GEOTECHNICAL CHARACTERIZATION OF THE TEXAS SUPERCONDUCTING SUPER COLLIDER SITE -- HYDRAULIC FRACTURING TESTS -- BORING BE5
GEOTECHNICAL CHARACTERIZATION OF THE TEXAS SUPERCONDUCTING SUPER COLLIDER SITE

HYDRAULIC FRACTURING TESTS – BORING BE5

Topical Report RSI-0369

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EXECUTIVE SUMMARY

An in situ stress profile was completed in one of the exploratory holes of the Superconducting Super Collider (SSC) project near Waxahachie, Texas. A series of microhydraulic fracturing tests were conducted from a depth of 326 feet to a horizon as shallow as 76 feet. Two different formations were targeted: the Austin Chalk and the Taylor Marl. The data interpretation revealed a consistent picture and the tests were considered successful in that five of them resulted in both vertical and horizontal hydraulic fractures.

In both formations, the vertical overburden stress is the minimum stress component. Both horizontal stresses are larger (more compressive) than the vertical stress. The maximum horizontal stress is approximately twice as large as the vertical, and the minimum horizontal stress is approximately 30 percent larger than the vertical.

The stress measurement campaign did not result in an accurate determination of stress orientation. The stress orientation can be inferred from the structural geology but should be measured in the future.

Laboratory hydraulic fracture tests revealed that the Austin Chalk displays a remarkable strength size effect. The strength size effect of the Austin Chalk should be considered in all past and future property measurement projects.
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<th>Page</th>
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1.0 INTRODUCTION

The design of the underground openings for the Superconducting Super Collider (SSC) project requires knowledge of the virgin state of stress at depth. Although the weight of the overburden can easily be determined from the integration of the density logs, the horizontal principal stress components need to be determined via experimental techniques. This report describes an in situ measurement campaign to determine the stress profile in an exploratory hole (BE5) drilled near Palmer, Texas, situated about 12 miles west of Waxahachie, Texas.

North Central Texas is underlain by a thick sequence of sedimentary rocks that dip gently southeastward toward the Gulf of Mexico. The outcropping units in Ellis County belong to the Upper Cretaceous Gulf Series including the Taylor, Austin, Eagle Ford, and Woodbine Groups. The Austin Chalk and the Taylor Marl groups outcrop at the SSC site, and the majority of the tunnel would be in these two rocks. Figure 1-1 shows the general arrangement of the tunnels and the BE5 borehole location.

The Taylor Marl is characteristically a green-gray to blue-gray, fine-grained, laminated, calcareous claystone with interbedded chalk. Although it contains 60 to 70 percent of illite and montmorillonite clays, the cores are of good quality when fresh. The permeability of this formation is of the order of $10^{-8}$ cm/sec, corresponding to 100 md. The contact between the Taylor Marl and the underlying Austin Chalk is unconformable and marked by a few inches of reddish-brown clay containing reworked fossils and phosphate modules.

The Austin Chalk is primarily light to medium gray chalk (microgranular calcite) with interbedded calcareous claystone. The average calcium carbonate content of the chalk is about 85 percent, and its physical characteristics are quite uniform. The permeability of this formation is of the order of $1.6(10^{-8})$ cm/sec, or 170 md.

Stress measurements were attempted in the Austin Chalk and the Taylor Marl; the contact being at 120.4 feet. The horizons to be fractured were determined after careful inspection of the core logs: zones of fracturing, more argillaceous chalk, and vugular regions were avoided to minimize packer problems and to fracture in as homogeneous a rock interval as possible (see core logs in Appendix A).

The stress measurement campaign relied on the microhydraulic fracturing technique ($\mu$HF). The tests were performed using mechanically expanded straddle packers. Because of the shallow depth of the measurements, it was critical that every attempt be made to initiate vertical fractures instead of horizontal fractures, which lift the overburden. Horizontal fractures do not allow the determination of the principal horizontal stress components. The use of mechanically expanded packers allowed the introduction of an additional vertical stress component, which was hoped to be sufficient to allow vertical fractures to initiate.
Figure 1-1. General Layout of Superconducting Super Collider Site and Borehole BE5.
After the vertical fracture was propagated, it would reorient itself to become perpendicular to the minimum principal stress component, the vertical overburden stress. When this happened, a second set of pertinent pressures was recorded in order to complete the full stress tensor.

Following the microhydraulic fracturing measurements, the hole was logged with a Schlumberger Formation MicroScanner (FMS) to obtain fracture location/orientations. The FMS also measures borehole ellipticity and breakouts.

Chapter 2 of this report presents the chronology and equipment used during the field testing effort. Chapter 3 reviews the microhydraulic fracturing technique, the results of the fracturing tests, and the results of the Formation MicroScanner logging. Chapter 4 provides a summary of the results in the form of conclusions and recommendations.
2.0 CHRONOLOGY AND EQUIPMENT

2.1 INTRODUCTION

Borehole BE5 near Palmer, Ellis County, Texas, was drilled by Southwestern Laboratories between January 10 and January 13, 1990. After core drilling, the hole was reamed to nominally 6.75-inch diameter on January 15. Wireline logging (including sonic, electrical, and gamma logs) was performed the evening of January 15. Microhydraulic fracturing tests were originally scheduled to begin the morning of January 16; however, heavy rains were forecast for the next several days, and the measurement campaign was postponed several times until it began the morning of January 27. Caliper logging was repeated on January 25 and confirmed that the condition of the borehole had not deteriorated.

Microhydraulic fracturing tests were made on January 27 (one), January 29 (four), and January 30 (five). Only one microhydraulic fracturing test was completed on January 27 because the drill rig could not free the packer assembly after the first test. Late in the evening, a hydraulic crane was mobilized at the site and used to free the packer. On January 28, the packer was being lowered into the borehole when an unforecasted rain storm forced cancellation of further testing. Testing began again on January 29 and concluded on January 30. Eight microhydraulic fracturing tests were made in the Austin Chalk (lower formation) and two microhydraulic fracturing tests were made in the Taylor Marl. A summary of the test locations is given in Table 2-1.

Table 2-1. Summary of Microhydraulic Fracturing Tests in Borehole BE5

<table>
<thead>
<tr>
<th>Test I.D.</th>
<th>Depth (feet)</th>
<th>Formation</th>
<th>Date</th>
<th>Time Start</th>
<th>Time Stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>BE5-A</td>
<td>326</td>
<td>Austin Chalk</td>
<td>Jan. 27</td>
<td>11:30</td>
<td>11:55</td>
</tr>
<tr>
<td>BE5-B</td>
<td>285</td>
<td>Austin Chalk</td>
<td>Jan. 29</td>
<td>11:00</td>
<td>11:30</td>
</tr>
<tr>
<td>BE5-C</td>
<td>210</td>
<td>Austin Chalk</td>
<td>Jan. 29</td>
<td>13:45</td>
<td>14:00</td>
</tr>
<tr>
<td>BE5-D</td>
<td>304</td>
<td>Austin Chalk</td>
<td>Jan. 29</td>
<td>16:45</td>
<td>16:54</td>
</tr>
<tr>
<td>BE5-E</td>
<td>192</td>
<td>Austin Chalk</td>
<td>Jan. 29</td>
<td>19:30</td>
<td>19:45</td>
</tr>
<tr>
<td>BE5-F</td>
<td>162</td>
<td>Austin Chalk</td>
<td>Jan. 30</td>
<td>9:49</td>
<td>10:30</td>
</tr>
<tr>
<td>BE5-G</td>
<td>152</td>
<td>Austin Chalk</td>
<td>Jan. 30</td>
<td>11:30</td>
<td>12:08</td>
</tr>
<tr>
<td>BE5-H</td>
<td>127</td>
<td>Austin Chalk</td>
<td>Jan. 30</td>
<td>13:40</td>
<td>14:15</td>
</tr>
<tr>
<td>BE5-I</td>
<td>107</td>
<td>Taylor Marl</td>
<td>Jan. 30</td>
<td>15:25</td>
<td>15:45</td>
</tr>
<tr>
<td>BE5-J</td>
<td>77</td>
<td>Taylor Marl</td>
<td>Jan. 30</td>
<td>16:38</td>
<td>16:56</td>
</tr>
</tbody>
</table>
2.2 EQUIPMENT

2.2.1 Packer Assembly

The packer assembly used in the testing was a Halliburton Services open hole compression straddle packer with Duro 50 packer rubbers. The length of the test interval was 36 inches. With one exception, an equalizing tube was used to avoid pressurizing the annulus below the lower packer. The proximity of the hole bottom precluded use of the equalization tube at the lowest test interval centered at 326 feet. A schematic drawing of the packer is shown in Figure 2-1.

