HIGH RESOLUTION SEISMIC

MAPPING OF A

SHALLOW AQUIFER

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Graduate Studies and Research
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By
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ABSTRACT

In the past, geological analysis did not often incorporate seismology into integrated environmental studies. This was due in part to the expense of running multi-fold reflection surveys, and additionally the lack of expertise of the individuals involved in the environmental and groundwater fields. However, in recent history, the progress of technology and increasing need for more detailed non-invasive investigations of subsurface geology has encouraged the use of imaging methods such as CDP reflection seismology.

The Dalmeny project was designed to address many of the issues related to the differences between a standard petroleum seismology survey and a shallow survey in glaciated areas. These differences exist in three principle areas: survey design and data acquisition (CDP reflection profiling), data processing, and interpretation.

The post-Cretaceous geology of central Saskatchewan is composed of several till and sand units (e.g. Dalmeny aquifer) and a non-glacial incised valley aquifer (Tyner Valley aquifer). The sands of the Dalmeny and Tyner Valley are major aquifers and were the principle targets for reflection surveying.

Utilisation of wave equation modelling in the survey design process provided opportunities to optimise survey parameter values economically. Additionally, the use of non-standard acquisition techniques provided enhanced data quality and increased resolution over previous shallow seismic surveys.

Rigorous interpretation techniques have been used to extract as much information as possible from the Dalmeny data set. Advanced interpretation techniques such as
complex trace attribute analysis and velocity inversion were attempted. Results indicate interesting variation and complexities which were not apparent on the standard section. Near surface analysis of refraction information was used to quantify elastic properties (velocities) for the highly weathered shallow (< 10 m) strata.

The results of the Dalmeny project provided have shown that the acquisition of high frequency (> 200 Hz) seismic data is possible in a glaciated terrain. The detailed analytical procedure used in obtaining the acquisition parameters facilitated these results. Enhanced data processing using advanced algorithms available for conventional seismology significantly increased the frequency content and data quality.
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<tr>
<td>AGC</td>
<td>Automatic Gain Control</td>
</tr>
<tr>
<td>CDP</td>
<td>Common Depth Point</td>
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<tr>
<td>COFF</td>
<td>Common Offset Stack</td>
</tr>
<tr>
<td>F-K</td>
<td>Frequency-wavenumber</td>
</tr>
<tr>
<td>Ka</td>
<td>Thousands of years</td>
</tr>
<tr>
<td>Ma</td>
<td>Millions of years</td>
</tr>
<tr>
<td>NMO</td>
<td>Normal Moveout</td>
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<td>RMS</td>
<td>Root Mean Square</td>
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CHAPTER 1

Introduction

1.1 High Resolution Seismology in Engineering and Environmental Applications

Geophysics has become an integral part of environmental and geotechnical investigations in the last part of the twentieth century. Within recent years, the use of non-invasive geophysical techniques, such as seismic reflection and refraction (Lankston, 1990), potential fields (Hinze, 1990), electromagnetic (Goldstein, et. al, 1990), ground probing radar (Annan et. al., 1991), VLF (McNeill, 1990), resistivity (Ward, 1990) and radioactive methods have been implemented in varying situations to image shallow, near surface geology. These methods have been utilised both on surface and within boreholes (Daniels and Keys, 1990).

While seismic reflection survey methods have been available as standard techniques in petroleum exploration for the last 70 years, application of the technique to shallow targets has only been attempted in the last 20 years (Steeples and Miller, 1990). The standard assumptions inherent in both applications are the same, however, the equipment which is directly suitable to measure data recorded in the shallow environment has been available only since the late 70's. The major differences between the deeper investigations and the shallow studies are in the thinner layers imaged and the smaller depths of detection. These differences in spatial conditions of the geology demand
differences in survey geometry and recording characteristics (Steeples and Miller, 1991).

The particular characteristics of these shallow thin beds require significantly higher frequencies (100 - 500 Hz) than those used in the petroleum industry (25 - 80 Hz). To record these higher frequencies, the equipment must have the ability to record considerably higher digital sample rates (e.g. < 1 ms). These higher frequency rate analog to digital converters were only developed in the last 20 years (Steeples and Miller, 1991).

In recent years, a number of techniques have been designed to take advantage of the special considerations of shallow seismic profiling. One of the most popular is the “optimum offset” technique, developed at the Geological Survey of Canada by J. Hunter and others (Slaine et al., 1990). The optimum offset technique utilises a window of offsets designed from field test records (or expanding spreads). In this way, the available channels are used effectively and the trace spacing is set by the “optimum” window and available data recording channels. The particular strength of the “optimum offset” technique is the efficient approach for depth to bedrock studies where a large velocity contrast is often evident. The technique is also very suitable in areas of structure where changes in acoustic properties are also significant (Pullan and Hunter, 1990). The primary limitations are in the lower signal to noise ratio inherent due to the lack of stacking.

However, since the early 80’s, conventional CDP reflection survey procedures have increasingly been utilised in shallow complex geological environments. Wolfe and Richard (1990) describe an integrated geophysical study over a buried valley. In the American mid-west, Steeples and Miller (1990) and others are commonly implementing conventional CDP techniques for mapping of shallow geologic targets. These surveys
may include: imaging depth to the top of the bedrock (Miller et. al, 1989), pollution monitoring (Birkelo et. al., 1987, Miller and Steeples, 1990), and identification of large structural anomalies (e.g. grabens - Miller et. al., 1990). Within the coal seams in the American Appalachian region, palaeo-channel anomalies are a significant mining hazard. The use of high-resolution seismic techniques has afforded mining companies an opportunity to properly evaluate the existence and extent of these channels and modify mining activity accordingly (Goichioco and Kelly, 1990).

Comparable investigations are also conducted in other parts of the world. Recent advances in instrumentation have allowed workers in Denmark to use high resolution seismic reflection to map and interpret shallow aquifers using sequence stratigraphy (Olsen et. al., 1993).

1.2 Previous Geophysical Investigations in the Dalmeny Area

The first step before further studies were initaited, was the investigation of previous geophysical work in the Dalmeny area. The intent was to ensure that geophysical studies would provide guidance on elastic properties (velocities) necessary for the adequate planning of a reflection survey. Unfortunately, very little geophysical work has been undertaken in the Dalmeny area, or for that matter, similar areas in central Saskatchewan.

Only two studies are known to have been performed. The most recent was performed by Doug Neilson (unpublished M. Sc. thesis, 1993), and is discussed in chapter 3. The only other known geophysical investigation in the region was an integrated Transient Electromagnetic (TEM) survey and seismic survey near the Dalmeny
test well by Multiview Geoscience (Mark Simpson, personal communication). The purpose of the Multiview investigation was to compare data from an undisturbed area (Dalmeny) to possible altered or disturbed tailings ponds at a potash mine site.

The seismic data was collected using the "optimum offset" technique of Hunter and others (Hunter et. al., 1982). The final section consisted of 144 traces with a 5 m trace spacing. The poor data quality, caused by the use of sledge hammer sources and single fold configuration, limited the use of this data in the Dalmeny project analysis. Additionally, errors were made in the final interpretation due to erroneous assumptions about the near surface velocity structure. After careful analysis, the conclusion was reached that little of substantial value could be obtained from this data, and that information for modelling must be obtained from more reliable sources, such as Neilson (1993).

1.3 Dalmeny Project Objectives

The primary objective of this project is to establish a more rigorous methodology for the application of high resolution CDP reflection profiling in a glacial till terrain. In this way, the optimal seismic reflection acquisition and processing parameters and field methodologies for the subsurface mapping of shallow glacial aquifers could be determined.

The second goal was to map, with the highest possible detail, the depositional irregularities within the various till and gravel units which form the stratigraphy of the Dalmeny study area. The use of CDP profiling should significantly enhance the resultant image of the shallow geological environment. The method should provide for the
resolution of thin (< 5 m) layers within the near surface geology.

The lack of significant information on the acoustic properties of the till was discovered in the course of literature searches. An attempt was made to better delineate poorly understood acoustic properties of till and to study the near-surface attenuation of acoustic signals.

1.4 Dalmeny High Resolution Seismic Survey

1.4.1 Site Location

Upon consultation with the co-sponsors of the project, the Saskatchewan Research Council (SRC), a site just north of Saskatoon known as the Dalmeny test site, was chosen for the field acquisition portion of this project (Figure 1.1). This particular site was selected because of three criteria:

1) easy access from the University to the site,

2) relatively good geologic control in the immediate area (two deep groundwater wells),

3) excellent road access for vehicles during the survey acquisition stage.

1.4.2 Methodology

In the past, environmental and petroleum seismology have been distinctly separate in their approaches to acquisition design. This was partly due to the significant effects of scale (time and space) as well as to the economics of cost recovery in petroleum versus expense in the environmental field. However, in recent history, the development of
Figure 1.1. Location map for the Dalmeny project (modified from Keller, 1985)
equipment suitable for shallow seismology has progressed to the extent that rigorous large fold CDP reflection techniques can be applied to the shallow near surface. The Dalmeny project was initiated to address these differences in three principle areas: survey design and data acquisition (CDP reflection profiling), data processing, and interpretation.

The application of wave equation modelling to the survey design process is not commonly attempted. This procedure affords the opportunity to test a large number of survey parameter values economically. The rigorous analysis of the survey design procedures in a new environment with few guidelines requires that techniques be utilised to examine all possible values for the geometrical and recording parameters. While certain well established guidelines exist (e.g. Steeples and Miller, 1991), their applicability within a glaciated environment such as that in the Canadian Prairies was uncertain. Therefore, examination of parameter values beyond the limits of these guidelines increased the chances that optimal values were used. It was felt in the beginning of the project that, with no useful seismological information in the study area, few constraints (except financial) should be placed on the survey design.

The utilisation of the CDP profiling technique, in which most of petroleum seismic data is acquired (Dobrin and Savit, 1988), provides a highly detailed image of the shallow near-surface geology. The use of non-standard acquisition techniques such as very small sources and receivers below the surface provides enhanced data quality.

Data enhancement routines used previously in shallow reflection processing have tended to remain unsophisticated. This was primarily due to the relatively simple survey geometry (e.g. "optimum offset" or refraction) and lack of available algorithms on existing personal computers. The availability of a wealth of untried algorithms (for high
resolution seismology) on a high-end UNIX processing system (Insight Processing System - Landmark, 1994) provided an opportunity to rigorously investigate possible processing techniques necessary to enhance the high resolution shallow reflection data.

Since the CDP reflection technique contains a significant amount of information, rigorous interpretation techniques were undertaken to extract as much information as possible. Beyond standard horizon picking, analysis by the use of complex trace attributes and velocity inversion was also attempted. Velocity inversion was attempted to analyse lateral velocity variations and enhance the seismic interpretation of the local geology.

To rigorously provide detailed analysis of the elastic properties for near-surface weathered tills, the calculation and interpretation of the refraction velocities and depths was undertaken.
CHAPTER 2
Glacial Geology of the Dalmeny Area

2.1 Introduction

The near-surface stratigraphy of central Saskatchewan is dominated by deposits formed by glaciation during the Quaternary (Figure 2.1). Guided by chemical analysis and lithological interpretation, stratigraphic variations were defined within these shallow semi-consolidated deposits. Basic descriptions and stratigraphy are provided for the known units within the shallow sub-surface.

2.2 Stratigraphy

2.2.1 Empress Group

Throughout central and southern Saskatchewan, shallow aquifers commonly occur within incised valleys (Whitaker and Christiansen, 1972) which were formed by fast-flowing rivers eroding into the underlying rocks (primarily Cretaceous shales). These valleys are commonly filled with sediments of the Empress Group. A typical example is the Tyner Valley, which has cut into the underlying Cretaceous Lea Park Formation. The lower portions of the Tyner Valley are of Pliocene (Tertiary) age, whereas the upper sections were revealed to be very Early Pleistocene (Quaternary) (Whitaker and Christiansen, 1972). In the study area, the Tyner Valley is composed of sands,
Figure 2.1. Regional Quaternary stratigraphy of the Dalmeny area. Note that the division of the Dalmeny aquifer into two units is informal and used due to the expected reflectivity variations.

Elevation (m a.s.l.)
gravels and massive clays units bedded between the sand units.

