DEVELOPMENT OF A HIGH-RESOLUTION SHALLOW SEISMIC REFLECTION SYSTEM

by

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It is curious that the region of the earth that has been the least successfully explored by means of elastic energy is the first few hundred feet below the surface.

F. F. Evison (1952)
DEDICATION:

To my parents, brothers, sisters and friends.
Development of a High-Resolution Shallow Seismic Reflection System

Ja'afar W. Ali

ABSTRACT

The aim of this study was to investigate the applicability of the seismic reflection method for exploration at shallow depths (<100m) and to develop a high-resolution system capable of achieving such objectives. This would have a wide range of applications including engineering scale surveys and hydrogeological studies. The system used comprised high-frequency response equipment coupled with a data-logging microcomputer.

Trial surveys were made at two sites in the Bardon Hill area (Charnwood Forest) where Triassic sediments (0-100m thick) overlie a Precambrian basement, providing large acoustic impedance contrasts. Site 1 was characterized by a thin (1-2m) weathered layer, shallow water table (<2m) and a firm topsoil while in Site 2 the weathered layer was 2 to 4 times as thick as that in the first site, the water table was deeper and the soil was cultivated. The variations in near-surface material strongly affected the quality of the results.

Detailed comparisons were made of a number of different modifications of the signal production, data acquisition and data processing aspects of the seismic reflection system. Among the most important factors needed to produce the most successful reflection system was the nature of the seismic energy source: the 'Buffalo gun' proved most effective in providing high frequency energy required for this scale of survey; modifications to it in the course of this study further increased its effectiveness. The high-frequency (100Hz) geophone and the nature of its coupling with the ground were crucial in extracting and recording high-resolution data. Another important element in the system was the field microcomputer, useful for storing data and providing immediate quality control of data in addition to being a cheap processor.

Both preliminary processing on a microcomputer and a standard processing package on a mainframe computer were used. The effectiveness of all types of process was dependent on the quality of the seismic field records. Preliminary processing was adequate to produce a satisfactory image of subsurface geology provided that field data were of high quality (in Site 1) and a number of programs were developed to enable this. The common mid-point stacking technique provided an improved image of shallow subsurface structure by increasing the signal to noise ratio and enhancing reflections. The most useful advantages of using the standard processing package were in improving the continuity and increasing the resolution of the reflections by the application of residual statics and deconvolution, respectively.

The dependence of signal quality on variation in physical properties of the near-surface material were analysed in detail. The thickness of the weathered layer and the firmness of the topsoil were the most important factors affecting the transmission and recording of high frequencies.

The reflection data can be directly compared with both seismic refraction results and borehole logs obtained along the same survey lines. The reflection data provided a significantly more accurate model of the sub-Triassic surface than did the refraction data; in addition, they provided information on the internal structure of the Triassic strata. The resolution and accuracy of the reflection data demonstrate the applicability of this method in engineering geophysical investigations. Further refinement of this system may be effected by investigating the use of lower-energy sources and more powerful field microcomputers with additional software.
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LIST OF ABBREVIATIONS

Amps.  
AGC  
A/D  
cm  
CMP  
CDP  
CPU  
CRT  
CVS  
dB  
DFS  
DFT  
E  
FFT  
FT  
g, G  
gm  
gr  
h  
Hz  
IFF  
K  
km  
LVL  
m  
M  
ms, msec  
N  
NMO  
O.D.  
P, P-wave  
PGC  
RAM  
rms  
ROM  
s, S  
S-wave  
s, sec  
S/N  
t  
t₀, TWT  
T  
t₁, TI  
TP, TM  
V, V  
V  
VDU  
x, X  
α  
Δt  
θ  
λ  
f  
μ  
ρ  
τ  
Amperes  
Automatic gain control  
Analogue to digital  
centimetre (0.01 metre)  
Common mid-point  
Common depth-point (=CMP)  
Central processing unit  
Cathode-ray tube  
Constant velocity stacks  
Decibel  
Disc filing system  
Discrete Fourier transform  
Energy, East, Easting  
Fast Fourier transform  
Fourier transform  
Geophone  
Gram  
Grain (0.0648 gram)  
Depth to an interface (also Z)  
Hertz  
Instantaneous floating-point  
Kilobyte (1024 byte; also Kbyte)  
Kilometre  
Low-velocity layer  
Metre, milli- (10⁻³)  
Megabyte (10²⁴ K)  
Millisecond (0.001 second)  
North, Northing  
Normal moveout (also Δtn)  
Ordnance datum (mean sea level)  
Compressional body wave  
Programmed gain control  
Random access memory  
Root mean square  
Read only memory  
Shot, shear wave  
Shear wave  
Second  
Signal to noise ratio  
Time, traveltime  
Two-way vertical time  
Traveltime, period  
Intercept time  
Plus and minus times  
Velocity  
Volt, voltage  
Visual display unit  
Distance  
Angle, dip angle, absorption coefficient  
Time differences  
Angles of incidence  
Wavelength, elastic constant  
Frequency  
micro (10⁻⁶)  
Density  
Time delay, period  

xvii
CHAPTER 1
INTRODUCTION

1.1 SCOPE

Seismic reflection has long been a standard geophysical method for oil exploration. It has been very successful in providing unequivocal evidence of subsurface structural and stratigraphical conditions known to be suitable for hydrocarbon accumulations. The dramatic success of the method in the search for oil has diverted attention from the limitations of the method when applied to other problems, such as groundwater investigation and civil engineering applications.

The method, however, had not been applied to shallow problems until the early fifties (Allen et al, 1952). This is because the petroleum industry, which was behind the development of seismic prospecting, has been exploring to greater and greater depths for new discoveries. Instrumentation difficulties were another barrier in the way of using the method for shallow exploration.

Ironically, conventional reflection seismology provides an exceptionally successful model for shallow reflection to copy. A simple scaling down, however, will not assure an equivalent success. Shallow seismic reflection faces problems and difficulties that are not present in conventional reflection work. These are mainly caused by the interference from source-generated noise, the attributes of the seismic energy itself, and the heterogeneity of near-surface materials.

1.2 PURPOSE OF THE STUDY

The main purpose of this study is to develop a seismic reflection system capable of obtaining reflection data from shallow depths (depth range of about 100 metre to 30 metre or less). Such a system needs to be cost-effective, reliable, versatile and above all of high resolution.

Seismic reflection has a greater potential in revealing a detailed subsurface image than other geophysical methods such as gravity, electrical, electromagnetic, and seismic refraction. The recent development of seismic recording
equipment with a high-frequency response has made it possible to extract and record high-resolution seismic data. In addition, the introduction of low-cost portable "micro" computers has enabled seismic data to be stored on magnetic discs and furthered the processing capabilities of the recording system.

At Leicester University, the development of shallow seismic reflection began in 1984. Five major areas were recognized as being crucial to the development of a viable system. These were: 1) seismic energy source; 2) seismic detector; 3) recording equipment; 4) field acquisition techniques; and 5) data processing.

These areas were investigated. Field trials and tests were made to better understand the problems involved, and the measures needed to solve them. The results are presented in the following seven chapters.

CHAPTER 2
This contains the results of plus-minus interpretation of seismic refraction data from the study area. Limitations of the refraction methods are discussed.

CHAPTER 3
Here, problems encountered in shallow seismic reflection and the theory and development of the high-resolution seismic reflection method are discussed. From this an initial specification of a shallow reflection system is derived.

CHAPTER 4
This contains a detailed method to compute field statics from first breaks of the reflection records, a computer program for its implementation and examples of synthetic data interpreted by this method.

CHAPTER 5
This chapter describes: field trials made to determine the most suitable seismic energy source; seismic detector; recording equipment, including microcomputers; and field acquisition techniques. The findings of this chapter have been published by Hill and Ali (1988; see Appendix A).

CHAPTER 6
This covers the processing aspects of the reflection system and methods used to improve data quality, and includes
the computer software used to conduct the various recording and processing steps.

CHAPTER 7

Here, the results of applying the various types of processing (chapter 6) to seismic reflection data are evaluated. The final seismic sections and their geological interpretation are presented.

CHAPTER 8

This contains a summary of the conclusions and recommendations for future work.

1.3 SHALLOW SEISMIC REFLECTION

1.3.1 Definition of shallow seismic reflection

The term "shallow" has been rather loosely defined. In the early fifties, shallow reflection was viewed as a 1/10 model of the conventional seismic reflection (Pakiser and Warrick, 1956). Schepers (1975) denoted that the depth to the deepest reflector and the thickness of the thinnest layer in shallow reflection are less than 1/40 of that in conventional reflection. Mooney (1984) set an arbitrary depth range between 0-150m to be the limit of shallow reflection. At this range of depths, shallow reflection will be directed towards targets of small size and will have a wide range of applications. Figure 1.1 shows a comparison of depth classified reflection methods.

1.3.2 Application of shallow seismic reflection

Shallow seismic reflection has a wide variety of possible applications. These include: the mapping of bedrock /drift contacts in both unfrozen terrain and in permafrost (important to both civil engineering and groundwater exploration); cavity detection; the mapping of lithological changes within Pleistocene deposits; the investigation of glaciers and ice-sheets; the location of aquifers within unconsolidated deposits; the investigation of stratigraphically or structurally controlled mineralization; and the refinement of conventional seismic work by giving more detailed information on the (generally variable) surface layers.
Figure 1.1 Schematic diagram of depth classified reflection methods.
1.3.3 History of research

Among the earliest attempts to adopt new techniques for shallow reflection, were investigations made by the Stanford Research Institute in the early fifties (Allen et al, 1952). They emphasized the importance of the duration of the initial pulse in deciding the least time at which a reflection is obtainable. They recommended the use of high frequencies in shallow reflection work and expected that reflections from depths less than a wavelength could be resolved. In their experiments, they reported success in obtaining reflections with a good degree of accuracy from an overburden-bedrock interface at depths of 100-200m. Reflections with frequencies as high as 100 Hz were observed.

Evison (1952) from the New Zealand Department of Scientific and Industrial Research indicated that an ideal source would be the one which is capable of generating an impulse with any desired frequency and for any desired duration. He developed an electromechanical "vibrator" source. However, he was faced with technical difficulties such as generating a very large current at high frequencies (200-1000 Hz), and coupling the source rigidly to a large ground area.

In 1953 and in the course of routine refraction survey in the Monument Valley of Arizona and Utah, a group from the U. S. Geological Survey had unexpectedly observed reflections from depths less than 12m (Pakiser and Warrick, 1956), and these were first thought to be erratic arrivals.

This accident stimulated the U. S. Geological Survey, in the mid fifties, to commission the developing of a special seismograph to satisfy shallow work requirements. A twelve-channel portable seismograph was constructed. It had features such as high-frequency response, fast-acting automatic gain control, and high paper speed (Pakiser et al, 1954; Pakiser and Warrick, 1956).

Recent work in shallow seismic reflection is covered in Chapter 3 (Section 3.3).
CHAPTER 2
THE PLUS-MINUS METHOD OF SEISMIC REFRACTION INTERPRETATION

2.1 INTRODUCTION

The seismic refraction method has been used routinely in shallow subsurface exploration (e.g. groundwater studies). Several interpretational techniques have been developed for this type of data. These techniques differ in the field arrangements and in the detail sought from the survey. Each approach has its own scope, limitations and range of applications.

A seismic refraction exercise was carried out in the study area to produce an interpretation which could be compared in detail with the seismic reflection study.

For detailed investigation and continuous mapping of subsurface structure with irregular topography, two seismic refraction methods with distinct raypath configurations can be used. The first method employs critically refracted waves from the refractor towards a common point on the surface of the ground while the second method utilizes critically refracted waves from a common point on the refractor towards the surface of the ground. Forward and reverse first arrival times are required in both methods.

The plus-minus method (Hagedoorn, 1959), the reciprocal method (Hawkins, 1961) and the ABC method (Sjogren, 1979) are examples of the first approach while Hales's method (1958) and the generalized reciprocal method (Palmer, 1980) are examples of the second. The first method is relatively insensitive to variations in surface elevation and near-surface velocity and is useful for shallower depth investigation. The second method is less sensitive to irregularities in the refractor and is useful in mapping high-relief and deeper structures (Sjogren, 1979).

In this study, the plus-minus method was used to map a relatively shallow refractor near Bardon Hill, Leicestershire.

2.2 THE PLUS-MINUS METHOD

2.2.1 The plus times

The plus-minus method is an approximate form of
Thornburgh's (1930) wavefront method of seismic refraction interpretation (Hagedoorn, 1959). According to Thornburgh's method, the sum of the arrival times for refracted waves from two end-shots to any point on the boundary of the refractor is equal to the end-to-end "reciprocal" times ($T_{ab}$). Since refracted arrival times are usually measured by a geophone at the surface of the ground, a plus time ($TP$) is given:

$$TP = T_{ag} + T_{gb} - T_{ab} = TP$$  \hspace{1cm} (2.1)

Figure 2.1 shows that the plus time actually represents two geophone delay times ($DT_g$):

$$TP = 2(DT_g)$$  \hspace{1cm} (2.2)

The depth ($Z$) to the refractor below each geophone in the reversed zone, therefore, can be determined from the plus times as follows:

$$TP = (2Z \cos \theta)/V_1$$  \hspace{1cm} (2.3)

The velocity of the overburden ($V_1$) is determined outside the reversed zone by means of direct waves (normal traveltime graph) and the velocity of the refractor $V_2$ is best estimated in the reversed zone by the minus times (see Section 2.2.2).

Plus times in the non-reversed zones can be estimated by two methods:

**Pseudo plus time method**

An average shot delay time ($DT_s'$) is measured for each shot from the reversed refracted times using the general refraction travel-time equation:

$$T = X/V_2 + DT_s + DT_g$$  \hspace{1cm} (2.4)

Using the same equation and substituting for $DT_s'$, we can estimate the geophone delay times ($DT_g$) in the non-reversed zones.