The open hole compression straddle packer relies on the weight of the drill pipe to compress the packer rubbers and expand them against the borehole wall. Because of the shallow depth, thick-walled pipe (drill collars) was used to increase the weight above that of standard pipe. For the shallower tests, the weight was supplemented with 4,000 to 6,000 pounds of pull down from the drill rig. After 10 tests the packer rubbers showed no indications of damage or wear.

The rationale for selecting mechanically compressed straddle packers rather than inflatable straddle packers involves several interrelated lines of reasoning which include depth, fracture propagation, and packer-induced stresses. These items are discussed in the remainder of this section.

The depths at which tests were contemplated are unusually shallow for the microhydraulic fracturing technique. Indeed, previous experience in in situ stress measurements has shown that below about 1,000 feet to 1,500 feet, the minimum principal stress is horizontal. At shallower depths, a reversal in the principal stress directions occurs, and the overburden stress becomes the minimum principal stress component (refer to Figure 2-2).

Fractures always propagate "the easiest way," that is, they will tend to run parallel to the minimum stress direction. At shallow depths, horizontal fractures will usually be induced. If this occurs, the unfortunate consequence is that the field pressure records only allow the determination of the overburden pressure, a rather expensive way to integrate the density log. Consequently, to determine the horizontal stress components at shallow depths, one needs to either initiate a vertical fracture or initiate both a horizontal and vertical fracture, knowing very well that the vertical fractures will reorient themselves and become horizontal. Both of these options are discussed in this report. The first option is discussed here, and the second option is discussed in Section 2.2.2.

The theory of microhydraulic fracturing for in situ stress determination relies on the elasticity solution for stress around an infinitely long pressurized cylindrical cavity [Scheidegger, 1962]. Kehle [1964] introduced the effects of longitudinally rigid packers and a finite pressurized length. In actuality, the packers used in hydraulic fracturing are neither longitudinally rigid nor radially bonded to the rock. Inflatable packers, because of their length and tremendous expansion capabilities, are allowed to slide along a central mandril. This sliding reduces the tensile stress increment.
Figure 2-1. Schematic of Open Hole Compression Straddle Packer.
Figure 2-2. Typical In Situ Stress Profiles.
introduced in the rock surrounding the borehole when the packers are inflated. The mechanical-expansion straddle packer, however, has the opposite reaction. Rather than introducing an axial tensile stress increment, a compressive stress increment is induced in the rock between the packer elements. The combination of the compressive stress increment and the axial rigidity of the straddle section resists the formation of a horizontal fracture. Essentially, the packer assembly "pins" the rock together. Additional aspects of packer selection are discussed by Roegiers, et al. [1973] and Roegiers [1974].

2.2.2 Pump and Data Logging

The pump used in the testing was a Haliburton Services RCM cementing truck. A special conversion kit was installed to reduce the pump piston diameter to 1 inch (from the standard 4-inch diameter). The pumping rate could be controlled from about 0.5 gpm to more than 10 gpm. Radio contact was maintained between the test operator and the pump operator, such that shut-in instructions and flow rate changes could be instantly communicated.

Flow rates were measured using several impeller-type flowmeters with throat sizes between 0.5- and 2-inch diameter. Considerable problems were encountered in maintaining the small-diameter meters. When flow meter problems were encountered, the flow rates were calculated by the pump operator based on volume removal from the calibrated supply tank. The test records included in Appendix B sometimes show peaks in flow rate. Such a transient is sensed at the surface because of either switching gears on the pumping unit or closing valves in the surface piping. For example, when the hydraulically driven fractures were shut-in, a spike will be seen in the flow rate. This spike is inherent in the use of turbine flowmeters which will record a positive flow rate when spinning in either direction.

Pressures were measured using strain-gaged pressure transducers. Originally, a 0–1,000 psi transducer was intended to be the primary transducer. During the second microhydraulic fracturing test, it was obvious that this transducer was in error (possibly because of being frozen during the previous night). The transducer was replaced with a 0–15,000 psi transducer for Tests B through E. For the final five tests, 0–1,000 psi and 0–300 psi transducers were simultaneously used.

Both the Haliburton Services Compuvan and Compupack data loggers were used during the tests. The Compuvan allowed playback of selected portions of the test cycles and rigorous inspection of the data in the field. The Compupack records the same information, but is less versatile in terms of in-the-field plotting and data inspection.

The apparently over-sized pumping unit was selected because we were uncertain whether or not it would be possible to initiate a vertical hydraulic fracture. If a horizontal fracture is initiated and propagated, then the only remaining option is to attempt to initiate a second vertical fracture while propagating the horizontal fracture. This can only be achieved if a large pumping capacity is available.
For example, assume that a horizontally fractured borehole is pressurized and that pumping has resumed (i.e., the horizontal fracture is being propagated). A relationship exists between the pressure in the borehole and the width of the horizontal fracture, but this relationship is nonlinear (i.e., doubling the pressure does not double the fracture width at the borehole). Consequently, if water is pumped into the borehole at a rate faster than the fracture can accommodate, a choke will be introduced. The pressure in the borehole will increase and hopefully a second vertical fracture will be induced. Upon shut-in, two instantaneous shut-in pressures will be recorded: one for the vertical fracture followed by one for the horizontal fracture.

2.2.3 Fracture Detector

The Schlumberger Formation MicroScanner (FMS) Service was used to log the borehole after the microhydraulic fracturing tests. The FMS provides a high resolution image of the borehole surface using a dense array of electrical sensors. Major applications of the FMS are in fracture identification, analyzing thinly bedded formations, recognizing secondary porosity developments in carbonates, and defining sedimentary structures and depositional environments.

Ideally, the FMS should be used both before and after microhydraulic fracturing. Because of budget limitations, the FMS was used only after the microhydraulic fracturing tests. The location of fractures existing in the borehole before the tests were based on the core logs.
3.0 STRESS DETERMINATIONS

3.1 INTRODUCTION

A series of microhydraulic fracturing tests were performed in a single borehole in an attempt to determine the in situ stress field prevailing in the Austin Chalk and in the Taylor Marl. It was recognized beforehand that the tests would be performed at depths where horizontal fractures are usually induced. An attempt was made to increase the longitudinal (i.e., along the borehole axis) stress concentration by using mechanical-expansion packers. It was hoped that this axial stress increment would resist a horizontal fracture from forming at the borehole wall.

3.2 MICROHYDRAULIC FRACTURING

3.2.1 Introduction

The microhydraulic fracturing technique consists of sealing off a section of an open hole and pressuring it until the borehole wall fails in tension (i.e., a hydraulically induced fracture occurs). The hydraulic fracture is then propagated and shut-in to record the pressure that just holds the fracture open. Several pressurization/propagation cycles provide data which can be related to the in situ stress field.

