Summary

This report presents the results of stress measurements using the hydraulic fracturing method carried out at the proposed site for the XYZ Hydro Scheme.

It is understood that information on the minimum stress is required for the design of the alignment of headrace tunnel and powerhouse and to determine the requirements for lining of the tunnel.

The tests were conducted generally in accordance with the ISRM Commission on Standardisation of Laboratory and Field Tests, Suggested Method for Rock Stress Determination.

The results of the measurements are summarised in the following table:

Borehole	Depth	Measured minimum stress	Calculated vertical stress
	m	MPa	MPa
PT3A	-279.5	8.3	7.5
PT3A	-285.0	11.2	7.7
PT3A	-293.0	11.7	7.9
PT4A	-216.8	9.1	5.9
PT4A	-226.8	9.5	6.1
PT4A	-231.5	7.7	6.3
PT5	-241.5	7.1	6.5
PT5	-256.0	8.0	6.9
PT5	-258.0	7.6	7.0

The measured values of the minimum horizontal stress are greater than the values of vertical stress calculated from the weight of overburden. The minimum principal stress is therefore the vertical stress which may be calculated from the weight of overburden.

There is generally a consistent pattern of stress magnitude with some minor variations between the depths tested in each borehole and between boreholes. The stress magnitude appears to be increasing with depth. The magnitude of the variations in stress magnitude encountered is considered consistent with the variations that might be caused by variations in rock modulus and the presence of fault and fracture zones.

The orientation of the fractures was generally consistent and indicated that the minimum principal stress was oriented 104/284°.

1. Introduction

This report presents the results of stress measurements using the hydraulic fracturing method carried out at the proposed site for the XYZ Hydro Scheme.

Tests were made in three of the site investigation boreholes, PT3A, PT4A and PT5. These boreholes were drilled in HQ size with a nominal hole diameter of 99 mm at the depths tested.
All the boreholes tested were vertical. The location and survey information on the boreholes is summarised on Table 1.1.

The field work was carried out in two phases. Boreholes PT3A and PT5 were tested on completion of drilling, and one impression taken in PT3A. Borehole PT4A was tested on completion of drilling and impressions made in boreholes PT4A and PT5.

Table 1.1 – Borehole location and survey data.

Borehole	Easting*	Northing*	Ground Level	Approx Ch along Tunnel	Incl. (declination)	Approx. Tunnel Axis (from section)	Approx. Tunnel Invert	Depth to Invert	Borehole length
	m	m	m.O.D.	m	degrees	m	m.O.D.	m	m
PT1	243577.336	805182.507	555.429	2100	60	N/A	N/A	N/A	350
PT2	243068.375	805853.502	504.300	3100	60	N/A	N/A	N/A	100
PT3	241830.540	806286.666	397.953	4400	60	94.07	91.82	353.492	360
PT3A	241346.771	807356.976	318.056	5400	90	24	21.75	296.306	302
PT4A	240659.572	807916.281	264.542	6280	90	23	20.75	243.792	250
PT5	240247.614	808009.083	269.508	6650	90	23	14	255.508	260
PT6	240224.924	808708.618	210.743	7100	60	N/A	N/A	N/A	29.4
PT7	239134.108	808639.220	73.641	7900	60	N/A	N/A	N/A	20

* Major grid = NH

The rock types encountered in the boreholes were typically quartz-mica-garnet schists of Precambrian age with a distinct foliation.

It is understood that information on the minimum stress is required for the design of the alignment of headrace tunnel and powerhouse and to determine the requirements for lining of the tunnel.

2. Test Equipment

The equipment comprised a double straddle packer to isolate a test section in the borehole with a test interval length of 0.95 m and packer lengths of 0.85m (Figure. 2.2). The packer was lowered down the boreholes on special high pressure 1"-rods (see figure. 2.3) of 3 m length which were used to conduct the fluid to the test section. Leakage of the couplings of this type of tubing was prevented by two O-rings. Packer inflation and electrical conductors for instrument signals were provided in an umbilical cable that was strapped to the rods. Fresh water was used as the medium for the testing and pressure provided by an air driven pump with a maximum flow capacity of about 20 litres per minute at the test pressures encountered. Two pumps were available with maximum pressures of 50 MPa and 35 MPa.