**Phantom plus time method**

Phantom plus times are estimated by having an off-end shot (Figure 2.2). The average of the differences in the refracted arrival times ($\Delta T$) from a shot (B) and an off-end shot (B) into geophones in the reversed zone is measured. $\Delta T$
Figure 2.1 Reversed first arrival traveltime curve for a single horizontal interface.

Figure 2.2 Off-end shot for estimating phantom arrival time in the non-reversed zone.
is then subtracted from refracted arrival times from the off-end shot into geophones in the near non-reversed zone. This gives refracted arrival times "phantom arrival times" for the non-reversed zone as if it had come from shot B itself, according to the law of parallelism (Sjogren, 1980). Phantom arrival times along with refracted arrival times from the other end shot (A) can then be used to estimate phantom plus times (Equation 2.1).

In both methods, the refracted arrival waves in the non-reversed zones must come from the same refractor as in the reversed zone.

2.2.2 The minus times

The difference of the refracted travel times from two end-shots into a geophone in the reversed zone defines the minus time \( T_M \). Figure 2.1 shows that the minus time for a geophone on the surface in the reversed zone is:

\[
T_M = \frac{2X - L}{V_2} + DT_a - DT_b \quad \ldots \quad (2.5)
\]

The velocity of the refractor \( V_2 \) measured by the minus method is more accurate than that determined by the normal traveltime graph because it eliminates the geophone delay time; reducing the effect of irregularities in both the velocity of the upper medium and the depth to the interface (Hawkins, 1961).

The derivation of the plus-minus equations can be found in Griffiths and King (1981).

2.3 LIMITATIONS OF THE PLUS-MINUS METHOD

2.3.1 The effect of the structure of the refractor

The plus-minus method of refraction interpretation is constrained by two assumptions: 1) that the refractor is locally plane below the geophone (refractor segment DE in the triangle DGE; Figure 2.1), and 2) that the refraction paths are common for all waves up to the point where they leave the refractor. Departure of the real earth model from these assumptions results in misinterpretation (Dampney and Whiteley, 1980).
Steep topographical features such as a concave down structure (Figure 2.3a) and a fault (Figure 2.3b) cause the boundary of the refractor not to be the minimum time trajectory. Here, the measured reciprocal times are less than in the case where the refractor boundary itself was the least traveltime path. This underestimation of the reciprocal times leads to an overestimation of plus time, and a consequent overestimation of the depth of the refractor.

The error caused by topography is proportional to the difference in the lengths of the seismic wave paths CDE and CE, which is most strongly dependent on the distance of D from the minimum travel-time path CE (Figure 2.3). This mechanism may cause serious errors in areas where refractor topography dips at greater than 10°.

A concave up structure of the refractor (Figure 2.4), however, lengthens the travel-distance of a refracted wave between successive geophones. This results in a lower refractor velocity estimate.

Other limitations of the plus-minus method are related to the regional dip of the refractor which has effects on depth and velocity determination of the refractor (Figure 2.5). The dip of a refractor (α) causes the distance scale in the minus time plot to be expanded (Figure 2.5a). This results in a higher velocity estimate. The actual velocity of the refractor can be determined as follows:

\[
\text{Actual } V = \text{Apparent } V \cos \alpha \quad \cdots (2.6)
\]

Refractor dip up to 15° may be considered to have negligible effect on the accuracy of the determination of velocity.

The effect of dip on the velocity of a refractor is opposite to the effect of the previously mentioned concave up refractor (Figure 2.4).

Figure 2.5b, however, illustrates the effect of the dip on the refractor depth determination. The DGE triangle is tilted by the dip angle. Therefore, the actual distance measured from the plus times is the line GQ. Plotting this line directly beneath the geophone (GB), however, results in a shallower depth to the refractor. The actual depth to the refractor can be determined by:
Figure 2.3 Steep refractor topographical features:
  a) concave-down structure.
  b) fault.

Figure 2.4 Effect of a concave-up structure on refractor velocity determination.
Figure 2.5 Effects of dip on the plus-minus determination (AI, DI are actual and determined interfaces):

a) on the velocity.
b) on the depth.

Figure 2.6 Effect of rough refractor surface on depth determination (AI, DI are actual and determined interfaces):

a) deeper estimation.
b) shallower estimation.
Actual Depth = Measured Depth / \cos \alpha \quad \ldots \ldots \quad (2.7)

Whenever possible, refracted depth determinations should be corrected for dip.

Another limitation of the plus-minus method is related to the roughness of the refractor surface. Since the determined depth and attitude of the refractor are averaged out within the DGE triangle (Figure 2.1), a relatively planar base "refractor" in the triangle is required. Figure 2.6 shows that a rough surface for the refractor within the DGE triangle results in depth misinterpretation.

2.3.2 Depth determination error

Equation (2.3) indicates that $Z$ is directly proportional to $TP$. The relation of $Z$ to $V_1$ and $V_2$, however, is not linear. Three velocity structures (2-layer) were used to examine the effect of errors in $V_1$ and $V_2$ on depth. These have velocity contrast ratios ($V_2 : V_1$) of 1.5 : 1.0, 2.0 : 1.0, and 2.5 : 1.0. The results of this error test are listed in Table 2.1 and the ratio of the measured to actual depth ($Z/Z_0$) is plotted against a range of percentage errors in $V_1$ and $V_2$ in Figure 2.7.

An error up to about 5% in $V_2$ can be considered to be negligible in $Z$ determination, while a smaller percentage of error in $V_1$ is significant in $Z$ determination. It is the $V_1$, however, which might be less accurately determined in reality.

The error in $V_1$ can come from assigning a constant velocity value for the overburden while it actually changes laterally. The plus-minus method, however, can compensate for that since the depth to the refractor is determined separately for each geophone along the line. Multiple shots distributed along the seismic line would allow determination of variation in $V_1$.

Sources of error in $V_2$ are discussed in Section 2.3.1. The error in $V_2$ due to the dip is less significant than that due to the curvature. A dip of about 15° results in an error of about 3.5% in $V_2$.

The errors in $TP$ are due to arrival time picking errors and reciprocal time error. An error of about 1 ms is expected in the arrival times from picking. The reciprocal time error
Table 2.1 The effect of errors in velocities on depth determination from the plus times.

<table>
<thead>
<tr>
<th>Velocity Ratio ( (V_2:V_1) )</th>
<th>( %\text{Error} )</th>
<th>( Z/Z_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 1.5:1.0 )</td>
<td>( V_1 )</td>
<td>1.09 0.91 1.20 0.84 1.33 0.77 1.49 0.70</td>
</tr>
<tr>
<td></td>
<td>( V_2 )</td>
<td>0.96 1.05 0.94 1.11 0.91 1.20 0.89 1.35</td>
</tr>
<tr>
<td>( 2.0:1.0 )</td>
<td>( V_1 )</td>
<td>1.07 0.93 1.14 0.87 1.22 0.81 1.30 0.75</td>
</tr>
<tr>
<td></td>
<td>( V_2 )</td>
<td>0.98 1.02 0.97 1.04 0.96 1.07 0.95 1.11</td>
</tr>
<tr>
<td>( 2.5:1.0 )</td>
<td>( V_1 )</td>
<td>1.06 0.94 1.12 0.88 1.19 0.83 1.25 0.77</td>
</tr>
<tr>
<td></td>
<td>( V_2 )</td>
<td>0.99 1.01 0.98 1.02 0.98 1.04 0.97 1.06</td>
</tr>
</tbody>
</table>

Figure 2.7 Plots of errors in the determined depths to an interface caused by errors in velocities (\( Z/Z_o \) is the ratio of calculated to actual depths; solid line= \( V_1 \), dashed line= \( V_2 \)).
is more serious and is due to steep topographic structures (Figures 2.3a and 2.3b).

2.4 APPLICATION OF THE PLUS-MINUS METHOD—CASE STUDY

Seismic refraction data collected during the summer of 1984 at Bardon Hill, Leicestershire, were used.

The main refractor in this area is a low-grade metamorphic basement of igneous and sedimentary rocks with irregular topography lying at shallow depth. The basement is overlain by Triassic sedimentary rocks of variable thickness (0-150m). These are covered by a thin weathered layer, and drift sediments (see Section 5.1.1).

Several seismic refraction lines were shot across the study area (Figure 2.8). The interpretation of seismic Line 10 is given here. The line is 686.3 m long and consists of seven shots (A-G), and 35 geophones at 20m intervals along the line. Appendix B.1 summarizes the seismic refraction arrival-time data for Line 10.

2.4.1 Seismic data reduction

Uphole velocities were measured at the shotpoints along Line 10 and listed in Table 2.2. Raw arrival times were plotted against geophone separations for the shots along the line (Figure 2.9a). Two velocity layers were revealed for the seismic section except at shot A where another "upper" layer was evident. The upper, second, and third layers have velocities of about 1.5, 1.7 to 2.1, and 3.5 to 5 m/ms, respectively. These velocity layers probably represent, in descending order, weathered Triassic sediments or drift, Triassic rocks, and the underlying basement. Table 2.3 summarizes seismic velocities for Line 10.

The velocities of upheole layer(s), Triassic rocks, and the basement obtained from the different shots on the line (Tables 2.2 and 2.3), were averaged to simplify the correction of the arrival times. Average velocities of about 0.6, 1.9, and 4.9 m/ms were used in the correction representing the upheole layer(s), the Triassic rocks, and the underlying basement, respectively.

There were only small variations in the elevation of the ground surface along Line 10 and so no elevation correction
Figure 2.8 Map of Bardon Hill showing the field layout of the refraction line (RFR-10) and some boreholes (BH) in the area (values in brackets are the depths (m) to the basement); G1 and G35 are the first and last geophones along the line and A, B, C, D, E, F, and G are the shots.
### Shotpoints

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uphole Velocity (m/ms)</td>
<td>0.9</td>
<td>0.8</td>
<td>0.7</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

**Table 2.2** Uphole velocities measured at shotpoints A-G.

### Velocity Layer

<table>
<thead>
<tr>
<th></th>
<th>Seismic Velocity (m/ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Weathered Triassic sediments</td>
<td>1.5</td>
</tr>
<tr>
<td>Triassic Rocks</td>
<td>2.1</td>
</tr>
<tr>
<td>Basement</td>
<td>5.0</td>
</tr>
</tbody>
</table>

**Table 2.3** Seismic velocities of subsurface layers measured along Line 10.
Figure 2.9 Plots of first arrival times for shots A–G:
   a) raw data, and b) corrected data.
was needed. Position corrections, however, were made to some geophones and shotpoints. Geophones 1 and 30, and shotpoint D were moved laterally onto the seismic line. Shotpoints B, C, F, and G were corrected to the positions of geophones 9, 17, 30, and 35, respectively. Appendix B.2 lists corrected seismic data for Line 10. The plots of these data are shown in Figure 2.9b. The equality of the reciprocal times was used as an indication of the accuracy of arrival time corrections.

The velocity of 1.9 m/ms that was used for the Triassic rocks in the correction, however, is simply an average of the velocities of these rocks determined by the shots along the line. The range of basement velocities, obtained from the minus time plots (Figure 2.9a; Table 2.3), was 3.5 to 5.0 m/ms, but only the limited range of about 4.5 to 5.0 m/ms was considered; the lower velocities determined at shots C, D, and E were attributed to the effect of refractor curvature in the middle of the line (see Section 2.3.1, Figure 2.4).

Since the uphole velocity represented an average velocity of the layer(s) above the charge in the shothole rather than of a distinct layer, a short hammer refraction survey (33 m) was carried out at shotpoint B to define near-surface structure. Hammer refraction data are listed in Appendix B.3. Two velocity layers were indicated by this survey. The upper layer has an average velocity of about 0.3 m/ms while the lower layer has an average velocity of about 1.4 m/ms. These layers probably represent the soil and the saturated Triassic sediments, respectively. Seismic data from this short line combined with that of shot B (Line 10) were used to determine the thickness of the upper part of the Triassic rocks. The near-surface velocity layers interpreted from the hammer refraction survey at shotpoint B, however, were assumed to be uniform along the entire seismic line (10). Table 2.4 summarizes the results of the hammer refraction interpretation.

2.4.2 The plus-minus calculation

The plus-minus interpretation started by determining a better estimate of the velocity of the "basement" refractor using the minus times determined from the corrected data. Velocity values of about 4.7 and 4.4 m/ms were obtained from
<table>
<thead>
<tr>
<th>Velocity Layer</th>
<th>SP B1 $V$ (m/ms)</th>
<th>SP B2 $V$ (m/ms)</th>
<th>SP B3 $V$ (m/ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Z$ (m)</td>
<td>$Z$ (m)</td>
<td>$Z$ (m)</td>
</tr>
<tr>
<td>Soil</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Weathered Triassic sediments</td>
<td>1.5</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>6.2</td>
<td>6.2</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Table 2.4 Results of seismic interpretation for the short hammer spread.

<table>
<thead>
<tr>
<th>Velocity Layer</th>
<th>Velocity (m/ms)</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>0.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Weathered Triassic sediments</td>
<td>1.4</td>
<td>6.2</td>
</tr>
<tr>
<td>Triassic Rocks</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>Basement</td>
<td>4.7</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.5 Subsurface velocity structure defined for the plus-minus calculation.
the minus time plots for the profiles A-G and A-F, respectively.

The plus times were then determined in the reversed zones of the two profiles while pseudo plus times were estimated for the non-reversed zones. Subsequently, the depth to refractor below each geophone on the surface was estimated. Table 2.5 lists the velocities and the thicknesses of the near-surface layers that were defined for the plus-minus interpretation.

A BBC microcomputer, using available BASIC computing programs, was used to perform the plus-minus interpretation.