3.2.2 Theoretical Background

If one assumes that rock behaves as a linear elastic solid, and that the borehole is drilled parallel to one of the principal stress directions, the following expressions can be obtained for the stresses around a vertical borehole.

\[
\sigma_r = \frac{1}{2}(\sigma_{H_{max}} + \sigma_{H_{min}})(1 - \frac{a^2}{r^2}) + \frac{1}{2}(\sigma_{H_{max}} - \sigma_{H_{min}})(1 - \frac{4a^4}{r^4} + \frac{3a^4}{r^2}) \cos 2\theta
\]

\[
\sigma_\theta = \frac{1}{2}(\sigma_{H_{max}} + \sigma_{H_{min}})(1 + \frac{a^2}{r^2}) - \frac{1}{2}(\sigma_{H_{max}} - \sigma_{H_{min}})(1 + \frac{3a^4}{r^4}) \cos 2\theta
\]

\[
\tau_{r\theta} = -\frac{1}{2}(\sigma_{H_{max}} - \sigma_{H_{min}})(1 + 2\frac{a^2}{r^2} - 3\frac{a^4}{r^4}) \sin 2\theta
\]

where \(a\) is the radius of the borehole, \(r\) is the radial distance from the center of the borehole, and \(\sigma_4\) represents the horizontal or in plane principal stresses. The angle \(\theta\) defines the direction relative to the \(\sigma_{H_{min}}\) direction.
If one is interested only in what happens at the borehole wall then, with \( r \rightarrow a \), the following expressions are obtained:

\[
\begin{align*}
    \sigma_r &= 0 \\
    \sigma_\theta &= (\sigma_{H\text{max}} + \sigma_{H\text{min}}) - 2(\sigma_{H\text{max}} - \sigma_{H\text{min}}) \cos 2\theta \\
    r_{r\theta} &= 0
\end{align*}
\]

Considering only the directions parallel and perpendicular to the minimum horizontal stress direction (i.e., \( \theta = 0 \) and \( \theta = \frac{\pi}{2} \), respectively), these expressions further simplify to:

\[
\begin{align*}
    \sigma_\theta \big|_{\theta=0} &= 3\sigma_{H\text{min}} - \sigma_{H\text{max}} \\
    \sigma_\theta \big|_{\theta=\pi/2} &= 3\sigma_{H\text{max}} - \sigma_{H\text{min}}
\end{align*}
\]

If one provides hydraulic pressure to a sealed-off interval of the borehole, a radial fracture initiates as soon as the hydraulic pressure exceeds the tensile strength of the rock and the circumferential stress concentration (the breakdown pressure, \( P_b \)). It should be noted that the stress concentration diminishes rapidly to zero away from the wellbore. Consequently, the stress concentration affects the pressure to induce a fracture, but not the pressure to propagate the fracture away from the wellbore wall (the fracture reopening pressure, \( P_r \)).

The following expression can be written for the breakdown pressure of an uncased, smooth wellbore:

\[ P_b = 3\sigma_{H\text{min}} - \sigma_{H\text{max}} - p + T \text{ with } \sigma_{H\text{max}} \geq \sigma_{H\text{min}} \]

or, in terms of effective stresses, \( \sigma_{H\text{min}}' \) and \( \sigma_{H\text{max}}' \):

\[ P_b = 3\sigma_{H\text{min}}' - \sigma_{H\text{max}}' + T \]

where \( p \) is the formation pore pressure and \( T \) is its tensile strength.

This equation is valid only in the case of no fluid penetration; hence, it actually gives an upper bound for the breakdown pressure. Also, it assumes that the initiation and propagation directions are identical.

It should be noted that an increase in the pore pressure in the vicinity of the well corresponds to a decrease in the breakdown pressure [Bredehoeft et al., 1976]. Therefore, the use of low-viscosity fluids and/or low pumping rates will decrease the pressure for breakdown.

After the fracture has propagated, the pumps are stopped and an instantaneous shut-in pressure, \( P_{ISIP} \), is recorded. Based on the action/reaction principle, this pressure should only be slightly above the magnitude of the minimum principal stress (assuming the influence of the borehole is negligible). Hence, a second equation can be written as follows:

\[ P_{ISIP} \approx \sigma_{H\text{min}} \]
The last unknown, $T$, is obtained by letting the pressure bleed off and starting a second cycle of pressurization using the same fracturing fluid and the same pumping rate as for the first cycle. The tensile strength of the rock is effectively nullified by the presence of the fracture, and the fracture reopening pressure can be expressed as

$$P_r = 3\sigma_{H\min} - \sigma_{H\max} - p$$

The stress-state solution requires a knowledge of the pore pressure, $p$. For this testing, the pore pressure is assumed to be equal to the calculated downhole hydrostatic pressure shown in Table 3-1.

Table 3-1. Microhydraulic Fracturing Testing Horizons and Hydrostatic Pressures

<table>
<thead>
<tr>
<th>Formation</th>
<th>Test Identification</th>
<th>Depth to Center of Pressurized Interval (ft)</th>
<th>Date of Test</th>
<th>Hydrostatic Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austin</td>
<td>BE5-A</td>
<td>326</td>
<td>1/27</td>
<td>141</td>
</tr>
<tr>
<td>Chalk</td>
<td>BE5-B</td>
<td>292</td>
<td>1/29</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>BE5-C</td>
<td>210</td>
<td>1/29</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>BE5-D</td>
<td>303</td>
<td>1/29</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td>BE5-E</td>
<td>192</td>
<td>1/29</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>BE5-F</td>
<td>162</td>
<td>1/30</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>BE5-G</td>
<td>152</td>
<td>1/30</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>BE5-H</td>
<td>127</td>
<td>1/30</td>
<td>55</td>
</tr>
<tr>
<td>Taylor</td>
<td>BE5-I</td>
<td>107</td>
<td>1/30</td>
<td>46</td>
</tr>
<tr>
<td>Marl</td>
<td>BE5-J</td>
<td>77</td>
<td>1/30</td>
<td>33</td>
</tr>
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</table>

The system of three equations and three unknowns allows the determination of both in situ stresses, $\sigma_{H\max}$ and $\sigma_{H\min}$, and the tensile strength of the formation, $T$. One should note that these expressions assume smooth, openhole conditions which are rarely the case in practice. However, the data from a microhydraulic fracturing test always give, at least, the value of the minimum principal stress.

The calculated values for the in situ stresses should be used cautiously because they are only approximations. Sources of error include effects of leakoff, stress concentrations, pore pressure, and rock strength. For instance, one must make sure that the pore pressure is not altered during the test period; otherwise, the shut-in pressure will increase as has been reported in the literature. These problems are minimized when high-viscosity fluids are used.

In practice, several pump/shut-in cycles are performed, involving the injection of progressively larger volumes of fluid. However, in most cases, the instantaneous shut-in pressure (taken as the pressure at which the downhole pressure curve depar
from the initial drop immediately following the shut-in) are sometimes observed to change from cycle to cycle. This procedure should be repeated until subsequent instantaneous shut-in pressures are repeatable.

Because it was felt that vertical fractures would eventually turn horizontal as they were propagated, it was essential to “capture” this feature. Hence, the usual microhydraulic fracturing procedure was modified in the sense that the fracture was shut-in (pumping was stopped) as soon as breakdown was indicated. If the shut-in is preformed fast enough, the instantaneous shut-in pressure may reflect the attitude of the fracture close to the borehole wall. A number of pressurization cycles were performed. Careful monitoring of the instantaneous shut-in pressure values until they became repetitive, reveals when the fracture attitude has stopped changing. Consequently, the following possibilities are contemplated:

- **Fracture starts horizontal and stays horizontal**
  Uniform instantaneous shut-in pressures from first breakdown cycle on.

- **Fracture starts vertical and stays vertical**
  Uniform instantaneous shut-in pressures from first breakdown cycle on. The difference with the previous case is that, in general, the breakdown peak is sharper than for the horizontal case and propagation will usually occur at pressures below the overburden stress magnitude.

- **Fracture starts vertical and turns horizontal**
  Definite higher instantaneous pressure in first breakdown cycle with a tendency to lower $P_{ISIP}$ as number of cycle increases. Finally, constant shut-in pressures are recorded that are consistent with the overburden pressure.

- **Fracture starts horizontal and turns vertical**
  Impossible unless a major structural discontinuity is encountered by the propagating hydraulic fracture.

- **Both horizontal and vertical fractures are initiated and propagated**
  After shut-in, two changes in slope of pressure decay curve are observed; two definite plateaus, $P_{ISIP}$, will be recorded.