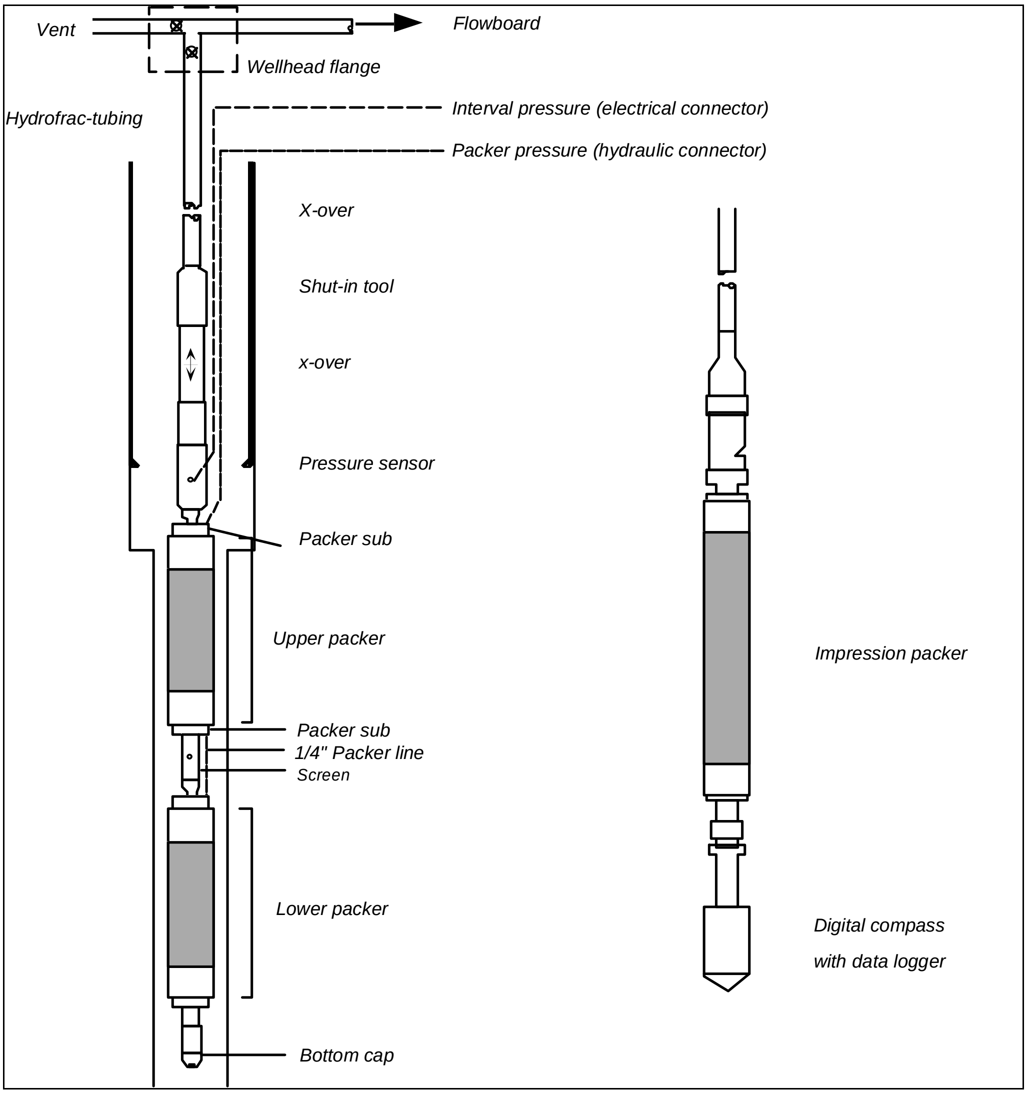

Figure 2.1: Schematic overview of the hydrofrac double packer system and the impression packer with attached orientation tool.

Test pressures were measured down the hole in the test interval. Packer pressure, flow rate and an additional measurement of the test pressure were made on the flowboard at the surface. Data was recorded at the surface using an A/D-converter connected to a PC which provided a graphical display of the pressures and flow rates as they were recorded using a special software created which allowed high sampling rate during the injection phase. Data was generally recorded at a frequency of one second, but during the pumping phases a special mode allowed for about 50 samples per second.

The test was controlled with a so called flow control board (“flowboard”), basically a manifold system with two 60 MPa pressure sensors, three overpressure release valves, and ten pressure check valves. The entire system is designed for a pressure of 50 MPa.

