DRAFT REPORT

Hydraulic Fracturing Stress Measurements
At Steelpoort Pumped Storage Scheme
South Africa

Prepared for:

BKS Engineering and Management
Hatfield Gardens D
Cnr Grosvenor & Arcadia St
Hatfield
P.O. Box 3172
Pretoria
0001 South Africa

Distribution:

2 copies	BKS Engineering and Management
2 copies	Golder Associates Ltd., Mississauga

January 2007 06-1119-010

TABLE OF CONTENTS

SECTION **PAGE**

1 INTRODUCTION 1
1.1 Project Description 1
1.2 Geology 1
1.2.1 Lithology and Stratigraphy 2
1.2.2 Topography 2
1.2.3 Structural Geology and Tectonics 2
1.3 Stress Measurement Program 3
2 TEST METHOD 5
2.1 Test Zone Selection 5
2.2 Fracture Generation Procedures 5
2.3 Fracture Orientation Procedures 7
2.4 Hydrofracture Tensile Strength 7
3 HYDRAULIC FRACTURING THEORETICAL BACKGROUND 9
3.1 Analysis of Horizontal Stresses, σ_{Hmax} and σ_{Hmin} 9
3.2 Interpretation of Shut-In Pressure, P_{si} 11
4 TEST RESULTS 13
4.1 General 13
4.2 Results of Hydrofracturing Tests 13
4.2.1 Parameters from Test Records 13
4.2.2 Hydraulic Fracturing Data 14
4.2.3 Orientation Survey Results 14
4.2.4 Tensile Strength Results 14
4.3 Stress Evaluation 15
4.3.1 Stress Calculations 15
5 DISCUSSION OF RESULTS 17
5.1 State of Stress 17
5.2 Regression Analysis of Stress Data 18
It should be noted that as testing was only undertaken over a small depth range, the area of interest and it maybe better to take average values given in section 5.1. 19
5.3 Analysis of Jacking Pressure 19
5.4 Analysis of Orientation of $\sigma_{H\max}$ 19
6 SUMMARY AND CONCLUSIONS 21
7 REFERENCES 23

List of Tables
List of Figures
List of Appendices

LIST OF TABLES

Table 1	Borehole PT01 Test Zones	24
Table 2	Borehole SC01 Test Zones	25
Table 3	Borehole PT01 Summary of Hydrofracture Test Results	26
Table 4	Borehole SC01 Summary of Hydrofracture Test Results	27
Table 5	Average Tensile Strengths	28
Table 6	Summary of Minimum Horizontal Stress Values	29
Table 7	Summary of Calculated Stress Values	30

LIST OF FIGURES

Figure 1 Layout Plan
Figure 2 Schematic of Hydraulic Fracturing Equipment
Figure 3 Pressure – Flow versus Time in a Hydraulic Fracturing Test
Figure 4 Typical Orientation Fracture Trace
Figure 5 Minimum Stress Summary (2nd Cycle and Jacking)
Figure 6 Maximum – Minimum Stress Summary (1st Cycle)
Figure 7 Maximum – Minimum Stress Summary (2nd Cycle)
Figure 8 Stress v Lithostatic Stress (based on 1st breakdown)
Figure 9 Stress v Lithostatic Stress (based on 2nd cycle reopening pressure)
Figure 10 Stress v Lithostatic Stress (based on Jacking Pressure)
Figure 11 Jacking Pressure v Depth (all data)
Figure 12 Jacking Pressure v Elevation (all data)

Appendix A

Figure A.1 Hydrofracture Test BH PT01 – 51.86 m
Figure A.2 Hydrofracture Test BH PT01 – 264.7 m
Figure A.3 Hydrofracture Test BH PT01 – 293.43 m
Figure A.4 Hydrofracture Test BH PT01 – 304.5 m
Figure A.5 Hydrofracture Test BH PT01 – 308.2 m
Figure A.6 Hydrofracture Test BH PT01 – 314.64 m
Figure A.7 Hydrofracture Test BH PT01 – 322.34 m
Figure A.8 Hydrofracture Test BH SC01 – 210.7 m
Figure A.9 Hydrofracture Test BH SC01 – 216.5 m
Figure A.10 Hydrofracture Test BH SC01 – 230.0 m
Figure A.11 Hydrofracture Test BH SC01 – 242.04 m

Figure A.12 Hydrofracture Test BH SC01 – 269.5 m

Appendix B

Figure B.1 Fracture Orientation BH PT01 – 51
Figure B.2 Fracture Orientation BH SC01 – 210
Figure B.3 Fracture Orientation BH SC01 – 216
Figure B.4 Fracture Orientation BH SC01 – 230
Figure B.5 Fracture Orientation BH SC01 – 242
Figure B.6 Fracture Orientation BH SC01 – 269

LIST OF APPENDICES

Appendix A Plots of Hydraulic Fracturing
Appendix B Fracture Orientation Traces
Appendix C Calibration Records

1 INTRODUCTION

1.1 Project Description

The proposed Steelpoort Pumped Storage Scheme is planned for construction over the next seven years. The scheme is located in the Steelpoort area, Limpopo and Mpumalanga Provinces about 12 km northeast of Roossenekal. The proposed scheme will include:

- an upper reservoir;
- low pressure headrace tunnel;
- surge shafts;
- pressure tunnels;
- powerhouse complex;
- tailrace tunnel;
- lower reservoir; and
- other ancillary underground excavations.

The installed capacity of the scheme is planned for 1520 MW (four 380 MW units). An outline of the layout of the scheme showing the location of the test holes is given in Figure 1.

1.2 Geology

The rocks in the area of the project fall within the Bushveld Igneous Complex and comprise felsic rocks of the Rashoop Granophyre Suite overlying mafic rocks of the Upper and Main Zones of the Rustenburg Layered Suite[1]. The Bushveld Complex is an extremely large, 2 billion year-old layered igneous intrusion which is unique in its size, covering an aerial extent of some 66,000 km^2, and in the economic importance of its mineral deposits. The high plateau is underlain by granophyre in the south of the area and by mixed granite and granophyre in the north. These felsic rocks are several hundred metres thick and form steep scarp slopes. Below the bottom of the scarp at the base of the felsic rocks is a leptite formation approx. 250 m thick, dipping approx. 10º westwards into the slope. This is in turn underlain by diorite beneath the pediment slope, grading into olivine bearing diorite and gabbro beneath the valley floor. These mafic rocks underlying the leptite formation contain bands of anorthosite and magnetite, with all of the horizons dipping around 10º westward. All of these rocks have been intruded by dolerite/lamprophyre dykes.

1.2.1 Lithology and Stratigraphy

The lithology and stratigraphy tend to influence the stress very locally. Lithologic effects are least when the rocks are homogeneous and isotropic in their mechanical properties. The effects can be very significant where sites consist of rock types with widely varying mechanical properties. In such cases, in situ stress will tend to concentrate in the mechanically more competent units, and shed itself from more elastic or ductile units.

1.2.2 Topography

Topography is the second major control on in situ stress. Topography alters the in situ stress both by stress relief near large steep slopes or by stress concentration in the floor of narrow valleys. Topographic effects on stress can have significant impacts on the performance of underground structures. These effects may be difficult to predict particularly at sites with high topographic relief and complex topography.

The project site is located at the edge of an escarpment, a feature that dominates the topography of eastern and south-eastern South Africa. The escarpment has a large-scale northeast-southwest trend, which would lead to stress relief in a northwest to southeast direction in the vicinity of the escarpment. However, the escarpment is not a simple uniform slope. Thus the topography may be expected to provide stress relief from the tectonic stresses in both a regional and local sense that can be hard to predict based on numerical simulation of stress conditions. This complexity provides a significant motivation for direct measurements of stress.

1.2.3 Structural Geology and Tectonics

The third major effect on in situ stress is the tectonic setting. These stresses arise from crustal scale deformation and movements associated with plate tectonics. Tectonic stresses dominate the in situ stress values at depths below topographic influence.

Tectonic stresses are the major component of stress at depth. These stresses arise from regional if not global movements in the earth's crust. Tectonic stresses have consistent orientations on a regional basis. The relative magnitudes of the vertical and horizontal stresses also have regional consistency depending on the compressional, extensional, or shearing nature of crustal deformation. In southern Africa, the direction of horizontal compression is generally northwest-southeast due to plate motions associated with the spreading centres in the south-western Indian Ocean. Information on the tectonic stress in southern Africa is available at http://www-wsm.physik.uni-karlsruhe.de/pub/introduction/introduction_frame.html as part of the World Stress Map Project, Heidelberg University.

1.3 Stress Measurement Program

Golder Associates Ltd. was awarded a contract to carry out hydrofracture stress measurements, in two (2) boreholes as follows:

- *Borehole PT01* – inclined borehole (60º to the horizontal, approx. 400 m long) drilled down to the penstocks and the purpose of this hole is to establish the minimum principal stress in the vicinity of the penstocks for the purposes of assisting with the assessment of the length of steel liners that maybe required; and

- *Borehole SC01* - vertical borehole (approx. 350 m deep) to investigate the conditions throughout the height of the power station complex, looking for the magnitude and direction of the sub-horizontal in situ stresses over a range of levels between the cavern roof and the draft tubes.

The site team arrived at site on November 22, 2006 and left site after completing the testing program on December 4, 2006.

Tests were carried out at or near depths identified in conjunction with the client, in diorite, magnetite and anorthosite. The actual test zones were selected by inspecting the core photographs initially at the required depths and selecting areas free from fractures where possible, from the actual core.

The measurements followed the ASTM test procedure for hydraulic fracturing stress measurements, ASTM Designation D 4645-87[2] (Standard Test Method for Determination of the In-Situ Stress in Rock Using the Hydraulic Fracturing Method). The testing consisted of two parts, fracture generation and fracture orientation. The equipment and test procedures are described in the following sections.

Hydraulic fracturing has become a widely used method for measuring the in situ stresses in boreholes deeper than a few tens of metres. The method is based on the principle that rock will fracture from a borehole in direction normal to the minimum horizontal stress and in the direction of the maximum horizontal stress. The pressure-time behaviour provides indications of when the pressure inside the fracture balances the rock stress normal to the induced fracture thus providing an estimate of the minimum horizontal stress. The calculation of the maximum horizontal stress comes from an analysis of the breakdown, or fracturing pressures that reflect the stress concentration around the borehole.

This report presents the results and analysis of the hydraulic fracturing stress measurements carried out at Steelpoort.

2 TEST METHOD

2.1 Test Zone Selection

The boreholes used in testing were drilled to a 76mm (NQ) diameter by Weppelmann Drilling using wireline coring equipment. The holes were cored over their entire length, and the cores were available at the core shack for inspection. The schedule allowed for the stress measurements to be performed shortly after completion of drilling. Before testing, an inspection of core logs, photographs and core itself provides a basis for selecting test zones that are ideally free of natural fractures or other planes of weakness.

The testing was performed in two boreholes, BH PT01, BH SC01. For each hole, target test zones were identified in conjunction with the client as areas of interest and the test zones selected by the field team on the basis of location relative to critical depths for the planned underground construction as well as rock quality in terms of the absence of fracturing. The borehole test zone depths, and test zone lithologies are given in Tables 1 – 2.

2.2 Fracture Generation Procedures

The fracturing equipment is shown schematically in Figure 2. The packer system consisted of two 2-5/8 in (66.7mm) packers in a straddle arrangement. These packers provide packer seals up to 6000 psi (41.37 MPa) in 3-in (76.2 mm) boreholes. The straddle pipe gave a test section length of 0.6 m. The flow to the packers was channelled through relatively new AQ drill rods. Packer inflation was achieved using 3/16" hydraulic hose run along the outside the drill rod.

The pumping system consisted of a Honda pressure washer with a 3500 psi (24.13 MPa) pressure and 4.5 gpm [US] (17.03 l/min) flow capacity. The flow was controlled through a manifold that allowed for packer inflation and test zone injection from the same pumping source. The packer pressure was monitored using an Omega PX-303, 0 – 5000 psi (0 – 34.47 MPa) pressure transducer mounted on the packer inflation line of the manifold. A similar pressure transducer was used to monitor pressure in the test interval. The pressure losses in the AQ rod, packer and straddle pipe were considered negligible for the flow rates used in the testing. The control manifold also had Bourdon tube pressure gauges for visual indication of the packer pressure, pump pressure, and test zone pressure during testing.

The manifold contained two flow lines, one for a higher rate flow meter [1 to 10 gpm (3.78 to 37.8 l/min)] and the other for a lower rate flow meter [0.1 to 5 gpm (0.38 to 18.9 l/min)]. Each flow line had two valves one for controlling the flow rate and the other for shut off.

The data from the instruments was monitored using a National Instruments data acquisition system that was connected to a notebook computer through its USB port. The data acquisition system used the DasyLab 8.0 software. The data acquisition rate was set at 10 Hertz on all channels for the testing.

All instruments were calibrated prior to testing and calibration specifications are given in Appendix C.

The fracturing procedure followed ASTM guidelines (ASTM, 1997[2]). A test began by setting the packers to approximately 80% of the expected fracturing pressure. Once the packers were set, water was injected through the system with the test-zone pressure measurement line open to flush air from the hydraulic hose and the drill rod. Once a steady flow of water was achieved, the zone was closed.

The hydraulic fracturing tests consisted of four or five pressurization cycles (Figure 3). The first pressurization cycle began at a rate of approximately 1 to 1.5 gpm (3.78 to 5.67 l/min). The test zone was pressurized at this constant flow rate until a rapid drop in pressure indicated the creation of the hydraulic fracture. At this point the flow system was immediately shut-in and the pressure was allowed to decay to provide a shut-in pressure value. After a few minutes of pressure decay the pressure was bled off. The flow from the test zone during bleeding was routed through the flow meters to allow an estimate of how much fluid was lost to the rock during the fracturing.

The second cycle was generally identical to the first pressurization cycle. For the second cycle, the peak pressure is typically lower as the rock has already fractured and there is no effect of the rock's tensile strength. The difference between the first and second pressurization cycle provides an estimate of the reopening pressure, which reflects the stress concentration around the borehole. The reopening pressure is usually taken as the deviation of the pressure build-up in the second cycle from the record of the first cycle. After the pressure peaks, the test zone is immediately shut-in and allowed to decay as in the first cycle.

The third pressurization cycle is usually similar to the first two cycles however, unlike the first two cycles, the flow rate is maintained for several minutes after the peak and the flow approaches a steady pressure. This pressure usually corresponds closely to the shut-in pressure of the first two cycles.

The fourth and fifth cycles are the hydraulic jacking cycles, which involve a stepped pressure test. For laminar flow in a non-deforming fracture, the flow rate is a linear function of the injection pressure. Once a fracture has opened, the flow rate increases at a much greater rate with each pressure step. The transition between the rigid regime and the deformed regime is termed the jacking pressure. Another distinction between the flows in a deforming or non-deforming fracture is the transient flow rate, that is, the change in rate with time. In a non-deforming fracture the flow is either steady or the rate gradually decreases with time. However, in a fracture that is deforming, the rate increases with time as the opening of the fracture increases its permeability.

2.3 Fracture Orientation Procedures

Vertical and inclined hydraulic fractures grow normal to the minimum horizontal stress; hence the hydraulic fracture orientation is a measure of the orientation of the stress field. The hydraulic fracturing process has minimal effect on the stresses along the borehole axis while creating a significant tangential tension in the borehole wall prior to fracturing. Thus hydraulic fractures have a strong tendency to initiate coaxially with the borehole even when the minimum stress is vertical or the rock contains significant strength anisotropy. The most common fracture orientations are thus vertical or steeply dipping along the hole unless the horizontal stresses are very large compared to vertical or there is extreme strength anisotropy (bedding or foliation).

To determine the fracture orientation, we normally use impression packers. This method is time consuming as it is necessary to run the packers in an out of the hole for each test. For this series of tests it was decided to use the services of Reeves Wireline and for them to determine the orientation of the fractures using their acoustic televiewer. In order to determine that this approach would work, an initial test at shallow depth in borehole PT01 was used. Reeves ran the televiewer into the borehole and produced a trace of the borehole at the test location before hydrofracture testing was carried out. Once the test was completed, Reeves ran the televiewer into the hole and this allowed them to pick up the fracture and its orientation by comparing the before and after test traces. Figure 4 shows the trace before and after and indicates the change produced by the hydrofracture testing.

Other than the shallow (51 m) test in borehole PT01, fracture orientation was only carried out in borehole SC01 where testing was carried out in the vicinity of the proposed powerhouse complex and where orientation is critical.

2.4 Hydrofracture Tensile Strength

The tensile strength of the rock is a requirement for analyzing the maximum horizontal stress by the first breakdown pressure method. Some Brazilian tests have been carried out on samples from the core at Steelpoort, however they are not from the holes hydrofractured and not necessarily from the same test horizons. The average tensile strength values used for the various rock types are given in Table 5. These values were determined by averaging the values provided to us from the testing undertaken. Further tensile testing is to be carried out on test samples from the zones that were hydrofractured. Results of this testing are not currently available but will be included in the final report with any modifications to the calculated stresses made at that time.

3 HYDRAULIC FRACTURING THEORETICAL BACKGROUND

3.1 Analysis of Horizontal Stresses, σ_{Hmax} and σ_{Hmin}

Hydrofracturing has become a standard method for determining the in-situ state of stress in rock masses for use in engineering design, and is one of the few methods available for testing in deep boreholes (Haimson, 1993[3]). The method consists of sealing off a short segment (typically 0.6 m) of a borehole at a desired depth (using inflatable packers), injecting fluid (usually water) into the isolated zone at a sufficient rate to raise the hydraulic pressure rapidly and bring about hydraulic fracturing of the borehole wall.

Hydraulic fracturing analysis generally assumes that the borehole is coincident with a principal stress direction. For the purposes of this discussion, we assume the borehole is vertical, although this was not the case for borehole PT01 at Steelpoort, and that vertical stresses are lithostatic, that is, controlled by rock density, gravity, and depth, or ρgh.

The determination of stress magnitudes from hydraulic fracturing relies on two fundamental principles:

- The fracture initiates when the pressure in the test zone overcomes the tangential stress concentrations around the borehole plus the rock's tensile strength;

- The hydraulic fracture propagates normal to the minimum horizontal stress; and

- The minimum horizontal stress on a vertical fracture (from a vertical hole) can be determined from the opening and closing pressure on the fracture.

A typical hydrofracturing test record is shown in Figure 3. Hydrofracturing occurs when the fluid pressure in the isolated portion of the borehole reaches a critical level, called "breakdown", or P_b. At breakdown the rock fractures in tension causing borehole fluid loss and a drop in pressure. When pumping is stopped the hydraulic line feeding the test interval is held shut. The pressure value when injection ceases and the test zone is "shut in" is called the shut-in pressure, or P_{si}. There are several methods of interpreting shut in pressure that are discussed further in section 3.2. In any case, the shut in pressure reflects a balance between the internal pressure in the fracture and the in-situ stress acting on the fracture face. Hence, the shut-in pressure is equated to the minimum horizontal stress, σ_{Hmin}.

Several minutes into the shut-in phase the test zone pressure is bled off (purged) and the first pressurization cycle is thus completed. Several additional cycles are conducted. From these cycles, supplementary shut-in values are obtained, as well as the fracture reopening P_r. During testing, the pressure and injection fluid flow rate are continuously recorded.

The far-field stresses are calculated using the pressures (P_b, P_{si}, and P_r) recorded during the test using one or several available analytical models. Section 4 discusses further the models used for the Steelpoort analysis. The direction of the in-situ stresses is determined from the orientation of the induced hydraulic fracture trace on the borehole wall.

Most analytical models of hydrofracturing make use of a plane strain analysis of the stress concentration around a pressurised borehole penetrating a poroelastic medium which is subjected to unequal far-field stresses. The technique assumes that the borehole axis approximately coincides with a principal stress axis, such as is often the case with vertical holes. Hydraulically induced fractures in a vertical borehole have a strong tendency to propagate axially along the borehole wall normal to the minimum principal stress ($\sigma_{H\min}$). Figure 2 illustrates this schematically.

As noted above, the shut-in pressure, P_{si}, of a hydrofracturing test in a vertical borehole is considered a measure of the minimum horizontal rock stress ($\sigma_{H\min}$) provided the fracture is vertical. The magnitude of σ_{Hmax} is then calculated using the following equation (after Haimson, 1978[4]):

$$\sigma_{H\max} = 3\sigma_{H\min} - P_b - P_0 + T \qquad 3.1$$

where: $\sigma_{H\min}$ is assumed equivalent to the instantaneous shut-in pressure, P_{si}
P_b is the breakdown pressure
P_0 is the pore pressure
T is the tensile strength of the rock

The tensile strength of the rock is usually determined using either laboratory-scale hydraulic-fracture tensile tests with small (~5mm) holes in ~15cm core lengths or Brazilian tensile strength tests on cores.

Tensile strength is a significant area of uncertainty in hydraulic fracture analysis due to effects of scale, pressurization rate, and rock variability. To avoid the questions of tensile strength several practitioners (Bredehoeft, et al , 1976[5], Zoback et al, 1980[6]) proposed using the second pressurisation cycle for calculating $\sigma_{H\max}$. Rather then use the peak pressure, which can be rate dependent, they use a reopening pressure, which is the pressure where the second cycle deviates from the first cycle due to fracture reopening. The reopening pressure is presumed to reflect only the stress concentration around the hole free of influences of tensile strength. The measurement of reopening by comparison of the first and second cycle pressure curves presumes that both cycles were run at the same injection flow rate. The resulting equation for determining σ_{Hmax} is the following:

$$\sigma_{H\max} = 3\sigma_{H\min} - P_r - P_0 \qquad 3.2$$

where: $\sigma_{H\min}$ is assumed equivalent to the instantaneous shut-in pressure, P_{si}
P_r is the fracture reopening pressure
P_0 is the pore pressure

To use P_r for stress evaluation one must assume that the hydraulic fracture closes after the first cycle and does not have significant permeability. The question of fracture permeability after the first cycle is itself a source of uncertainty, thus analyses of hydraulic fracturing tests are prudent to report both the P_b based and the P_r based $\sigma_{H\max}$ values.

3.2 Interpretation of Shut-In Pressure, P_{si}

The most critical measurement in the stress determination is the shut-in pressure. The shut-in pressure is a measure of the stress acting on the hydraulic fracture, which propagates normally to the minimum horizontal stress, $\sigma_{H\min}$. The shut-in pressure also figures in the calculation of the maximum horizontal stress, $\sigma_{H\max}$, based on the stress concentration around the borehole. As stated in equations 3.1 and 3.2, uncertainties in shut-in pressure are amplified by a factor of three for the maximum stress analysis, hence maximum stress values determined by hydraulic fracturing are inherently less certain than minimum stress values.

For the analyses in this report, we used three different methods for obtaining the shut-in pressure as follows:

- Instantaneous shut-in pressure (P_{si})
- Pressure derivative shut-in pressure (P_{dpdt})
- Jacking pressure (P_j).

The instantaneous shut-in pressure is the pressure observed immediately upon termination of injection. This shut-in pressure appears often as an immediate, step-like, drop in pressure followed by a slower rate decline. The P_{si} is reported for each pressurization cycle.

The pressure derivative shut-in pressure, P_{dpdt}, presumes that the fracture has two leakage rates. The higher rate occurs when the internal pressure in the fracture exceeds $\sigma_{H\min}$, and the fracture open. The low rate occurs when the internal pressure of the fracture drops below $\sigma_{H\min}$, and the fracture is closed, though not necessarily impermeable. The derivative shut-in pressure analysis uses a "dpdt" plot of the time rate of change (dP/dt) against pressure (P) for the pressure decline after shut-in, or the termination of injection. The shut-in pressure, P_{dpdt}, is the pressure value of the intersection of two straight lines manually fitted to the early, rapid decline in pressure, and the later slow decline in pressure.

Generally these approaches give very comparable shut-in pressure values. A significant difference among them lies in the total amount of fluid injection. This distinction does not make a great difference when a minimum horizontal stress is σ_3 and the fracture tends to propagate in a vertical plane with distance from the hole. However, when the minimum horizontal stress is σ_2, the fracture will tend to rotate with distance from the hole into an orientation normal to σ_3. The distance of fracture propagation is a function of the total volume of fluid injection; hence a method of shut-in pressure determination that requires more injected fluid volume, as slow-pumping or hydraulic jacking, will be more likely to produce a shut-in pressure value that reflects the rotated fracture orientation. A method that uses pressure decay or instantaneous shut-in after relatively small volumes of fluid injection will be more likely to reflect the shut-in pressure of the vertical fracture without the effects of fracture rotation. In order to capture the shut-in pressure of the fracture before its extensive propagation, the first fracturing cycle and often the second fracturing cycles are shut-in quickly after the critical breakdown pressure is reached.

The third method of obtaining the shut-in pressure is hydraulic jacking. Hydraulic jacking involves injection by constant-pressure steps. A steep, non-linear increase in the flow rate with pressure indicates the opening of the fracture. The hydraulic jacking analysis uses a plot of the pressures versus flow rates to determine this value.