### 3.2.3 Procedure

The same basic steps were followed in each test:

- Determine the test interval based on the core log.
- Position the packer at the interval and circulate clear water for 5 minutes.
- Isolate a 3-foot section of a borehole, using a mechanical straddle packer assembly.
• Inject into the formation at minimum rate\(^1\) until fracture occurs.

• After short propagation, shut-in the well and observe the pressure decline.

• Open the valves and flow back under controlled conditions (i.e., constant rate) and note any breaks in the pressure decline curve.

• Monitor the well head for flow-back, which indicates either packer failure or vertical fracturing around the packer.

• Repeat pressurization cycles until consistent picture emerges. The last cycle can be carried out at higher pumping rate.

3.2.4 Field Data

Ten microhydraulic fracturing tests were attempted, starting from the bottom of the hole. Table 3-1 summarizes the tested intervals and the assumed hydrostatic pressure at the test interval. The raw pressure/time curves from the field are included in Appendix B.

Table 3-2 summarizes the data interpretation and Table 3-3 gives the in situ stress values obtained from the pressure data. To illustrate how breakdown and instantaneous shut-in pressures were determined, a few field pressure-time plots will be discussed. Figure 3-1 shows the pressure-time plot from Test BE5-A. Two curves are shown: the tubing pressure and the bottom hole treatment pressure (BHTP). For these tests, the two curves are offset from each other by the hydrostatic pressure produced by the water column in the borehole (see Table 3-1). Pumping began at 11:21 and continued intermittently until about 11:43 when an apparent breakdown occurred \((P_b = 510\, \text{psi})\). The pumping was erratic because the flow meter was not responding and several start/stops occurred while attempting to fix it. After the apparent breakdown, a shut-in pressure of 338 psi was detected (Point B in Figure 3-1). The \(P_{ISIP}\) was 338 psi suggested a horizontal fracture was induced. At 11:53, a very high pumping rate (20 gpm) was started. An apparent breakdown occurred at 685 psi and was followed by a shut-in pressure of 338 psi. This suggests that the same horizontal fracture was shut-in and that the high pumping rate failed to induce a vertical fracture.

Figure 3-2 shows the pressure-time plot for Test BE5-C. Five successful cycles of pressurization were performed. Unfortunately, the pressure transducer momentarily stopped recording at 400 psi during the first cycle (Point A); hence the peak pressure was missed. The \(P_{ISIP}\) for the first cycle was 291 psi (Point B). The next four cycles suggest that a vertical fracture had been induced and that it remained vertical because the \(P_{ISIP}\) for each cycle is about the same (range 291 to 321 psi). The breaks in pressure during cycles 2 and 3 (Point C) correspond to a change in gear on the pumping unit.

\(^{1}\)Just sufficient to overcome the natural formation permeability.
Table 3-2. Microhydraulic Fracture Data

<table>
<thead>
<tr>
<th>Test I.D.</th>
<th>( P_i ) (psi)</th>
<th>( P_r ) (psi)</th>
<th>( T ) (psi)</th>
<th>Number of Shut-Ins</th>
<th>( P_{ISIP} ), Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>of Fractures</td>
<td>Horizontal Fractures</td>
</tr>
<tr>
<td>BE5-A</td>
<td>510</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>338</td>
</tr>
<tr>
<td>BE5-B</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BE5-C</td>
<td>397/524(^{(a)})</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>BE5-D</td>
<td>710</td>
<td>547</td>
<td>163</td>
<td>4</td>
<td>302</td>
</tr>
<tr>
<td>BE5-E</td>
<td>418/462(^{(b)})</td>
<td>-</td>
<td>-</td>
<td>7</td>
<td>251</td>
</tr>
<tr>
<td>BE5-F</td>
<td>410</td>
<td>400</td>
<td>10</td>
<td>4</td>
<td>250</td>
</tr>
<tr>
<td>BE5-G</td>
<td>365</td>
<td>365</td>
<td>0</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>BE5-H</td>
<td>368</td>
<td>342</td>
<td>26</td>
<td>4</td>
<td>250(^{(c)})</td>
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<tr>
<td>BE5-I</td>
<td>336</td>
<td>307</td>
<td>29</td>
<td>4</td>
<td>178</td>
</tr>
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<td>BE5-J</td>
<td>133</td>
<td>100</td>
<td>33</td>
<td>4</td>
<td>93</td>
</tr>
</tbody>
</table>

Comments
- Started horizontally
- Bad data, problems with pressure transducers
- Ignored first two pressurization cycles
- Vertical fracture turning horizontal
- Vertical fracture turning horizontal
- Vertical fracture turning horizontal
- Vertical fracture
- Vertical or horizontal fracture
- Vertical fracture turning horizontal
- Horizontal fracture

Notes:
- (a) 397 psi corresponds to the first breakdown, but later cycles revealed higher pressures.
- (b) 418 psi corresponds to the first breakdown, but later cycles revealed higher pressures.
- (c) No way to know if vertical or horizontal fracture was induced.
Table 3-3. Interpreted Instantaneous Shut-In Pressures for Each Test Cycle

<table>
<thead>
<tr>
<th>Test Identification</th>
<th>Depth In Ft.</th>
<th>No. of Cycles</th>
<th>No. of $P_{ISIP}$</th>
<th>ISIP's In psi</th>
</tr>
</thead>
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<tr>
<td>BE5-A</td>
<td>326</td>
<td>1</td>
<td>1</td>
<td>338</td>
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<tr>
<td>BE5-B</td>
<td>285</td>
<td>0</td>
<td>0</td>
<td></td>
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<tr>
<td>BE5-C</td>
<td>210</td>
<td>5</td>
<td>5</td>
<td>291, 321, 311, 291, 311</td>
</tr>
<tr>
<td>BE5-D</td>
<td>304</td>
<td>4</td>
<td>3</td>
<td>462, 302, 302</td>
</tr>
<tr>
<td>BE5-E</td>
<td>192</td>
<td>7</td>
<td>5</td>
<td>323, 293, 253, 248, 253</td>
</tr>
<tr>
<td>BE5-F</td>
<td>162</td>
<td>4</td>
<td>4</td>
<td>300, 252, 250, 250</td>
</tr>
<tr>
<td>BE5-G</td>
<td>152</td>
<td>3</td>
<td>2</td>
<td>300, 300</td>
</tr>
<tr>
<td>BE5-H</td>
<td>127</td>
<td>4</td>
<td>4</td>
<td>240, 250, 253, 258</td>
</tr>
<tr>
<td>BE5-I</td>
<td>107</td>
<td>4</td>
<td>3</td>
<td>215, 180, 175</td>
</tr>
<tr>
<td>BE5-J</td>
<td>77</td>
<td>4</td>
<td>4</td>
<td>100, 95, 95, 80</td>
</tr>
</tbody>
</table>

Figure 3-3 shows the four pressurization cycles for Test BE5-D. The breakdown pressure (Point A) is very distinct at 710 psi. The shut-in pressure for the first cycle occurred at 462 psi (Point B). The second cycle revealed a distinct fracture reopening pressure (Point D) at 547 psi. The pressure difference between Points A and D reflect a tensile strength of 163 psi. No clear $P_{ISIP}$ shows up on the second cycle. The third and fourth cycles reveal a distinct and repeatable $P_{ISIP}$ of 302 psi. This suggests that an initially vertical fracture has turned horizontal.

Figure 3-4 shows seven pressurization cycles performed in Test BE5-E. In this test, very low pumping rates were used: 0.05 to 0.15 gpm. The breakdown pressure (Point A) was 418 psi on the first cycle. The fracture reopening pressure increased to about 460 psi (Point C) on each of the later cycles. The shut-in pressures dropped from an initial 323 psi to 293, 253, 248, and 253 psi on subsequent cycles. Again, this behavior is suggestive of an initially vertical fracture turning horizontal.