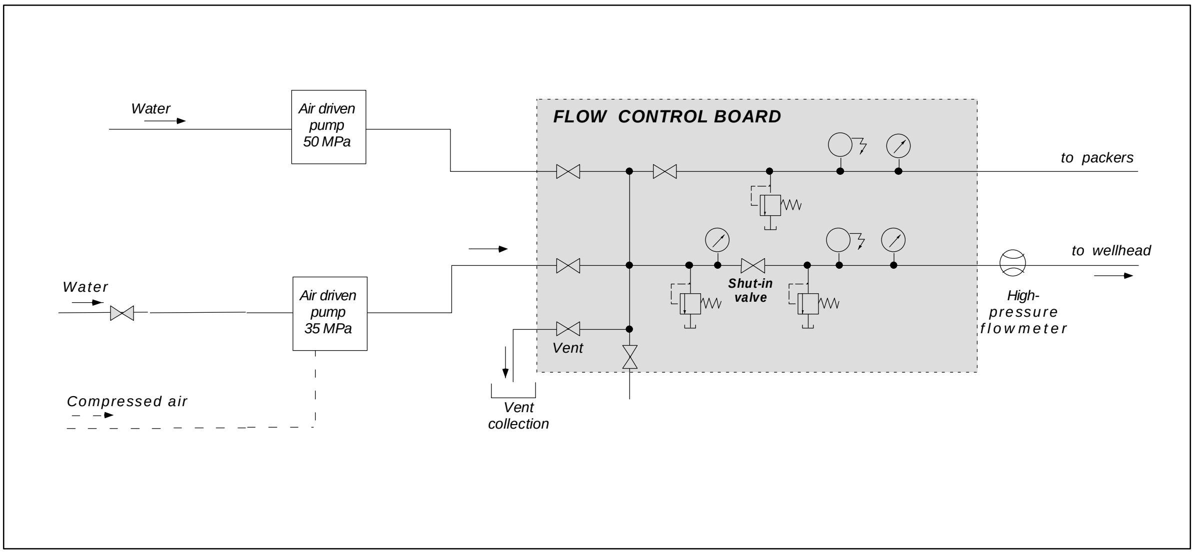

Figure 2.2: Schematic overview of the hydrofracturing surface system including flow control board, pumps, and flow measurement.

Impressions of the test sections were obtained using two impression packers with a soft rubber covering. The impression packer sleeves are 1.5 m and 2 m long to allow for an overlap of the test section. The impression packers were either lowered down the hole on the test tubing (used in boreholes PT3A and PT4A) or a wire line (used in borehole PT5). The impression packer was inflated to a pressure in excess of the fracture opening pressure and this pressure maintained for about half an hour. A borehole compass equipped with a data logger was used to determine orientation of the packer. On recovery the packer was inspected and any fractures observed were marked with a felt tip pen (Figure 2.3). A tracing of these fractures was then made using a plastic film. This was later scanned and the fracture traces digitised for analysis of the fracture orientation.

Figure 2.3 – Impression packer recovered from BH PT3A at 279.5 m depth with fractures traces marked up with felt tip pen.

3. Test Method

The boreholes and desired depth range of tests were provided by the Engineer. The test sections were selected by examining the geophysical logs as well as the drill cores. Sections with a minimum length of about two metres without fractures were selected for testing. Although the rock is quite highly fractured it was possible to find three suitable test sections around the selected depth range in each of the boreholes tested.

The tests were conducted generally in accordance with the ISRM Commission on Standardisation of Laboratory and Field Tests, Suggested Method for Rock Stress Determination. Int. Journ. Rock Mech. & Min. Sci. & Geomech. Abstract. 1987, 24(1), 53-73.

The packers were inflated to a down hole pressure of about 4.0 MPa, the test section was then pressurised to about 4.0 MPa, while the packer pressure increased automatically to about 6.0 MPa. Test pressure was then shut in and pressure drop observed to demonstrate that the test section did not have any significant leaks. The test pressure was then increased over a period of about 30 – 45 seconds (rate of pressure increase approx. 10 MPa/min) until breakdown occurred. The test pressure was shut in at the surface as soon as possible after the initial breakdown and the pressure drop observed to determine the shut-in pressure. After about 2 – 5 minutes the test section was drained and the water return observed, after about a minute the test section was shut-in and the pressure in the test section observed. This was repeated as necessary until there was very little return of water and minimal pressure build-up.

After this initial fracturing, a further two to four cycles of fracture pressurisation was carried out. For each pressurisation cycle, the pressure was increased at about the same rate and the re-fracture pressure observed, pumping was continued to extend the fracture and generally until a stable pressure was achieved. The test pressure was then shut in at the surface and the pressure observed to determine the shut-in pressure again. The results from a typical test are shown on Figure 3.1

In the first test in borehole PT5 at 258m a stepwise fracture re-opening test was carried out. In this test the flow rate to the test zone is controlled and the pressure observed. The flow rate is increased in steps until the maximum flow rate is achieved. A plot of test pressure against flow rate shows a break in the curve at about the pressure that the fracture opens, after which little increase in pressure occurs for large increases in flow rate, Figure 3.2.