2.2.2 Sutherland Group

The oldest Pleistocene deposits are of the Sutherland Group which contains three formations: the Mennon, Dundurn, and the Warman (Christiansen, 1992). They have been designated as pre-Illinoian in age (Figure 2.2). Each of these formations are composed of tills, pro-glacial sediments, and some non-glacial stratified sediments. The different types of lithologies reflect fluctuations in geologic conditions (Christiansen, 1992). The upper contact of the units is commonly considered to be the top of the non-glacial sediments, or weathered zones. In hand samples and cuttings, the formations are almost indistinguishable (B. Schreiner, personal communication). In most cases, the tills can only be distinguished from each other on the basis of the carbonate (CO$_2$) content or trace element analysis (Schreiner, 1990). Even geophysical logs (single point resistance and spontaneous potential) do not exhibit a significant response contrast between the individual formations.

The oldest formation of the Sutherland, the Mennon, is composed mainly of unoxidized till, but also includes stratified deposits (interbedded sands) (Christiansen, 1992). Although this is currently considered to be one formation, there is evidence (carbonate content) to suggest that more than one till exists within this unit (Christiansen, 1992). However, this unit does not occur at the Dalmeny site.

The overlying formation, the Dundurn is the thickest and more prevalent of all the Sutherland tills. It is easily differentiated from the underlying Mennon till by the very distinct values of carbonate content (Schreiner, 1990). The Dundurn is characterised by
Figure 2.2. Quaternary stratigraphy of central Saskatchewan (based on Schreiner, 1990). Note divisions in the Dalmeny aquifer are informal and used solely due to expected variations in elastic properties (velocity and density).
fairly large quantities (relative to the other Sutherland tills) of sand, silts, and clay. In some places, the content of sands and silts can reach up to 50% of the total volume. As in the Mennon, carbonate changes suggest the presence of two tills, however, the lack of weathering events reduces the confidence in further differentiating these tills (Christiansen, 1992).

The uppermost till is the Warman Formation and can be differentiated from the underlying Dundurn on the basis of lower carbonate content (similar to the Mennon till). The base of this formation is marked by a thin oxidised zone at the top of the Dundurn, and its unconformable relationship above the Dundurn. The unit is composed of till with large amounts of clay (Christiansen, 1992). This unit is also not found at the Dalmeny site.

The Sutherland Group is thought to have been deposited during earlier glaciations at ages greater than 40 Ka (Christiansen, 1968b). It is believed that there were at least three distinct glacial phases, the evidence for which is the marked change in carbonate content within the Sutherland Group. There is also some evidence for up to five distinct glacial events (Christiansen, 1992).

2.2.3 Saskatoon Group

The Saskatoon Group consists of the Floral and Battleford formations. These have been dated from Illinoian to Late Wisconsinan in age (from 38 Ka to 18 Ka - Figure 2.2) (Christiansen, 1992).
2.2.3.1 Floral Formation (Lower Member)

The Floral Formation consists of two compositionally identical tills, separated by a locally extensive sand/gravel deposit, known as the Riddell member. The lower Floral (Illinoian) till can be differentiated from the underlying tills of the Sutherland Group mainly on chemical composition (carbonate content), rather than in hand sample or cuttings (Christiansen, 1992). This unit is believed to represent a distinct (in relation to the Sutherland) glacial phase due to the contrast in the carbonate content and an interpreted unconformity. Within the study area, it is composed of significant amounts of clay and sand as well as till.

2.2.3.2 Floral Formation (Riddell Member)

Near the end of the deposition of the lower Floral till, a significant geologic event occurred represented by the Riddell Member. Within the study area, this event consists of a non-glacial period representing an extended time of non-glaciation, broken only by a short glacial period. The lithology consists of a significant sand and gravel unit representing the non-glacial period and the glacial event is represented by an sparsely deposited till. The non-glacial sands and gravels contains large volumes of ancient flora and fauna, which have been dated at around 38 Ka (Late Rancholabrean age) (SkwaraWoolf, 1981). This suggests that the ice frontal position during most of the time of Riddell deposition was at a significant distance from the Saskatoon area.

Informal names applied to the Riddell Member in the study area designate the lower unit of gravels as the lower Dalmeny aquifer and the upper sand unit as the upper Dalmeny aquifer. This informal designation of an upper and lower aquifer occurs due
only to the presence of this sparsely deposited till (e.g. within the study area) (B. Schreiner, personal communication). South and east of Saskatoon, the Riddell Member is known as the Forestry Farm aquifer and is a stratigraphic equivalent of the Dalmeny.

2.2.3.3 Floral Formation (Upper Member)

The overlying formation is that of the upper Floral till. Although this till represents another distinct glacial event, it is impossible to distinguish the upper and lower Floral tills based on chemical differences (Christiansen, 1992). Whereas the lower till is Illinoian in age, the upper till is thought to be Early Wisconsinan. The upper contact of the upper Floral is marked by a significant weathered zone and boulder pavement at the base of the overlying Battleford Formation (Christiansen, 1968a).

2.2.3.4 Battleford Formation

The Battleford Formation (Late Wisconsinan) represents the last distinct glacial event in the Saskatoon area till (Christiansen, 1968a). However, it is not found in the Dalmeny study area, possibly because of non-deposition, or erosion by later post-glacial events (e.g. scouring by the ancient North/South Saskatchewan River system and the associated glacial Lake Saskatchewan) as the glacier retreated around 12 Ka.

2.2.4 Surficial Deposits

The extensive surficial deposits consist of many non-glacial types of strata, including lacustrine, outwash sediments (glacial Lake Saskatchewan), eolian and landslide deposits. The lacustrine deposits reflect the final pro-glacial stage, as Lake
Saskatchewan flooded the area in front of the ice sheets (Christiansen, 1979). During the formation of this lake, deltas of the North and South Saskatchewan Rivers were being formed, and added upward coarsening sands and clays. Some of the sediments were formed by the drowning of large areas of exposed ice.

2.3 Summary

Understanding the Pleistocene geology of central Saskatchewan hinges on the comparison of the glacial processes that shaped the region. The resultant near surface stratigraphy is simple and without significant structural features. Studies of the Pleistocene stratigraphy are important for understanding the consequences of groundwater and pollution interaction in the shallow formations.
CHAPTER 3

Modelling and Survey Design

3.1 Introduction

Modelling represents a process where the theoretical elastic responses are computed for a specified geologic stratigraphy (Mooney, 1983). The modelling was undertaken with two objectives in mind: 1) to determine expected frequency responses and the resulting resolution limits for the expected stratigraphy, and 2) to test various acquisition parameters to optimise the survey design. In case one, the seismic parameters were held constant while the geologic models were changed; whereas in the second case, the models were held constant and the seismic parameters were changed.

3.2 Reflectivity Modelling

The reflectivity or wavenumber integration method is one of a number of methods which are applied to simulate acoustic wave propagation through the earth (Müller, 1985). The software technique utilised for the present study is capable of computing responses where sources and receivers can be placed at arbitrary depths so that the influence of the free surface (air) can be considered. Also known as the wave-number integration method, it is a popular technique because surface waves can be included in the synthetic seismograms, producing a more realistic seismic trace.
3.2.1 Selection of Geological and Geophysical Parameters

The construction of an appropriate geological and geophysical parameter model was the first step in the modelling process. The geologic parameter consists of the thicknesses of the various stratigraphic units, while the associated geophysical parameters include the velocities (P and S), densities, and attenuation factors for each unit.

Due to the lack of published information about the mechanical parameters of glacial till in Saskatchewan, these geophysical parameters were derived or estimated from various secondary sources. The near-surface weathering layer and Floral Formation velocities (400 m/s and 1750 m/s) were obtained from the work of Neilson (1993) near Saskatoon (Goodale Farm) and Maymont. The aforementioned velocities were determined from interpretation of seismic refraction surveys and from computed interval velocities of reflection data (Neilson, 1993). The Lea Park Formation shale velocity (2300 m/s) was taken as an average value obtained through surveys conducted in many parts of southern Saskatchewan (D. Gendzwill, Z. Hajnal, personal communication). Velocities for the Dalmeny and Sutherland layers were derived by interpolation of the known densities for these layers.

The S-wave velocity ($V_S$) values for all layers were obtained by setting $V_S = 0.577 \times V_P$ (i.e. assume an estimated Poisson's ratio value of 0.25). (This is a very high value for tills, and is more applicable for rocks such as limestones. Recent work has determined that a more appropriate relationship for the S-wave velocities is $V_S = 0.277 \times V_P$ (B. J. Carr, personal communication)). The layer densities were taken from measurements on well cuttings and cores published by Sauer et al. (1993). The attenuation parameters ($Q_P$ and $Q_S$) used were calculated by the modelling software utilising velocity data and internal
conversion rules ($\alpha (Q_p)$ and $\beta (Q_S)$ rules) (Sierra, 1989). These steps were necessary since no Q estimates for till were available in the literature.

3.2.1.1 Frequency and Resolution Considerations

An acoustic modelling project requires estimates of the expected frequency range of seismic signals to properly compute synthetic records. Resolution of lithologies with particular dimensions (thickness and lateral extent) necessitate propagation of specific signal frequencies (Widess, 1973; Steeples and Miller, 1991). Ideally, the optimum situation is a signal frequency spectrum equal to that of an impulse response ($-\infty < f < \infty$).

Since the Earth acts as a low pass filter, seismic signal frequencies are typically less than 100 Hz (Dobrin and Savit, 1988; Sheriff and Geldart, 1995). In this discussion, for the purposes of clarity, the effects of acquisition equipment on the recorded spectrum were ignored.

3.2.1.1.1 Vertical Resolution

Based on the Widess's criterion (Widess, 1973) for vertical resolution, the most optimistic estimate of the vertical resolution limit is:

$$R = \frac{\lambda}{8} = \frac{v}{8f_0}$$

(3.1)

where $\lambda$ is the wavelength of the dominant frequency,

$f_0$ is the dominant frequency, and

$v$ is the velocity of propagation in the medium.

This solution assumes an ideal, noise free environment. However, in a more
realistic noisy field setting, the vertical resolution is better estimated by (Yilmaz, 1987):

\[ R = \frac{\lambda}{4}. \]  

(3.2)

A wave propagation velocity of 2000 m/s and a 200 Hz upper frequency limit would permit resolution of layer thicknesses of approximately 2 m to be resolved (Table A-1, Appendix A).

3.2.1.1.2 Horizontal Resolution

The important consideration to evaluate the horizontal resolution in seismic data is the "Fresnel zone". The first Fresnel zone is defined as the area enclosed by a wavefront after it has travelled one-quarter wavelength following impinging on the reflector surface (Sheriff, 1991; Steeples and Miller, 1991) (Figure 3.1). However, the "effective" Fresnel zone is defined by Sheriff (1985) as being equal to one-half of the first Fresnel zone, or, in other words, the radius of the first Fresnel zone. The equation for the first Fresnel zone radius (\(R_F\)) is given by (Sheriff, 1985) (Table A-1, Appendix A):

![Figure 3.1. Illustration of the first Fresnel zone (from Sheriff, 1991).](image-url)
\[ F_R = \frac{V_P \sqrt{t_0}}{2 \sqrt{f}} \]  

(3.3)

where \( V_P \) is the P-wave velocity in the layer,

\( f \) is the frequency of the wave in the layer,

\( t_0 \) is the two-way zero-offset travel time.

Steeples and Miller (1991) illustrated that this first-order approximation of the analytic expression is adequate for estimation of horizontal resolution for high resolution shallow reflection studies.

This equation (3.3) reveals that under known geological settings (Schreiner, 1990), lenses smaller than 10 m in diameter would not be resolved. Due to the sparse well control, current knowledge of laterally compact geologic units is limited. Therefore, defining the horizontal boundaries of any of these layers to any detailed accuracy (± 12 m) is not significant with the existing well density.

3.2.1.1.3 Summary

While it is preferable to have spatial resolution as small as possible, near-surface attenuation effects place severe limitations on the resolution limits. However, migration of the stacked data may further increase the horizontal resolution, offsetting some of these problems (Yilmaz, 1987).

Assuming thin units prevalent in the upper 50 metres in the Dalmeny area, it was apparent that the desirable vertical resolution limits would be on the order of 2 m.

Therefore, seismic frequencies of at least 200 Hz were required for mapping the essential features of shallow aquifers in the study area.
3.2.1.2 Geological Model

The final geological model utilised in the computations (Figure 3.2) represents the average thicknesses of the Dalmeny aquifer over the entire subcrop area (see chapter 2). It also incorporates a relatively thick (3 m) till layer within the Dalmeny aquifer which can be found in several locations in the Dalmeny subcrop area (B. Schreiner, G. Bowers, personal communication).

