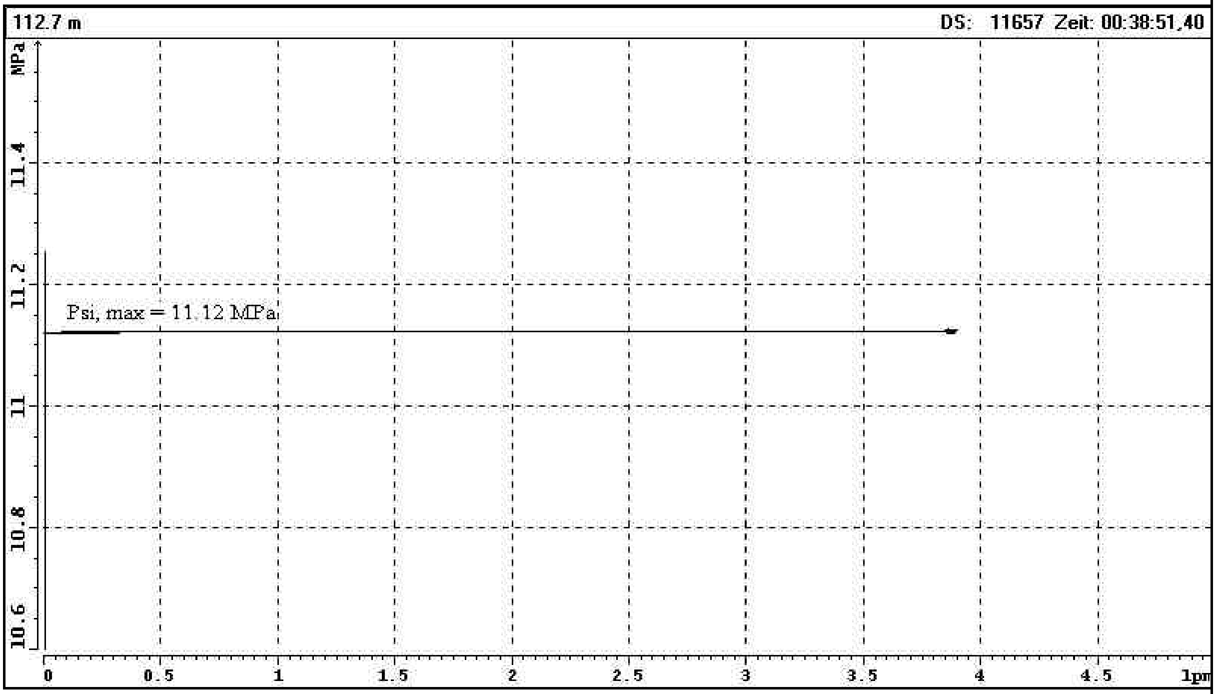
Test at 112.7 m MD: Estimation of P_c (Frac - Cycle)



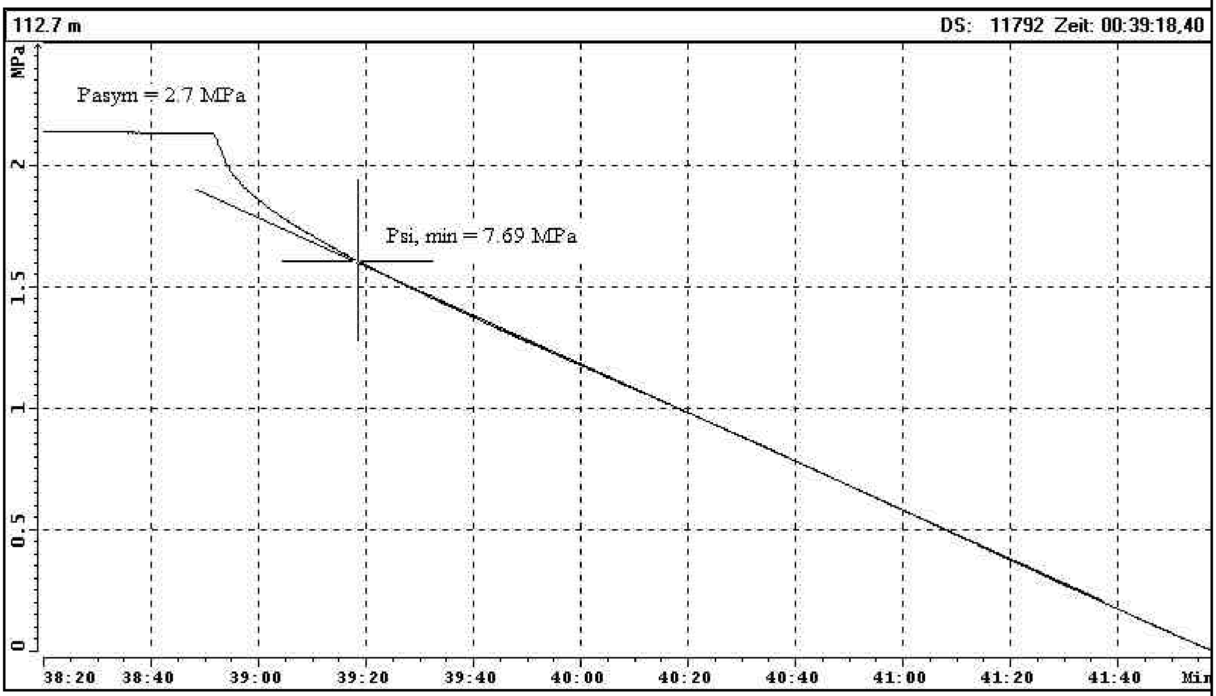
Test at 112.7 m MD: Estimation of P_r (1. Refrac - Cycle)



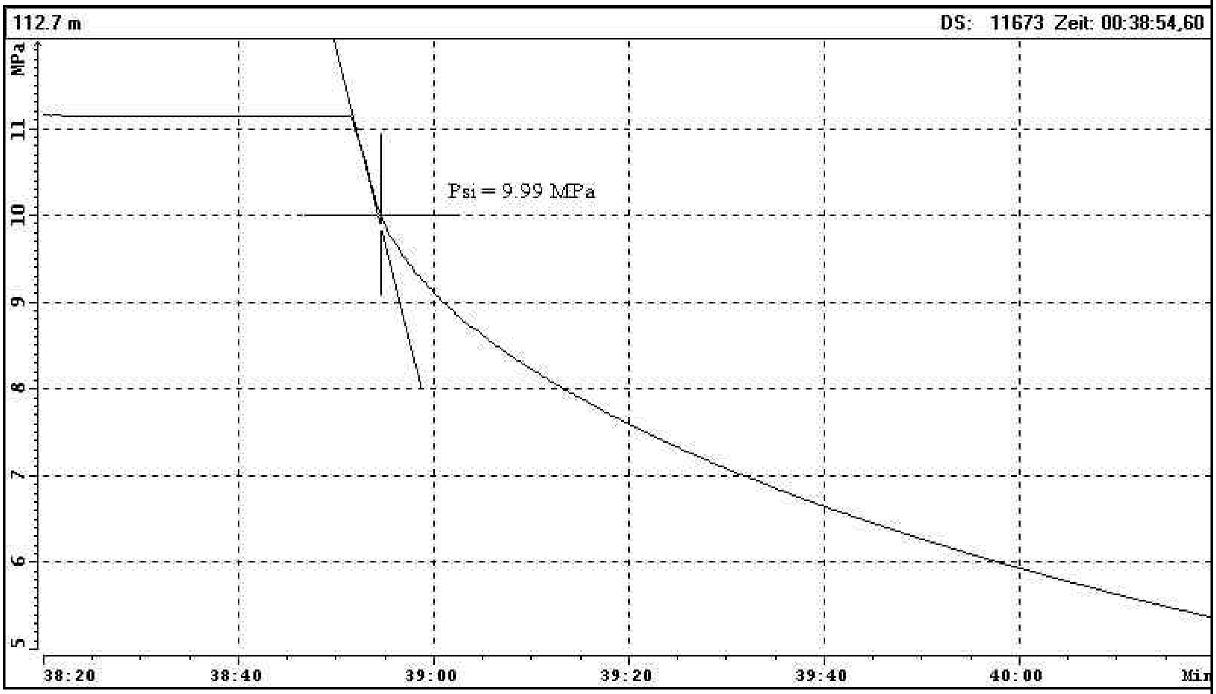
Test at 112.7 m MD: Estimation of $P_{si,max}$ (3. Refrac - Cycle)



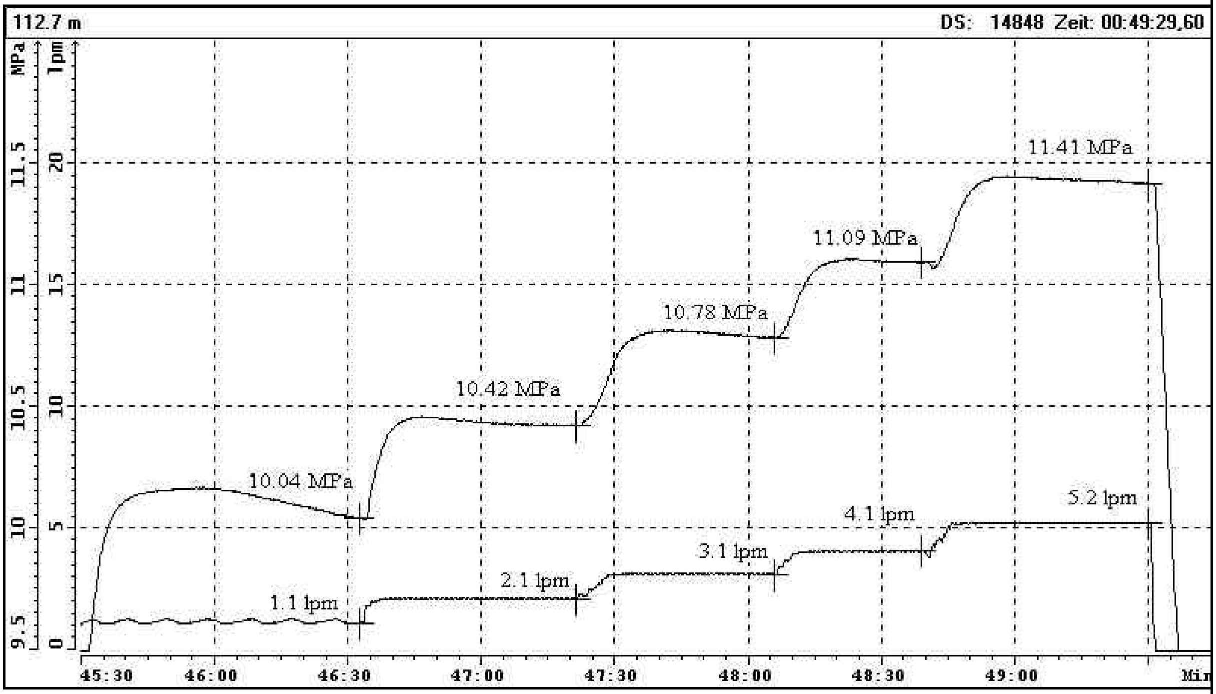
Test at 112.7 m MD: Estimation of $P_{si,min}$ (3. Refrac - Cycle)



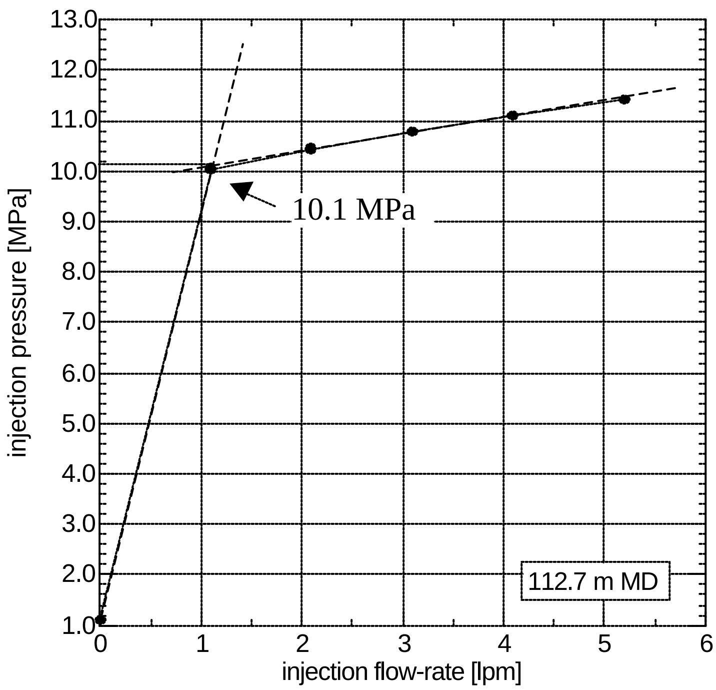
Test at 112.7 m MD: Estimation of P_{si} (3. Refrac - Cycle)



7.1.2 Test at 112.7 m MD: Analysis of Slow - Pump / Step - Rate - Test

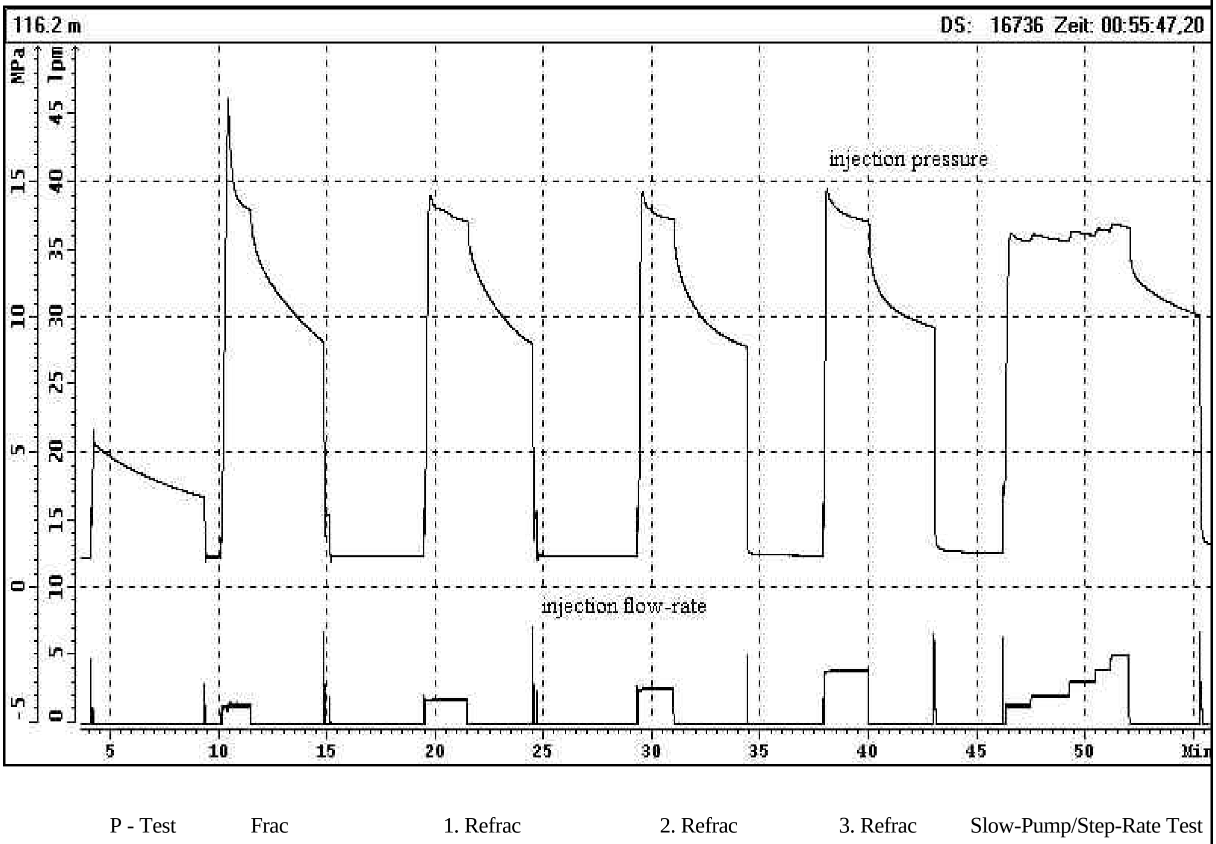


Test at 112.7 m MD: Examination of P_{si} (Step - Rate - Test)



Test at 116.2 M MD / 457.4 M TVD

Test at 116.2 m MD : Overview - Plot

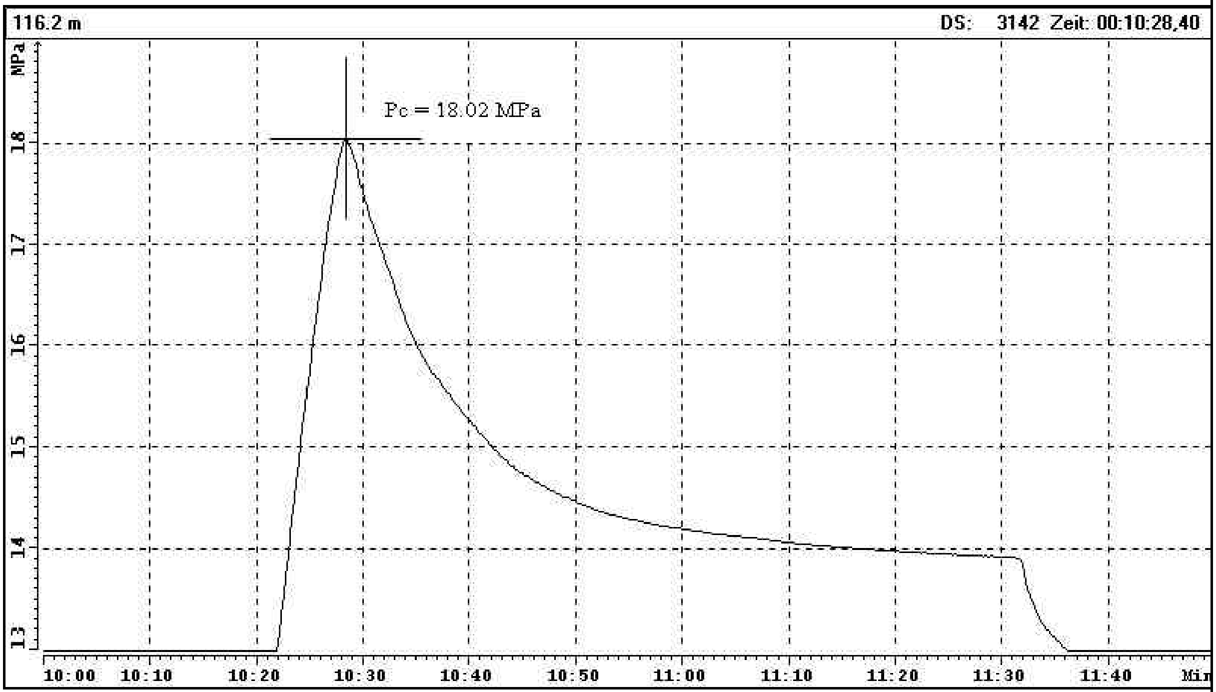


<u>Test Summary</u>

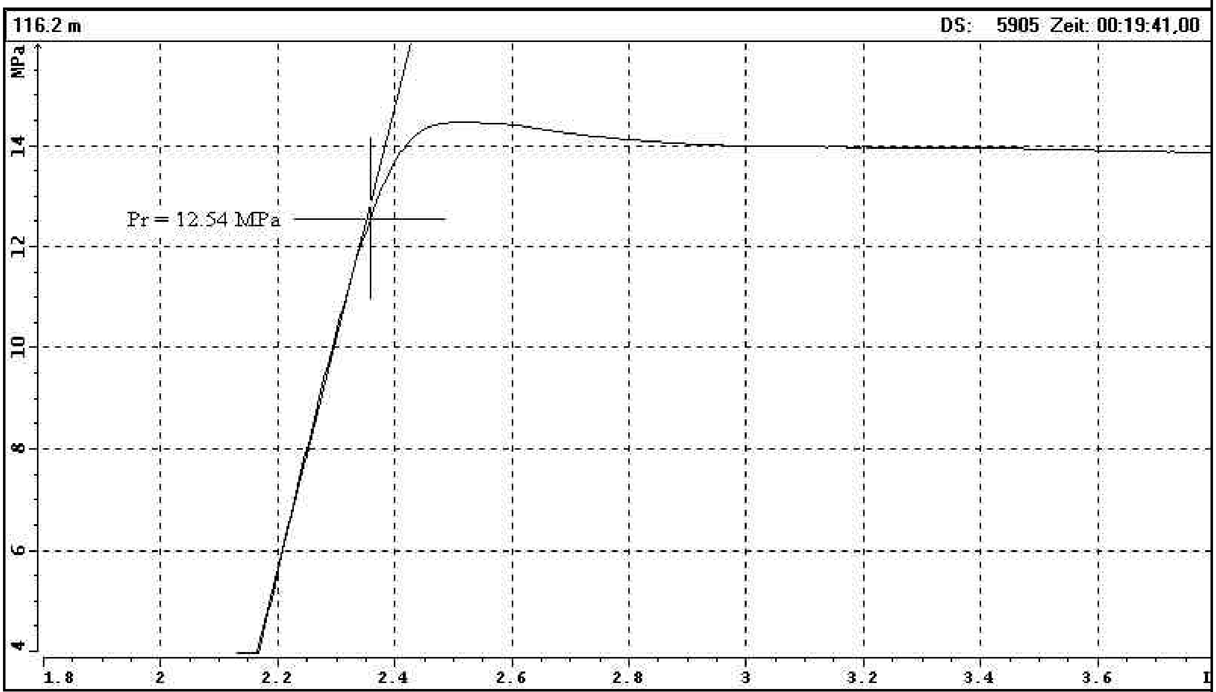
P - Test :	pressure decrease: 1.9 MPa in 5 min.
Frac - Cycle :	injection-rate Q_i= 1.3 lpm, injected volume V_i = 1.8 l, back-flow volume V_r = 0.2 l clear fracture initiation (breakdown event)
1. Refrac - Cycle :	Q_i = 1.8 lpm, V_i = 3.5 l, V_r = 0.2 l
2. Refrac - Cycle :	Q_i = 2.6 lpm, V_i = 4.2 l, V_r = 0.2 l
3. Refrac - Cycle :	Q_i = 3.9 lpm, V_i = 8.0 l, V_r = 0.2 l
Step-Rate Test :	Q_i = 1.4-5.1 lpm, V_i = 16.1 l, V_r = 0.3 l

total injected volume = 33.6 l, recovered volume = 1.1 l (3.3 %)

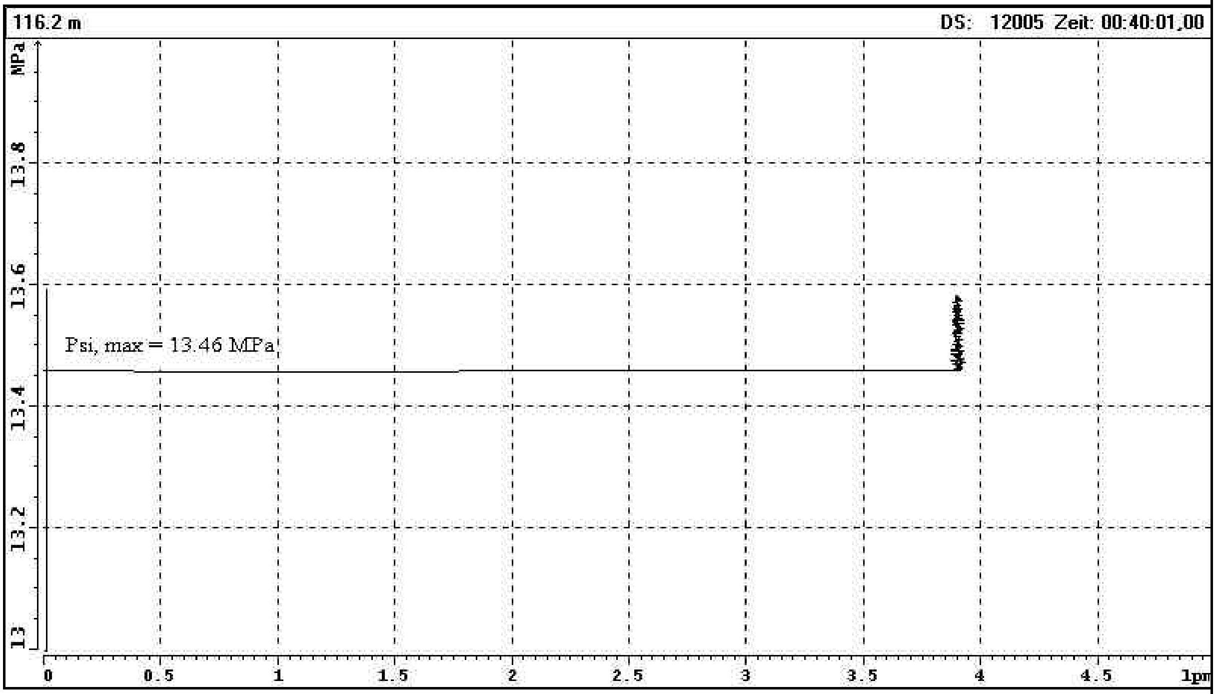
Test at 116.2 m MD: Estimation of P_c (Frac - Cycle)



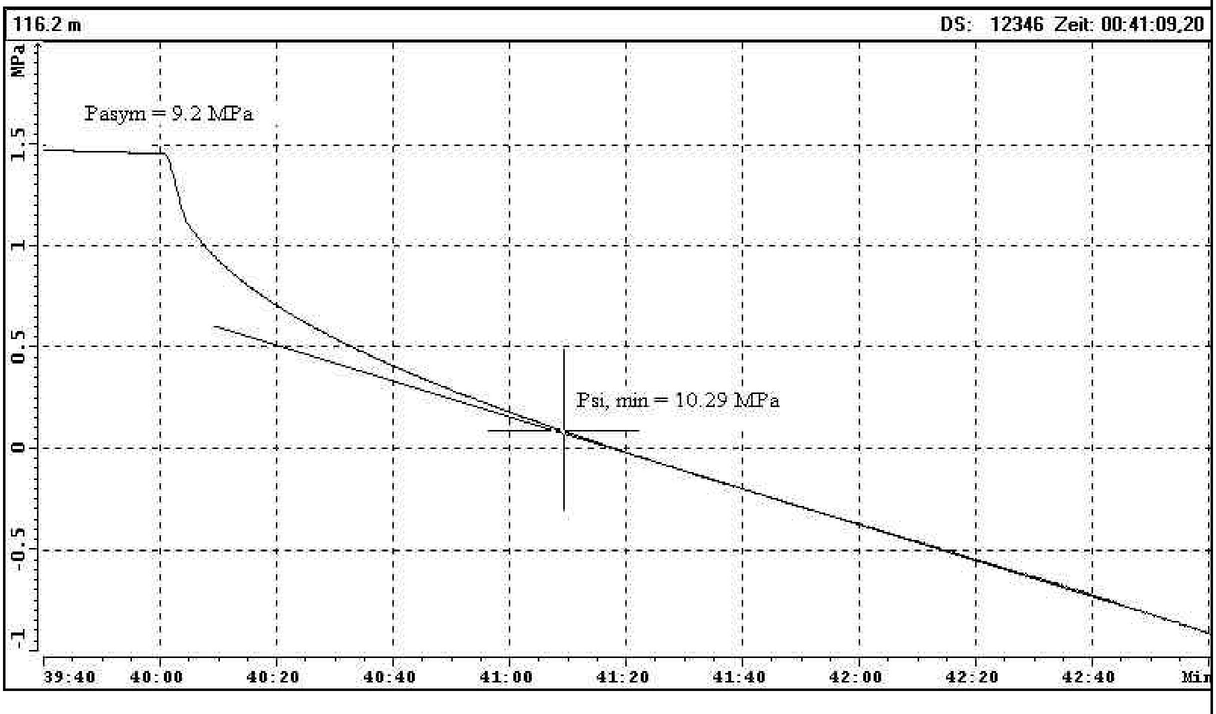
Test at 116.2 m MD: Estimation of P_r (1. Refrac - Cycle)



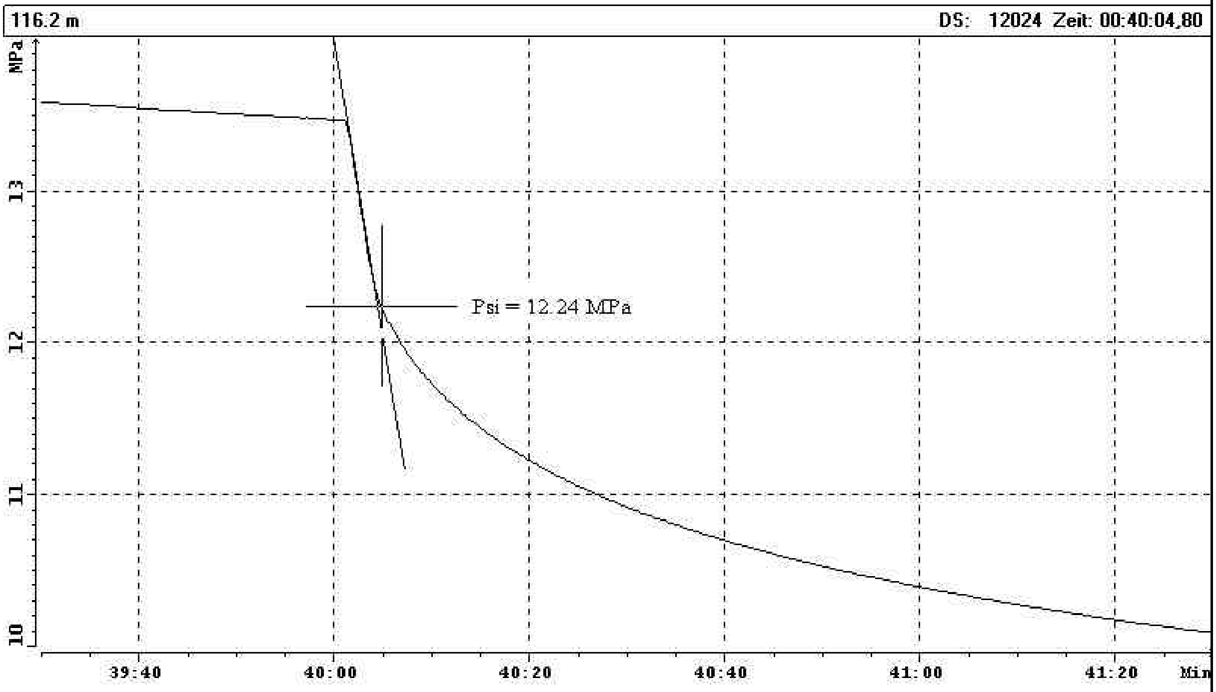
Test at 116.2 m MD: Estimation of $P_{si, max}$ (3. Refrac - Cycle)



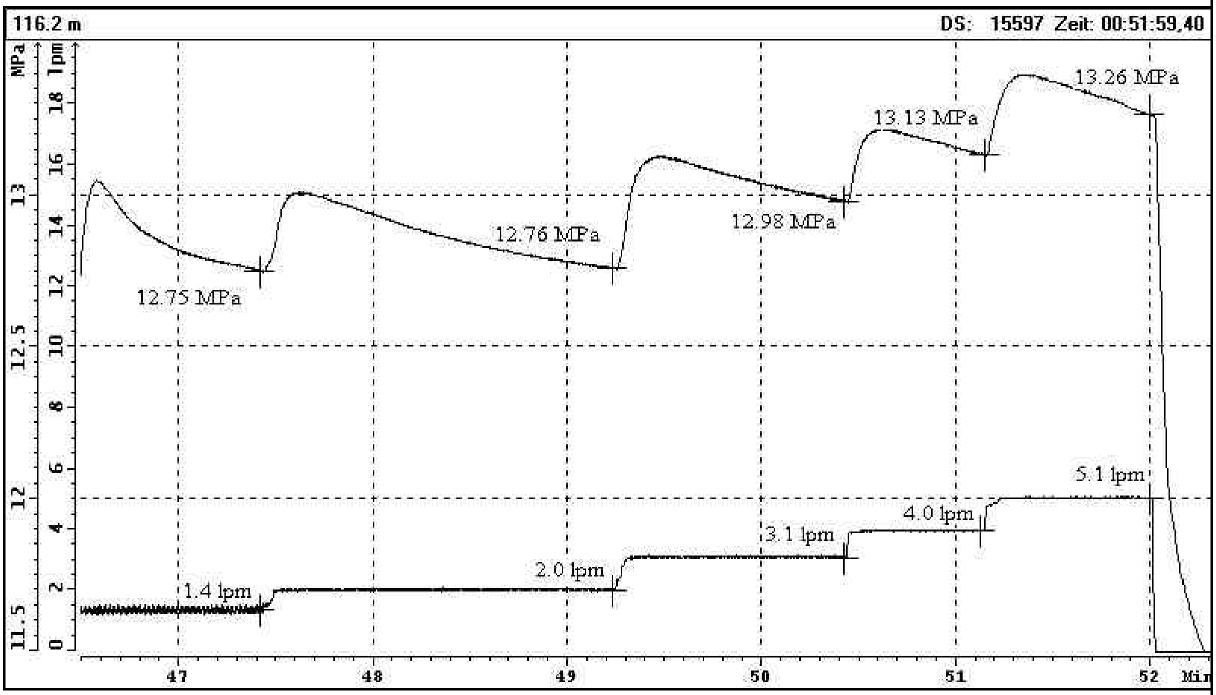
Test at 116.2 m MD: Estimation of $P_{si, min}$ (3. Refrac - Cycle)