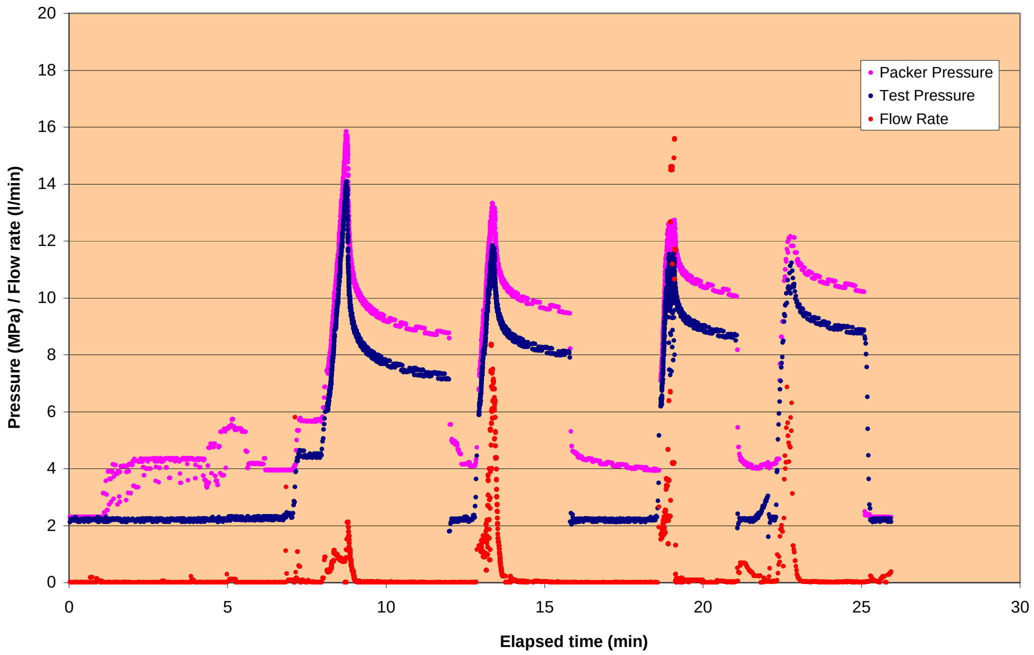

Figure 3.1 – Pressure cycles in the hydraulic fracture test in borehole PT4A at a depth of 226.8m.

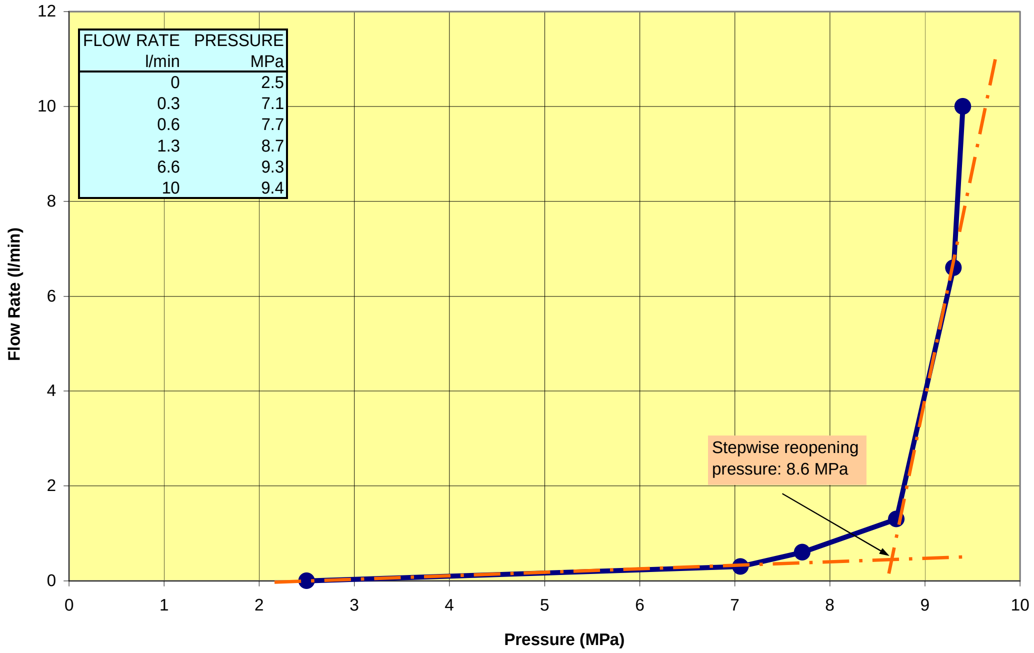

Figure 3.2 – Interpretation of the re-opening pressure in a stepwise reopening test in BH PT5 at 258m depth.

4. Interpretation

The raw data was imported into an EXCEL spreadsheet for further interpretation. Initially the breakdown pressure and re-opening pressures were recorded and a preliminary interpretation of the shut-in pressure made by visually identifying the inflection of the change in slope of the pressure decay graph caused by the closing of the fracture, Figure 4.1. This inflection point in the graph was generally not distinct and other interpretation methods were used to give a better estimate of the shut-in pressure. Two methods were applied: the tangent intersection, Figure 4.2; and rate-of-pressure-decay plotted against pressure, Figure 4.3. The tangent intersection method was also difficult to apply as the pressure decay was a smooth curve and there were no distinct segments on the curve for drawing the tangents. The rate-of-pressure-decay plotted against pressure generally produced graphs with a distinct inflection which was interpreted as the shut-in pressure. This was quite close to the values interpreted visually from the pressure decay curves and the tangent intersection methods.