3.2.2 Theory of the Reflectivity Method

During elastic wave propagation within a homogeneous, isotropic, and perfectly elastic layered medium, seismic boundaries are created by discontinuities in acoustic impedance at layer interfaces. At the boundary, the critical parameters are the reflection and transmission coefficients which describe the difference in acoustic impedance (Müller, 1985). In a complete solution of a layered earth response, there are many reflection coefficients, one for every combination of incident, reflected, and transmitted P, S_v, and S_H waves, in both upward and downward propagation directions (Aki and Richards, 1980).

The propagation of seismic energy through a horizontally layered media is analytically solved by the integration of the horizontal wavenumbers (horizontal slowness) or reflectivities (reflection coefficients) at each interface above and below the source (Müller, 1985). Frequency dependence of the elastic properties during wave propagation is generally discounted in this type of modelling.

One of the most powerful aspects of the reflectivity method is that it can generate a complete wave solution. In addition to the primary waves, the method can yield
The Dalmeny model includes an interbedded till layer within the Dalmeny aquifer.

**Figure 3.2** Dalmeny model log plot of the geological/geophysical parameters. The model includes an interbedded till layer within the Dalmeny aquifer.
converted waves, multiples and Rayleigh (surface) waves into the final synthetic record (Müller, 1985). The resultant record bears a significantly greater similarity to actual field records than do synthetic records created with algorithms which incorporate only primary waves.

3.2.2.1 VESPA Method

One version of the reflectivity algorithm is incorporated into the VESPA (ViscoElastic Seismic Profile Algorithm) software routine (Sierra, 1989). The output response is created from the input model which contains computed reflection coefficients at each interface. These interfaces must be horizontal, homogeneous and isotropic and be separated by first order (simple) discontinuities (Müller, 1985) (Figure 3.3). The integration of the reflection coefficients is performed in the frequency domain, taking advantage of mathematical properties to reduce the 3-D partial differential equations to ordinary differential equations in F-K space (Sierra, 1989).

3.2.3 Selection of Seismic Acquisition Parameters for Modelling

Beyond the acoustic signal parameters necessary for modelling, estimates for seismic acquisition parameters are also required. These parameters include: trace spacing, offset (spread), source types/depths and receiver patterns/depths, sample rate and record length. Literature surveys and simplistic analyses were performed to quantify the values used for these parameters in the modelling process.
Figure 3.3. Illustration of the reflectivity model used by the VESPA program (Sierra, 1989).
3.2.3.1 Receiver Spacing

The receiver spacing is an essential parameter in the modelling process and a value of 2 m was initially chosen. Subsequent modelling and analysis revealed that a spatial aliasing problem can occur as a result of this selection (Figure 3.4). Spatial aliasing can be derived by (Steeples and Miller, 1991):

\[ x = \frac{v_s}{2f_s} \]  \hspace{1cm} (3.4)

where \( x \) is the trace spacing,

\( v_s \) is the surface wave velocity

\( f_s \) is the dominant frequency of the surface waves.

For example, at Dalmeny with \( v_s = 330 \text{ m/s} \), \( f_s = 140 \text{ Hz} \), the appropriate trace spacing to eliminate possible spatial aliasing of the surface wave is less than 1.2 m.

However, the use of receiver spacing smaller that 2 m is an unacceptable constraint, largely due to financial and logistical concerns. Upon closer examination of the original model for the near surface layer, it was apparent that using one solid 3 m thick layer with a 700 m/s velocity was unrealistic. Assuming the weathering patterns of soils from many parts of the world (Dobrin and Savit, 1988), a gradational velocity structure for this layer seems more appropriate. Thus, the model was adjusted to mimic a gradient such that the near surface consisted of three layers, each 1 m thick, with a gradational increase in P-wave velocities (Figure 3.5).
Figure 3.4. F-K spectrum of a shot record containing spatially aliased data.

Legend

A. First near surface layer - 330 m/s (aliased).
A2. Event due to mistake in modelling algorithm.
B. Second near surface layer - 850 m/s.
C. Deeper reflections (e.g. Dalmeny, Lea Park).
\[ V_p = 400 \text{ m/s, 1 m thick} \]

\[ V_p = 850 \text{ m/s, 1 m thick} \]

\[ V_p = 1300 \text{ m/s, 1 m thick} \]

Figure 3.5. Modifications to the model assuming a gradational near surface velocity structure.

3.2.3.2 Offset (Spread)

The model was computed with 96 traces in an end on survey geometry, which provided an enhanced view of NMO and makes survey design easier. The near offset is equal to one trace spacing (1 m) and the far offset was 96 m.

3.2.3.3 Source/Receiver Geometry

An important consideration in modelling and field acquisition is the source and receiver geometry. The geometry defines the lateral and vertical positioning of the sources and receivers. Due to basic field limitations, only certain values which appear likely were tested. In the case of both shot and receivers, the depth of each can be modelled. As well, the lateral position or pattern was tested only for shot records.

Modelling of receiver patterns was not attempted because the use of receiver patterns is detrimental to recording an enhanced broad-band frequency spectrum. This situation is created because the output signal for each station is composed of several input signals, which are not necessarily in phase, and which when added together created lower
frequencies than those of the original signals from each receiver (Sheriff and Geldart, 1995).

To test near-surface attenuation conditions, the model was computed with three source depths: 1, 2, and 4 metres. The first two shot depths were included to evaluate the condition where the source is within a vertically varying near surface (section 3.2.1.2). The four metre case evaluated the data quality and the improvement in signal to noise (S/N) ratio when the source was placed below the near surface layer.

3.2.3.4 Digital Sampling Parameters (Sample Rate and Record Length)

Due to inherent limitations within the VESPA program, restrictions were placed on the choices available for the digital sampling parameters. The sample rate used was the lowest sample rate that the VESPA program could implement (1 ms). The record length (1.0 s) was chosen as the longest necessary to properly sample the deepest possible reflection and to prevent temporal aliasing artifacts from interfering with the reflections of interest. However, only 0.2 s of the calculated data was utilised for further analysis. It is important to note that higher digital sampling parameters were employed during subsequent acquisition due to the options available in modern engineering seismographs (Bison, 1990).

3.2.4 Modelling Results

Final computations included adjustments of the shot/receiver geometry to discover the best possible choices for the final survey. The model was also modified to test the effect of receiver depth on the computed record.
The final output records consisted of P, S (vertical) and surface waves. VESPA is not directly able to compute these waves, so records were created by adding P and S waves together with an assumed surface wave component (Sierra, 1989). This manipulation was easily accomplished using the VISTA (Viewpoint In Seismic Trace Analysis) 6.6 analysis package (Seismic Image Software, 1994). All computed records were convolved with a 200 Hz Ricker wavelet (Sheriff, 1991).

3.2.4.1 Dalmeny Model - Thin Till within the Dalmeny Aquifer

To properly enhance reflection energy clearly, the calculated records must be scaled (Figure 3.6). For this data, a 150 ms AGC function was used (Yilmaz, 1987). The display of the one metre case indicates no observable reflection events, and is dominated by the ground roll. Significant improvement in the refracted energy on the two metre shot depth has occurred. However, abundant ground noise is still visible, as well as one reflection at 0.17 s. On the four metre shot depth record, the ground roll has been significantly attenuated, and a few reflections are visible. These reflections correspond to the top and bottom of the Dalmeny aquifer.

The records indicate that as the shot depth increases, the surface waves (330 m/s) and the direct waves (800 m/s) were attenuated. The highest quality records were at the 4 m depth because the shot is below the near-surface weathering layer. Yet, significant differences were found between the 1 m and 2 m source depths (source within the near-surface layer). The relative strength of the reflection at 0.170 s (Lea Park) is enhanced as the source depth deepens.
Figure 3.6. Dalmeny model scaled (AGC) shot records. a) 1 m, b) 2 m, c) 4 m shot depths.
A more appropriate method to assess the data quality of these shot records is to display the frequency-wavenumber spectra (F-K). F-K spectra are effective in distinguishing the reflection events from the surrounding noise as these are separated through differences in apparent moveout velocity (Figure 3.7).

The record of 1 m shot depth has a complex F-K spectrum which reveals a number of spatially defined events (Figure 3.7): event A-air wave (330 m/s), B-second near surface layer and the remaining data (C) are higher velocity events (indistinguishable from each other). Significant aliasing of the 330 m/s (air wave) and 800 m/s events is also evident. The F-K spectrum of the 2 m depth shot shows complete removal of the spatial aliasing, while the near-surface events (A and B) have been greatly attenuated. The 4 m case indicates that the near surface events have been eliminated with only data of an apparent velocity of 1750 m/s (refraction) and greater (reflections) remaining (event C on Figure 3.7).

Due to the small velocity contrast in the shallower (<0.050 s) parts of the model, a technique was required to separate the refraction events from the reflection events. A properly designed F-K filter (Figure 3.8) can greatly enhance the reflection energy by removing the interfering refraction data. Reflections are clearly evident on both the one and two metre shot depths (Figure 3.8 - a, b), and the reflections on the four metre case (Figure 3.8 - c), are even better. Deeper reflections at 0.175 s (Lea Park) are also readily apparent. In general, the aliased air wave energy has been removed from the data, except for some remnants still present on the 1 m case (Figure 3.8 - a). In addition, the top and bottom of the interbedded till can be detected on the 2 and 4 m cases (events B and C -
Figure 3.7. F-K spectrum of typical synthetic shot records. a) 1 m, b) 2 m, c) 4 m shot depths.
Figure 3.8. Dalmeny model F-K filtered shot records. a) 1 m, b) 2 m, c) 4 m shot depths.
Figure 3.8). The linear data evident at 0.100 s are artifacts from the F-K filtering process (event F - Figure 3.8).

3.3 Survey Design

3.3.1 Offset Ranges (Near and Far)

For most shallow seismic reflection surveys, the near offset is generally as small as possible and is usually a half integer value of the group spacing (Knapp, 1985). The far offset, on the other hand, is often placed such that it is no longer than the deepest reflection of interest (Sheriff, 1978). In the case of the Dalmeny survey, the Dalmeny aquifer base lies between 40 to 50 m deep, thus the far offset should not exceed 48 m. This empirical process does not take into consideration difficulties associated with NMO stretching (Miller, 1992) and velocity analysis. These problems arise in data processing because of the small move-outs and short spread lengths which typify these types of shallow reflection surveys.

3.3.2 Receiver Spacing

The determination of the optimal trace spacing was undertaken using the modelling tests where comparison was made of shot records with both 1 m and 2 m trace spacing (Figure 3.9). The records indicate that only minor differences exist between these records on an amplitude display.

As previously discussed in section 3.2.3.1, a value of 2 m may create a spatial aliasing in the data. However, the use of smaller spatial sampling values such as 1 m may eliminate the problem (Figure 3.9). Incorporating a more realistic near surface using a
Figure 3.9. Modelling tests of receiver spacing. a) 1 m, b) 2 m receiver spacing.

Legend
A. Dalmeny Top Reflection
B. Dalmeny Base Reflection
C. Lea Park Reflection
velocity gradient to reduce the contrast with the underlying layer severely attenuates
surface wave amplitude. With these modifications, 2 m spacing can still be considered
adequate for a shallow seismic survey (refer to section 3.2.3.1)

3.3.3 Source Depth

Field parameter modelling was also undertaken with variation in source depth to
evaluate differences between surface shots (hammer, gun) and those at depth (blasting
caps). The modelling results (Figure 3.10) indicate that there is a significant difference in
data quality and signal to noise (S/N) ratio between the surface and one metres depth
shots. The F-K spectra (Figure 3.11) supports this conclusion.

While it is clear from previous synthetic shot records (Figure 3.7; Figure 3.8) that
a four metre shot depth is the most preferable, drilling shot holes to this depth is
expensive and takes a significant amount of time. Additionally, simple equipment useful
for drilling these types of holes rarely can get past a depth of two metres. Therefore,
drilling the shot holes to four metres is advantageous but economically unrealistic. While
there is significant improvement in the data quality by placing the source at greater
depths, the signal improvement did not justify the expense of placing the source below
the near surface layer. Thus, a source depth of one or two metres was the most practical
scenario.