2.4.3 Discussion of results

The resultant subsurface seismic sections from Profiles A-G and A-F (Figures 2.10 and 2.11) show a trough in the middle of the line with a maximum depth of about 67 m. The ridges on either side rise to a depth of about 20-30 m (Appendices B.4 and B.5). The assumptions of the near-surface structure were held constant throughout the interpretation (Section 2.4.2, Table 2.5). The velocity of the refractor, however, was the only parameter to be varied. The first velocity assigned for the refractor is 4.7 m/ms. This was obtained from the minus times plot for Profile A-G.

Small changes in the velocity of the refractor, such as using a value of 4.9 m/ms in both profiles and a value of 4.4 m/ms in Profile A-F, made little difference to the calculated depths to the refractor in the reversed zone (between geophones 11 and 24). In the non-reversed zones, the same changes in the velocity of the refractor made a greater difference to the calculated depths. The smoothest and the most consistent solution for the basement was obtained when the 4.7 m/ms velocity value was used (Figures 2.10 and 2.11), in which case calculated depths for profiles A-G and A-F were found to agree within an error of ±5% in the reversed zone.

The resultant structure (shape) of the basement suggests a positive error (overestimate) in depth determination to the slopes and ridges of the basement due to reciprocal times error (Section 2.3.1, Figure 2.3). A negative error (underestimate) in the determined depths to the slopes of the basement is probable due to the dip of the refractor (Section
Figure 2.10 Subsurface section interpreted by the plus-minus seismic refraction method along Profile A-G.
**Figure 2.11** Subsurface section interpreted by the plus-minus seismic refraction method along Profile A-F.
2.4.4 Comparison of refraction results with borehole data

Borehole data in the area (Figure 2.8) indicate that the basement is much deeper than has been revealed by the plus-minus method. Comparison between the calculated depths at shotpoints C and E (=65 and 34m) and the actual depths at these points (=100 and 70m) shows negative errors in the calculated depths of approximately 35% and 50%, respectively. The effect (negative) of the dip of the refractor (around 15°) on the depth is minor (< 5%). Correction for this effect can be simply done by dividing the measured depths by the cosine of the dip of the refractor "migration".

These large errors may be caused by a combination of a negative error in the overburden velocities, a positive error in refractor velocity, assignment of a constant velocity structure above the refractor and the smoothing factor of the method itself which assumes a plane refractor and uniform velocity below the receiving geophone (in the triangle DGE; see Figure 2.1).

Methods to improve the accuracy of velocity and depth estimation by the plus minus refraction interpretation are discussed in Chapter 4.

2.5 CONCLUSION

The plus-minus method of seismic refraction interpretation detected the main feature of the geology, a Charnian basement with an irregular surface, overlain by Triassic sediments. However, it smoothed the actual topography of the refractor and underestimated its depth. Errors in depths were as high as 50%.

Further investigation of the irregular basement surface could be made using, for instance, the GRM interpretation method.

The succeeding chapters will analyse the performance of a variety of modifications of seismic reflection techniques to see whether a more accurate interpretation of the shallow subsurface geology can be obtained.
CHAPTER 3
THE SHALLOW SEISMIC REFLECTION METHOD

3.1 INTRODUCTION

Seismic methods of prospecting use the elastic properties of earth materials, which govern the propagation of the seismic wave through the earth, as a means to explore the subsurface. Reflection at discontinuities is one of the seismic wave characteristics in earth materials which is employed by the seismic reflection method. Here, velocity and density are directly important and both are highly variable at shallow depths (see Section 6.8.1). For a general introduction to seismic theory see Telford et al (1976).

In this chapter, problems encountered in shallow reflection and the theory and development of the high-resolution seismic reflection method are discussed.

3.2 PROBLEMS WITH SHALLOW SEISMIC REFLECTION

3.2.1 Source-generated noise

The seismic sources available are sufficiently powerful that the ambient noise is rarely a problem, but source-generated noise is the major difficulty. Interfering events include several types of seismic wave (P-waves, S-waves, surface waves (i.e. ground roll) and air-coupled waves) following different wave paths: direct, refracted, diffracted and multiples (Mooney, 1984). The most serious problem arises from the interference of the source-generated ground roll because of its large amplitude and prolonged wave train. When deep targets are involved (large record time), the different seismic events have sufficient time to be separated and identified. At shallow depths, however, because of the short time record the interference becomes more severe and therefore identifying and extracting reflections is much more difficult. The ground roll, for example, may extend across the time interval which includes reflections and hence obscure them (see Section 3.3.3).

The air-wave is a high-frequency pulse with a velocity of 330 m/s. The air-wave energy is dependent on the type of energy source; surface sources produce stronger air-waves
than buried charges.

All these types of source-generated noise are observable across many traces of the seismic record; hence they are coherent noise (Sheriff and Geldart, 1982). Source-generated noise can also be incoherent, though repeatable. These include scattering caused by local inhomogeneities and irregularities such as gravels, boulders, fissures and caves. The problem with source-generated noise, coherent or incoherent, is that its effect cannot be reduced by increasing the source energy.

3.2.2 Effect of near-surface materials

Recording high-resolution shallow seismic reflection requires the generation, transmission, and recording of high frequencies. High-frequency energy is needed to identify, discriminate and distinguish between reflections and interfering waves. Unfortunately, however, the high frequency component of the energy suffers maximum attenuation. This effect is more pronounced for the less consolidated rocks such as the near-surface materials. Thus, it is this near-surface layer which forms the major barrier to propagation of high-frequency waves.

The loss of energy due to attenuation, which is caused by internal friction in the medium, may be modelled as an exponential relationship with the propagated distance:

\[ I = I_0 e^{-\alpha r} \]  

where \( I \) and \( I_0 \) are intensities measured at two points distance \( r \) apart. \( \alpha \) is the absorption coefficient.

Attenuation is a complex process, highly dependent on complex properties of the medium. From empirical studies the absorption coefficient is proportional to the first power of the seismic wave frequency. The effect of the frequency selective absorption is a continuous loss of high frequency with distance for the travelling seismic waves (Dobrin, 1976; Telford et al, 1976).

Variations in the elevation, thickness and velocity of the "weathering layers" cause variable delays (statics) in the arrival times of reflections from deeper layers. As such, the horizontal subsurface layering and subsequently the
hyperbolic reflection moveout assumptions, which are used for velocity determination (Section 6.5), are affected and distorted by such statics. For high-resolution using frequencies around 200 Hz, assuming a \( \frac{1}{4} \) of a wave period as an upper limit for continuity across adjacent traces, static errors must be less than 1.25 ms.

The magnitude of these statics depends only on the surface geology, and is independent of the target's depth and the geometry of the system. Therefore, scaling down the physical dimensions for high-resolution shallow reflection does not reduce static anomalies.

3.3 THEORY AND DEVELOPMENT OF SHALLOW REFLECTION METHODS

The sole objective of all the recently developed methods and technology in shallow reflection seismology is to be able to record high S/N data with high resolution. The sequence of generating high frequencies, suppressing noise and extracting and recording high-resolution seismic data can be best accomplished by investigating the functions of the different elements which compose the whole shallow reflection system. Five main elements are recognized. These are: 1) the seismic energy source, 2) the seismic detector, 3) geometry, 4) data capture, and 5) data processing. The theory and development of each element are given below.

3.3.1 Seismic energy source

The details of seismic waveforms are determined by the source waveform and strongly influenced by the attenuation along the raypath. While the effect caused by the latter is beyond our control, the characteristics of the source waveform are dependent upon the source type. Such characteristics include the dominant frequency and bandwidth and the energy output of the source as well as its repeatability. Other factors such as cost, portability and convenience, environmental considerations and safety also dictate the choice of a seismic source for any particular work. Discussion of these latter factors can be found in Knapp and Steeples (1986b).

An ideal source would have an impulsive waveform, i.e. a flat amplitude spectrum up to high frequencies. For a
practical explosive source the frequency bandwidth determines the pulse width and the resolution (Knapp and Steeples, 1986b). For maximum resolution emphasis should be placed on frequency bandwidth. A vertical separation (of two interfaces) of approximately 1/4 of the dominant wavelength is considered to be the minimum resolvable limit (Sheriff, 1980).

The shift to higher frequencies is achieved by reducing the size of the explosive charge. According to the scaling law, the duration and amplitude of the pulse are proportional to the cubic root of the mass of the explosive charge (Ziolkowski and Lerwill, 1979). An appreciable amount of energy can be produced at high frequencies if the decay of the amplitude spectrum at these frequencies is slower than the inverse square of the frequency (Bredewout and Goulty, 1986). The shift to higher frequencies results in reducing the amplitude of the pulse and the level of the spectrum. Two factors are important here: the availability of the dynamic range in the recording system and the shape of the spectrum.

Deploying the energy source below the surface augments the high frequencies of the generated and transmitted seismic energy by: (1) ensuring better coupling to the ground, (2) minimizing attenuation for the high frequencies away from the surface, and (3) reducing distortion and degradation (in processing) of seismic signals caused by the static errors (weathering effect) which is more serious at and immediately below the surface (Ziolkowski, 1979; Ziolkowski and Lerwill, 1979). Also, it has the added advantages of low air-wave production and less excitation of ground roll. As such, the sub-surface sources are preferred in high-resolution shallow reflection work. Seismic characteristics of some sources commonly used in shallow reflection work are shown in Table 3.1.

The high-frequency characteristic of the projectile impact sources is related to the mechanism of seismic energy generation. At the time of impact the bullet generates a hypersonic shock wave directed downwards along the bullet’s movement path. This causes the compressional energy to be Doppler shifted to the high-frequency end of the spectrum (Steeples, 1984). The amount of energy produced by this
<table>
<thead>
<tr>
<th>SOURCE TYPE</th>
<th>DOMINANT FREQUENCY (Hz)</th>
<th>ENERGY</th>
<th>AIR-WAVE ENERGY</th>
<th>REPEATABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammer</td>
<td>&lt; 80</td>
<td>&lt; 300 J (for 4.54 Kg; Singh, 1983)</td>
<td>High</td>
<td>V. good.</td>
</tr>
<tr>
<td>Weightdrop</td>
<td>&lt;80</td>
<td>Variable; depends on mass of weight and height (Herber and Helbig, 1981)</td>
<td>High</td>
<td>V. good.</td>
</tr>
<tr>
<td>Wacker</td>
<td>80-120</td>
<td>65 J per impact; about 300 impacts per shotpoint are used (Barbier et al, 1976); 1000-2000 impacts per shotpoint (Knapp and Steeples, 1986b)</td>
<td>High</td>
<td>V. good.</td>
</tr>
<tr>
<td>Sparker</td>
<td>200-600</td>
<td>Variable- generally very low (McCann et al, 1985)</td>
<td>low</td>
<td>V. good.</td>
</tr>
<tr>
<td>Rifle</td>
<td>100-200</td>
<td>Depends on amount and type of explosive powder; mass, type and shape of projectiles; and bullet muzzle velocity (Steeples, 1984)</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Betsy seism gun</td>
<td>80-120</td>
<td>The same as above</td>
<td>High</td>
<td>Variable, depending on creation of cavity at depths (see Knapp and Steeples, 1986b).</td>
</tr>
<tr>
<td>Buffalo gun</td>
<td>80-120</td>
<td>Depends on gauge and type of explosive powder (Fullan and MacAultay, 1985)</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>Gas exploder</td>
<td>170-200</td>
<td>1000 J, possibly up to 15 KJ depending on the total volume of the gas (Singh; 1984a, b)</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>Detonator</td>
<td>&lt; 80</td>
<td>Depends on type and size of charge (Bradewout and Goult, 1986)</td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>Explosive</td>
<td>&lt; 80</td>
<td>Depends on charge size (Ziolkowski and Lerwill, 1979)</td>
<td>low</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1 Seismic characteristics of some of the commonly used seismic energy sources.
source depends on the type and shape of the projectile.

The MiniSOSIE method is derived from the marine SOSIE process which depends on sending a coded sequence of impulses into the ground (Barbier and Viallix, 1973; Barbier et al, 1976). For land work, an earth-tamper, which can produce between 10 to 40 impacts per second, is used as a source of energy. Some 1000-2000 impacts are usually stacked at each shotpoint. Decoding is done in real time using a SOSIE pulse sequence sent by a sensor on the plate of the tamper.

The repeatability of the seismic source is a very important criterion especially where signal enhancement is made by field processing the seismic record from the same shotpoint (vertical stacking). Table 3.1 summarizes the degree of the repeatability of the commonly used sources.

The Geological Survey of Canada made a source test where Buffalo gun, sledge hammer and weight drop were used (Pullan and MacAulay, 1985). They reported that the Buffalo gun was superior to the other sources in terms of energy output and frequency content. They found that the energy produced by the Buffalo gun (12-gauge) was about 30-40 times as much as that produced by the hammer for the frequency range 300-400 Hz and that substantial energy was obtained at higher frequencies up to 800 Hz. The 8-gauge Buffalo gun was more powerful than the 12-gauge gun. Also noted was the absence of air wave on the Buffalo gun records (Pullan and MacAulay, 1985, 1987).

The Kansas Geological Survey group tested different types of projectile impact sources which are commercially available. These included the Betsy (8-gauge) Seisgun, 0.22 and 0.30-60 rifles, and 0.50-calibre machine gun (Steeples, 1984). These sources produced high-frequency signals (above 200 Hz). The 0.50-calibre machine gun was found to be superior to the others in terms of energy output and frequency content. This was attributed to the shape of the projectile (bullet with a parabolic tip). With respect to the type of the projectile, they found that using a 1,300 grain iron slug for the 8-gauge gun gave higher energy than a 1,300 grain lead slug (Steeples, 1984).

They also tried MiniSOSIE as a seismic source (Steeples et al, 1986). It was used to resolve relatively deep reflectors (up to 300m below the surface) in an area with
noise caused by road traffic. They indicated that the method is very effective in suppressing noise and providing moderate resolution (dominant frequency 80-120 Hz).

