Hydraulic Fracturing Tests

Hydraulic fracturing is a technique for measuring in situ stresses in boreholes. For many years, a main application was determination of the minimum horizontal stress for hydro power pressure tunnels. However, this technique is more and more applied for the exploration of other underground excavations and construction.

1.1. Hydraulic fracturing technique

Hydraulic fracturing is conducted with a robust double packer system on short borehole intervals which are free of natural fractures (Haimson and Fairhurst, 1967). Following the inflation of the packers, the interval is pressurized until an axial fracture is induced. The interval is shut-in shortly after the breakdown pressure is reach and the pressure decline is monitored. The fracture is then subjected to several re-opening and draining cycles by injecting small fluid volumes (typically 5 - 15 l). The objective is to define the pressure at which the walls of the fracture are just supported by a fluid cushion. This pressure represents the rock stress component normal to the plane of the fracture, and is variously referred to as 'closure pressure' or 'jacking pressure'.

Due to the nature of the stress field induced around the borehole during pressurisation, the induced fracture will tend to be axial, and the fracture will initiate and extend in the direction of the larger of the two principal stresses that act normal to the borehole axis. Thus the normal stress acting upon the fracture plane will be the smaller of these two principal stresses. By subjecting the fracture to a series of injection/draining cycles, the magnitude of this principal stress can be determined to a high degree of accuracy. Analysis of the pressure at which the fracture is formed, or alternatively the interval pressure required to re-open the fracture in later injection cycles, permits the larger of the two principal stresses acting normal to the borehole axis to be estimated, although much less accurately than the smaller of the two. Thus, the test yields a direct measure of the magnitude of the smaller of the two principal stresses acting normal to the plane of the fracture, and an indirect measure of the magnitude of the larger of the two. The orientation of the two principal stresses is obtained by determining the orientation of the induced fracture generally using an impression packer system with measurement of its orientation.

1.2. Test Equipment

The equipment consists of a robust double packer system (IPI DST-tool) to isolate a test section in the borehole with a test interval length of 1.67 m and length of the packer elements of 1.0 m. The packer system is lowered down the boreholes on small diameter drill rods (e.g. BQ). This rods string is also used for opening and closing of the downhole valve. A stainless steel line for packer inflation and injection of water into the isolated borehole section is run along the drill rods. Alternatively, special test rods or drill rods that can be exposed to high pressure can be used for installation and injection of water.

Fig.1: Robust double packer system designed for permeability testing and hydraulic fracturing (please note: here with extended straddle interval for permeability testing).

The test pressure is measured downhole in the test interval with two memory gauges with high record sampling (10 Hz). Flow rate and an additional measurement of the test pressure are made on the flowboard at the surface. Data is recorded at the surface using an A/D-converter connected to a PC which provides a graphical display of the pressures and flow rates as they are recorded using a special software which allows high sampling rate during the injection phase.

The test is controlled with a so called flow control board (“flowboard”), basically a manifold system with a 60 MPa pressure sensor, with a overpressure release valve, and pressure check valves. The entire system is designed for a pressure of 50 MPa. A schematic sketch of the surface equipment is presented in fig. 2.