3.3.4 Receiver Depth

Modelling was also conducted with both surface and buried (10 and 20 cm)
receivers to establish possible differences in signal quality with changing receiver depth
Figure 3.10. Synthetic modelling test using varying source depth. a) surface, b) 1 m depth
Legend
A. First near surface layer - 330 m/s (aliased)
A2. Event created by error in modelling algorithm
B. Second near surface layer - 850 m/s
C. Deeper reflections (e.g. Dalmeny, Lea Park)

Figure 3.11. F-K spectrum of source depth tests. a) surface, b) 1 m depth.
However, changing the receiver depths does not appear to cause significant differences in data quality. This is confirmed by analysis of the F-K spectra (Figure 3.13).

It should be noted that the modelling of receiver depth does not take into account the primary reason for receiver burial; namely removal of the effects of wind and other natural noise. The burial of receivers has a significant impact on the S/N ratio in a natural environment compared to leaving the phones on the surface and thus was attempted for the Dalmeny survey.

In most seismic reflection studies, the attenuation of wind noise is undertaken with the use of receiver arrays (Rigdon and Thomas, 1987). However, this is detrimental to the maintenance of higher frequency content because receiver patterns cause low frequency bias due to array summation (see section 3.2.3.3). This situation must be avoided if at all possible to maintain high frequency content in the recorded seismic signal.

3.3.5 Mutes and Survey Fold

To properly establish fold requirements for a shallow survey, particular attention was paid to the applied mutes. These mutes were applied to remove any data which is NMO stretched (reduction of frequency) beyond some critical value and to remove coherent noise in the trace which can not be removed by other means. However, muting must be kept to a minimum to prevent detrimental loss of fold on these shallow reflectors. Thus, it is important when designing mutes to balance the opposing effects of fold reduction (reduced reflection clarity), and removal of stretched data (enhanced reflection
Figure 3.12. Modelling test of varying receiver depth. a) surface, b) 10 cm depth, c) 20 cm depth.
Figure 3.13. F-K spectrum of receiver depth tests. a) surface, b) 10 cm depth, c) 20 cm depth.

Legend

A. First near surface layer - 330 m/s (aliased)
B. Second near surface layer - 850 m/s
C. Deeper reflections (e.g. Dalmeny, Lea Park)
The NMO stretch (frequency reduction) is given by (Miller, 1992):

\[ \frac{\Delta f}{f} = \frac{\Delta t}{t_0} \quad (3.5) \]

where \( f \) is the dominant frequency of the data,
\( \Delta f \) is the change in frequency,
\( t_0 \) is the two way travel time at vertical incidence,
\( \Delta t \) is the change in the move out time given by (Miller, 1992):

\[ \Delta t = \sqrt{\frac{x^2}{v^2} + t_0^2} - t_0 \quad (3.6) \]

where \( x \) is the source-receiver offset,
\( v \) is the P-wave velocity.

Thus, based on the various depths and velocities of the Dalmeny model (offset range 1 m to 48 m), calculations for various layers can be established (Figure 3.14).

Miller (1992) has shown that mutes should only be applied to remove data with frequency stretch of more than 15-20%. Such a mute will balance the effects of fold reduction versus improvement in signal quality. If stretched data greater than 20% is incorporated into the output record, fold will be maintained, however too much lower frequency data will be left in the output record. On the other hand, if data with smaller stretch values (< 10%) are removed, then higher frequencies will result at the expense of significant fold reduction. The stretching of data inevitably creates higher amplitude as well as lower frequency (Yilmaz, 1987). The possibility that false amplitude (AVO type) anomalies created by the addition of large amplitude data can not be discounted.
While the previous discussion evolved from previous surveys (i.e. Steeples and Miller, 1991; Miller, 1992), the appropriate mutes for each data set must be determined individually. This is accomplished through experimentation with different stretch values. Using this methodology, the most appropriate values can be found which take into account the trade-offs between dominant frequency, S/N ratio, and coherency of the stacked events (Miller, 1992). Given this discussion and a typical stretch value of 15%, the theoretically ideal offset dependent mute for the Dalmeny region was 3 m/8 ms, 26 m/30 ms, 43 m/45 ms at the Floral top, Dalmeny top, and Dalmeny base respectively.

The application of a mute on shallow seismic data where important reflections are present in the upper part of the record, will have a detrimental effect on the survey fold. For instance, with 2 m trace spacing and 2 m source spacing, the nominal survey fold is 24 (assuming 48 receivers). With the application of the indicated Dalmeny mute, the fold on the Dalmeny top reflector drops to 13 (Figure 3.15). Consequently, the Dalmeny survey design was planned based on the reduced fold (e.g. 13) not the nominal fold (e.g.
Therefore, the reduction in fold has a significant impact on survey cost since in order
to obtain a particular multiplicity on a shallow, muted reflector the nominal fold must be
doubled to maintain consistent coverage.

3.3.6 Undetermined Parameters

The use of reflectivity modelling can not address every necessary acquisition
parameter. In particular, parameters such as source type, record length and analog field
filter are more appropriately determined under realistic field conditions and are discussed
in the following chapter.

In the case of source type, two relatively simple types will be analysed. Sub-
surface sources (i.e., blasting caps) generate broad-band frequency content, but require
significant time to prepare. Surface sources, on the other hand, do not necessarily
produce improved frequency content, but are generally simpler and faster to use.

![Figure 3.15. Reduction in fold due to muting of shallow reflectors.](image-url)
3.4 Summary

The reflectivity method is an extremely powerful and useful method for obtaining synthetic shot records. These records allow the geophysicist to analyse potential survey designs and make the appropriate choices without major time and money investments in the design process. This is particularly important with the Dalmeny data set where little or no seismological information was available to assist the survey design.

Modelling of this type was also useful in later interpretation as important knowledge of reflectivity was gained well in advance of the actual survey. For example, the modelling can compensate for the lack of adequate velocity information, and later assist in interpretation.
CHAPTER 4
Acquisition and Processing

4.1 Introduction

The most critical step of any seismic survey are the field acquisition and signal enhancement procedures. Mistakes made during acquisition can rarely be corrected; resulting in lower quality seismic data. Therefore, the time spent on testing processing parameters provided an assurance that the highest quality seismic section was created.

4.2 Acquisition

4.2.1 Field Testing

Although the comprehensive modelling of the acoustic responses of the known geologic model established guidelines for the geometrical field parameters, some parameters were determined through in-situ testing. In early May 1993, field tests were carried out in the area of the proposed survey near the Dalmeny test well (well 2407) (Figure 4.1). The goal was to verify, evaluate, and possibly adjust the optimum survey parameters established by modelling under field conditions. The parameters which had to be established included:
Figure 4.1. Map of the Dalmeny study area.

Legend

2407  Groundwater well
——  Geologic cross-section Dal-1 (see Figure 5.1)
-----  DLS grid line
----------  Seismic line
- source (caps versus hammer),
- quantity of source (single versus multiple caps or hammer blows), and
- analog filter settings.

The tests were carried out using a simple 24 channel recording system with an end-on geometry and receiver spacing of two metres. The recording instrument was a Bison 9024 engineering seismograph, borrowed from the Potash Corporation of Saskatchewan (PCS). Data were recorded for a total of 0.250 s with a sample interval of 0.25 ms. The 24 individual receivers (single 50 Hz instruments) were buried to a depth of approximately 0.3 cm to reduce the ambient cultural and wind noise.

4.2.1.1 Source Tests

The field tests indicate that the best quality (highest S/N) data were obtained using an in-hole (cap) source. Data quality improved slightly by deploying multiple (two or three) cap sources, but the addition of more caps increases survey costs more than justifiable with the increased signal levels. Thus, the multiple cap system was avoided during acquisition. It was apparent that a single cap in the Dalmeny area was an adequate source to record 200+ Hz frequencies to the depths of interest (125 m).

Comparison of in-hole (explosives) versus surface source test reveals significant differences in data quality (Figure 4.2). On the hammer records, the relative strength of the ground roll compared to that of the visible reflection energy is fairly high. On the explosive records the reflections have considerably stronger amplitude relative to the ground roll (event B - Figure 4.2).
Figure 4.2. Field tests comparing in-hole versus cap sources. a) ten hammer blows (single plate location), b) one cap (0.7 m deep hole), c) three caps (same hole as in (b)).
4.2.1.2 Analog Filter Tests

Another objective of the field tests was to establish the optimal analog field filter. The analog real time filter is intended to attenuate much of the ground roll and other ambient noise, thereby increasing the signal to noise ratio and enhancing the dominant frequency of the data (Knapp and Steeples, 1986).

An important observation is that the higher filter cut-offs (frequency) produced higher frequency content of the signals (96 Hz low-cut to 256 Hz low-cut). Thus, it is advisable to use the highest possible cut-off to obtain the highest possible frequency content of the data (Figure 4.3). Therefore, in order to increase frequency content but not enhance the aliased data, a low cut value of 192 Hz was chosen as a compromise value.

4.2.2 Dalmeny Reflection Acquisition

With the acquisition parameters established, the final step before acquisition proceeded, was the determination of possible survey layouts (i.e. number of lines and line orientations). After evaluating logistical and financial concerns, the final survey configuration consisted of two lines at 90° to each other, along the existing road beds. Line 1 (east to west) was deployed along the south side ditch of Lutheran Road. Line 2 was lain out along the western flank of a north-south trending road (Figure 4.1).

The final survey parameters were chosen based on the modelling (chapter 3) and field testing (section 4.2.1), and are listed in Table 4.1. The final spread geometry for the reflection data is illustrated in (Figure 4.4)
Figure 4.3. F-K spectrum for analog filter field tests. a) filter of 96-2000 Hz (single cap in a 0.7 m hole), b) filter of 128-2000 Hz (same hole as in (a)), c) filter of 256-2000 Hz (same hole as in (a)).
Figure 4.4. Illustration of spread geometry for the Dalmeny reflection survey.
Table 4.1. Dalmeny Reflection Survey Acquisition Parameters

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<tr>
<th>Recording Parameters</th>
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<tr>
<td>Sample Interval</td>
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<tr>
<td>Record Interval</td>
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<th>Geometry Parameters</th>
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<tr>
<td>Receiver Interval</td>
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<tr>
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<tr>
<td>Receiver Depth</td>
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<tr>
<td>Source Type</td>
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<td>Source Array</td>
<td>Single hole</td>
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<tr>
<td>Source Depth</td>
<td>1.1 m</td>
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4.2.3 Dalmeny Refraction Acquisition

Due to the limited offsets (0-47 m) available in the reflection survey, an additional long offset refraction survey was required to resolve some of the deeper (0.075 to 0.150 s) reflections. In addition, it was expected that the refraction events from the top of the Dalmeny could also be detected and thus a velocity for the upper Dalmeny aquifer could be obtained. These data were collected in October 1994.

Time constraints and logistics prevented the collection of a large amount of data and reduced the offset range that could be attempted (far offset - 237.5 m). This special survey was restricted to profiles on the east (station 170) and the west side of Line 1 (station 500) (Figure 4.1; Figure 4.5). The refraction survey on the east side targeted a structural anomaly on the top of the Dalmeny (see section 5.3.5) while the refraction survey on the west side was assumed to be horizontally layered and thus ideal for refraction analysis. However, the limited offset information prevented the collection of refraction data to evaluate the Dalmeny velocity.

The acquisition parameters for this data are summarised in Table 4.2. There were four shots on each end of Line 1 (one east and one west) with a 10 m shot interval (Figure 4.5). Further discussion of this data is in the section on velocity analysis (section 4.3.6).

4.3 Reflection Processing

The processing of the Dalmeny data followed a fairly typical land dynamite signal enhancement sequence (Figure 4.6) (Yilmaz, 1987), but with some important modifications for high resolution seismic data. This modifications included increased
Figure 4.5. Illustration of the spread geometry for the Dalmeny reflection survey. (a) Source geometry, (b) receiver geometry.
Table 4.2. Dalmeny Refraction Survey Acquisition Parameters

<table>
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<tr>
<th><strong>Recording Parameters</strong></th>
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<td>Receiver Interval</td>
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<tr>
<td>Near Offset</td>
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<tr>
<td>Far Offset</td>
<td>237.5 m (2 spreads)</td>
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<tr>
<td># of Phones/spread</td>
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</table>

<table>
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<th><strong>Source/Receiver</strong></th>
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<tr>
<td>Receiver Type</td>
<td>Mark Products L25-50Hz</td>
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<td>Receiver Array</td>
<td>Single with spike base</td>
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<td>Receiver Depth</td>
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<tr>
<td>Source Type</td>
<td>10 hammer blows</td>
</tr>
<tr>
<td>Source Array</td>
<td>Single plate location</td>
</tr>
</tbody>
</table>
Figure 4.6. Dalmeny reflection processing sequence.
emphasis on refraction statics and velocity analysis.