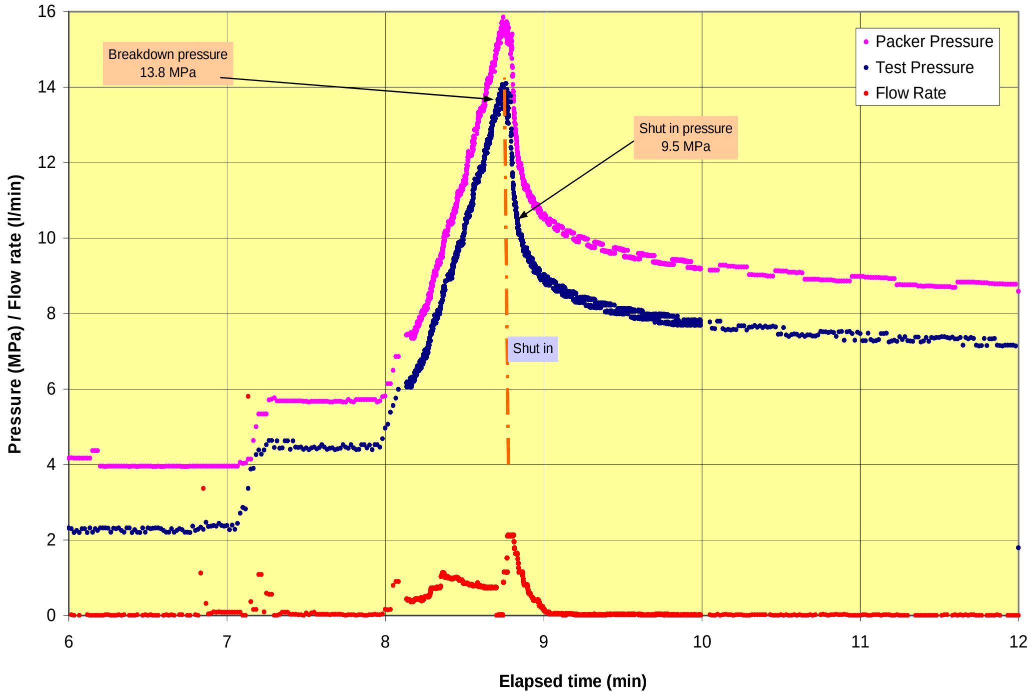

Figure 4.1 – Pressure cycle in hydraulic fracture test showing interpretation of breakdown pressure and shut-in pressure.

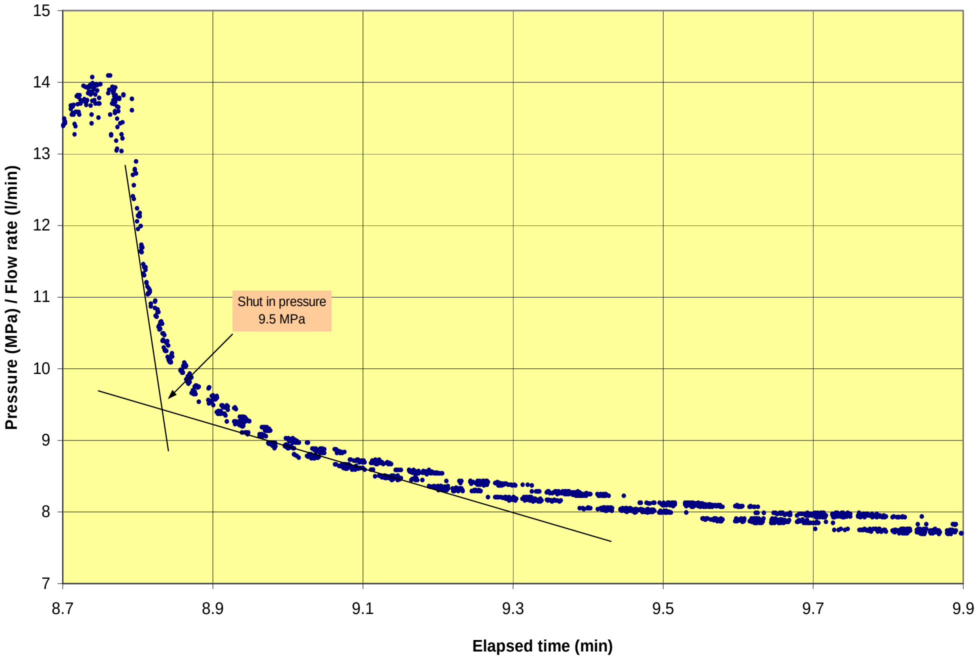

Figure 4.2 – Pressure decay curve in shut-in phase of hydraulic fracture test showing interpretation of shut-in pressure using the tangent intersection method.