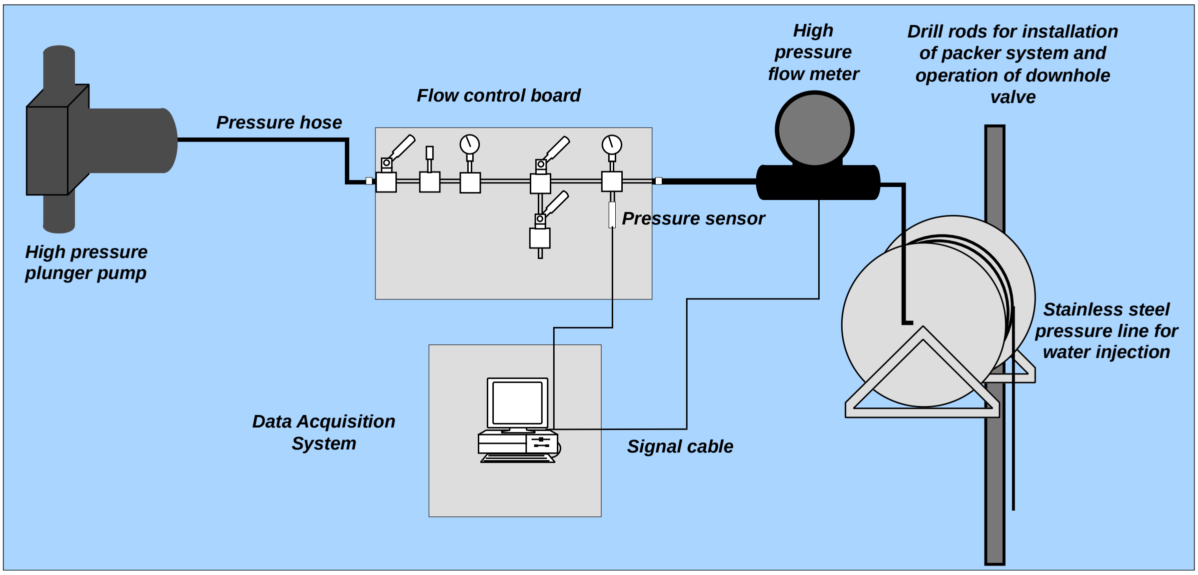

Fig.2: Schematic overview of surface equipment for deep borehole HF-tests with the IPI DST-tool.

Impressions of the test sections are obtained using an impression packer with a soft rubber coating. A borehole compass equipped with a data logger or a borehole survey tool (multishot tool) is used to determine orientation of the packer.

1.3. Testing procedure

In general Polymetra GmbH employs the classical hydrofracture stress measurement methodology as described by Haimson and Cornet (2003) and according to ASTM designation D 4645-87. A hydrofracture test consists of a sequence of injection cycles during which interval pressure, packer pressure and injection flowrate are monitored and recorded with a high sampling rate.

Preparation and pulse test: Once the hydrofracturing tool has been placed at the test depth, the packers are inflated to about 5 MPa above surface pressure. A permeability test (Pulse Test, also called Formation Integrity Test) is then conducted by raising the interval pressure by 1-2 MPa above the ambient level and closing the shut-in valve. The objective is to ensure that no permeable natural fractures are present in the test interval, as indicated by a stable pressure level. If this is the case, the interval pressure is restored to ambient levels and preparations are made for the first pump cycle (breakdown cycle).

Breakdown cycle: Prior to injection into the interval, a steady flow of 3-15 l/min is established through the flow-board vent valve. This valve is then closed to divert the flow to the stainless steel line and thus into the interval. Initially, the pressure rises quickly according to a system stiffness of typically 40 MPa/l. Injection is terminated as soon as breakdown is recognized and the interval is shut-in. The interval pressure and flow rate are sampled using the high sampling rate mode (ca. 20 Hz). After waiting for the pressure to decline to a stable level, the interval pressure is vented through the flow-board and the returned fluid volume is measured.

Re-open cycles (Refrac cycles): The fracture is then subjected to several re-open injection cycles during which the injected fluid volume is progressively increased. The 'fracture re-opening pressure' is a key quantity that can, under certain conditions, be used to estimate the maximum principal stress acting in the plane normal to the borehole axis using the method proposed by Bredehoeft et al. (1976). The re-open pressure is taken to be the point at which the pressure first deviates from the initial climb controlled by the system compliance. The theory of Bredehoeft et al. (1976) assumes that the fracture remains completely impermeable until the circumferential stress across the entrance to the fracture becomes tensile, at which point the fracture opens. Water injection is quickly terminated by closing the shut-in valve.

Step-rate test: This test is similar to the Lugeon-type hydro-jacking test and is conducted at the end of a test. As in hydro-jacking tests, the objective is to determine the pressure at which a significant increase in transmissivity occurs reflecting fracture opening.

An overview of a complete hydrofracturing test is presented in fig. 3.

1.4. Test analysis

The minimum principal stress (σ_3) is considered to be equal to the shut-in pressure which was determined from each cycle.

$$\sigma_3 = P_{shut\text{-}in}$$

Two methods can be applied to determine the shut-in pressure from the change in slope of the pressure decay graph caused by the closing of the fracture: the tangent intersection and the rate-of-pressure-decay plotted against pressure (Tunbridge, 1989). The tangent intersection method is not always easy to apply as the pressure decay sometimes is a smooth curve and there are no distinct segments on the curve for drawing the tangents. The rate-of-pressure-decay plotted against pressure generally produces graphs with a distinct inflection which is interpreted as the shut-in pressure.

The vertical stress is calculated from the overburden weight.