Hydraulic jacking serves not only as a method of obtaining minimum stress. For pressure tunnel design, it is also a direct experimental simulation of the hydraulic jacking mode of tunnel failure. Thus a hydraulic jacking value serves as both a measure of minimum stress and as a value to support tunnel design directly. As hydraulic jacking involves larger volumes of fluid injection than the other methods of shut-in pressure determination, the hydraulic jacking cycle is run as one of the last cycles. Hydraulic jacking therefore tends to reflect the minimum principal stress, σ_3, rather than σ_{Hmin}, if σ_3 is vertical. For this reason, the shut-in value used for σ_{Hmax} is usually taken as the derivative or instantaneous shut-in value from one of the earlier cycles, usually cycle 2 or cycle 3. We also analyse the jacking pressures independently of the stress calculations for assessments of hydraulic jacking potential.

4 TEST RESULTS

4.1 General

A total of 12 hydrofracture tests were undertaken for the Steelpoort test program, all of which have been evaluated in this report. Details of the borehole test zone depths, and test zone lithologies are given in Tables 1 – 2.

4.2 Results of Hydrofracturing Tests

4.2.1 Parameters from Test Records

During each of the tests the following parameters were continuously monitored through a data acquisition unit and recorded on a notebook computer using DasyLab 8.0 software:

- Packer Pressure;
- Zone Pressure; and
- Flow rate

After the test, data was transferred into a Microsoft Excel template and plots of pressure and flow against time generated. As there is a significant amount of data for each of the tests plots have generally been split into three:

- Hydrofracture phase of the test (first 3 cycles);
- Hydrojacking phase of the test (constant pressure, monitoring flow); and
- Pressure versus flow from the hydrojacking phase.

The results of the tests are given graphically in Appendix A, Figures A.1 to A.12.

The presentation of the results has three parts:

- The hydraulic fracturing data listed by borehole in Tables 3 - 4;
- The interpretation of minimum horizontal stress values (Table 6);
- The interpretation of maximum stress values (Table 7); and
- The interpretation of overall stress state at Steelpoort by regression against lithostatic stress and depth (Section 5).

4.2.2 Hydraulic Fracturing Data

The data tables (Tables 3 - 4) present the pressure values interpreted from the pressure-time records as well as the orientation data from the impression surveys. Separate tables give the data for each hole, PT01 and SC01. The critical pressure data include:

- P_{b1} first cycle breakdown pressure
- P_{si1} first cycle instantaneous shut-in pressure
- P_r second cycle reopening pressure (same as P_r in Section 2)
- P_{b2} second cycle breakdown pressure
- P_{dpdt2} second cycle pressure derivative analysis of shut-in pressure
- P_{si2} second cycle instantaneous shut in pressure
- P_{b3} third cycle reopening pressure (not used)
- P_{si3} third cycle instantaneous shut in pressure
- P_j jacking pressure from the hydraulic jacking cycle
- *Fracture Orientation* as strike and dip in degrees from magnetic and true North
- *Fracture type* (see Section 4.3)

It should be noted that pressures in Tables 3 - 4 are those measured at the readout panel at surface, the column of water should be added to show pressure at the test section.

4.2.3 Orientation Survey Results

Tables 3 - 4 also present the results of the fracture orientation measurements for one test in PT01 and all tests in SC01. Appendix B, Figures B.1 to B.6, contains traces obtained from the acoustic televiewer traces.

Generally the fracture trace quality was good with well defined traces as can be seen from the comparative plots before and after (Figures B.1 – B.6). These show that inclined fractures were induced in each case.

4.2.4 Tensile Strength Results

Tensile strength tests have been carried out on selected samples from boreholes drilled prior to the boreholes used for hydraulic fracture tests. The results have been made available to us for the determination of $\sigma_{H\max}$. For the purposes of calculation the average tensile strength of the various rock types has been used as shown in Table 5.

4.3 Stress Evaluation

Hydraulic fracture records can occur in a number of different forms, three basic types as follows:

- Classic hydraulic fracture record (vertical or inclined fracture)
- Horizontal-type fracture record
- Anomalous fracture record.

For the tests at Steelpoort all fractures that had orientation tests carried out showed inclined fractures and can be classified as classic hydraulic fractures. The classic hydraulic fracture achieves a sharp breakdown after the first cycle. If pumping is stopped quickly after breakdown, the pressure rapidly declines to an instantaneous shut-in pressure. The pressure continues to drop gradually at a slower rate. The second cycle builds up generally to a lower peak pressure, as the tensile strength of the rock in the test zone is zero after the initiation of the fracture in the first cycle. An instantaneous shut-in pressure is also observed followed by gradual pressure decay. Subsequent pressurization cycles have similar behaviours as the first, with perhaps a gradual decrease in the overall pressure levels. The change in shut-in levels appears mainly in stress states where the minimum principal stress is vertical and fractures may rotate to horizontal with distance from the hole.

4.3.1 Stress Calculations

Table 6 and Figure 5 present the minimum stress, σ_{Hmin}, values for all tests. The table also includes the calculated vertical stress, σ_v , values based on an average rock density of 2700 kg/m^3. The minimum stress interpretations use the second cycle derivative value (P_{dpdt}). The rationale for using the second cycle is that the fracture should be sufficiently developed to give a good shut in pressure, but not so extended that it may rotate from the plane normal to $\sigma_{H\min}$ or extend into rock with stresses different from those immediately around the borehole. The jacking pressure in particular, which involves larger volumes of fluid injection, may reflect conditions beyond those determining the stress concentration around the hole and therefore lose value for calculating $\sigma_{H\max}$. On the other hand, jacking pressure should be a more accurate reflection of the true minimum stress regardless of its orientation relative to the borehole, hence jacking pressures are the appropriate values to use for hydraulic jacking assessments of the pressure tunnel and its lining.

The maximum stress, σ_{Hmax}, calculations use both equations 3.1 and 3.2. The pore pressure value is based on hydrostatic pressure assuming a water level depth of 40 m below the surface, hence the pore pressure values are approximately 0.4 MPa less than the water column pressure values that were used to correct surface pressures to downhole pressures. The water levels were not known with great certainty, hence the pore pressure maybe an uncertain parameter within a range of a few tenths of an MPa. The Cycle 1 calculation uses the first breakdown pressure (Equation 3.1) and tensile strength values come from Table 5. Cycle 2 calculation uses the second cycle reopening pressure and Equation 3.2. Figures 6 and 7 show the maximum and minimum stress calculations by borehole. Both figures include reference lines for lithostatic stress as calculated from each borehole collar elevation, although it should be noted that at about 315 m (near test locations), the ground surface elevation is about 1310 m which would add to the plotted values.

The Cycle 1 and Cycle 2 calculations both use the same σ_{Hmin} value, that is, the values in Table 6 that are based on the second cycle derivative analysis. Table 7 also presents the orientation of σ_{Hmax} for those fractures having inclinations greater than 60 degrees (all measured values). Details of orientation including strike and dip are given in Tables 3 - 4.

The summary of stresses given in Table 7 show a large discrepancy between the maximum stresses calculated using the first cycle breakdown pressures and the second cycle reopening pressures. The key parameter in the calculation of maximum stress from the first cycle is the tensile strength of the rock. Values that have been used in this calculation seem rather high and were the results from tests carried out in holes other than those where hydrofracture testing was carried out. Normally, when there is a high tensile strength it could be expected that the difference between the peaks from the first and second cycle tests would be much larger than they are in the Steelpoort tests. Therefore it is possible that the use of the current values for tensile strength are skewing the results.

5 DISCUSSION OF RESULTS

5.1 State of Stress

An inspection of the stress-elevation plots presented in the previous section reveals several key findings. These are the following:

- The maximum stresses are much higher taking the first cycle data than the second cycle;
- The minimum stresses are between 15% higher than lithostatic and 30% lower;
- The minimum stress in borehole PT01 (inclined hole) could be as much as 40% lower than lithostatic taking into consideration that the ground surface elevation is higher (vertical) at the test locations; and
- The orientation of the stresses measured in SC01 are reasonably consistent.

In discussing the points above the determination of the maximum stresses from the first cycle is dependent on the tensile strength of the rock (equation 3.1) whereas the second cycle relies on the reopening pressure (equation 3.2). The values for the tensile strength are assumed from other tests on the site and maybe significantly different at the test locations. When testing is complete on core from the actual test locations the stresses will be recalculated.

The calculated maximum stresses are:

1. Based on the 1st breakdown:

Borehole	Average (MPa)	Minimum (MPa)	Maximum (MPa)
PT01	22.1	14.3	28.6
SC01	23.8	16.8	31.1
Overall	22.8	14.3	31.1

2. Based on the 2nd cycle reopening pressure:

Borehole	Average (MPa)	Minimum (MPa)	Maximum (MPa)
PT01	9.3	6.0	12.9
SC01	13.2	7.0	20.9
Overall	10.9	6.0	20.9

It is possible that the rocks tested are weaker than the tensile strength is showing which if the case would bring the results much closer, as the tensile strength is added in the equation (3.1). There are other fractures that can be seen in the core from the acoustic televiewer results and it is possible that some of the fractures were pre-existing although not visible. Closer inspection of core may useful to try to understand the tensile strength results better.

The minimum stresses range from 15% above to 30% below lithostatic and could be as much as 40% below taking into consideration that at a depth of the tests the ground surface elevation is about 1310 m, some 65 m above the borehole collar elevation.

The minimum stresses are as follows:

Borehole	Average (MPa)	Minimum (MPa)	Maximum (MPa)
PT01	6.7	5.1	8.3
SC01	8.4	5.8	11.0
Overall	7.4	5.1	11.0

The orientation of the fractures is fairly consistent with a strike of between -5 to +19 from true north and inclinations of the fractures of 62º to 78º

5.2 Regression Analysis of Stress Data

In evaluating the stresses at depth we have used a linear regression analysis, assuming that there is zero stress at ground level (i.e. zero intercept). This is the only assumption that we can make as most of the tests were concentrated over a small depth range. The results are given below for:

- The first breakdown numbers using the first cycle peak pressure and tensile strength along with the second cycle derivative shut in pressure (Figure 8);
- The second cycle calculations use the second cycle reopening pressure and the second cycle derivative shut in pressure values (Figure 9); and
- The third alternative uses the second cycle reopening and the hydraulic jacking pressure (Figure 10).

In addition the table below gives the projected stress values at a depth of 265 m, the average depth of testing in the areas of the proposed tunnels.

		Horizontal Stress versus		Stress at 265 m
		Lithostatic	Depth	
	Units	(MPa/MPa)	(MPa/100 m)	(MPa)
1st cycle	$\sigma_{H\max}$	3.31	8.93	23.6
	$\sigma_{H\min}$	1.11	2.99	7.9
2nd cycle	$\sigma_{H\max}$	1.63	4.40	11.7
	$\sigma_{H\min}$	1.08	2.99	7.9
Jacking cycle	$\sigma_{H\max}$	1.37	3.70	9.8
	$\sigma_{H\min}$	1.10	2.97	7.9

It should be noted that as testing was only undertaken over a small depth range, the area of interest and it maybe better to take average values given in section 5.1.

5.3 Analysis of Jacking Pressure

In addition to the assessments of $\sigma_{H\max}$ and $\sigma_{H\min}$, we also looked at the jacking pressure. The jacking pressure values are important for the design of the tunnel lining systems.

We assessed the jacking pressure data in two ways, as a function of depth (Figure 11) and as a function of elevation (Figure 12). In the depth-based analysis data from both holes are plotted and fitted together. From the plot it can the average stress over the tunnel elevation is about 8 MPa with a range from 5.5 MPa to 11.1 MPa. Similarly the elevation plot gives the same range but over a slightly smaller depth range.

5.4 Analysis of Orientation of $\sigma_{H\max}$

The direction of the maximum horizontal stress, $\sigma_{H\max}$, arises from surveys conducted before and after testing by Reeves Wireline. The figures in Appendix B show both the before trace and the after trace. The orientations of the fractures is fairly consistent running almost north south, almost parallel to the regional trend of the escarpment.

6 SUMMARY AND CONCLUSIONS

The state of stress in the Steelpoort site has been measured using twelve tests in two boreholes to depths from near surface to 322 m. The measurements were carried out from surface in the vicinity of the proposed pressure tunnels and powerhouse complex with the exception of the first test which was a trial for the orientation process.

Although the measurements were carried out over a small depth range, linear regression has been applied to the plots assuming no stress at ground surface and the results have been presented. Average values have also been presented.

The orientation of the maximum stress is approximately north south, which is roughly parallel to the regional trend of the escarpment. The hydraulic fracturing suggests that the regional topography of the escarpment controls the state of stress in the area.

Dependent on the data used (1^{st} cycle or 2^{nd} cycle) there is a significant difference between the results. It should be emphasised that the results may change when the tensile strengths of the test zone rocks have been included. It may also be worth carrying out additional tests if the discrepancy cannot be attributed to the tensile strength and if it is a concern for the design of the caverns.

GOLDER ASSOCIATES LTD.

J.L. Gilby, P. Eng.
Principal

T. Doe, PhD, P. Geologist
Principal

jlg/td/06-1119-010 - Draft January 2007
06-1119-010 Steelpoort Report.doc

7 REFERENCES

1 Draft Environmental Scoping Report for the proposed pumped storage generation facility in the Steelpoort area, Limpopo and Mpumalanga Provinces, Eskom, 2006.

2 ASTM, Standard Test Method for Determination of the In-Situ Stress in Rock Using the Hydraulic Fracturing Method, D4646 – 87 (Reapproved 1997), 1997.

3 Haimson, B.C., The Hydraulic Fracturing Method of Stress Measurements : Theory and Practice, in : Fundamental Rock Engineering, Fairhurst, C. ed., pp. 396 – 412, 1993.

4 Haimson, B.C., The Hydrofracturing Stress Measuring Method and Recent Results, Int. J. Rock Mech. Min. Sci. And Geomech. Abstr., col. 15, pp. 167 – 178, 1978.

5 Bredehoeft, J.D.,Wolff, R.G., Keys, W.S. and Dhutter, E., Hydraulic Fracturing to determine the regional in-situ stress field, Piceance Basin, Colorado, Geol. Soc. Am. Bull., vol. 87, pp. 250 – 258, 1976.

6 Zoback M.L. and Zoback M., State of stress in the continuous United States, J. Geophys. Res. 10, 6113 – 6156, 1980.

Table 1 Borehole PT01 Test Zones

Test Zone (m)[1]	*Depth (m) centre of section*	*Depth (m)*[2]	*Elevation (m) Collar = 1245*[3]	*Lithology*[4]
51.86 – 52.46	52.16	45.17	1199.83	Strong to very strong medium grained Diorite
264.70 – 265.30	265.00	229.50	1015.50	Strong to very strong medium grained Diorite
293.43 – 294.03	293.73	254.38	990.62	Very strong to extremely strong coarse grained olivine rich Magnetite and Anorthosite
304.50 – 305.10	304.80	263.96	981.04	Very strong to extremely strong coarse grained olivine rich Magnetite and Anorthosite
308.20 – 308.80	308.50	267.17	977.83	Very strong to extremely strong coarse grained olivine rich Magnetite and Anorthosite
314.64 – 315.24	314.94	272.75	972.25	Very strong coarse grained anorthosite rich Diorite
322.34 -322.94	322.64	279.41	965.59	Very strong coarse grained anorthosite rich Diorite

[1] Test zone depth is along hole, borehole declination is 60º
[2] Vertical depth
[3] Collar elevation approximate
[4] Lithology taken from borehole log information

Table 2 Borehole SC01 Test Zones

Test Zone (m)	*Depth (m) centre of section*	*Depth (m)*	*Elevation (m) Collar = 1216[3]*	*Lithology[2]*
210.70 – 211.30	211.00	211.00	1005.00	Very strong coarse grained quartzite rich Magnetite
216.50 – 217.10	216.80	216.80	999.20	Extremely strong coarse grained Anorthosite
230.00 – 230.60	230.30	230.30	985.70	Strong to very strong medium to coarse grained Diorite
242.00 – 242.60	242.30	242.30	973.70	Strong to very strong medium to coarse grained olivine rich Diorite
269.50 – 270.10	269.80	269.80	946.20	Very strong medium to coarse grained olivine rich Diorite

[1] Collar elevation approximate
[2] Lithology taken from borehole log information

Table 3 Borehole PT01 Summary of Hydrofracture Test Results

Field Test No.	Depth (adjusted) (m)	Lithology	Cycle 1		Cycle 2				Cycle 3		Jacking
			P_{b1} (MPa)	P_{isip1} (MPa)	P_{r2} (MPa)	P_j (MPa)	P_{dpdt2} (MPa)	P_{si2} (MPa)	P_{b3} (MPa)	P_{si3} (MPa)	P_j (MPa)
51	45.17	Diorite	9.2	7.3	7.6	10.7	4.7	1.0	7.3	1.9	3.4
264	229.50	Diorite	10.3	8.3	7.6	9.0	5.9	5.8	7.9	6.9	5.9
293	254.38	Magnetite	10.5	8.3	7.2	9.5	5.9	0.7	9.4	4.0	8.6
304	263.96	Magnetite	9.4	3.5	5.9	6.3	3.8	3.8	6.1	3.5	4.1
308	267.17	Magnetite	5.6	4.1	4.1	6.1	2.5	2.6	5.5	2.8	3.8
314	272.75	Diorite	10.0	6.8	7.7	9.0	5.6	4.0	8.7	4.4	5.2
322	279.41	Diorite	10.8	6.9	4.1	5.0	2.8	2.3	4.1	3.4	2.8

Field Test No.	Depth (adjusted) (m)	Lithology	Fracture Configuration: Orientation (°) Mag	Orientation (°) Corr	Inclination (°)	Type	Comments
51	45.17	Diorite	232	215	48	inclined	
264	229.50	Diorite					No orientation measured
293	254.38	Magnetite					No orientation measured
304	263.96	Magnetite					No orientation measured
308	267.17	Magnetite					No orientation measured
314	272.75	Diorite					No orientation measured
322	279.41	Diorite					No orientation measured

Legend: P_b = Breakdown pressure, P_r = Reopening pressure, P_{si}, P_{isip} or P_{dpdt} = Shut-in pressure, P_j = Opening pressure during jacking, magnetic declination = 17.03° west of true north. Note that pressures tabled are those measured at the readout panel at surface, the column of water should be added to show pressure at the test section.

Table 4 Borehole SC01 Summary of Hydrofracture Test Results

Field Test No.	*Depth (adjusted)*	*Lithology*	*Cycle 1*		*Cycle 2*				*Cycle 3*		*Jacking*
			P_{b1}	P_{isip1}	P_{r2}	P_j	P_{dpdt2}	P_{si2}	P_{b3}	P_{si3}	P_j
	(m)		*(MPa)*	*(MPa)*	*(MPa)*	*(MPa)*	*(MPa)*	*(MPa)*	*(MPa)*	*(MPa)*	*(MPa)*
210	211.0	Magnetite	11.3	7.3	7.7	10.3	4.7	5.0	7.6	4.4	4.5
216	216.8	Anorthosite	11.3	6.9	7.5	9.6	6.9	3.6	8.9	5.2	5.1
230	230.3	Diorite	11.4	8.5	8.3	10.8	8.7	8.9	10.9	8.0	6.9
242	242.3	Diorite	12.0	7.3	8.1	10.0	6.9	2.9	9.0	4.9	4.8
269	269.8	Diorite	9.4	6.2	5.2	6.9	3.2	3.2	5.7	4.0	3.5

Field Test No.	*Depth (adjusted)*	*Lithology*	*Fracture Configuration*			*Type*	*Comments*
			Orientation		*Inclination*		
	(m)		*(°) Mag*	*(°) Corr*	*(°)*		
210	45.17	Diorite	36	19	78	inclined	
216	229.50	Diorite	16	359	73	inclined	
230	254.38	Magnetite	12	355	66	inclined	
242	263.96	Magnetite	18	1	77	inclined	
269	279.41	Diorite	15	358	62	inclined	

Legend: P_b = Breakdown pressure, P_r = Reopening pressure, P_{si} , P_{isip} or P_{dpdt} = Shut-in pressure, P_j = Opening pressure during jacking, magnetic declination = 17.03° west of true north. Note that pressures tabled are those measured at the readout panel at surface, the column of water should be added to show pressure at the test section.

Table 5 Average Tensile Strengths

Lithology	*Tensile Strength (MPa)*
Diorite (upper)	19
Diorite (lower)	14
Magnetite	15
Anorthosite	15

Note that average tensile strengths given in this table and used in stress calculations were taken from values given by BKS

Table 6 Summary of Minimum Horizontal Stress Values

Borehole	*Field Test No.*	*Depth (adjusted) (m)*	*Lithology*	$\sigma_{H\mathrm{Min}}$ *2nd cycle (MPa)*	$\sigma_{H\mathrm{Min}}$ *Jacking (MPa)*	σ_v *(MPa)*	*Comments*
PT01	51	45.17	Diorite	5.1	3.9	1.2	
	264	229.50	Diorite	8.1	8.1	6.2	
	293	254.38	Magnetite	8.4	11.1	6.9	
	304	263.96	Magnetite	6.4	6.7	7.1	
	308	267.17	Magnetite	5.1	6.4	7.2	
	314	272.75	Diorite	8.3	7.8	7.4	
	322	279.41	Diorite	5.5	5.5	7.5	
SC01	210	211.0	Magnetite	6.7	6.6	5.7	
	216	216.8	Anorthosite	9.0	7.2	5.9	
	230	230.3	Diorite	11.0	9.2	6.2	
	242	242.3	Diorite	9.3	7.2	6.5	
	269	269.8	Diorite	5.8	6.1	7.3	

Table 7 Summary of Calculated Stress Values

Borehole	*Field Test No.*	*Depth (adj) (m)*	*Lithology*	$\sigma_{H\text{Max}}$ *Cycle 1 (MPa)*	$\sigma_{H\text{Max}}$ *Cycle 2 (MPa)*	$\sigma_{H\text{Min}}$ *(MPa)*	σ_v *(MPa)*	*T (MPa)*	P_h *Water Column (MPa)*	P_o *Pore Pressure (MPa)*	*Fracture Orientation (°) Corr*	*Comments*
PT01	51	45.17	Diorite	24.3	6.9	5.1	1.2	19	0.4	0.4	215	
	264	229.50	Diorite	28.6	12.3	8.1	6.2	19	2.3	2.2		
	293	254.38	Magnetite	24.6	12.9	8.4	6.9	15	2.5	2.5		
	304	263.96	Magnetite	19.6	8.1	6.4	7.1	15	2.6	2.6		
	308	267.17	Magnetite	19.5	6.0	5.1	7.2	15	2.6	2.6		
	314	272.75	Diorite	23.6	11.9	8.3	7.4	14	2.7	2.7		
	322	279.41	Diorite	14.3	6.9	5.5	7.5	14	2.7	2.7		
SC01	210	211.0	Magnetite	19.8	8.3	6.7	5.7	15	2.1	2.1	19	
	216	216.8	Anorthosite	26.5	15.4	9.0	5.9	15	2.1	2.1	359	
	230	230.3	Diorite	31.1	20.2	11.0	6.2	14	2.3	2.2	355	
	242	242.3	Diorite	25.1	15.0	9.3	6.5	14	2.4	2.4	1	
	269	269.8	Diorite	16.8	7.0	5.8	7.3	14	2.6	2.6	358	

LAYOUT PLAN

FIGURE 1

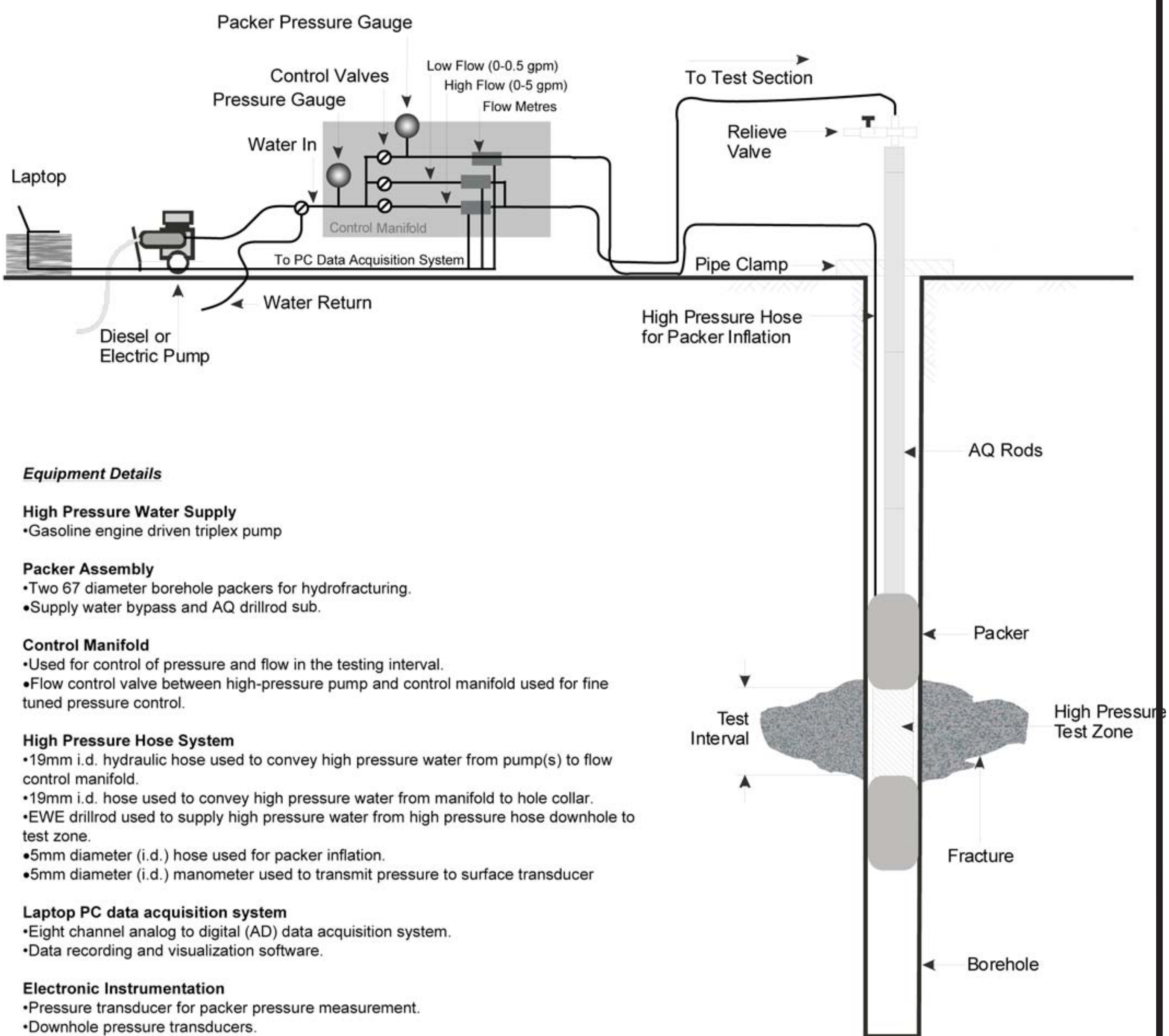
Project: 06-1119-010

Golder Associates

Date: January 2007

SCHEMATIC OF HYDRAULIC FRACTURING EQUIPMENT

FIGURE 2



Equipment Details

High Pressure Water Supply
- Gasoline engine driven triplex pump

Packer Assembly
- Two 67 diameter borehole packers for hydrofracturing.
- Supply water bypass and AQ drillrod sub.