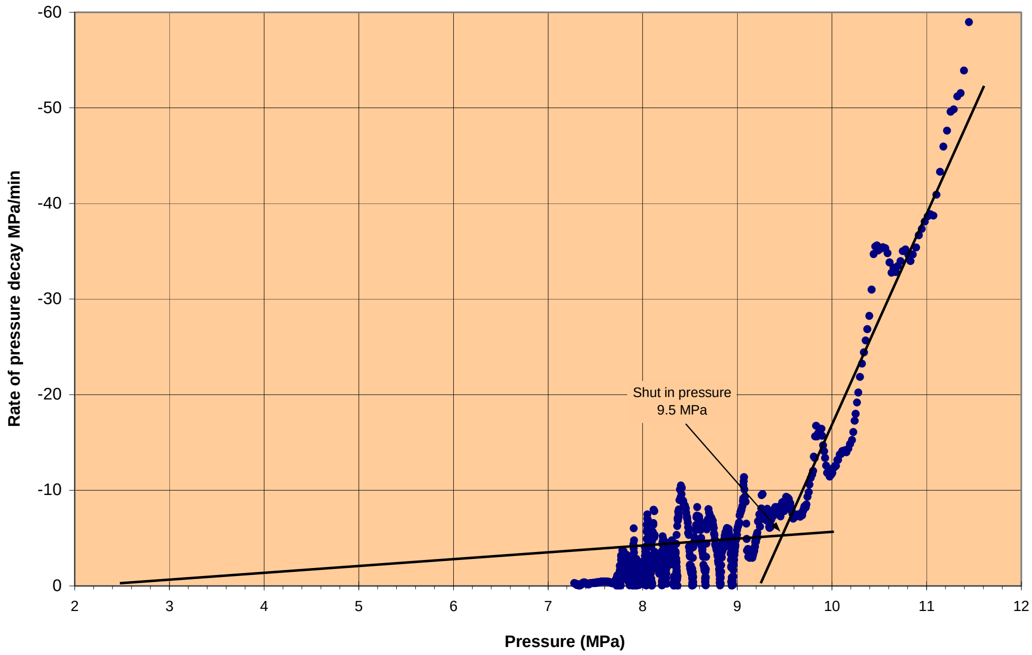

Figure 4.3 – Rate of pressure decay from shut in phase of hydraulic fracture test showing iinterpretation of the shut-in pressure.

5. Test Results

The test results are summarised in Table 5.1 and Figure 5.1, and full details are presented in the appendices. The minimum stress quoted is the minimum value of the shut-in pressure determined at each depth from all the pressure cycles and using all the methods of interpretation that were applied. This represents a conservative (or lowest probable) value of the minimum horizontal stress assuming that a fracture has been created or opened perpendicular to the minimum principal horizontal stress. Generally the range in the measurements was of the order of 1 MPa.

The vertical stress is calculated from the overburden weight assuming a rock mass weight of 0.027 MN/m^3.

The maximum horizontal stress (σ_1) was estimated from equation 5.1:

$$\sigma_1 = 3\, P_{shut\text{-}in} - P_{reopen} \quad \text{.. 5.1}$$

where $P_{shut\text{-}in}$ is the measured minimum shut-in pressure and P_{reopen} is the pressure recorded at first re-opening of the fracture. The value of the maximum horizontal stress is not very well constrained as it depends on the minimum stress, which is itself subject to considerable measurement error and the interpretation of the re-opening pressure. The re-opening pressure did not show a distinct peak which suggests that the ratio of horizontal stresses, σ_1/σ_3, is greater than 2, whereas the ratio measured is between 1.6 and 1.9, and it is therefore considered that the maximum horizontal stress could be greater than the estimated values presented in this report. A better value might be obtained by using the average or mean value of the shut-in pressure rather than the minimum value. It has to be noted that often the formation pressure is used to estimate the maximum horizontal stress ($\sigma_1 = 3\, P_{shut\text{-}in} - P_{reopen} - P_o$). However, the observed drillcores consisted of fine grained and highly metamorphosed rocks which we considered as totally impermeable during the short period of the test. Under these circumstances the simplified expression (equation 5.1) for estimation of the maximum horizontal stress can be used.

Table 5.1 – Summary of test results

Borehole	Depth	Measured minimum stress	Calculated vertical stress*	Calculated maximum stress
	m	MPa	MPa	MPa
PT3A	-279.5	8.3	7.5	14.1
PT3A	-285.0	11.2	7.7	18.8
PT3A	-293.0	11.7	7.9	18.6
PT4A	-216.8	9.1	5.9	14.8
PT4A	-226.8	9.5	6.1	17.4
PT4A	-231.5	7.7	6.3	14.2
PT5	-241.5	7.1	6.5	12.3
PT5	-256.0	8.0	6.9	13.2
PT5	-258.0	7.6	7.0	14.1