The maximum principal stress (σ_1) can be estimated as:

$$\sigma_1 = 3 P_s - P_{ro} - P_o$$

where P_s is the measured average shut-in pressure, P_{ro} is the pressure recorded at first re-opening of the fracture and P_o is the formation pore pressure.

However, there is considerable controversy in the literature concerning its interpretation based on the re-opening pressure. It appears to be more reliable to base the magnitude of the maximum principal stress on laboratory results of tensile strength of the tested rock and on the breakdown pressure.

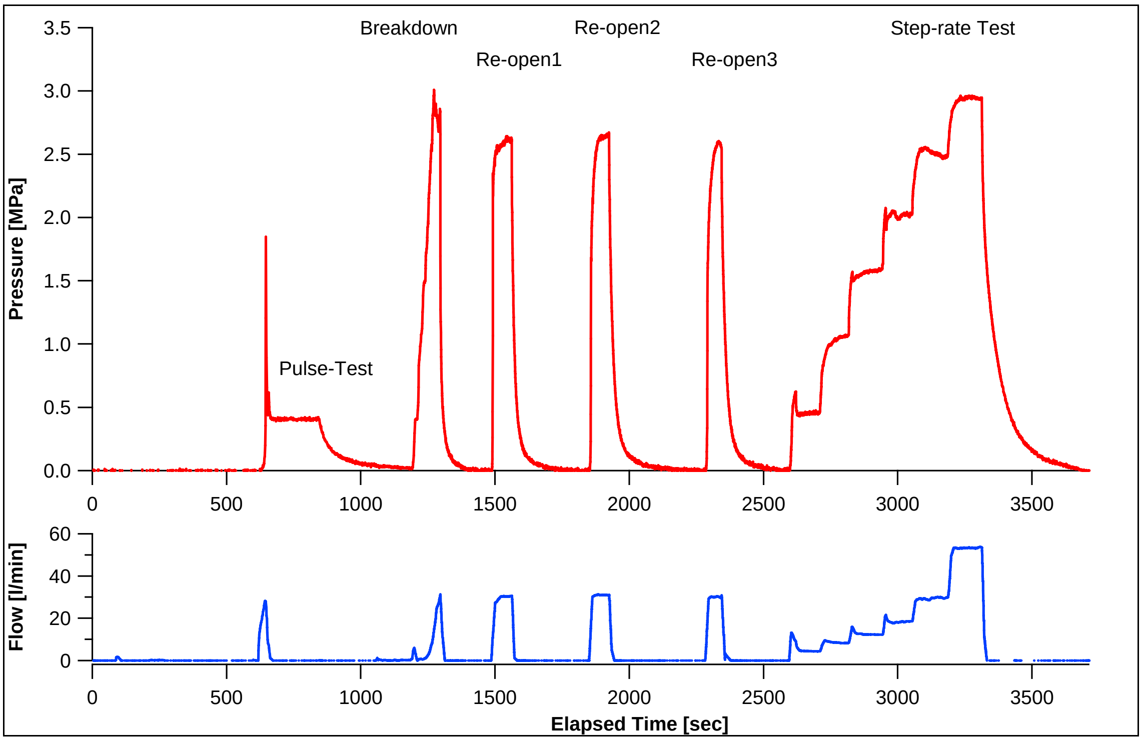

Fig.3: Hydrofracturing test with a breakdown cycle, three re-open cycles and a step-rate test.

Once the hydrofracture phase has been completed, the hydro-fracture tool is removed from the borehole and replaced by an impression packer system. This consists of an impression packer coupled to a digital downhole compass and enables impressions from the tested intervals. The system is run down the hole on the same tubing that was used for the double packer system. The packer is then inflated to a pressure higher than the estimated level of the minimum stress. This pressure is maintained for 20 - 30 minutes. The packer is then deflated and the tool is retrieved from the hole. After marking the traces on the packer surface, the new fractures are copied onto transparent film. The tool is then returned to the hole to image the next interval.

Fig.4: Impression packer with traces of induced fractures

1.5. Representation of results

As described above, the goal of hydraulic fracturing tests is to measure the magnitude minimum principal stress as well as it's orientation. Thus, every hydrofracturing test is reported with graphs and tables. Fig. 5 represents the results of the test depicted in fig. 3 with the direct measurement of the minimal principal stress and the estimated maximum principal stress.