3.2.5 Discussion

Ten microhydraulic fracturing tests were carried out in borehole BE5. Eight of the tests were in the Austin Chalk, and two tests were in the Taylor Marl. One of the tests, BE5-B did not produce any usable data because the pressure transducers did not work properly. In two of the tests, BE5-A and BE5-J, it is believed that a horizontal fracture was initiated from the borehole wall. Four of the tests are believed to have initially produced a vertical fracture at the borehole wall, which subsequently turned horizontal as it was propagated. Two of the remaining tests resulted in vertical fractures initiating from the borehole wall which were not detected to have turned horizontal. The orientation of the fracture in test BE5-H could not be resolved.
Figure 3-1. Photocopy of Pressure-Time Plot For Test BE5-A.
Figure 3-2. Photocopy of Pressure-Time Plot For Test BE5-C.
Figure 3-3. Photocopy of Pressure-Time Plot For Test BE5-D.
Figure 3-4. Photocopy of Pressure-Time Plot For Test BE5-E.
Table 3-3 supplements Table 3-2 by listing the interpreted instantaneous shut-in pressure for each test cycle. The stress profile information is summarized in Table 3-4 and Figure 3-5.

Table 3-4. Calculated Stresses From the Micro-hydraulic Fracturing Tests

<table>
<thead>
<tr>
<th>Test I.D.</th>
<th>Depth (ft)</th>
<th>Calculated Stresses (psi)</th>
<th>Vertical</th>
<th>Minimum Horizontal</th>
<th>Maximum Horizontal</th>
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</thead>
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<tr>
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<td>326</td>
<td>338</td>
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<td>BE5-B</td>
<td>285</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>BE5-C</td>
<td>210</td>
<td>—</td>
<td>283</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>BE5-D</td>
<td>304</td>
<td>302</td>
<td>462</td>
<td>707</td>
<td></td>
</tr>
<tr>
<td>BE5-E</td>
<td>192</td>
<td>251</td>
<td>328</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>BE5-F</td>
<td>162</td>
<td>250</td>
<td>300</td>
<td>430</td>
<td></td>
</tr>
<tr>
<td>BE5-G</td>
<td>152</td>
<td>—</td>
<td>300</td>
<td>469</td>
<td></td>
</tr>
<tr>
<td>BE5-H</td>
<td>127</td>
<td>250</td>
<td>250</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>BE5-I</td>
<td>107</td>
<td>178</td>
<td>215</td>
<td>292</td>
<td></td>
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<tr>
<td>BE5-J</td>
<td>77</td>
<td>93</td>
<td>—</td>
<td>—</td>
<td></td>
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</tbody>
</table>

The vertical stress was obtained from the instantaneous shut-in pressures in horizontal fractures (Tests BE5-A, -D, -E, -F, -I, and -J). The resulting stress gradient in the Taylor Marl is higher than would be indicated from the density of Taylor Marl. However, there are only two measurements in this unit and any error in one of the measurements could result in a significant error in the gradient. The vertical stress gradient in the Austin Chalk resulting from the measurements is 0.87 psi/ft. This stress gradient compares remarkably well with that which would result from the density of the Austin Chalk.

The minimum horizontal stress was resolved at six test intervals in borehole BE5; five in the Austin Chalk and one in the Taylor Marl. The minimum horizontal stress is approximately 30 percent larger (more compressive) than the vertical stress in the Austin Chalk. The minimum horizontal stress gradient in the Austin Chalk is 1.08 psi/ft.

The maximum horizontal stress can be resolved at four of the test intervals. In the Austin Chalk, the maximum horizontal stress is approximately double the vertical stress and exhibits a gradient of 1.73 psi/ft.
Figure 3-5. In Situ Stresses as a Function of Depth in Borehole BE5.
These relatively large and unequal horizontal stresses in the Austin Chalk are consistent with the hypotheses of Gough and Bell [1981]. These investigators evaluated borehole breakouts in the Austin Chalk in south Texas and stress measurements by others in various locations throughout south and south central Texas. The occurrence of horizontal stresses greater than the vertical stress at shallow depth is commonly accepted (e.g., Brady and Brown [1985]). Surface topography, erosion, residual and tectonic stresses, and fracture sets and discontinuities can all affect horizontal stresses.

Based on experience from the oil and gas industry, it is also common for the magnitudes and orientations of the stresses to be quite different when going from one lithology to another. Many reasons have been suggested but thus far, none has gained overwhelming acceptance.

### 3.3 FORMATION MICROSCANNER

#### 3.3.1 Introduction

The Formation MicroScanner tool represents a recent advance in borehole imaging. The instrument is essentially a conventional two- or four-pad dipmeter, but the tool has the added capability of producing high resolution images of the borehole wall using a dense array of electrical sensors. The high resolution of this tool allows the identification and orientation of testing-induced fractures.

#### 3.3.2 Principle

Basically, the Formation MicroScanner produces a continuous record of the electrical conductivity of the borehole wall. After processing, the electrical conductivity image is displayed on a variable intensity gray scale or optional color image. For our purposes, changes in the conductivity of the borehole wall, caused by the presence of a fluid filled or healed fracture, are easily identified on the displayed images. Depending on the conductivity contrasts, fractures with apertures as small as 10\(\mu\)m to 1 mm can be identified.

The tool used for this logging contained four sets of imaging sensors, and was run several times hoping for better coverage. The imaging sensors produce four, 7-cm-wide oriented records of the borehole wall per pass. All pads contain electrical sensors for the dipmeter measurements, and therefore, the tool can simultaneously acquire dipmeter data while imaging.

#### 3.3.3 Field Data

The Formation MicroScanner was run after the hydraulic fracturing tests were completed. A copy of the variable intensity gray scale image, as well as enhanced color images, are provided in Appendix C.
In reviewing the color-enhanced images, two types of images are apparent:

i. **Bedding planes** Based on 75 independent measurements of the thousands available, these planes were almost horizontal, gently dipping at 3° toward the S80°E. As seen on the color-enhanced images, each of these bedding planes is fitted with an oriented sine curve in green.

ii. **Natural fractures** Two sets of steeply dipping fractures were detected via stereographic projections, the poles being respectively (Figure 3-6):

\[ P_1(54/269) \text{ and } P_2(67,100) \]

As seen on the color-enhanced images, the ten natural fractures were fitted with an oriented sine wave in yellow.

No hydraulically induced fractures from the tests were detected by the Formation MicroScanner. This is possibly explained by the fact that we were unable to rotate the pads during successive FMS loggings; hence, only 50 percent of the borehole circumference was covered. Apparently, the FMS followed a drill-bit groove in the borehole despite repeated efforts to reorient the tool.

### 3.3.4 Discussion

No induced fractures were detected by the Formation MicroScanner. It is possible that the device simply missed the vertical fractures, because only one half of the borehole wall was actually logged. Any induced horizontal fractures would have been obscured by the bedding planes. Since the fractures were not detected, stress orientation could not be determined. The Formation MicroScanner did detect fractures revealed in the core (including a fault not specifically identified) and provided information on their apparent strike and dip.

### 3.4 BOREHOLE BREAKOUTS

#### 3.4.1 Introduction

Borehole ellipticity sometimes allows the determination of the orientation of the stresses acting in a plane perpendicular to the borehole axis. Numerous papers describing borehole breakouts are available in the literature [e.g., Gough and Bell, 1981].

#### 3.4.2 Principle

The existence of differential stresses will deform a circular borehole. Whenever the resultant stress concentrations overcome the strength of the rock, typical *dog-ear*
Figure 3-6. Stereographic Projection of Natural Fracture Poles.
breakouts will appear. These breakouts have, therefore, the tendency to align with the direction of the maximum in situ component acting in a plane perpendicular to the borehole. Consequently, an accurate caliper survey may reveal the in situ stress orientation.

One should note that breakouts will only occur if the strength has been exceeded. Hence, only in weak formations, or at great depths, or in locations where large differential stress conditions prevail will this technique work. Any attempts to correlate the geometry of such breakouts with the magnitude of the stresses, or stress differential, is futile unless the failure mechanisms are fully understood, especially the influence of the stress redistributions upon fracture propagation.

3.4.3 Field Data

Appendix C contains the traces of the FMS borehole caliper. Three regions of the borehole exhibit ellipticity: between 40 and 95 feet; between 120 and 166 feet; and between 280 and 340 feet.