Knapp and Steeples (1986b) recommended the use of rifles and the propane-oxygen detonator for target depths less than 15 metres and the sledge hammer, blasting caps and rifles for depths between 15-45m. For deeper targets, weight drops, Betsy Seisgun, MiniSOSIE, and dynamite were suggested.

Singh (1983) from the Mining Research Institute of Malaysia used a propane-oxygen detonator as a seismic source for shallow reflection work. This source was developed to replace the sledge hammer which was initially used in reflection work (Singh, 1983, 1984a, 1984b, 1986). However, he found that the detonator was not consistent in producing the seismic signature due to the difficulty of attaining the critical gas mixture.

The Exploration Geophysics group at Utrecht University in Netherlands obtained high quality shallow reflection data (resolution of about 2-3m) using a weight drop in tidal flat areas (Herber et al, 1981; Doornenbal and Helbig, 1983). The peak frequency of the source was 200-300Hz and the target depth was between 10-20m.

This source was also tested on dry land in the vicinity of the village of Winterswijk in the Netherlands. Reflection from depths as shallow as 30m was reported to be seen on records with vertical resolution of better than 10m (Bredewout and Goulty, 1986). They indicated that frequencies in the range 35-180 Hz were produced by the weight drop.

Finally, Miller et al (1986) conducted a major field trial of seismic energy sources. However, they made no conclusions or recommendations about which source is best used in shallow reflection surveys. They indicated that any of these sources can dominate the comparison items under certain geological conditions.

3.3.2 Seismic detector

The detector is the most critical element in the seismic recording system. There are several types of seismic detector: hydrophones, accelerometers and geophones.

Hydrophones are reported to give better results in areas
where the water table is shallow or when deep detectors are used (Ziolkowski and Lerwill, 1979). They have flat amplitude response up to high frequencies with mechanical resonance as high as 1000 Hz. Hydrophones are placed below the water table or in holes filled with water. This, however, limits their application in shallow reflection work (Mooney, 1984).

Accelerometers have a very high resonant frequency and a frequency dependent response (Lepper, 1981). This response (6dB/Octave) acts as a high pass filter attenuating the large amplitude low frequencies and emphasising the high frequencies (Figure 3.1). They are especially recommended for use in hard-rock environments (Mooney, 1984). However, current designs of accelerometers have two weaknesses: 1) they are fragile, and 2) their output voltage is low (Knapp and Steeples, 1986a).

Geophones are moving coil systems which can be used in two orientations: vertical and horizontal. The vertical geophone measures the vertical component of the particle velocity (the time derivative of ground displacement) and is the most commonly used detector. Less often, geophones sensitive to horizontal ground motion are deployed and are usually used to record shear waves.

Geophones used in conventional seismic work are designed to respond to the lower end of the spectrum (10-50 Hz). Since the emphasis in high-resolution shallow reflection work is to record broad high-frequency bandwidth and to attenuate low frequency surface waves, a fundamentally different response is necessary.

The performance of the geophone is determined by several factors. These include the natural resonant frequency, the mechanical resonance, the damping factor, and the harmonic distortion (Knapp and Steeples, 1986a). The natural resonant frequency of the geophone is determined primarily by the character of the suspension springs (Lepper, 1981). The mechanical "parasitic" resonance introduces spurious effects above certain frequencies where the geophone response to horizontal motion becomes significant (Lepper, 1981). The mechanical resonant frequency is usually designed to occur at more than ten times the natural frequency of the geophone.

Damping is used to cut down the large amplitude at the
Figure 3.1 Schematic frequency response curves for high frequency geophone (solid line) and accelerometer (dashed line) excited with constant velocity; output voltage is plotted on logarithmic scale.
resonant frequency, and reduce the phase distortion. Geophones are normally damped by shunt resistors to about 0.5-0.7 critical (Lepper, 1981; Knapp and Steeples, 1986a). Increased damping pushes the resonant peak to higher frequencies in the amplitude frequency response curve, and causes the phase-frequency response curve to slope more gradually. It also reduces the sensitivity of the geophone. 0.7 critical damping is recommended for high-resolution work (Evenden and Stone, 1971).

Non-linearity of sensitivity and damping of the spring-mass system cause harmonic distortion. Less than 0.2% total harmonic distortion by the geophone at its resonant frequency is essential (Huan and Pater, 1985; Knapp and Steeples, 1986a).

A geophone with high resonant frequency is required for shallow reflection work. Its broad flat response above the natural frequency does not distort the frequency range of interest, while its response below the natural frequency acts as a low-cut filter which helps to suppress the low-frequency noise, especially the high-amplitude ground roll. Hence, it acts against the effect of the earth's attenuation of high frequencies and helps to balance the spectrum of the recorded seismic signal. It also reduces the dynamic range of the output voltage, thereby reducing the problems imposed by the limited dynamic range of recording systems (Knapp and Steeples, 1986a). In addition, it reduces the amplitude of the noise harmonics which, otherwise, might severely distort and degrade high-frequency signals (Stanley, 1986).

The presence of a geophone on the surface of the "elastic" earth forms a damped oscillating system (Wolf, 1944). The performance of this resonant system "the coupling", depends on whether the geophone case follows faithfully the motion of the ground; otherwise distortion in both the amplitude and the phase may be introduced into the recorded seismic signal. This is particularly true for frequencies higher than the resonant coupling frequency, since the response of the resonant system acts as a low-pass filter eliminating the high-frequency component of the signal (Hoover and O'Brien, 1980).

A light-weight geophone with a large earth contact shows
a high resonant coupling frequency and increased damping. Apart from the effect of the area of contact, the resonant frequency increases with increased soil consolidation (Hoover and O'Brien, 1980). The effect of soil firmness on the coupling resonance was emphasized by Krohn (1984) while the effect of the geophone mass or diameter was dismissed. Knapp and Steeples (1986a) attributed the difference in the above studies to differences in the geophone design. Modern geophones are spike coupled to the ground while plate base coupled geophones were used in early studies.

To achieve better coupling, geophones need to be planted firmly either by burial or using long spikes. The former kind of plant has the added advantage of avoiding the frequency dependent filtering effect which is more profound at the surface. A disadvantage of the sub-surface plant, however, is the reduction in signal amplitude due to the geophone being away from the free surface where the particle velocity is at a maximum (Ziolkowski and Lerwill, 1979).

Since earth surface materials vary considerably, geophone performance may differ significantly along a survey line. This can seriously degrade data quality even when small geophone arrays are used since phase shifts may occur due to slight differences in ground coupling (Ziolkowski and Lerwill, 1979). Safar (1978), however, argued that a group of geophones can be used to advantage in some cases. He noted that distortion introduced by geophone-ground coupling can be reduced significantly by increased damping of the system due to mutual interaction between closely spaced geophones. In this case, the distance between any two geophones needs to be much smaller than the shortest wavelength of interest (Safar, 1978).

The advantages of using single geophones over geophone arrays is not only to prevent the high-frequency attenuation caused by differences in the coupling but also to avoid frequency "wavelength" filtering usually caused by arrays. An array is an apparent wavelength filter usually employed in conventional reflection work to attenuate both source-generated and ambient noise (Meidav, 1969; Anstey, 1970; Dobrin, 1976). Its action can be achieved whether it is used with shots or geophones though the latter type is common
because of cost and convenience.

In high-resolution work, because of the shallow depths involved, the angle of emergence of the reflected signal tends to be large, especially with increased shot-geophone offset, which results in a smaller apparent wavelength. So to preserve this signal, array length needs to be reduced possibly to < ¼ of the wavelength, where approximately -3dB attenuation in the signal occurs (Knapp and Steeples, 1986b). However, an array design on this basis may not be effective in filtering out surface waves (being too small as compared with their wavelengths). Practically, wavelength filtering occurs and affects the high frequencies even if short arrays are used, the effect being exaggerated with dipping reflectors (Ziolkowski and Lerwill, 1979).

The Geological Survey of Canada obtained useful reflection data with low frequency geophones though they recommended high-frequency single geophones (50 or 100 Hz) for high-resolution work (Hunter et al, 1982a; 1984). They placed the "spiked" geophones on the surface and reported that burial of geophones was useful to reduce the noise level and to ensure a good and a uniform coupling (Hunter et al, 1982a).

The Kansas Geological Survey recorded high-resolution reflections (above 200 Hz) from depths as shallow as 10m using single 100 Hz geophones with 13cm long spikes to ensure a firm plant (Treadway et al, 1984). They used geophone (10 and 28 Hz) arrays to collect moderate-resolution (100 Hz) reflections from deep (up to a few hundred meters) horizons (Knapp, 1986; Steeples et al, 1986).

Singh (1986) reported success in recording reflections from 40m deep bedrock using 28 Hz geophones.

The Utrecht University research group noted a significant improvement in the reflection data recorded by the 100 Hz geophones over that by 25 Hz geophones (Doornenbal and Helbig, 1983). They found that pressing the geophone completely into the ground successfully recorded the high-resolution signal and minimized the airborne noise on tidal flat areas.

Mooney (1984) stressed the need for a shovel hole in areas with humus, loose vegetation, and aerated soil and to
avoid planting geophones on the surface.

Finally, Knapp (1986) tested a very small array using two vertically spaced geophones. He indicated that the horizontally propagated waves (e.g. surface waves) are attenuated when the output of the two geophones are subtracted. He found that a differencing rather than cancellation occurs to the vertically travelled wave (reflection) due to the phase shift. He reported that best results were obtained when one of the geophones was placed on the surface while the other was planted in a 1m deep hole.

3.3.3 Geometry

The raypath geometry is controlled by the geological structure of the subsurface and the recording geometry at the surface e.g. the length of the spread, the minimum and maximum source-geophone offsets. The use of single geophones or arrays and then the array length are decided by the target depth and the resolution sought.

Three types of geometry "acquisition techniques" are used in shallow reflection work. These are the optimum window, optimum offset, and the common mid-point (CMP) methods. The first two methods, which are known as "Hunter's optimum seismic reflection techniques", are simple to operate in the field and require little post-recording processing (Hunter et al, 1981; 1982a, b; 1983; 1984; Pullan et al, 1983). In these methods each reflecting point is sampled once. Hence, they can only be employed in areas where strong reflectors (large acoustic impedance contrasts) and good transmission of high frequencies occur.

In the optimum window method, geophones are placed with respect to the source so that reflection is observed with minimum interference from source generated noise. The near geophone is located beyond the zone of the ground roll interference. The far side of the window is usually the point where other events (i.e. headwaves) start to interfere with reflections (Figure 3.2).

The shot-geophone "optimum window" is dependent on the depth and the velocity contrast across the interface. It increases with increased depth and decreased contrasts. However, large phase shifts occur with large velocity
Figure 3.2 Time-distance graph of seismic waves from two-layer earth structure showing a window in time for uncontaminated reflection recording.
contrasts (Hunter and Hobson, 1977; Pullan and Hunter, 1985). The windows are chosen to give the good reflector moveout necessary for velocity analysis, yet phase and amplitude changes (near critical reflection) due to offset increase should be at a minimum. Such a change in phase may cause a great change in the character of the reflected wavelet.

In Hunter's optimum offset technique, a shot-geophone offset is chosen from the first method and the whole seismic section is shot one channel at a time using the selected offset.

The CMP method provides multifold coverage data; a reflecting point is sampled more than once (Figure 3.3). It is a data acquisition as well as processing technique and is the standard in conventional seismic reflection. It is used to improve the signal to noise ratio by summing reflection signals obtained from one mid-point by rays with different shot-receiver offsets. The processing aspect of the method is discussed in Chapter 6.

The fold of coverage may vary depending on the improvement sought though 6-fold and 12-fold recording are commonly used. A number of geophones (e.g. 24) are used to collect seismic data from each shotpoint along the seismic line.

Two types of spread are used with the CMP geometry: 1) the split "dip" spread, and 2) the end-on spread. For the first type, the source is located in the middle of the spread while it is located at the end (either end) of the spread for the second type. Split-spread is recommended if the length of the spread is adequate for velocity analysis. A gap or an offset (in-line spread) can be left between the shot and the geophones to avoid strong ground roll at small offsets.

The multiplicity of the coverage is determined by the number of geophones in the spread and by the shot interval. Usually, shots are placed at integer offsets along the line (multiples of geophone spacing, i.e. 0, 1, 2, ....etc). For a split-spread CMP geometry, the use of half integer source offsets is recommended (Knapp, 1985). With this technique, shots are placed midway between geophone points rather than at the actual points as in the case of the integer offsets. Then, each trace in a CMP gather represents a unique distance
Figure 3.1 Diagram showing the concept of the CMP technique:
(a) CMP recording profile. (in processing) into gathers.
(b) Traces which share the same CMP are sorted

\[ T^2 = \frac{X^2}{V^2} - 4Z^2/V^2 \]
\[ T_0 = \frac{2Z}{V} \]
\[ \Delta T = T - T_0 = \frac{X^2}{2V^2} \]

where \( T \) is slant two-way time (TWT), \( T_0 \) is vertical TWT, \( V \) is velocity, \( Z \) is depth, \( \Delta T \) is normal moveout (NMO) and \( X \) is horizontal distance (Grant and West, 1965).
from the source. This technique is powerful in suppressing source-generated noise, and gives a 3dB improvement over the integer source offset. Also, shooting half integer offsets has advantages, statistically, in velocity analysis and better automatic static corrections (Steeples et al, 1983; Knapp, 1985).

The length of the spread is related to the depth of target and is determined by the minimum and maximum shot-geophone offsets. To avoid wide angle reflection and to make use of the CMP geometry, at least four geophones should be placed closer to the shotpoint than the smallest depth of interest and the offset to the far geophone should not be greater than the maximum depth of interest. A spread defined by Hunter's optimum window technique can be exploited. Small offsets, however, are useful to provide information about near-surface materials from first break data although such offsets can lead to interference of the ground roll with reflection signals (Knapp and Steeples, 1986b).