In many ways, the processing of high resolution shallow reflection data is still in its infancy and tends to be relatively unsophisticated. Very few rules and guidelines exist for what works and what does not, so algorithms and parameters utilised are still widely dependent on the experience and equipment available to the individual. This situation occurs because processing is often undertaken on PC based systems, rather than on workstation based environments. This imposition would have severely limited the quality of the final sections. Thus, the UNIX based system Insight (Landmark, 1994), was used for all but the initial processing steps.

4.3.1 Data Reformat

The first step was the conversion of the raw Bison SEG-2 files into standard SEG-Y (Society of Exploration Geophysicists, 1980). This was accomplished using the DOS based package VISTA 6.6 (Seismic Image Software, 1994). The data was then converted from SEG-Y data into the Insight format (DIO). The remainder of the processing was accomplished using the Insight package (Landmark, 1994).

4.3.2 Geometry and Refraction Statics

The next step was the calculation of the survey geometry. The details from the observer's notes were input to provide correct spatial locations for all traces in the survey. After the completion of geometry input, first break arrival values were picked (Figure 4.7) and analysed using Insight algorithms to develop a refraction statics model. The basic model was computed using the ABC method (Landmark, 1994). The refraction statics
Figure 4.7. Interactive picking of first breaks using the Insight VAQ picker.

were computed using a datum of 514 m above sea level and a replacement velocity of 1900 m/s.

The computed statics were then edited using an interactive program, REFED (Landmark, 1994), in order to improve the statics model. Editing was necessary in certain anomalous areas where the automatic routines were unable to function properly. These zones were the result of complicated near-surface velocity anomalies created by surface topography (1 m elevation) and low velocity material under road beds.

Further first break analysis was computed in order to more rigorously establish refraction velocity variations along the lines (see section 5.4.1).
4.3.3 Bandpass Filtering

After refraction statics corrections were completed the signal enhancement procedures were initiated. The first procedure was to determine frequency limits and prepare deconvolution parameters. Tests were performed to properly determine the filter parameters which best emphasised the important reflections.

Filter tests were performed after elementary spectral analysis was performed on various shot records across Line 1. The most appropriate choice was a very wide filter of 80/130-350/400. This filter passes the entire data spectrum, but removes the low frequency ground roll and noise (Figure 4.8). This filter was implemented as a pre-filter for deconvolution to remove some of the spurious very high frequency noise (B. Pandit, personal communication).

4.3.4 Deconvolution

The primary signal enhancement routine (noise removal) was a form of deconvolution. Various deconvolution algorithms were tested to discover the most effective procedure to enhance the data (Landmark, 1994). The applicability of both spiking (zero and minimum-phase) and predictive deconvolution on shallow high-resolution data was evaluated. Spiking (minimum-phase) shot ordered deconvolution was attempted in temporal varying forms. Spiking (zero-phase) and predictive (gapped) deconvolution were only attempted in non-temporal forms.

Zero-phase (spiking) deconvolution was attempted for completeness, although it would be more correct to use a minimum-phase algorithm since the source (cap) was minimum-phase (Yilmaz, 1987). These output shot records are of good quality, with
Figure 4.8. Fourier spectrum for typical near and far offset traces.
clarity on all the various shot records (Figure 4.9) and the ground roll has been strongly attenuated.

In comparison, the minimum-phase shot deconvolution tests are quite similar in nature with excellent clarity on the reflectors (Figure 4.10). Qualitatively, there are few apparent differences with the zero-phase records. The near traces on these tests, however, are cleaner than on the zero-phase records.

Tests were also performed using predictive (gapped) deconvolution (Figure 4.11). Predictive deconvolution is often performed in a processing stream to remove multiple energy (Yilmaz, 1987). The results from these tests using similar parameters to the spiking deconvolution tests indicate a significantly noisier record than the former. The predictive deconvolution records appear to be of significantly higher frequency, but some of the stronger reflections are degraded. Thus, it appears that predictive deconvolution was not beneficial in filtering the records, and would be unnecessary. In addition, the data set does not contain any recognisable multiple events within the important upper 0.150 s.

Based on the results of these tests, it was apparent that the most appropriate deconvolution to use was the minimum-phase deconvolution. The next step involved determining the precise deconvolution parameters: operator length, pre-whitening factor, taper, and frequency limits. Early on, it was established that 1% pre-whitening and a taper of 1 ms (4 samples) was adequate for the Dalmeny data set. The most important parameter was then the operator length. Various lengths from 4 to 9 ms were tested, and a 5 ms length was considered to be optimal for signal enhancement. The basic design gate was from 0.03 s to 0.20 s at near offsets and 0.05 s to 0.20 s at far offsets.
Figure 4.9. Deconvolution test record - zero-phase spiking. a) Raw record, b) Deconvolved record.
Figure 4.10. Deconvolution test record - minimum-phase spiking. a) Raw record, b) Deconvolved record.

Legend
A. Identifiable reflection (Dalmeny Aquifer Base)
Figure 4.11. Deconvolution test record - predictive. a) Raw record, b) Deconvolved record.

Legend
A. Identifiable reflection
(Dalmeny Aquifer Base)
In addition, temporal variance was also tested to determine whether further enhancement of the output data could occur (Figure 4.12). Three windows were designed to accommodate the three zones within the data:

1) the near surface reflections (0.03 to 0.09 s),

2) the middle reflections with complicated geology (0.09 to 0.16 s), and

3) the zone defining the basement and deeper (0.16 to 0.21 s).

The records are similar to those of the non-varying deconvolution, however, there is slightly more continuity in several of the near-surface reflections (Figure 4.12).

The frequency limits of the deconvolution were set at 90/140 - 310/360 after several tests. Wide tapers on these frequency limits were necessary after preliminary tests revealed severe Gibb's phenomenon (Sheriff, 1991) occurring at taper values less than 50 Hz (e.g. 90/100 instead of 90/140) (Figure 4.13).

Deconvolution application can be attempted only if certain assumptions are valid. The primary assumption is that the wavelet does not vary with either offset or time (within a defined window) and that it can be collapsed to a spike (Yilmaz, 1987). The tests with predictive (gapped) (Figure 4.11) and spiking (Figure 4.10; Figure 4.12) deconvolution indicated that spiking (minimum-phase) deconvolution would be preferable for the Dalmeny data set since there were no identifiable multiples in the important parts of the data.

4.3.5 F-K Filtering

Conventional data enhancement consists of band-pass filtering and deconvolution.
Figure 4.12. Deconvolution test record - time variant minimum-phase spiking. a) Raw record, b) Deconvolved record.
Figure 4.13. Record displaying the effect known as Gibb's phenomenon. a) with Gibb's phenomenon, b) parameters modified such that the Gibb's (ringy) data is severely reduced.
These techniques were utilized because they are computationally efficient, effective and normally remove most of the noise (ambient and ground roll) on a seismic trace. Due to the shallow nature of the reflections of interest, the small differences in refraction and reflection velocities (< 150 m/s), and the resultant far offset merging of reflections and refractions, a more powerful technique, such as a velocity oriented filter, was needed to separate the refractions from the reflections. Using this technique, data which essentially varies only by velocity and which interferes at far offsets with critical reflections can be effectively eliminated.

In the case of the Dalmeny survey, it was necessary to remove the refractions without destroying the reflections in the upper 0.035 s. In conventional data processing, this is accomplished by muting out the refractions. However, in the case of shallow surveys, the muting out of refraction energy results in a significant, unwanted loss of fold for the upper reflections (as discussed in section 3.3.5).

The F-K polygon mutes were designed on individual shots using polygon mutes to eliminate the unwanted energy (Landmark, 1994). The shot points chosen were those judged to be the highest quality and overall representative of the entire line. Particular attention was paid to those shots exhibiting clear distinction of the various events and thus easiest polygon creation (Figure 4.14).

The resultant records exhibit greatly enhanced reflection clarity and hyperbola continuity. A potential problem with the F-K is the creation of artifacts. This is a particular concern at the later times (> 0.150 s) where the small NMO produces relatively flat reflections. However, as is evident in a comparison of deconvolution filtered shots versus deconvolution and F-K shots (Figure 4.15), the F-K filtered shot does not contain
Figure 4.14. F-K spectrum of a typical shot record with F-K mute filter.
**Figure 4.15.** Comparison of a deconvolved shot (a) versus the same shot with deconvolution and F-K filtering (b).
abundant artificial events at the times of interest.

4.3.6 Velocity Analysis

Once the signal enhancement procedures were completed, the data were then analysed for velocity variation. Velocities were analysed in the common offset stack (COFF) domain. The zones consist of fifteen (15) common depth point (CDP) gathers summed together on the basis of absolute offset. These COFF panels were then analysed to determine the apparent velocity sequence (Figure 4.16). The initial velocity picking was accomplished with only a few panels in order to provide a brute stack of the data. The panels used were chosen from around station 200 and station 500 where data quality was highest.

After assessment of the initial brute velocities, velocity analysis was re-iterated using a 25 CDP (25 m) interval between COFF zone centres. In the picking process, close attention was paid to the RMS and interval velocities to keep them within acceptable ranges. This was important in the shallow zones due to the relatively small velocity constraints in the layers. For the deeper events, this was particularly important as the relatively small NMO times made accurate velocity analysis difficult. The interval velocity ranges were established from refraction data analysis (refer to section 5.4.1). After velocity analysis and stack, quality inspection was performed on the NMO corrected gathers and resultant stacked section. Based on these results, problem areas were determined and velocity analysis re-computed on these zones.
Figure 4.16. Semblance plot illustrating the velocity structure in the Dalmeny data set.
4.3.7 Residual Statics

After velocity picking was completed, the data were stacked as a conventional structure stack. The stacked section was evaluated, and a decision was made on the basic improvement between the new stack and the previous conventional stack. If the improvement was negligible or non-existent, velocity analysis was carried out. However, if the conventional stack improved, then residual statics were calculated.

Residual statics were performed to remove any small scale statics variations which could not be removed with conventional refraction statics calculations. The computation used a modified and streamlined version of the Ronen-Claerbout algorithm (Ronen and Claerbout, 1985; Landmark, 1994). The calculation flattens the NMO corrected reflection events out on the individual gather resulting in a stack with improved lateral coherency.

The residual statics were then applied to the NMO corrected gathers and the data re-stacked. The resultant structure section was again evaluated to assess any improvement in clarity and coherency of the reflected events. With continually improving velocities and residual statics, significant improvements were usually made over the entire line. In the later iterations, emphasis was placed on zones which displayed low lateral coherency. These zones were created along the lines where geology and/or field geometry produced lateral incoherency.

The resultant residual static corrected stack was again evaluated for enhanced coherency. If improvements were made, then these residual statics values were used to recreate the COFF zones and velocity analysis re-performed (Figure 4.17).
Figure 4.17. Comparison of two adjacent CDP gathers, uncorrected (a, c) and with residual statics applied (b, d).
4.3.8 Migration

One of the standard final steps in any processing sequence is the migration of the data. Using analysis presented by Black et. al. (1994), it would seem unnecessary to migrate the Dalmeny data set due to the lack of large true dips. However, the obvious clear diffraction patterns on the stacked data set made migration a necessity for their removal. These diffractions were caused by abrupt (50 to 100 m/s) lateral velocity changes between sands and shale/till layers.

A pre-stack time phase shift migration (Gazdag, 1978; Landmark, 1994) was used to remove these diffractions. Figure 4.18 (a) shows a section of Line 1 unmigrated with two labelled diffraction events. The migrated stack (Figure 4.18 - b) indicate the removal of the diffractions and exhibits excellent clarity on the deeper reflections (event B).

4.4 Summary

The processing of the Dalmeny data set followed a typical land dynamite processing sequence. However, due to the nature of high resolution seismic data, some important modifications had to be made in order to properly enhance reflection signals. Compared to conventional processing, a great deal more time was spent on the application of refraction statics, velocities and residual statics. With respect to refraction statics, typical processing usually involves one automatic pass of statics calculations, and rarely any further editing. It is assumed no further iterations are needed as variations in the remaining time errors are considerably small, and will not greatly affect stack quality.
Figure 4.18. Comparison of unmigrated (a) and migrated (b) stacked data (Line 1).