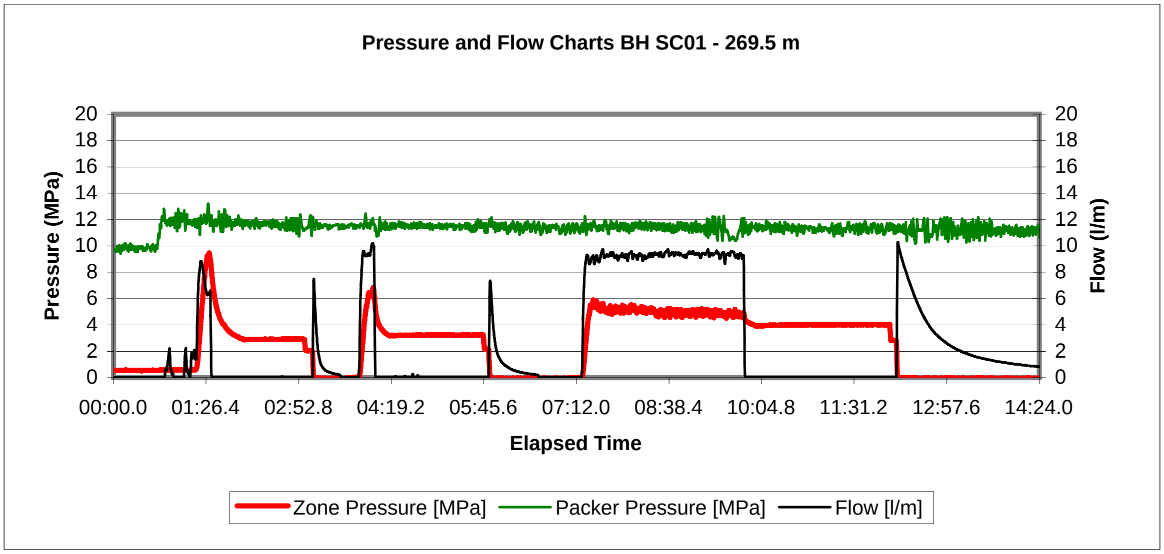
Control Manifold
- Used for control of pressure and flow in the testing interval.
- Flow control valve between high-pressure pump and control manifold used for fine tuned pressure control.

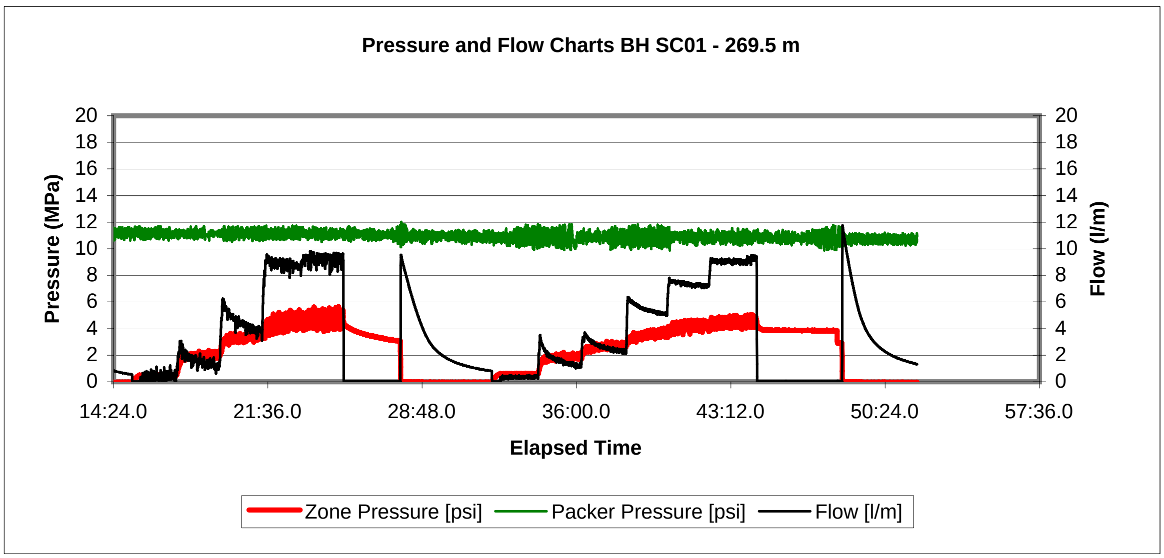
High Pressure Hose System
- 19mm i.d. hydraulic hose used to convey high pressure water from pump(s) to flow control manifold.
- 19mm i.d. hose used to convey high pressure water from manifold to hole collar.
- EWE drillrod used to supply high pressure water from high pressure hose downhole to test zone.
- 5mm diameter (i.d.) hose used for packer inflation.
- 5mm diameter (i.d.) manometer used to transmit pressure to surface transducer

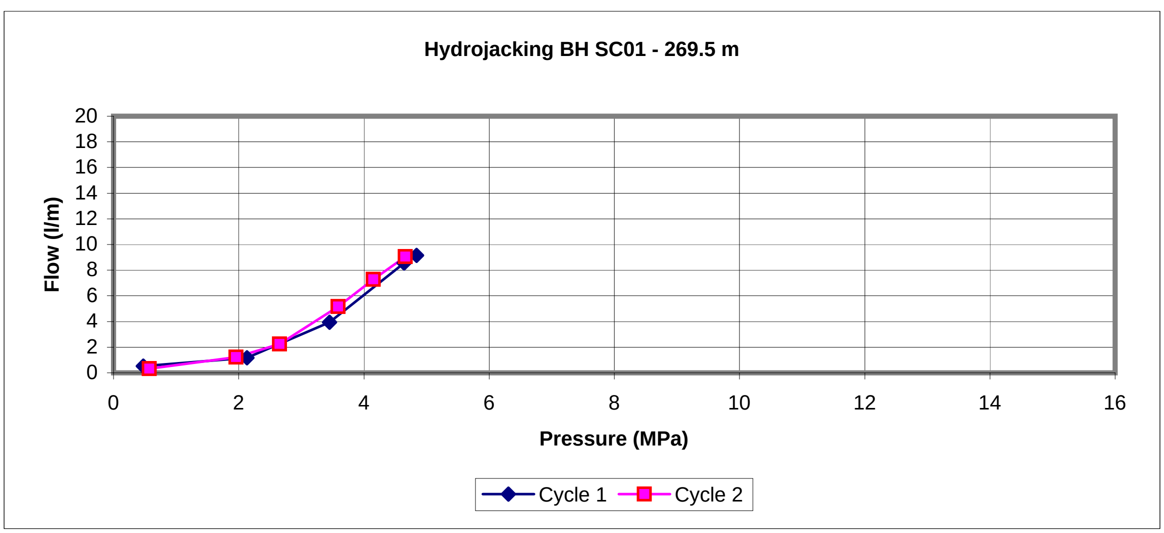
Laptop PC data acquisition system
- Eight channel analog to digital (AD) data acquisition system.
- Data recording and visualization software.

Electronic Instrumentation
- Pressure transducer for packer pressure measurement.
- Downhole pressure transducers.
- Electronic flowmeters of variable rating.

PRESSURE - FLOW v TIME IN A HYDRAULIC FRACTURING TEST	FIGURE 3



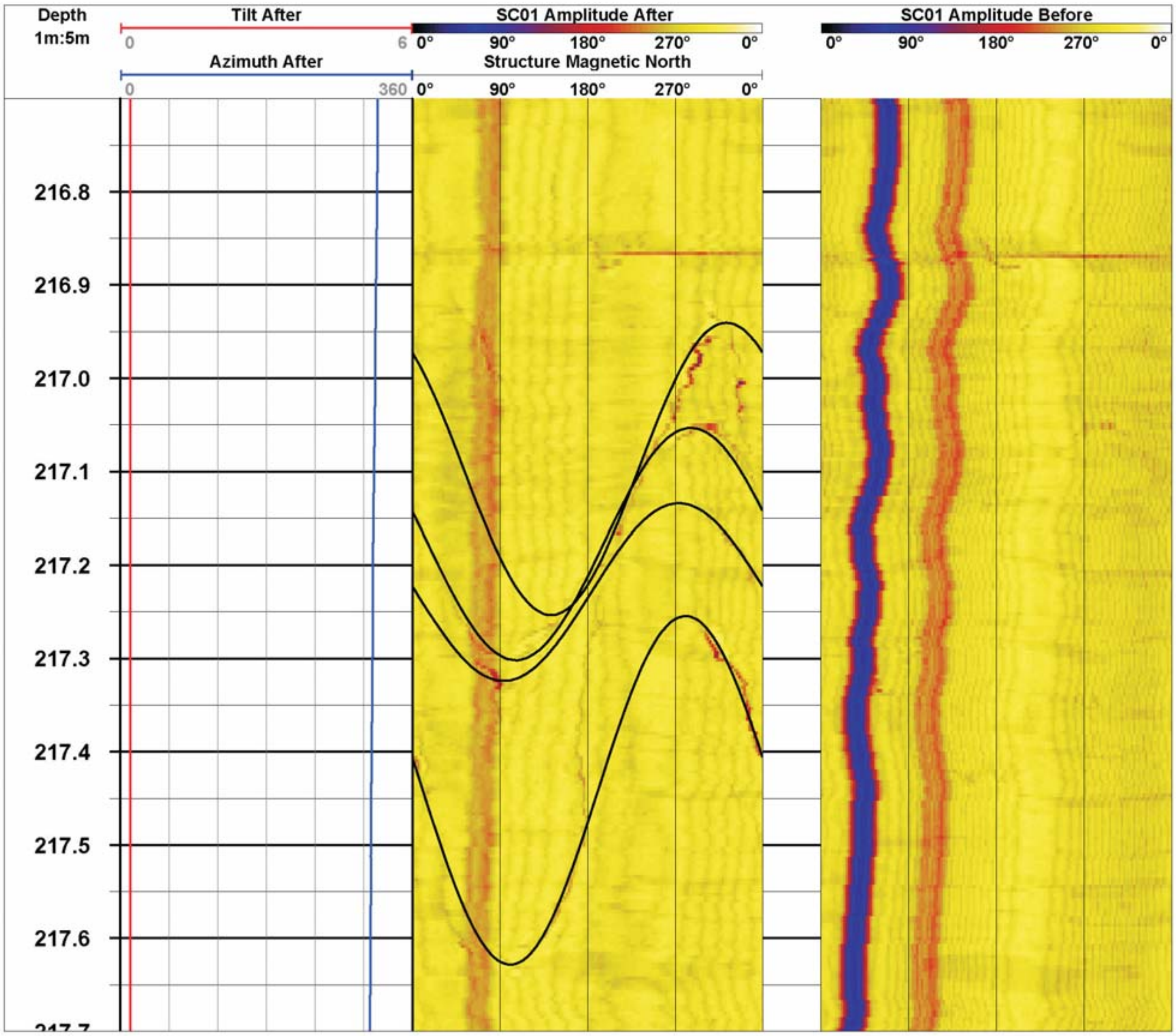




Golder Associates

Project No. 06-1119-010
Date January 2007

TYPICAL FRACTURE ORIENTATION TRACE	FIGURE 4

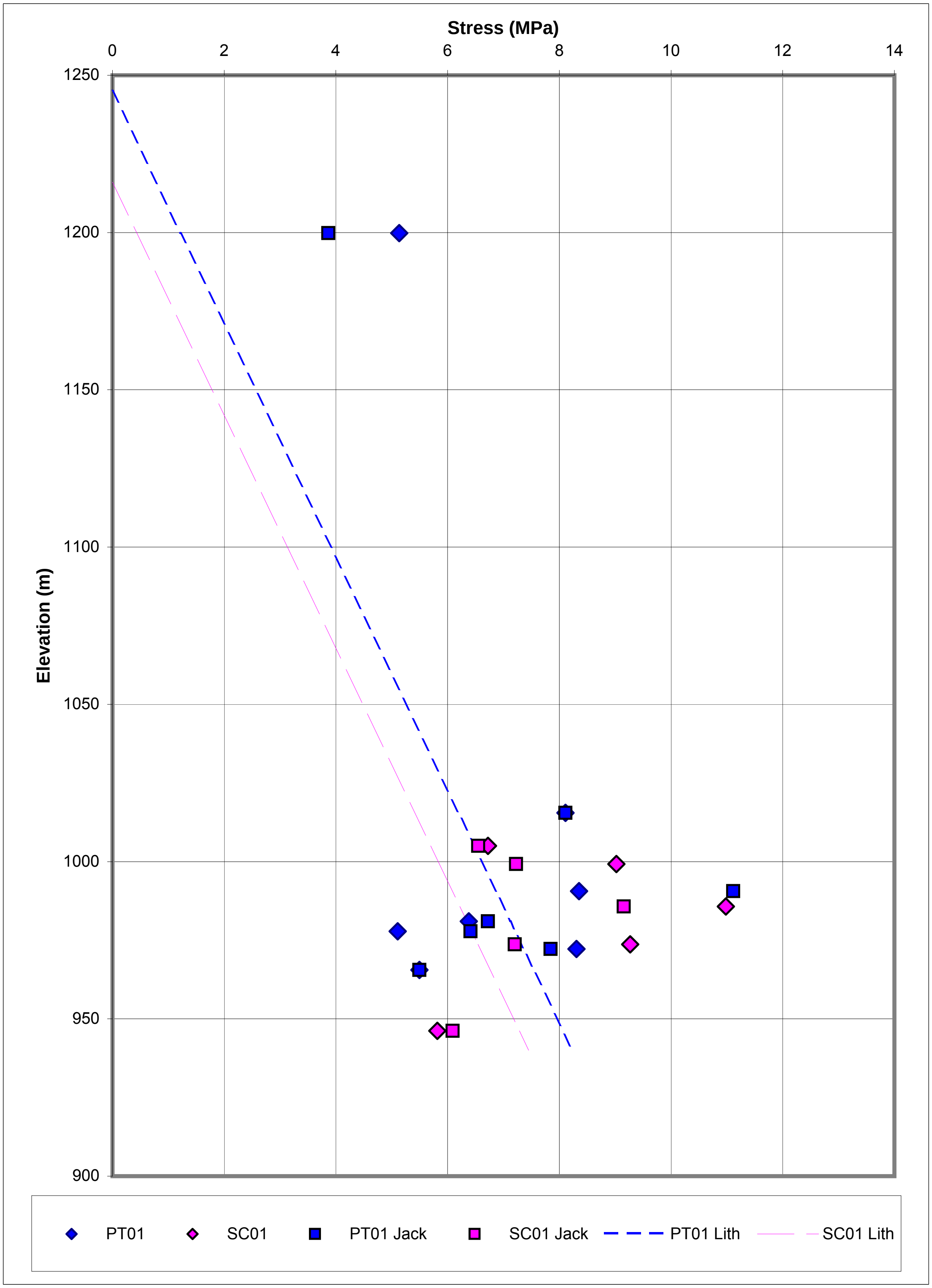


After

Before

Project: 06-1119-010 **Golder Associates** Date: January 2007

MINIMUM STRESS SUMMARY (2nd Cycle and Jacking)	FIGURE 5

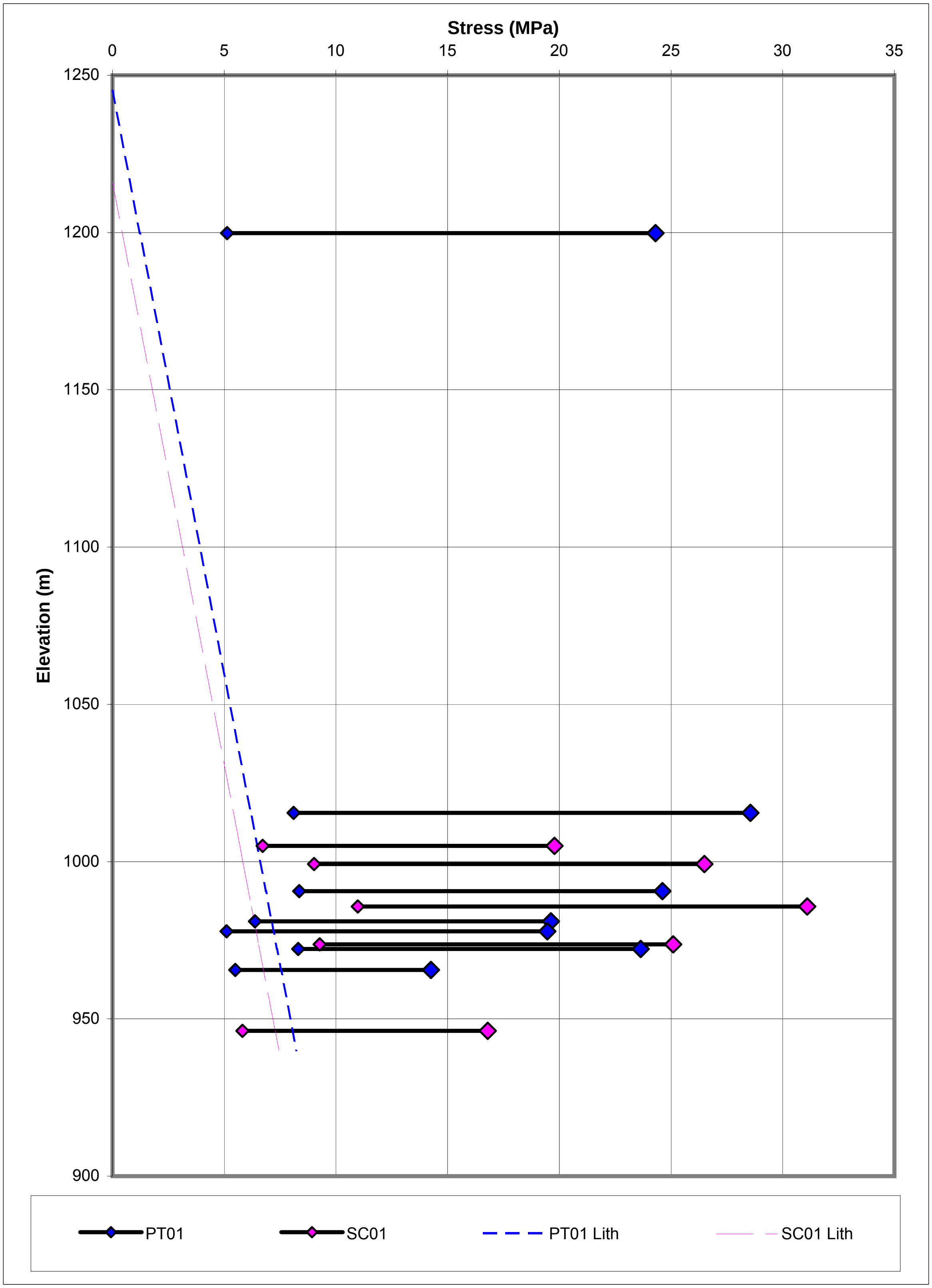


Golder Associates

Project No. 06-1119-010
Date January 2007

MAXIMUM - MINIMUM STRESS SUMMARY
(1st Cycle)

FIGURE 6



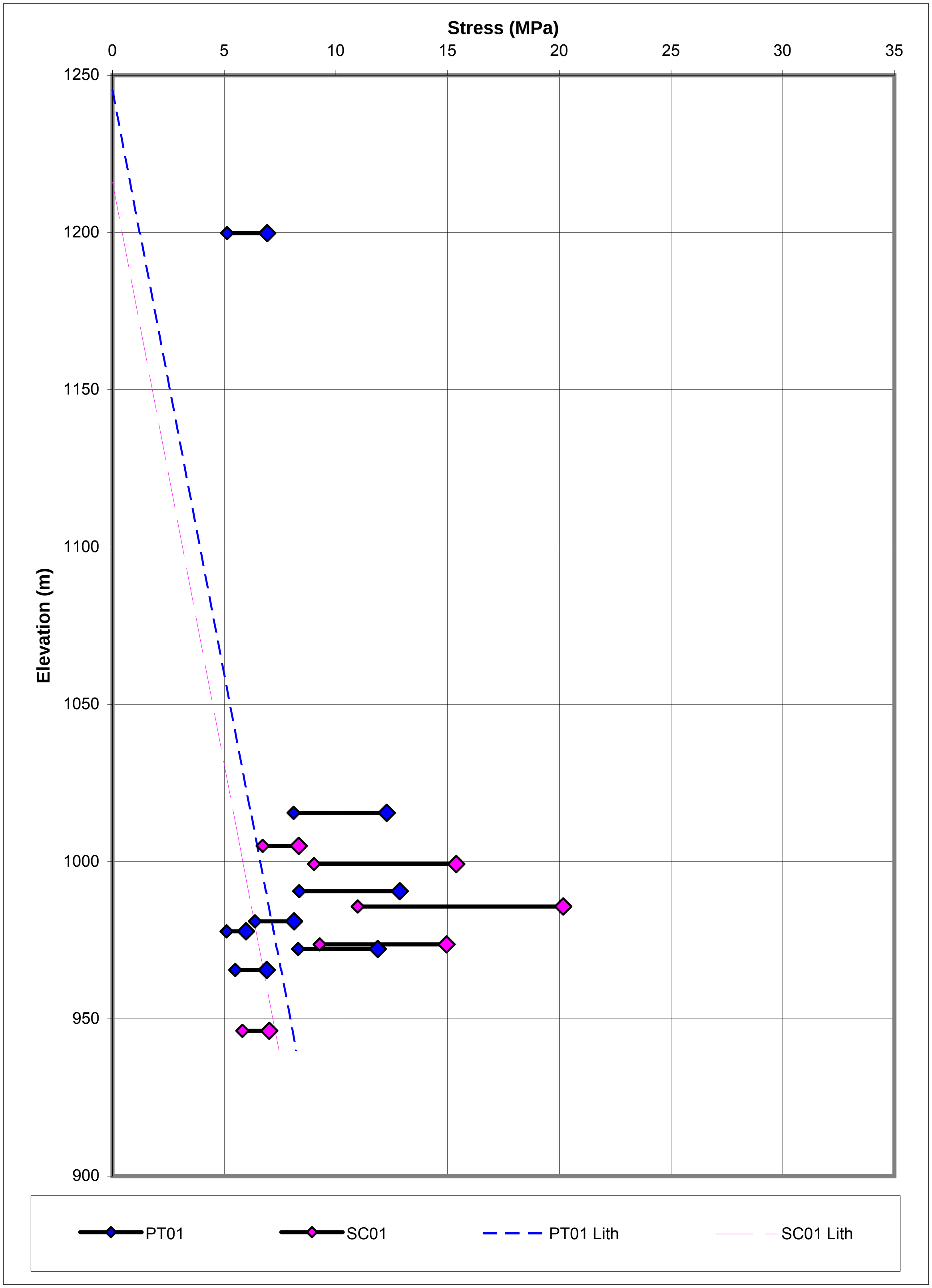
Golder Associates

Project No. 06-1119-010

Date January 2007

MAXIMUM - MINIMUM STRESS SUMMARY (2nd Cycle)