* 0.027 MPa/m

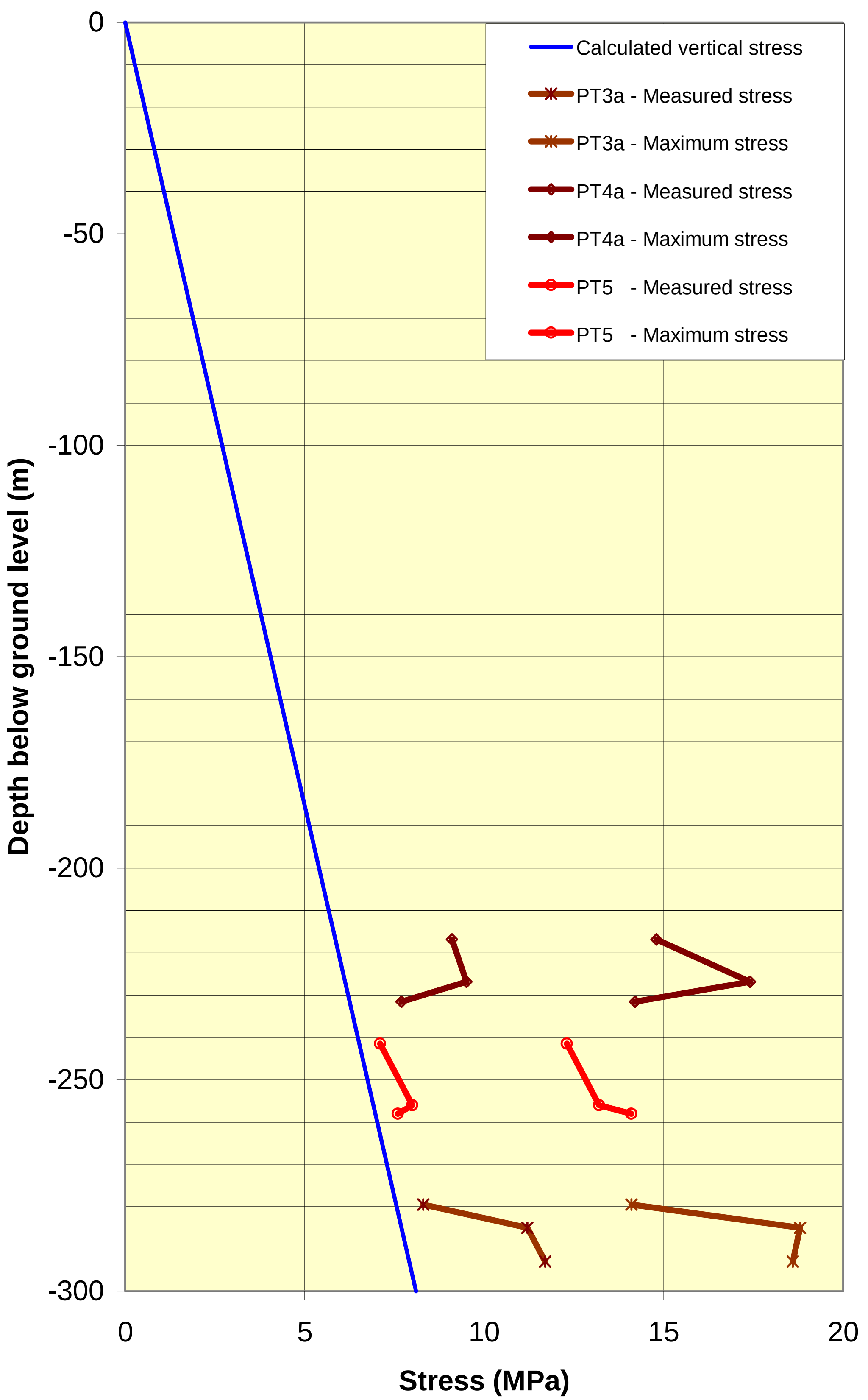

Figure 5.1 - Plot of measured stresses against depth

Another way to estimate the maximum horizontal stress (σ_1) is based on the tensile strength (T) of the rock and the measured breakdown pressure ($P_{breakdown}$). Tensile strength data from rock samples taken from the drill cores within or near the test intervals were used to estimate the maximum horizontal stress using equation 5.2. As discussed above, the rock was considered to be impermeable. The results are listed in table 5.2.

$$\sigma_1 = T + 3\,P_{shut\text{-}in} - P_{breakdown} \qquad (5.2)$$

As discussed above, the rock was considered to be impermeable. The results are listed in table 5.2.

Table 5.2: – Summary of estimated maximum horizontal stress based on tensile strength and breakdown pressure data.