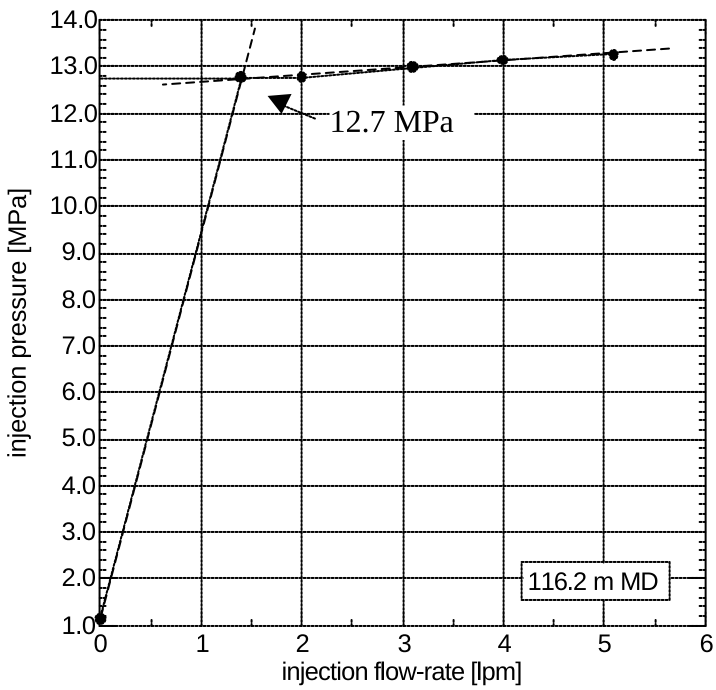
Test at 116.2 m MD: Estimation of P_{si} (3. Refrac - Cycle)



Test at 116.2 m MD: Analysis of Slow - Pump / Step - Rate - Test

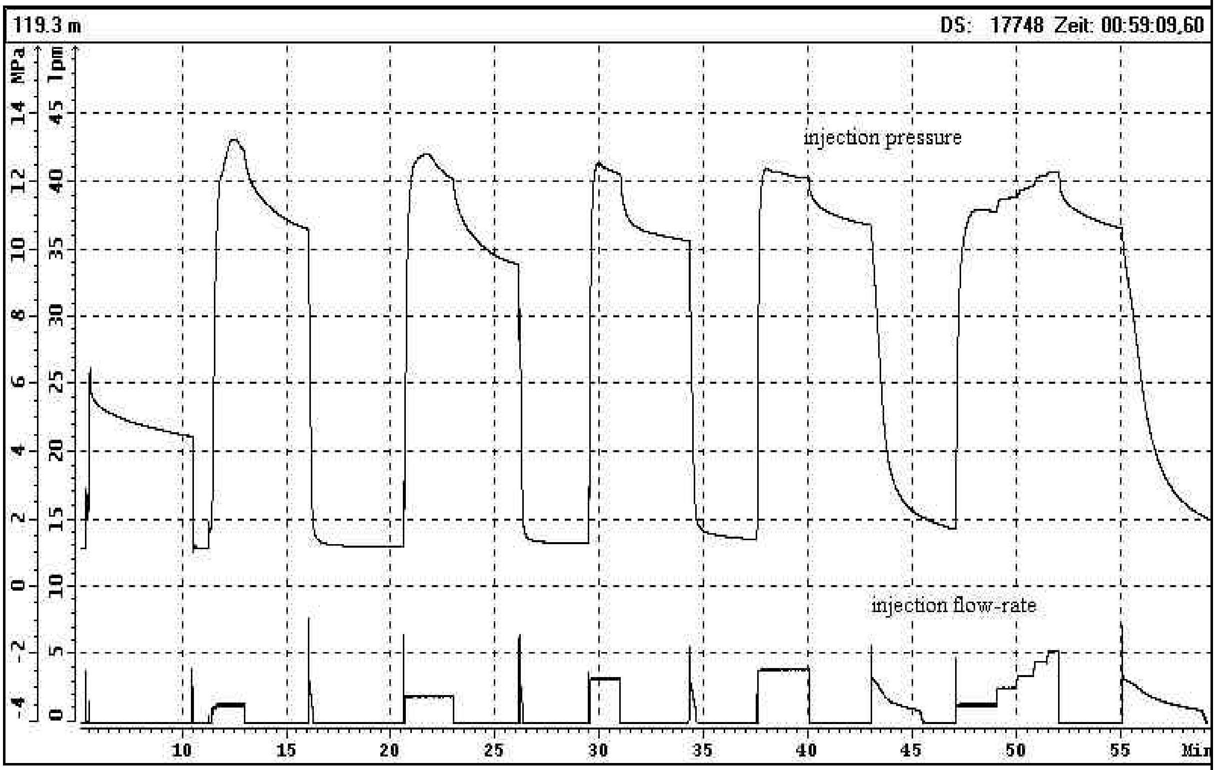


Test at 116.2 m MD: Examination of P_{si} (Step - Rate - Test)



Test at 119.3 M MD / 460.5 M TVD

Test at 119.3 m MD : Overview - Plot



P - Test Frac (1. Refrac) 2. Refrac 3. Refrac 4. Refrac Slow-Pump/Step-Rate Test

<u>Test Summary</u>

P - Test : pressure decrease: 1.3 MPa in 4 min. 51 sec.

Frac (1. Refrac) - Cycle : injection-rate Q_i= 1.3 lpm, injected volume V_i = 2.1 l, back-flow volume V_r = 0.5 l stimulation of an existing fracture (no breakdown event)

2. Refrac - Cycle : Q_i = 1.9 lpm, V_i = 4.6 l, V_r = 0.4 l

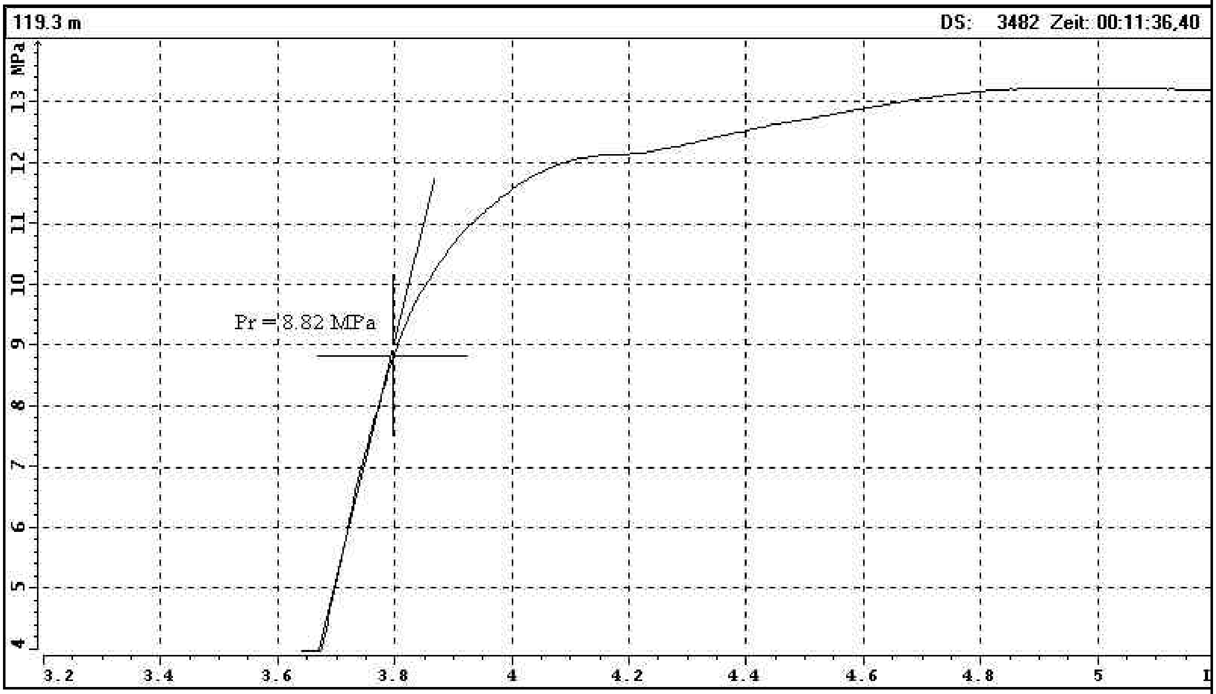
3. Refrac - Cycle : Q_i = 3.3 lpm, V_i = 4.9 l, V_r = 0.8 l

4. Refrac - Cycle : Q_i = 3.9 lpm, V_i = 9.6 l, V_r = 4.0 l

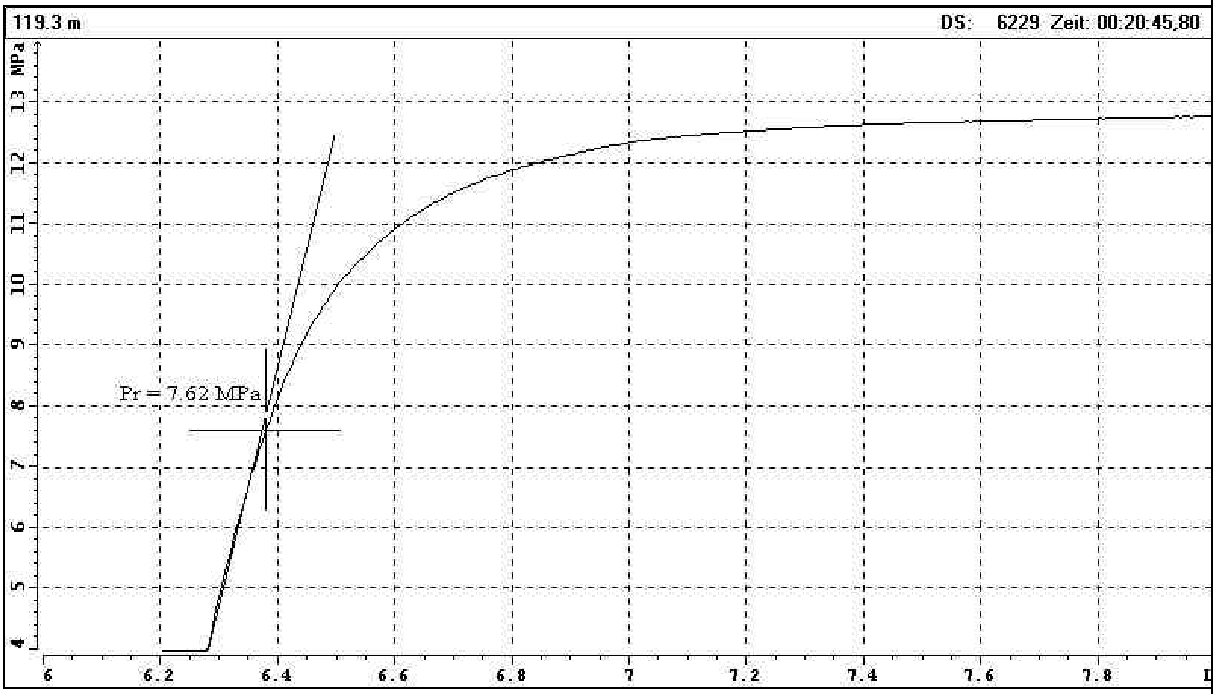
Step-Rate Test : Q_i = 1.3-5.3 lpm, V_i = 13.6 l, V_r = 7.0 l

total injected volume = 34.8 l, recovered volume = 12.7 l (36.5 %)

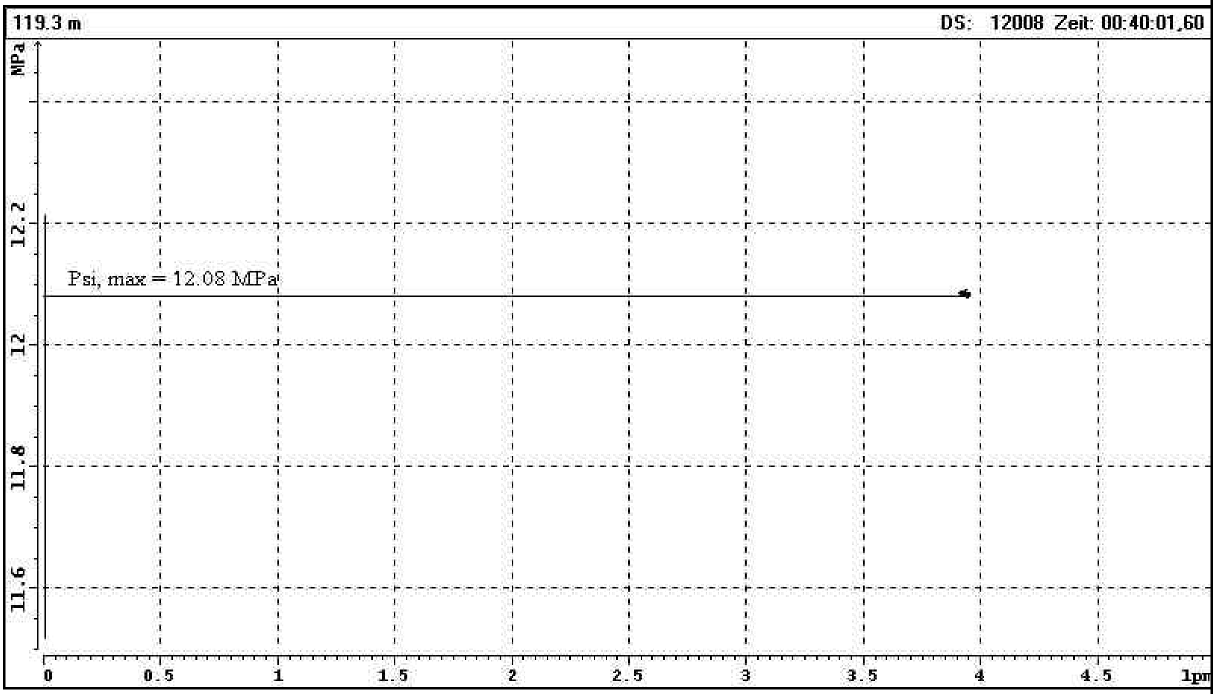
Test at 119.3 m MD: Estimation of P_r (Frac (1. Refrac) - Cycle)



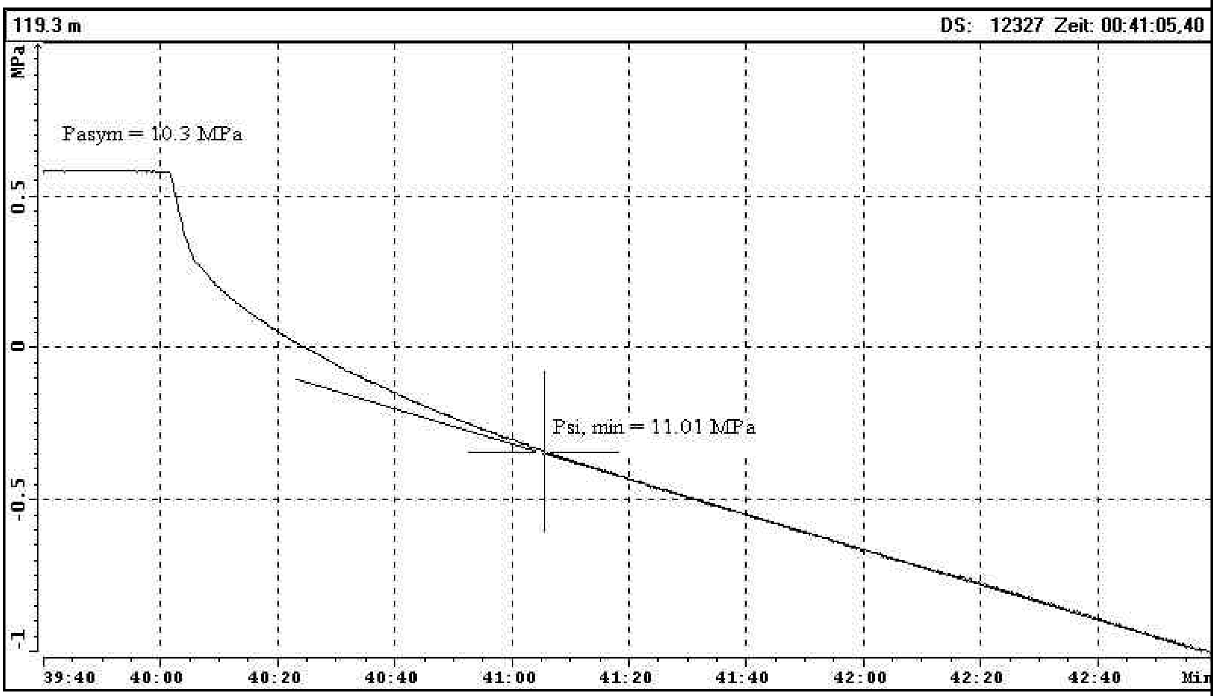
Test at 119.3 m MD: Estimation of P_r (2. Refrac - Cycle, for comparison)



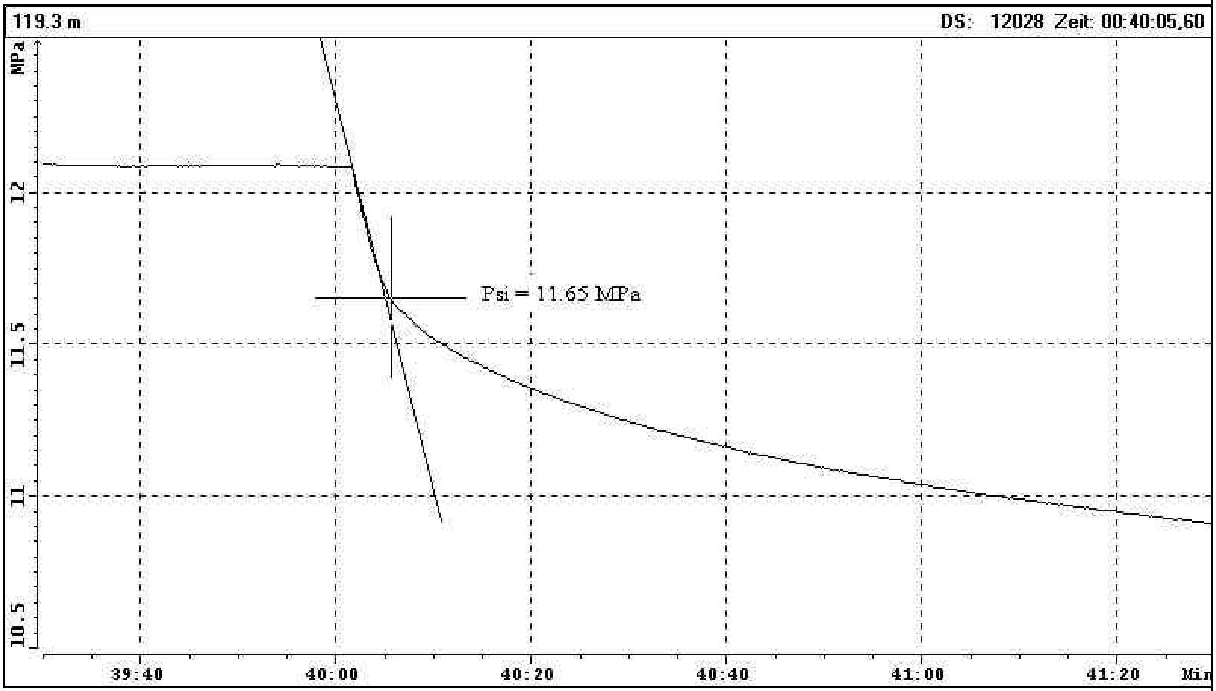
Test at 119.3 m MD: Estimation of $P_{si, max}$ (4. Refrac - Cycle)



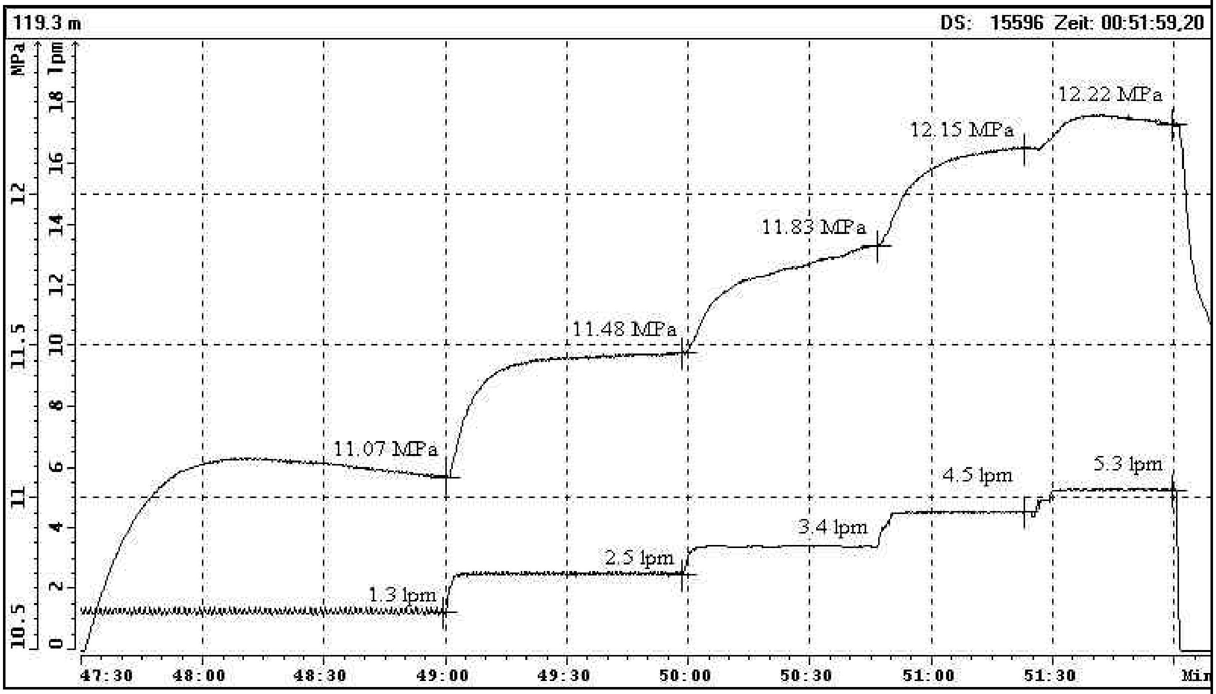
Test at 119.3 m MD: Estimation of $P_{si, min}$ (4. Refrac - Cycle)



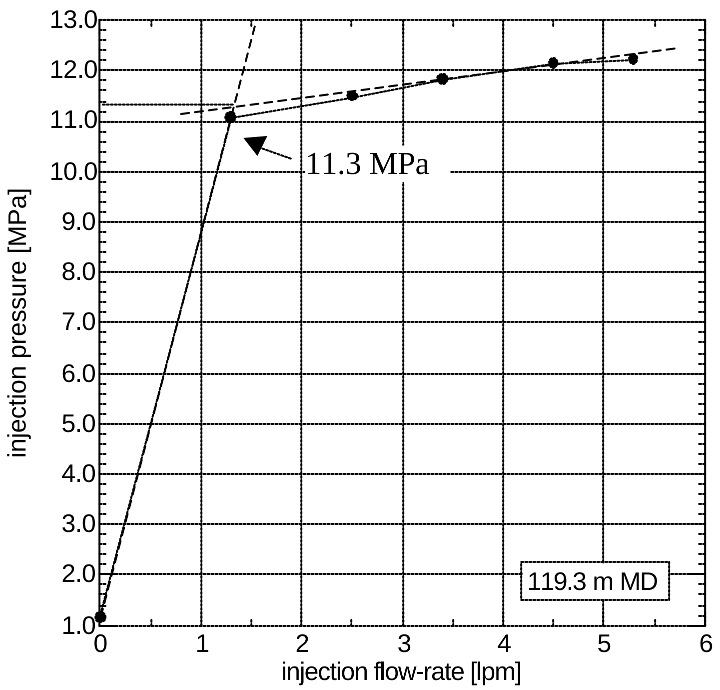
Test at 119.3 m MD: Estimation of P_{si} (4. Refrac - Cycle)



Test at 119.3 m MD: Analysis of Slow - Pump / Step - Rate - Test

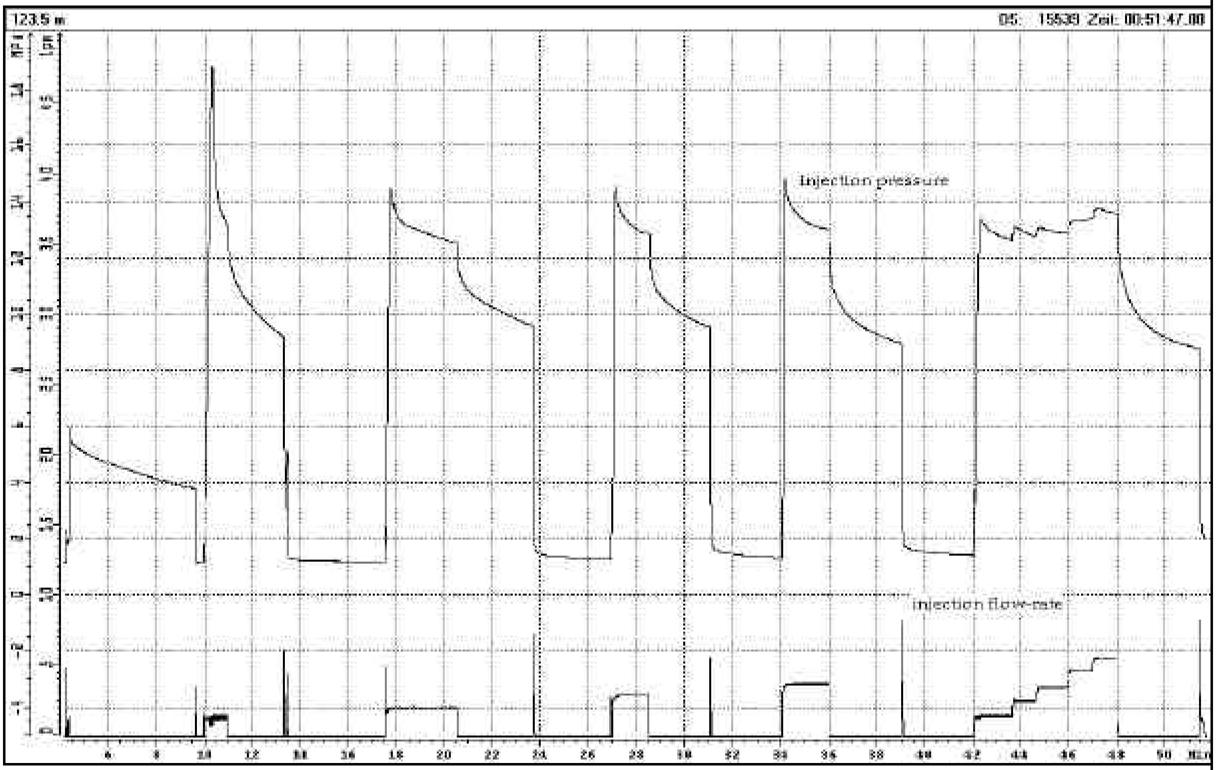


Test at 119.3 m MD: Examination of P_{si} (Step - Rate - Test)



Test at 123.5 M MD / 464.5 M TVD

Test at 123.5 m MD : Overview - Plot



P - Test   Frac   1. Refrac   2. Refrac   3. Refrac   Slow-Pump/Step-Rate Test

<u>Test Summary</u>

P - Test : pressure decrease: 1.6 MPa in 5 min. 8 sec.