FIGURE 7



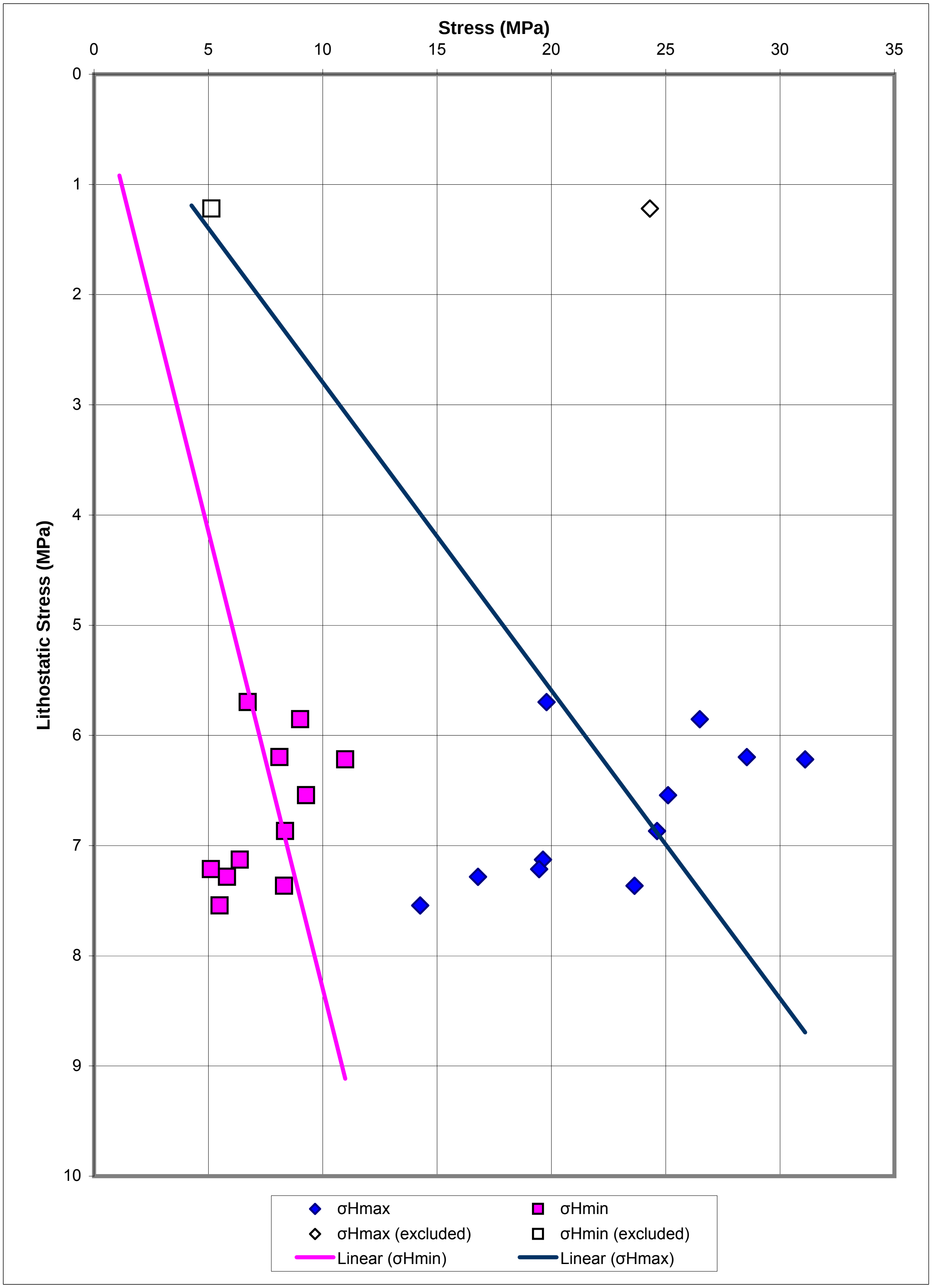
Golder Associates

Project No. 06-1119-010

Date January 2007

STRESS v LITHOSTATIC STRESS
(based on 1st breakdown)

FIGURE 8

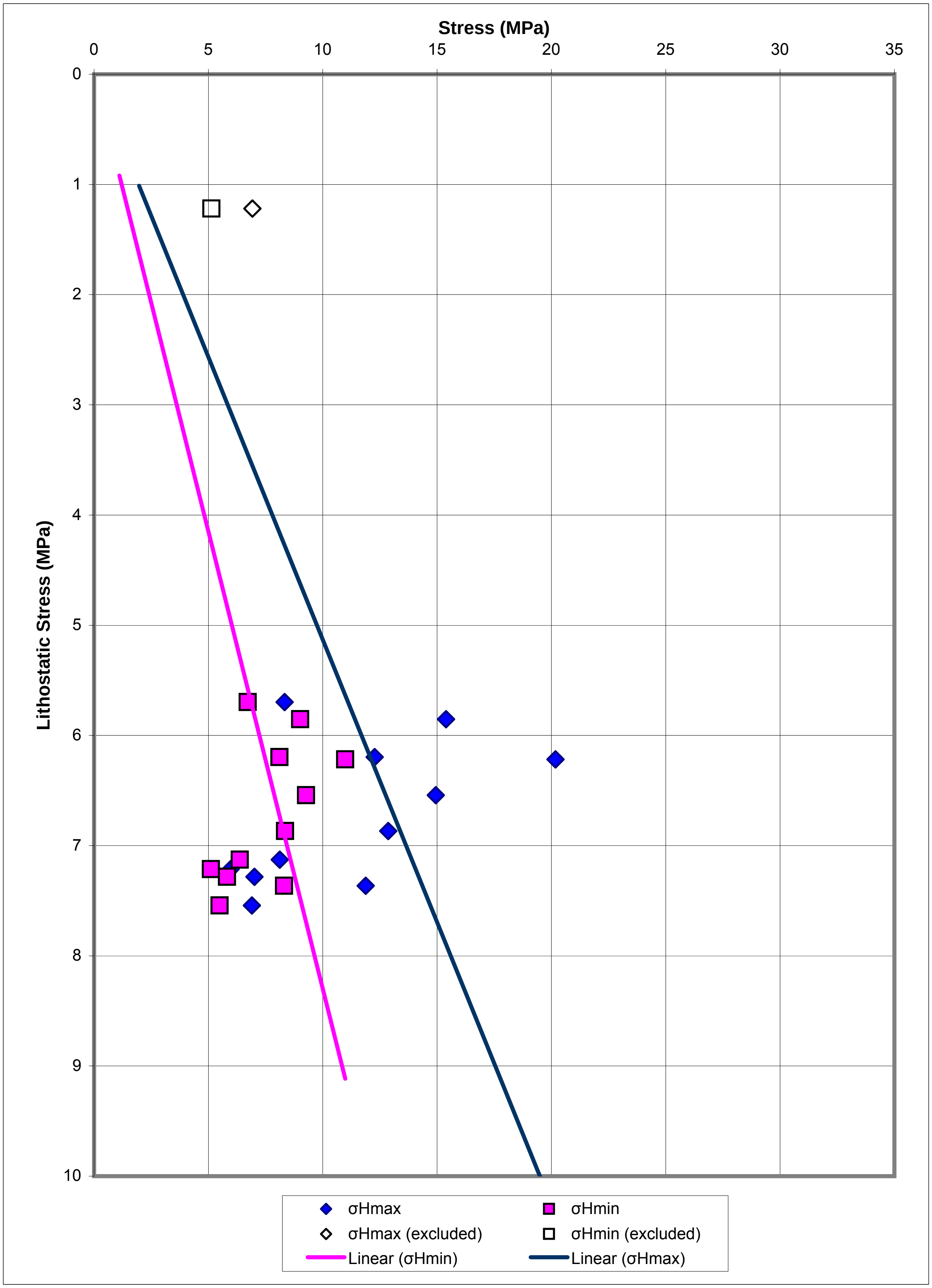


Golder Associates

Project No. 06-1119-010
Date January 2007

STRESS v LITHOSTATIC STRESS
(based on 2nd cycle)

FIGURE 9

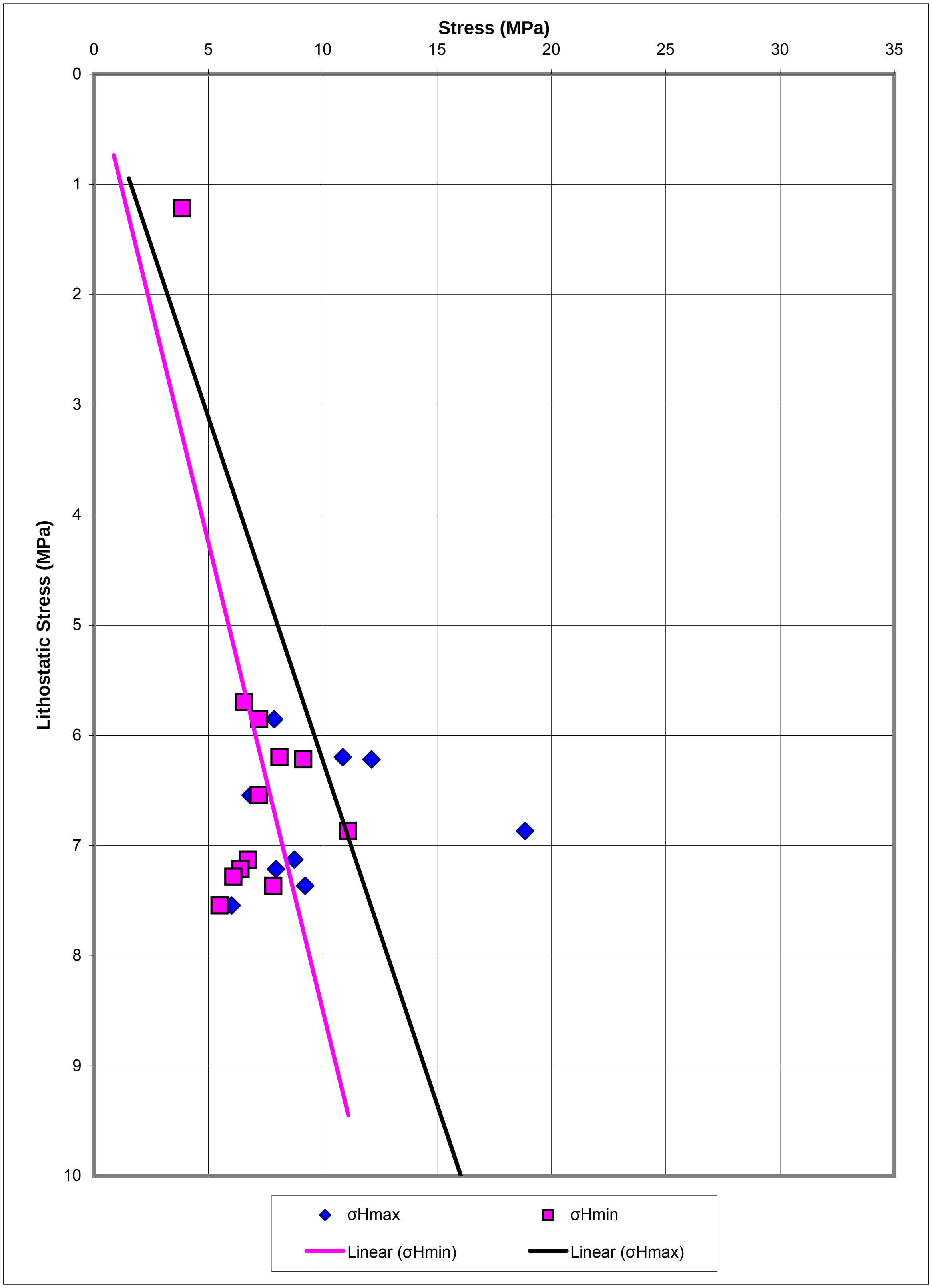


Golder Associates

Project No. 06-1119-010
Date January 2007

STRESS v LITHOSTATIC STRESS
(based on Jacking Pressure)

FIGURE 10

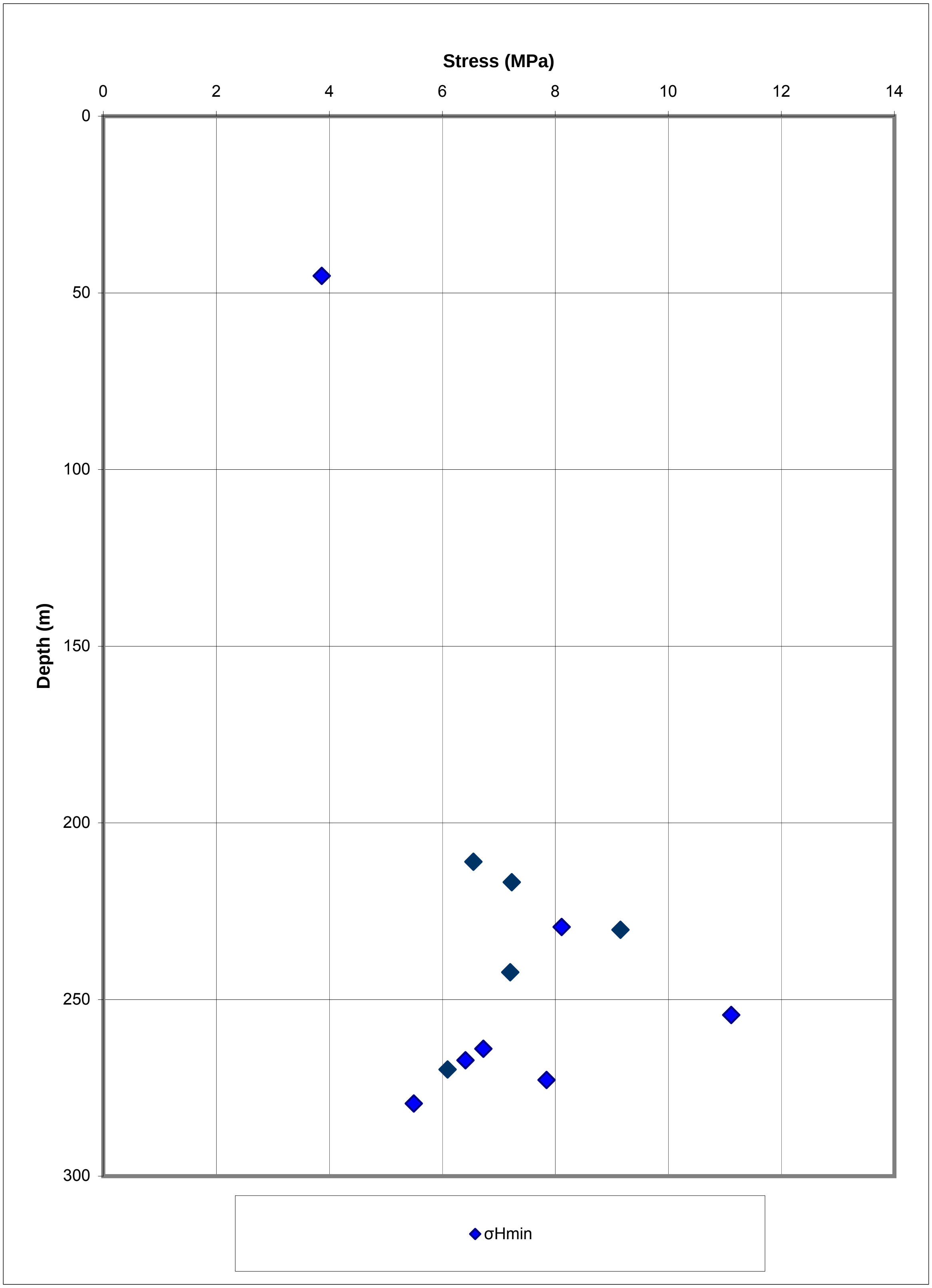


Golder Associates

Project No. 06-1119-010
Date January 2007

JACKING PRESSURE v DEPTH
(all data)

FIGURE 11

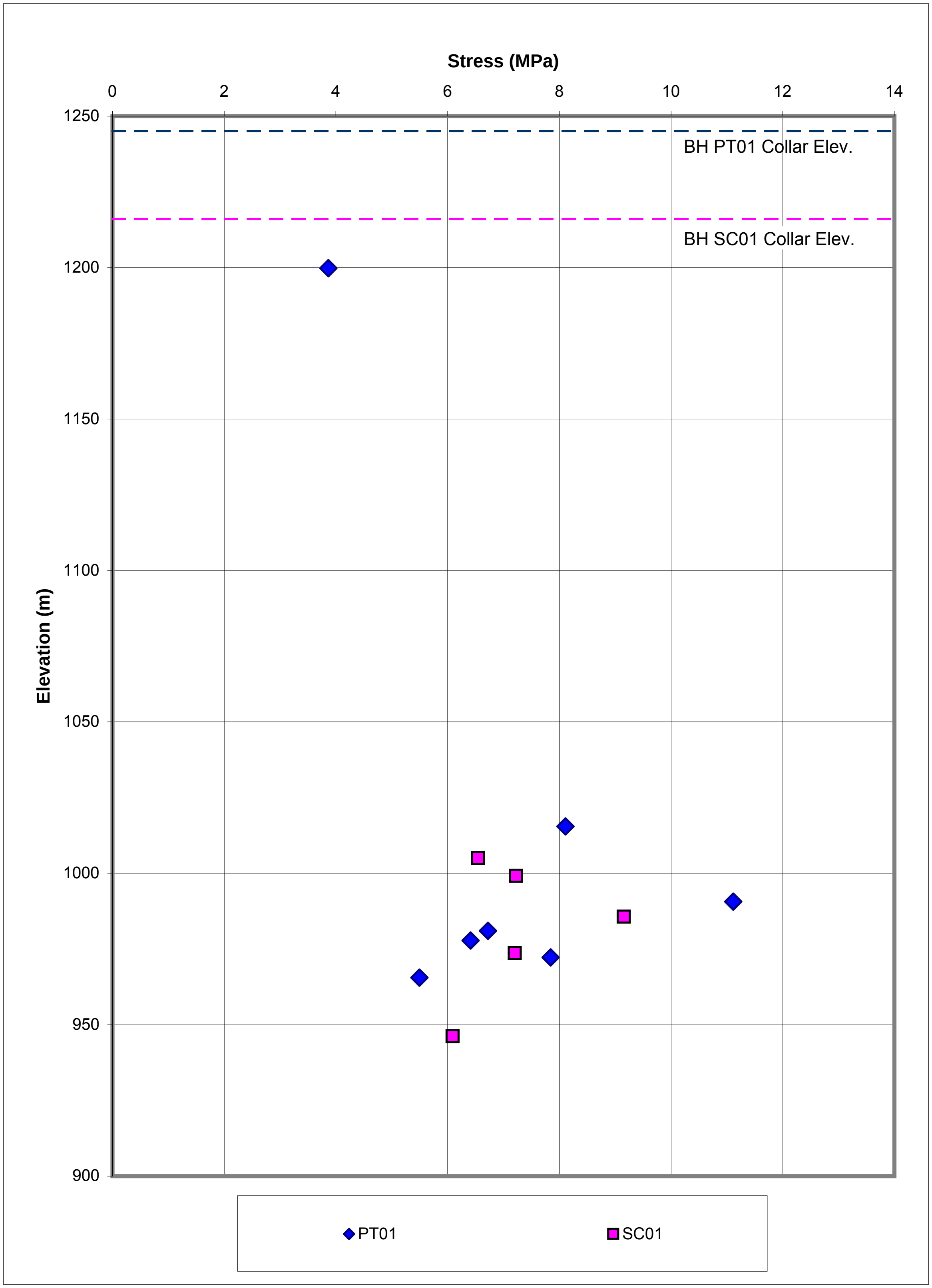


Golder Associates

Project No. 06-1119-010
Date January 2007

JACKING PRESSURE v ELEVATION
(all data)

FIGURE 12



Golder Associates

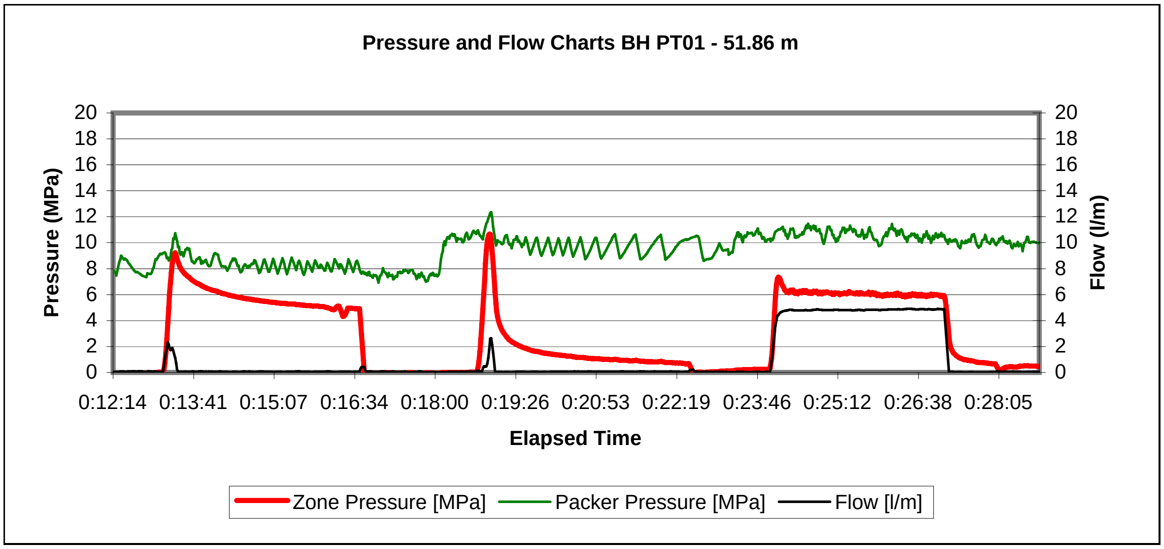
Project No. 06-1119-010
Date January 2007