Legend
A. Identifiable diffraction events.
B. Zone of complex reflectivity caused by diffraction interference.
C. Same zone as (B) exhibiting enhanced reflection clarity as a result of migration.
In this study, small statics changes of only a few milliseconds, which represent about 20 samples, may significantly destroy the clarity of a reflection. The static shifts associated with road beds are a prime example, and a great deal of time was devoted to the enhancement of these zones. The results enhanced the static solutions over these zones, but was, by no means, optimal.

Velocity analysis is usually a one shot pass in standard processing. In contrast, the high resolution survey required more detailed velocity analysis due to the complex nature of the contrasts. In the Dalmeny study, the small (200 m/s) velocity contrasts can change RMS velocity significantly, and may completely destroy true reflection geometry, or modify reflectivity contrasts. Therefore, it is advantageous to spend the time to obtain the highest quality velocity structure to ensure that the interval velocities calculated from the RMS velocities are geologically viable. The use of refraction data greatly assisted in constraining RMS and interval velocities to realistic values within the deeper zones (> 0.120 s).
5.1 Introduction

Interpretation of the Dalmeny seismic data was accomplished using various techniques available to the petroleum seismologist, although some have not previously been attempted on shallow seismic data. Some of these techniques include: basic horizon picking and geological correlation, analysis of refraction data for near surface acoustic properties, complex trace attribute analysis and velocity inversion. These latter techniques can provide more quantitative analysis of the data than can be supplied from horizon picking alone.

The aim of this interpretation was three fold. Primarily, the interpretation provided substantial information on the depositional framework of the Quaternary stratigraphy. In addition, the high-resolution nature of the data provided an opportunity to emphasise the use of shallow seismology as a tool for interpreting similar near-surface groundwater/environmental problems. Quantitative analysis of the elastic properties of tills can also be enhanced utilising these interpretation techniques.
5.2 Correlation of Geology and Seismic Information

5.2.1 Geology

Till differentiation has been accomplished by a number of qualitative and quantitative techniques involving geochemistry and visual examination of lithologic variations. These techniques include (Sauer, 1992; Schreiner, 1992):

1. carbonate (CaCO$_3$) content,
2. stratigraphic sequences (e.g. unconformities),
3. weathered zones,
4. inter-till deposits,
5. colour,
6. jointing,
7. staining,
8. trace element and isotope geochemistry,
9. electrical resistance.

None of these techniques can be directly correlated to the elastic properties used in seismology. Of these, only electrical resistance is a quantitative value applicable to geophysical investigations. Therefore, when using the existing database of information for geological correlation, some of these techniques may differentiate layers in which the related geophysical properties (e.g. velocities and densities) do not change. Similarly, these properties may differ between layers, but the existing geological analysis does not indicate any apparent differences. Only in certain situations will the existing techniques equate non-elastic variations with elastic changes. Weathered zones and inter-till deposits may commonly (although not always) indicate variation in elastic properties.
However, features such as carbonate content and colour will not necessarily be indicative of variation in velocities and densities. S-wave information may be utilised to detect jointing and fracturing, but P-wave information will not be useful in analysing this information (Telford et. al., 1990).

For the purposes of the geologic correlation of the Dalmeny data set, the major divisions were created utilising two single point resistance logs from nearby wells (1521 and 2407) adjacent to Line 1 (Figure 5.1). Fortunately, considerable changes in lithology (and velocity) where till units are separated by thick (> 3 m) sand/gravel bodies provide sufficient impedance contrast.

Although these two wells are only about 250 m apart, considerable changes are apparent in the Dalmeny and Tyner units (Figure 5.1). The Dalmeny exhibits differences within the interbedded till which varies in thickness from 3 m (2407) to 5 m (1521). Assuming a 235 Hz seismic signal (velocity - 1850 m/s), the top and base of the till are just resolvable at the 2407 well. Whereas at the 1521 well, the 5 m of till should be clearly resolvable (Figure 5.2).

Detailed analysis of the stratigraphy of the available groundwater wells has revealed the existence of buried channels within the Tyner Formation. The 1521 well shows an upper and a lower sand unit separated by a massive clay/rewilded till unit. However, the 2407 well demonstrates a more complex geology with a lower sand unit and a thinner clay zone overlain by a sequence of interbedded clays and sands. There are 6 -7 geologically identifiable layers within the upper zone, although only 3 to 4 have sufficient thickness to be resolvable at frequencies in the range of the Dalmeny data
Figure 5.1. Geologic section (Dal 1) adjacent to Line 1. The wells 1521 and 2407 tie to Line 1 at 5 and 250 m respectively. Refer to Figure 4.1 for location.
Figure 5.2. Resolution requirements for the imaging of a thin layer (assuming a constant velocity and frequency for both examples). a) a 3 m thick layer, b) 5 m thick layer.

Wavelet Frequency = 235 Hz
Velocity = 1850 m/s
Sub-Cretaceous control was established using a petroleum exploration well (B. A. Warman, 16-16-38-5W3) that penetrated rocks of Silurian age. The wireline logs from this well provide detail of the underlying stratigraphy, but these logs were run only from 150 m below the surface. Thus, the log information, particularly the sonic log, could not be effectively utilised for seismic correlation.

5.2.2 Creation of Synthetic Seismograms

To pick the appropriate horizons, existing geological information must be combined with velocity information to create synthetic seismograms. However, in the Dalmeny study area, lack of independent velocity information made this procedure difficult. While geological parameters (depths and formation tops) were in abundance in close proximity to the reflection data (section 5.2.1), interval velocity information for the various units was not available.

To overcome this difficulty, stacking velocities originating from data processing and refraction analysis were adapted for use in synthetic creation (Figure 5.3). These velocities are not the optimal choice because they may contain errors created by the lack of significant moveout information in the reflection data. This problem makes the use of these velocities somewhat speculative, but the knowledge of geologic depths establishes significant indirect control on this information. In addition, some near-surface control was derived by adopting refraction velocities from relevant first break analysis.

Deeper (> 0.140 s) velocity control was established by utilising an independent refraction survey (section 4.2.3) (Figure 5.4). No significant reflections are evident above
Figure 5.3. Diagram illustrating the ties of the Line 1 migrated and balanced seismic data to the synthetic seismograms created for the adjacent wells (2407 and 1521).

- **A** Floral (Upper) Top
- **B** Dalmeny Top
- **C** Dalmeny Till Top
- **D** Dalmeny Till Base
- **E** Dalmeny Base
- **F** Floral (Lower) Base
- **G** Tyner Valley Top
- **H** Tyner Channels Base
- **I** Tyner Lower Sand Base
- **J** Lea Park

Time (s)

350 2407 1521 300
Figure 5.4. Refraction shot illustrating deep velocity control in the Dalmeny area.
0.08 s, but events from strata at or near the basement (Lea Park shale) are unmistakable. This information indicates that the velocities of the deeper layers are approximately 2000 m/s.

While well 1521 is immediately adjacent to Line 1, well 2407 is about 250 m north of the Line (Figure 4.1). This well was tied to Line 1 assuming a preliminary orientation of the key geological features (Tyner Valley channels) of 15° (see section 5.3.2).

5.3 Structural and Depositional Framework in the Dalmeny Study Area

The migrated and balanced version of Line 1 (Figure 5.5 - located in back pocket) show through the laterally traceable reflections that the regional geology is more complex than imagined by the nearby well information. At the tie points for the two wells, significant changes in geology are matched with significant changes in the regional reflectivity on the section. The two existing wells tie to Line 1 at approximately station 301 (1521) and 330 (2407).

Initially, the intention was to interpret Line 2 (Figure 5.6 - located in back pocket) with the same detail and thoroughness as Line 1. Lower signal to noise ratio, however, prevented analysis of the results of Line 2 with comparable thoroughness. Across this line, shallow (< 0.050 s) information was distorted by incoherent noise generated within the near-surface material of the roadbed. Bad weather during the final day of shooting further exaggerated this situation.
5.3.1 Lea Park

The deepest significant reflection on Line 1 is at approximately 0.13 s (Figure 5.5 (Line 1); Figure 5.6 (Line 2) - event J - located in back pocket). Based on the correlation with the synthetic seismogram (synthetic), this reflection is interpreted to be the top of the Lea Park Formation. Below this event are a number of similar appearing events which are believed to be multiple energy. There is one deeper event, at around 0.2 s which appears to be a significant horizon within the Lea Park, however no well information exists to tie this reflection to a lithologic change.

The Lea Park reflection is a relatively flat event across both lines, although minor topographical variations occur. Significant static shifts are apparent along the reflection, making the existence of faulting a possible scenario. However, it is unlikely that these shifts are faults, but more likely caused by differential travel time paths through the distorted zone immediately above the Lea Park.

5.3.2 Tyner Valley

Overlying the Lea Park reflection is a significant zone of distorted reflectivity between 0.085 and 0.130 s (Figure 5.7). Based on the geologic analysis and subsequent synthetic generation, this zone is correlated to the Tyner Valley Formation. The reflectivity is a consequence of the complex geology apparent in the geological section (Figure 5.1).

The complicated reflectivity is suggested by the changing attitudes of a few reflectors (Figure 5.7 - event G, H and I) which form distinctive shapes interpreted as the signatures of buried channels. Outside of these channels, there is consistent lateral
Figure 5.7: Seismic response of channels within the Tyner Formation - Line 1.
coherency of reflectivities. Within the anomalies, the lateral coherency is limited to short patterns.

On Line 2, rather than multiple lateral channels, only two longitudinal structures are present, separated by a fairly well defined bank edge (Figure 5.8). This view, enhanced by a map of the reflector, indicates that Line 2 cuts the channels longitudinally nearly parallel to the strike, 015° (Figure 5.9). The northernmost channel (station 150 to 300) corresponds to the feature at station 275 on Line 1 and the southern channel corresponds to the one at station 175. Comparison of the relevant geometry of the adjacent channel supports this conclusion (i.e. both the northern channel (Line 2) and the corresponding Line 1 channel are quite deep).

5.3.3 Dundurn

The reflectivity zone above the Tyner Valley is a fairly flat uncomplicated area with one significant reflection within the zone from 0.055 to 0.085 s (between event F and G - Figure 5.5; Figure 5.6 - located in back pocket). Based on the well ties, this zone correlates to the Dundurn Formation of the Sutherland Group. However, the reflection at 0.075 s (both lines) cannot be placed into the associated geologic interpretation. The interpretation suggests that this is a sand layer within the Dundurn Formation. However well logs adjacent to the line (1521 and 2407) suggest that no comparable sand deposit exists at this depth. It is assumed that some layers exhibit properties (e.g. velocity) unaccounted for by previous geological investigations.
Figure 5.8. Seismic response of a Tyner channel edge on Line 2.
Figure 5.9. Map of the base of the Tyner Valley channels in the Dalmeny study area.
5.3.4 Lower Floral

Above the Dun durn, is a thin zone of intermittent reflectivity. Well log comparisons indicate that this zone corresponds to the lower Floral (Figure 5.3). Structurally, there are three zones within this unit, differentiated by significant changes in reflectivity and isochron values. At the west end of Line 1, is a consistent zone with no internal reflectivity. From station 450 to 280 is a complicated zone which indicates thickening of the unit to the east. The zone from station 180 to the beginning of the line is similar in nature to the first zone. The final zone was created by complete erosion of the lower Floral till between station 180 and 280.

The two zones at either end of the line contain little internal reflectivity, and are thus likely composed simply of one lithology (e.g. well 1521 - Figure 5.1). This indicates that these two zones are highly eroded, and any overlying layers were removed subsequent to further deposition.

However, the zone in the middle of the line, between stations 450 and 300, has internal reflectivity, which is caused by more than one lithology (clays and sands - well 2407 - Figure 5.1). Between the two wells, the top of the layer changes 5 ms over a short distance, indicating an approximate 6 m change in thickness (Figure 5.1). The till eventually pinches out at approximately station 260. It achieves sufficient thickness at station 190 and attains an average thickness of around 14 m (15 ms) on the east end of the line. However, the reflection is abruptly terminated at station 250 and again at station 185. East of station 185, a weakly coherent reflection defines the lower Floral on the other side of this anomaly.
5.3.5 Dalmeny

Above the lower Floral is a highly variable zone, generally of consistent thickness, but which has infilled the erosional surface on the lower Floral (see previous section). This zone correlates to the Dalmeny aquifer (Figure 5.3). The top of the Dalmeny reflection is well defined and partly buried by the coherent noise at around 0.028 s.