Frac - Cycle : injection-rate Q_i= 1.2 lpm, injected volume V_i = 1.3 l, back-flow volume V_r = 0.2 l
clear fracture initiation (breakdown event)

1. Refrac - Cycle : Q_i = 2.0 lpm, V_i = 6.0 l, V_r = 0.2 l

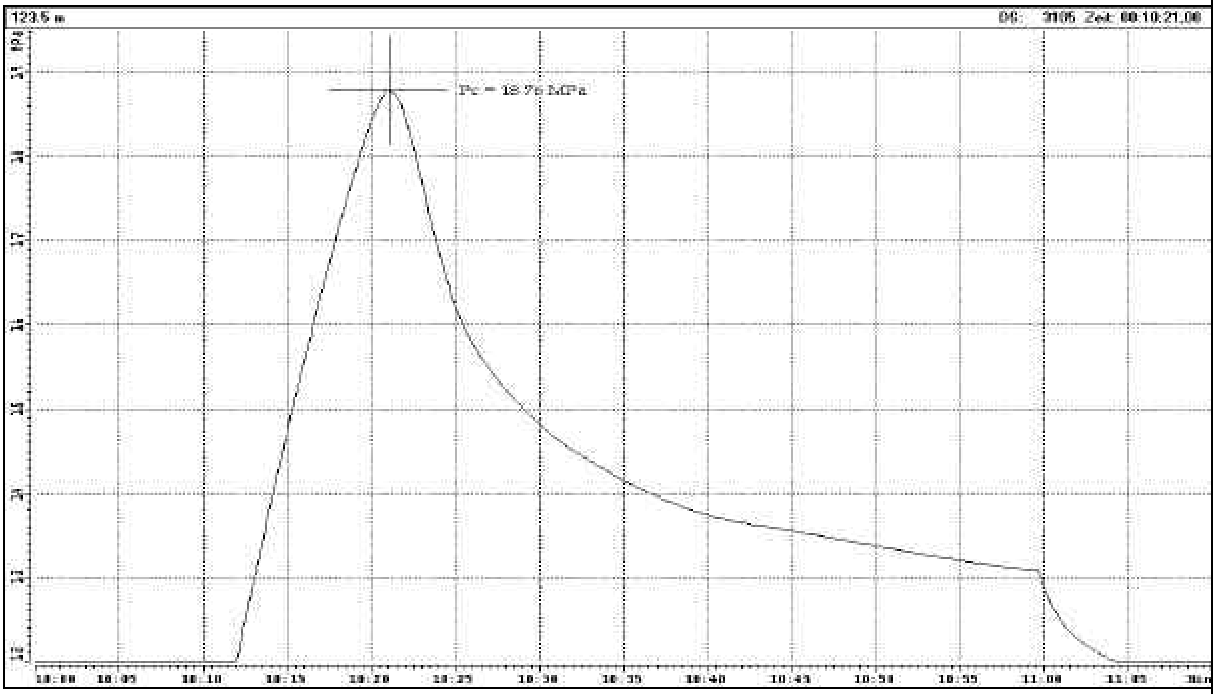
2. Refrac - Cycle : Q_i = 2.9 lpm, V_i = 4.4 l, V_r = 0.2 l

3. Refrac - Cycle : Q_i = 3.7 lpm, V_i = 7.2 l, V_r = 0.2 l

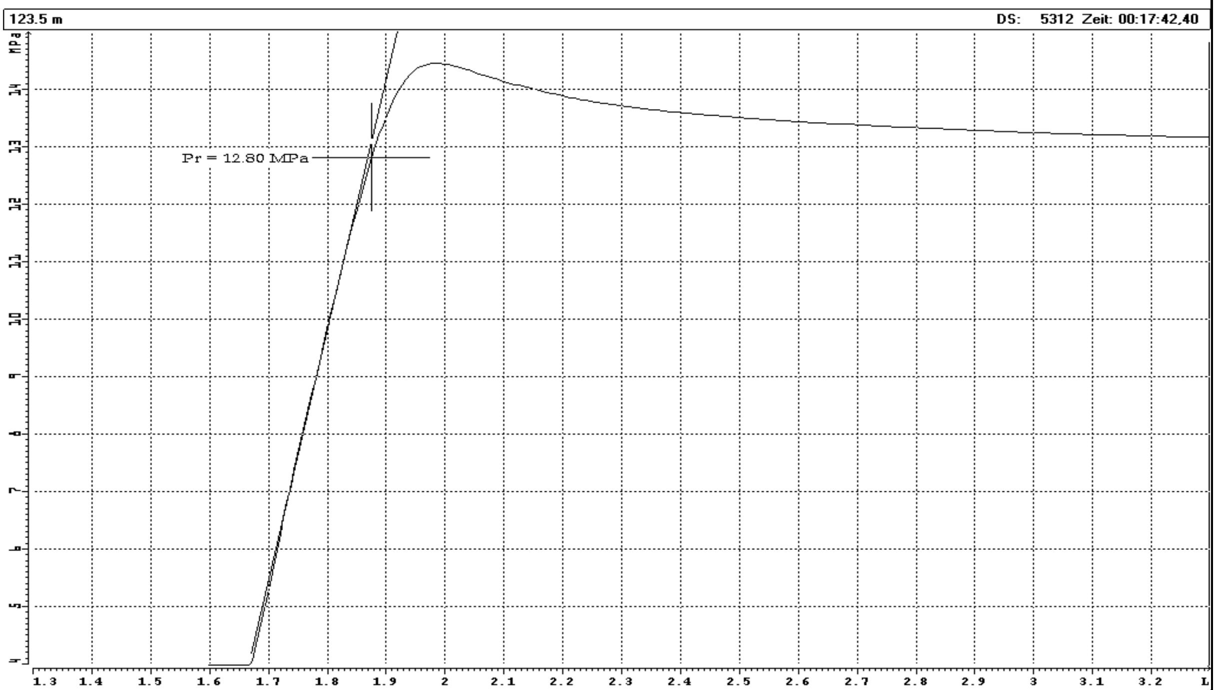
Step-Rate Test : Q_i = 1.5-5.6 lpm, V_i = 19.9 l, V_r = 0.3 l

total injected volume = 38.8 l, recovered volume = 1.1 l (2.8 %)

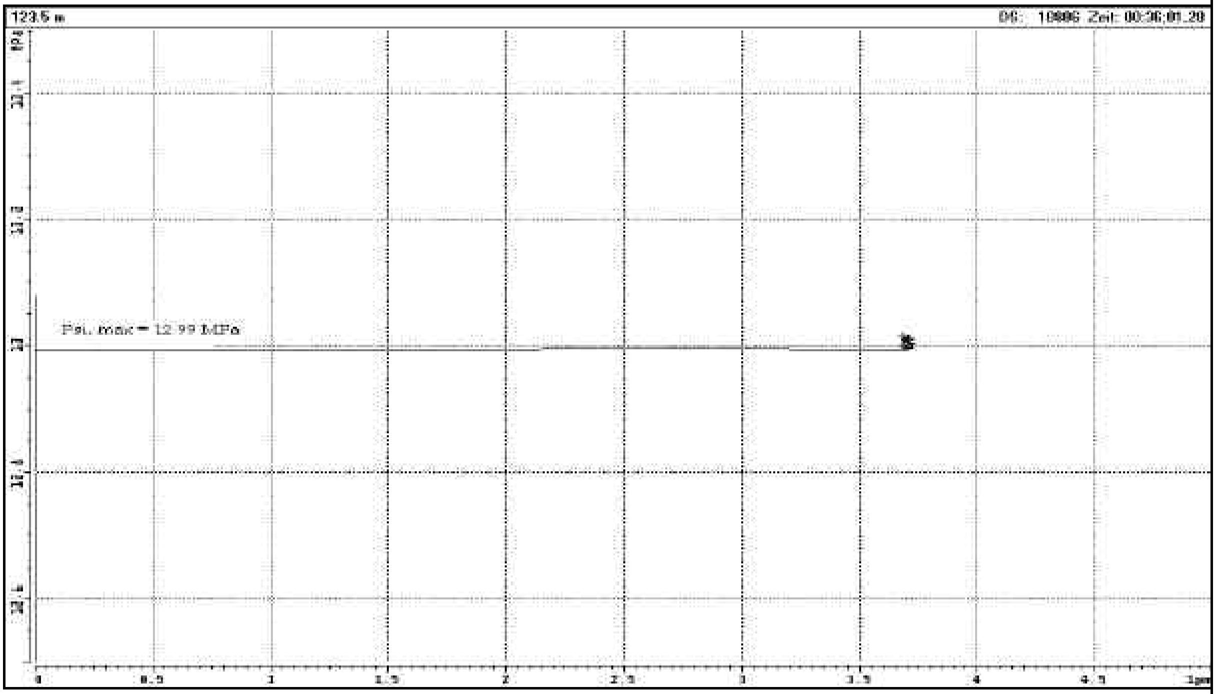
Test at 123.5 m MD: Estimation of P_c (Frac - Cycle)



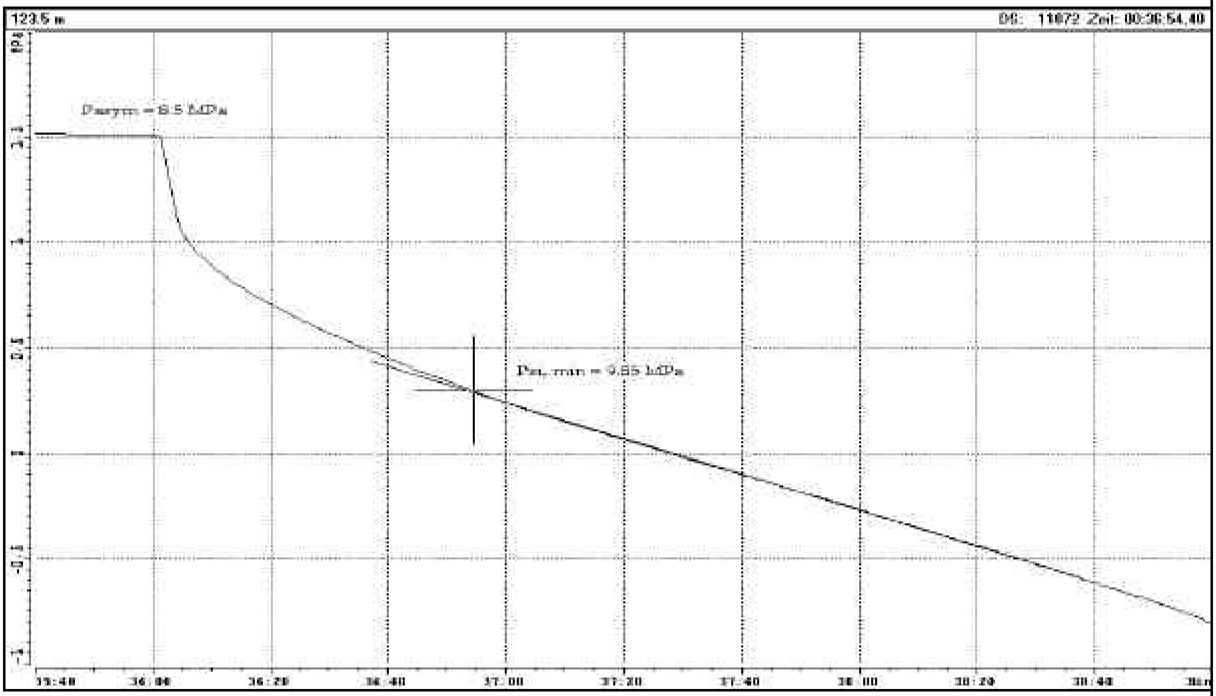
Test at 123.5 m MD: Estimation of P_r (1. Refrac - Cycle)



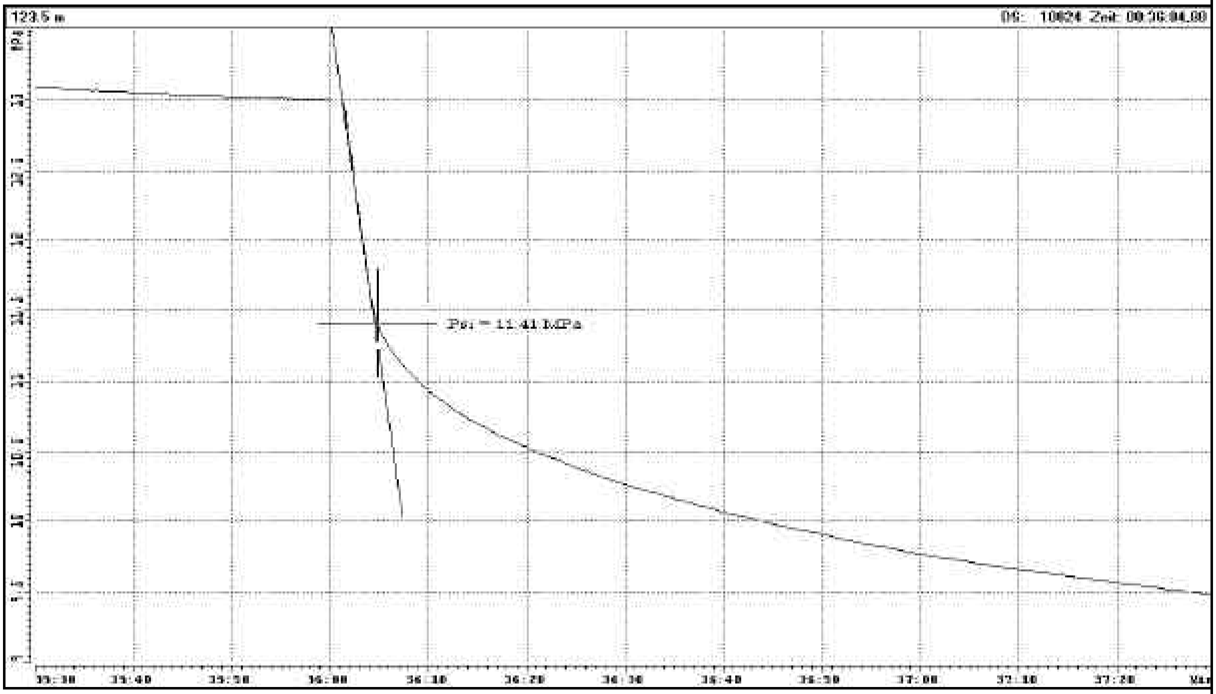
Test at 123.5 m MD: Estimation of $P_{si, max}$ (3. Refrac - Cycle)



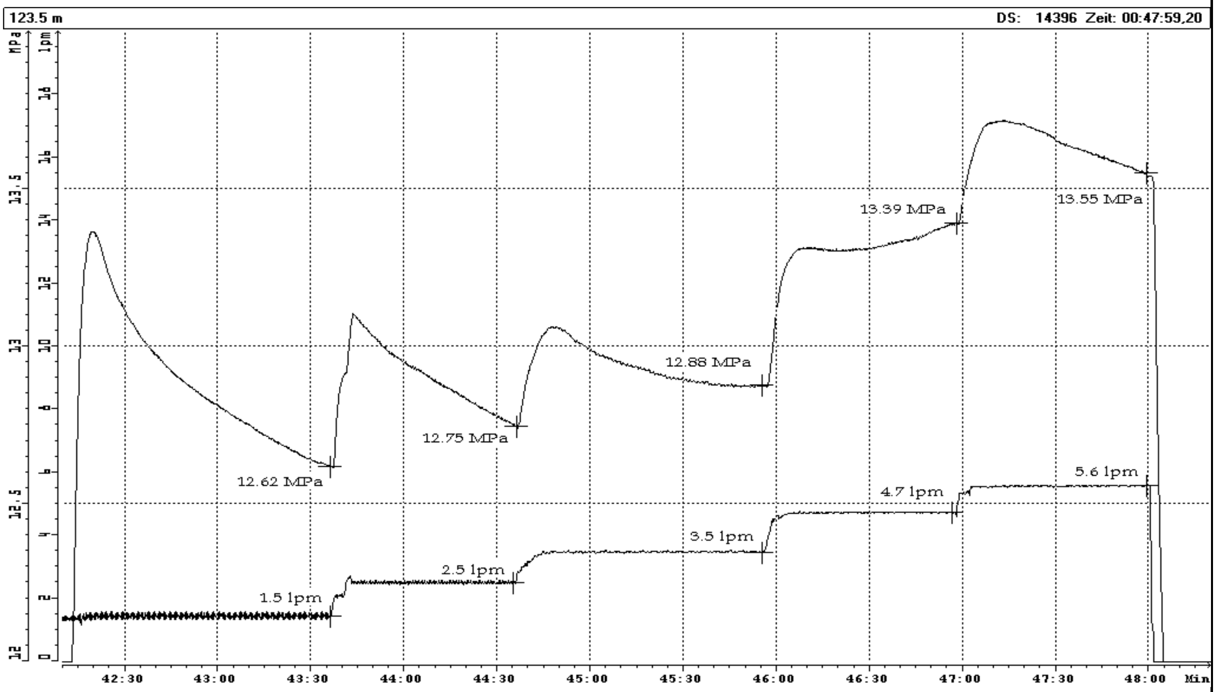
Test at 123.5 m MD: Estimation of $P_{si, min}$ (3. Refrac - Cycle)



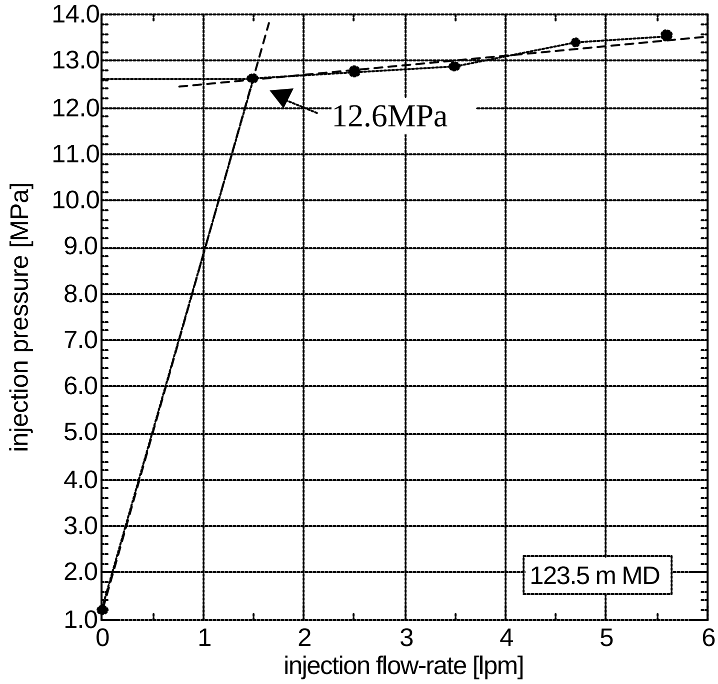
Test at 123.5 m MD: Estimation of P_{si} (3. Refrac - Cycle)



Test at 123.5 m MD: Analysis of Slow - Pump / Step - Rate - Test



Test at 123.5 m MD: Examination of P_{si} (Step - Rate - Test)



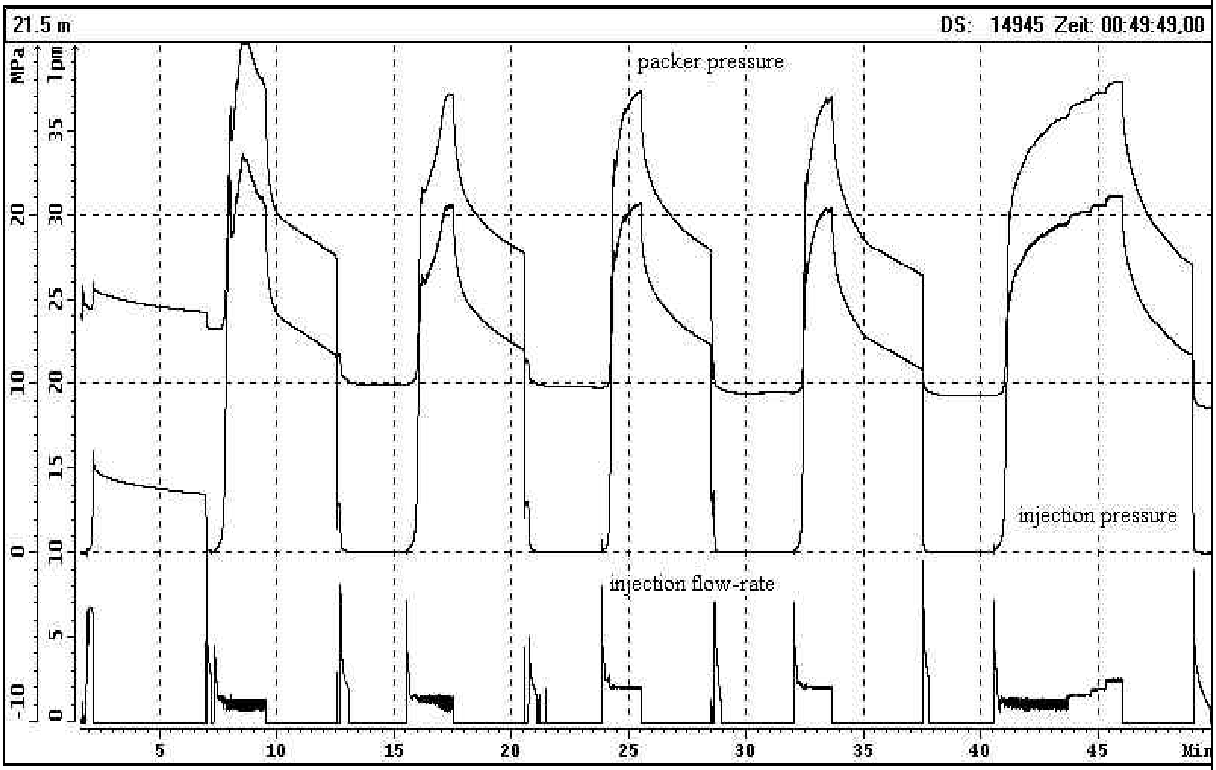
APPENDIX A2

Records from in-situ hydrofrac tests together with evaluation of characteristic pressure data

borehole no. KF0093A01

Test at 21.5 M

Test at 21.5 m : Overview - Plot



P - Test Frac 1. Refrac 2. Refrac 3. Refrac Slow-Pump/Step-Rate Test

<u>Test Summary</u>

P - Test : pressure decrease: 2.6 MPa in 4 min. 48 sec.

Frac - Cycle : injection-rate Q_i= 1.1 lpm, injected volume V_i = 3.0 l, back-flow volume V_r = 1.0 l
fracture initiation (weak breakdown event)

1. Refrac - Cycle : Q_i = 1.4 lpm, V_i = 3.1 l, V_r = 1.0 l

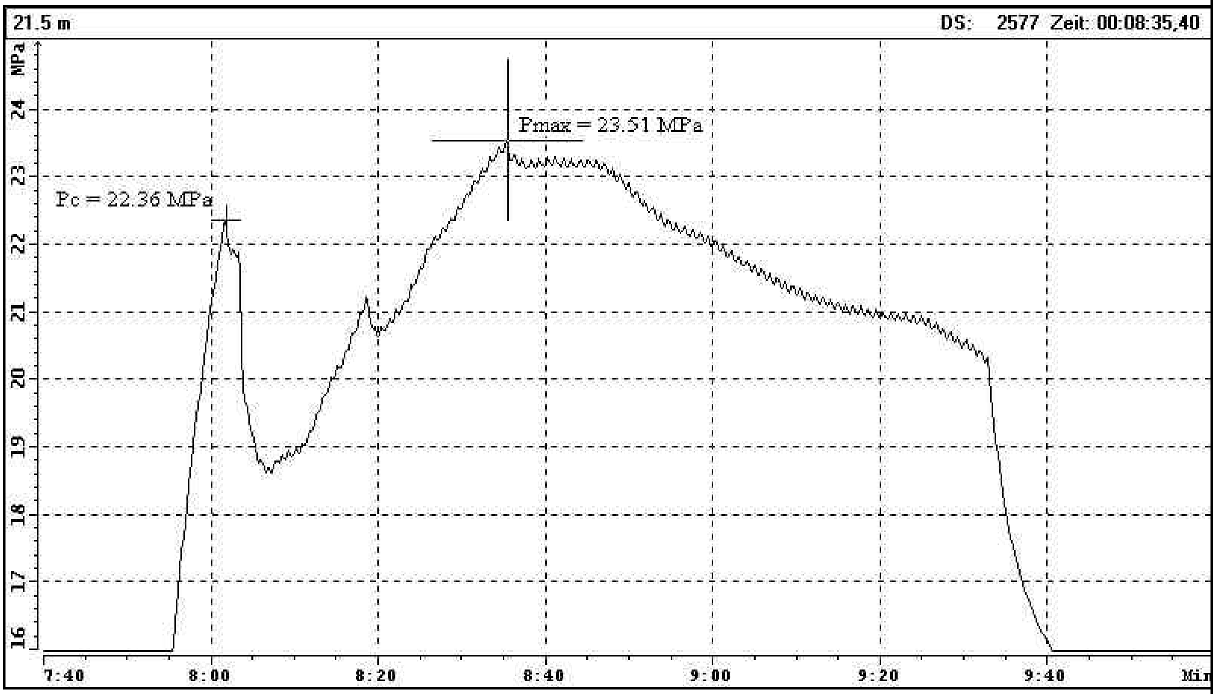
2. Refrac - Cycle : Q_i = 2.1 lpm, V_i = 3.7 l, V_r = 1.0 l

3. Refrac - Cycle : Q_i = 2.1 lpm, V_i = 3.7 l, V_r = 1.0 l

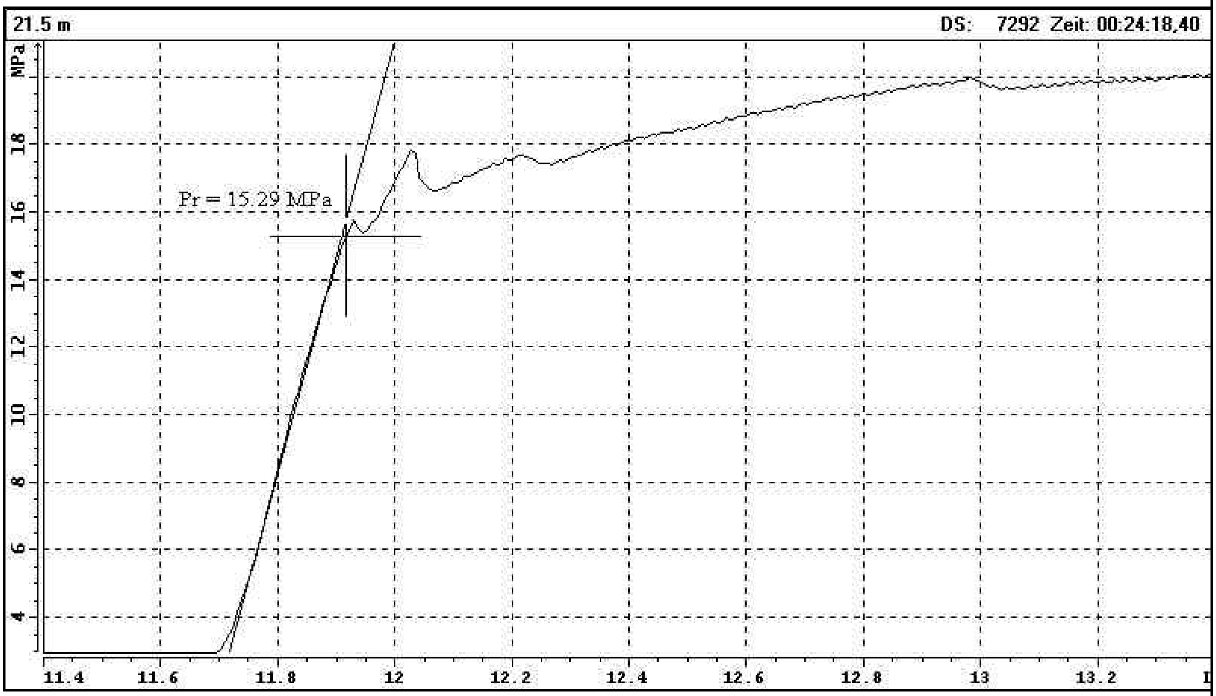
Step-Rate Test : Q_i = 1.2-2.6 lpm, V_i = 8.9 l, V_r = 1.7 l

total injected volume = 22.4 l, recovered volume = 5.7 l (25.4 %)

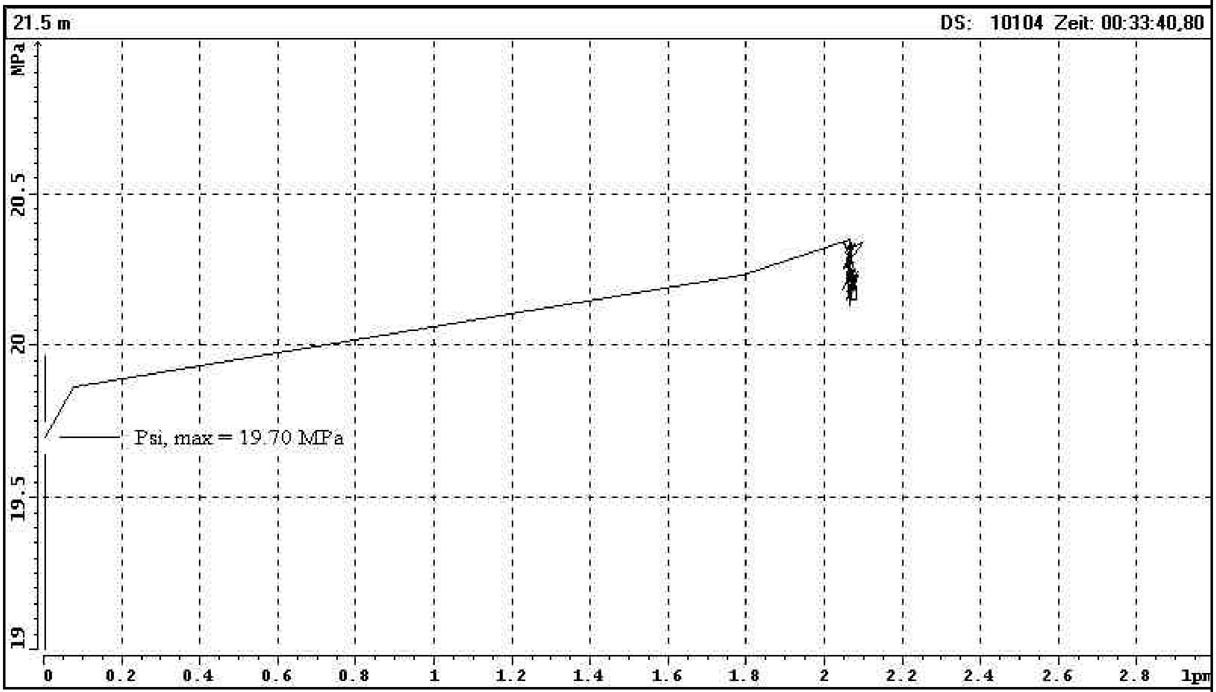
Test at 21.5 m: Estimation of P_c (Frac - Cycle)



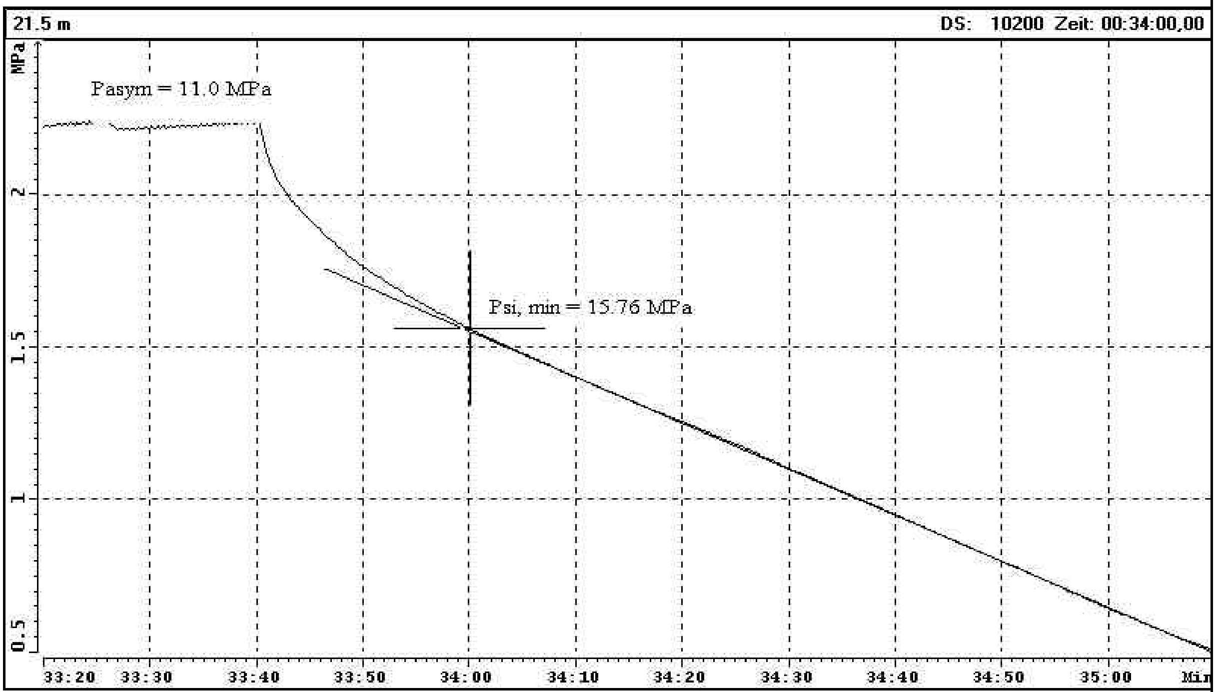
Test at 21.5 m: Estimation of P_r (1. Refrac - Cycle)



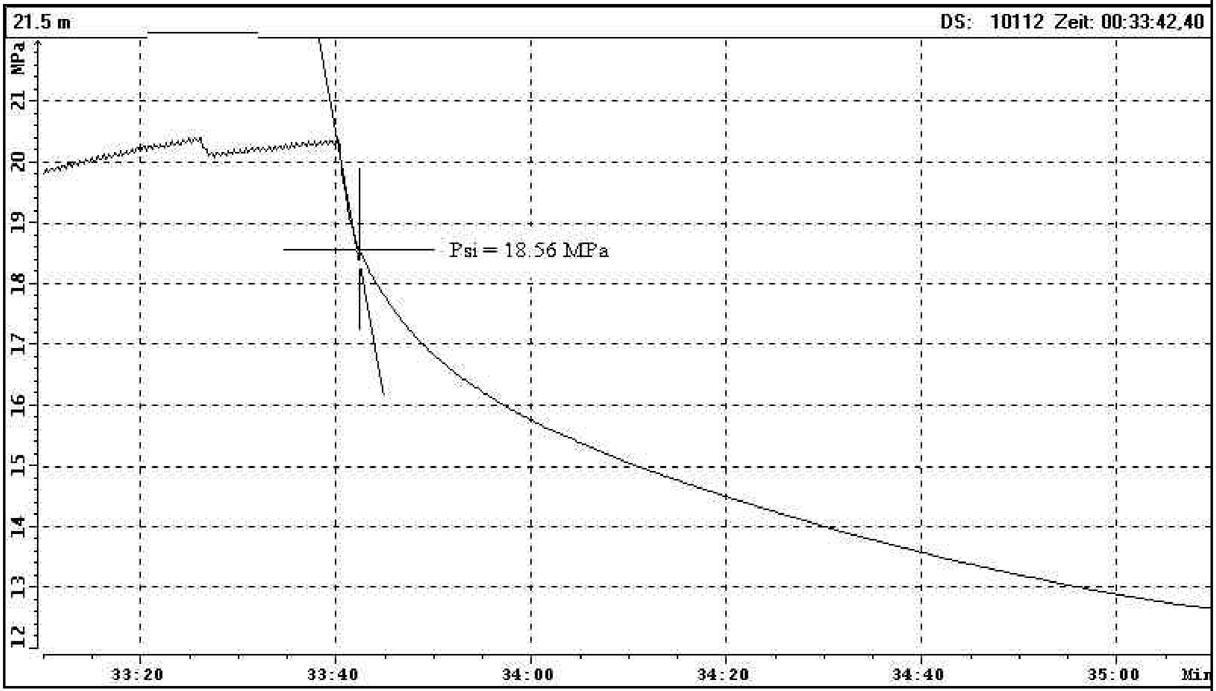
Test at 21.5 m: Estimation of $P_{si, max}$ (3. Refrac - Cycle)