The orientation of the stresses is analyzed from the impression packer tests. The intersection of the fracture with the borehole as recorded with the impression packer is transferred to a transparent film which is first scanned and then digitized. The results are represented in a graph for each test as shown in fig. 6 (red sinusoidal traces represent existing fractures and blue longitudinal traces represent fractures induced by hydrofracturing).

An overview of the stress orientation from all tests in a project is best represented in a rose diagram (fig. 7).

Testing

Event	Start Time *Elap. sec.*	End Time *Elap. sec.*	Duration *sec.*	p-start *MPa*	p-end *MPa*	Volume injected *l*
Pulse-Test	623.08	845.18	222.11	0.00	0.41	-
Breakdown	1191.30	1306.30	115.00	0.01	0.47	16.86
Refrac. 1	1486.92	1579.15	92.23	-0.02	0.59	37.08
Refrac. 2	1851.03	1947.52	96.49	-0.01	0.64	38.47
Refrac. 3	2285.29	2362.10	76.81	-0.01	0.80	30.69
Step-rate Test	2598.19	3372.20	774.01	0.01	0.86	264.33
Total Volume injected =						**370.57**

Analysis

Pulse-Test Pressure Change:			0.0097 MPa in 171 sec	
Cycle	**Breakdown** *MPa*	**Reopening** *MPa*	**Tangent Shut-in** *MPa*	**dP/dT Shut-in** *MPa*
Breakdown	3.05			
Refrac. 1		2.35	2.32	2.25
Refrac. 2		2.15	2.41	2.25
Refrac. 3		2.12	2.27	2.04
Minimum stress =			**2.26 MPa**	
		±	**0.12 MPa**	
Maximum stress =			**4.42 MPa**	

Fig.5: Table of results from test represented in fig. 3.

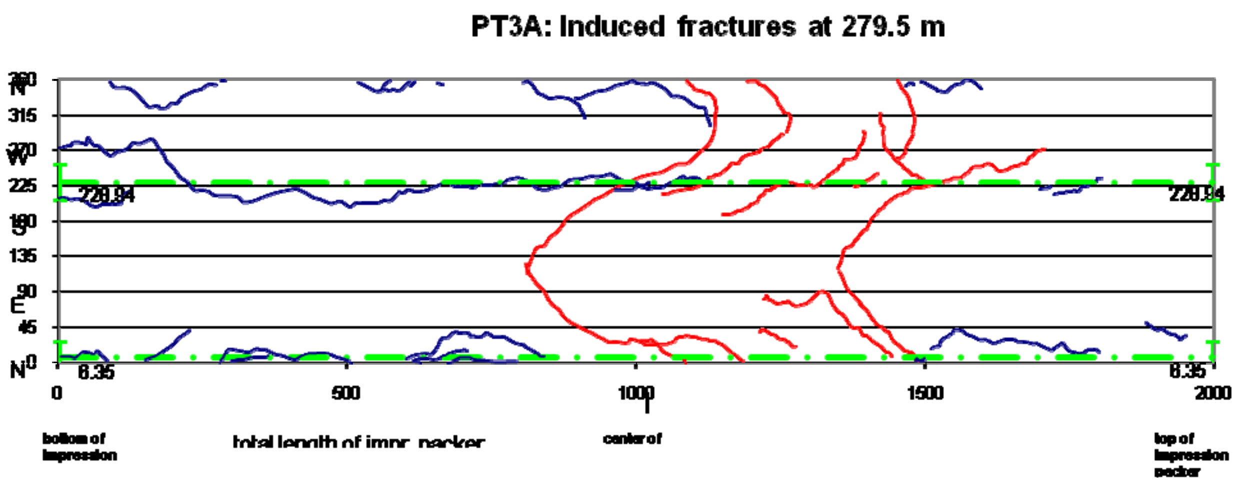

Fig.6: Digitized traces of induced fractures and preexisting fractures.