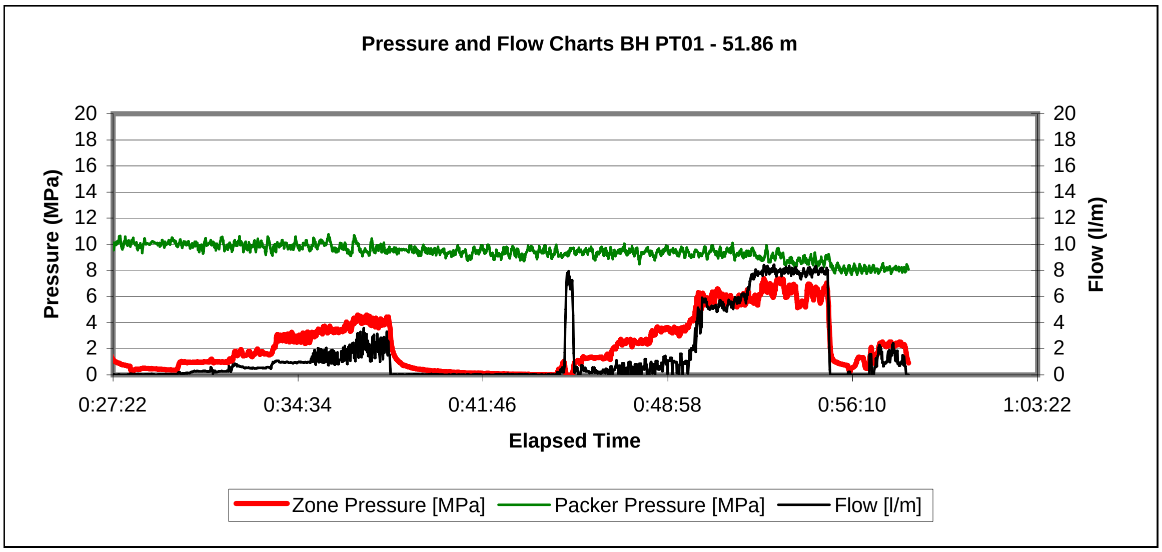
APPENDIX A

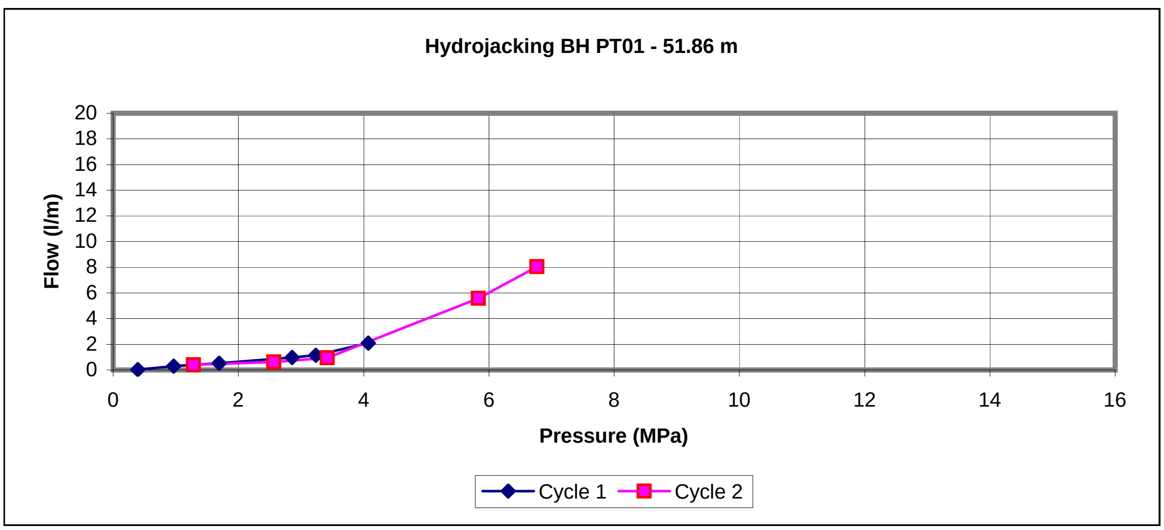
PLOTS OF HYDRAULIC FRACTURING TESTS

HYDROFRACTURE TEST BH PT01 - 51.86 m

FIGURE A.1





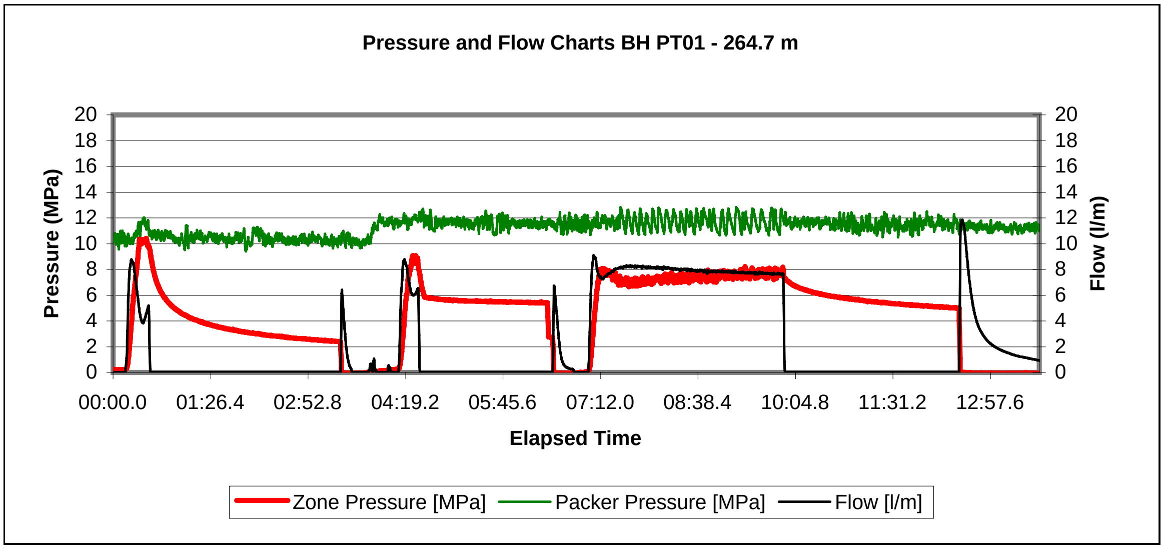


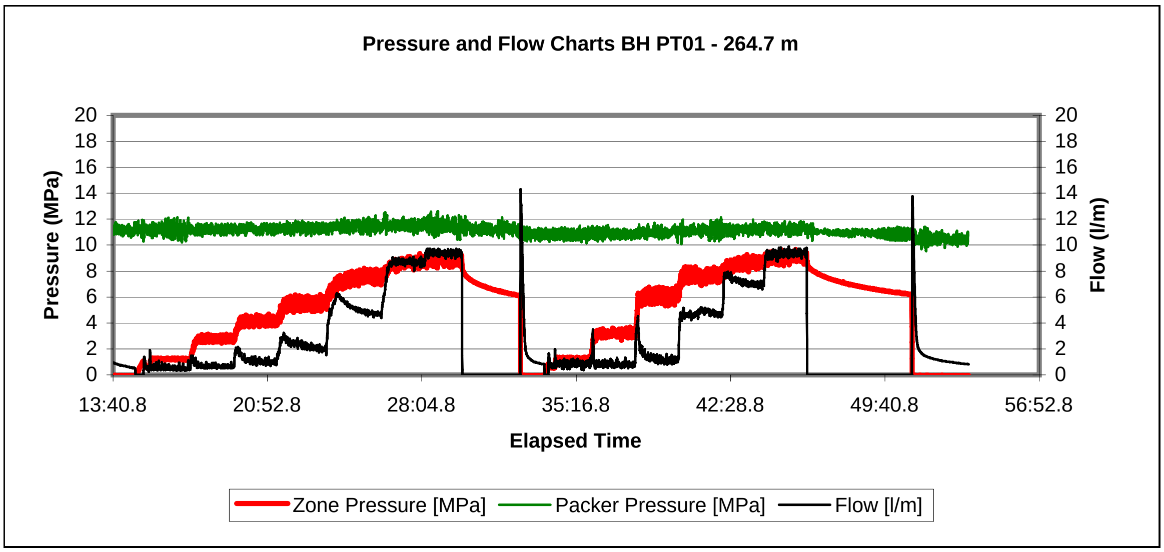
Golder Associates

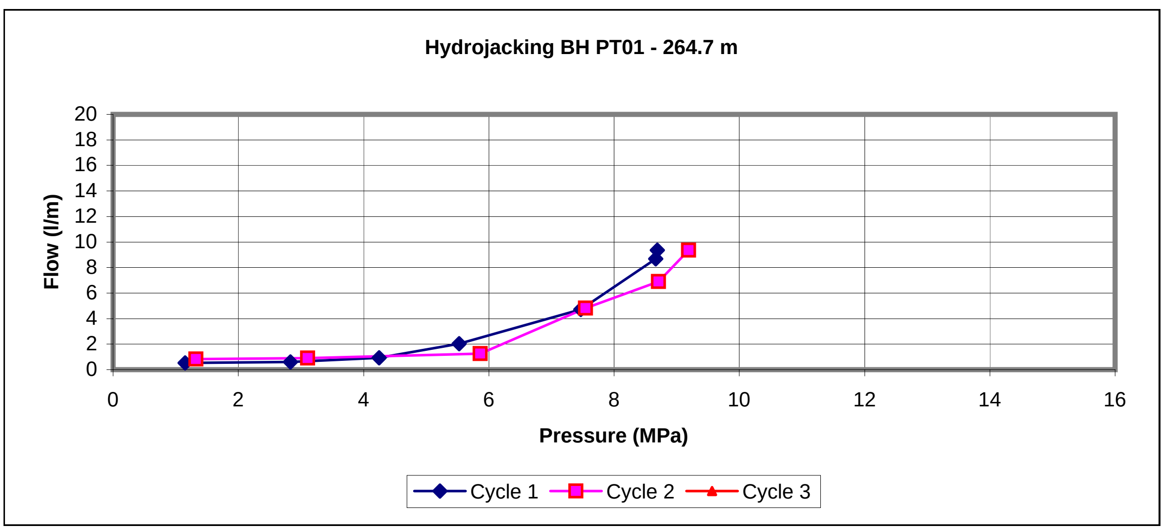
Project No. 06-1119-010
Date January 2007