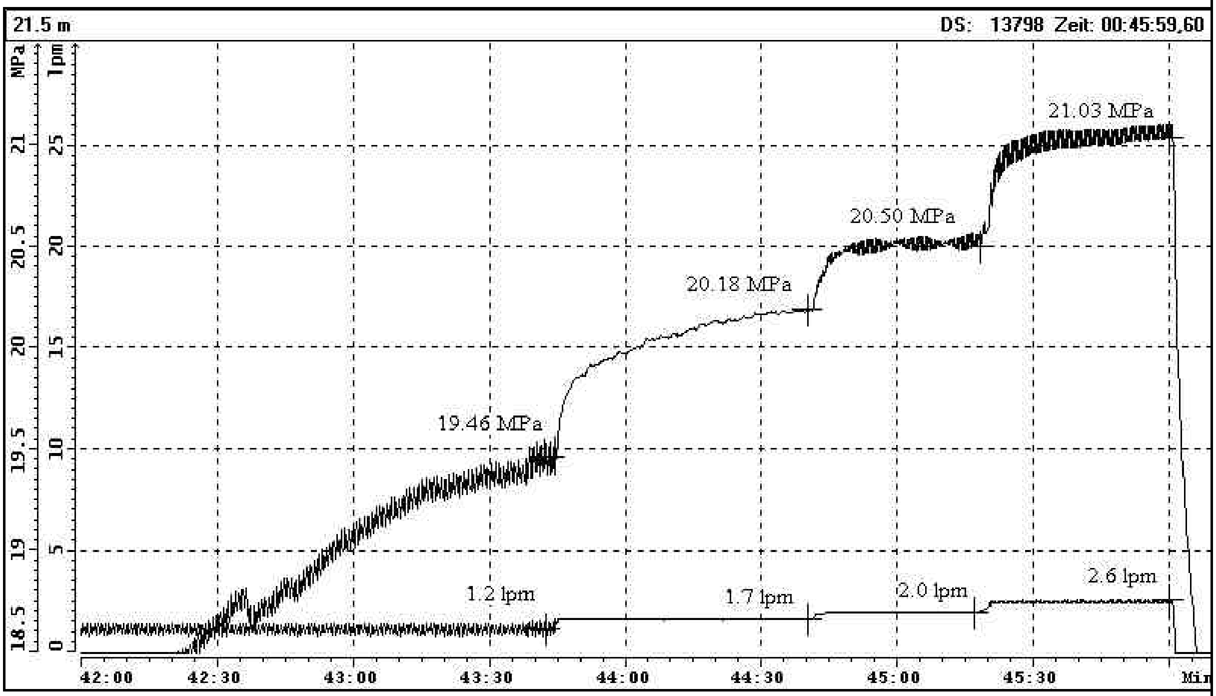
Test at 21.5 m: Estimation of $P_{si, min}$ (3. Refrac - Cycle)



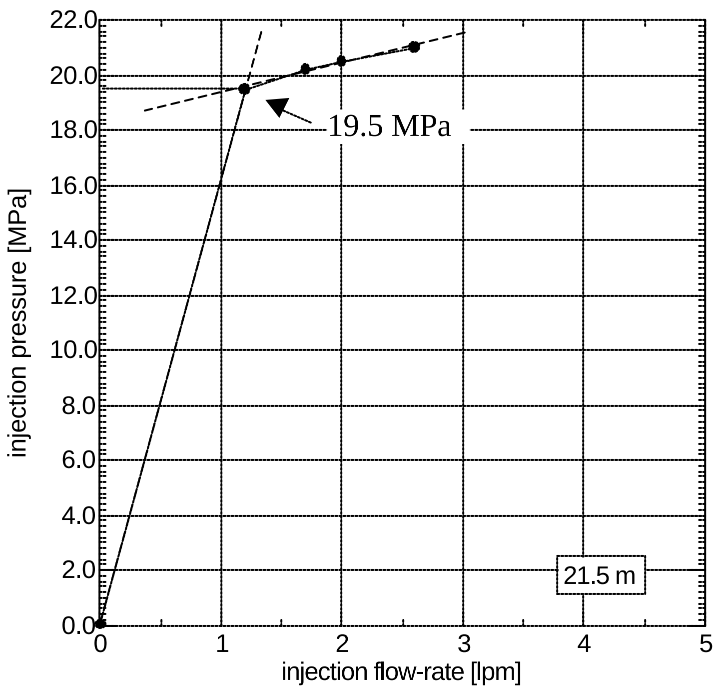
Test at 21.5 m: Estimation of P_{si} (3. Refrac - Cycle)



Test at 21.5 m: Analysis of Slow - Pump / Step - Rate - Test

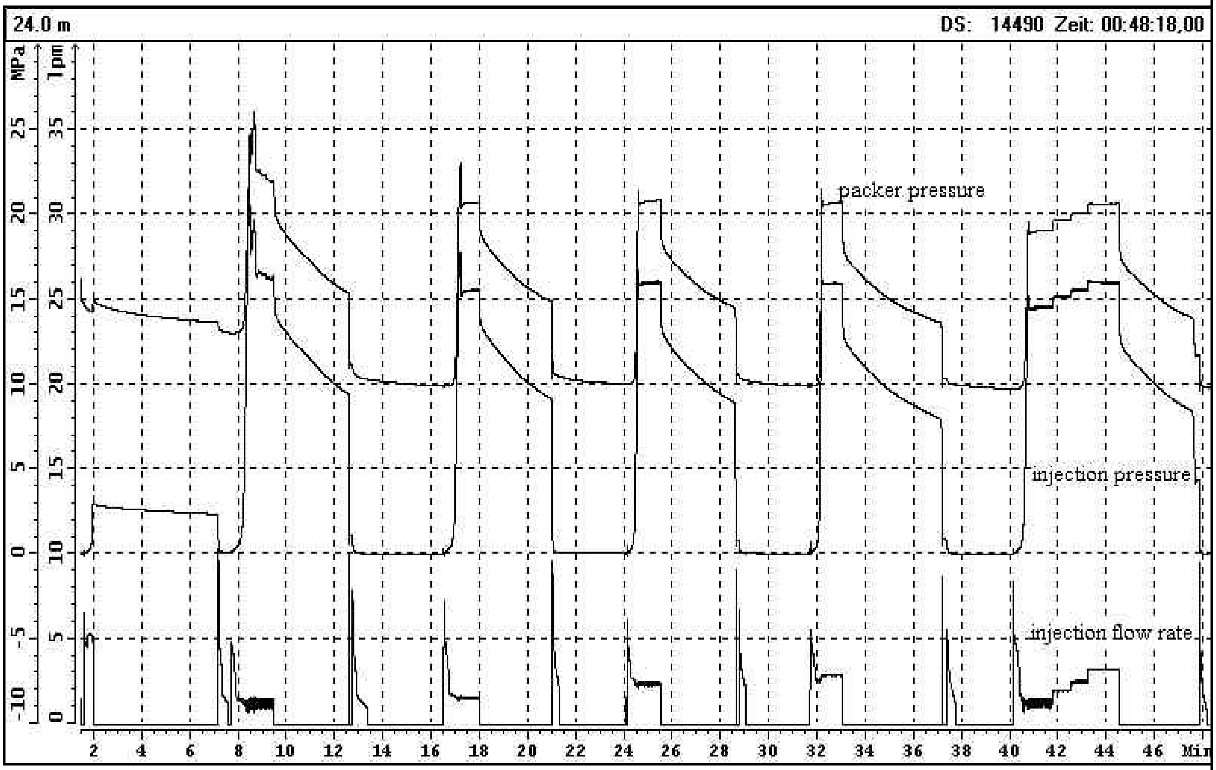


Test at 21.5 m: Examination of P_{si} (Step - Rate - Test)



Test at 24.0 M

Test at 24.0 m : Overview - Plot



P - Test | Frac | 1. Refrac | 2. Refrac | 3. Refrac | Slow-Pump/Step-Rate Test

<u>Test Summary</u>

P - Test : pressure decrease: 2.9 MPa in 3 min. 34 sec.

Frac - Cycle : injection-rate Q_i= 1.3 lpm, injected volume V_i = 2.7 l, back-flow volume V_r = 1.4 l
clear fracture initiation (breakdown event)

1. Refrac - Cycle : Q_i = 1.6 lpm, V_i = 3.0 l, V_r = 1.0 l

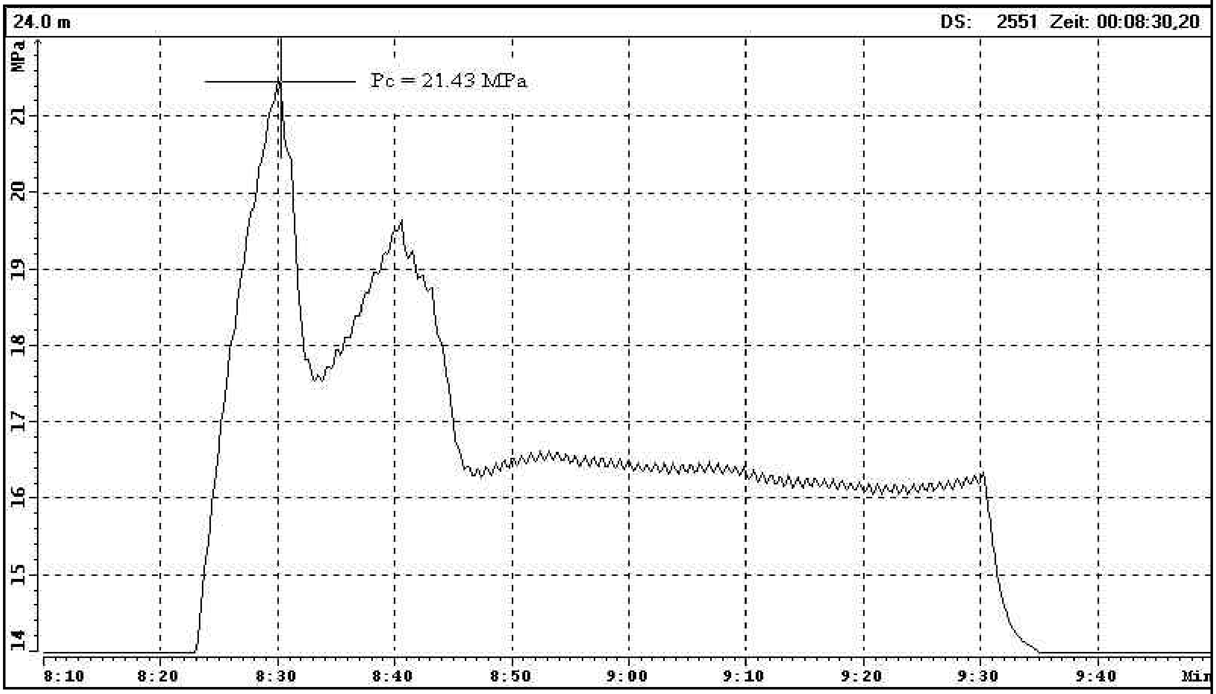
2. Refrac - Cycle : Q_i = 2.5 lpm, V_i = 3.6 l, V_r = 1.1 l

3. Refrac - Cycle : Q_i = 2.7 lpm, V_i = 4.1 l, V_r = 1.0 l

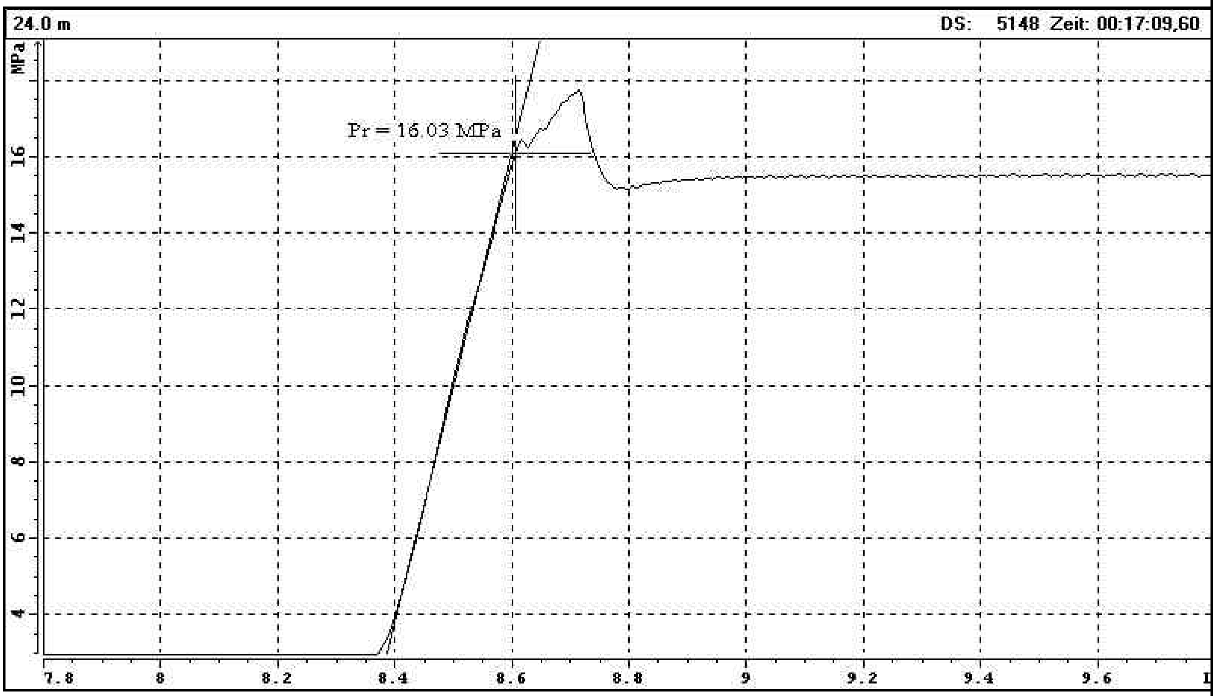
Step-Rate Test : Q_i = 1.3-3.2 lpm, V_i = 10.3 l, V_r = 0.5 l

total injected volume = 23.7 l, recovered volume = 5.0 l (21.1 %)

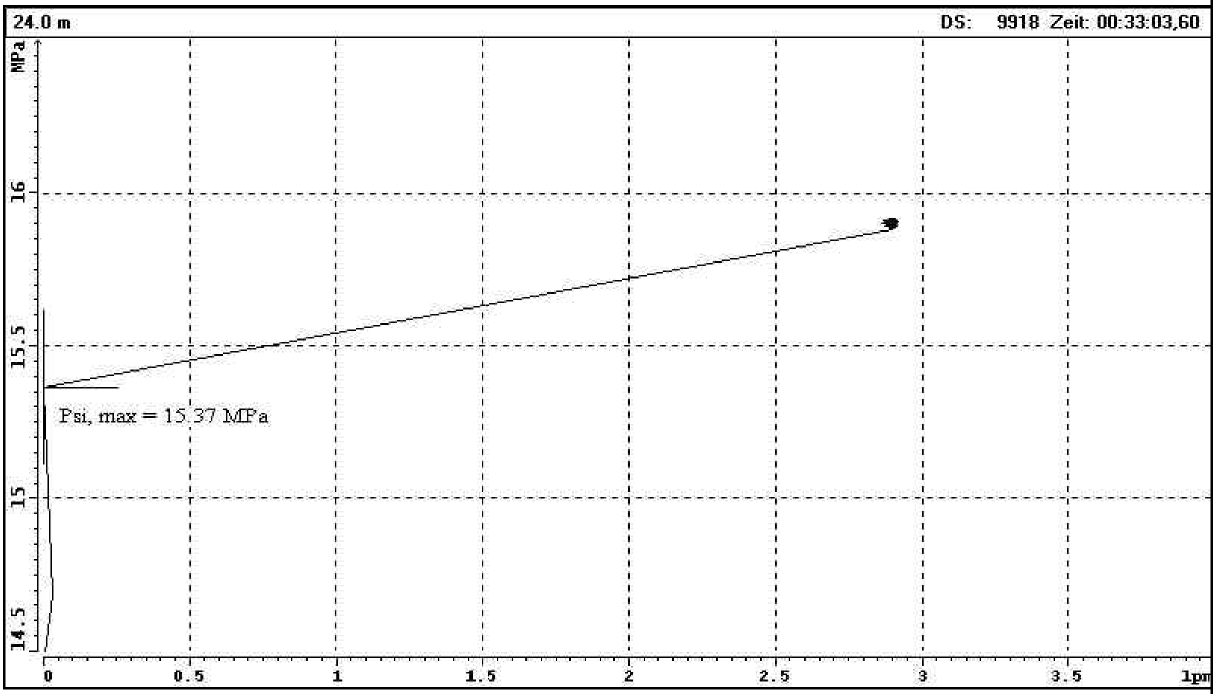
Test at 24.0 m: Estimation of P_c (Frac - Cycle)



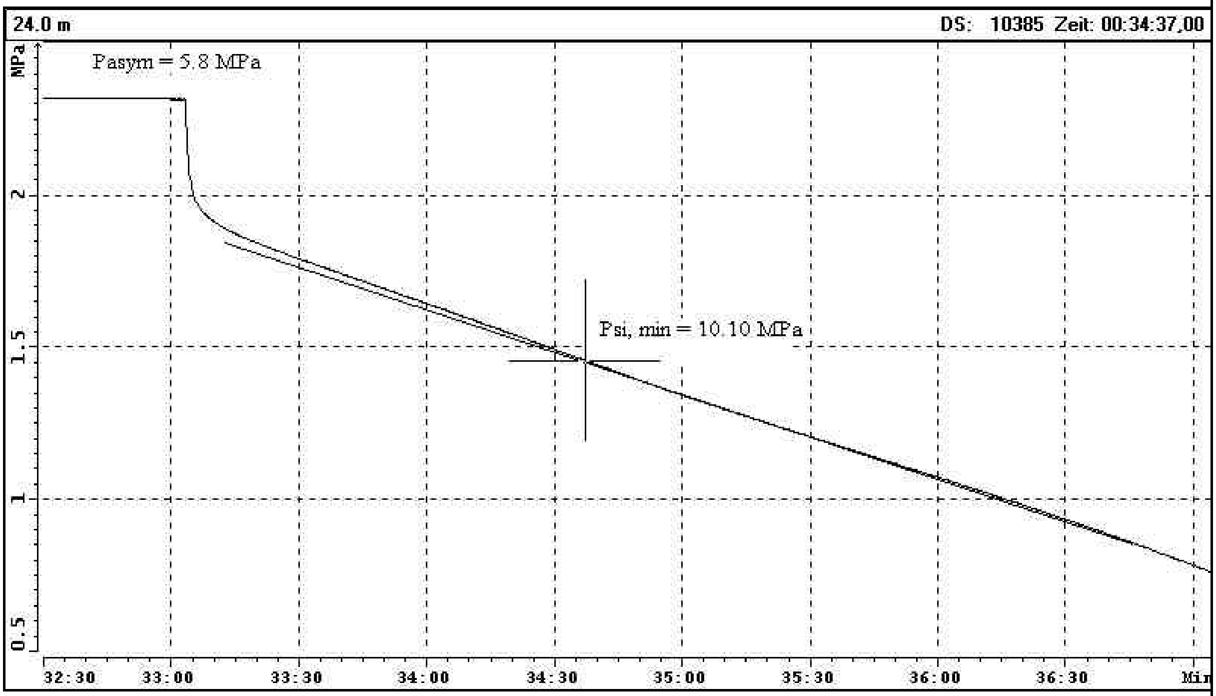
Test at 24.0 m: Estimation of P_r (1. Refrac - Cycle)



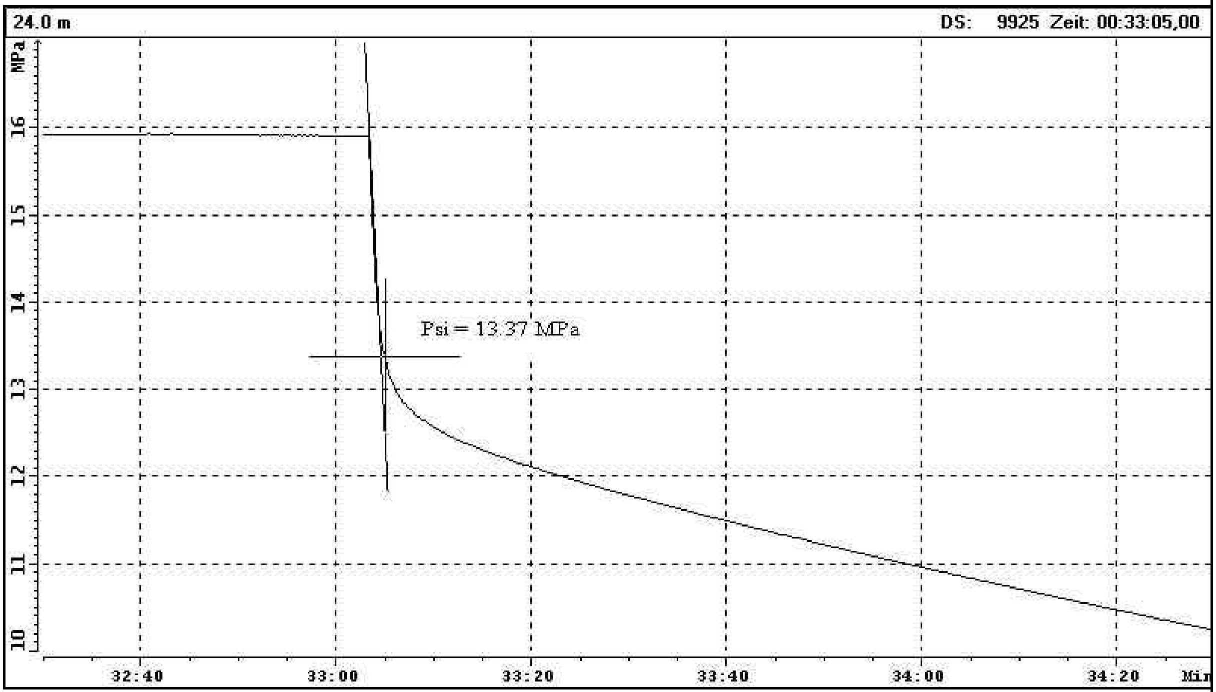
Test at 24.0 m: Estimation of $P_{si, max}$ (3. Refrac - Cycle)



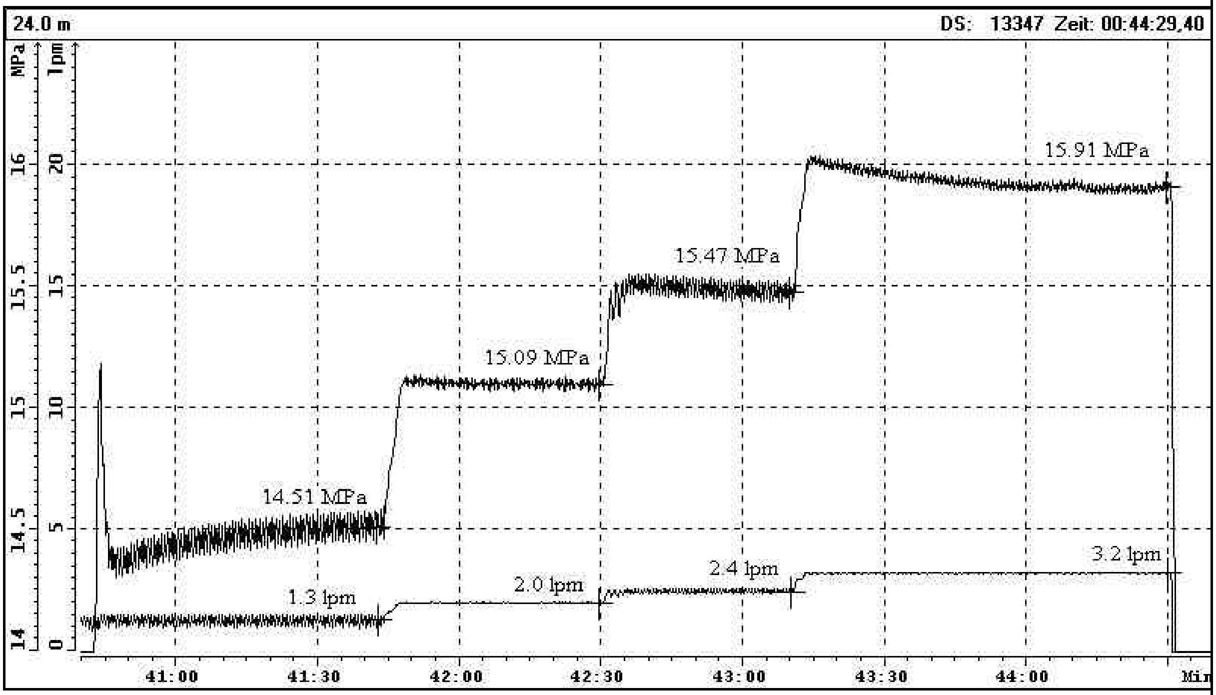
Test at 24.0 m: Estimation of $P_{si, min}$ (3. Refrac - Cycle)



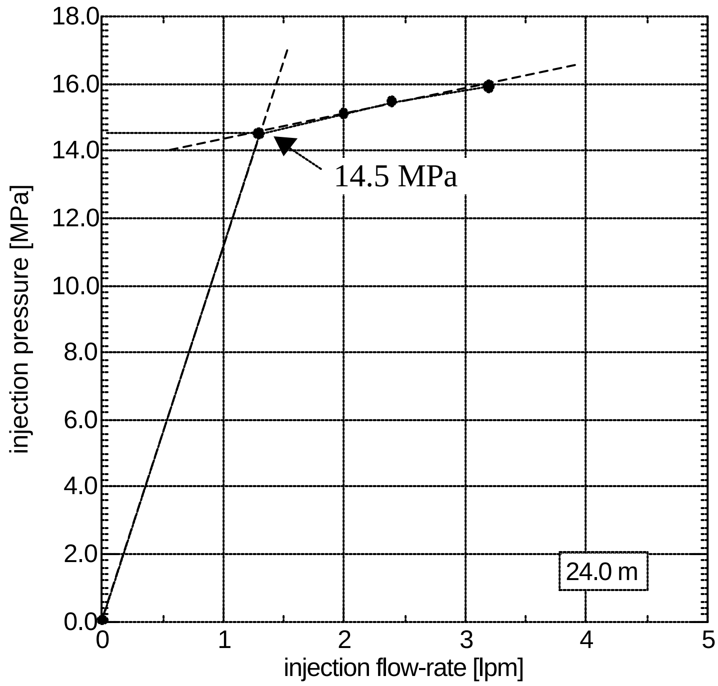
Test at 24.0 m: Estimation of P_{si} (3. Refrac - Cycle)



7.1.3 Test at 24.0 m: Analysis of Slow - Pump / Step - Rate - Test

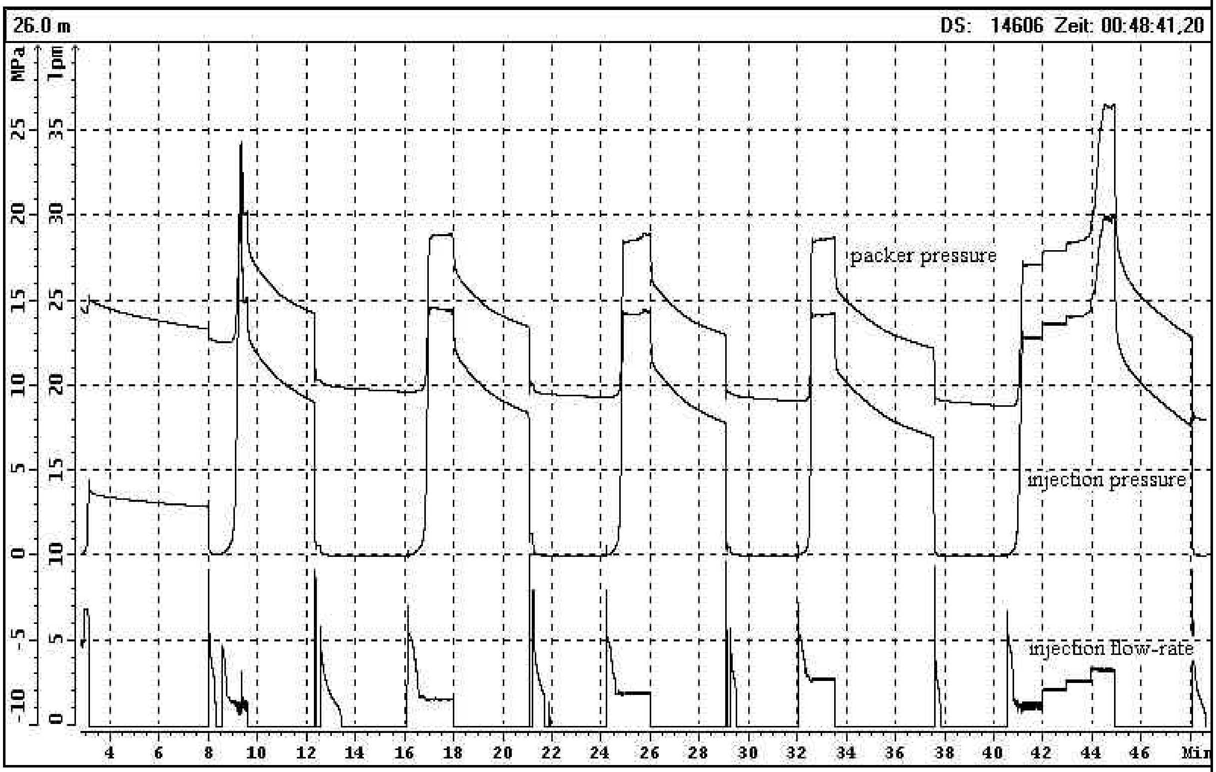


Test at 24.0 m: Examination of P_{si} (Step - Rate - Test)



Test at 26.0 M

Test at 26.0 m : Overview - Plot



P - Test Frac 1. Refrac 2. Refrac 3. Refrac Slow-Pump/Step-Rate Test

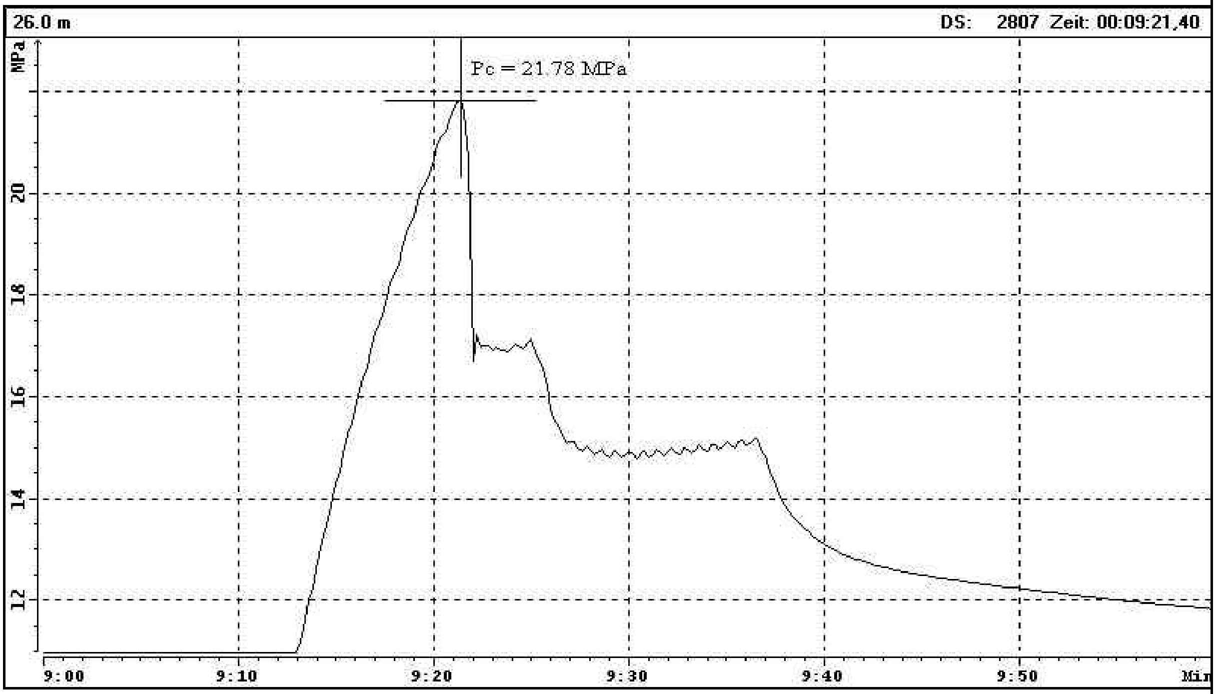
<u>Test Summary</u>

P - Test :	pressure decrease: 1.6 MPa in 4 min. 51 sec.
Frac - Cycle :	injection-rate Q_i= 1.1 lpm, injected volume V_i = 1.9 l, back-flow volume V_r = 2.1 l fracture initiation (breakdown event) observed
1. Refrac - Cycle :	Q_i = 1.6 lpm, V_i = 4.4 l, V_r = 1.6 l
2. Refrac - Cycle :	Q_i = 2.0 lpm, V_i = 4.3 l, V_r = 1.0 l
3. Refrac - Cycle :	Q_i = 2.7 lpm, V_i = 4.7 l, V_r = 0.8 l
Step-Rate Test :	Q_i = 1.2-3.3 lpm, V_i = 10.6 l, V_r = 1.2 l

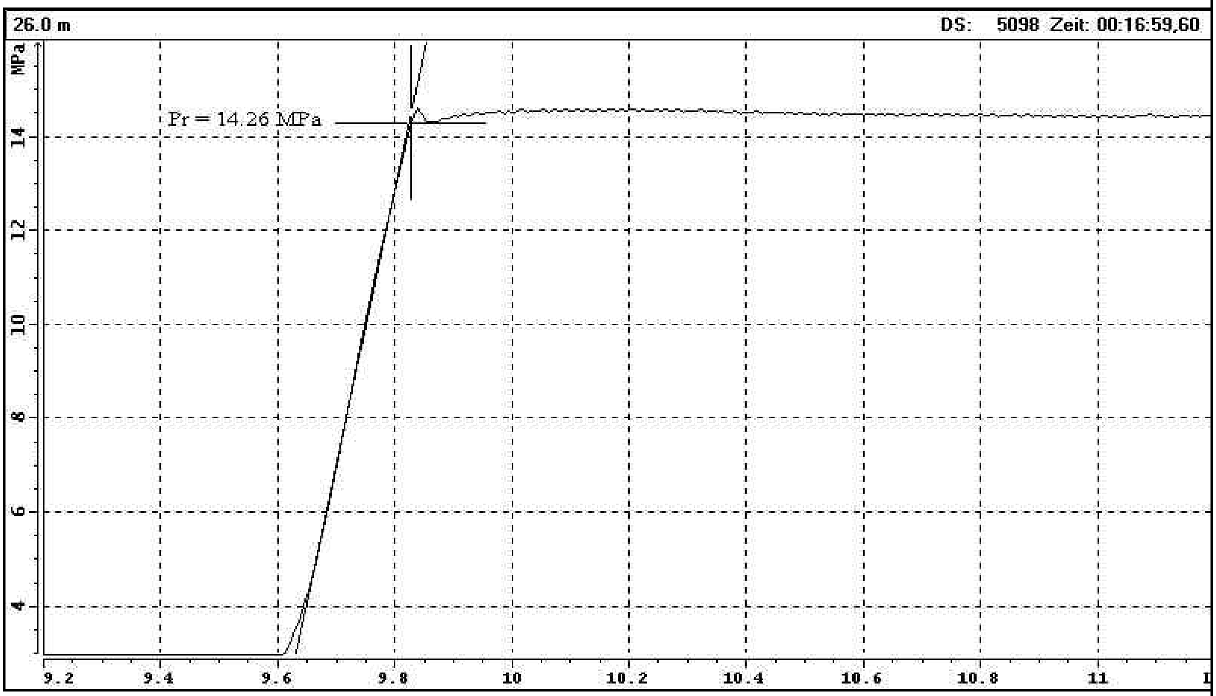
total injected volume = 25.9 l, recovered volume = 6.7 l (24.9 %)

<u>Remark:</u> During the final stage of the slow-pump/step-rate test, a significant increase of the injection pressure from 15.5 MPa to about 20 MPa was observed.