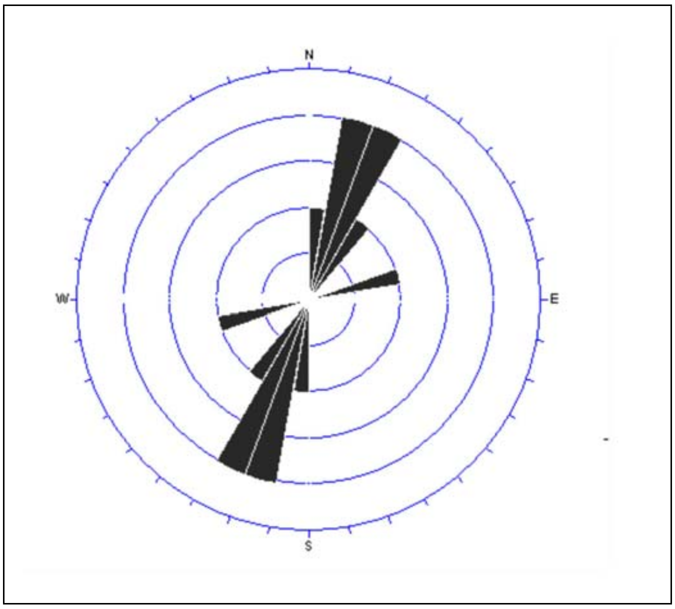

Fig.7: Rose diagram with results of impression packer measurements in all boreholes of the project.

2. Literature

ASTM International, 1987, Standard Test Method for determination of the in-situ stress in rock using hydraulic fracturing Method, Designation D 4546 – 87, ASTM International, West Conshocken, PA, USA

Bredehoeft, J. D., R. G. Wolff, W. S. Keyes, and E. Shuter, 1976, Hydraulic fracturing to determine the regional stress field in the Piceance basin, Colorado, Geol. Soc. Am. Bull., 87, 250-258.

Haimson B.C. and F.H. Cornet, 2003, ISRM Suggested methods for rock stress estimation- Part 3: hydraulic fracturing (HF) and/or hydraulic testing of pre-existing fractures (HTPF), Int. J. Rock Mech. Min. Sci., 40, 1011-1020.

Tunbridge L.W., 1989, Interpretation of the shut-in pressure from the rate of pressure decay, Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., 26 , 351-360.

Equipment for stress measurements with hydraulic fracturing

1. Introduction

Hydraulic fracturing uses injection of water into an isolated borehole section. This requires a high pressure injection pump, a manifold (flow control board) to divert the flow and to measure the pressure at the surface, a flow meter, tubing that holds the high pressure, a robust packer system and a downhole pressure sensor. A data acquisition system with record rate of 10 – 20 Hz is required in order to measure the fracture closure pressure (ISIP) accurately. To represent the induced fracture, a impression packer is required together with an orientation system.

An overview of the system layout is depicted in figure 1.

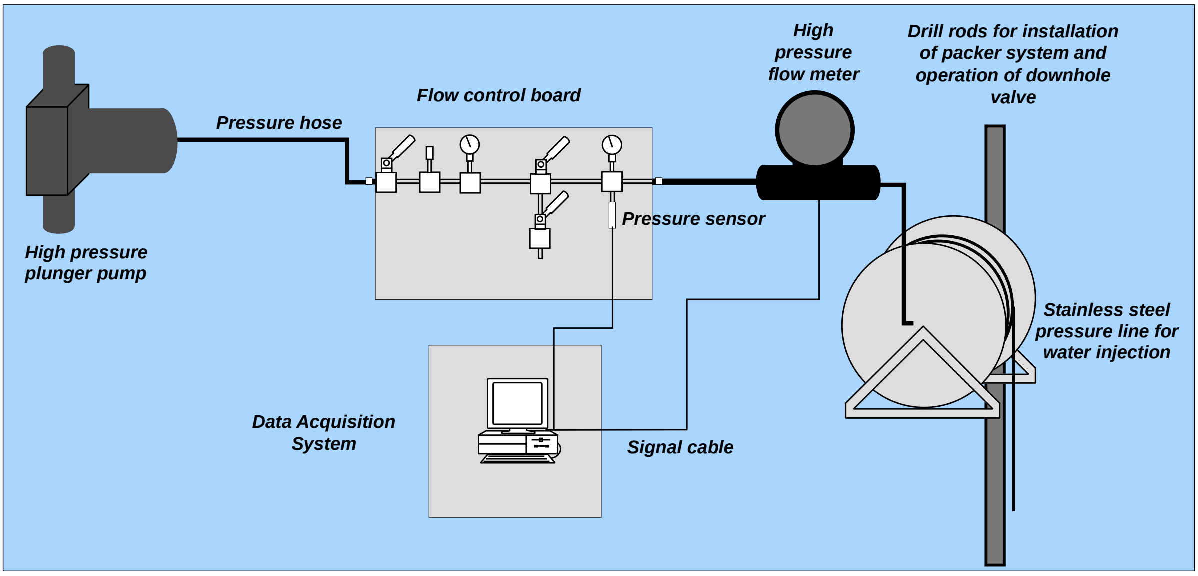

Fig.1: Schematic overview of surface equipment for deep borehole HF-tests with the IPI DST-tool.