The magnitude of the ellipticity reached 0.50 inches in the nominally 6.75-inch-diameter borehole at 314 feet. However, it should be recognized that a single logging run with a four-arm caliper may not result in the sampling of the maximum ellipticity amount and orientation.

3.4.4 Discussion

Three regions of small magnitude ellipticity developed in borehole BE5 in the Austin Chalk. However, because of the potential that the maximum ellipticity location was not sampled, ellipticity (and therefore, stress) orientation is difficult to establish from these measurements.
4.0 CONCLUSIONS AND RECOMMENDATIONS

- In situ stress determinations both in the Austin Chalk and in the Taylor Marl were quite successful and indicated minimum and maximum horizontal stress magnitudes 30 percent and 100 percent greater (more compressive) than the vertical stress.

- The magnitudes of the horizontal stresses and the resulting stress differential seem to be quite high. This finding will need to be taken into consideration when designing both tunnels and shafts.

- Based on the experience gained in this first exploratory hole, microhydraulic fracturing tests should definitely be considered as a technique to determine the in situ stress tensor in future boreholes associated with the Superconducting Super Collider site. Indeed, by judiciously selecting the straddle packer configuration it has been possible — in at least 50 percent of the cases — to induce vertical and horizontal fractures.

- Although inflatable packers might speed up the stress profiling, one needs to determine the induced secondary stress field by inflating them in an instrumented steel cylinder and compare the induced stress field to the mechanically activated system used in BE5.

- MicroScanner imaging is not recommended in the future as the direction of those exploratory holes coincide exactly with the vertical fracture traces; hence, unless 100 percent coverage is guaranteed (for example by 8 pads), the chances to detect the orientation of the induced fractures is only as good as the percentage of coverage. Consequently, the orientation of the stress field ought to be determined by other independent techniques such as Differential Strain Curve Analysis (DSCA) and/or Anelastic Strain Recovery (ASR) which are conducted on oriented core.

- Based on the assumption that both the Austin Chalk and the Taylor Marl are believed to be massive homogeneous formations, similar in situ stress determination campaigns should be carried out at the boundaries of the property (i.e., most northern, southern, and eastern exploratory boreholes).
5.0 REFERENCES


Note: Shading has been added in the column labeled "Standard Penetration Test Per 6 Inches" to show the hydraulic fracturing test intervals.
# LOG OF BORING

## PROJECT:
Superconducting Super collider

## CLIENT:
The Earth Technology Corporation

## TASK NO.:

### DATE: 1-10-90

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<th>SAMPLE TYPE &amp; NUMBER</th>
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<th>PERCENT RQD.</th>
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### CONTRACTOR:
SwL

### CASED TO: 21.0'

### SAMPLE LEGEND
- S = SPLIT SPOON
- T = 2" THIN WALL TUBE
- U = 3" THIN WALL TUBE
- C = NX ROCK CORE

### WATER INFORMATION
- DRILLING GEOLGYST: Ron Randall
- ASSISTANT: Dale Brown
- CHECKED BY: 

### DESCRIPTION OF STRATUM

1.5 CLAY, soft, dark brown, organics, wood, moist
2.5 CLAY, soft, brown, pebbles, organics, moist some medium sand
3.5 CLAY, soft, light brown, fine to medium sand, small pebbles

6.0

CLAY, soft, yellowish tan, fine sand, moist

9.0 MARL (Taylor), soft brown, trace of fine sand moist, weathered, sound

15.0 MARL, (Taylor Marl) soft to medium, fresh, sound, calcareous, dark gray with trace fossils

(1-11-90) started coring at 22.0'

signal parting 29.5'
**LOG OF BORING**

**PROJECT:** Superconducting Supercollider  
**CLIENT:** The Earth Technology Corporation

**DATE:** 1-11-90  
**TYPE:** NX Core  
**CASED TO:** 21.0'  
**CONTRACTOR:** SwL

**DEPT. IN FEET** | **SYMBOL** | **SAMPLE TYPE & NUMBER** | **DEPTH RANGE** | **PERCENT REC.** | **PERCENT RQD.** | **STANDARD PENETRATION TEST PER 6 INCHES** | **HAND PULL TSF** | **DESCRIPTION OF STRATUM**
--- | --- | --- | --- | --- | --- | --- | --- | ---
-45 | C-5 | 100 100 | | | | | | MARL (Taylor), soft, to medium, fresh, sound, calcareous, dark gray with trace fossils

**SAMPLE LEGEND**  
*S* = SPLIT SPOON  
*T* = 2" THIN WALL TUBE  
*U* = 3" THIN WALL TUBE  
*C* = NX ROCK CORE

**WATER INFORMATION**  
See p. 1 of 9

*Note: Photo indicated core loss, but was trace fossil at 70.1'
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**Note:** core barrel jammed, drill induced fractures 112' and 118'-121'

120.4' (last core run 1-11-90)

LIMESTONE (Austin Chalk), medium, fresh, sound, light gray, arillaceous with occasional very argillaceous layers, trace fossils, and fossil partings
## LOG OF BORING

### PROJECT:
Superconducting Supercollider

### CLIENT:
The Earth Technology Corporation

### TASK NO.:

### DATE:
1-12-90

### TYPE:
NX Core

### CASED TO:
21.0'

### CONTRACTOR:
SwL

### BORING NO.:
BE 5 PG 4 OF 9

### LOCATION:
E 2245.051

### GROUND EL:
462.51 feet

### SAMPLE LEGEND
- **S** = SPLIT SPOON
- **T** = 2" THIN WALL TUBE
- **U** = 3" THIN WALL TUBE
- **C** = NX ROCK CORE

### WATER INFORMATION
See p. 1 of 9

### DESCRIPTION OF STRATUM

**LIMESTONE (Austin Chalk) medium, fresh, sound, light gray, argillaceous with occasional very argillaceous layers, trace fossils and fossil partings**

- fossil partings at 125.3' and 129.4'

- slightly more argillaceous layer gradational contact from 131.0' to sharp contact at 133.7'

- fossil partings at 137.3'

- more argillaceous layer gradational contact from 138.0' to sharp contact 140.0'

- more argillaceous layer gradational contact from 141.0' sharp contact at 148.0'

- 1" shale layer at 148.0'

- fossil parting at 149.6'

- slight fossil increase 156' - 160'

- fossil partings 157.8' - 158.6'

- bedding plane partings 155.5' and 159.7'

- bentonite seam 159.7'

- more argillaceous layer gradational contact from 159.0' to sharp contact at 159.7'

---

**DRILLING GEOLOGIST**
Ron Randall

**ASSISTANT**
Dale Brown

**CHECKED BY**

---

**DRAFT**
**LOG OF BORING**

**PROJECT:** Superconducting Supercollider  
**CLIENT:** The Earth Technology Corporation  
**TASK NO.:**  
**DATE:** 1-12-90  
**TYPE:** NX Core  
**CASED TO:** 21.0'  
**CONTRACTOR:** SwL  
**LOCATION:** N 278,967 feet  
**GROUND EL:** 462.51 feet

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**DESCRIPTION OF STRATUM**

- LIMESTONE (Austin Chalk) medium, fresh, sound light gray, argillaceous with occasional very argillaceous layers, trace fossils and fossil partings  
  - slightly more argillaceous layer gradational contact from 164.5'-165.4'  
  - fossil partings 165.1', 169.0' and 169.3'

- argillaceous layer gradational contact from 171.1' to sharp contact at 171.6'  
  - fossil partings 172.6', 173.7', 175.6' and 180.7'

- 60° joint, planar, slickensided, groved, closed at 179.0'

- 2-75° shears parallel 1" apart, both calcite filled 1/" healed, disturbed limestone with calcite between the shears, trace pyrite  
  - 182', 60° joints, groved, slickensided, closed approximately 20° rotation at each other  
  - clay chalk layer gradational contact from 186.1'  
  - sharp contact at 186.8' and gradational contact from 189.2' to sharp contact at 189.6'  
  - shale seams 186'-189'

- 3/4 fossiliferous layer 196.0'  
  - argillaceous layer gradational contact from 198.0'-199.