HYDROFRACTURE TEST BH PT01 - 264.7 m

FIGURE A.2







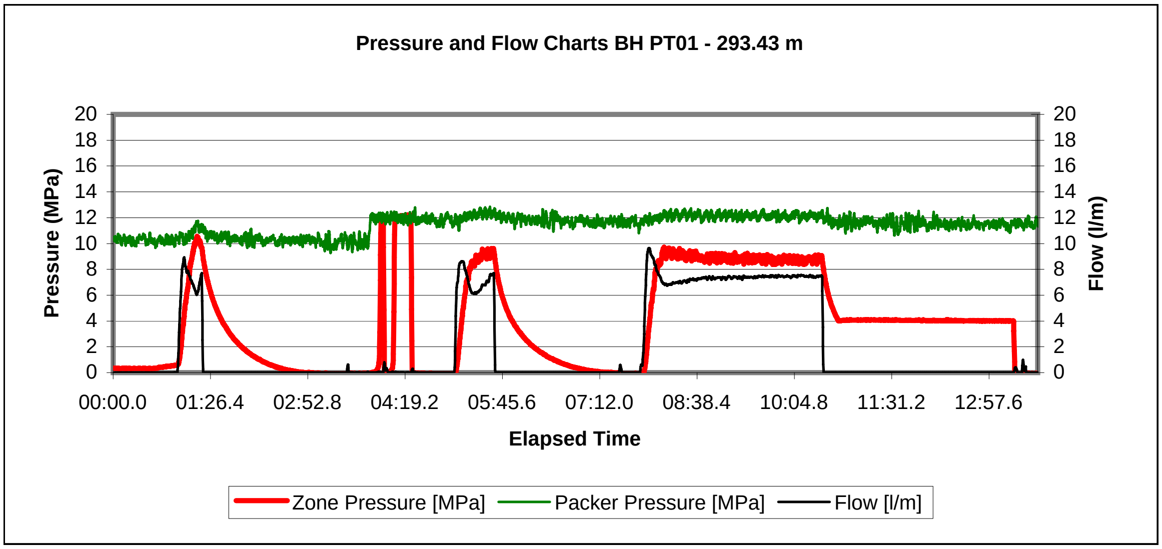
Golder Associates

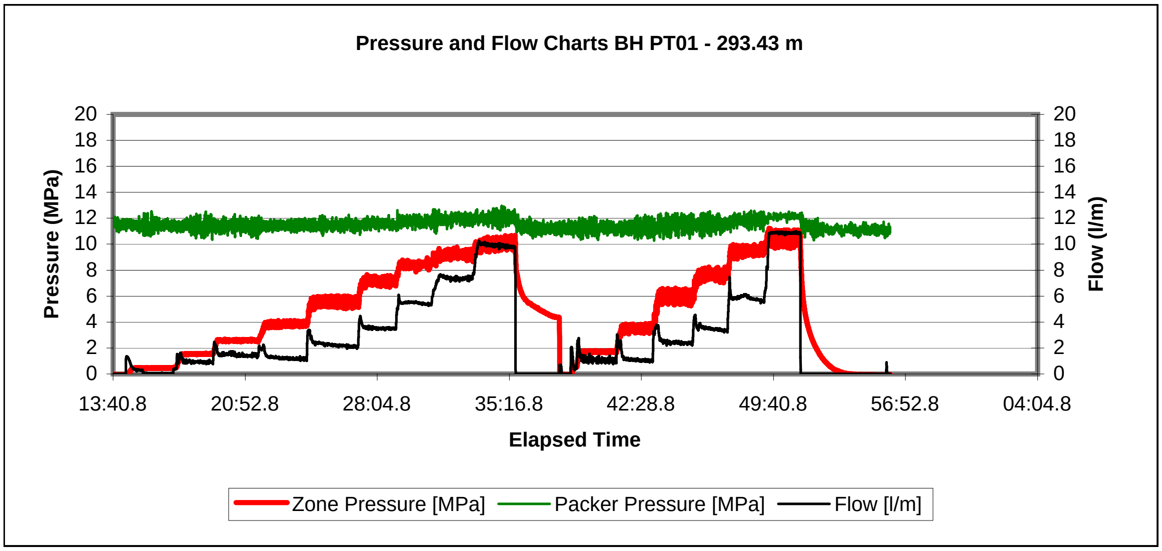
Project No. 06-1119-010

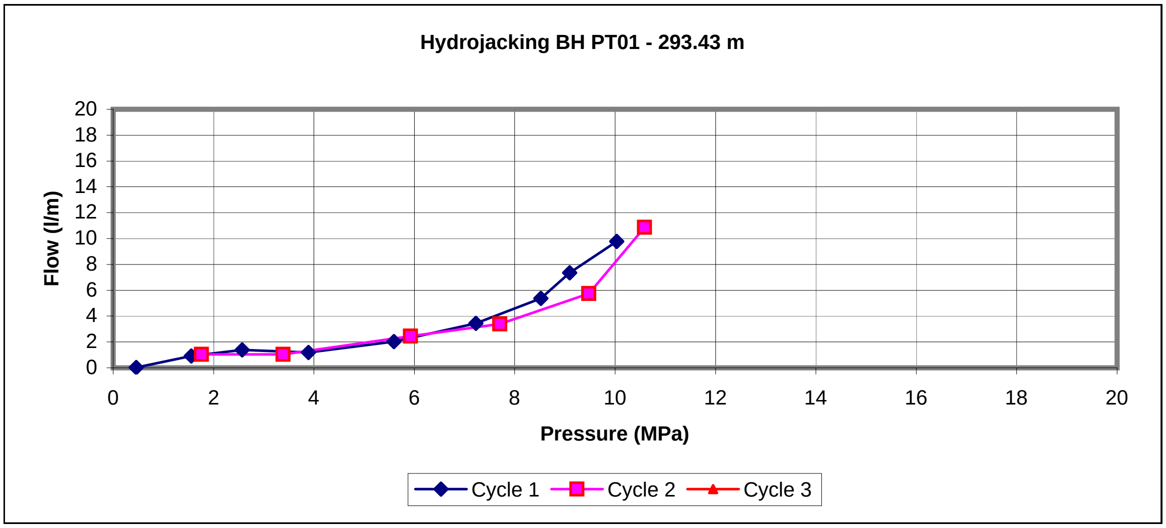
Date January 2007

HYDROFRACTURE TEST BH PT01 - 293.43 m

FIGURE A.3







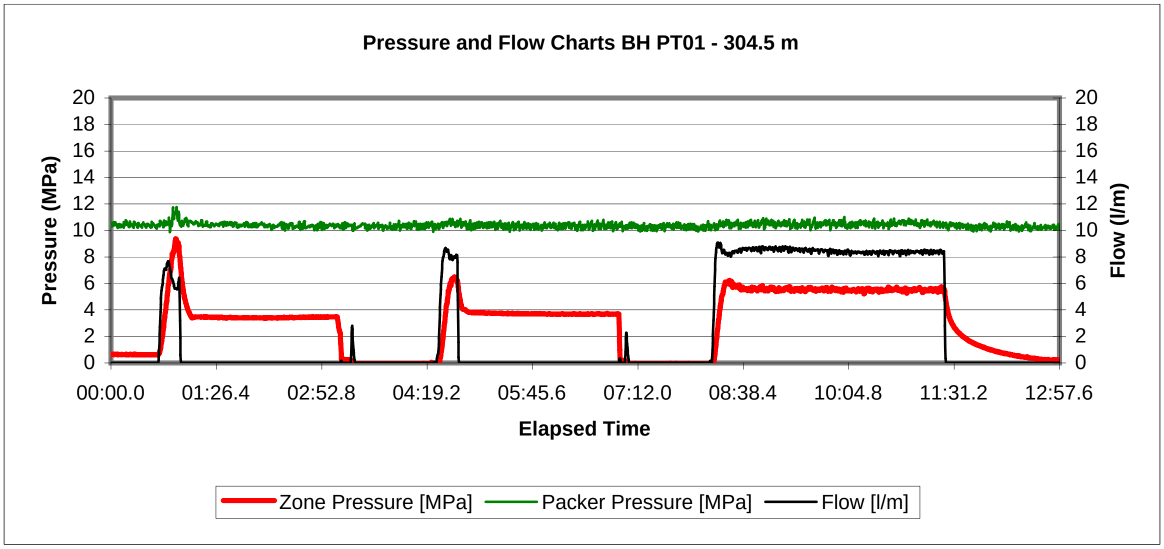
Project No. 06-1119-010

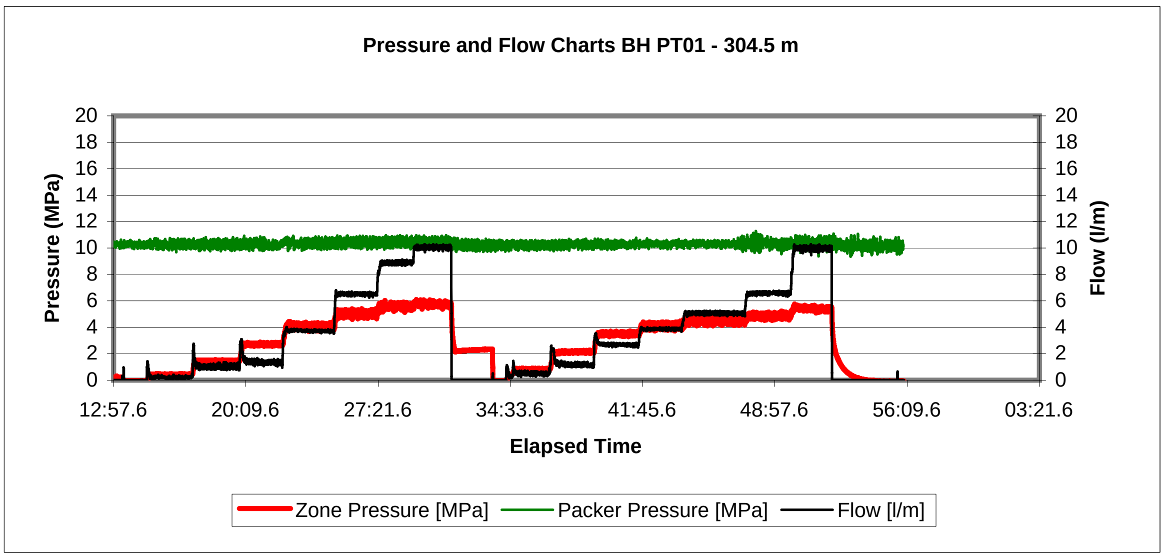
Golder Associates

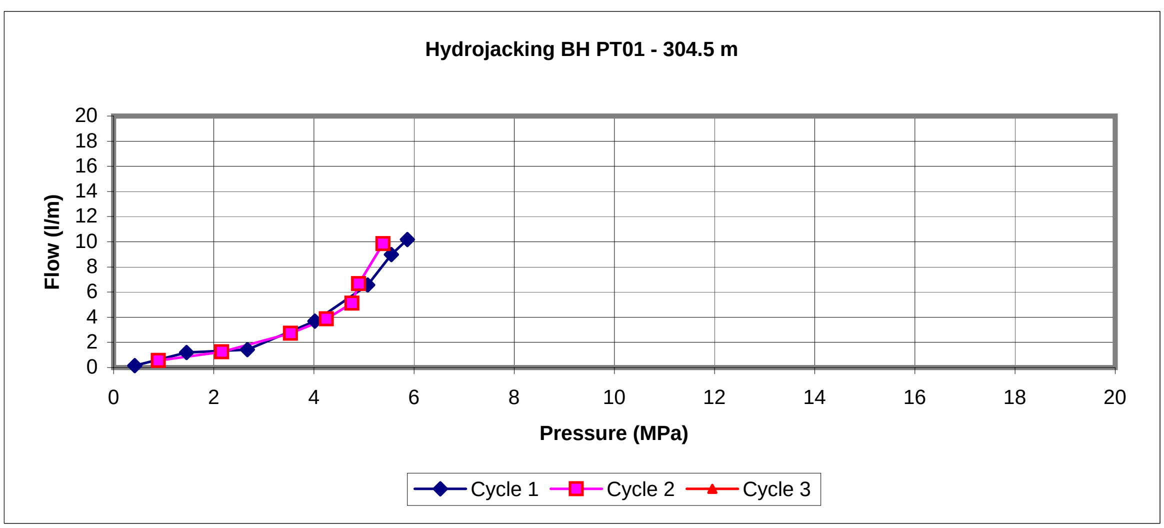
Date January 2007

HYDROFRACTURE TEST BH PT01 - 304.5 m

FIGURE A.4



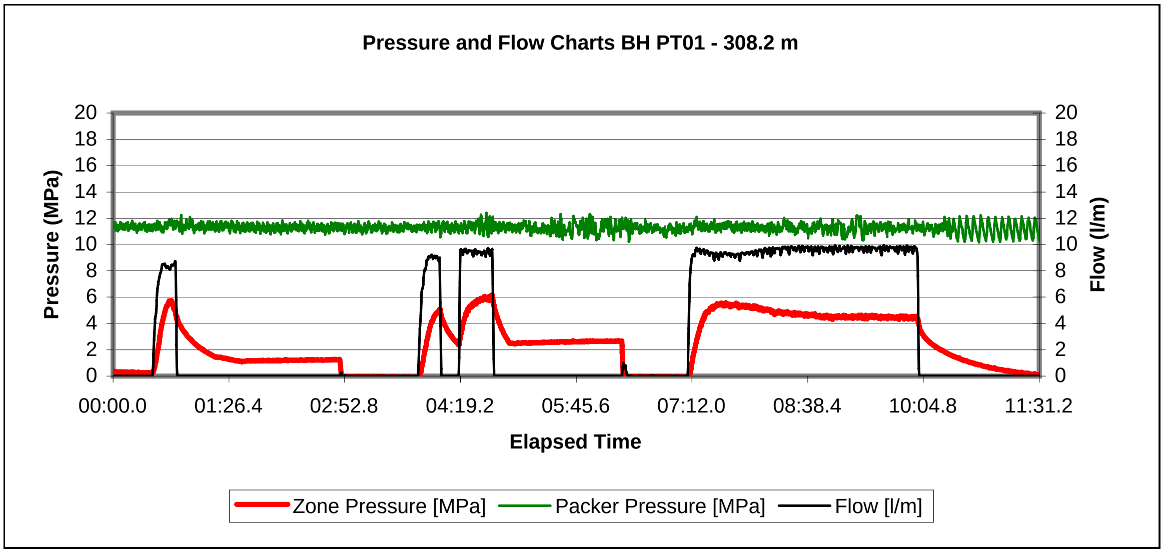


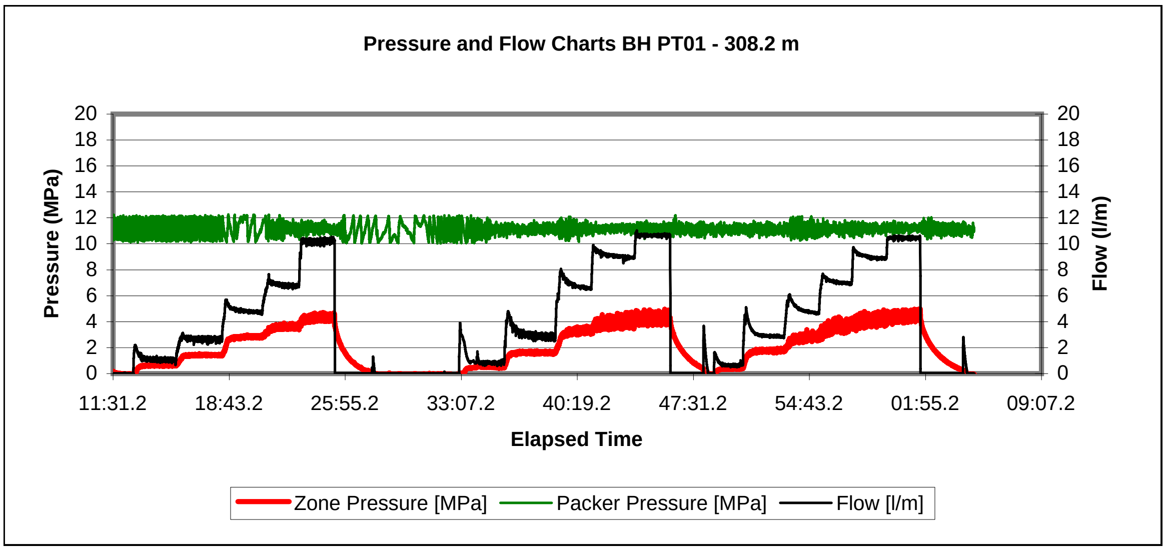


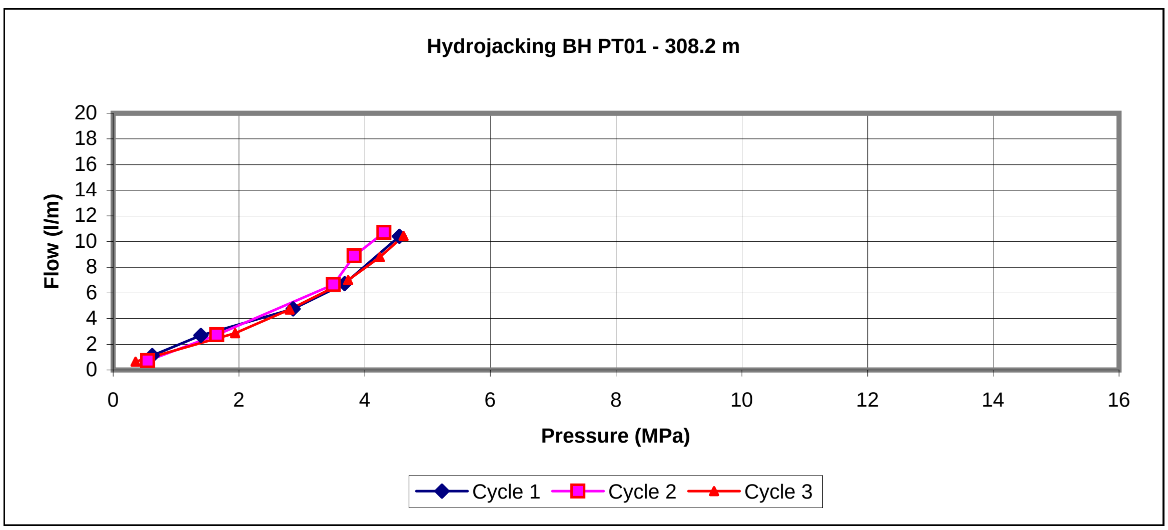
Golder Associates

Project No. 06-1119-010
Date January 2007

HYDROFRACTURE TEST BH PT01 - 308.2 m	FIGURE A.5



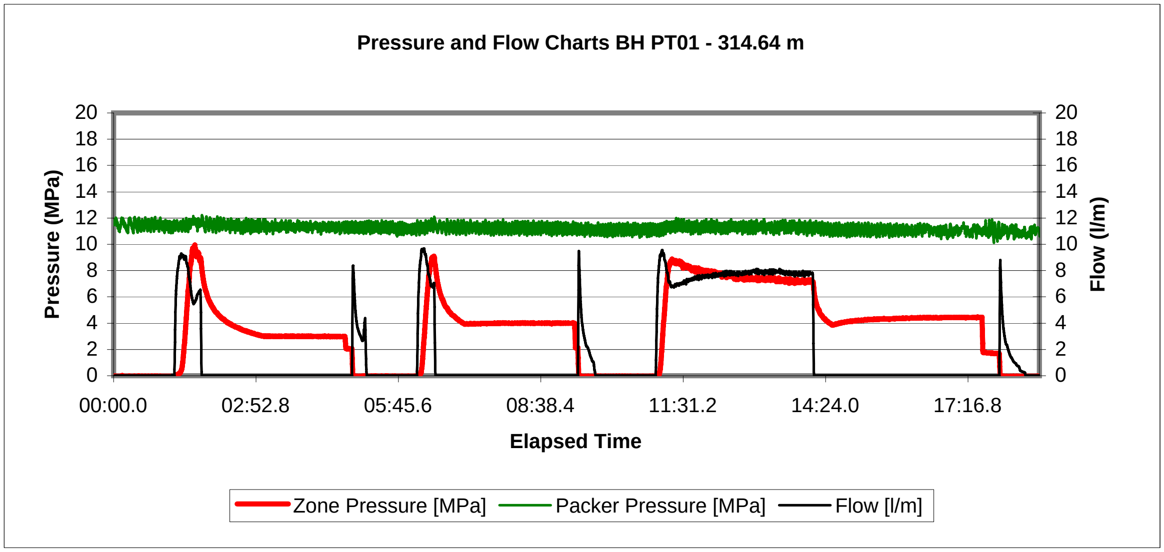


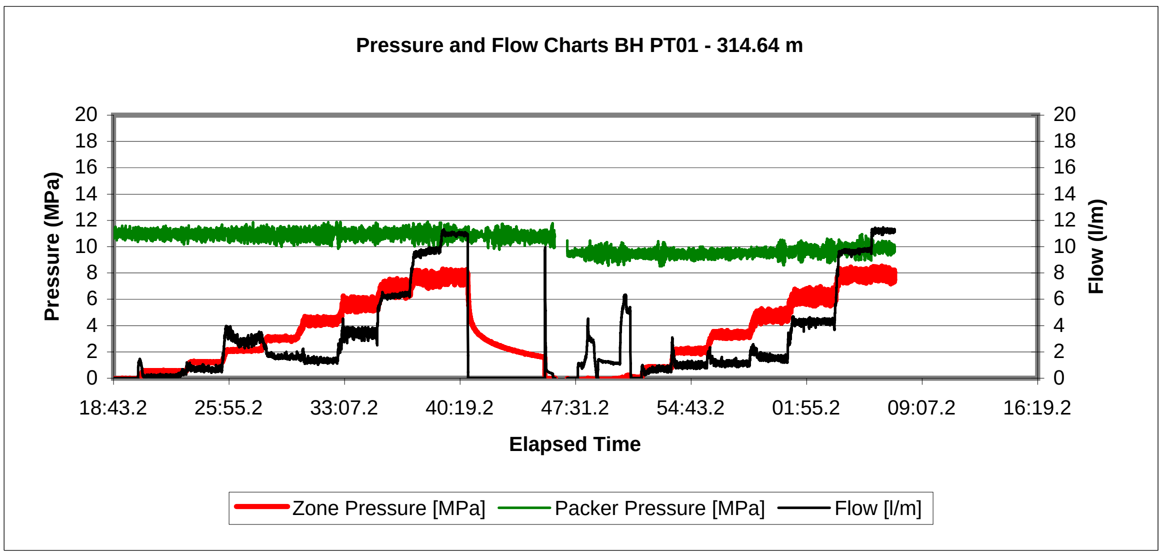


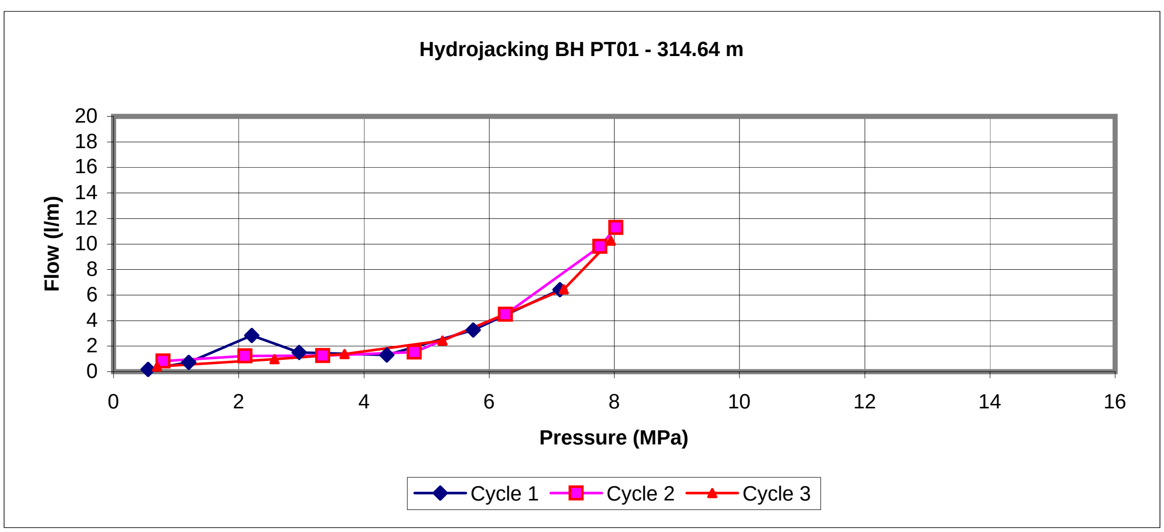
Golder Associates

Project No. 06-1119-010
Date January 2007

HYDROFRACTURE TEST BH PT01 - 314.64 m	FIGURE A.6





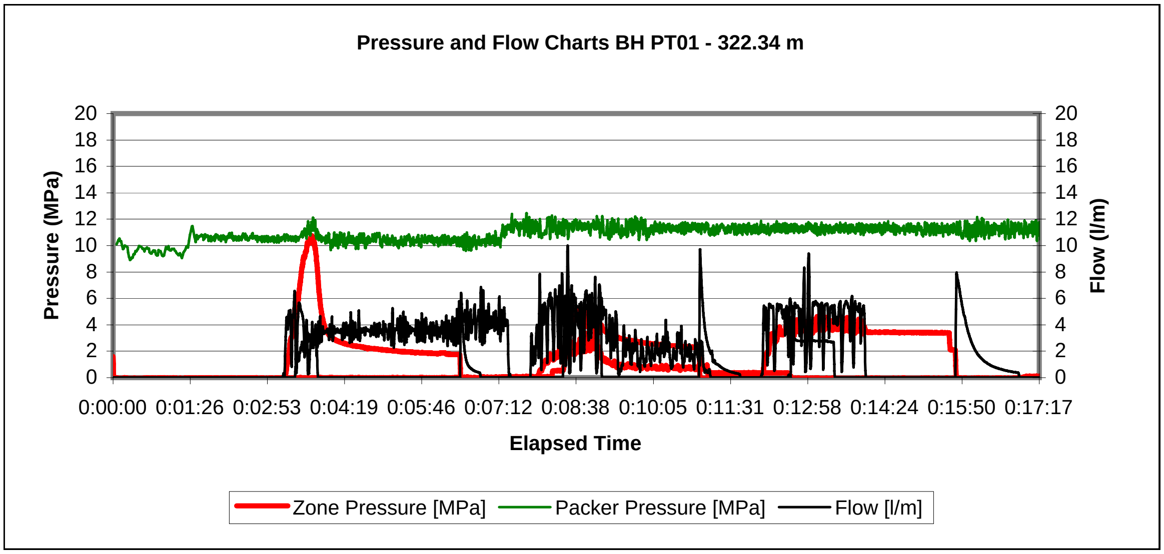


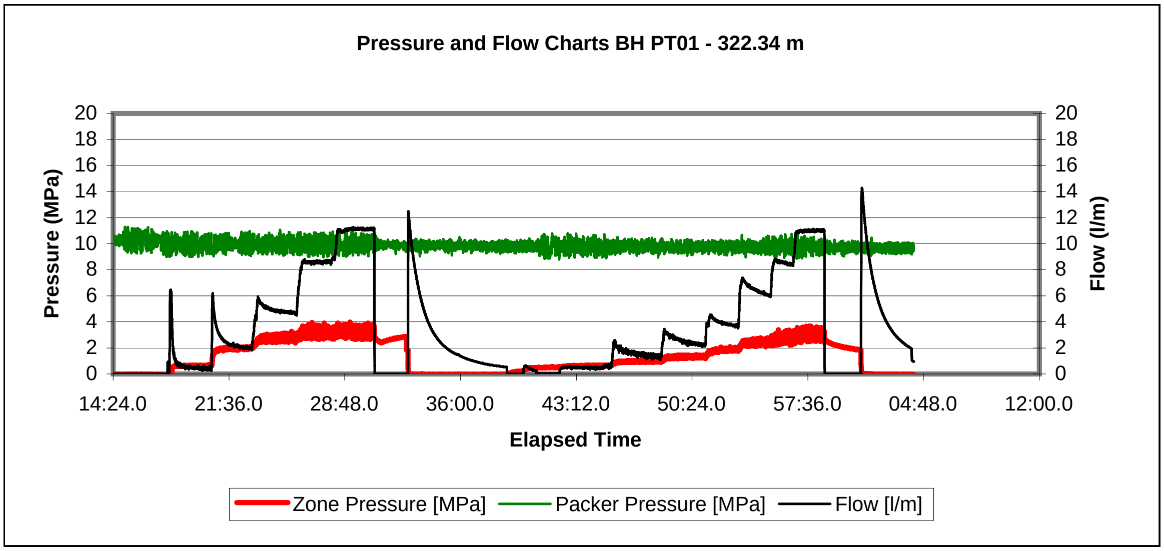
Golder Associates

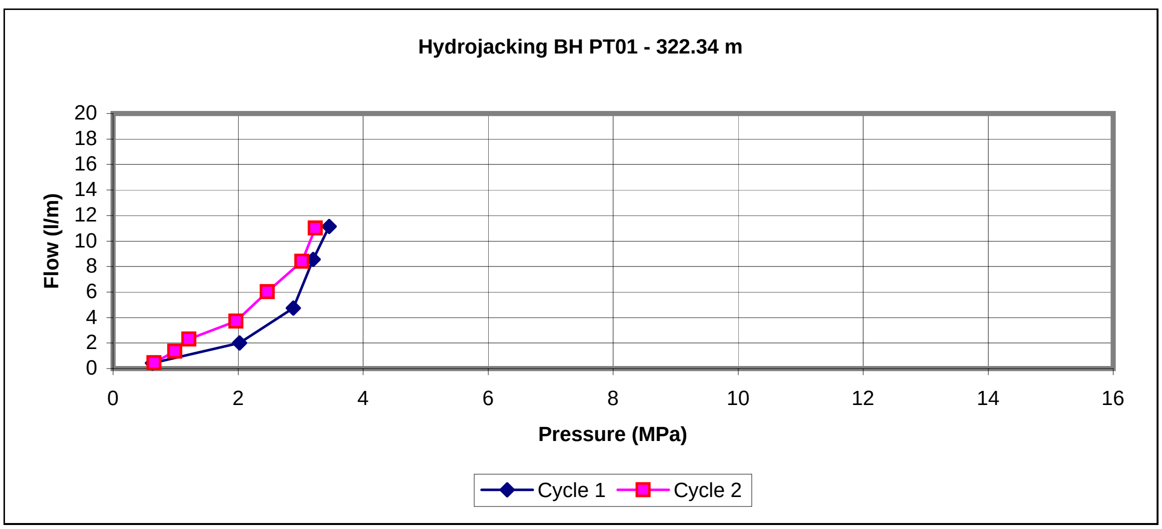
Project No. 06-1119-010
Date January 2007