2. High pressure pump

Triplex pump (three plungers) with a pressure regulating valve driven by a speed controlled electrical motor.
Injection flow rate: 4 – 18 l/min
Maximum pressure: 35 MPa
Motor: 18.5 kW
Voltage: 400 V

3. Flow control board

The flow control board is basically a manifold with high pressure check valves and over pressure relief valves. The flow board also includes a pressure sensor (0 – 600 bar) for measuring the injection pressure at the surface. The flow control board, together with the pump, is the mayor piece of equipment to control a test. Further is used to saturate the flow line properly before starting the test, to monitor the injection pressure at the surface and to collect the reverse flow after each injection cycle.
The flow control board is designed and manufactured by Polymetra.

4. Flowmeter

A turbine flowmeter is used to record the injected water downstream of the flowboard:
Flowrate: 0 – 20 l/min
Output signal: 4 – 20 mA
Maximum pressure: 630 bar

Alternatively, a magnetic inductive flow meter as it is used for standard packer tests (permeability testing) rated for a maximum pressure of 40 bar can be installed upstream of the injection pump.

5. Data acquisition

Hydraulic fracturing requires recording of pressure and flow data with a higher record rate compared to standard packer testing. For this we have developed the data acquisition system polyDAQ *hf* consisting of hardware and software. The 8-channel system allows recording simultaneously various sensors with current or voltage output signal.
Standard record rate for hydraulic fracturing tests: 10 or 20 Hz
Power supply for passive sensors: 24 V
Interface to PC: USB 2.0

6. Coil tubing

The packer system is installed with small size drill rods (e.g. BQ-rods). These rods can be used for injecting water for standard packer tests (e.g. injection – falloff tests). But these rods are not suited for the high injection pressures used in hydraulic fracturing tests. Therefore the water is injected via stainless steel coil tubing. The packer system is installed with the small size drill rods to which the coil tubing is attached with steel bands.
Coil tubing: stainless steel tubing, 1.4571
OD: 3/8”
Wall thickness: 0.049”
Test pressure: 540 bar

Alternatively

7. Packer system

The packer system which we use for hydraulic fracturing is a DST-system of IPI. It can be applied for standard packer testing but also for hydraulic fracturing. The system has a multi-position valve that is used for packer inflation, shut-in position to measure the static formation pressure and for injection of water into the packed-off test section.
OD of system (including packers) : 86 mm
Maximum pressure in hole diameter 96 mm: 350 bar
Length of test section (with memory gauge carrier): 1.67 m
Option: sensor housing with downhole pressure sensor and wire line cable for online downhole pressure measurement.

8. Downhole pressure measurement

There are two options for downhole pressure measurement.
When working with memory gauges only, the test is controlled by the surface pressure reading. Two oil-field type memory gauges are installed in the packer system. The data of these gauges are used for analysis of the tests.
Memory gauges: oil-field type piezo-resistive pressure sensors with data logger
Special version suited for sampling rate of 10 Hz
OD: 0.75”
Maximum pressure: 3000 psi
Resolution: 0.0003% fs
Accuracy: ± 0.03% fs

The other option is to install a sensor housing with the packer system which holds a pressure sensor connected to the surface via a mono-conductor wireline cable. The wireline cable is strapped together with the coil tubing to the
Cable: 1/8” mono-conductor logging type wireline cable
Sensor housing: IPI
Pessure sensor: 0 – 400 bar
Linearity: ± 0.25% fs
Output signal: 4 – 20 mA

9. Impression packer

Impression packer is designed and manufactured by IPI for imaging of the induced fractures.
OD: 86 mm
Length of rubber sleeve: 1500 mm

10. Borehole compass

An electronic compass with a data logger is mounted below the impression packer to record its orientation during the impression packer imaging. The compass system is designed and manufactured by Polymetra.

OD: 40 mm

Length: 600 mm

Polymetra GmbH, Fröschbach 15, CH-8117 Fällanden, Switzerland
Mail: info@polymetra.ch; Tel: +41 44 825 05 55; Fax: +41 44 825 05 54; MWST-Nr. 681 439