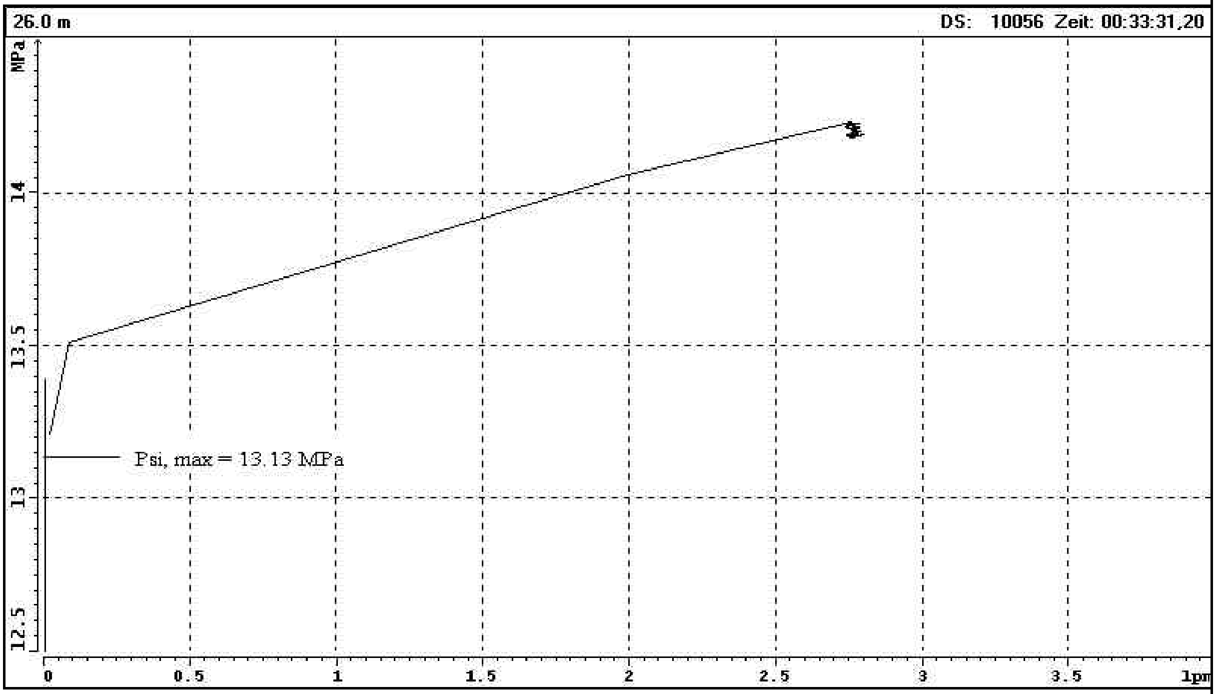
Test at 26.0 m : Estimation of P_c (Frac - Cycle)



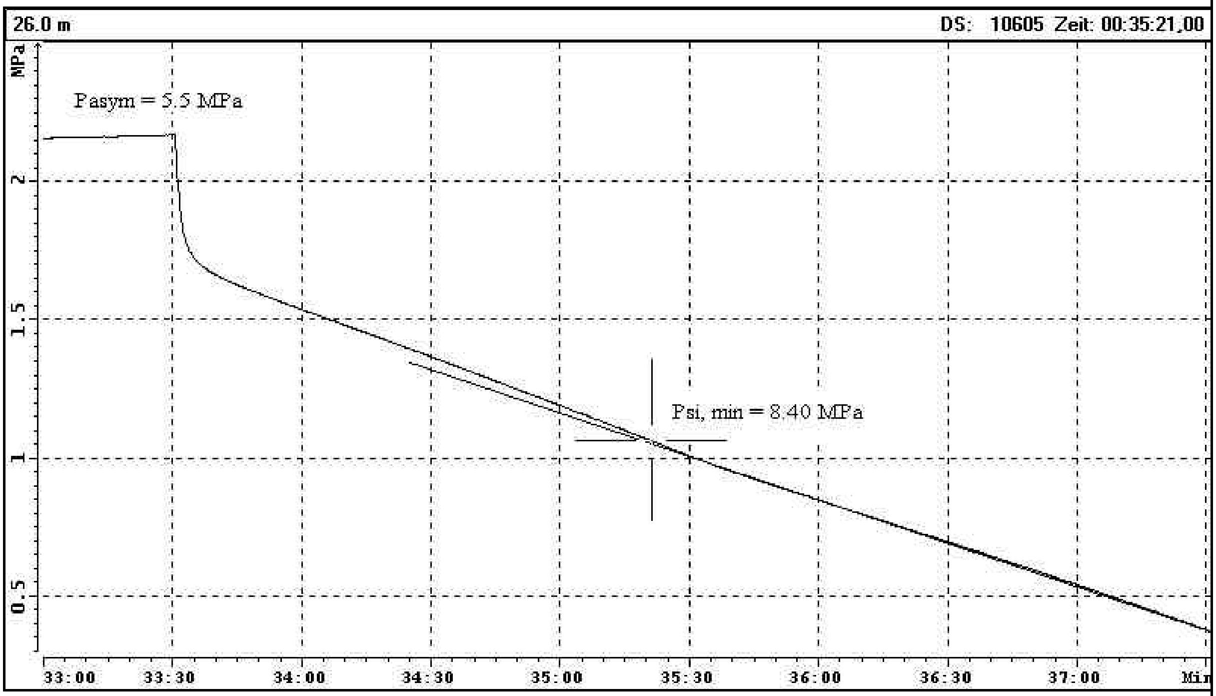
Test at 26.0 m : Estimation of P_r (1. Refrac - Cycle)



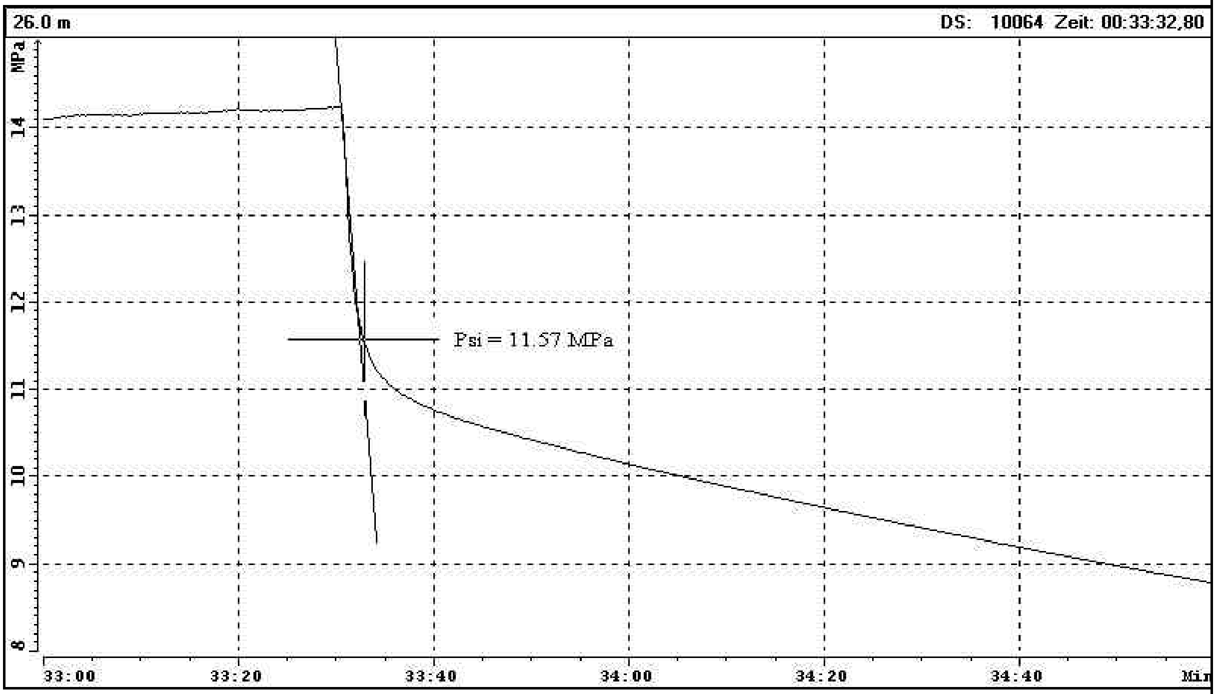
Test at 26.0 m : Estimation of $P_{si, max}$ (3. Refrac - Cycle)



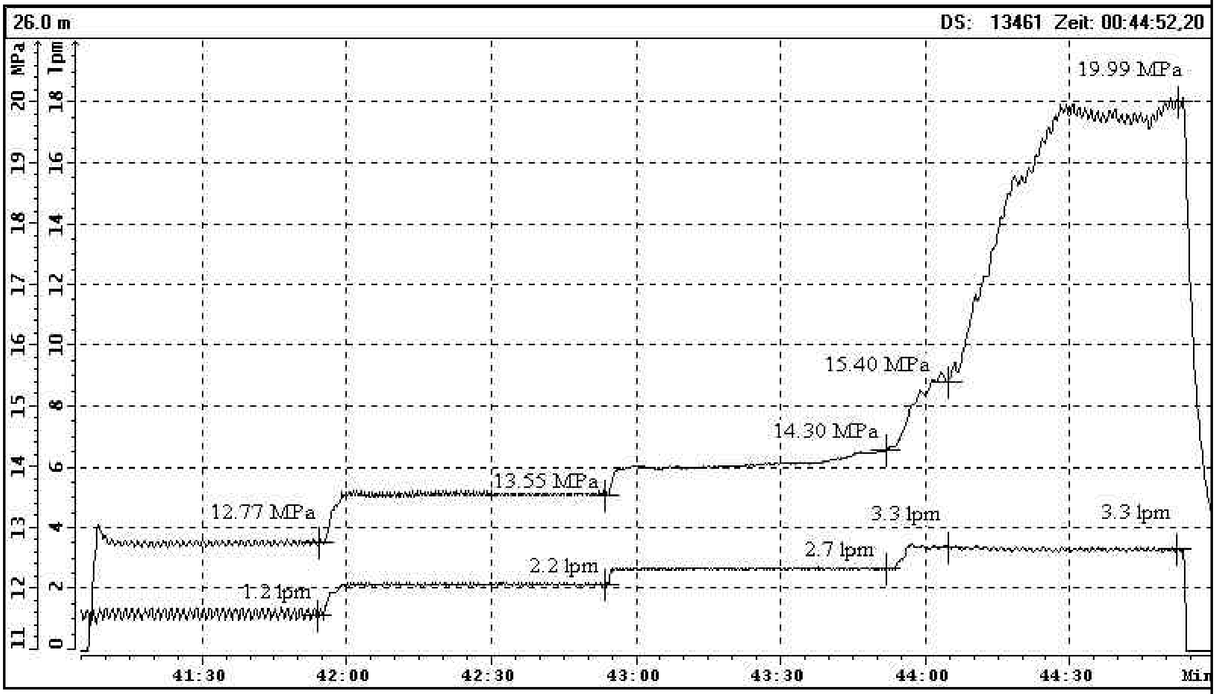
Test at 26.0 m : Estimation of $P_{si, min}$ (3. Refrac - Cycle)



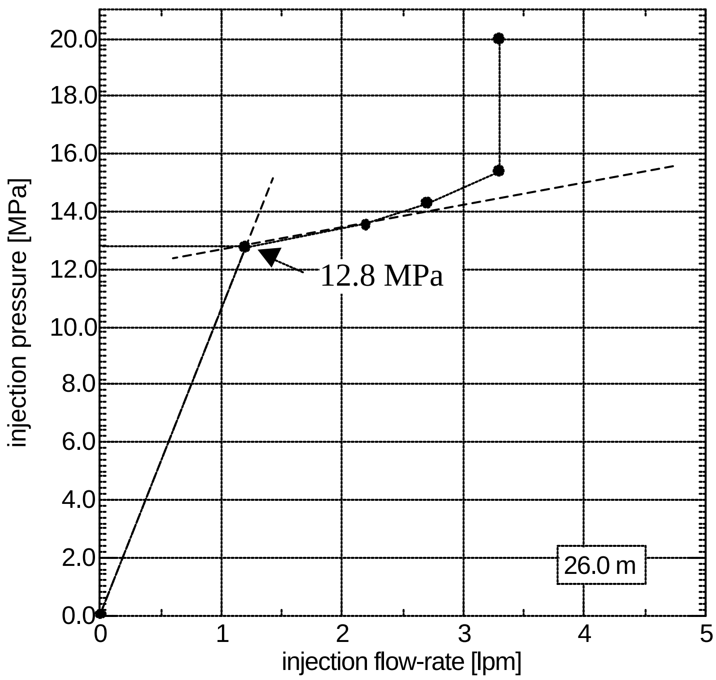
Test at 26.0 m : Estimation of P_{si} (3. Refrac - Cycle)



7.1.4 Test at 26.0 m : Analysis of Slow - Pump / Step - Rate - Test

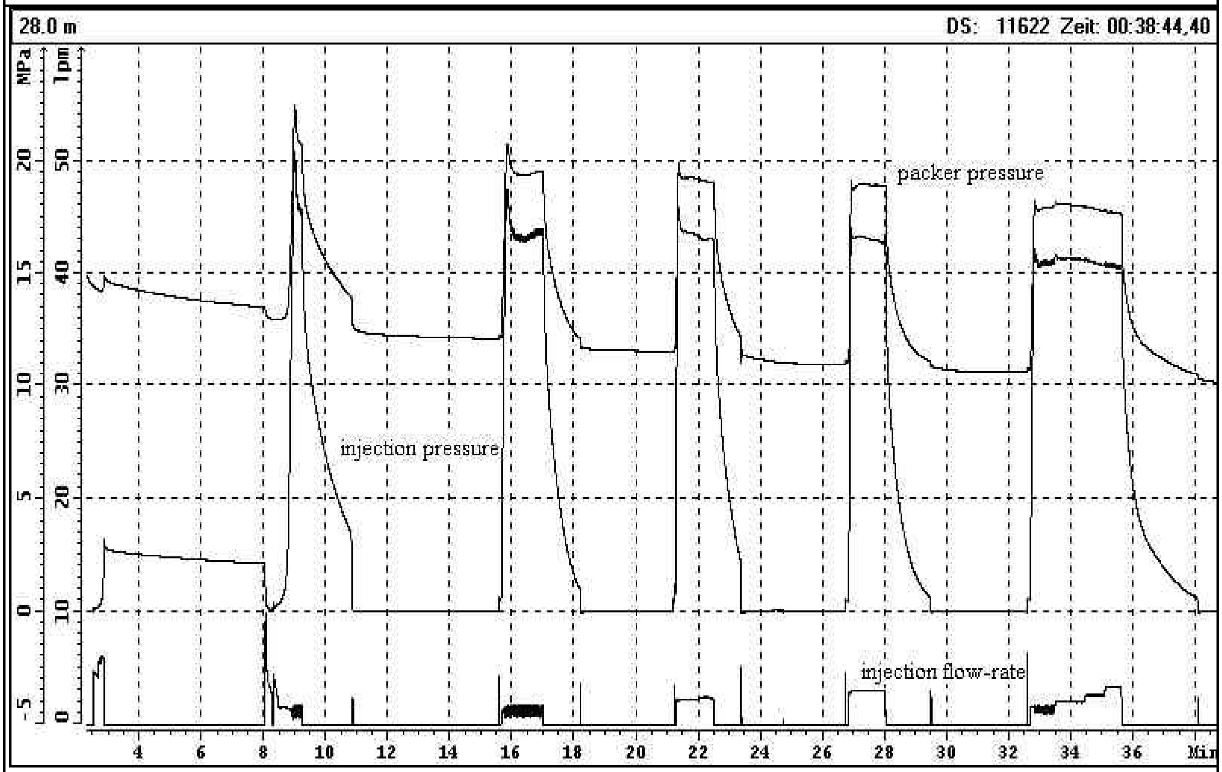


Test at 26.0 m : Examination of P_{si} (Step - Rate - Test)



Test at 28.0 M

Test at 28.0 m : Overview - Plot



P - Test | Frac | 1. Refrac | 2. Refrac | 3. Refrac | Slow-Pump/Step-Rate Test

<u>Test Summary</u>

P - Test : pressure decrease: 0.9 MPa in 5 min. 10 sec.

Frac - Cycle : injection-rate Q_i= 1.4 lpm, injected volume V_i = 1.5 l, back-flow volume V_r = 0.1 l
fracture initiation (breakdown event) observed

1. Refrac - Cycle : Q_i = 1.3 lpm, V_i = 1.7 l, V_r = 0.1 l

2. Refrac - Cycle : Q_i = 2.2 lpm, V_i = 2.9 l, V_r = 0.1 l

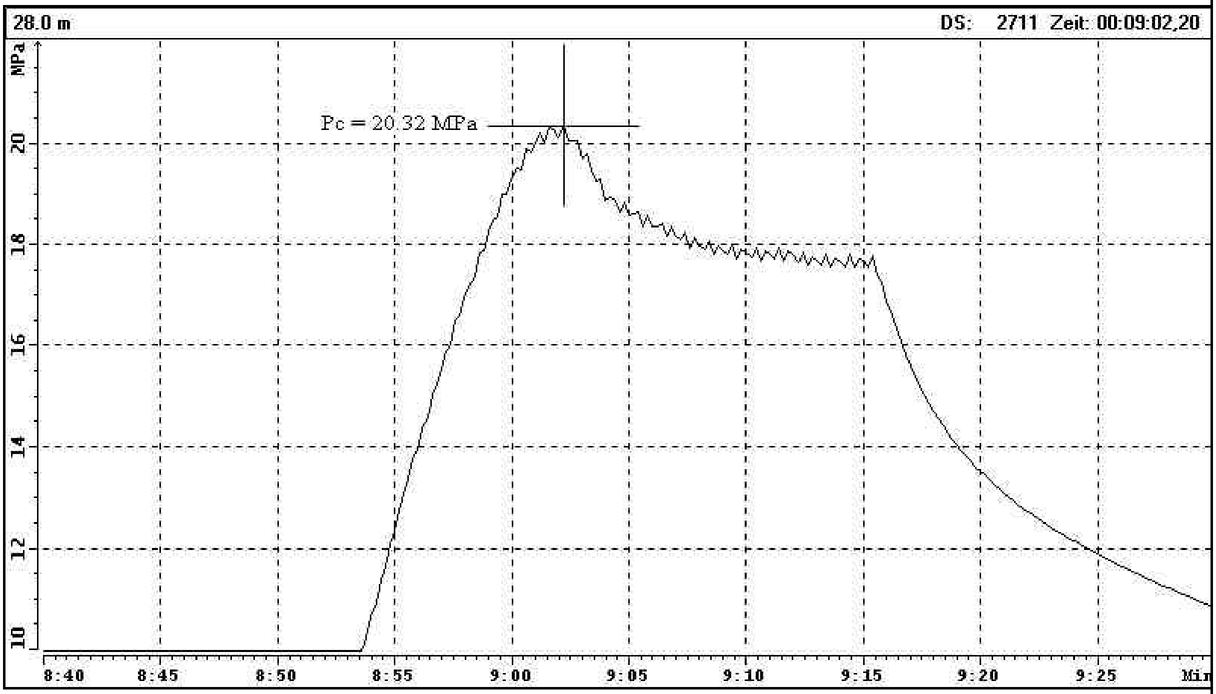
3. Refrac - Cycle : Q_i = 3.0 lpm, V_i = 3.5 l, V_r = 0.1 l

Step-Rate Test : Q_i = 1.4-3.3 lpm, V_i = 6.6 l, V_r <0.1 l

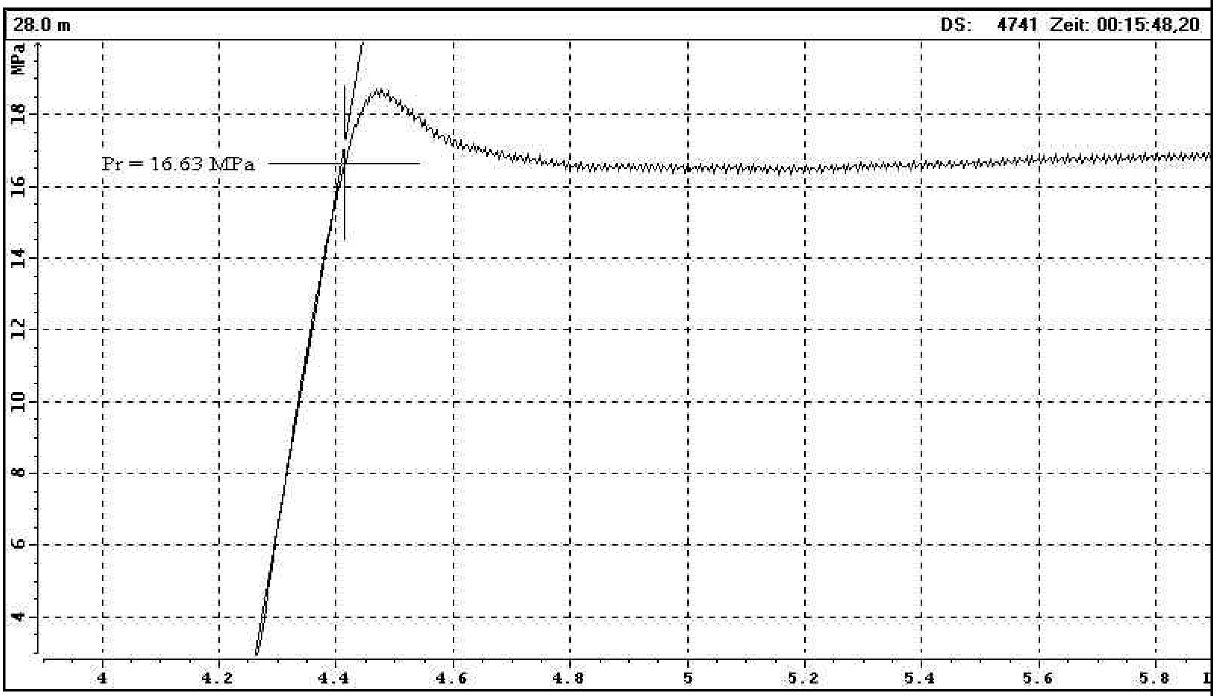
total injected volume = 16.2 l, recovered volume = 0.4 l (2.5 %)

<u>Remark:</u> Due to the high fracture conductivity, the analysis of the shut-in pressure is difficult.

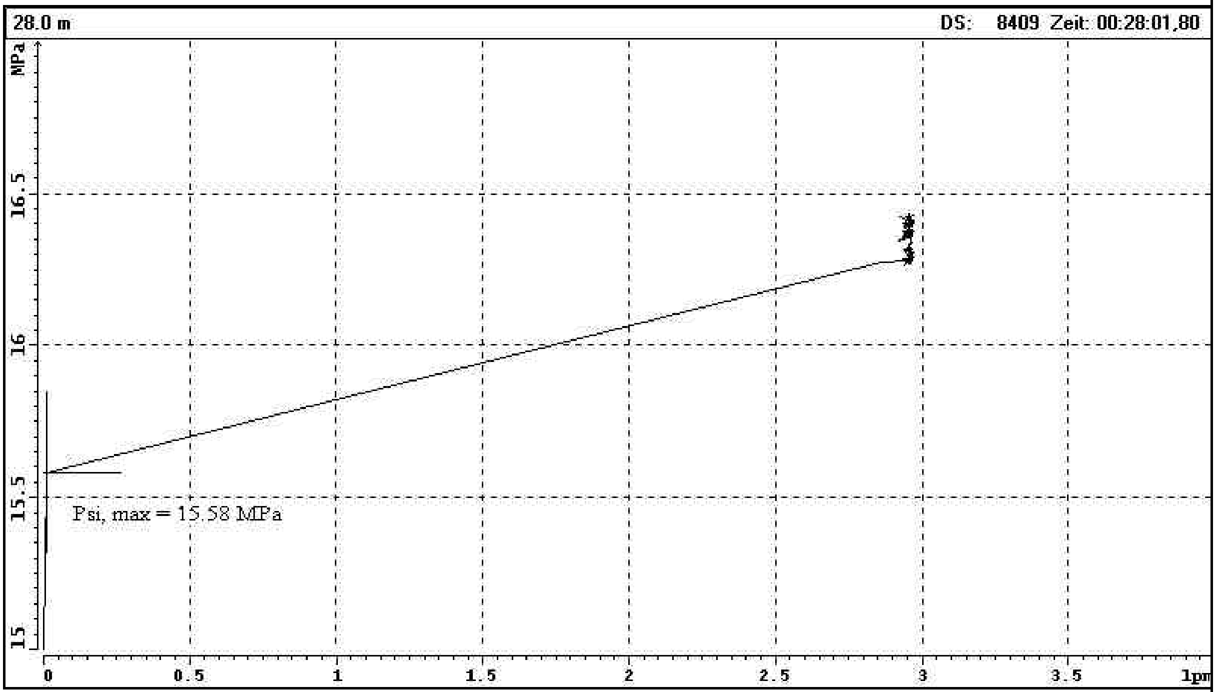
Test at 28.0 m : Estimation of P_c (Frac - Cycle)



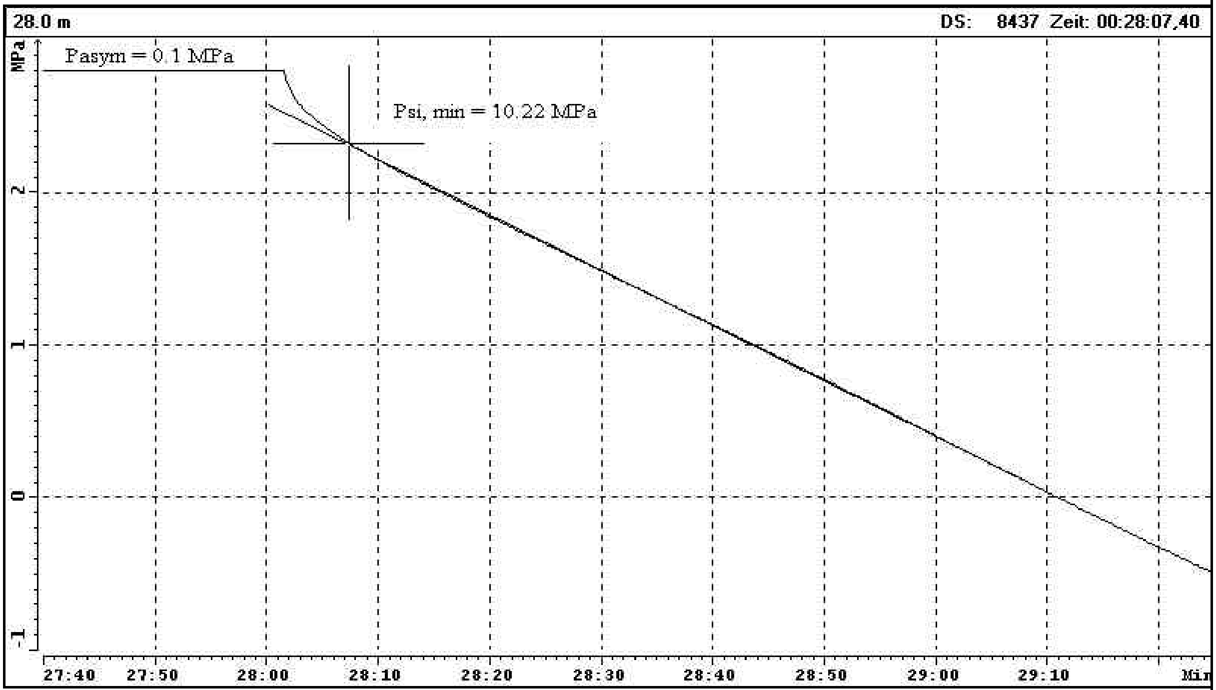
Test at 28.0 m : Estimation of P_r (1. Refrac - Cycle)



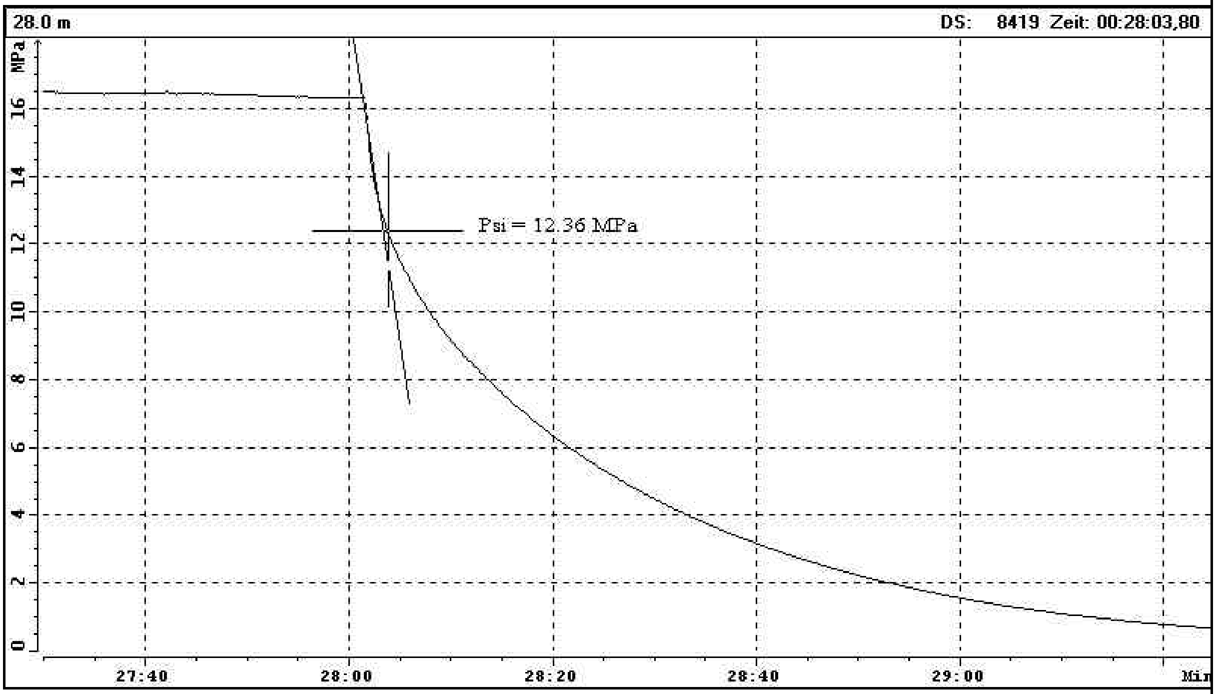
Test at 28.0 m : Estimation of $P_{si, max}$ (3. Refrac - Cycle)