HYDROFRACTURE TEST BH PT01 - 322.34 m

FIGURE A.7





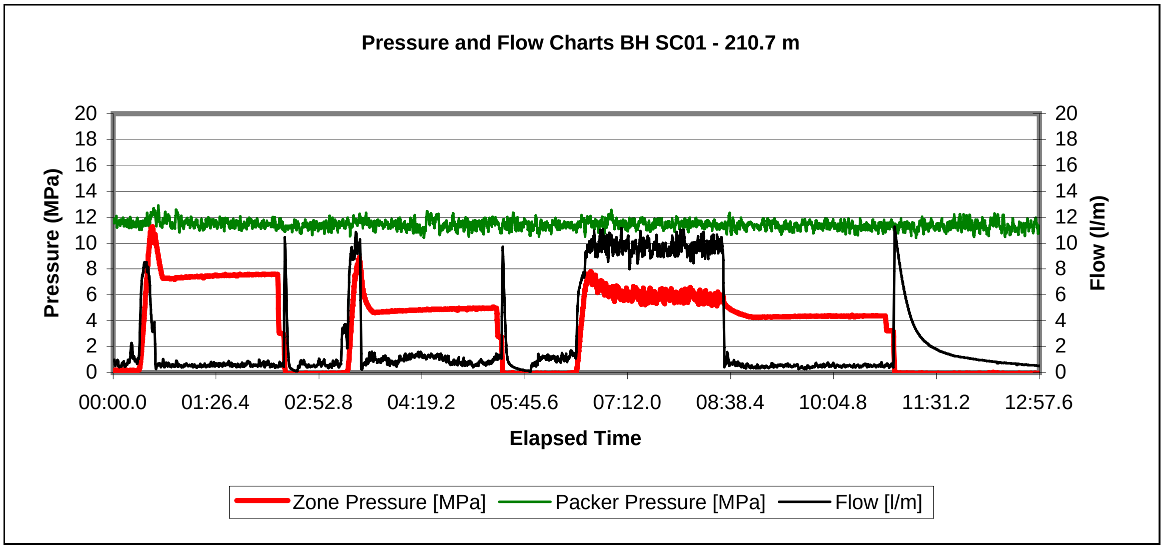


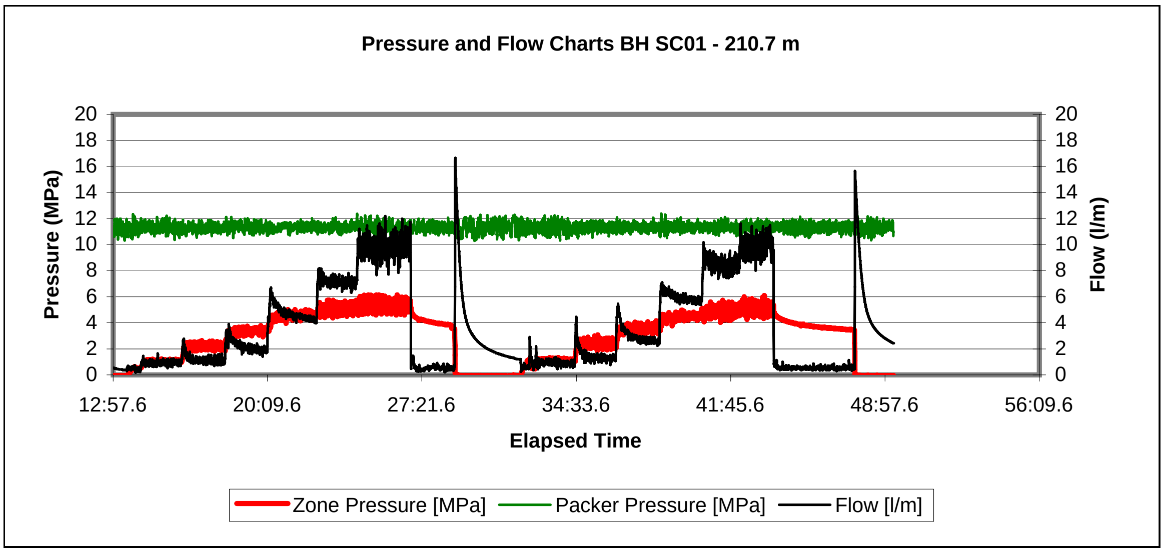
Golder Associates

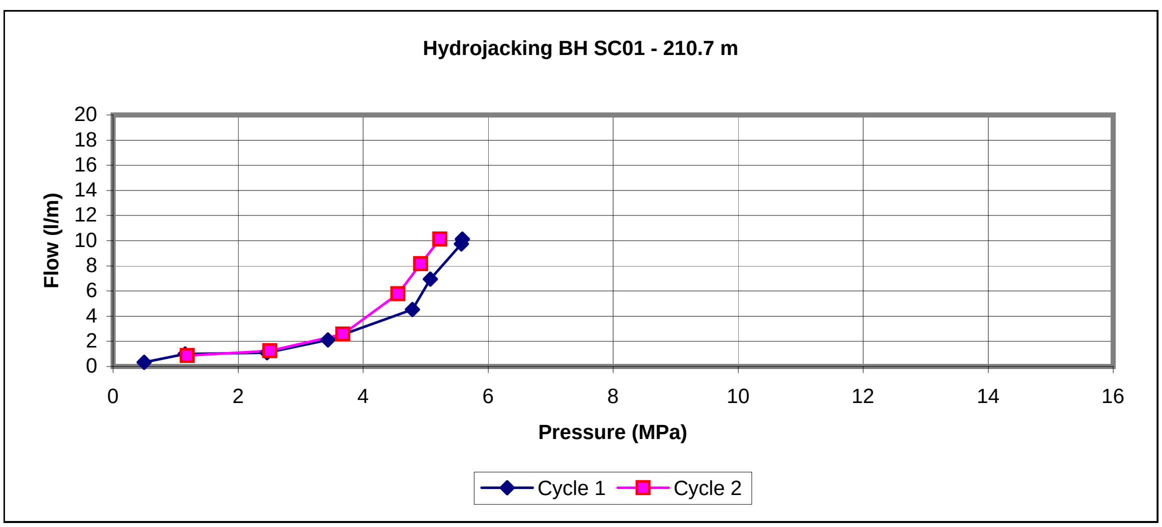
Project No. 06-1119-010

Date January 2007

HYDROFRACTURE TEST BH SC01 - 210.7 m	FIGURE A.8



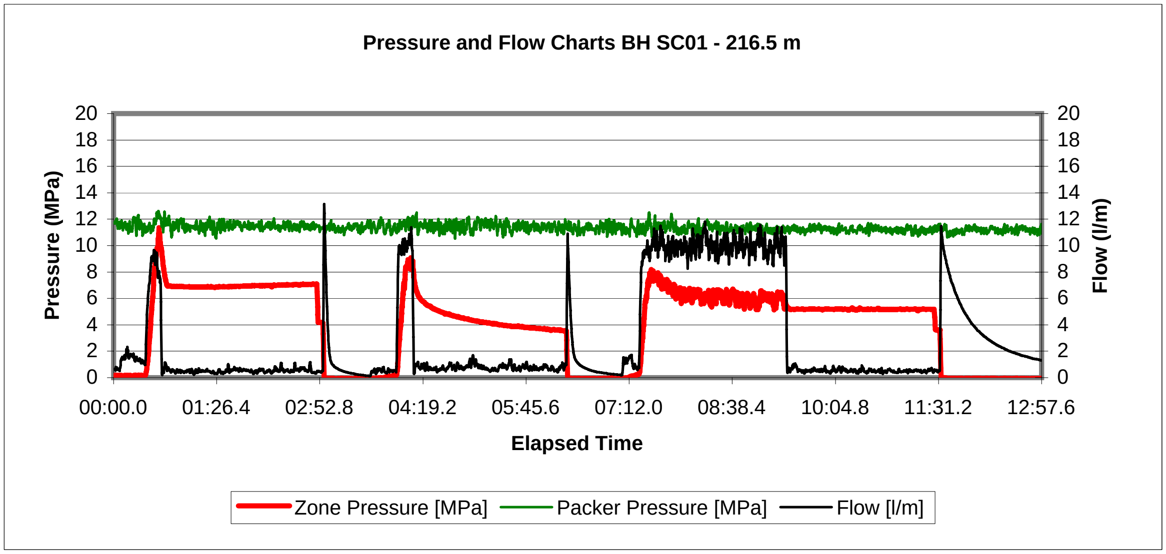


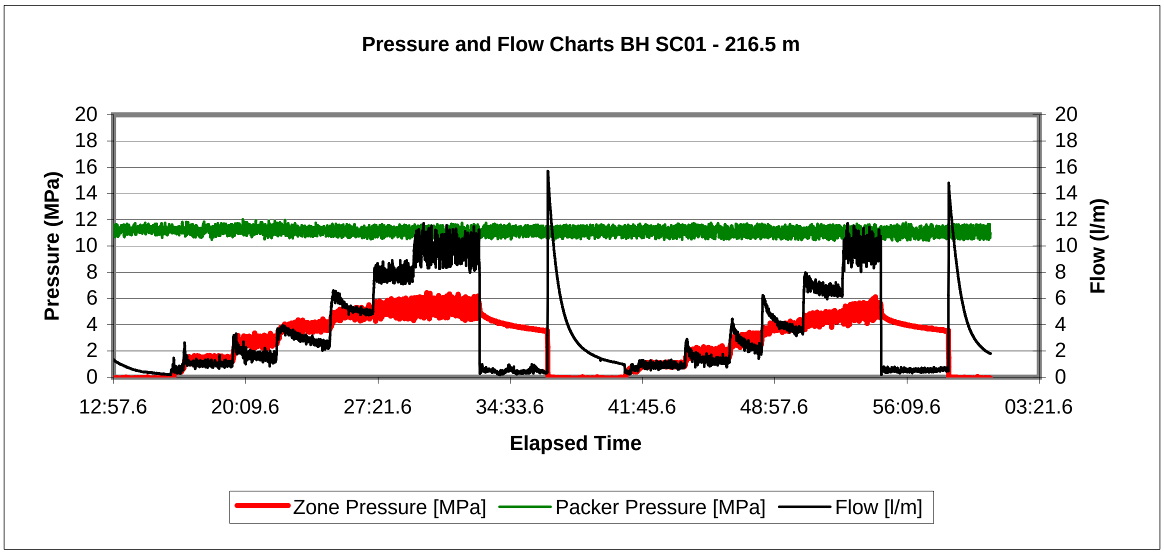


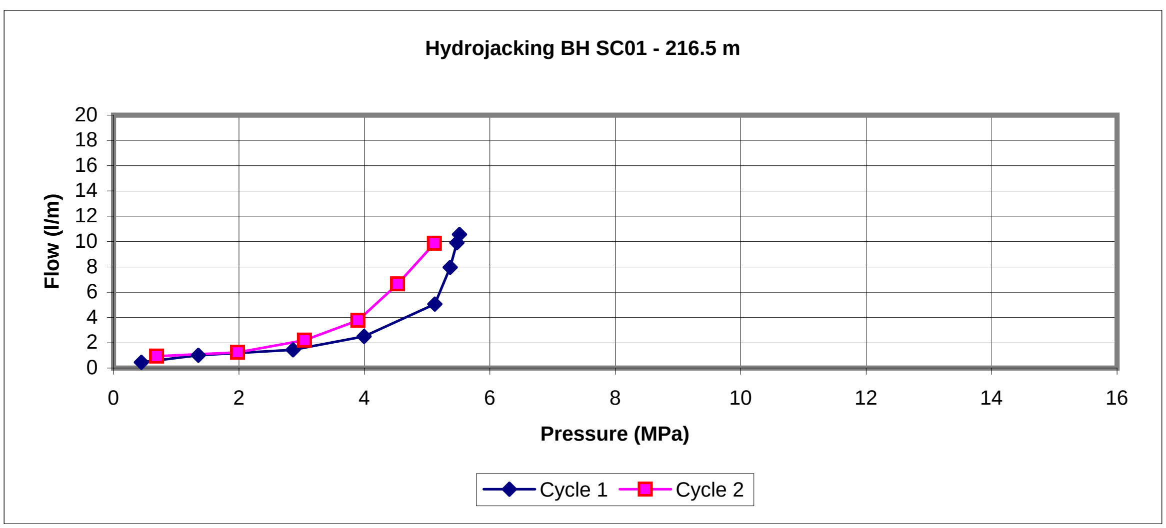
Golder Associates

Project No. 06-1119-010
Date January 2007

HYDROFRACTURE TEST BH SC01 - 216.5 m	FIGURE A.9



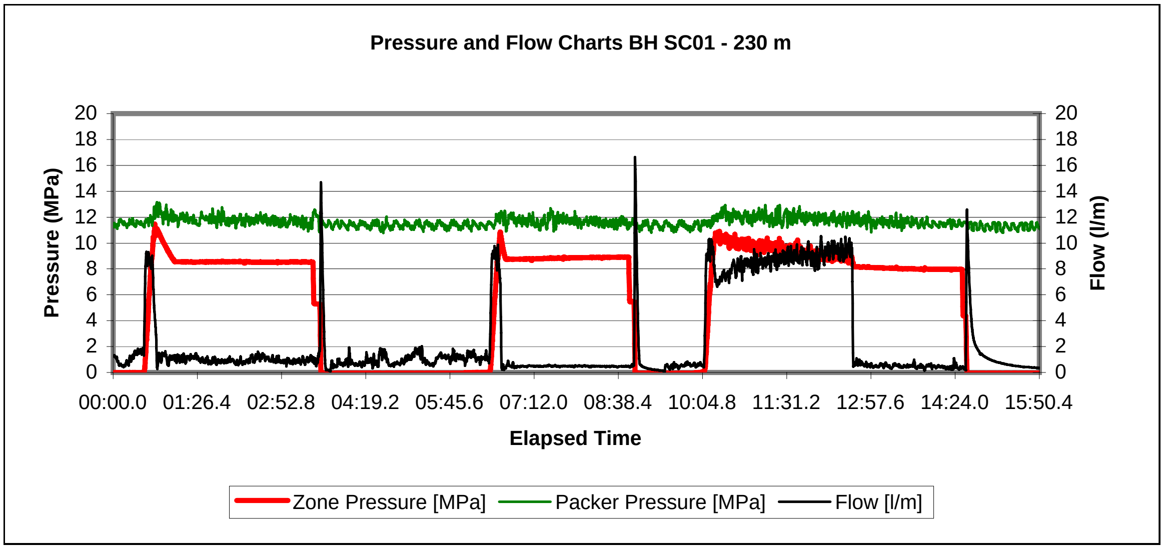


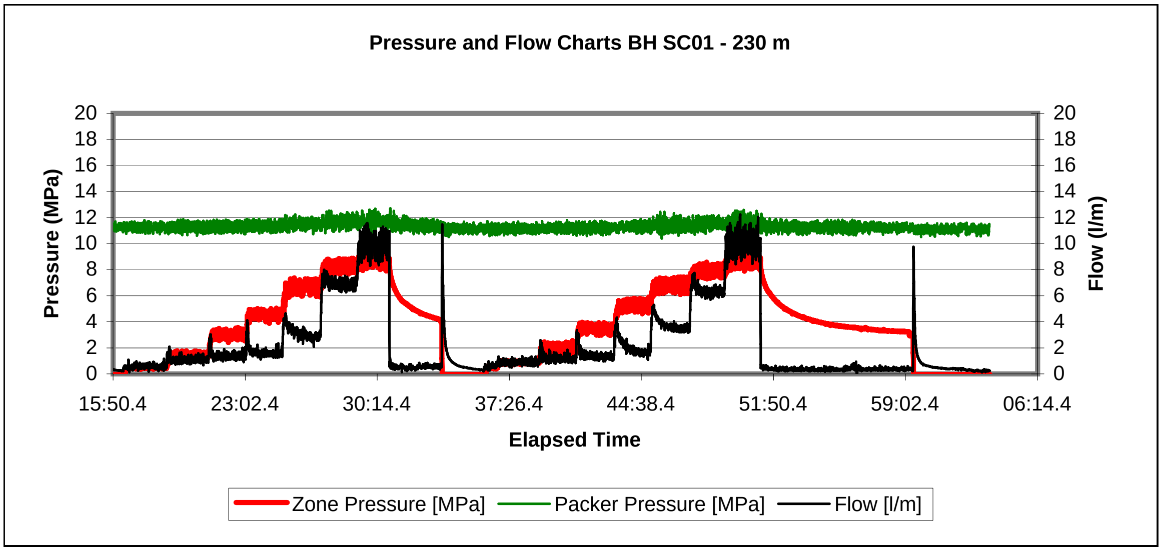


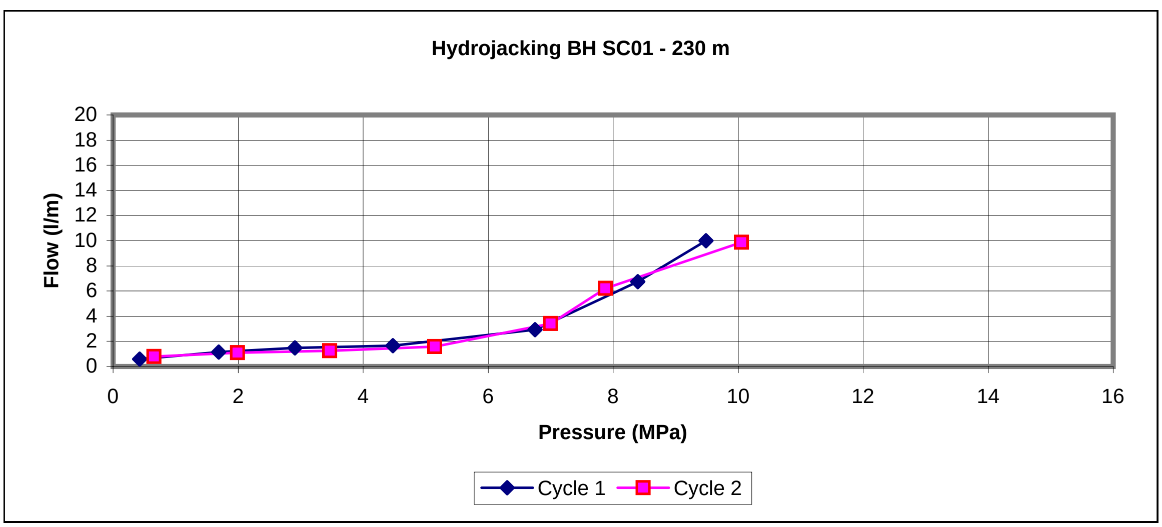
Golder Associates

Project No. 06-1119-010
Date January 2007

HYDROFRACTURE TEST BH SC01 - 230.0 m	FIGURE A.10





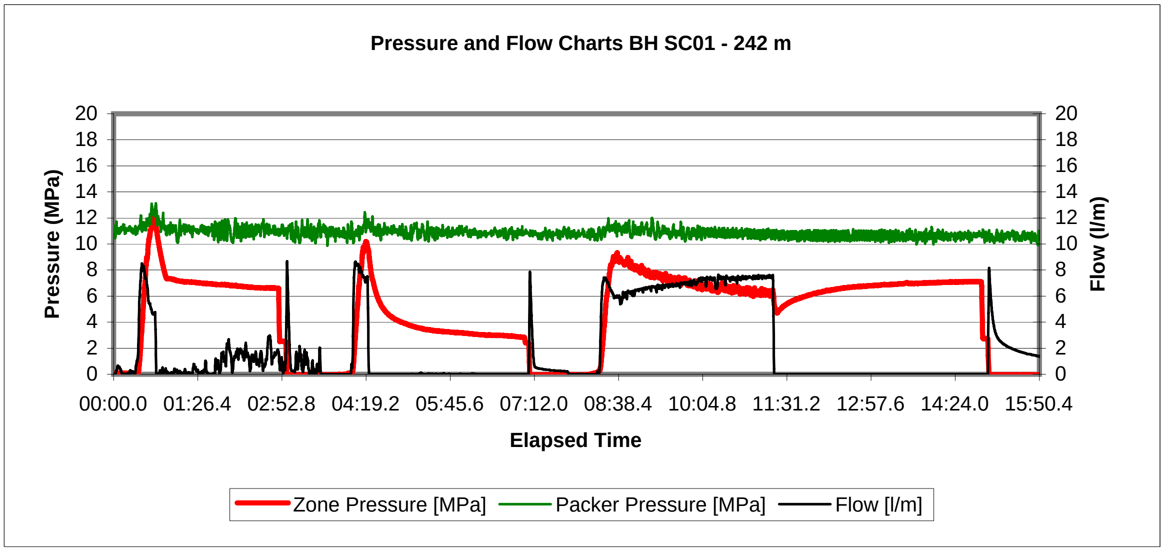


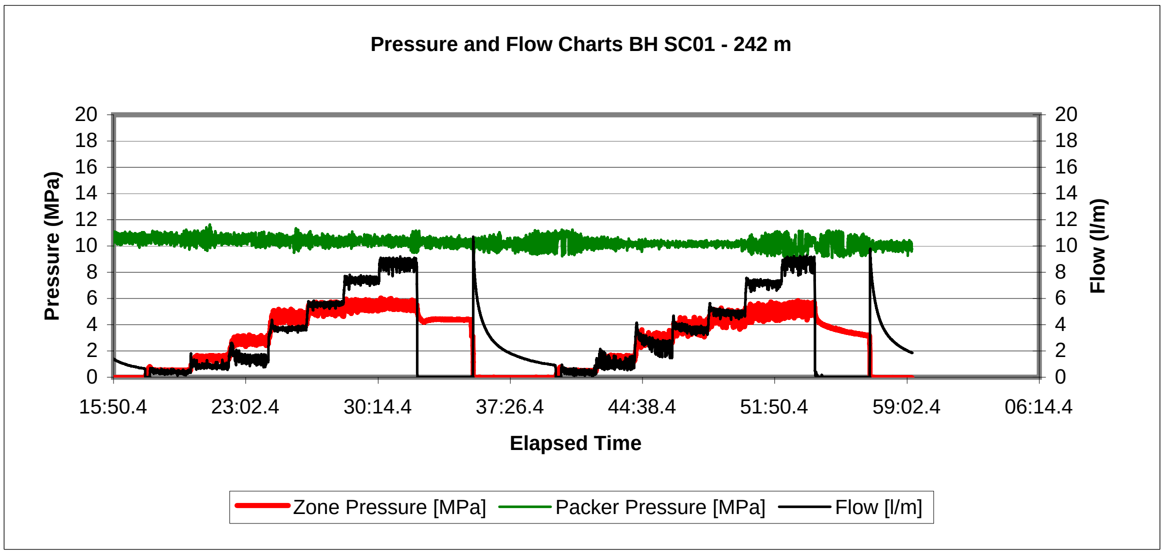
Golder Associates

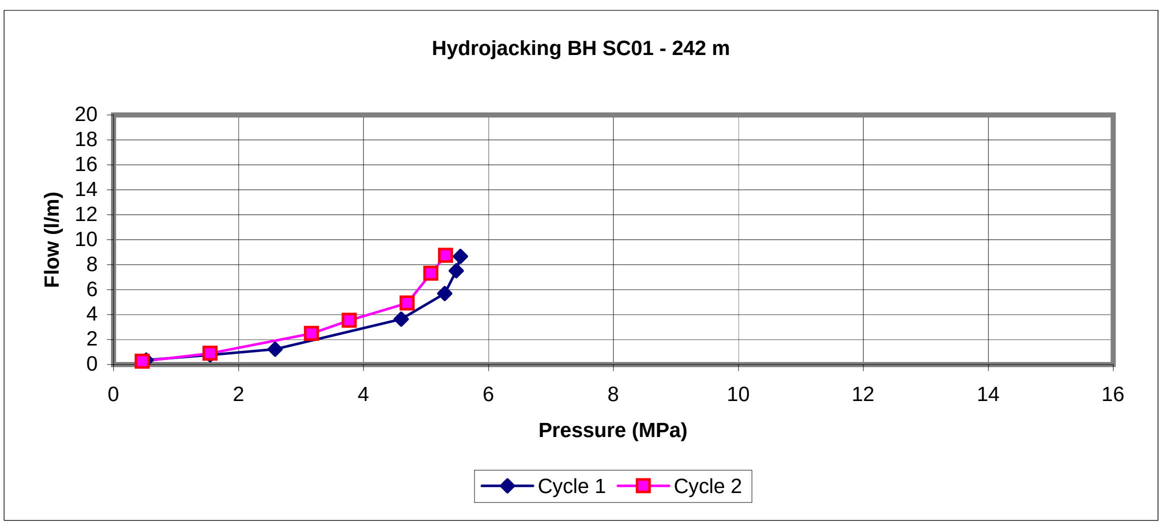
Project No. 06-1119-010
Date January 2007

HYDROFRACTURE TEST BH SC01 - 242.04 m

FIGURE A.11



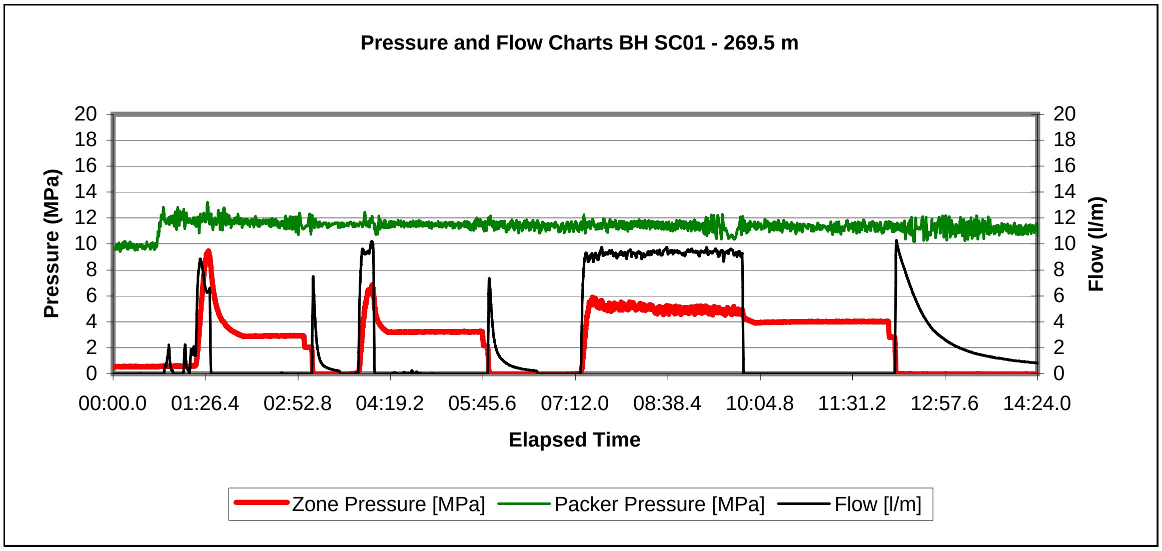


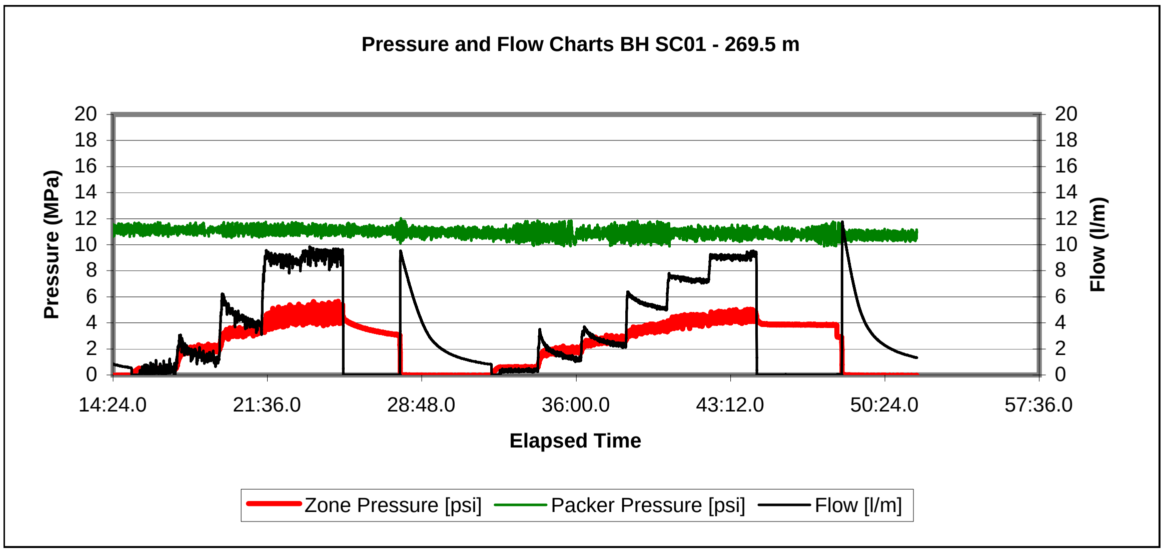


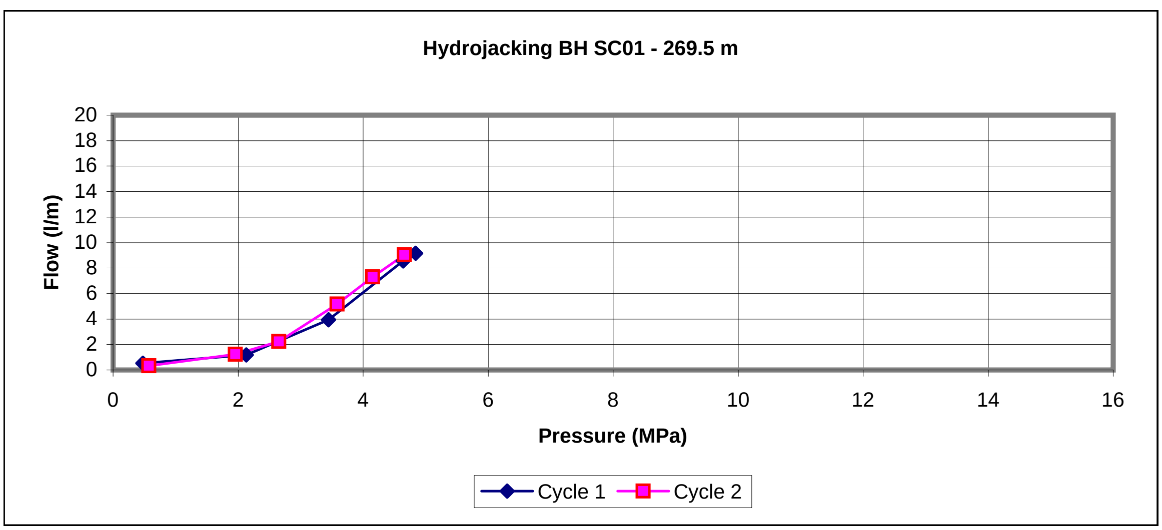
Golder Associates

Project No. 06-1119-010
Date January 2007

HYDROFRACTURE TEST BH SC01 - 269.5 m	FIGURE A.12







Golder Associates

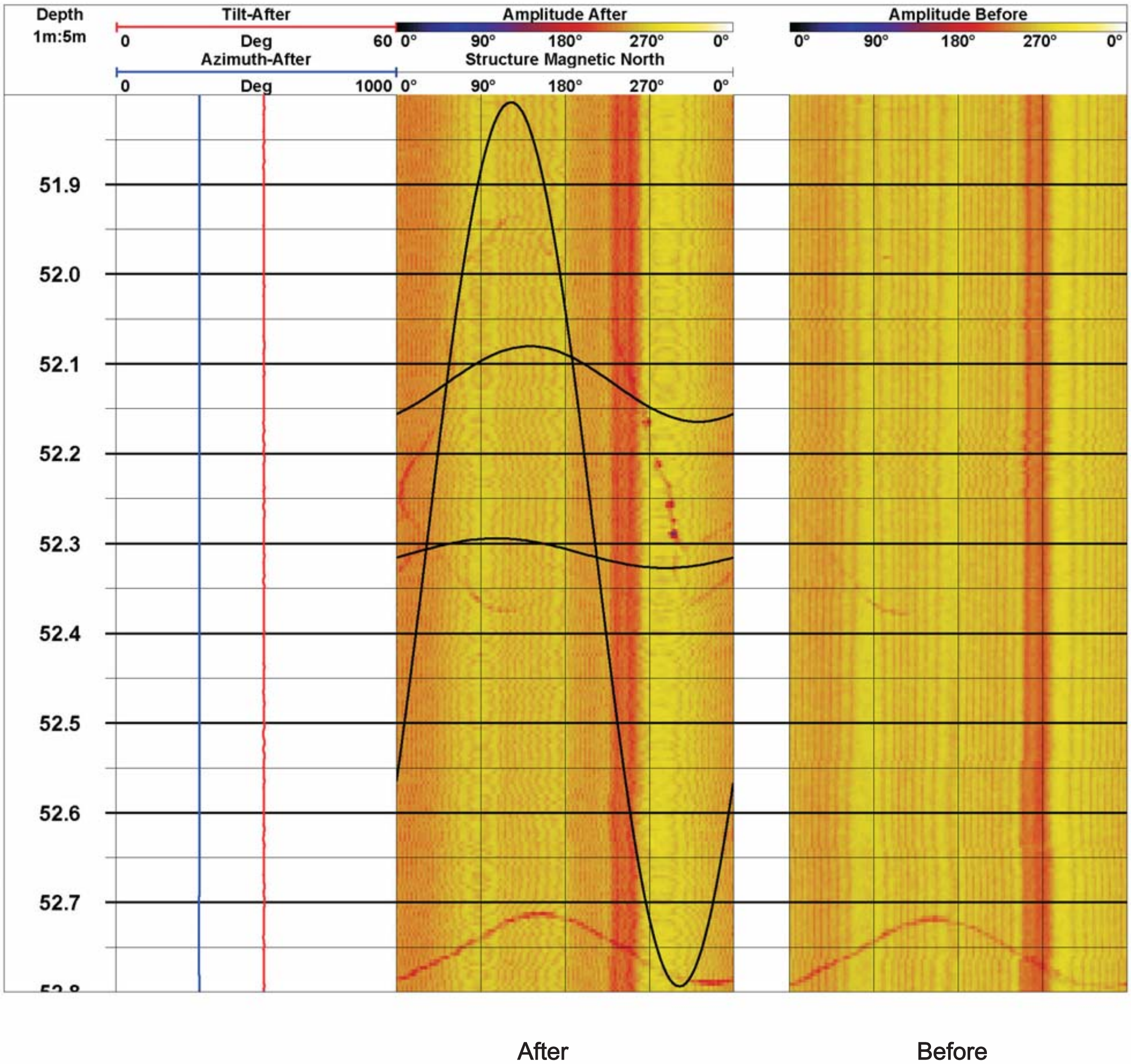
Project No. 06-1119-010
Date January 2007