Geophone spacing is determined by the source-generated ground roll, the horizontal sampling "resolution" required as well as by the number of channels available in the recording system. It should be smaller than \( \frac{1}{2} \) the wavelength of the ground roll to prevent aliasing of this low frequency wave. It should also be no more than twice the spatial sampling sought for the reflector. The term "reflection point" rather represents an area of the reflector surface. It is related to the first Fresnel zone from which most of the reflected energy is returned (Sheriff, 1984). The size of this zone \( R \) is determined as follows:

\[
R = (0.5\lambda h)^{\frac{1}{2}} = 0.5 V(t/f)^{\frac{1}{2}} \quad \ldots \quad (3.2)
\]

where \( R \) is the radius of the first Fresnel zone, \( h \) is the depth of the reflector, \( \lambda \) is the wavelength, \( V \) is the velocity, \( t \) is the two-way time (TWT), and \( f \) is the frequency of the signal.

For adequate horizontal sampling, at least four CMPs should be included in a Fresnel zone (Knapp and Steeples, 1986b). Spatial sampling is of particular importance in preventing spatial aliasing of steep structures. Geophone spacing ought to be smaller than one half of the projection
of the shortest wavelength of interest on the surface:

\[ GS < 0.5(\lambda/\sin \alpha) = 0.5[(V/f)/\sin \alpha] \quad \cdots \quad (3.3) \]

where \( GS \) is geophone spacing, \( \alpha \) is the dip angle, \( \lambda \) is the minimum wavelength, \( V \) is the average velocity, and \( f \) is the maximum frequency.

The optimum window and offset techniques were used by the Canadian group for shallow reflection work (Hunter et al., 1982a, b; and 1984). They reported successful results with these methods (Figure 3.4) and observed, under favourable field conditions, high frequencies (300-400 Hz) transmitted to considerable depths. They obtained reflections from bedrock at depths as shallow as 15m (Pullan et al, 1984). They reported success in mapping a gravel layer above the bedrock which would have been a hidden layer in refraction survey. However, they preferred not to use the CMP geometry because of the cost of field operation and post-recording processing needed by this technique (Hunter et al, 1984).

Singh (1986) successfully used the reflection-window shooting technique in mapping bedrock. He obtained reflections from bedrock at depths as shallow as 25m and reported the transmission of high frequencies (above 250 Hz when a propane-oxygen detonator was used as a seismic source) from such depths. He found the constant-offset geometry attractive because the shape of bedrock topography can be directly deduced from field records and less processing is needed. He reported that the CMP shooting was not attempted because of the severe bedrock topography.

The CMP method was used routinely and extensively by the Kansas Geological Survey in shallow reflection work (Steeples et al, 1983; Treadway et al, 1984; Miller et al, 1985; Steeples et al, 1986). They used both the end-on and the split spreads in CMP recording. They reported success in resolving a fault, with vertical displacement of a few metres, produced by an earthquake near Borah Peak, Idaho (Treadway et al, 1984). They used an end-on spread 20m in length, with 1.22m geophone spacing and shot interval (Figure 3.5). For moderate resolution and deeper reflectors (up to a few hundred metres), they used a 120m spread length with geophone arrays placed at 12m group intervals. Each group
Figure 3.4 Seismic reflection sections shot by the Geological Survey of Canada using:
(a) optimum window technique; Bedrock depth varies from 70 to 180m.
(b) optimum offset technique; Bedrock depth varies between 65 and 95m.
(After Hunter et al., 1984).
Figure 3.5 12-fold CMP stacked section shot by the Kansas Geological Survey in Idaho showing discontinuous reflection horizons (After Treadway et al, 1984).

Figure 3.6 6-fold CMP stacked section shot by the Utrecht University group in SW-Netherlands revealing several unconformities (After Doornenbal and Helbig, 1983).
consisted of three geophones 1.5m apart (Steeples et al, 1986).

The CMP geometry was also used by the Utrecht University group to record 6-fold subsurface coverage in a tidal flat area (Herber et al, 1981; Doornenbal and Helbig, 1983). The CMP method was used for a minimum target depth between 10-20m. A line was shot at 3m interval and the geophones were 3m apart with an 18m shot-first geophone offset. A 6-fold coverage was provided with this arrangement, obtaining high quality data with a resolution of about 3m (Figure 3.6).

3.3.4 Data capture

Multichannel digital seismographs with a fast response to changes in signal level (by AGC, PGC, and IFP), high-frequency components (amplifiers), low noise level, low-cut filters, signal enhancement, and digital filtering are now available. The output data are usually displayed on a VDU, as a paper record print and stored on magnetic media. Either magnetic tape recorders, disc drives or microcomputers are used for this purpose. Storage of the digital data is essential for post-recording processing.

The dynamic range of the recording system is determined by the analog-to-digital converter. A 12-bit A/D converter (72 dB), for example, is better than that of an 8-bit converter (48 dB) but to make use of the available dynamic range, amplification should be as high as possible. Amplifiers with programmed gain control (PGC) or Instantaneous floating-point (IFP) are being used to achieve that. More detailed discussion can be found in Knapp and Steeples (1986a and b).

Because of the limitation in the dynamic range of most engineering seismographs, and to prevent these from saturation by the low-frequency, high-amplitude source-generated noise (i.e. ground roll), analog low-cut filters are usually incorporated on such seismographs. Filters with corner frequencies of 200-300 Hz are required. Record length of about 200 ms is common in shallow work, and adequate for the depths of interest. A sampling rate of at least 2000 Hz is necessary, giving a Nyquist frequency of over 1000 Hz which is well above present day high-resolution requirements.
(200-600 Hz). Anti-alias filters should always be used.

The Geological Survey of Canada used the 12-channel Nimbus 1210F seismograph to collect shallow reflection data and the G-724S digital tape recorder for storage (Hunter et al, 1982c). They applied a low-cut filter up to 300 Hz and obtained high-resolution reflections from bedrock at a depth of about 15m (Hunter et al, 1984; Pullan et al, 1984).

The 12-channel Nimbus seismograph (ES-1200), with a 10-bit accuracy and 1024 words per channel, and the G-724S digital tape recorder were used by the Utrecht University group (Doornebal and Helbig, 1983). They applied a 100Hz low-cut filter and obtained high quality reflection records.

Singh (1986) used a 12-channel signal enhancement seismograph in mapping shallow bedrock. His system consisted of three units for enhancement, display, and processing. The enhancement unit has a 12-bit A/D converter and the processing unit can be interfaced to a microcomputer for additional processing. A 100 Hz low-cut filter was used.

The Kansas Geological Survey group used a 24-channel seismograph (the DHR 2400) for shooting shallow CMP reflection. It had a 12-bit A/D converter giving a 66 dB dynamic range (Steeples et al, 1983). It can record, plot, and save a 24-trace file on tape every half a minute. For shallow target depths, they recorded 200-250ms, used 0.25ms sample interval and applied a severe (up to 220 Hz) low-cut filter prior to A/D conversion (Steeples et al, 1983; and Treadway et al, 1984). However, they used different recording parameters for deeper targets.

### 3.3.5 Data processing

Processing in shallow reflection does not need to be a duplicate of that used in conventional reflection seismology (as e.g. in Sheriff and Geldart, 1983 P.75).

Two types of processing procedure are usually followed in shallow reflection work. These are used to produce: 1) a constant-offset section, and 2) a CMP processed section. The first is simple and cheap to make. Small and inexpensive microcomputers (e.g. Apple II with 48 Kbyte of user memory) are adequate for such a task (Hunter, 1981; Hunter et al, 1982c; Singh, 1986). This, however, is only useful when
reflections are visible on field seismic records.

The CMP processing method is somewhat expensive. It is very useful to improve data quality by increasing the S/N ratio and can bring out reflections which are not visible on field records, and to derive velocity (Steeples et al., 1983). Such processing has usually required a mainframe computer; however, basic processes required to obtain stacked CMP section can be made in a reasonable time with a microcomputer of sufficient power (Zenith Z-200, 16 Mbytes of user memory; Somanas et al., 1987). More effective processing will undoubtedly be achieved with future generations of microcomputers.

CPU intensive processing, such as migration and wavelet processing, which are commonly used on conventional scale data, are rarely used in shallow reflection. With respect to the first, the relatively simple shallow structures (gently dipping) render such a process unnecessary (Doornenbal and Helbig, 1983).

Wavelet processing "i.e. deconvolution", which is applied to improve resolution, requires the use of a wide time window to obtain satisfactory statistics (Sheriff and Geldart, 1983). Hence, the sought improvement of such a process may not be obtainable on short length "shallow reflection" records. Despite this, Schepers (1975) found that deconvolution improved data quality significantly, in resolving two reflectors at depths as shallow as 4.1 and 7 m below ground surface. Deconvolution was tested in this study (Chapters 6 and 7).

A crucial process for shallow reflection data is static corrections. A method of computing field statics used in this study is discussed in Chapter 4 while residual statics and other types of process applied in this study are discussed in Chapter 6.

The Canadian group used the Apple II microcomputer (48 Kbyte of memory) to process their optimum methods data. This processing included refraction velocity and depth calculations, reflector velocity determination, static corrections, moveout corrections, and digital filtering. CMP processing stacking was not attempted by the Canadian group because of the limitations of the microcomputer in performing
complicated processing and because of the cost of using such a method (Hunter et al, 1984).

Singh (1986) processing his constant-offset seismic data included analog filtering, band-pass digital filtering, and gain control. These types of processing were made by the processing unit of the seismograph. He also applied extra processing such as static and dynamic corrections of the seismic records by using a microcomputer.

The Utrecht University group and the Kansas Geological Survey both used a standard processing software package for the shallow reflection data (Herber et al, 1981; Doornenbal and Helbig, 1983; Treadway et al, 1984). This was possible because of their access to more powerful "mainframe" computers. The first group used the HP 1000F/45 mainframe computer (with 512 Kbytes RAM) while the second group used a 32-bit computer for data processing. In both cases, the final seismic sections (constant-offset section and CMP stacked section) were not migrated. For the first group, such processing was considered unnecessary because of the moderate dip of the reflector while the second group lacked the necessary software.

More recently, the Kansas group used a microprocessor to perform CMP stacking in the field (Somanas et al, 1987). They indicated that basic processing steps can be made relatively fast (about 41 minutes for 100 shotpoints of 24-channel, 1000 sample per channel) in the field. They pointed out that in-field preliminary processes, such as velocity and spectral analysis, frequency filtering, normal moveout correction and CMP stacking, are useful to optimize acquisition parameters.

The Zenith Z-200 microcomputer with an 80278 co-processor system was used as a field processing unit, having 16 Mbytes of user memory. Although this size of memory is large for a microcomputer, it was reported to be not enough for adequate processing and that the storage capabilities of the system are to be increased up to 60 Mbytes.
CHAPTER 4
FIELD STATICS DETERMINATION FROM FIRST ARRIVAL TIMES

4.1 INTRODUCTION

High-resolution shallow seismic reflection processing requires static errors to be minimal (Section 3.2.2). Residual static corrections are useful for small amplitude and short wavelength statics (see Section 6.6). Field statics computation prior to the residual statics procedure is, therefore, important for the correction of medium and long wavelength statics.

First arrival times can be used for statics determination. Two refraction interpretation methods (with distinct raypath configuration) can be used: the plus-minus and the GRM methods (Section 2.1). These techniques are used for detailed investigation of subsurface weathering layers and both require forward and reversed arrival data; Success depends on the complexity of the subsurface earth structure. In this study, the plus-minus method was used to interpret subsurface structure and subsequently to determine field statics. It is more applicable than the GRM method to the investigation of very shallow subsurface ground structure (Sjrogren, 1979), which tends to be more complex than the deeper subsurface. In addition, the small thickness of the near-surface layers minimizes errors in the method caused by the assumption of a locally plane refractor below the geophone (Section 2.3.1).

A computer program has been developed to employ the plus-minus method along with the conventional interpretation "intercept time" method on first arrivals picked from multifold CMP reflection records. Synthetic data were used to test the capability and reliability of the method.

4.2 FIELD STATICS

The velocity structure of the weathering layers needs to be determined so that the variable delays can be corrected for during processing by reducing seismic data to a reference datum. Field statics can be determined either from LVL (low-velocity layer) surveys and uphole time surveys or from the reflection production survey itself (Rogers, 1981).
For shallow reflection work, the LVL and uphole time surveys are generally not needed since first break information can be deduced from the small reflection spread and uphole time measurement may be obtained when shooting below the surface of the ground. However, there are some problems associated with the reflection production data which might limit the capabilities of obtaining accurate and valid static corrections:

(1) End-on reflection surveys do not provide reversed first break data which are usually required by most refraction interpretation techniques.

(2) When shooting below the surface of the ground (i.e. Buffalo gun), uphole time measurements do not provide complete weathering information since such shots are normally within the weathering layer.

The choice of datum is also a crucial factor which dictates the way statics are computed and applied. A general rule is to choose a datum so that static corrections can be as small as possible along the seismic profile. This has the advantages of avoiding the loss of shallow reflection data as well as minimizing static errors (Ziolkowski, 1979). The datum can be either above or below the shots (and geophones). Also, it can be either plane (horizontal or dipping) or contoured depending on the surface and weathering layer topography. The latter type, however, needs to be smooth (constant gradient) over the length of the spread to prevent distortion of the seismic section.

4.3 REVERSED ARRIVAL TIMES FROM FORWARD PROFILES

Most seismic refraction interpretation techniques, for dipping plane or irregular interfaces, require both forward and reversed first arrival times. Conventionally, this is done by shooting forward and reversed seismic profiles (e.g. split-spread recording geometry). It is possible, however, to construct reversed profiles and simulate the field configuration needed by these techniques for end-on geometry by exploiting the reciprocity of the travel paths between source and receiver positions. First arrival times are picked
from the CMP collected records.