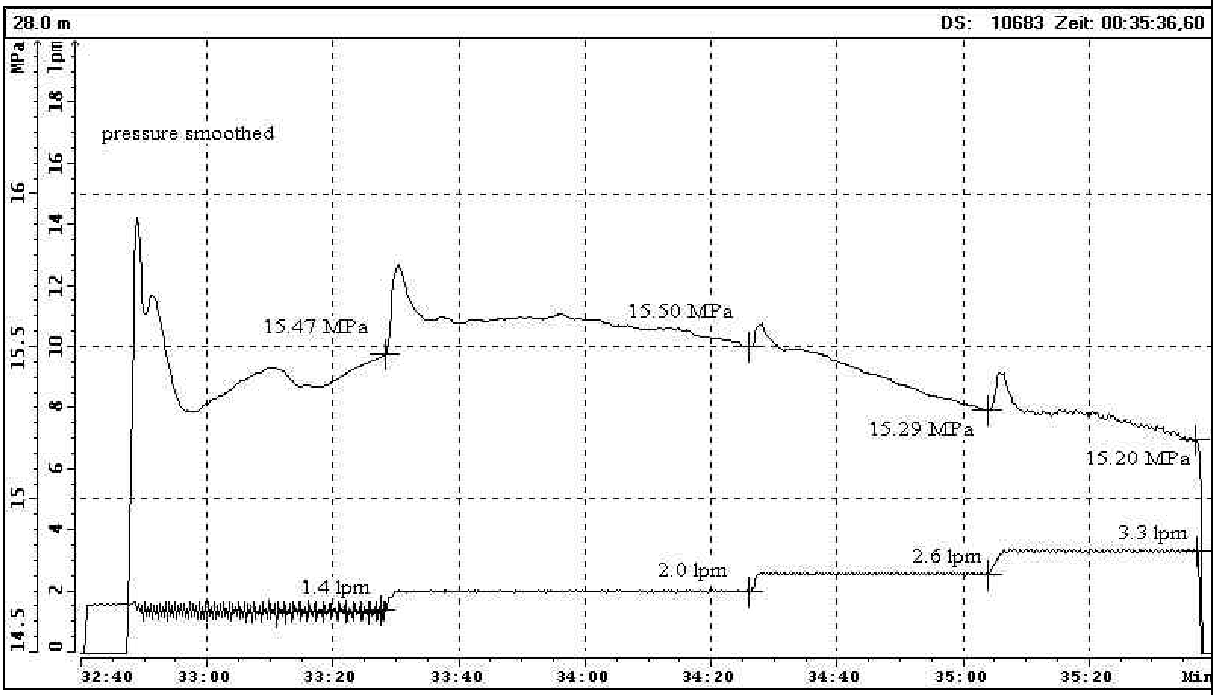
Test at 28.0 m : Estimation of $P_{si, min}$ (3. Refrac - Cycle)



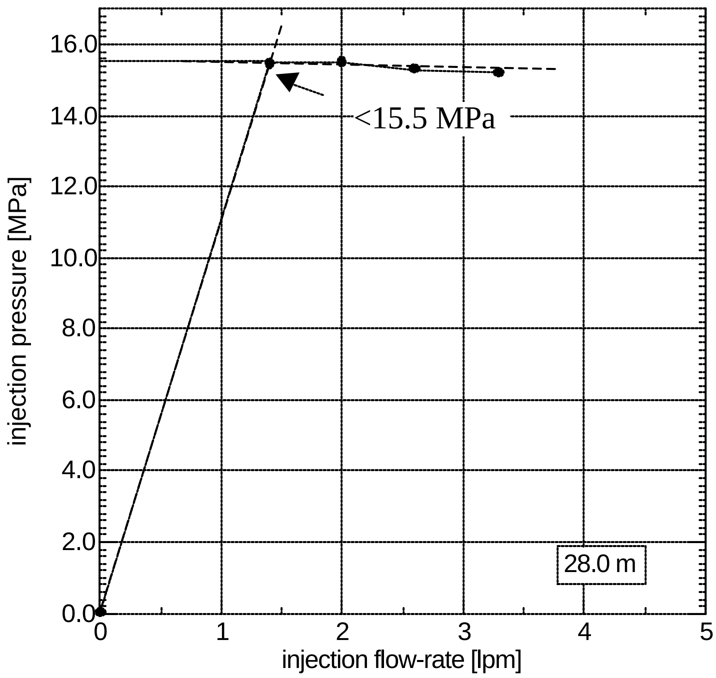
Test at 28.0 m : Estimation of P_{si} (3. Refrac - Cycle)



Test at 28.0 m : Analysis of Slow - Pump / Step - Rate - Test

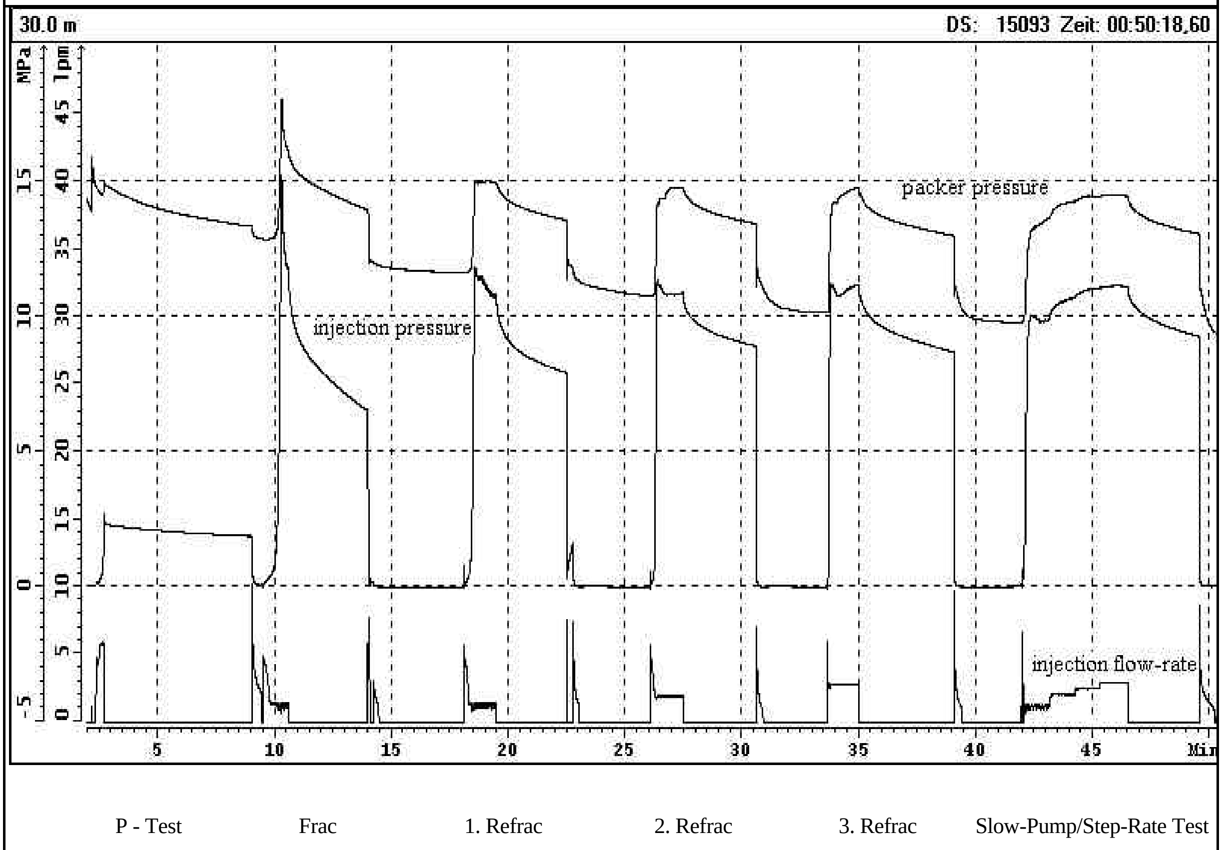


Test at 28.0 m : Examination of P_{si} (Step - Rate - Test)



Test at 30.0 M

Test at 30.0 m : Overview - Plot



<u>Test Summary</u>

P - Test : pressure decrease: 0.8 MPa in 7 min. 40 sec.

Frac - Cycle : injection-rate Q_i= 1.3 lpm, injected volume V_i = 2.0 l, back-flow volume V_r = 0.8 l
clear fracture initiation (breakdown event)

1. Refrac - Cycle : Q_i = 1.3 lpm, V_i = 2.3 l, V_r = 0.7 l

2. Refrac - Cycle : Q_i = 1.9 lpm, V_i = 3.1 l, V_r = 0.6 l

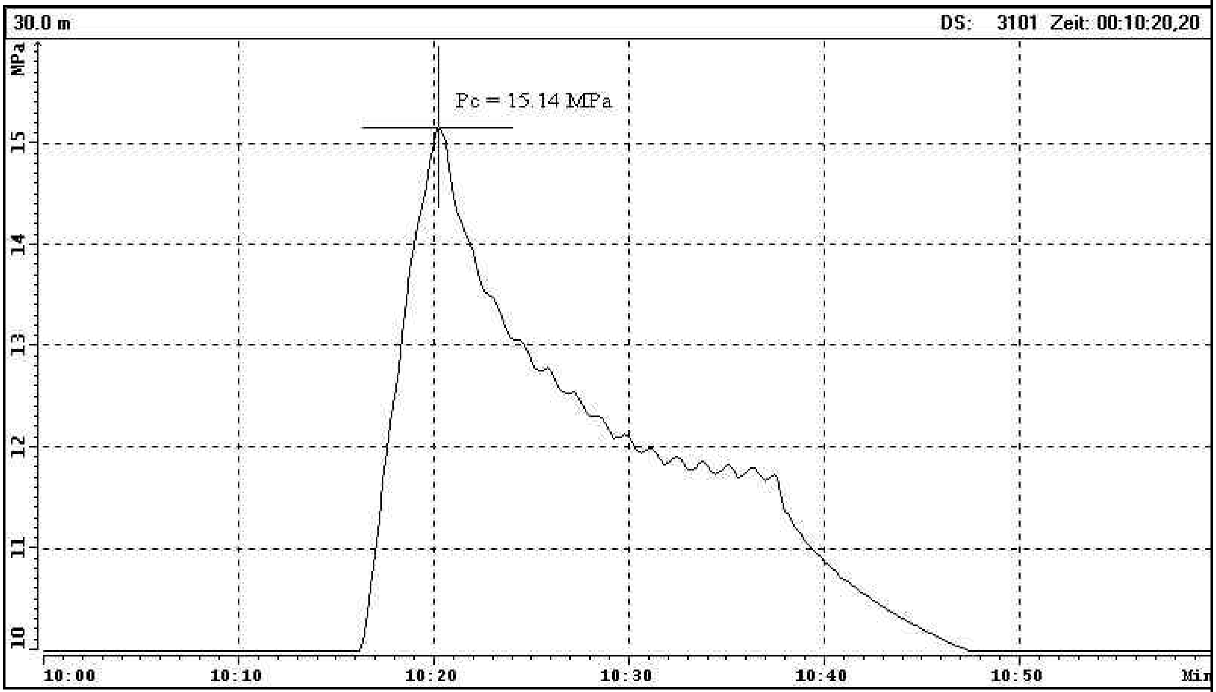
3. Refrac - Cycle : Q_i = 2.8 lpm, V_i = 3.9 l, V_r = 0.7 l

Step-Rate Test : Q_i = 1.1-2.9 lpm, V_i = 10.0 l, V_r = 1.3 l

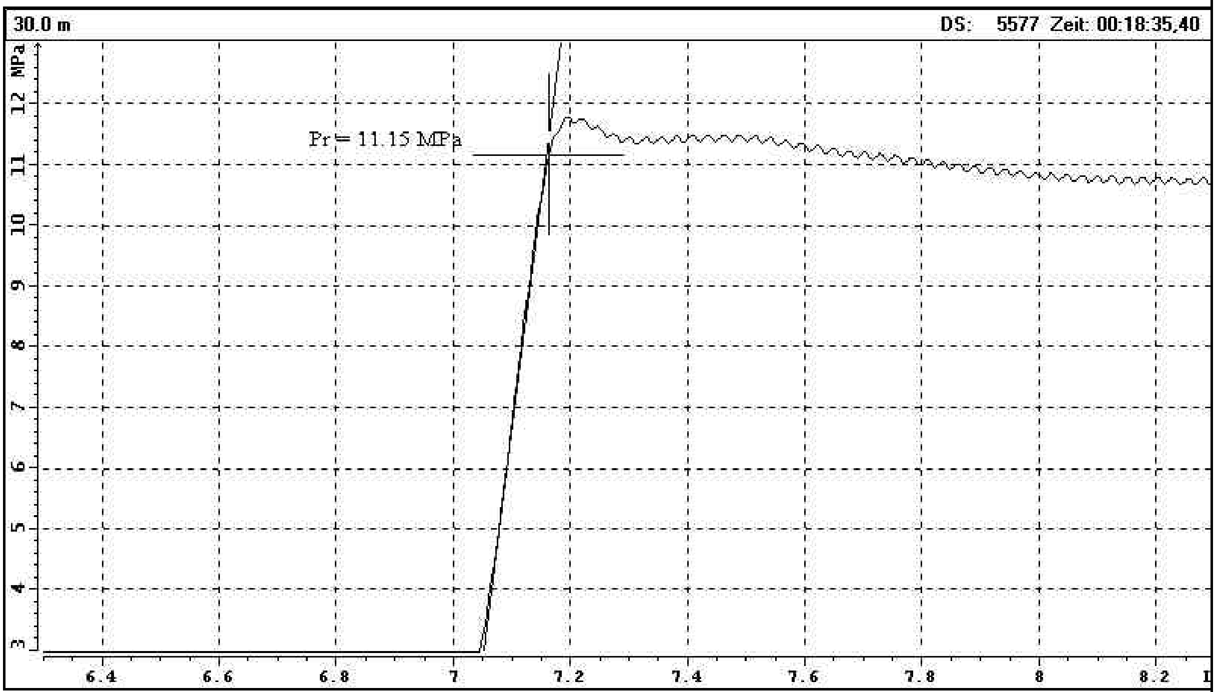
total injected volume = 21.3 l, recovered volume = 4.1 l (19.2 %)

<u>Remark:</u> During the injection - cycles, an increase of the shut-in pressure was observed. The P_{si} - value was therefore determined from the 1. refrac - cycle.

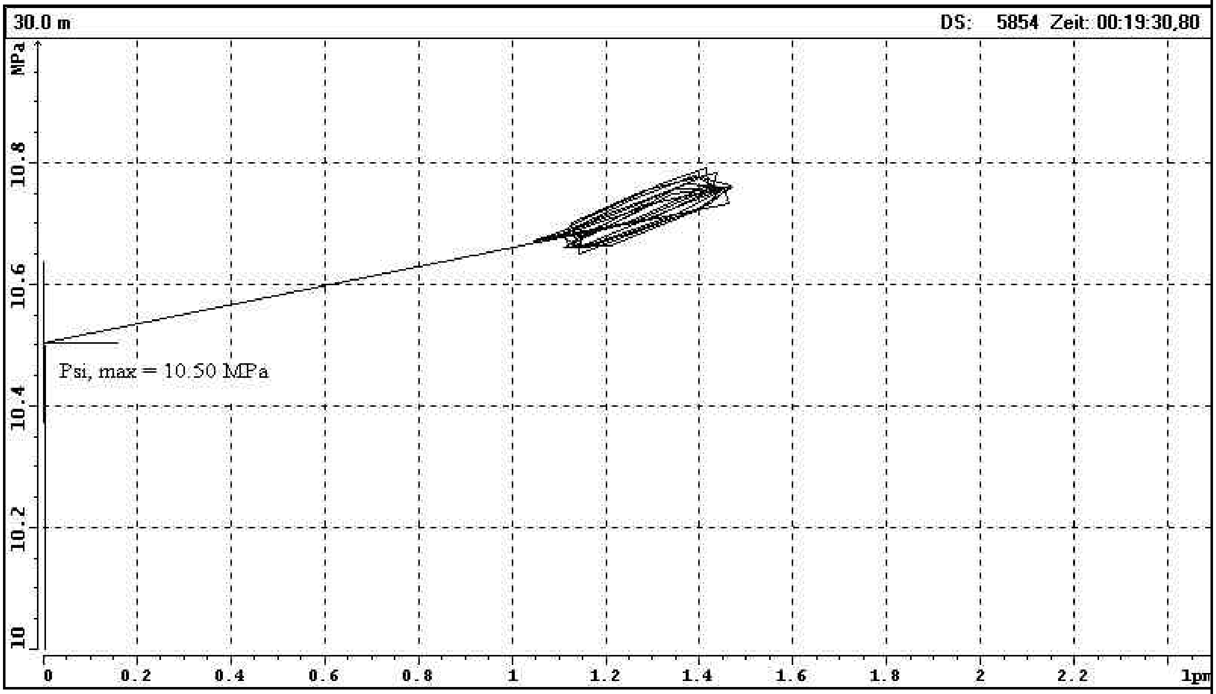
Test at 30.0 m : Estimation of P_c (Frac - Cycle)



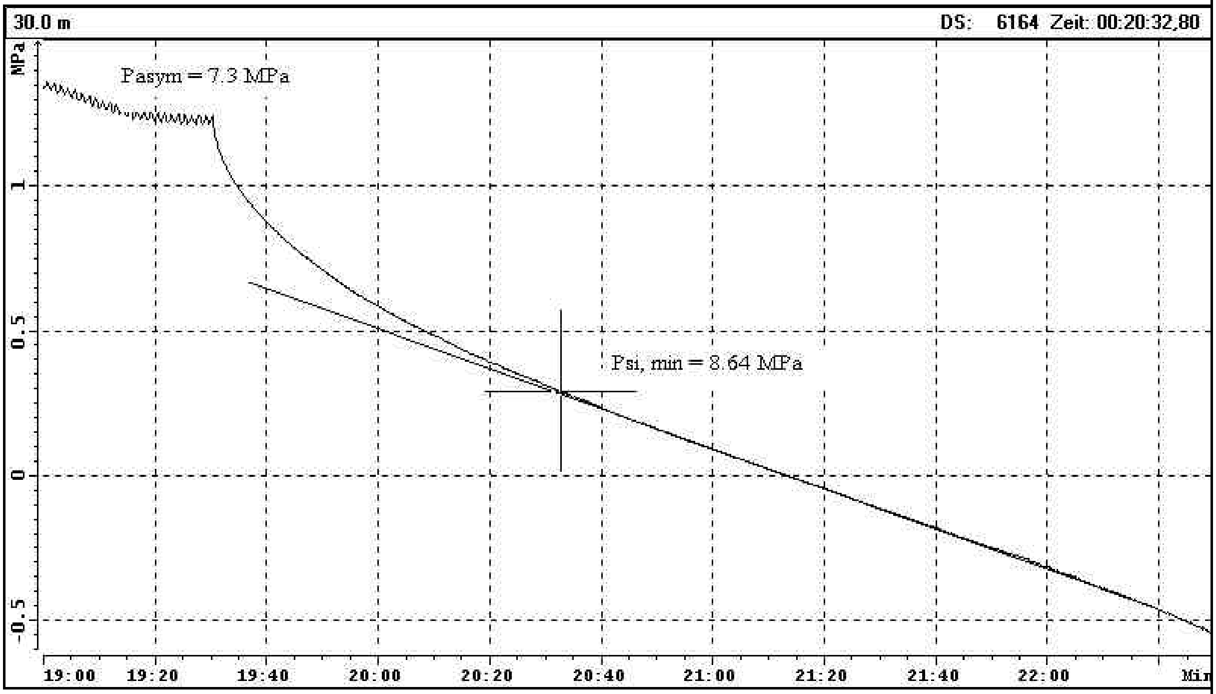
Test at 30.0 m : Estimation of P_r (1. Refrac - Cycle)



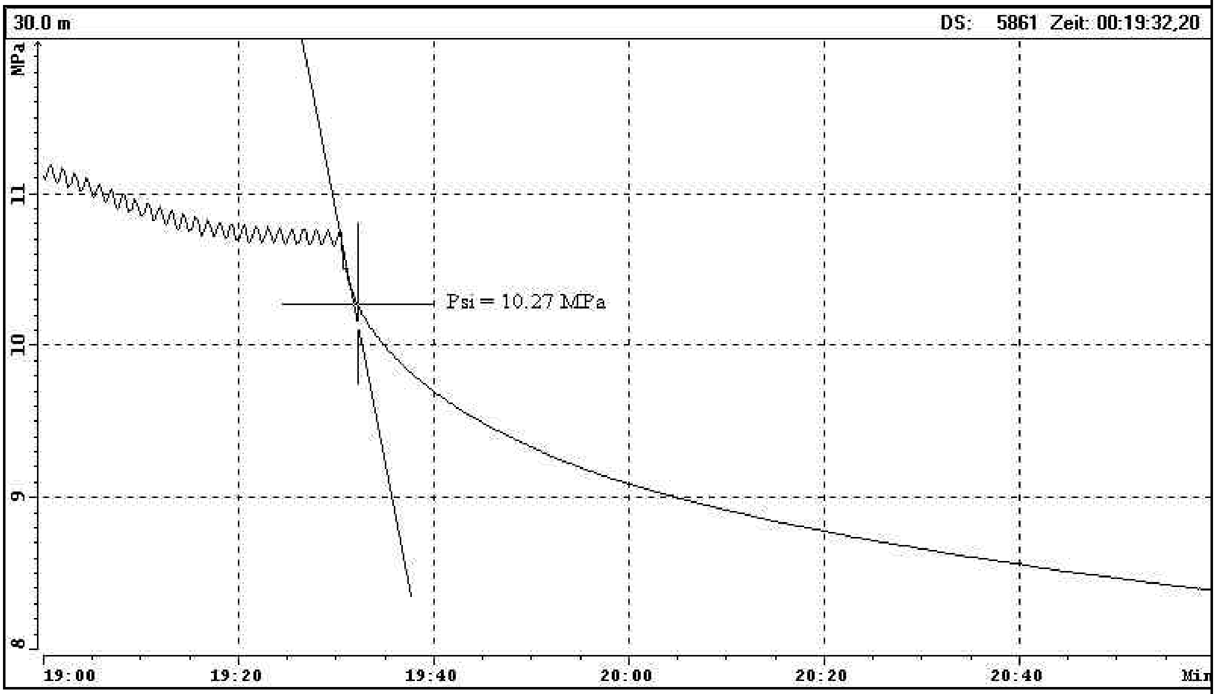
Test at 30.0 m : Estimation of $P_{si, max}$ (1. Refrac - Cycle)



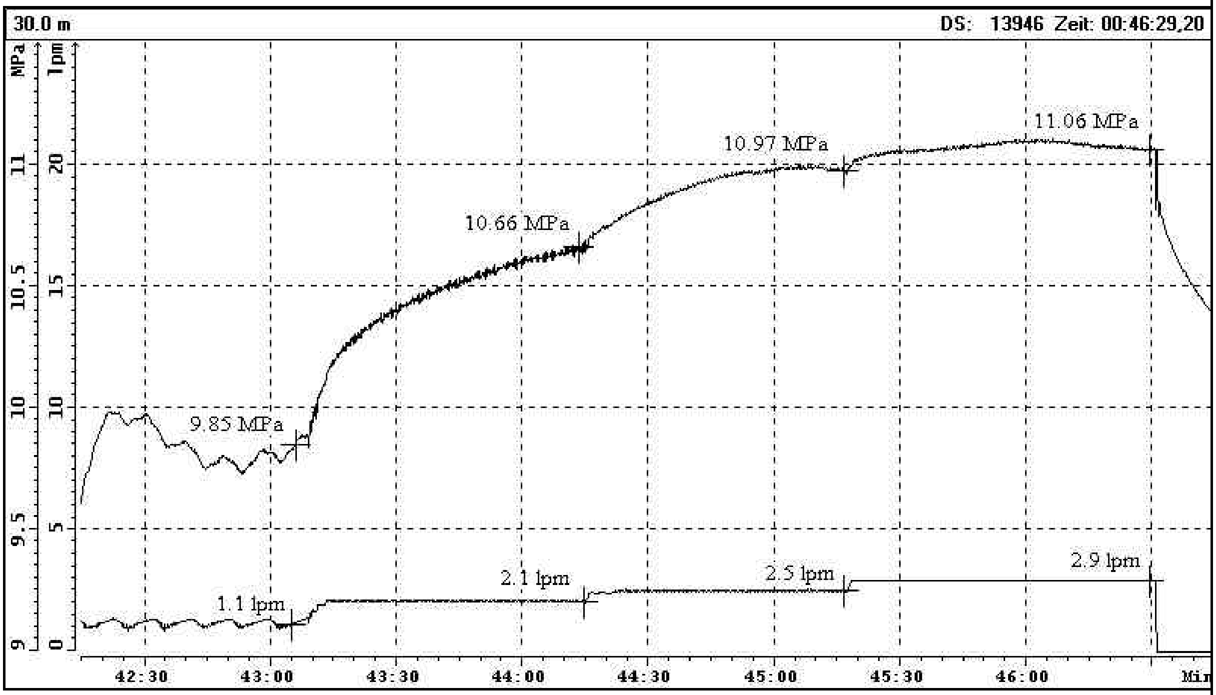
Test at 30.0 m : Estimation of $P_{si, min}$ (1. Refrac - Cycle)



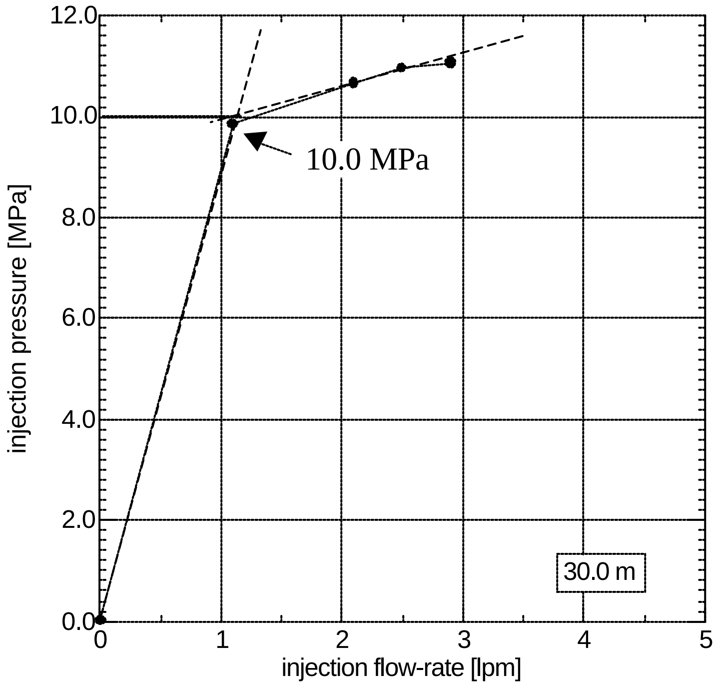
Test at 30.0 m : Estimation of P_{si} (1. Refrac - Cycle)



Test at 30.0 m : Analysis of Slow - Pump / Step - Rate - Test

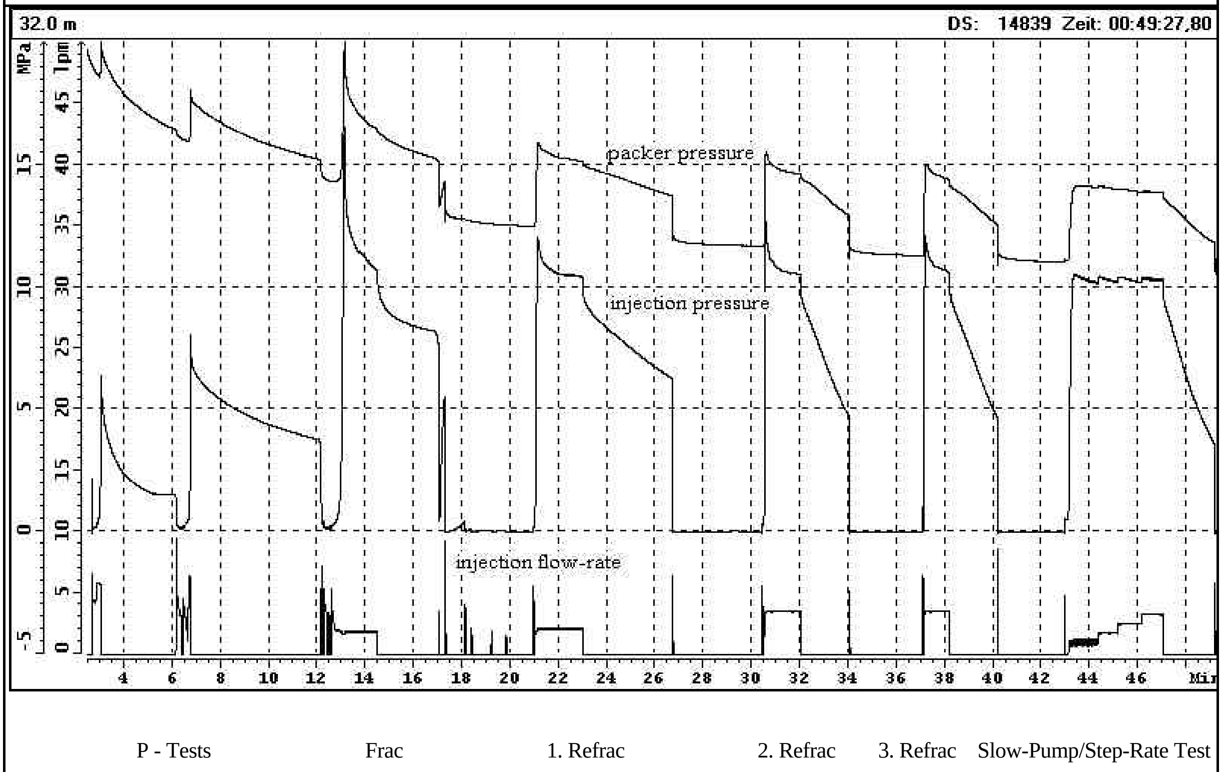


Test at Test at 30.0 m : Examination of P_{si} (Step - Rate - Test)



Test at 32.0 M MD

Test at 32.0 m : Overview - Plot



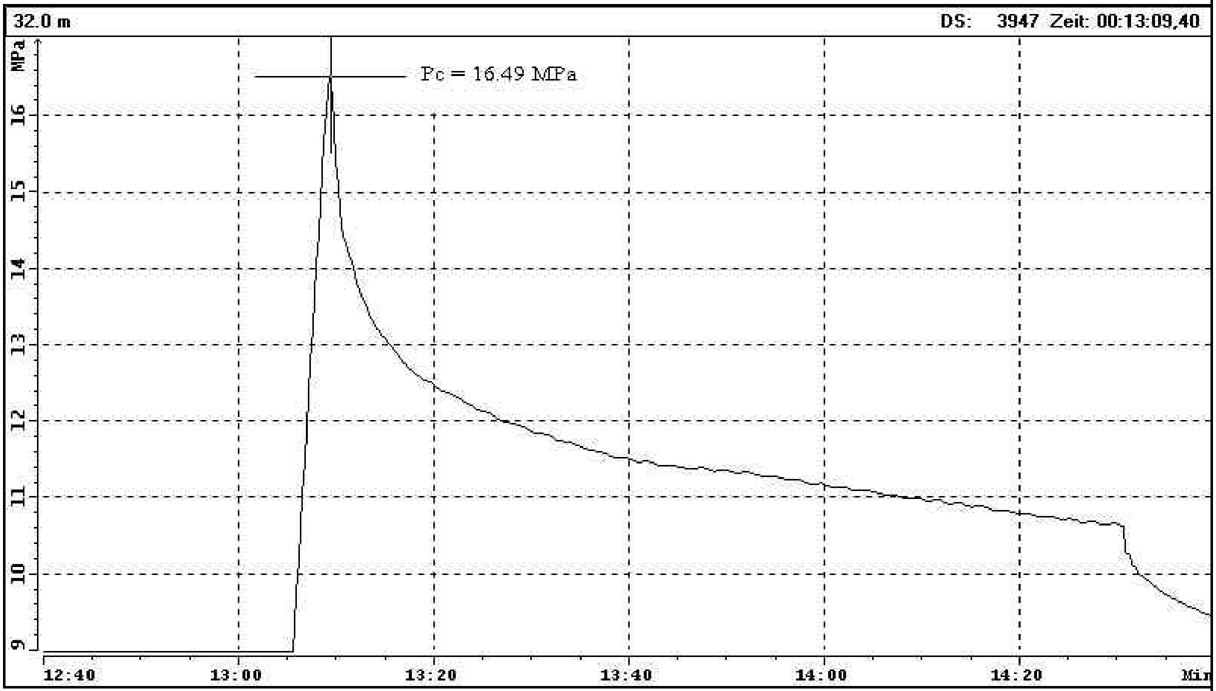
<u>Test Summary</u>

P - Test :	pressure decrease: 4.2 MPa in 5 min. 19 sec.
Frac - Cycle :	injection-rate Q_i= 1.9 lpm, injected volume V_i = 3.8 l,
	back-flow volume V_r = 0.4 l
	clear fracture initiation (breakdown event)
1. Refrac - Cycle :	Q_i = 2.1 lpm, V_i = 4.3 l, V_r = 0.1 l
2. Refrac - Cycle :	Q_i = 3.5 lpm, V_i = 5.4 l, V_r = 0.1 l
3. Refrac - Cycle :	Q_i = 3.5 lpm, V_i = 3.8 l, V_r = 0.1 l
Step-Rate Test :	Q_i = 1.0-3.3 lpm, V_i = 8.0 l, V_r = 0.1 l

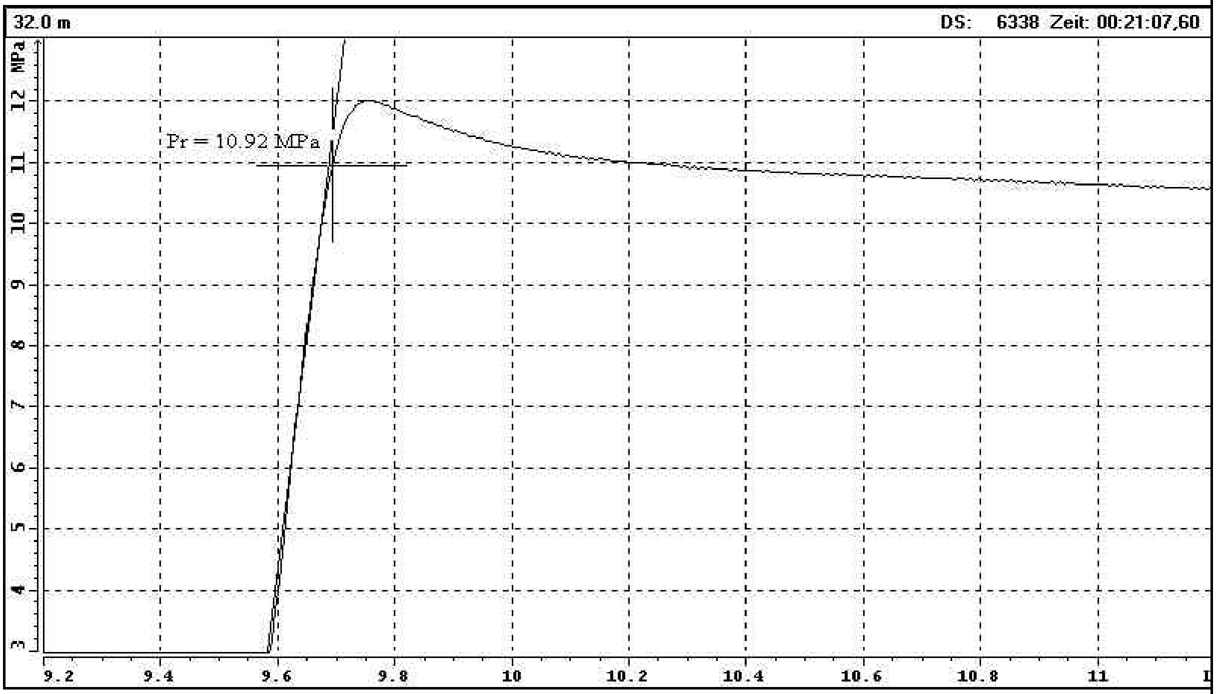
total injected volume = 25.3 l, recovered volume = 0.8 l (3.2 %)

<u>Remark:</u> The pulse test was repeated due to a leckage in the pressure control unit. During the injection cycles, the conductivity of the fracture increased. Therefore, the analysis of the shut-in pressure from the 2. and 3. refrac - cycle is difficult (estimation of $P_{si,\ min}$ not possible).