The most striking feature about the seismic response of this layer is the anomalous change in the reflectivity from a relatively flat surface on the west end of the line to the significant dipping reflectors in the region of station 300 to station 150 (Figure 5.10 - event E). Deposition of the Dalmeny was influenced by the topography on top of the lower Floral after the significant erosion of the upper part of this layer. Isochron changes for the Dalmeny aquifer indicate significant thickening in this complex zone, but with relatively constant thickness elsewhere (Figure 5.11).

Within the Dalmeny aquifer, significant reflectivity is evident. The adjacent well logs also indicate the presence of a significantly thick (3-5 m) till horizon within the sands. The position of the wells on the seismic line indicate that the 2407 well (3 m of till) is at the critical thickness necessary for resolution, so the top and bottom reflections are very close together (Figure 5.2). However, at the 1521 well, the erosional anomaly just begins and the till thickens to 5 metres. East of the wells, the interior of the anomaly indicates significant thickness of tills (10 metres) (Figure 5.12). Approaching the end of the line, the erosional anomaly begins to diminish from station 170 to 101 (tills thin), and likely vanishes off the end of the line. On the west end of Line 1, the till is thicker, from the 3 m thick zone east of station 450 to a 8 m (10 ms) zone from station 450 to the end of the line (Figure 5.12). Within the interval between stations 300 and 420, the isochron
Figure 5.10. Seismic response of a thickening geological strata due to an existing topographical anomaly - Line 1. (a) Seismic data over the anomaly, b) diagram illustrating progression of deposition of the Dalmeny.

Illustrating progression of deposition of the Dalmeny.
Figure 5.11. Isochron plot of the Dalmeny aquifer - Line 1 illustrating the feature at station 200 and approximate thickness increases associated with it. a) plot of Dalmeny horizons, b) isochron plot of Dalmeny aquifer (interval velocity of 2000 m/s).
Figure 5.12. Isochron plot of the Dalmeny till - Line 1. a) plot of top and base of Dalmeny till, b) isochron of Dalmeny till (interval velocity of 1900 m/s).
drops below 10 ms (2.5 m) revealing that the till either pinches out or is just not resolvable with 200 Hz data (Figure 5.13; Figure 5.14).

The interbedded till thickening, evident at station 200 of Line 1 can also be traced to Line 2. In the area of station 410, a slight dip is visible on the Floral, Dalmeny and interbedded till reflectors (Figure 5.6 - events C, D, E, and F - located in back pocket), and indicates that this feature continues to the south. It appears more gentle on Line 2, revealing a progressive thinning of the erosional channel to the south-west (Figure 5.15). In addition, the lower Floral pinches out against the Dalmeny edge at stations 380 and 425. Isochron analysis of the Dalmeny and the interbedded till reveals that this feature is quite small (200 m). The dips of the reflectors indicate only 0.05 ms/m for the Dalmeny reflection (E), and about 0.025 ms/m for the lower Floral reflector (Figure 5.6 - F). Whereas, on Line 1, the dips are on the order of 0.25 ms/m (0.075) and 0.125 ms/m (0.05) (Figure 5.16; Figure 5.17). The geometry of this feature is also interesting in that it is nearly symmetrical, as opposed to the asymmetric nature of this anomaly on Line 1.

This asymmetric shape (Line 1) suggests that it may have been formed by an erosional channel, where the seismic line crosses the feature at a bend. Typically, channels form a roughly symmetric geometry. However, at bends, the channels become asymmetric, where the faster water velocity is on the outside (deeper part of the channel - station 230) and the inner portions of the channel have slower (less erosion) water velocity (station 280 - Line 1).

5.3.6 Upper Floral and Surficial Deposits

Overlying the Dalmeny aquifer is a flat series of reflections which belong to the
Figure 5.13. Seismic response of thin Dalmeny till on Line 1. Event C is the till top and event D is the till base.
Figure 5.14. Seismic response of Dalmeny till thickening - Line 1. Event C is the till top and event D is the till base.
Figure 5.15: Dalmeny attitude change on Line 2. Event E is the Dalmeny base.

A Floral (Upper) Top
B Dalmeny Top
C Dalmeny Till Top
D Dalmeny Till Base
E Dalmeny Base
F Floral (Lower) Base
G Tyner Valley Top
Figure 5.16. Isochron plot of Dalmeny - Line 2. a) plot of top and base of Dalmeny, b) isochron of Dalmeny (interval velocity of 2000 m/s).
Figure 5.17. Isochron of the Dalmeny till - Line 2. a) plot of top and base of Dalmeny till, b) isochron of Dalmeny till (interval velocity of 1900 m/s).
upper Floral till and to surficial deposits. Because of the nature in which the data was recorded, very little reflectivity has been recorded, and interpretation of these layers is best accomplished through refraction analysis (section 5.4.1).

5.3.7 Complex Trace Analysis

Standard analysis of seismic data depends normally on the amplitude of the trace. However, the seismic trace may contain other attributes (properties) including: amplitude envelope, instantaneous phase, and instantaneous frequency (Taner et al., 1979). These attributes are derived by the additional processing of the seismic trace to separate the trace into two components: amplitude (real) and phase (complex) (Taner et al., 1979).

Complex trace analysis is not a standard procedure of post stack data analysis and there are no published records of its application in shallow seismic investigations, although it is often applied in petroleum seismology (e.g., Taner et al., 1979; Robertson and Nogami, 1984). Previous applications of complex trace attributes to seismic data indicate that the amplitude envelope enhances the detection of major lithologic changes and fluid accumulations. Instantaneous phase can be useful as a means of accessing continuity of events and geologic geometry. The instantaneous frequency is often helpful in analysing fracturing and absorption.

5.3.7.1 Line 1 Instantaneous Phase

For the Dalmeny data set, instantaneous phase was utilised to clarify and support the existing interpretation in areas where the amplitude information is deficient (Figure 5.18 - located in back pocket). This situation is best illustrated on Line 1 in zones where
the Lea Park reflection, laterally continuous over most of the line, was difficult to interpret in particular zones, such as near station 310 (Figure 5.5 - located in back pocket). The assistance of the instantaneous phase data, while is also complex in this zone, helps to clarify the existing interpretation (Figure 5.18- located in back pocket).

Within the complicated zone of the reflections of the Tyner aquifer, the geometry of the channels were well emphasised by the instantaneous phase display. An excellent example is the channel centred at station 265 (Figure 5.5 - located in back pocket), with edges at stations 225 and 300. Approaching station 225, a significant change in the phase continuity and a slight dip were apparent. Outside limits of the channels are much more evident. This characteristic behaviour was expected as the shallow channels are filled with lenses of differing material (sands and clays) (Figure 5.1). Comparable geologic settings within the Dalmeny aquifer reveal similar instantaneous phase responses (stations 325 and 500) (Figure 5.18 - located in back pocket).

5.3.7.2 Line 1 Instantaneous Frequency

While the instantaneous frequency data for this line is generally monochromatic, there are several interesting anomalies (Figure 5.19 - located in back pocket). One of the most obvious is the coherent zones of frequency (coloured green) around 0.05 s. These correspond to the sands of the lower Dalmeny aquifer. Immediately above and below this layer were the tills of the Dalmeny and Floral (coloured red). It is apparent that there are differences in the absorption of the sands and the tills, however more rigorous analysis has not been attempted. The instantaneous frequency response of the unrecognised Dundurn layer is around 225 Hz, similar to that of the lower Dalmeny sands and suggests
that this layer is a sand as well.

Since the Tyner aquifer contains significant sand layers, significant changes in the instantaneous frequency response should be evident, based on the interpretation of the response from the Dalmeny sands and the inferred Dundurn sands. A possible reason for the differences could be that the beds in question are more heterogeneous than those sands of the Dalmeny. Geological analysis (Figure 5.1) indicates that the sands of the Tyner are not pure sand, but mixtures of sand, silt and tills.

5.4 Quantitative Analysis of Glacial Till Properties

Attempts were made to utilise various interpretation techniques to more rigorously quantify some of the elastic properties of tills, namely velocity and density. The methods included refraction analysis to obtain near-surface velocities and depths, and velocity inversion to obtain deeper lateral velocity and impedance information.

5.4.1 Refraction Analysis

5.4.1.1 Methodology

Using the refraction information is a necessary step to evaluate the near-surface velocities. As the first layer reflection times were very small and buried within the noisier upper portion of the record, the most viable option for obtaining the near-surface velocities (and depths) was the refraction information.

The refraction data was inverted using simple Marquardt-Levenston (least squares) inversion (Meju, 1992). The kernel of the data was created using a simple finite difference scheme. The starting model was chosen from basic analysis of the raw shot
records. The resultant inversion was very fast, and required only 3 to 5 iterations for convergence on each shot. Testing revealed that the algorithm was sufficiently stable enough that the starting model could be considerably different than the final inversion results.

5.4.1.2 Line 1

The refraction analysis indicate that the variation in near-surface velocities were not large. In observing the first layer velocities (Figure 5.20), it is clear that the first layer velocities tend to cluster around 600 m/s (means of 608 and 597 m/s for positive and negative offsets respectively) and most values fall within 120 m/s (20%). The actual velocities vary from extremes of 500 m/s to upwards of 800 m/s.

The rather significant slow zone between stations 150 and 175 is likely due to an observed near surface anomaly, a patch of near-surface boulders, likely placed there during road construction. Therefore, the ground in and near this anomaly is significantly softer and thus slower than the surrounding unaltered areas. A significantly fast anomaly at station 350 has no apparent origin and nothing was noted during acquisition which could account for it. Thus this zone is likely a higher velocity lens of material within the near-surface layer.

Second layer (upper Floral) velocities (Figure 5.21) are somewhat smoother, and do not vary by any more than 10%, with most of the values falling within 5% of 1800 m/s. The most significant correlation with the first layer velocities is near station 500 to station 550. A significant reduction of the velocities indicated a less consolidated geology, best demonstrated by the first layer velocity.
Figure 5.20. Refraction analysis of Line 1 - velocity of layer 1 (weathering layer). a) positive offsets, b) negative offsets.
Figure 5.21. Refraction analysis of Line 1 - velocity of layer 2 (upper Floral). a) positive offsets, b) negative offsets.
The depths to the top of the second layer (weathering layer thickness - Figure 5.22) have a relatively constant value of about 4 m (means of 3.96 and 3.85 m). In general, there were two major zones and one minor zone within the data. The first major zone was from about station 170 to station 300, with an average depth of about 4 m. A minor zone from station 300 to 435 is slightly deeper, averaging around 4.5 m, but which has significant variability. The final major zone was between station 435 to 575, where the thickness is nearer 3.5 to 3.75 m. Interestingly, the first zone was roughly equivalent to the channel feature located within the Dalmeny aquifer. Thus, there appears to be a small topographic feature remnant of this anomaly as late as the end of the Pleistocene.

Variations existing on the end of the lines are not discussed as they are due to end of line effects. Interestingly, these zones do not appear on the first layer velocities, as they were generally flatter over the entire line and only zones near station 350 have increased velocity.

5.4.1.3 Line 2

The data for Line 2 is similar to that of Line 1. However, the variations are in general caused primarily by the lower data quality and softer near surface. The first layer velocities (Figure 5.23) are slightly slower than on Line 1 (means of 587 and 571 m/s for + and - offsets respectively). There were a couple of noticeably slower zones, such as between station 200 and 235. As nothing was noted during acquisition that could account for them, they are inferred to be true near-surface anomalous zones within the weathered layer. It is also interesting to note that from station 375 to the end of the line, the velocities do not change.
Figure 5.22. Refraction analysis of Line 1 - depth to the top of layer 2 (upper Floral). a) positive offsets, b) negative offsets.
Figure 5.23. Refraction analysis of Line 2 - velocity of layer 1 (weathering layer). a) positive offsets, b) negative offsets.
The second layer velocities (Figure 5.24), on the other hand, were much more variable. They vary by as much as 10%, although most values are less than 5% (of 1800 m/s). In general, the zone between station 100 and 350 is slower than the zone between station 350 and 625 (end of line), with a notable slower area between station 450 to 500. Interestingly, the fast zone around station 475 corresponds to a farm access road, while the slower zone at around 495 is also an access road. None of the other anomalies correspond to any surface feature noted during acquisition.