- 1/8" burrow hole 200.3'-200.7'

**DRILLING GEOLOGIST** Ron Randall  
**ASSISTANT** Dale Brown  
**CHECKED BY**

[DRAFT]
**LOG OF BORING**

**PROJECT:** The Superconducting Super collider

**CLIENT:** The Earth Technology Corporation

**TASK NO.:** 3J9R5NG

**LOCATION:**
- N 278,967 feet
- E 2,245,051 feet

**GROUND EL.:** 462.51 feet

**DATE:** 1-12-90

**TYPE:** NX Core

**CASED TO:** 21.0’

**CONTRACTOR:** SwL

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**S =** SPLIT SPOON

**T =** 2” THIN WALL TUBE

**U =** 3” THIN WALL TUBE

**C =** NX ROCK CORE

**WATER INFORMATION**

See p.1 of 9

---

**ASSISTANT** Dale Brown

**CHECKED BY**

---

**DESCRIPTION OF STRATUM**

LIMESTONE (Austin Chalk), medium, fresh, sound, light gray, argillaceous with occasional very argillaceous layers, trace fossils and fossil partings.

-60° joints at 202.1' and 203.3', 180° opposite direction, grooved, planar, slickensided, closed

-70° joint at 216.3', grooved, planar, slickensided, closed

-two intersecting joints 60° at 219.8', grooved planar, slickensided, closed

-65° joint at 224.2', grooved, planar, slickensided, closed

-more argillaceous layer gradational contact from 226.0' to sharp contact at 227.4'

-2-60° joint at 232.5', grooved, planar, slickensided, closed, 20° off rotation

-65° joint at 233.7', grooved, planar, slickensided, closed

-fossiliferous layer 239.8'-240.0'

-very argillaceous layer gradational contact from 242.8' to sharp contact at 243.8'

-very argillaceous layer gradational contact from 245.5' to sharp contact at 245.8'

-very argillaceous layer gradational contact from 247.1' to sharp contact at 247.6'

---

**DRILLING GEOLOGIST** Ron Randall

**ASSISTANT** Dale Brown

**CHECKED BY**

---

**DRAFT**
**LOG OF BORING**

**PROJECT:** Superconducting Supercollider

**CLIENT:** The Earth Technology Corporation

**DATE:** 1-12-90

**TYPE:** NX Core

**Cased To:** 21.0'

**LOCATION:** N 278,967 feet E 2,245,051 feet

**GROUND EL:** 462.51 feet

**DEPHT IN FEET** | **SYMBOL** | **SAMPLE TYPE & NUMBER** | **DEPTH RANGE** | **PERCENT REC.** | **PERCENT ROD.** | **STANDARD PENETRATION TEST PER 6 INCHES** | **HAND PEN. TFSF.** | **SAMPLE LEGEND** | **WATER INFORMATION** |
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- **LIMESTONE (Austin Chalk)**
  - clayey chalk 243.0'-243.7'
  - more fossiliferous at 243.0'-250.4'
  - 30° healed joint at 244.0'
  - 60° joint at 248.9'
  - pyrite nodule at 245.6'

- Last core run 1-12-90
  - more argillaceous gradational contact from 251.0' to 252.0'
  - pyrite nodule at 252.0'
  - fossil partings at 253.4', 255.3', 257.3, 258.2', 258.8', 259.3', and 260.0'
  - very argillaceous layers with thin shale layers sharp contact from 255.4'-256.0'
  - bedding plane parting 256.1' with broken shell fragments
  - numerous broken fossil fragments 258.0'-262.0'
  - 60° shear with calcite fill extending in core from 262.0'-272.0'
  - 70° joint at 263.1', closed, healed, planar, gorge between the two joints
  - 45° joint at 263.2', planar, gravel
  - numerous fossil debris 263.3'-265.5'

- more fossiliferous 269.0'-278.0'
  - fossil partings 268.6', 269.0', 269.8', 271.1', 273.2', 275.0', 275.8', 276.3', 277.1, and 277.7'
  - 1" fossil bedding planes at 270.2' and 275.0'
  - reworked sediment, light gray at 269.0'-278.0'
  - 1½" shale layer at 275.8'

**ASSISTANT:** Dale Brown

**CHECKED BY:**

**DRILLING GEOLOGIST:** Ron Randall
## LOG OF BORING

**PROJECT:** Superconducting Supercollider  
**CLIENT:** The Earth Technology Corporation  
**TASK NO.:**  
**DATE:** 1-13-90  
**TYPE:** NX Core  
**CASED TO:** 21.0'  
**CONTRACTOR:** SwL III  
**GROUND EL:** 462.51 feet  

### LOCATION

- N 278,967 feet  
- E 2,245,051 feet  

### SUMMARY

- **SAMPLE LEGEND:**
  - S = SPLIT SPOON  
  - T = 2" THIN WALL TUBE  
  - U = 3" THIN WALL TUBE  
  - C = NX ROCK CORE

- **WATER INFORMATION:** See p. 1 of 9

### DESCRIPTION OF STRATUM

- **LIMESTONE (Austin Chalk), medium, fresh, sound, light gray to gray, argillaceous with occasional argillaceous layers, trace fossils and fossil parting:**  
  - Fossil partings at 278.0', 279.5', 280.0' and 282.0'
  - Numerous fossils and sediment filled burrows 281.1'-289.9', light gray and gray
  - 3/4" broken fossil layer 281.0'
  - Very argillaceous layer gradational contact from 281.5' to sharp contact at 282.5'
  - Fossil partings at 288.9', 289.8', 292.6', 293.7', 293.9', 295.3', 297.4' and 297.8'
  - Very argillaceous layer gradational contact from 295.4' to sharp contact 295.7'
  - 45° shear 295.7, planar, grooved, closed 11" bentonite layer at 295.7'
  - Very argillaceous layer gradational contact from 300.0' to sharp contact at 300.4'
  - Shale layer 300.4'-301.0'
  - Fossil partings at 298.5', 301.1', 301.5', 301.8', 305.5', 306.8', and 307.4'
  - Gray sediment filled burrows 308.0'-311.5'
  - Color change in limestone to gray at 311.6'
  - More argillaceous layer gradational contact from 313.0'-314.5'
  - Fossil partings at 308.8', 310.5', 311.0', 313.6', 314.0', 315.2', and 317.2'
  - Bentonite shale gradational contact from 318.6' to sharp contact at 319.4'
  - Bentonite shale gradational contact at 319.4' to sharp contact at 320.1'
  - Trace bentonite at 318.7'
  - 1/4" bentonite layer gradational contact 320.1'

---

**DRILLING GEOLOGIST:** Ron Randall  
**ASSISTANT:** Dale Brown  
**CHECKED BY:** 

---

**DRAFT**
## LOG OF BORING

**PROJECT:** Superconducting Supercollider  
**CLIENT:** The Earth Technology Corporation  
**LOCATION:**  
- **N:** 278,967 feet  
- **E:** 2,245,051 feet  
**GROUND EL:** 462.51 feet

### TASK NO.:
- **DATE:** 1-11-90  
- **TYPE:** NX Core  
- **CASED TO:** 21.0'  
- **CONTRACTOR:** SwL

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### SAMPLE LEGEND
- **S:** SPLIT SPOON  
- **T:** 2" THIN WALL TUBE  
- **U:** 3" THIN WALL TUBE  
- **C:** NX ROCK CORE

### WATER INFORMATION
- See p. 5 of 9

### DESCRIPTION OF STRATUM

**LIMESTONE (Austin Chalk), medium, fresh, sound, gray, argillaceous layer, with occasional very argillaceous layer, trace fossils and fossil partings**

- 45° joint at 320.0', planar, grooved, slickensided, closed  
  - fossil partings 321.7' and 324.0'

- 30° fracture at 330.0', irregular  
  - very argillaceous layer 331.0'-331.3'