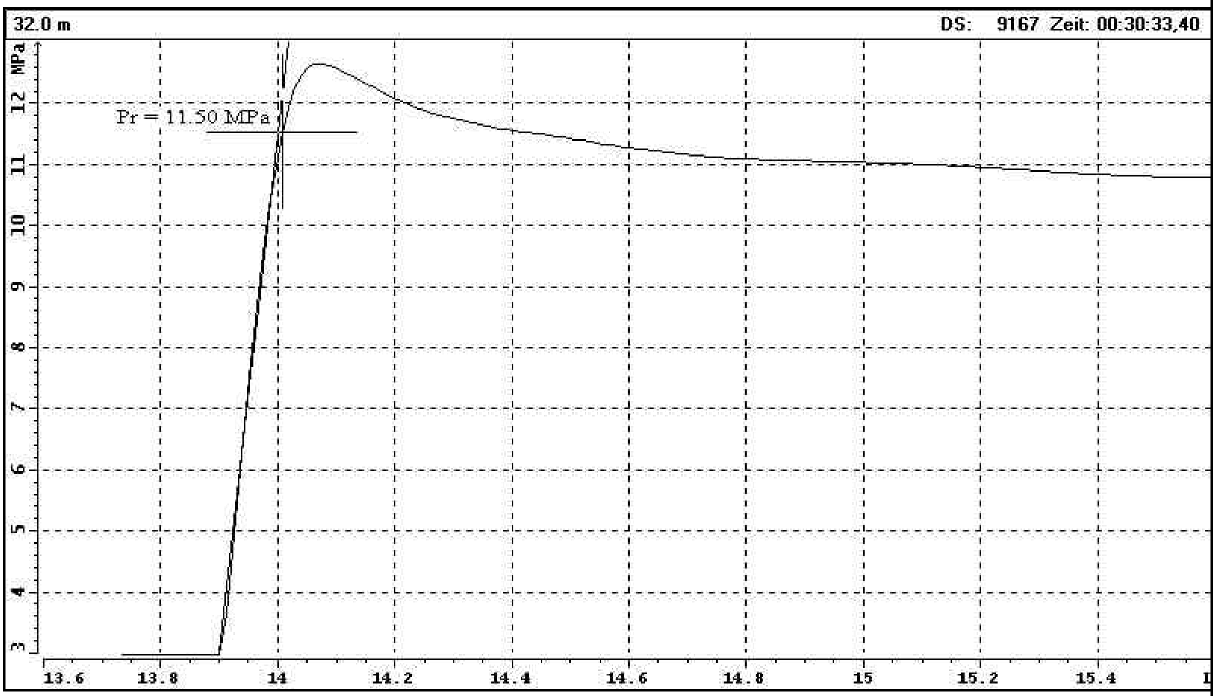
Test at 32.0 m : Estimation of P_c (Frac - Cycle)



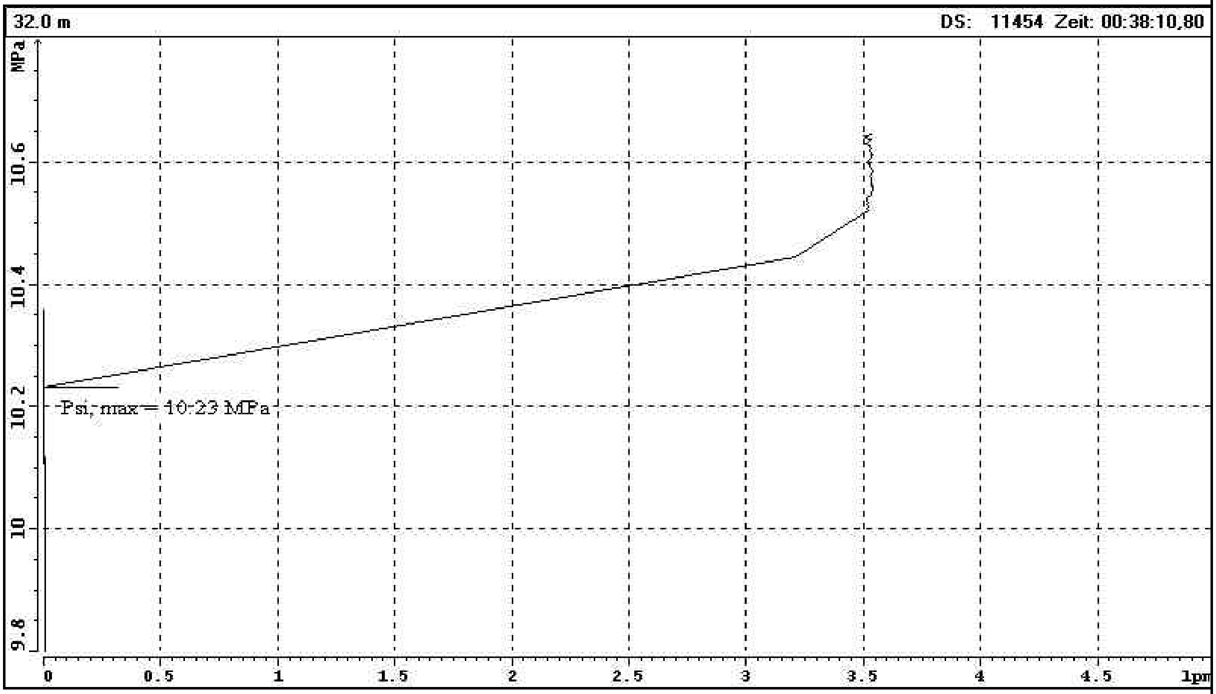
Test at 32.0 m : Estimation of P_r (1. Refrac - Cycle)



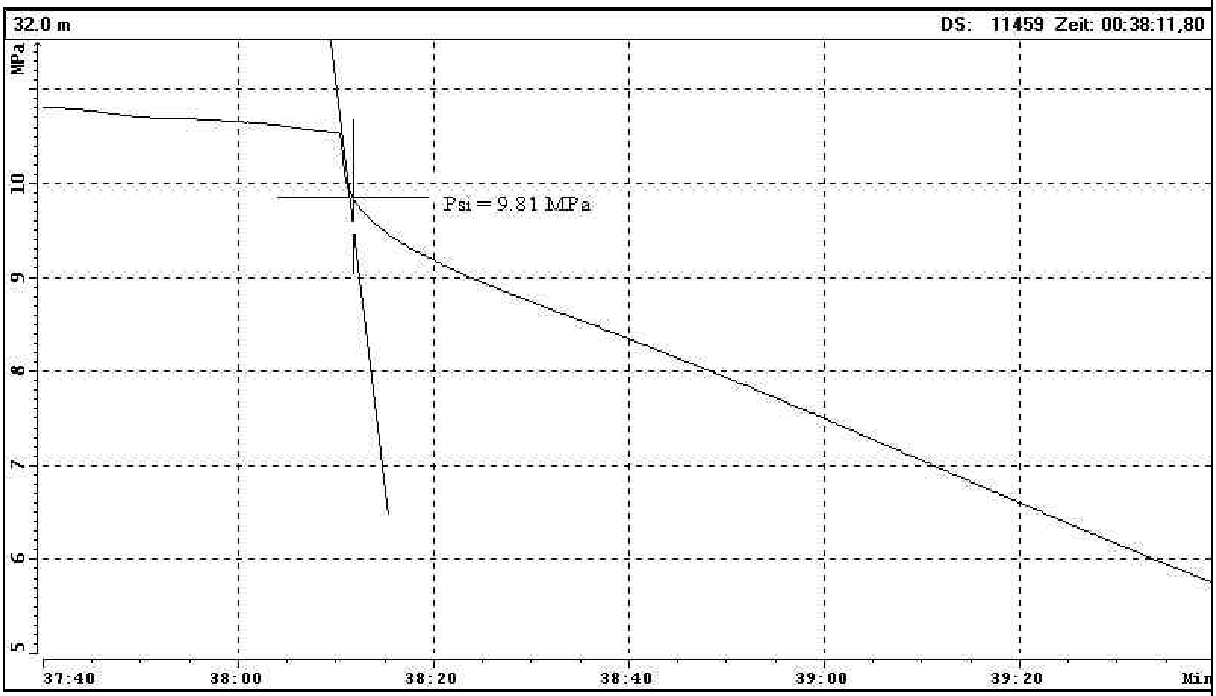
Test at 32.0 m : Estimation of P_r (2. Refrac - Cycle)



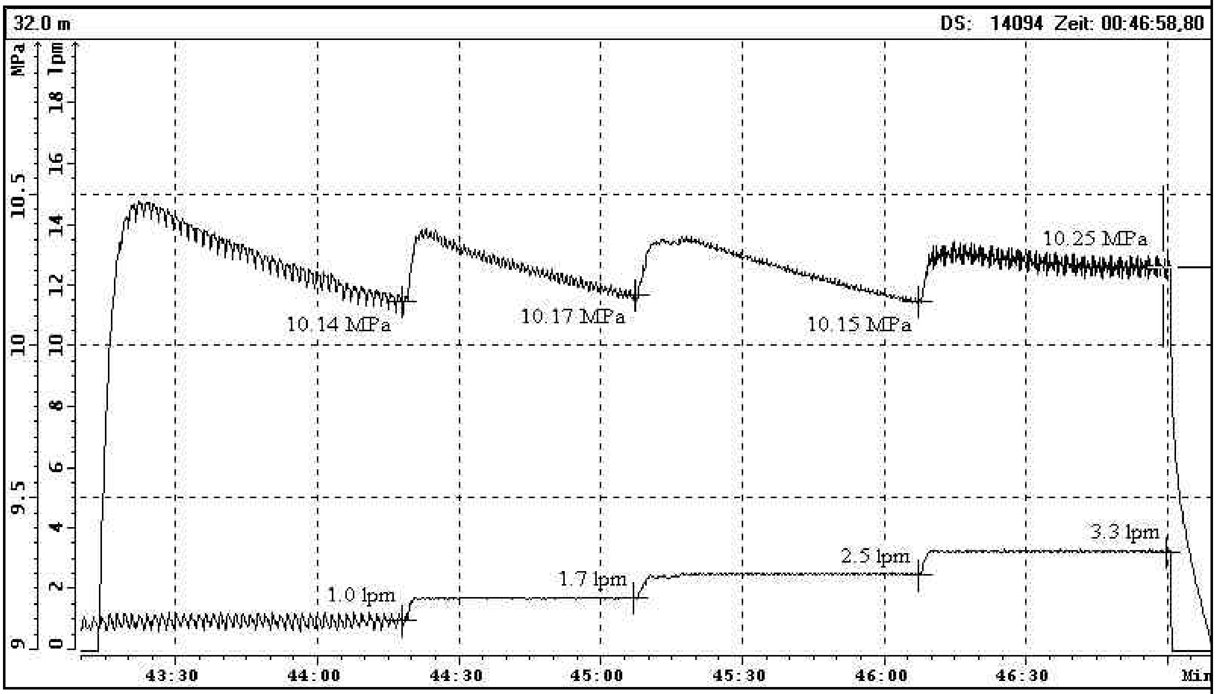
Test at 32.0 m : Estimation of $P_{si, max}$ (3. Refrac - Cycle)



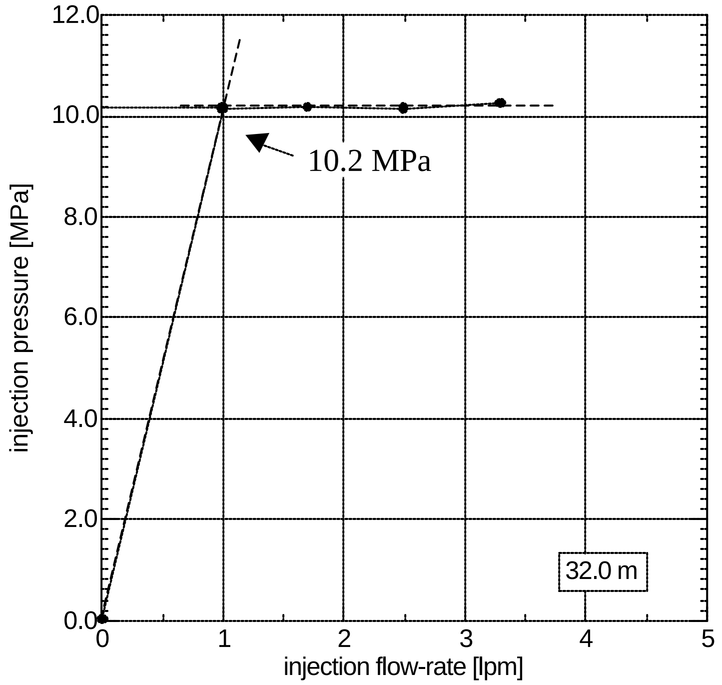
Test at 32.0 m : Estimation of P_{si} (3. Refrac - Cycle)



Test at 32.0 m : Analysis of Slow - Pump / Step - Rate - Test



Test at 32.0 m : Examination of P_{si} (Step - Rate - Test)