Cunningham (1974) used this criterion to fabricate reverse profiles and determine the true velocity of subsurface layers. He used the conventional reverse profiling "intercept time" method to interpret subsurface structure from single-ended "forward" refraction data. He pointed out that the accuracy achieved with this method is equivalent to that obtained by the conventional reversed profiling method. He used this method to compute statics, which made a considerable improvement to the reflection data. However, this technique is limited, as are all conventional interpretation methods, by the assumptions of a plane interface, constant velocity and dip in the direction of the profile.

Bahorich et al (1982) used a modified GRM "ABCD" method on first arrival times deduced from forward reflection profiles. They found that statics obtained by this technique have a better effect on the quality of reflection data than those produced by the conventional elevation method (Dobrin, 1976; Telford et al, 1976). However, there are some disadvantages with the method: 1) it makes the assumption of horizontal weathering base, and 2) it fails to distinguish between the lateral variation in the velocity of weathering and subweathering layers.

Coppens (1985) used the plus-minus "delay time" method to interpret 2-layer subsurface structure and compute statics at shot-receiver positions. He developed a computer program for automatic picking of first arrivals from common-offset collections of seismic traces gathered from CMP reflection records. The plus part of the method is similar to the ABO method used by Singh (1983). This routine can be repeated on several collections of traces with different common offsets in order to improve the quality of results by averaging. This method was reported (Coppens, 1985) to be superior to the standard method in improving reflection data quality by accurately determining statics.

4.4 DETAILED REFRACTION INTERPRETATION METHOD— THEORY

The method incorporates the plus-minus, modified geophone delay time and the conventional reversed profiling
techniques. Raypath configurations required by these techniques are constructed from the multiplicity of CMP records. However, if these raypath configurations can not be simulated and reversed arrival times can not be fabricated, forward velocities can be obtained and the 'horizontally plane layered' intercept time method can be used.

4.4.1 The plus-minus method

This method consists of two parts: the plus time and the minus time. The first is used to calculate the plus time (twice the delay time) at a source-receiver position 'station'. This may then be converted into depth below the station. The second part is used to measure the minus time between shot and receiver stations, which is used to obtain the refractor velocity over the distance separating the two stations. This method is discussed in Chapter 2.

The plus time

Figure 4.1 simulates the raypath configuration of the plus-minus technique from multifold forward shot records using end-on recording geometry with geophones leading the shots along the seismic line. The plus time $T_P$ is measured for a shot-receiver station $I$ as follows:

$$T_P = T_{ji} + T_{ik} - T_{jk} \quad \ldots \ldots \quad (4.1)$$

The $(J-I-K)$ configuration can be simulated about the shot-receiver $I$ by using different combinations of shots in the interval $J-I$ and geophones in the interval $I-K$.

If $n$ is the number of geophones per spread, $d$ is the shot-geophone offset (in terms of stations) and $g$ "gap" is the number of stations which receive direct arrivals (or different types of arrivals), then the plus time can be calculated, separately, at station $I$ from combinations of the following stations:

Shots $\{a\}$: $i+g-(n-1) \quad \ldots \quad i-(g+d)$

Geophones: $i+(g+d) \quad \ldots \quad \{a\}+(n+d-1)$

The number (frequency) of $T_P$ calculations depends on the number of geophones in the spread and the subsurface geology. For a 2-layer case, if $n=24$, $d=0$ and $g=2$, the frequency is
Figure 4.1 Plus-minus raypath configuration simulated from multifold CMP end-on recording (geophones leading the shots along the line) for two-layer subsurface structure.

■ = shot-receiver station.
Such multiples of TP have a significant effect on the quality of the results, since they can be used as a means of reducing errors in the picked arrival times. The average TP can be converted into the depth (Z) below station I as follows:

$$Z_i = \frac{TP \cdot V_i}{2 \cos \theta} \cdots (4.2)$$

This depth is normal to the interface and is also used as vertical depth ignoring the effect of dip of the refractor segment BC (Figure 4.1).

The process can be repeated for all shot-receiver stations provided the raypath layout can be constructed. The depth to the second interface can be obtained in a similar manner.

The minus time

The raypath configuration used to calculate the minus times is similar to that used to calculate TP (Figure 4.1). The time TM is measured over the distance I-J using the shot-receiver station I as a reference point, though it can equally be done over the distances JK or IK:

$$TM_{ji} = T_{jk} - T_{ik} \cdots (4.3)$$

The total number of TM calculations and combinations of shots and receivers are equivalent to that of TP. However, they differ in details, such that TM calculations can be divided into stages. In each stage, TM is measured between shot-receiver station I and a shot-receiver station in the interval JI. This is repeated for each receiver in the interval IK, which is common to both shots. The values of TM are averaged and assigned to the station midway between the two shots (JI):

$$TM_{(i+j)/2} = TM - TP_{j}/2 + TP_{i}/2 \cdots (4.4)$$

This time is then converted into velocity (V) and assigned to the station j+i/2 as follows:

$$V_{(j+i)/2} = \frac{x_{ji}}{TM_{(j+i)/2}} \cdots (4.5)$$

This process is done between reference point I and each of the shots in the interval JI. This procedure is then repeated
for the next reference point (I+l) and so on. The minus times are calculated for the third layer in a similar way.

With regard to the velocity of the first layer, it is measured independently of the plus-minus method (see next section).

4.4.2 The conventional method

Forward velocity determination

1) Direct velocity ($V_1$)

The velocity of the upper layer is measured from the direct first arrival times by fitting a straight regression line using the least square method:

$$V = \left[ \frac{\sum_i X_i^2 - n\bar{X}^2}{\sum_i T_i - n\bar{T}} \right] \quad \text{(4.6)}$$

$$a = \left[ \frac{\sum_i X_i T_i - n\bar{X}\bar{T}}{\sum_i X_i^2 - (\sum X_i)^2/n} \right] \quad \text{where}$$

- $V$ is velocity.
- $a$ is correlation coefficient, $n$ is number of geophones.
- $X$ is shot-geophone distance, $\bar{X}$ is the mean distance.
- $T$ arrival time, $\bar{T}$ is the mean arrival time.

The measured velocity is assigned to the station midway between the shot station and the furthest geophone station receiving the direct arrival in the shot spread.

2) Refractor velocity

The velocity of the refractor $V_2$ (or $V_3$) is measured from the forward refracted arrivals by the same method used for $V_1$. The velocity is assigned to the station midway between the nearest and furthest geophone stations receiving these arrivals.

Intercept time ($T_I$) is also measured and assigned to the shot station:

$$T_I = \bar{T} - \left( \frac{1}{V} \right) \bar{X} \quad \text{..... (4.7)}$$
True velocity determination

True refractor velocity is determined from forward arrival times (a shot record) and reverse arrival times fabricated from combinations of shots and a given geophone, usually the last geophone of the shot record. Figure 4.2 shows the construction of a reversed profile from forward arrivals. This is equivalent to having a reverse profile with the shot being stationed at the furthest geophone. The reversed data may have noise due to shot variability.

The true velocity is then measured from those stations with both forward and reversed refracted arrival times using a least square method "Hobson-Overton technique" (Scott et al, 1972; Scott, 1973) assuming planar dipping layers as follows:

\[
V = \left\{ \frac{\sum \Delta x_i^2 - (\sum \Delta x_i)^2 / n}{\sum (\Delta x_i)(\Delta t_i) - (\sum \Delta x_i)(\sum \Delta t_i) / n} \right\} \quad \ldots \quad (4.8)
\]

where

- \( V \) is true velocity,
- \( n \) is the number of geophones,
- \( \Delta t \) is the time difference between arrival times at geophone \( i \) from 2 shots at opposite ends of the spread, and
- \( \Delta x \) is the corresponding difference in distances.

The standard error (SDER) is also measured as follows:

\[
SDER = \left[ \frac{\sum (\Delta x_i)^2}{n} \right]^{1/2} \quad \ldots \quad (4.9)
\]

where

- \( DTD \) is an average of the difference in delay times at the two shot stations, and
- \( ERG_i \) is the error of fit for each arrival time.

Once the true and the forward velocities are known, the reverse velocity is measured and used along with the forward velocity to calculate the dip (see Sheriff and Geldart, 1982; pp 89-94).
Figure 4.2 Diagram showing the construction of a reversed profile from multifold CMP shot records.

- = shot-geophone station.
♦ = arrivals from shot S1 into geophones G1 - G24.
* = arrivals from shots S1 - S24 into geophone G24.
Depth determination

The depth to the interface is determined at the shot position using the intercept time:

\[ Z = \frac{T_I V_1}{2 \cos \theta} \]  \hspace{1cm} (4.10)

This formula is similar to that used for the depth conversion of plus time except that \( T_P \) (2 geophone delay times) is substituted by the intercept time \( T_I \) (shot and geophone delay times). This depth is normal to the interface.

4.4.3 Modified geophone delay time

In end-on recording geometry, neither the plus time nor the intercept time can be obtained at some stations. These stations are positioned beyond the last shot (if the geophones were leading the shots) and before the first shot (if the shots were leading the geophones) along the seismic line. A modified geophone delay time (time difference between successive geophones) can be measured at such stations by a special arrangement of shots and geophones.

Figure 4.3 shows a raypath configuration for the time measurement for a 2-layer subsurface structure. \( I \) is the last shot-receiver station where the depth was measured by either the plus time or the intercept time methods. To calculate the depths at the receiver station \( K \), the time associated with the path \( CK \) can be decomposed as follows:

\[ T_{MD} = T_{jk} - T_{ji} \]
\[ = T_{ck} + T_{ik} - T_{ib} \]  \hspace{1cm} (4.11)

where

\( T_{MD} \) is the modified delay time.

\( IK = BC \); since the distance is small (geophone spacing), the effect of dip is ignored.

The difference time \( T_{MD} \) is determined for all shots that have refracted arrivals received at stations \( I \) and \( K \). The \( T_{MD} \) values are averaged and used to calculate the depth at station \( K \) as follows:

\[ Z_k = T_{MD} \frac{V_1}{\sqrt{V_2^2 - V_1^4}} / V_2 \]  \hspace{1cm} (4.12)

The depth \( Z_k \) is normal to the interface.

Once \( Z_k \) is determined, the process can be repeated to
Figure 4.3 Illustrative diagram of modified geophone delay time measurement at the end of end-on seismic spread used for derivation of Equation 4.11.

* = shot-receiver station.
calculate the depth for the next station \( L \) by using the time difference between arrivals \( T_{jl} \) and \( T_{jk} \) and so on.

The accuracy of the depth determined by the geophone difference time is affected by the accuracy of the depth at the previous station. Therefore, errors can be accumulated towards the furthest station. Also, because the number of TMD determinations at each station decreases towards the end of the profile, the effectiveness of averaging in improving results is reduced in that direction.

If the spacing between the two geophones used in TMD determination is large, then the dip of the refractor and the slope of the ground surface introduce error in the determined depth. The dip has a negative effect on TMD while the slope results in larger TMD.

4.4.4 Shot correction

Correction is made to arrival times from a shot fired below the surface of the ground. A time delay associated with the shot being below the surface is added to these arrivals in order to simulate surface to surface times. In effect, this routine is equivalent to bringing the shot to the surface (or more precisely to the height and position of the geophone at that station). Further discussion of this can be found in Section 6.3.

4.4.5 Errors and proposed methods for results improvement

In Chapter 2, the limitations and errors in the plus-minus refraction interpretation were discussed. These errors can be classified into three categories:

1) Picking error in arrival times. This can be random or systematic (on a spread). The latter may be caused by increased attenuation with increased travelled distance.

2) Structural error caused by the regional dip of the refractor. This is a systematic error and affects both the interpreted velocity and depth (Figure 2.5).

3) Structural "systematic" error caused by the departure of earth structure from the assumptions of: a) common refractor
paths (Figure 2.3) and b) a locally plane refractor below the recording geophone (Figure 2.6).

Two methods which might improve the quality of the results of the plus-minus interpretation are discussed below. These methods were not used in this study.

**Smoothing of velocity and depth**

This involves the use of a weighted running mean for smoothing the velocities and depths. The weights should be determined by the accuracy of the plus (or minus) times calculated at each station within the filter. The standard deviation from the mean and the frequency of calculations of the plus times can be used as criteria for the accuracy of the plus times. In this method, emphasis is given to the more accurately measured data.

In this study, an equally weighted running mean filter was used (see Section 4.5.1).

**Improving velocity measurement**

Equation 4.3 was used, in this study, to determine the minus time, and subsequently the velocity, over the interval IJ (Section 4.4.1). Figure 4.1 shows that the minus time can be measured twice over the interval IK using two different raypath arrangements:

\[ TM_{1ik} = T_{jk} - T_{ji} \quad \ldots \quad (4.13) \]

and

\[ TM_{2ik} = T_{il} - T_{kl} \quad \ldots \quad (4.14) \]

The multiplicity of minus time calculations should improve the quality of measured velocity.

Any difference between TM1 and TM2 may be caused by random error and/or by systematic structural error which is dependent on the "offset" interval IK:

\[ MTD = TM1 - TM2 \quad \ldots \quad (4.15) \]

Errors in TM1 and TM2 may be estimated by measuring the standard deviation from the mean of both calculated minus times. MTD can then be compared with the range of the errors. Where MTD is larger than a given threshold, there must be a
structural factor. This procedure can be used to indicate areas where the calculated plus times are incorrect.

Variations of MTD with increased offset (IK) need to be examined. If these variations are systematic, then they must be caused by a structure. Further investigation may reveal ways of extracting details of the structure.