---

**DRILLING GEOLOGIST** Ron Randall  
**ASSISTANT** Dale Brown  
**CHECKED BY**
APPENDIX B

RAW DATA FROM MICROHYDRAULIC FRACTURING TESTS

Test BE5-A
Test BE5-B
Test BE5-C
Test BE5-D
Test BE5-E
Test BE5-F
Test BE5-G
Test BE5-H
Test BE5-I
Test BE5-J
TEST: BE5-A
FORMATION: Austin Chalk
DEPTH: 326 feet
DATE OF FIELD TEST: January 27, 1990
TEST: BE5-B
FORMATION: Austin Chalk
DEPTH: 292 feet
DATE OF FIELD TEST: January 29, 1990

This test was unsuccessful because of pressure transducer problems.
TEST: BE5-C
FORMATION: Austin Chalk
DEPTH: 210 feet
DATE OF FIELD TEST: January 29, 1990
CUSTOMER: RE/SPEC
DATE: 01/29/80
TYPE JOB: STRESS TEST
TIME
FORMATION: AUSTIN CHALK
TICKET #1
(GPMS. 2)
TEST: BE5-D
FORMATION: Austin Chalk
DEPTH: 303 feet
DATE OF FIELD TEST: January 29, 1990
TEST: BE5-E
FORMATION: Austin Chalk
DEPTH: 192 feet
DATE OF FIELD TEST: January 29, 1990
TEST: BE5-F
FORMATION: Austin Chalk
DEPTH: 162 feet
DATE OF FIELD TEST: January 30, 1990
TEST: BE5-G
FORMATION: Austin Chalk
DEPTH: 152 feet
DATE OF FIELD TEST: January 30, 1990
TEST: BE5-H
FORMATION: Austin Chalk
DEPTH: 127 feet
DATE OF FIELD TEST: January 30, 1990
TEST: BE5-I
FORMATION: Taylor Marl
DEPTH: 107 feet
DATE OF FIELD TEST: January 30, 1990
TEST: BE5-J
FORMATION: Taylor Marl
DEPTH: 77 feet
DATE OF FIELD TEST: January 30, 1990
16:36:32 Event # 1 Start Job
16:56:51 Event # 2 End Job
APPENDIX C

FORMATION MICROSCANNER DATA

RAW FMS DATA
COLOR ENHANCED FMS
COLOR ENHANCED FMS, INTERPRETED VIA FLIP

Note: the depths mentioned on the enclosed FMS logs are 5.3 feet deeper than the depths recorded by the driller.
COLOR-ENHANCED FMS INTERPRETED VIA FLIP
APPENDIX D

LABORATORY HYDRAULIC FRACTURE TESTS
D.1 INTRODUCTION

Each microhydraulic fracturing tests involved several cycles of pressurization and depressurization. The difference between the fracture reopening pressure, $P_r$, and the initial breakdown pressure, $P_b$, is a measure of the apparent in situ tensile strength, $T$, of the rock mass. In order to compare the field-deduced tensile strength with laboratory data, a series of laboratory hydraulic fracturing tests were conducted on representative samples.

D.2 TENSILE STRENGTH SIZE EFFECT

Rocks are known to exhibit a strength size-effect in the laboratory hydraulic fracture test [e.g., Haimson, 1968; Ratigan, 1982]. Size effects in the microhydraulic fracture test are discussed in Ratigan [1990]. Laboratory testing of the rock specimens was performed with two different sized pressurized boreholes. The Austin Chalk was the only rock type tested in the laboratory.

When intact rock samples are taken into the laboratory and tested to determine tensile strength, three observations are invariably made.

1. The apparent tensile strength depends upon the sample size (the larger the specimen, the smaller the strength).

2. The apparent tensile strength depends upon the type of test being performed.

3. With any given test and specimen size, a scatter (usually skewed) about the mean is obtained.

The first dilemma (commonly referred to as the size effect) is also observed with respect to compressive strength and an apparent Young's Modulus, although to a lesser extent than with tensile strength (i.e., Heuze [1980]). However, the observation has prompted many investigators to recognize that tensile strength of brittle rock at the usual laboratory scale for many rocks is not a material property (e.g., Hudson and Fairhurst [1969]). The second observation noted above has been brushed away by using different names to refer to the strength observed in different tests. For example, the apparent tensile strength in bending is referred to as the Modulus of Rupture. The tensile strength determined by indirect tension tests is often referred to with an adjective taken from the test; for example, the Brazilian tensile strength or the split cylinder tensile strength. The third observation above is often totally neglected in the reporting of test results. Scatter about the mean is often attributed to testing methodology and/or sample inhomogeneity. Thus, more often than not, the only result of the tensile testing may be the mean without the standard deviation or any of the other statistical moments.
D.3 LABORATORY HYDRAULIC FRACTURING TESTS

The specimens used in the laboratory hydraulic fracture test were fabricated from nominally 2-inch-diameter core to lengths of approximately 4 inches. All samples tested were identified with a unique identification. A typical identification number is

\[ \text{BE-5/161/3/1} \]

where

\begin{align*}
\text{BE-5} & = \text{location of coring (Borehole BE5)} \\
161 & = \text{depth (feet) from which core was removed} \\
3 & = \text{sequential number of piece of core} \\
1 & = \text{the portion of the original piece/piece number resulting from preparation process}
\end{align*}

Each specimen was sawn to length and the ends were lapped until smooth and parallel. An internal borehole was drilled (axially) part way through the center of the specimen. A distance of approximately 1 inch was maintained between the bottom of the internal borehole and the end of the specimen. A steel tube, which extended about 1 inch above the specimen, was epoxied in the borehole. The end of the tubing fitted into the loading platen and an O-ring provided a hydraulic seal.

The laboratory specimen was loaded axially with a load sufficient to resist horizontal fracturing. An axial stress of approximately 300 psi was used when testing the Austin Chalk. The borehole was pressurized at a nearly constant rate of approximately 250 psi/minute. All specimens were monitored with acoustic emission instrumentation to determine if fracturing occurred before the peak pressure was attained.

Two internal borehole diameters were tested; 0.25 inch and 0.50 inch. The results of the testing are shown in Table D-1. The strength size effect (decrease in strength with increasing borehole size) illustrated is dramatic. An increase in borehole diameter from 0.25 inches to 0.50 inches resulted in a decrease in strength by a factor of about 2. In comparison, Haimson [1968] found a strength decrease of less than 20 percent for a similar increase in borehole size when testing Tennessee Marble. Ratigan [1981] found a strength decrease of about 10 percent for a similar increase in borehole diameter for Stripa granite. Clearly, the laboratory strengths in Table D-1 are far greater than the strengths that are exhibited in situ. The laboratory hydraulic fracture strengths are also significantly larger than the typical Brazilian tensile strength of Austin Chalk, approximately 250 psi [Bailey, 1990] and the tensile strength inferred from the field tests, between 0 and 163 psi.
Table D-1. Laboratory Hydraulic Fracture Tests

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Internal Borehole (inches)</th>
<th>Burst Pressure (psi)</th>
<th>Tensile Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BE-5/161/2/1</td>
<td>0.5</td>
<td>539</td>
<td>611</td>
</tr>
<tr>
<td>BE-5/108/5</td>
<td>0.5</td>
<td>294&lt;sup&gt;(a)&lt;/sup&gt;</td>
<td>333&lt;sup&gt;(a)&lt;/sup&gt;</td>
</tr>
<tr>
<td>BE-5/209/6/1</td>
<td>0.5</td>
<td>390</td>
<td>442</td>
</tr>
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<td>BE-5/161/1/1</td>
<td>0.25</td>
<td>869</td>
<td>897</td>
</tr>
<tr>
<td>BE-5/161/3/1</td>
<td>0.25</td>
<td>882</td>
<td>910</td>
</tr>
<tr>
<td>BE-5/161/3/2</td>
<td>0.25</td>
<td>919</td>
<td>948</td>
</tr>
</tbody>
</table>

<sup>(a)</sup> Horizontal fracture.

D.4 REFERENCES