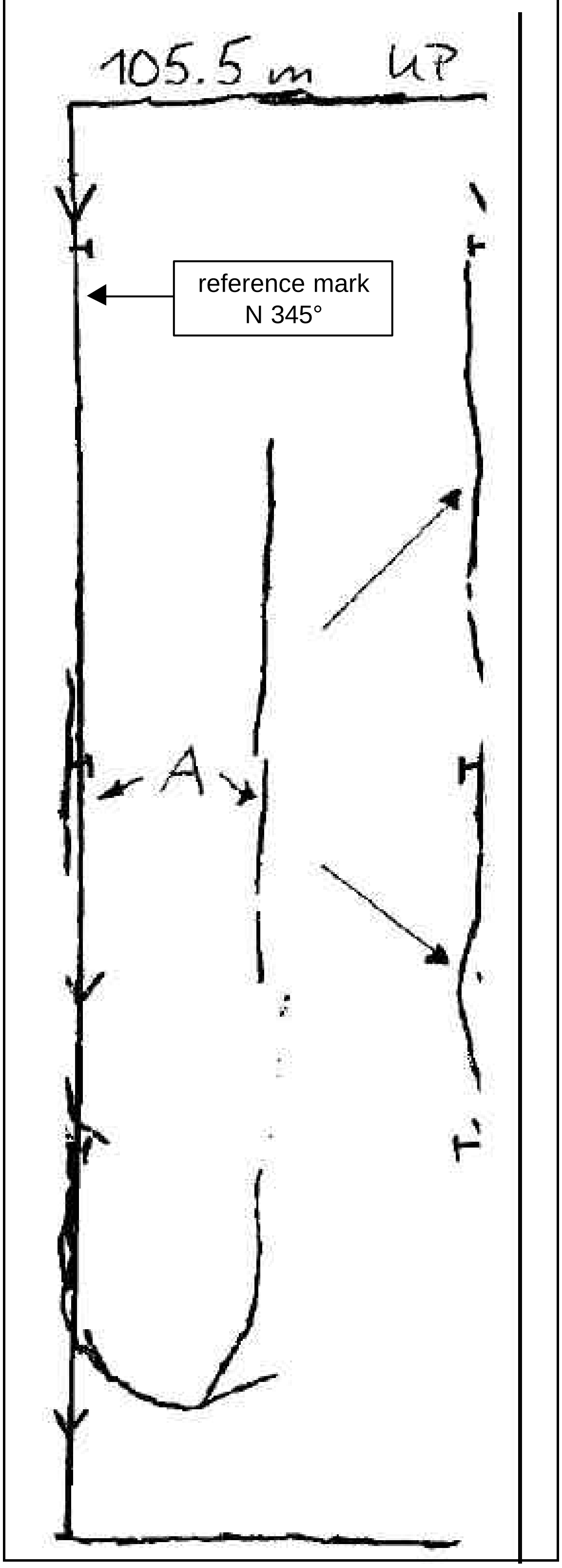
APPENDIX B1

Fracture traces on the impression packer sleeve

borehole no. KA2599G01

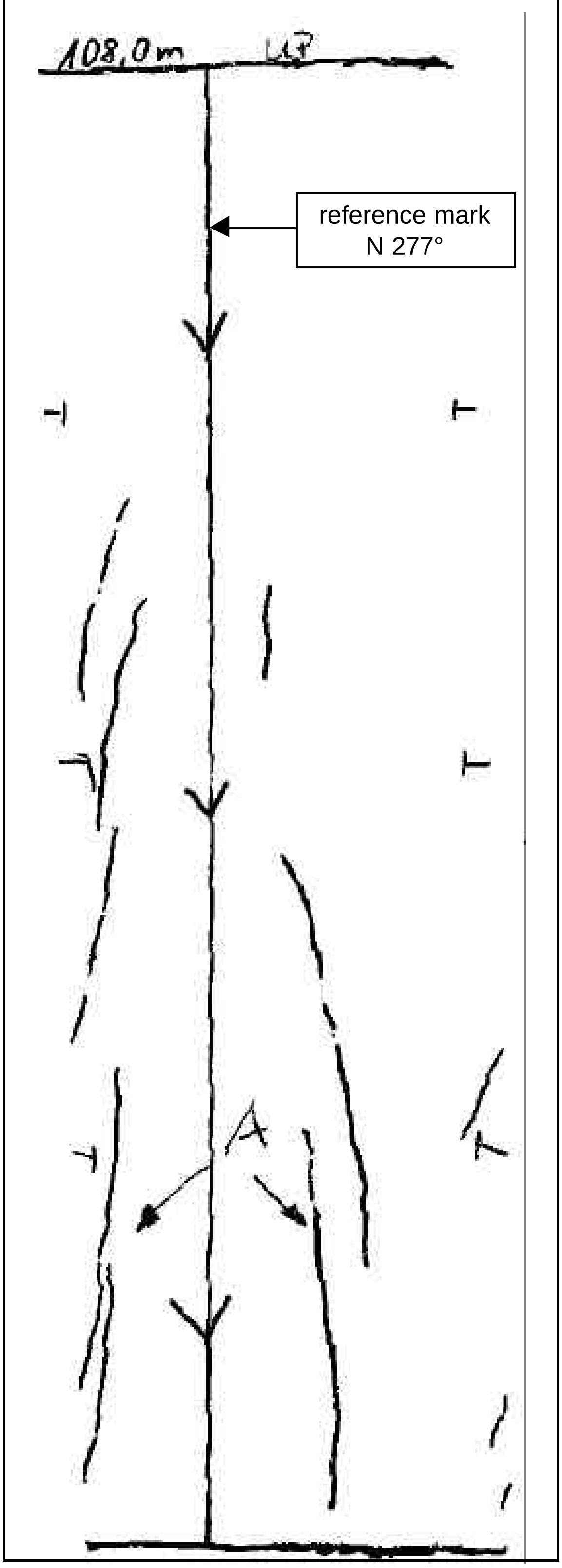
Test at 105.5 m MD

borehole dip / direction: 11° / N 303°



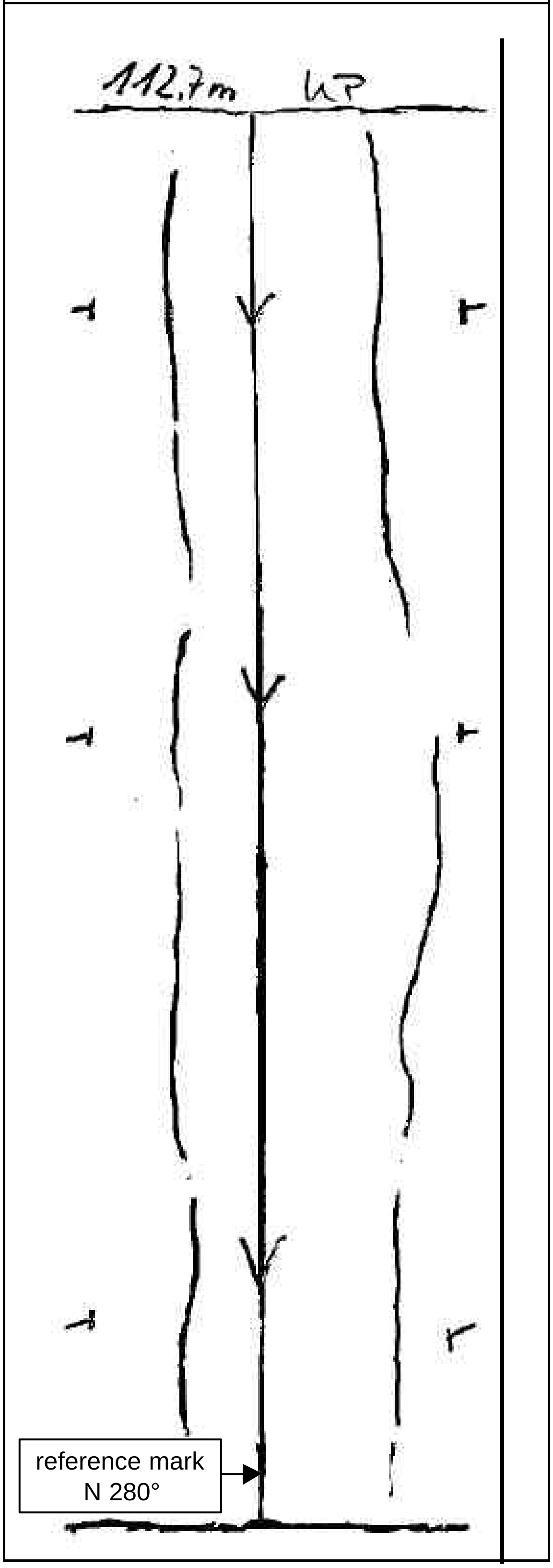
Test at 108.0 m MD

borehole dip / direction: 11° / N 298°



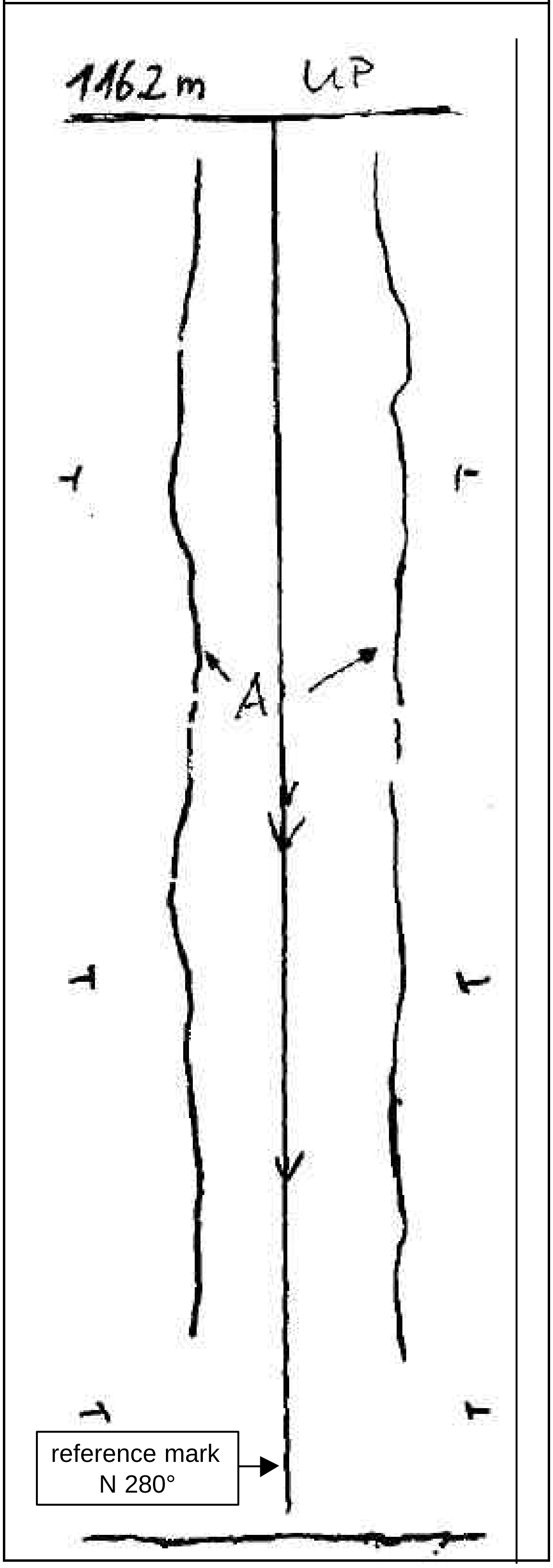
Test at 112.7 m MD

borehole dip / direction: 10° / N 298°



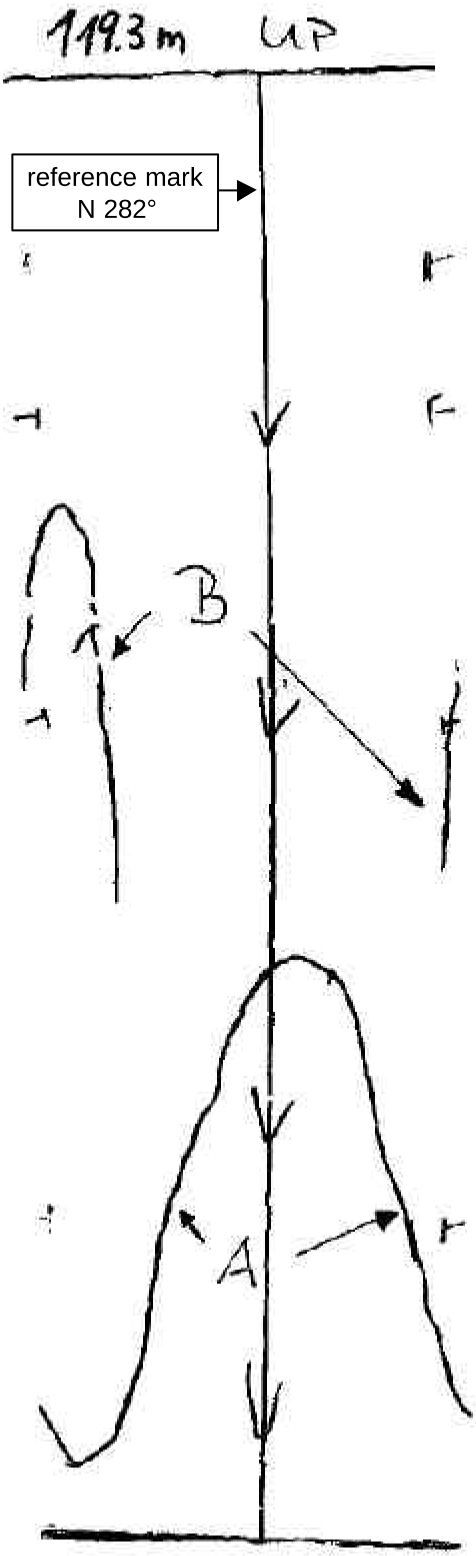
Test at 116.2 m MD

borehole dip / direction: 10° / N 298°



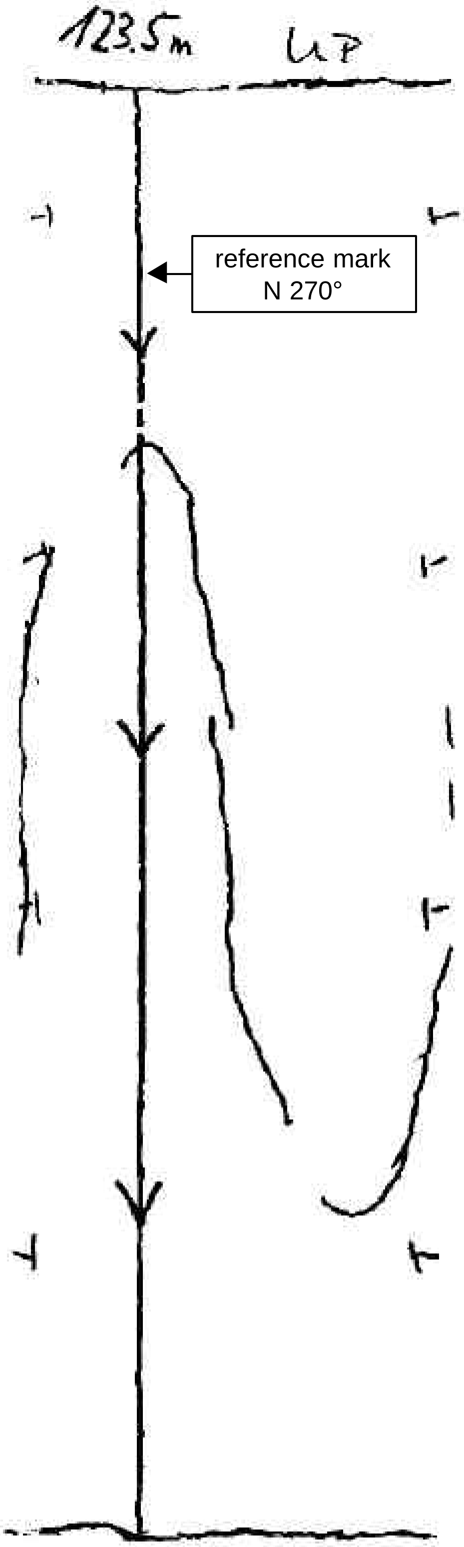
Test at 119.3 m MD

borehole dip / direction: 11° / N 299°



Test at 123.5 m MD

borehole dip / direction: 11° / N 296°

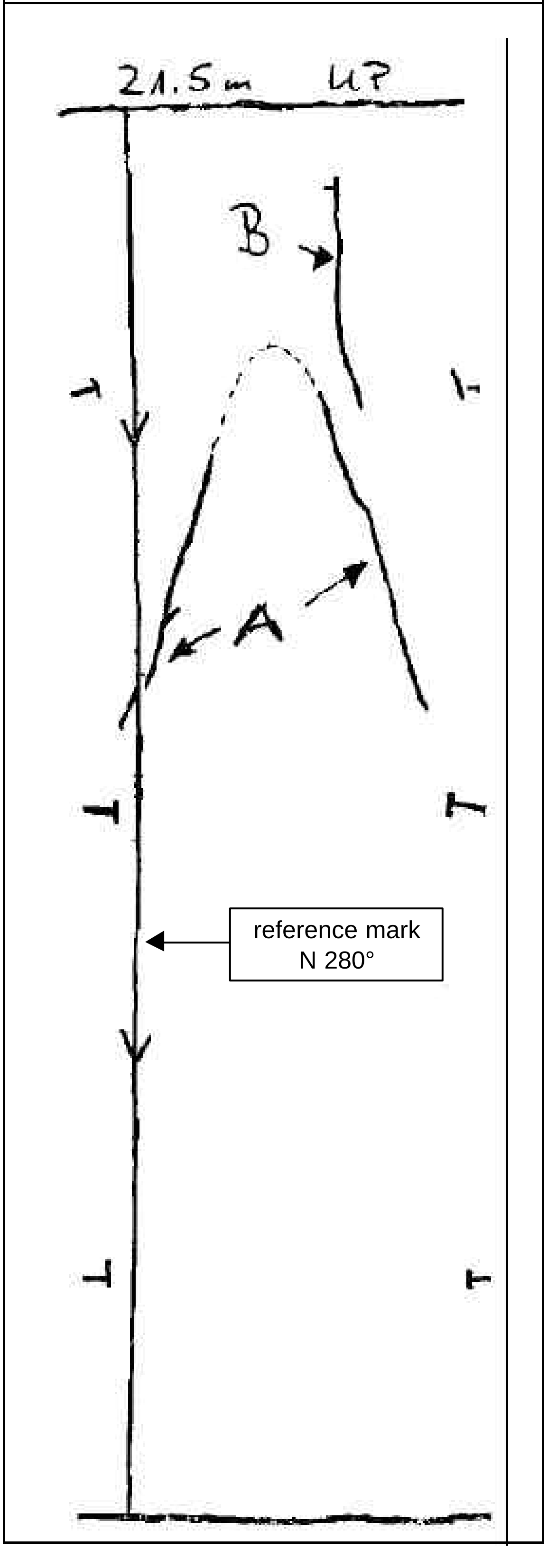


APPENDIX B2

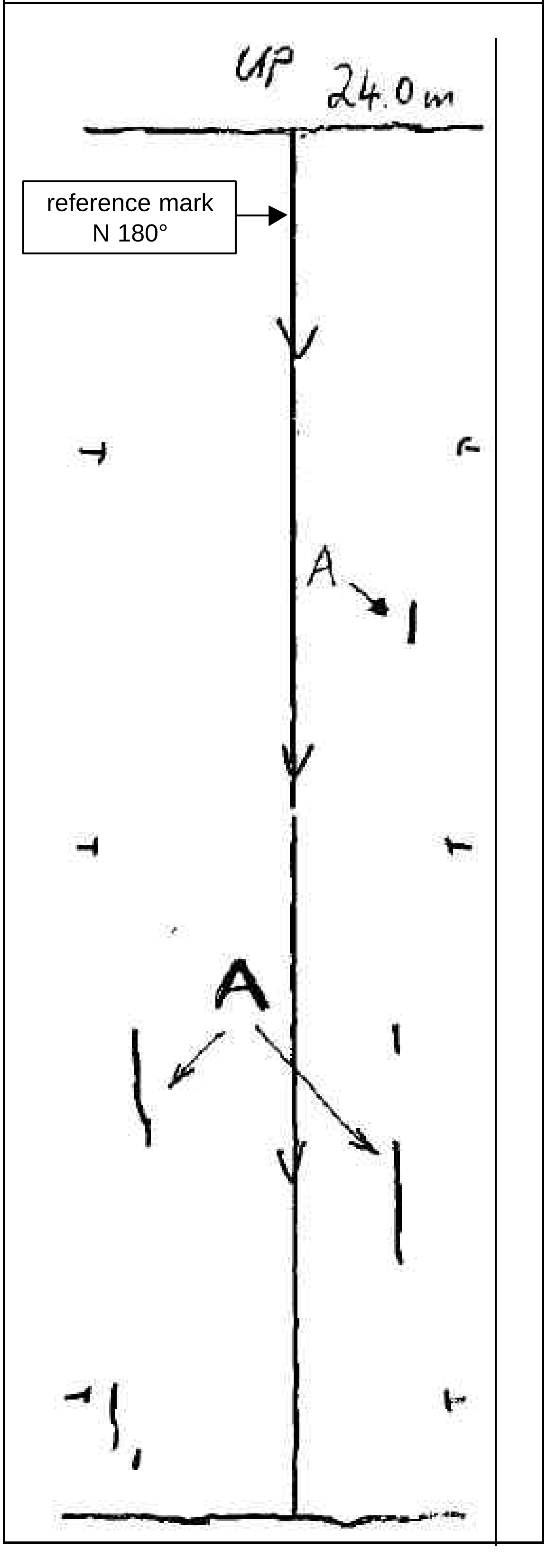
Fracture traces on the impression packer sleeve

borehole no. KF0093A01

Test at 21.5 m
borehole dip / direction: 92° / N 298°

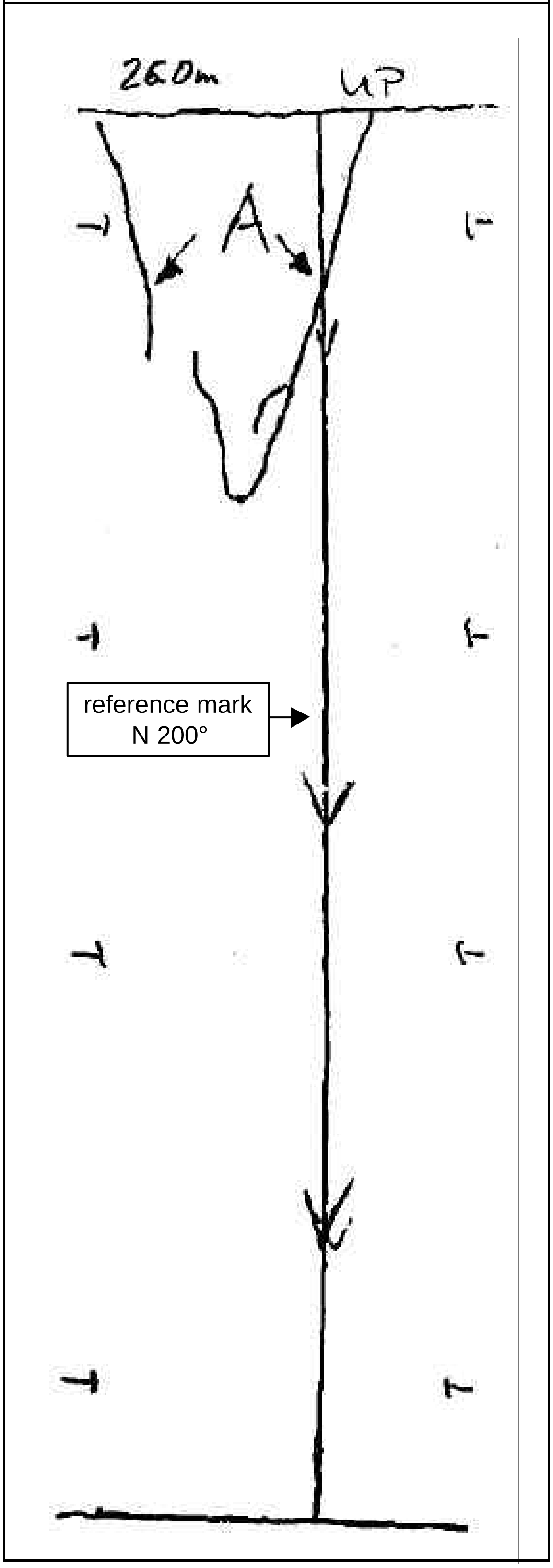


Test at 24.0 m
borehole dip / direction: 92° / N 298°



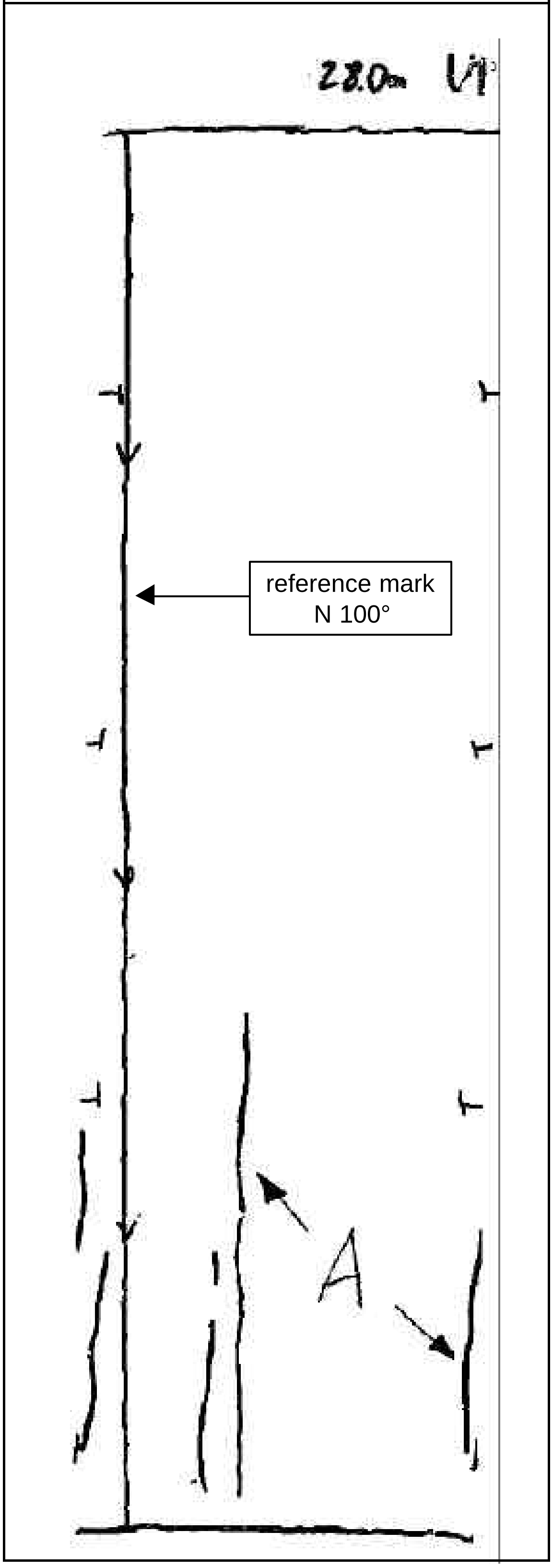
Test at 26.0 m

borehole dip / direction: 92° / N 298°



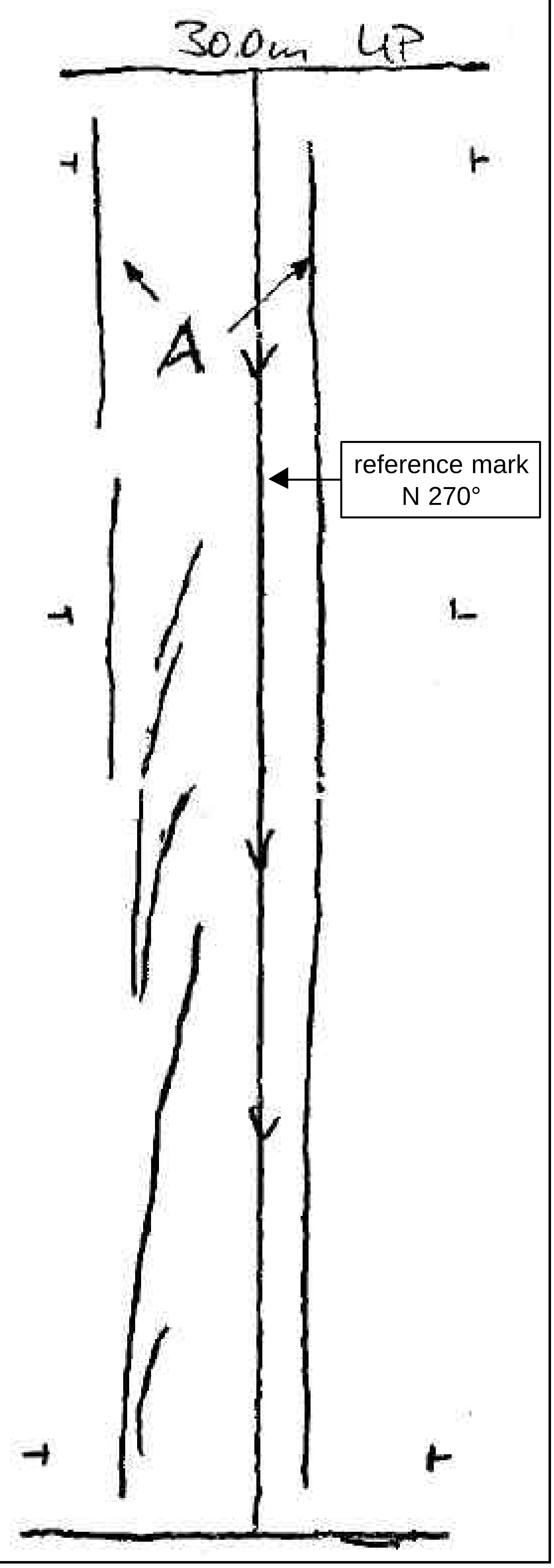
Test at 28.0 m

borehole dip / direction: 92° / N 298°



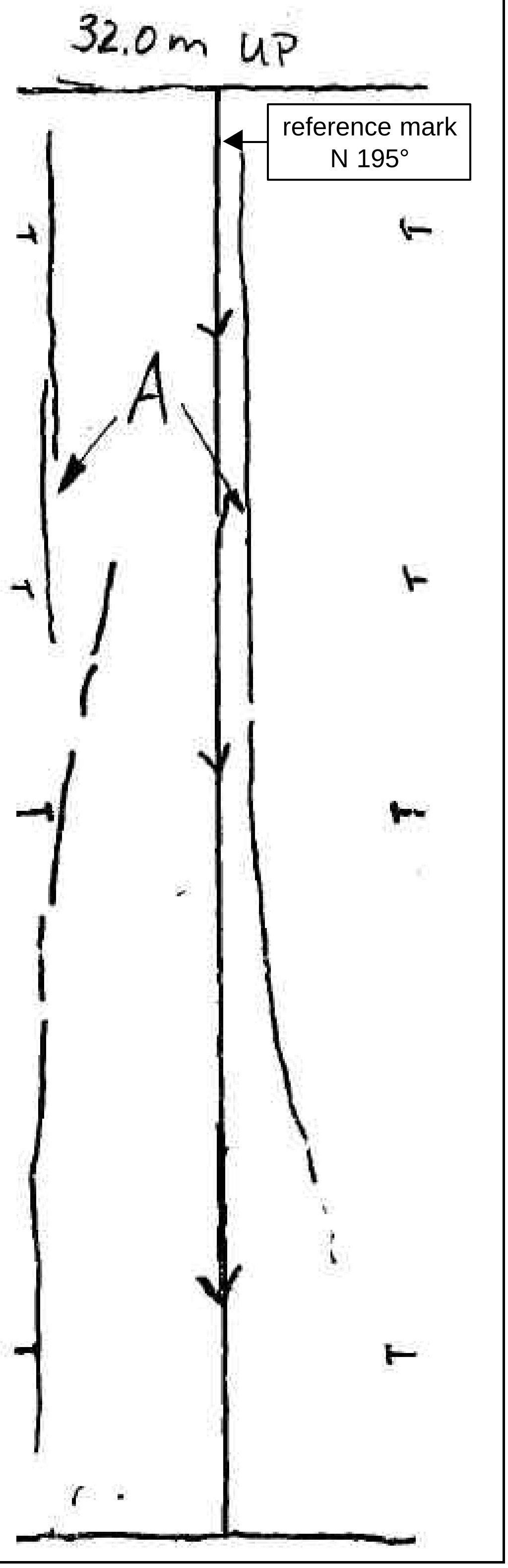
Test at 30.0 m

borehole dip / direction: 92° / N 298°



Test at 32.0 m

borehole dip / direction: 92° / N 298°



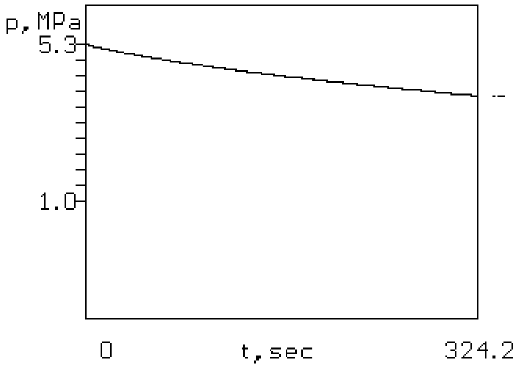
APPENDIX C1

Analysis of pressure pulse tests

borehole no. KA2599G01

Test at 105.5 M MD

Permeability-Estimation



INPUTPARAMETERS

filename:	105.txt
samplingrate, sec:	0.20
inv. Stiffness m³.m/Pa:	2.0E-11
interval length, m:	0.60
hole diameter, mm:	96.00
Phyd, MPa:	1.01
Tm (min, max), sec:	500 3000
number of models:	20000
error:	1.8E-03

result (mean value of all fitting models):

Permeability : (7.8 ± 0.1) µdarcy

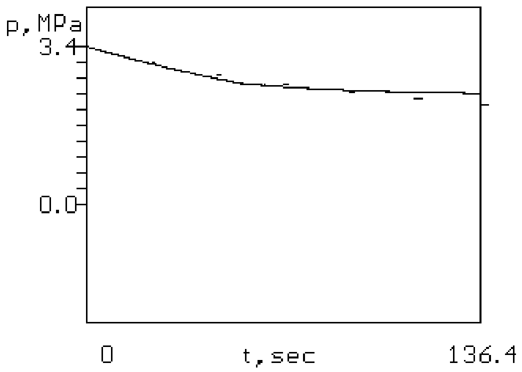
Kf : (7.8 ± 0.1) e-11 m/s 1

Alpha : (0.10000)

Number of fitting models: 46

Test at 108.0 M MD

Permeability-Estimation



INPUTPARAMETERS

filename:	108b.txt
samplingrate, sec:	0.20
inv. Stiffness m³.m/Pa:	2.0E-11
interval length, m:	0.60
hole diameter, mm:	96.00
Phyd, MPa:	0.00
Tm (min, max), sec:	251 752
number of models:	20000
error:	2.4E-02

result (mean value of all fitting models):

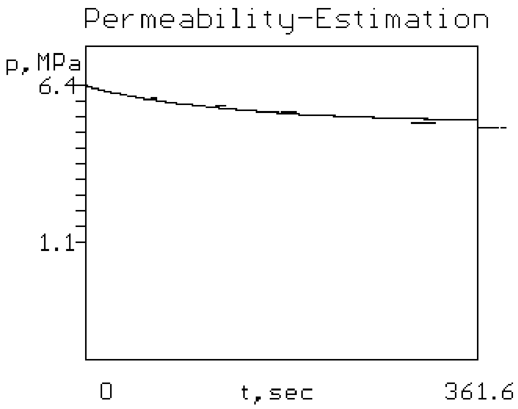
Permeability : (23.1 ± 0.1) µdarcy

Kf : (2.3 ± 0.0) e-10 m/s

Alpha : (0.10000)

Number of fitting models: 49

Test at 112.7 M MD



INPUTPARAMETERS

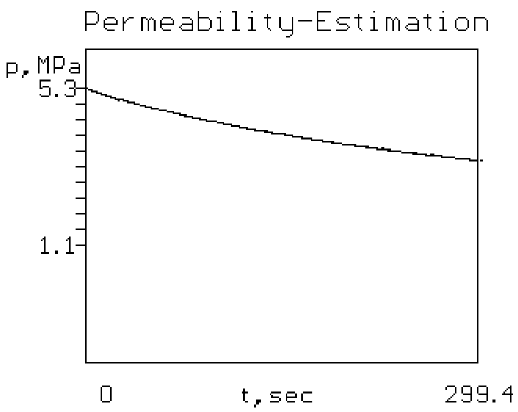
filename:	112.txt
samplingrate, sec:	0.20
inv. Stiffness m²·m/Pa:	2.0E-11
interval length, m:	0.60
hole diameter, mm:	96.00
Phyd, MPa:	1.07
Tm (min, max), sec:	926 2777
number of models:	20000
error:	1.2E-02

result (mean value of all fitting models):

Permeability : (8.5 ± 0.2) μdarcy
Kf : (8.5 ± 0.2) e-11 m/s
Alpha : (0.01000) -

Number of fitting models: 161

Test at 116.2 M MD



INPUTPARAMETERS

filename:	116.txt
samplingrate, sec:	0.20
inv. Stiffness m²·m/Pa:	2.0E-11
interval length, m:	0.60
hole diameter, mm:	96.00
Phyd, MPa:	1.12
Tm (min, max), sec:	251 752
number of models:	20000
error:	5.0E-03

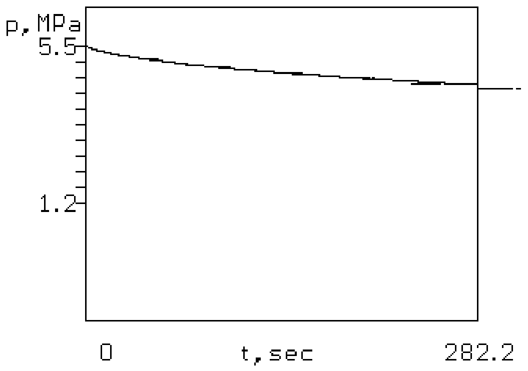
result (mean value of all fitting models):

Permeability : (42.1 ± 0.1) μdarcy
Kf : (4.2 ± 0.0) e-10 m/s
Alpha : (0.00100) -

Number of fitting models: 17

Test at 119.3 M MD

Permeability-Estimation



INPUTPARAMETERS

filename:	119.txt
samplingrate, sec:	0.20
inv. Stiffness m³.m/Pa:	2.0E-11
interval length, m:	0.60
hole diameter, mm:	96.00
Phyd, MPa:	1.16
Tm (min, max), sec:	801 2402
number of models:	20000
error:	6.5E-03

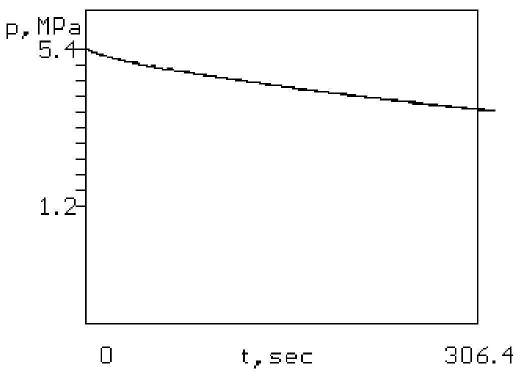
result (mean value of all fitting models):

Permeability	: (10.8 ± 0.3)	µdarcy
Kf	: (1.1 ± 0.0)	e-10 m/s
Alpha	: (0.01000)	

Number of fitting models: 210

Test at 123.5 M MD

Permeability-Estimation



INPUTPARAMETERS

filename:	123.txt
samplingrate, sec:	0.20
inv. Stiffness m³.m/Pa:	2.0E-11
interval length, m:	0.60
hole diameter, mm:	96.00
Phyd, MPa:	1.17
Tm (min, max), sec:	126 377
number of models:	20000
error:	5.5E-03

result (mean value of all fitting models):

Permeability	: (40.3 ± 0.6)	µdarcy
Kf	: (4.0 ± 0.1)	e-10 m/s
Alpha	: (0.00010)	

Number of fitting models: 227

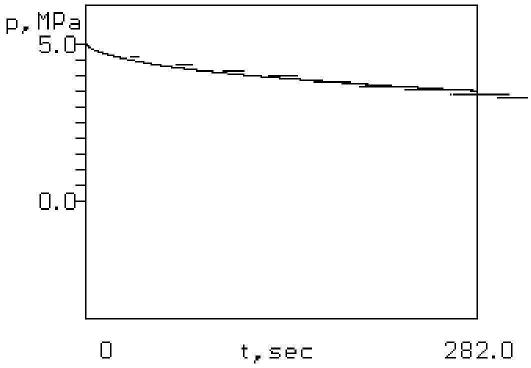
APPENDIX C2

Analysis of pressure pulse tests

borehole no. KF0093A01

Test at 21.5 M MD

Permeability-Estimation



INPUTPARAMETERS

filename:	21.txt
samplingrate, sec:	0.20
inv. Stiffness m³.m/Pa:	3.2E-11
interval length, m:	0.60
hole diameter, mm:	96.00
Phyd, MPa:	0.00
Tm (min, max), sec:	351 1052
number of models:	20000
error:	2.0E-02

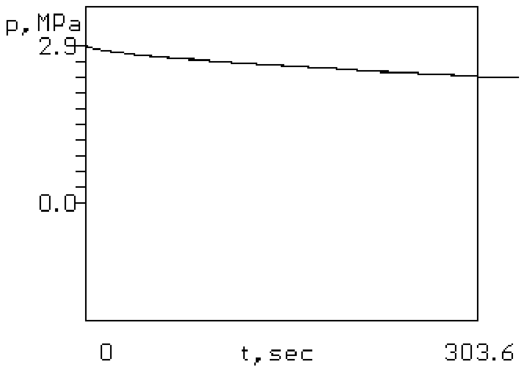
result (mean value of all fitting models):

Permeability : (23.8 ± 0.9) µdarcy
Kf : (2.4 ± 0.1) e-10 m/s
Alpha : (0.01000)

Number of fitting models: 553

Test at 24.0 M MD

Permeability-Estimation



INPUTPARAMETERS

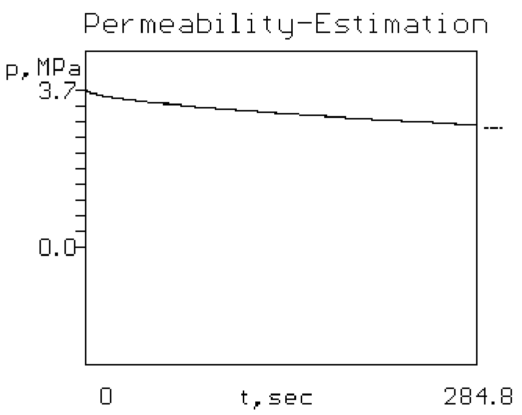
filename:	24.txt
samplingrate, sec:	0.20
inv. Stiffness m³.m/Pa:	3.2E-11
interval length, m:	0.60
hole diameter, mm:	96.00
Phyd, MPa:	0.00
Tm (min, max), sec:	801 2402
number of models:	20000
error:	6.0E-03

result (mean value of all fitting models):

Permeability : (10.7 ± 0.3) µdarcy
Kf : (1.1 ± 0.0) e-10 m/s
Alpha : (0.01000)

Number of fitting models: 362

Test at 26.0 M MD



INPUTPARAMETERS

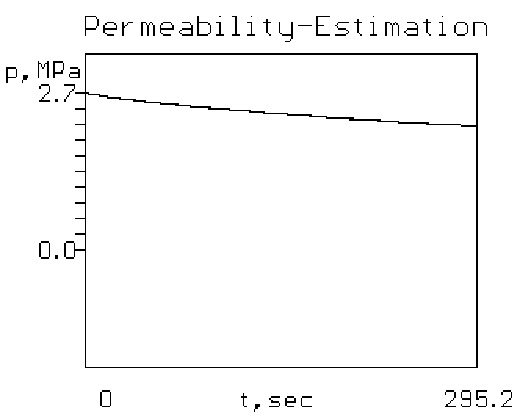
filename:	26.txt
samplingrate, sec:	0.20
inv. Stiffness m³.m/Pa:	3.2E-11
interval length, m:	0.60
hole diameter, mm:	96.00
Phyd, MPa:	0.00
Tm (min, max), sec:	801 2402
number of models:	20000
error:	5.0E-03

result (mean value of all fitting models):

Permeability : (14.3 ± 0.2) μdarcy
Kf : (1.4 ± 0.0) e-10 m/s
Alpha : (0.01000)

Number of fitting models: 78

Test at 28.0 M MD



INPUTPARAMETERS

filename:	28.txt
samplingrate, sec:	0.20
inv. Stiffness m³.m/Pa:	3.2E-11
interval length, m:	0.60
hole diameter, mm:	96.00
Phyd, MPa:	0.00
Tm (min, max), sec:	801 2402
number of models:	20000
error:	2.0E-03

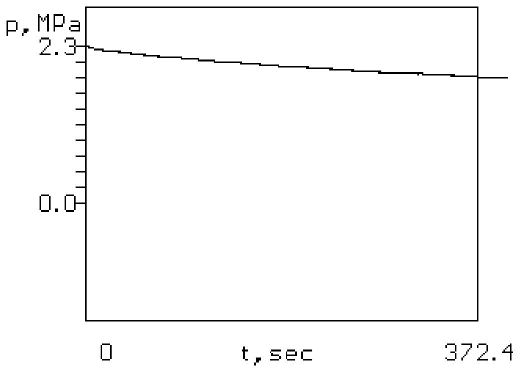
result (mean value of all fitting models):

Permeability : (12.2 ± 0.1) μdarcy
Kf : (1.2 ± 0.0) e-10 m/s
Alpha : (0.01000)

Number of fitting models: 111

Test at 30.0 M MD

Permeability-Estimation



INPUTPARAMETERS

filename:	30.txt
samplingrate, sec:	0.20
inv. Stiffness m².m/Pa:	3.2E-11
interval length, m:	0.60
hole diameter, mm:	96.00
Phyd, MPa:	0.00
Tm (min, max), sec:	801 2402
number of models:	20000
error:	2.0E-03

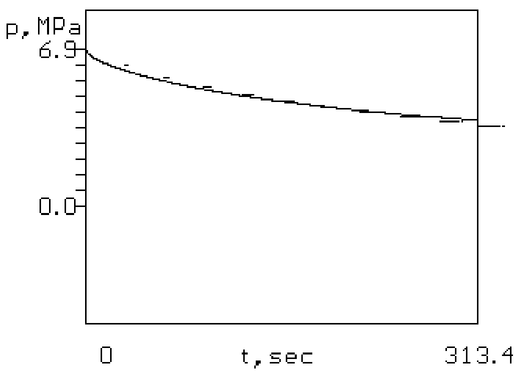
result (mean value of all fitting models):

Permeability	: (8.8 ± 0.2) µdarcy
Kf	: (8.8 ± 0.2) e-11 m/s
Alpha	: (0.01000)

Number of fitting models: 276

Test at 32.0 M MD

Permeability-Estimation



INPUTPARAMETERS

filename:	32b.txt
samplingrate, sec:	0.20
inv. Stiffness m².m/Pa:	3.2E-11
interval length, m:	0.60
hole diameter, mm:	96.00
Phyd, MPa:	0.00
Tm (min, max), sec:	326 977
number of models:	20000
error:	2.1E-02

result (mean value of all fitting models):

Permeability	: (26.2 ± 0.4) µdarcy
Kf	: (2.6 ± 0.0) e-10 m/s
Alpha	: (0.10000)

Number of fitting models: 173