4.5 DETAILED REFRACTION INTERPRETATION METHOD– IMPLEMENTATION

A computer program 'REFRAC' has been developed to conduct a detailed refraction interpretation to compute statics from CMP collected seismic reflection records. This program can deal with up to a 3-layer earth structure model. It is written in Fortran 77 using GHOST80 graphical libraries and is operational on a (VAX 8650) mainframe computer. It is adapted to run on end-on spread data: for both geophones leading shots and shots leading geophones along the seismic line. A datafile (e.g. Line10.dat), which contains arrival times, shot and geophone coordinates and other information, is read by the program. The results, which contain velocity, thickness, dip and statics of the interpreted layers along the line, are written into a datafile (e.g. Line10.res). Also written into a graphical output file (e.g. Plot10.grd) are plots of velocity, depth and statics along the seismic section. In addition, these results can be written into a datafile (e.g. Line10.mix) which can subsequently be used along with other datafiles by another program (MIXPLOT) to produce plots (e.g. Line10.grd) comparing different results.

For the successful operation of the program REFRAC, information about the number of layers in the model and the identification of the type of arrival times (e.g. direct, refracted) are required. The picking and identification of first arrival times are done independently of this program. In this study, the picking of first arrival times from CMP reflection records was performed manually and the types of data were identified by hand plotting the time-distance graphs.

The program consists of a number of subroutines. Reading of datafiles and printing and filing of results are accomplished by the main segment of the program. Subroutines are called from the main program and from other subroutines.
Figure 4.4 shows a flow chart of the program.

4.5.1 Program REFRAC

Interpretation starts with the determination of $V_1$ by fitting a regression line through a set of time-distance pairs using the least square method. Forward refractor velocities $V_2$ and $V_3$ are determined by the same method. Correlation coefficients of the time-distance fit and intercept times (for $V_2$ and $V_3$) are also determined.

Once forward velocities are obtained, the process of true velocity measurement begins by correcting arrival times. Data are reduced to a plane datum close to the surface of the ground at the lowest geophone height. True velocity is determined from a forward shot record and a constructed reverse profile using the Hobson-Overton least square method. Standard error of the travel times is measured too. The true velocity is used to calculate the depth and dip of the refractor.

If reverse profiles cannot be constructed from the forward arrivals, the forward velocities are used for subsequent calculations. The usable velocities are then linearly interpolated between stations and extrapolated at the end of the line. Shot correction of the raw data is then repeated using the newly determined velocities.

Stations (shots and geophones) which construct the required raypath configuration for the plus time determination are selected. The calculated plus times for each shot-receiver station are averaged (using either the mean, trimmed mean or median). In a similar manner, minus times are calculated and used to obtain the velocity of the refractor.

Next, depth is calculated for each station where the plus time was measured. For stations where $TP$ can not be obtained, intercept times and modified geophone delay times are used. Depth conversion normally uses velocities determined from the minus times, but true velocities are used if the number of points at which they are determined are greater than twice the number of points of those obtained by the minus time. If neither true velocities nor minus velocities can be obtained, forward velocities are used.
Figure 4.4 Flow chart of Program REFRAC.
Statics for subsurface layers are then calculated at each station along the seismic line.

Smoothing (filtering) can be applied to velocities and layer thickness. It can be done in two ways:

1) By using a weighted average (binomial) mean over 5 points using different weighting factors (5-1).
2) By using an equally weighted running mean over seven or nine points after rejecting the highest and the lowest values. For velocity only, the chosen number of points is used for smoothing $V_2$ while for $V_1$ smoothing is made over a lower (by 2) number of points and smoothing for $V_3$ is made over a higher (by 2) number of points. This filter has a steeper slope on the short wavelength response than the binomial mean.

The results of the interpretation which include layer thickness, least-square velocity, minus velocity, statics and dip are printed out. Plots of velocities, depths and statics can be obtained.

A detailed description of program REFRAC can be found in Appendix C. Listings of this program as well as those of program MIXPLOT can also be found there.

4.6 MODELLING AND TEST OF THE METHOD

Two (3-layer) models were used to test and develop program REFRAC. The first model had horizontal plane interfaces. Its arrival times were generated by a specially written program assuming minimum trajectory raypath and constant velocities (Sheriff and Geldart, 1982; PP 89-94). The second model is more complicated having a smoothly irregular first interface (synclinal structure) and a dipping plane second interface. The velocity of the first layer varies laterally while the second and third layers have constant velocities. The second model's arrival times were generated using a ray tracing program (SEIS83; Cerveny et al, 1974, 1977; Cerveny and Psencik, 1983).

In both models, a 24-geophone shot record was rolled along the model's section using end-on, geophone leading, spread. Geophone 'station' spacing and shot interval were 2m. The depth of the shot was 0.8m and at a zero offset from the
first geophone. The seismic line across the model was 200m in length and consisted of 100 stations. The first shot was near the origin point (2,0)m. The precision of the arrival times was approximated to the nearest 0.1ms.

4.6.1 Horizontal plane layered model

Original data

The number of shot records was 77. The first layer has a thickness of 2.5m while the second layer is 4.5m thick and the third layer has an infinite thickness. These layers have velocities of 0.5, 1.5 and 2.5 m/ms, respectively. The results of REFRAC interpretation of the data (datafile 1) match the original model. The plus-minus method was used to determine the model's structure as reversed arrivals were established for the second and third layers for most of the stations along the line. The intercept time was used to determine the depths at stations 1-3 and 1-10 for the first and second interfaces, respectively. The depths for both interfaces at stations 78-86 were obtained using modified geophone delay times. Table 4.1a,b contains statistics of the results of the interpretation without and with filtering. The effect of smoothing appears to be negligible since the results are highly accurate. The tiny errors in velocities and depths are due to rounding errors.

The accuracy of layer 1 thickness (Table 4.1a) is between 98.9% - 99.7% over a confidence interval of 95%. This error appears to be caused by an error in \( V_1 \). Rounding errors are random and seem to cancel out in plus and minus times calculations. The accuracy of layer 2 thickness is between 98.7% - 99.9% for a confidence level of 95%. Velocities obtained by the minus time are more accurate than those determined by the Hobson-Overton least square method. The high accuracy of the plus-minus method is related to the statistical advantage of these measures.

Data with errors

Errors from a random number generator were added to the original arrival times (Datafile 1) and two sets of new datafiles (2 and 3) were created. In File 2 the introduced
Table 4.1 Statistics of results of refraction interpretation of Model 1 (File 1).

VL, VM are velocities (m/ms) determined by the least square and minus time methods, respectively. Z, ST are the thickness (m) and statics (ms) of the layer. Mini = minimum; Maxi = maximum; S.dev = standard deviation; Freq = frequency.
errors ranged between -1 to +1 ms with an average of 0.5ms and a standard deviation of 0.288ms. For File 3 the errors ranged between -2 to +2 ms with a mean of 1ms and a standard deviation of 0.576ms. In both sets of data, the range of errors was reduced to half for the direct arrivals (nearest 3 geophones) of each shot record. Tables 4.2a,b and 4.3a,b contain the statistics of the results for Files 2 and 3, respectively. Each table includes the results without filtering and with filtering.

These results clearly show the superiority of the minus method in velocity determination as compared to the least-square method. Smoothing of velocity and depth was found to be important in producing reliable results. This is clearly manifested on Figure 4.5, which compares unsmoothed and smoothed results of File 3. The smoothed velocity curves at the ends of the profile are due to extrapolating constant velocities to those stations. Since the problem under investigation is a horizontal plane layered model, the advantage of the plus-minus method over the conventional method is merely statistical.

The generated errors were random on a population of 1848 (number of arrival times in the model). However, these errors cannot be treated as random on a small interval of calculation and can be highly biased on some occasions. The highly erroneous values "spikes" at the plot of the second depth (Figure 4.5), for instance, are results of such bias. Extreme examples of these are the overestimation of thickness of layer 2 at stations 27 (11.2m) and 40 (9.5m) and the underestimation at stations 67 (2.5m) and 70 (3.1m). These errors are caused by two main factors. In the first case, the +ve error in $V_2$ (27%) and the +ve error in TP (13%) caused the 148% increase in layer 2 thickness. A percentage of error in TP has greater effect on the accuracy of the calculated depths than a similar percentage of error in velocity (Section 2.3). A simple example can be cited for the thickness of layer 1 at the same station (number 27). A -5% error in TP caused about -5% error in depth while a +27% error in $V_2$ caused -3% error in depth. At station 40, similar causes resulted in the overestimation of the depth to the 2nd interface.
Table 4.2 Statistics of results of refraction interpretation of Model 1 (File 2).

VL, VM are velocities (m/ms) determined by the least square and minus time methods, respectively.
Z, ST are the thickness (m) and statics (ms) of the layer.
Mini = minimum; Maxi = maximum; S.dev = standard deviation; Freq = frequency.

### a) without smoothing

<table>
<thead>
<tr>
<th>Layer</th>
<th>Mini</th>
<th>Maxi</th>
<th>Mean</th>
<th>S.dev</th>
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b) with smoothing

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Table 4.3 Statistics of results of refraction interpretation of Model 1 (File 3).

VL, VM are velocities (m/ms) determined by the least square and minus time methods, respectively. Z, ST are the thickness (m) and statics (ms) of the layer. Mini = minimum; Maxi = maximum; S.dev = standard deviation; Freq = frequency.
RESULTS OF REFRACTION INTERPRETATION

Data files: data03.mx1 data03.mx2
Title: 3-Layer model 1 (+2ms err), unsmooth & smooth
Plots of Velocity (VL, VM), Depth (Z) and Statics (ST)

Figure 4.5 Comparison of the unsmoothed (light line) and smoothed (dark line) results of interpretation of File 3.
On the other hand, +14% error in $V$, and -7% error in $TP$ caused the -44% error in thickness of layer 2 at station 67. If all factors were constant, the +ve error in $V$, would have caused a -6% error in thickness while the -ve error in $TP$ would have caused a -27% error.

The process of smoothing of velocity and depth were useful in filtering out the spikes by rejecting the highest and the lowest values over the averaging interval. With regard to the depths at the left end of the profile, it might appear that those depths determined by the intercept time method are more accurate than those determined by the plus time at stations 27 and 40 since the errors are smaller. However, careful inspection of the data shows that added random errors were particularly large at these stations. At the other end of the profile, depths determined by the modified geophone delay are smoother due to the multiplicity though the errors tend to increase towards the end of the line. This is because these errors accumulate and the multiplicity decreases towards the end. The accuracy of the depths (stations 78-86) is influenced by the accuracy of the depth at station 77, which was determined by the plus time and had +38% error.

Figure 4.6 shows a comparison between the smoothed results of Files 1, 2 and 3. The plots clearly demonstrate the capability of the plus-minus method in obtaining reasonably reliable results. It is remarkable that the effect of error on depth and velocity has minimal effect on the statics. For File 3 (+2 ms), statics for layer 1 (Table 4.3b) range between 4.70 to 5.49 ms with a mean of 5.09ms while for layer 2 statics range between 2.57 - 3.97 ms with a mean of 3.27 at a confidence level of 95%. These results are reasonably good since the error in the statics does not exceed 1ms, which is the average value of the added errors.

4.6.2 Irregular and dipping plane layered model

Original data

The number of records made along the section of this model is 86. For the last records 78-86, the number of geophones in the spread was reduced (by 1) progressively
RESULTS OF REFRACTION INTERPRETATION
Data files: DATA01.MX2 DATA02.MX2 DATA03.MX2
Title: 3-Layer model 1 (+1ms, 2ms err), smooth (7, 9, 11)
Plots of Velocity (VL, VM), Depth (Z) and Statics (ST)

Figure 4.6 Comparison of the smoothed results of interpretation of File 1 (light line), File 2 (dark line) and File 3 (extra-dark line).
along the line (from 23-15 geophones) due to constraints of the model. The base of the first layer is smoothly irregular with depths ranging between 1.5-3.5 m and forming two synclinal shapes. The base to the second layer is a dipping plane varying in depth from 4-8 m, from the left to the right end of the line. Velocities were laterally constant for the 2nd and 3rd layers at 1.5 and 2.5 m/ms, respectively. Vertically, however, the velocities have a small gradient of between 1.49-1.51 and 2.49-2.51 for these layers, respectively. These gradients were required to generate refracted rays by the ray tracing package (Program SEIS83).

With respect to the first layer, its velocity was varied laterally along the line from 0.5-0.6-0.5 m/ms, from the left, middle and right end of the line. This varying velocity was used in order to increase the complexity of the model. Vertically, however, a gradient was introduced as velocity varied between 0.49 to 0.51, 0.59 to 0.61 and 0.49 to 0.51 m/ms across the layer.

Figure 4.7 compares the results of REFRAC interpretation of the synthetic arrival times (Datafile 4) with the original model. Velocities determined by the minus method were used in depth conversion. Depths were determined by:
1) intercept time at stations 1 and 2, 11-15 and 66-84 for layer 1 and stations 1-6 for layer 2.
2) geophone delay time at stations 87-95 for both layers.
3) plus time for the remaining stations.
The multiplicity of TP and TM calculations varied along the line up to a maximum of 15 for layer 2 and 21 for layer 3.

This figure (4.7) shows the reliability of the integrated method and specifically of the plus-minus method. The velocities and depths determined by the latter method were more accurate than other methods (Table 4.4a). The large depth estimate (to the 2nd interface) between stations 1-6 is due to the intercept time method. However, a lower depth estimate (−ve error), by the plus time method, can also be seen between stations 70-81; the lowest (−15%) is at station 71. Inspection of the results indicates that these errors are actually a consequence of the overestimation of layer 1 thickness between those stations by the intercept time method. Although the errors in the 1st layer are small, their
RESULTS OF REFRACTION INTERPRETATION
Datafiles: data04.mx1 data09.mod
Title: 3-Layer model 2, unsmoothed & original
Plots of Velocity (VL, VM), Depth (Z) and Statics (ST)

Figure 4.7 Comparison of the unsmoothed results of interpretation of File 4 (light line) and the original model (dark line).
### Table 4.4 Statistics of results of refraction interpretation of Model 2 (File 4).