APPENDIX B

FRACTURE ORIENTATION TRACES

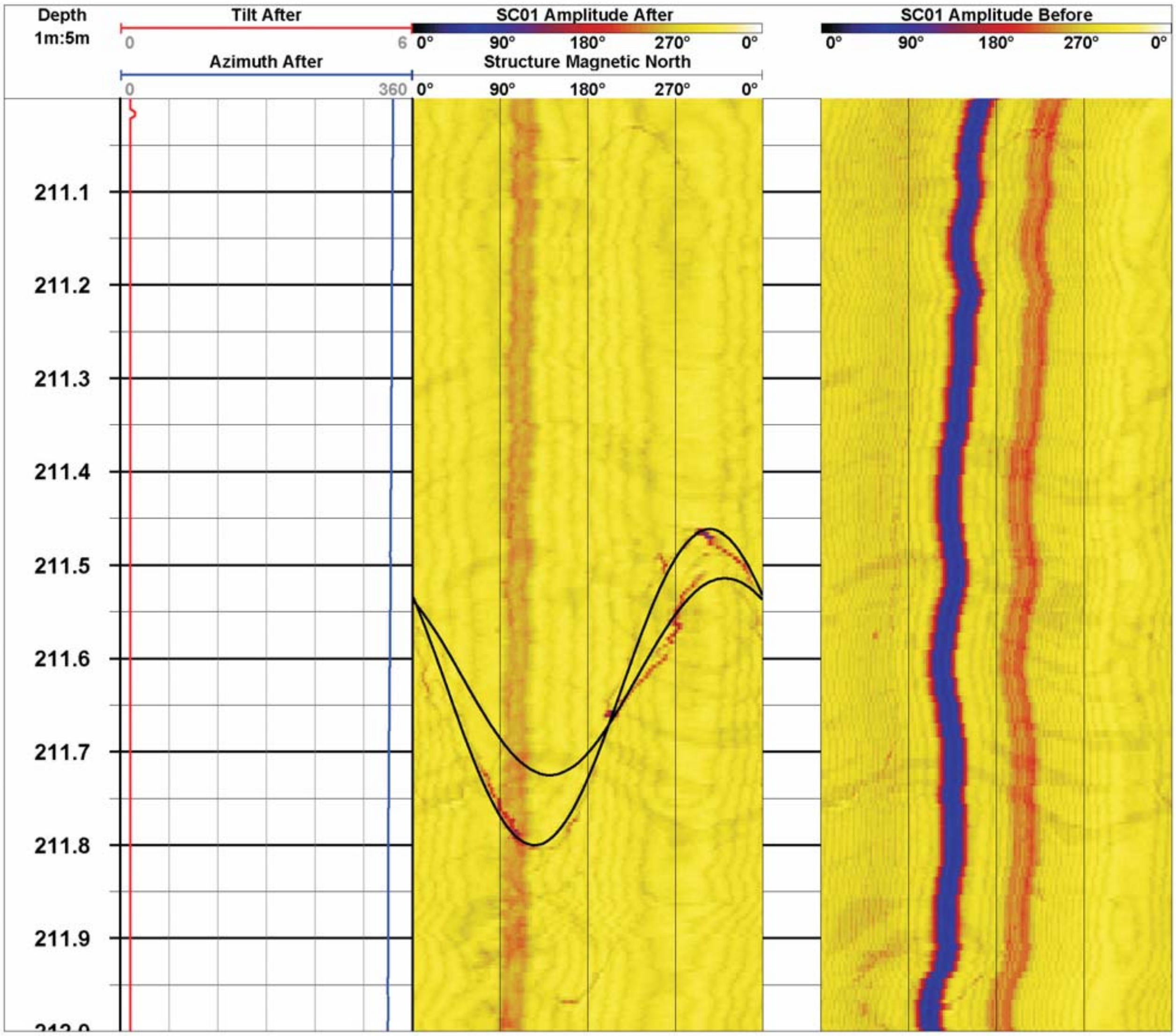
FRACTURE ORIENTATION BH PT01 - 51

FIGURE B.1



FRACTURE ORIENTATION BH SC01 - 210

FIGURE B.2

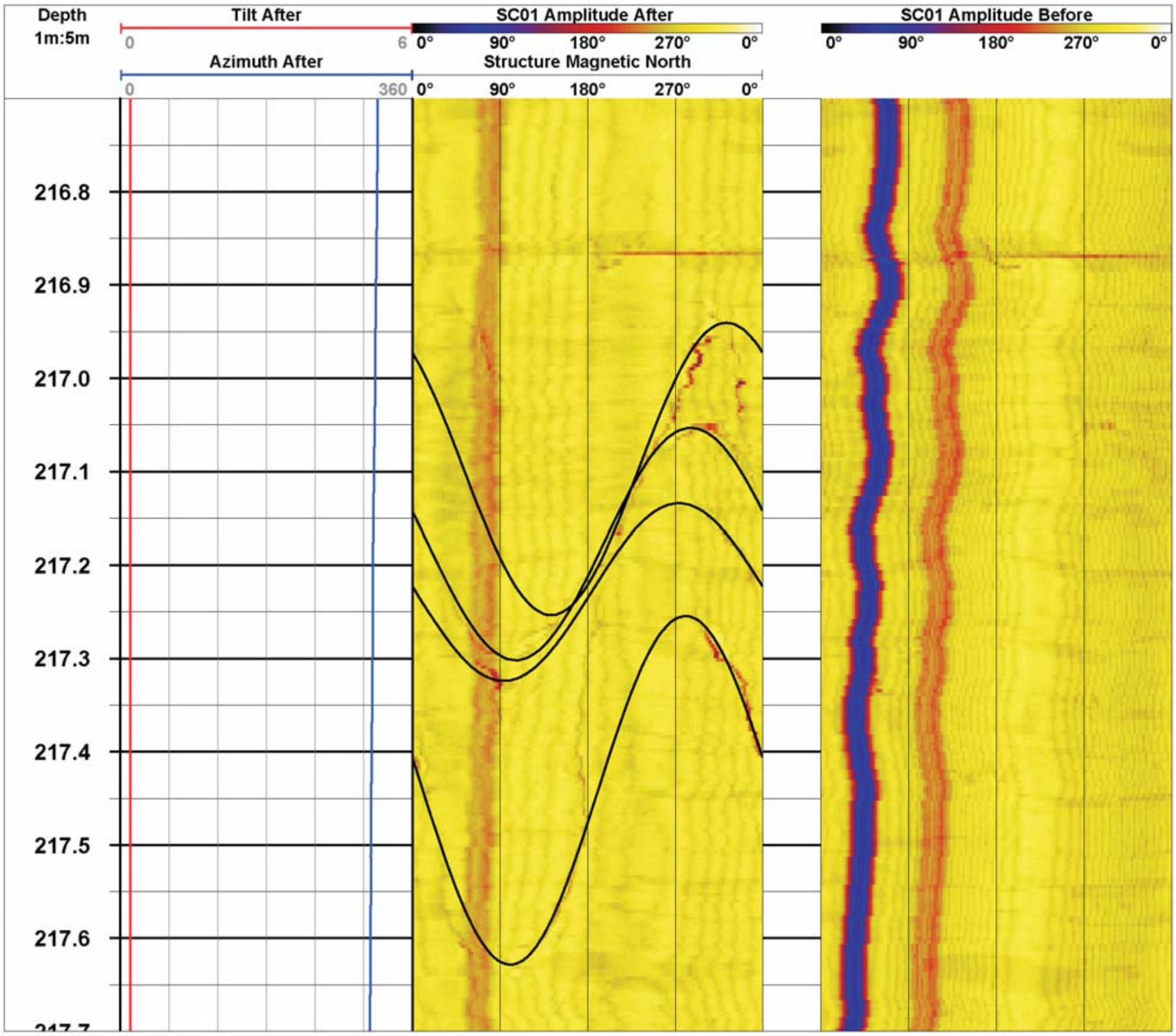


After

Before

FRACTURE ORIENTATION BH SC01 - 216

FIGURE B.3

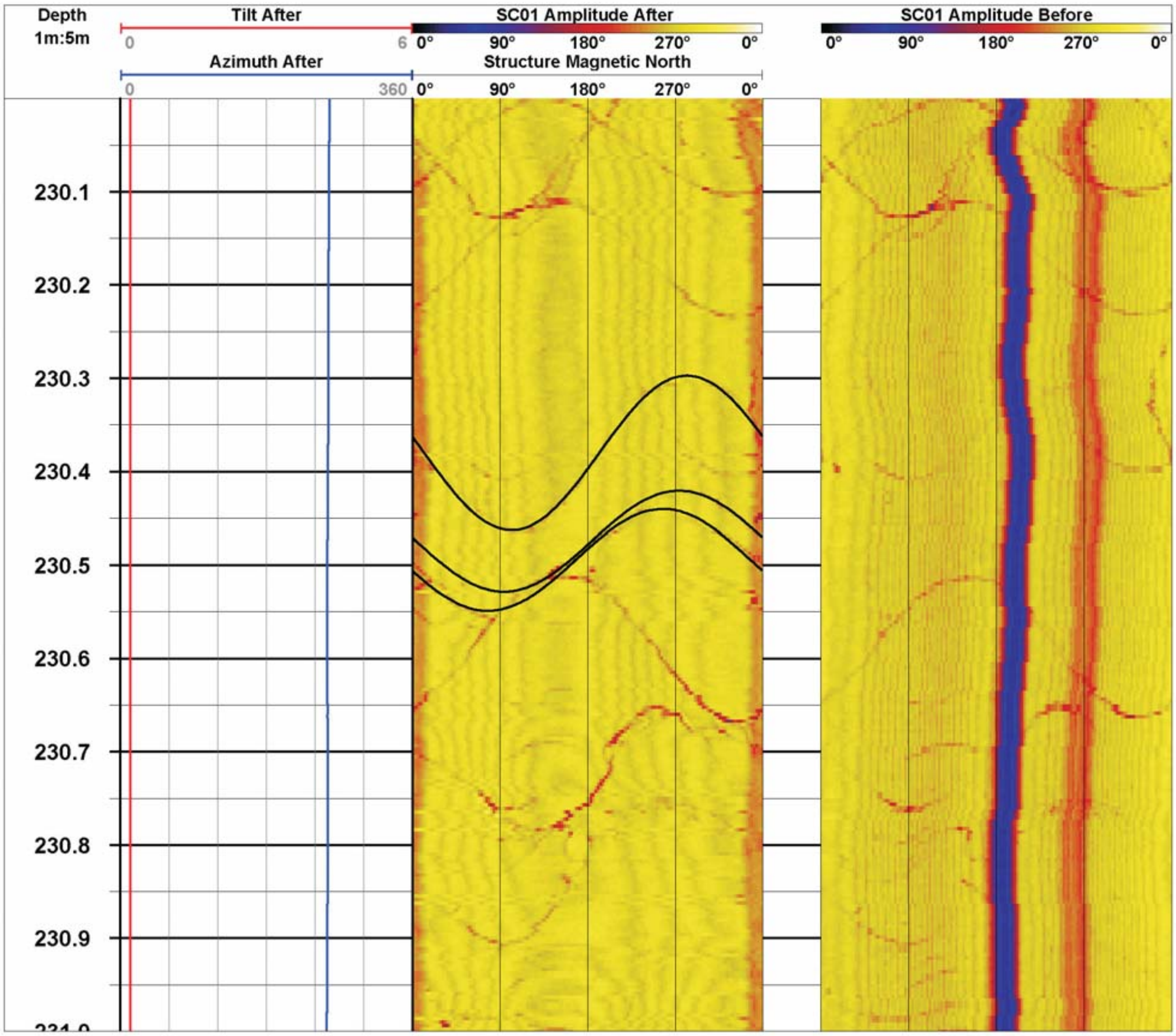


After

Before

FRACTURE ORIENTATION BH SC01 - 230

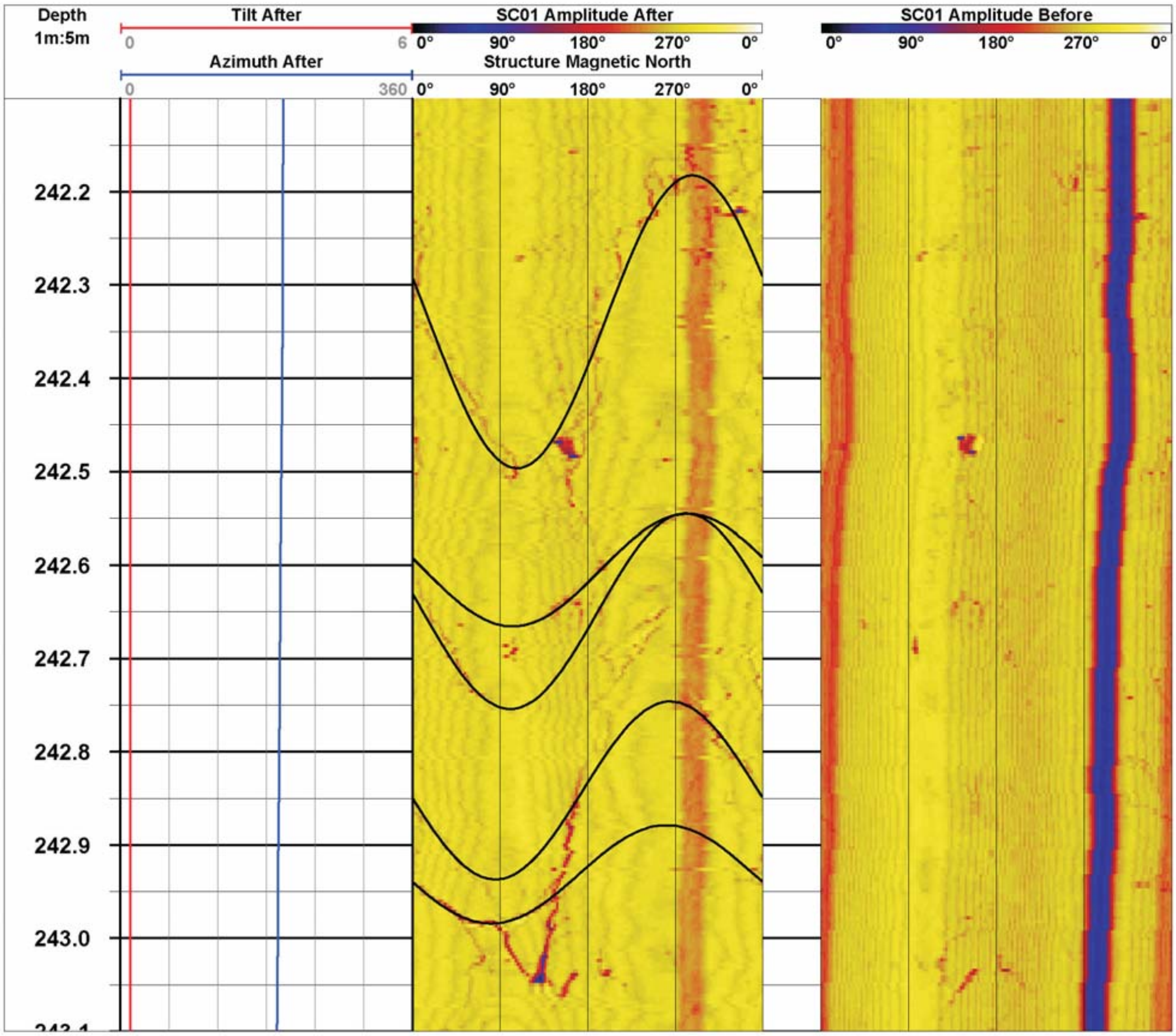
FIGURE B.4



After

Before

FRACTURE ORIENTATION BH SC01 - 242	FIGURE B.5

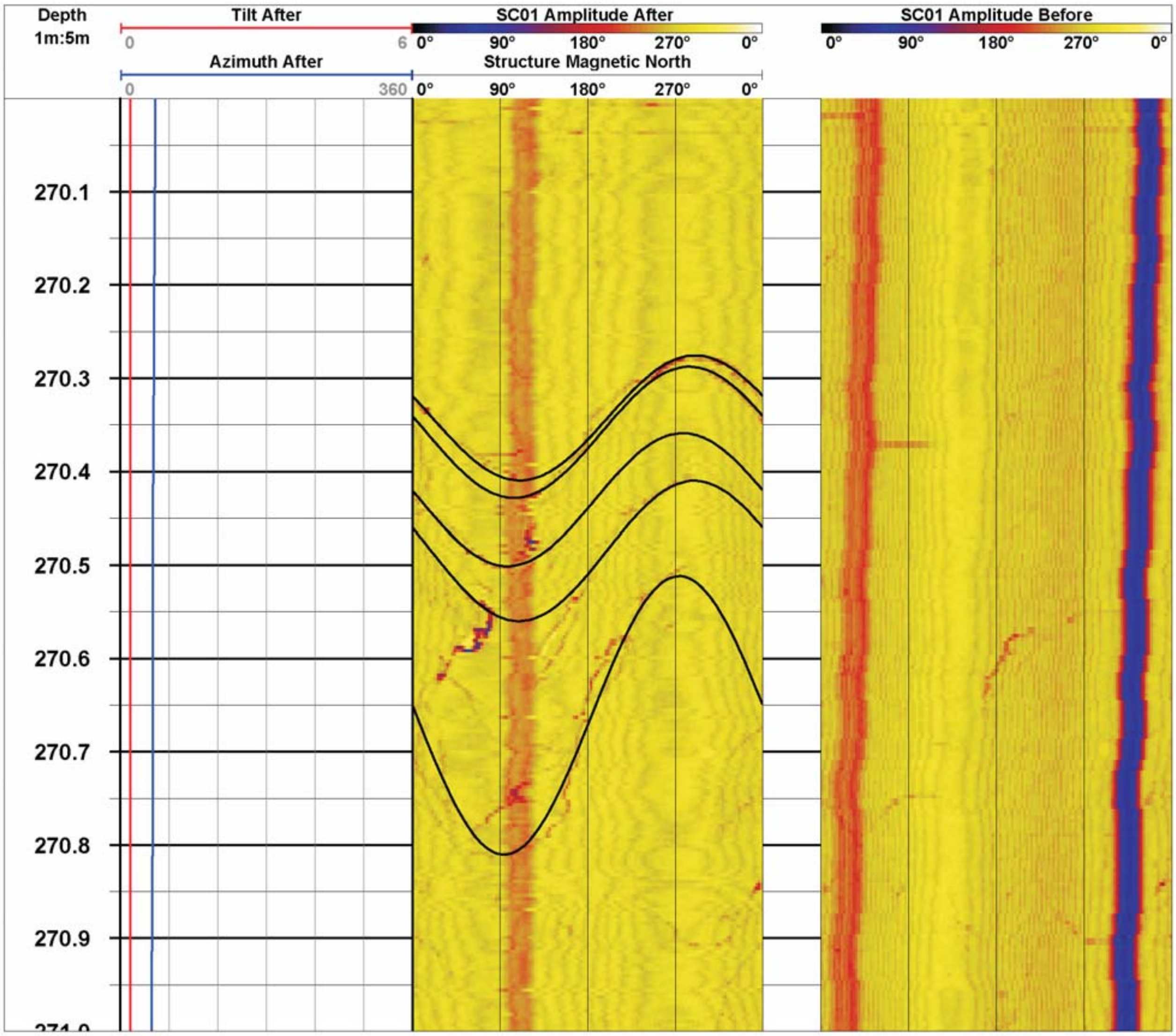


After

Before

FRACTURE ORIENTATION BH SC01 - 269

FIGURE B.6



After

Before

Project: 06-1119-010

Golder Associates

Date: January 2007

APPENDIX C

CALIBRATION RECORDS

Zone Pressure Calibration

CERTIFICATE OF CALIBRATION

NORTHWEST CALIBRATION SYSTEMS, INC.
5700 6th Ave So, Suite 101 Seattle, WA 98108-1205
Tel: (206)762-2515 Fax: (206)762-5880

~ NCS is ISO-9002 Registered ~
NCCB 6097 ANSI-RAB 10025

Certification Number: 1000355105

Company: GOLDER ASSOCIATES/REDMOND
Instrument ID: D095224
Instrument Type: PRESSURE TRANSDUCER, 0-5000 PSI
Instrument Size: 0 to 5000 PSI, 0.5 to 5.5 VDC
Instrument Model #: PX213-5KG5V
Department: Unassigned
Location: Unassigned
Received In Tolerance: YES
Instrument Rejected: NO

P O #: CREDIT CARD
Serial #: D095224
Manufacturer: OMEGA
Cal Date: 07/02/2005
Cal Due: 07/02/2006
Cal Procedure: 33K6-4-427-1
Cal Technician: NWM
Lab Temperature: 72.0 Deg F
Lab Humidity: 46.0 RH

INSTRUMENT ACCURACY : ±0.25% OF FULL SCALE

INSTRUMENT CONDITION: PRESSURE APPLIED mV OUTPUT 12 VDC EXITATION

PRESSURE APPLIED	mV OUTPUT
200 PSI	0.71959 mV
400 PSI	0.92355 mV
600 PSI	1.11619 mV
800 PSI	1.31572 mV
1000 PSI	1.51493 mV
1500 PSI	2.0128 mV
2000 PSI	2.5117 mV
3000 PSI	3.5112 mV
4000 PSI	4.5162 mV
5000 PSI	5.5147 mV

CALIBRATION STANDARD		Cal Due Date
101575	MULTIMETER, FLU 8840A	07/31/2005
100797	MULTIMETER, FLU 8020B	12/31/2005
101630	DEADWEIGHT PRESSURE TESTER	02/28/2007

NIST REFERENCE
(101575)501600 (100797)501600 (101630)514500

Northwest Calibration Systems certifies this instrument has been calibrated using standards with accuracies traceable to the National Institute of Standards and Technology, derived from natural physical constants, derived from ratio measurements, or compared to consensus standards. Northwest Calibration Systems' calibration system complies with the requirements of ISO-9002, ISO/IEC Guide 25, ANSI/NCSL Z540-1, and MIL STD 45662A

Packer Pressure Calibration

CERTIFICATE OF CALIBRATION

NORTHWEST CALIBRATION SYSTEMS, INC.
5700 6th Ave So, Suite 101 Seattle, WA 98108-1205
Tel: (206)762-2515 Fax: (206)762-5880

~ NCS is ISO-9002 Registered ~
NCCB 6097 ANSI-RAB 10025

Certification Number: 1000355104

Company: GOLDER ASSOCIATES/REDMOND
Instrument ID: D095227
Instrument Type: PRESSURE TRANSDUCER, 0-5000 PSI
Instrument Size: 0 to 5000 PSI, 0.5 to 5.5 VDC
Instrument Model #: PX213-5KG5V
Department: Unassigned
Location: Unassigned
Received In Tolerance: YES
Instrument Rejected: NO

P O #: CREDIT CARD
Serial #: D095227
Manufacturer: OMEGA
Cal Date: 07/02/2005
Cal Due: 07/02/2006
Cal Procedure: 33K6-4-427-1
Cal Technician: NWM
Lab Temperature: 72.0 Deg F
Lab Humidity: 46.0 RH

INSTRUMENT ACCURACY : ±0.25% OF FULL SCALE

INSTRUMENT CONDITION: PRESSURE APPLIED	mV OUTPUT 12 VDC EXITATION
200 PSI	0.69702 mV
400 PSI	0.89617 mV
600 PSI	1.09492 mV
800 PSI	1.29430 mV
1000 PSI	1.49802 mV
1500 PSI	1.9930 mV
2000 PSI	2.4901 mV
3000 PSI	3.4923 mV
4000 PSI	4.4931 mV
5000 PSI	5.4970 mV

CALIBRATION STANDARD		Cal Due Date
101575	MULTIMETER, FLU 8840A	07/31/2005
100797	MULTIMETER, FLU 8020B	12/31/2005
101630	DEADWEIGHT PRESSURE TESTER	02/28/2007

NIST REFERENCE
(101575)501600 (100797)501600 (101630)514500

Northwest Calibration Systems certifies this instrument has been calibrated using standards with accuracies traceable to the National Institute of Standards and Technology, derived from natural physical constants, derived from ratio measurements, or compared to consensus standards. Northwest Calibration Systems' calibration system complies with the requirements of ISO-9002, ISO/IEC Guide 25, ANSI/NCSL Z540-1, and MIL STD 45662A

High Range Flow Calibration

FLOW TECHNOLOGY INC.
Electronic Data Sheet V3.0
RC51070A

Customer Name: GOLDER ASSOCIATES LTD. Job Number: 27821

Elect. Model NO: RC51-1-C-0000-7 Elect. Serial NO: RC5192030070
Meter Model NO: FTO-4NI00-LHC-1 Meter Serial NO: FO01129677

RUN NO.	FREQUENCY HERTZ	FLOW RATE GAL/MIN	VOLTAGE OUT D.C. VOLTS
1	1282.50	1.3000	10.000
2	808.00	0.8317	6.300
3	497.88	0.5189	3.882
4	306.07	0.3237	2.387
5	186.88	0.2015	1.457
6	115.62	0.1275	0.902
7	70.92	0.0800	0.553
8	42.45	0.0496	0.331
9	25.93	0.0311	0.202
10	15.55	0.0194	0.121
11	0.00	0.0000	0.000

Sensitivity: ACTIVE RF Level: 11.0 Vp-p Tested by: WILLIAM HOLLAND
PULSE OUT: 10 Vp-p Date: 6/30/05
INV#'s 51508 51530 51594 APPROVED BY: ____________

Low Range Flow Calibration

FLOW TECHNOLOGY INC.
Electronic Data Sheet V3.0
RC51070A

Customer Name: GOLDER ASSOCIATES LTD. Job Number: 27821

Elect. Model NO: RC51-1-C-0000-7 Elect. Serial NO: RC5192030070
Meter Model NO: FTO-4NI00-LHC-1 Meter Serial NO: F001129677

RUN NO.	FREQUENCY HERTZ	FLOW RATE GAL/MIN	VOLTAGE OUT D.C. VOLTS
1	1282.50	1.3000	10.000
2	808.00	0.8317	6.300
3	497.88	0.5189	3.882
4	306.07	0.3237	2.387
5	186.88	0.2015	1.457
6	115.62	0.1275	0.902
7	70.92	0.0800	0.553
8	42.45	0.0496	0.331
9	25.93	0.0311	0.202
10	15.55	0.0194	0.121
11	0.00	0.0000	0.000

Sensitivity: ACTIVE RF Level: 11.0 Vp-p Tested by: WILLIAM HOLLAND
PULSE OUT: 10 Vp-p Date: 6/30/05
INV#'s 51508 51530 51594 APPROVED BY: ____________

Data Acquisition Board Certificate

Certificate of Calibration

Date: 6/9/05

Model Number: Personal Daq/55 **Serial Number: 260733**

This notification certifies that the instrument described above has been inspected and tested in accordance with specifications published by the manufacturer.

The standards used in the calibration of this instrument are traceable to the National Institute of Standards and Technology (NIST) and are calibrated at planned intervals. Evidence of traceability is on file at IOtech.

Calibration of IOtech products is performed utilizing a quality system registered to ISO9001.

Standard(s): 4615016 - Fluke 5440B Calibrator
US37036548 - HP34970A Switching Unit
40403 - Omega TRC3 Ice Point Cell

Edward Ciehanoski

Ed Ciehanoski
Production Supervisor

IOtech
25971 Cannon Road
Cleveland, OH 44146
440.439.4091
www.iotech.com

ISO 9001 REGISTERED

PR-3 Rev. 09/03