Borehole	Depth	Measured minimum stress	Measured tensilel strength*	Measured beakdown pressure	Calculated maximum stress
	m	MPa	MPa	MPa	MPa
PT3A	-279.5	8.3	8.48	10	23.4
PT3A	-285.0	11.2	5.96	15.1	24.5
PT3A	-293.0	11.7	11.2	17.4	28.9
PT4A	-216.8	9.1	2.25	13.3	16.3
PT4A	-226.8	9.5	3.63	13.8	18.3
PT4A	-231.5	7.7	5.99	10	19.1
PT5	-241.5	7.1	10.5	9.8	22
PT5	-256.0	8.0	-	12.3	-
PT5	-258.0	7.6	3.98	9.6	17.2

The values for the maximum horizontal stress estimated from equation 5.3 are higher and show a larger variation than those based on the reopening pressure values and the shut-in pressure values only. As mentioned before, the absence of a distinct pressure peak during the reopening of an induced fracture suggests that the ratio of horizontal stresses, σ_1/σ_3, is greater than 2. The ratio based on the values given in table 5.2 is generally between 2 and 3. The larger variability can be explained by the inhomogeneity of the rock which was already observed in the drill cores. Thus, the magnitude of the maximum horizontal stress is considered to vary between the values given in table 5.1 and table 5.2.

The results from the impression packer are summarised on Table 5.3. Details are presented in the appendices. The fractures identified on the packer were complex. Some traces of vertical axial fractures were found at each test zone tested. These axial fractures tended to run into fractures that appeared to be parallel to the foliation.

Table 5.3 – Summary of results from the impression packer tests

Borehole	Depth	Average orientation axial fracture	Average orientation foliation fractures	Comments
	m	°gridN	°gridN	
PT3A	-279.5	23	120	Complex fractures
PT3A	-285.0			No impression taken
PT3A	-293.0			No impression taken
PT4A	-216.8	78.0	140	Results not reliable
PT4A	-226.8	13.9	110	Weak axial fractures,
PT4A	-231.5	23.8	110/180	Complex fractures, several sets of nat. fractures
PT5	-241.5	34.2	50/160/200	Results not reliable, several sets of nat. fractures
PT5	-256.0	1.1	50/100/180	Complex fractures, several sets of nat. fractures
PT5	-258.0	16.3	135 -180	Weak axial fractures

The orientation of the axial fractures was generally consistent and indicated that the minimum principal stress is oriented 104/284°. This is based on the average of all impression packer measurement except PT4A/216.8 and PT5/241.5 where the results are not reliable.

The maximum horizontal stress is directed in north – south direction (14/194°). This corresponds well with direction of the maximum horizontal stress in ???land, reported in the generalized stress map of Europe (Regional patterns of tectonic stress in Europe, Müller et al. , J. Geophys. Res., Vol. 97, B8, 11783 – 11803, 1992).

6. Discussion

Although the rock was quite heavily fractured it was possible to find suitable sections of the boreholes suitable for testing. The leak tests indicated that the test sections were 'tight' and did not appear to include any existing open fractures.

The topography in the area is relatively flat compared to the depth of the boreholes and it is considered that the vertical stress is a principal stress and that the boreholes are therefore parallel to a principal stress satisfying one of the conditions for interpretation of the hydrofracture test.

The measured values of the minimum horizontal stress are greater than the values of vertical stress calculated from the weight of overburden. The minimum principal stress is therefore the vertical stress which may be calculated from the weight of overburden.

The impressions of the fractures showed a complex pattern of fractures partly axial along the borehole and partly along moderately dipping fractures believed to be parallel to the foliation in the rock. It is considered that the presence of axial fractures indicates that the tests have created new fractures perpendicular to the minimum horizontal stress and that therefore the measurements should give a reliable indication of the minimum horizontal stress. However, the anisotropic properties of the rock mass as indicated by the foliation may have affected the results as the hydraulically induced fractures have intersected foliation fractures. Measurements of shut-in pressure after some flow of water could indicate the stress across these foliation fractures which could be intermediate between the minimum horizontal stress and the vertical stress which appears to be the minimum principal stress.

The initial breakdown pressure recorded was generally only 1 to 2 MPa greater that the re-opening pressure recorded in later pressure cycles. This may indicate that the tensile strength of the rock is quite low and that the real fracture reopening pressure at the borehole wall may be lower than the value interpreted from the data which will be dependant on the minimum stress across the fracture away from the borehole wall. If the re-opening pressure on the borehole wall is lower than the minimum stress this indicates that the ratio between the maximum and minimum stresses is greater than 2:1. There is considerable uncertainty in the values of the maximum horizontal stress calculated from the measurements of shut-in pressure and re-opening pressure and it is considered possible that the maximum horizontal stress may be significantly greater than the values reported. This is supported by the values found based on tensile stress data and breakdown pressures.

There is generally a consistent pattern of stress magnitude with some minor variations between the depths tested in each borehole and between boreholes, Figure 5.1. The stress magnitude appears to be increasing with depth. The magnitude of the variations in stress magnitude encountered is considered consistent with the variations that might be caused by variations in rock modulus and the presence of fault and fracture zones.