The weathering layer thicknesses (Figure 5.25) do not exhibit any significant changes. While much of the data is highly variable (station 100 to 375), consistent zones within this information were not apparent. The end of the Line (station 375 to 600) indicates depths near 5 m, considerably thicker than those of Line 1. It should be noted that this data was not elevation compensated. Since the elevations for Line 2 are roughly one metre higher than those on Line 1, it is apparent that the actual depths are relatively similar.

5.4.2 Velocity Inversion

5.4.2.1 Methodology/Theory

The basic theory of the velocity inversion method (STRATA) used in this study is described in Hampson-Russell Software (1994). The algorithm utilised is known as the "blocky" inversion algorithm because it produces blocky pseudo-velocity logs (Hampson-Russell Software, 1994). One of the main problems in the inversion process is the question of uniqueness. A typical velocity inversion situation has far more equations than unknowns, leading to the likelihood of several different answers to the same problem.
Figure 5.24. Refraction analysis of Line 2 - velocity of layer 2 (upper Floral). a) positive offsets, b) negative offsets.
Figure 5.25. Refraction analysis of Line 2 - depth to top of layer 2 (upper Floral). a) positive offsets, b) negative offsets.
This is handled in the STRATA program through a process called stochastic inversion (Hampson-Russell Software, 1994). Stochastic inversion assumes that the seismic data and the initial model (from the synthetic log) are independent and possibly conflicting pieces of information. Thus, some parameter must be input which specifies a relative percentage of each to utilise in the computations, without allowing one of these to dominate. For the Dalmeny data set, a value of 0.5 (on a range of 0.0 to 1.0) was used.

5.4.2.2 Results

The inversion results of Line 1 (Figure 5.26 - located in back pocket) indicate that little significant velocity variation exists in many of the layers. In general, the velocities are constant and similar to those of the input model. Within the Dalmeny aquifer, the velocity averages around 2000 m/s. However, the interbedded tills have a velocity of around 1800 m/s to 1850 m/s.

An interesting correlation exists within the Tyner Valley. Although the horizon specifying the channel boundary was not used in the inversion, variations exists within this zone. In fact, within the upper part from 0.100-0.120 s, the velocity is consistently 1900 m/s, while in areas where no channels exist, e.g. station 360, there are slower velocities of less than 1850 m/s. This indicates that the reworked clay/tills were slower than the upper and lower sands.

5.5 Summary

One of the goals of the interpretation was to provide information in the Dalmeny and Tyner aquifers on a local, highly detailed nature as compared to the more regional
view afforded by well information.

Results from the interpretation of the Dalmeny data set indicate significant changes within the Pleistocene of central Saskatchewan. Geological analysis had indicated that variations could be expected, but the limited well coverage in the immediate area and over the entire Dalmeny aquifer could not provide the detail that has been established.

The deepest reflection of interest, the Lea Park, which is the basement for the purposes of this survey, was a relatively flat lying horizon, about 125 m or 0.130 s below the surface. Static shifts on the seismic data suggest significant faulting, but these anomalies are likely variations due to differential travel time though complex shallower layers.

The overlying zone, the Tyner Valley aquifer is a complexly layered unit consisting of sands and reworked clays forming significant channels features. The channels were previously recognised on the nearby geologic section and subsequently on the seismic data. Complex reflectivities have been created by the differing geology, with as many as 7 different layers (lenses) within the channels themselves. Many of these layers are too thin to be properly imaged, so only 3 to 4 were visible on the seismic data.

Overlying the Tyner were the significantly thick (30 m) tills of the Sutherland Group. Only the middle till, the Dundurn has been recognised in the Dalmeny area. Geologic information indicated that the Dundurn was a relatively uninteresting layer with no significant variation. The subsequent seismic interpretation recognised a previously unknown layer of strong reflectivity around 0.075 s on both seismic lines. This suggests that this layer has property variations (velocity and density) unrecognised through
previous geologic investigations.

The overlying layer consists of the lower till member of the Floral Formation. This unit is a 6 to 14 m thick till and sand. The isochron of this layer was quite consistent, except for a prominent zone where the till has been completely eroded. This surface is the base upon which the overlying Dalmeny sands have been deposited.

The primary target of this investigation, the Dalmeny aquifer, directly overlies the lower Floral till, and consists of 20 m of sand and gravel with a local unit of at least 3 m of interbedded till. One of the most significant things about the geological correlation of the Dalmeny aquifer is the prominent feature on the east end of the line. It was formed by erosion of the underlying lower Floral, and subsequent deposition of the sands and tills into it. The feature is believed to be an asymmetric channel. The tills and overlying sand layer were then deposited on to the surface formed by the lower Dalmeny sand.

The overlying layers consists of a not well imaged till layer (upper Floral), with a velocity of nearly 1800 m/s located between 3.5 and 5 m below the surface. The near-surface weathered layer has a fairly consistent velocity of approximately 600 m/s.
6.1 Introduction

To achieve the goals of resolution and imaging of thin beds, existing methodologies in shallow seismology and petroleum seismology would have to be adapted for use in a glaciated terrain. Very few reflection surveys of the type used in the Dalmeny study have been attempted in a till environment similar to that found in the Saskatoon area. Thus, additional work was necessary to optimise the parameters necessary for a successful reflection data set of this type. Design was required in the following areas to optimise the survey according to the goals of the project: 1) modelling and survey design, 3) acquisition, 4) processing, and 5) interpretation. The intention was to rigorously enhance existing methodologies for each of these areas using established techniques utilised in petroleum seismology and then applied to shallow seismology.

The results of the Dalmeny study provided have shown that the acquisition of high frequency (> 200 Hz) seismic data is possible in a glaciated terrain. The detailed analytical procedure in obtaining the acquisition parameters facilitated this result. Enhanced data processing using advanced algorithms available for conventional seismology significantly increased the frequency content and data quality.

At the outset of this project, very little was known about the seismic properties of
till layers in central Saskatchewan. Previous work gave some indication about elastic properties of the tills, however, much of this work was qualitative in nature only. After the high quality nature of the Dalmeny data became apparent, the opportunity arose to quantitatively enhance the knowledge of the properties of till layers. The intention was to provide more rigorous analysis for the acoustic variation in the till layers by various interpretation techniques as yet untried in shallow seismology.

### 6.2 Modelling and Survey Design

The use of modelling is a vital step in the planning of a seismic survey. It provided the opportunity to cheaply test possible field configurations to determine the most adequate for a particular situation. The reflectivity method is one of the best modelling methods available, and as the results have shown, provides a good match to field conditions.

Modelling has shown that the best field geometry for the Dalmeny area is a trace spacing of two metres, shot spacing of two metres with a near offset of one metre, and a far offset of 47 metres. The preferable configuration would be split-spread of 48 channels, which provided a sub-surface coverage of 24. The required sample interval must be one millisecond (ms) or less, giving a Nyquist frequency of 500 Hz or greater. Based on the field tests, using 0.25 ms sampling interval is more than adequate. The field work has shown that frequencies approaching 200 Hz are realisable in practice. The field tests also indicated that the best source in terms of data signal-to-noise and dominant frequency is electric blasting caps. The best source quantity would be multiple (two or three) caps, but budgetary conditions limited the survey to one. Thus, the selection of the
survey parameters from the modelling is an adequate method of obtaining parameters, although field testing is a wise precaution to verify the results and fine tune the parameters.

Another successful concept in the Dalmeny acquisition was the “burial” of the receivers. Commonly, receiver arrays are utilised in conventional seismology to affect ground roll and noise reduction. However, as receiver arrays act as a low-pass filter, another technique was necessary for the suppression of near surface noise and ground roll. The “burial” or placement of the phones below the surface provided this feature. Although this difficult procedure is more expensive, the resultant data quality has proven that in glaciated environments it is reasonable to attempt to bury the receivers to suppress the noise and enhance the higher frequencies.

6.3 Processing

The goal in processing was to apply rigorous petroleum seismic methodologies to produce the highest quality seismic data. The desire was to utilise as much of a standard processing sequence as possible.

The processing sequence for the Dalmeny data set was very typical of a land dynamite sequence. After geometry and refraction modelling, spiking deconvolution was applied. Following deconvolution, the only non-standard data enhancement technique was the use of frequency-wavenumber filtering (F-K) to remove first break and ground roll energy. F-K is rarely used in conventional seismic processing, however, it was a necessary step due to the extremely small velocity contrasts evident in this data set.

The remainder of the data processing followed well established routines. These
included velocity analysis, residual statics application and pre-stack migration. In most situation with relatively flat lying reflections, the use of migration is an unnecessary step (Black et. al., 1994). However, significant diffraction patterns evident on the structure stack indicated that the use of migration was a necessary step. Pre-stack migration drastically removed the evident diffraction and significantly improved data quality. Also, anomalous zones such as at station 240 on Line 1 were clearer after migration than before.

6.4 Interpretation

Results from the interpretation of the Dalmeny data set indicate significant variations within the Pleistocene of central Saskatchewan. Geological analysis had indicated that some variations could be expected, but the limited well coverage in the immediate area and over the entire Dalmeny aquifer could not provide the detail that has been established.

The deepest reflection of interest, the Lea Park, is a relatively uniform seismic horizon. However, static shifts on the seismic data suggest the possibility of significant faulting, but these anomalies are likely variations due to differential travel time though complex shallower layers.

The overlying zone, the Tyner Valley aquifer, was a complexly layered unit in which channel features had been previously recognised. Seismic investigation has supported this previous interpretation. Complex reflectivities have been created by the differing geology, with as many as 7 different layers (lenses) within the channels themselves, although many of these layers were too thin to be properly imaged.
Overlying the Tyner Valley is the thick (30 m) Dundurn till. The subsequent seismic interpretation indicated an unrecognised layer of strong reflectivity around 0.075 s on both seismic lines. It is assumed that this new layer exhibits properties (e.g. velocity) unaccounted for by previous geological investigations.

Investigation of the primary target, the Dalmeny aquifer, indicates that significant erosion occurred previous to deposition. The result was the creation of a channel feature into which significant thicknesses of sands and tills were deposited. The underlying Floral till was highly eroded, including total removal in one zone correlated on both seismic lines.

The overlying layers consists of a poorly imaged till layer (upper Floral), with a velocity of nearly 1800 m/s located between 3.5 and 5 m below the surface. The near-surface weathered layer has a relatively consistent velocity of approximately 600 m/s.

6.5 Recommendations

One of the most significant aspects of the Dalmeny data set was the high quality data and high frequency content. Since this was a significant step forward in the collection of shallow high-resolution data, a summary must therefore be conducted on what was done, how well it was done, and future recommendations for this type of work. Based on analysis of similar surveys in the geophysical literature, much of what has been learnt is most applicable to the type of environment in which the Dalmeny data was acquired, namely glaciated environments composed of tills.

The project was first begun with the use of reflectivity modelling (chapter 3). It must be said that the use of reflectivity modelling is a highly beneficial procedure in the
design of shallow surveys, particularly in this case where so little information is available. Thus, the use of wave-equation modelling should be attempted if a survey is to be designed for an area where little geophysical information is available.

The time spent in survey design was also an effective tool in the eventual success of the project. Careful literature surveys and the work from modelling facilitated many possible perturbations of survey parameters, and combined with the geology, created the best possible model for the targets in mind.

However, one aspect that was only readily apparent after data processing was initiated, was the lack of offset information. This is particularly evident with the semblance velocity analysis. In the velocity procedure, it was very difficult to pick adequate velocities for many of the reflections due to the small NMO changes and short offsets on these reflectors. This situation is particularly serious at the deeper reflections (> 0.130 s) where the reflections are nearly flat with existing offsets. While the data quality was not seriously degraded, it is considered beneficial that further work contain a greater range of offset information than the current survey. It would be preferable if a receiver spacing of at most 2 metres and a minimum of 60 or 96 channels were made available for data collection to provide the enhanced coverage of the reflectors necessary to eliminate some of the concerns in the Dalmeny data set.
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Figure 5-6 Line 2 Interpreted

Station

Elevation (m)

Time RMS Vel.

Tie to Line 1

Statics (ms)

Datum - 514 m a.s.l.
Replacement Velocity = 1900 m/s

100 m
Figure 5-18
Line 1 Instantaneous Phase

Station 0.0

Well 1521

Reflector Legend
A Upper Floral Top
B Dalmeny Top
C Dalmeny Till Top
D Dalmeny Till Base
E Dalmeny Base
F Lower Floral Base
G Tyner Valley Top
H Tyner Channel Base
I Tyner Lower Sand Top
J Lea Park Top

Time (s) 0.1

Phase (deg) -180 -90 0 90 180

100 m