VL, VM are velocities (m/ms) determined by the least square and minus time methods, respectively.
Z, ST are the thickness (m) and statics (ms) of the layer. 
Mini = minimum; Maxi = maximum; S.dev = standard deviation; 
Freq = frequency.

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effects are magnified on the layer 2 thickness estimate. An error of +0.2m in layer 1 thickness causes an error of about -0.5m in the layer 2 thickness estimate (station 71).

Statics plots on Figure 4.7, on the other hand, show excellent matching with the model with errors below 0.3ms, which are further reduced by the filtering process (Table 4.4b and Figure 4.8).

**Data with errors**

Two sets of data (Files 5 and 6) were produced with errors added to the synthetic arrival times (File 4). These errors were randomly generated, as in the previous horizontal model, and ranged between -1 to +1 and -2 to +2 ms, respectively. Tables 4.5a,b and 4.6a,b contain the statistics of the results of interpretation (unsmoothed and smoothed) to Files 5 and 6, respectively.

Figure 4.9 compares the results of File 6 with the model. The ±2ms errors appear to have caused enormous effects on the results with errors exceeding 100%. This is more evident on the depth to the second interface where at some stations thickness could not be determined because of the high errors in velocities (V₂ > V₁). Examples of these are stations 7 and 53 while at stations 14 and 66-69 the depths to 2nd interface could not be measured due to the high error in layer 1 thickness interpreted by the intercept time.

Figure 4.10 shows that filtering of these erroneous values by the smoothing process makes considerable improvement to the quality of the results. Smoothing was made over 7, 9 and 11 stations for V₁, V₂ and V₃ and over 9 stations for depths. Depths determined by the plus time seemed to be more accurate than those by the intercept time. The largest errors in depths to the 1st interface were obtained by the intercept time and geophone delay time methods between stations 66-95 (e.g. +27% at station 66; -20% at station 80) while at stations 60-65 the increase in errors was due to reduction in multiplicity of TP calculations. With regard to the 2nd interface, which was determined by TP, the large errors (+18%) were due to negative errors in the 1st interface depths. The errors in 1st interface also affected the 2nd interface at stations 87-95 and 7-18. For
RESULTS OF REFRACTION INTERPRETATION
Datafiles: data04.mx2 data09.mod
Title: 3-Layer model 2, smooth (7, 9, 11) & original
Plots of Velocity (VL, VM), Depth (Z) and Statics (ST)

Figure 4.8 Comparison of the smoothed results of interpretation of File 4 (light line) and the original model (dark line).
### Table 4.5 Statistics of results of refraction interpretation of Model 2 (File 5).

**VL, VM** are velocities (m/ms) determined by the least square and minus time methods, respectively.  
**Z, ST** are the thickness (m) and statics (ms) of the layer.  
**Mini** = minimum; **Maxi** = maximum; **S.dev** = standard deviation;  
**Freq** = frequency.

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</tbody>
</table>
Table 4.6 Statistics of results of refraction interpretation of Model 2 (File 6).

VL, VM are velocities (m/ms) determined by the least square and minus time methods, respectively.
Z, ST are the thickness (m) and statics (ms) of the layer.
Mini = minimum; Maxi = maximum; S.dev = standard deviation; Freq = frequency.
RESULTS OF REFRACTION INTERPRETATION

Datafiles: data06.mxl  data09.mod

Title: 3-Layer model 2 (+2ms err), unsmooth & original
Plots of Velocity (VL, VM), Depth (Z) and Statics (ST)

Figure 4.9 Comparison of the unsmoothed results of
interpretation of File 6 (light line) and the original model
(dark line).
RESULTS OF REFRACTION INTERPRETATION
Datafiles: data06.mx2 data09.mod
Title: 3-Layer model 2 (+2ms err), smooth (9) & original
Plots of Velocity (VL, VM), Depth (Z) and Statics (ST)

Figure 4.10 Comparison of the smoothed results of interpretation of File 6 (light line) and the original model (dark line).
stations 1-6, errors in 2nd interface depths, which were determined by the intercept time, are as high as +100%.

Despite the errors in depths being fairly high, their effects on statics are less serious. Figure 4.10 shows that errors in statics do not exceed the 2ms errors introduced to the data. The highest errors are at station 66 (about 1.6 ms; +30%) and at station 95 (about 1.8 ms; +37%).

The figure also shows that the general structure "trend" is well preserved. This is very important since the objective of the interpretation is to determine the long and medium wavelength statics. With respect to the 1ms error datafile (File 5), Figure 4.11 shows that the interpreted results match well with the original model with lesser errors in statics.

4.7 CONCLUSION

A computer procedure has been devised to compute field statics from detailed interpretation of first breaks obtained from reflection records (end-on geometry). It incorporates the plus-minus, modified geophone delay and the conventional reversed profiling methods. It uses both forward arrival times and reversed arrival times, which it fabricates from the multifold CMP records. The method was tested using synthetic data for horizontally plane, dipping plane and smoothly irregular interfaces. Two sets of random errors (-1 to +1 ms and -2 to +2 ms) were added to the arrival times to test the capability of the method.

The results showed the reliability of the integrated method and specifically of the plus-minus method in mapping subsurface structure. The velocity and depth determined by the latter method were more accurate than other methods. Smoothing of velocities and depths were useful to improve the quality of results. The general structure was well preserved along the section. This is important since the objective was to compute long and medium wavelength statics.

Two methods, which might improve the quality of results, were proposed. Further improvement can be made by incorporating an automatic procedure of first arrivals picking and screen plotting of the time-distance graphs.

The results of using Program REFRAC to real data are presented in Chapter 7.
RESULTS OF REFRACTION INTERPRETATION
Datafiles: data05.mx2 data09.mod
Title: 3-Layer model 2 (+1ms err), smooth(9) & original
Plots of Velocity (VL, VM), Depth (Z) and Statics (ST)

Figure 4.11 Comparison of the smoothed results of
interpretation of File 5 (light line) and the original model
(dark line).
CHAPTER 5
FIELD STUDIES INTO A SHALLOW SEISMIC REFLECTION SYSTEM

5.1 INTRODUCTION
Experience with shallow seismic reflection commenced in the autumn of 1984 when coherent seismic waves of a reflection pattern were observed on seismic records during a hammer refraction survey. The survey was made in the sports ground of Bardon Hill Quarry in the Charnwood Forest area.

This stimulated further attempts to develop a high-resolution shallow seismic reflection system, the subject of this study. A series of field tests were made accompanied by upgrading and modification of the seismic recording system and continuous development of the processing capabilities of the system. The objective was to enhance the detection of reflected waves and attenuate the interfering source-generated noise. Areas investigated in the tests included the seismic source, seismic detector, recording equipment and field acquisition techniques.

5.1.1 Geology of field site
Bardon Hill (278 m.O.D.) is the highest of several hills and ridges in the Charnwood Forest area which form an upland area rising abruptly from the Midland Plain. These hills represent the high points of a major structure: an anticline of Charnian rocks, which plunges towards the southeast. This anticline was heavily eroded in arid conditions with deep "wadis" incised into the Charnian rocks giving local topographic relief of over 100 metres. Thick Triassic sediments unconformably rest on the eroded Charnian rocks covering the wadi floors and hill slopes (Evans et al, 1968).

There has been some discussion as to whether the Charnian rocks in the Bardon Hill are pyroclastic or intrusive. Evans et al (1968) described a porphyroid with chilled margin contacts, suggesting an intrusive origin at least in part. The rocks are severely crushed and weathered, resulting in an irregular surface morphology, and also strongly cleaved, which locally enhances the irregularity of the eroded basement surface (Bosworth, 1912).

The overburden of Triassic sedimentary rocks (Mercia
Mudstones) varies in thickness in this area from zero to > 200m. It consists of mudstones with thin layers of sands and sandstone though a breccia is present immediately above the Charnian rocks. The breccia contains locally derived clasts of various sizes. It can be over 6m thick in the bases of the former wadis, thinning to a metre or less on more elevated areas. Thin beds of breccia are also present interbedded within the mudstones for a few tens of metres above the unconformity. Clast size diminishes away from the Charnian rocks and breccia beds pass gradationally into thin beds of sandstone and siltstone known as "skerries". The Triassic beds dip away at gentle angles from the Charnian Massif; the dip becomes more gentle at shallower depths (Bosworth, 1912; Taylor, 1968).

The Triassic and Charnian rocks have been re-exposed by Quaternary and recent erosion. The Triassic mudstones may be weathered to depths up to 10 metres and are overlain by variable thicknesses of boulder clay, alluvium and gravel.

At the field site, the plus-minus refraction interpretation of the area (Chapter 2) revealed a steep 'wadi' structure with the Charnian basement at depths of 65 to 21 metres below ground level (Figure 5.1) though borehole data (Figure 2.8) indicated that the depths were seriously underestimated by this method.

The area is covered by a thin weathered layer and drift sediments and the water table is at depth of 1 to 2 metres below the surface of the ground.

5.2 SEISMIC SOURCE TEST

5.2.1 Comparison of headwaves

Six different seismic energy sources were examined: the sledge hammer, weight drop, Betsy Seisgun, Buffalo gun, detonators, and explosives. The explosive charges were fired at different depths within a borehole while the surface sources were shot at three shotpoints along the seismic profile (Figure 5.1). A description of the sources and detailed information about the shots are summarized in Tables 5.1 and 5.2.

A Nimbus ES-1200, multi-channel signal enhancement
Figure 5.1 Geological cross-section of the field test site interpreted from the plus-minus method of seismic refraction (Chapter 2); B and C represent the positions of shotpoints B and C along line RFR-10 in Figure 2.8.

Figure 5.2 A typical seismic field record (S3) showing various types of seismic wave: air-wave (AIR), ground roll (GR), reflected (RFL) and refracted (RFR) waves.
<table>
<thead>
<tr>
<th>SEISMIC SOURCE</th>
<th>WEIGHT/GAUGE</th>
<th>CHARGE TYPE</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explosive</td>
<td>6 (100 gm) sticks</td>
<td>dynamite</td>
<td>Fired in a borehole.</td>
</tr>
<tr>
<td>Detonator</td>
<td>3 (1 msec) electric delay</td>
<td>No. 8 Star strength explosive</td>
<td>Detonated just below the surface of the ground.</td>
</tr>
<tr>
<td>Weight drop</td>
<td>52 Kg cylindrically shaped weight</td>
<td>impact</td>
<td>Dropped from 4 m height directly onto the ground.</td>
</tr>
<tr>
<td>Sledge hammer</td>
<td>6.3 Kg</td>
<td>impact</td>
<td>Struck a plastic plate on the surface of the ground.</td>
</tr>
<tr>
<td>Betsy Seisgun</td>
<td>8-gauge shotgun</td>
<td>lead projectile</td>
<td>Fired directly onto the ground.</td>
</tr>
<tr>
<td>Buffalo gun</td>
<td>12-gauge shotgun</td>
<td>blank cartridge</td>
<td>Fired below the surface of the ground.</td>
</tr>
</tbody>
</table>

Table 5.1 Description of the seismic sources used in the source test.
<table>
<thead>
<tr>
<th>SHOT-POINT</th>
<th>SOURCE TYPE</th>
<th>DISTANCE</th>
<th>OFFSET</th>
<th>DEPTH</th>
<th>SAMPLING RATE</th>
<th>RECORD LENGTH</th>
<th>NUMBER OF STACKS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X (m)</td>
<td>Y (m)</td>
<td>Z (m)</td>
<td>(Hz)</td>
<td>(sec)</td>
<td>CHANNELS</td>
</tr>
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<td>Exp.*</td>
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<td>0.0</td>
<td>18</td>
<td>2000</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.8</td>
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<td>16</td>
<td>2000</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.8</td>
<td>0.0</td>
<td>11</td>
<td>1000</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.8</td>
<td>0.0</td>
<td>6</td>
<td>1000</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.8</td>
<td>0.0</td>
<td>4</td>
<td>1000</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>Hammer</td>
<td>12</td>
<td>2.4</td>
<td>0.0</td>
<td>2000</td>
<td>0.5</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12</td>
<td>0.0</td>
<td>0.0</td>
<td>1000</td>
<td>1.0</td>
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</tr>
<tr>
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<td>Weight</td>
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<td>4.4</td>
<td>0.0</td>
<td>1000</td>
<td>1.0</td>
<td>4 3 3 3 3 3 3 3</td>
</tr>
<tr>
<td></td>
<td>Betsy</td>
<td>12</td>
<td>2.4</td>
<td>0.5</td>
<td>1000</td>
<td>1.0</td>
<td>3 3 3 3 3 3 3 3</td>
</tr>
<tr>
<td></td>
<td>Buffalo</td>
<td>12</td>
<td>2.4</td>
<td>0.5</td>
<td>1000</td>
<td>1.0</td>
<td>3 3 3 3 3 3 3 3</td>
</tr>
<tr>
<td>2</td>
<td>Hammer</td>
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<td>0.0</td>
<td>2000</td>
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<td>7</td>
</tr>
<tr>
<td></td>
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<td>0.0</td>
<td>2000</td>
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<td>5 5 5 5 5 5 5 5</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>Buffalo</td>
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<td>0.5</td>
<td>0.5</td>
<td>2000</td>
<td>0.5</td>
<td>3 3 3 3 3 3 3 3</td>
</tr>
<tr>
<td></td>
<td>Det.*</td>
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<td>2000</td>
<td>0.5</td>
<td>1 1 1 1 1 1 1 1</td>
</tr>
<tr>
<td>3</td>
<td>Weight</td>
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<td>0.0</td>
<td>2000</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Betsy</td>
<td>163</td>
<td>0.0</td>
<td>0.0</td>
<td>2000</td>
<td>0.5</td>
<td>3 3 3 3 3 3 3 3</td>
</tr>
<tr>
<td></td>
<td>Buffalo</td>
<td>160</td>
<td>4.0</td>
<td>0.5</td>
<td>2000</td>
<td>0.5</td>
<td>2 2 2 2 2 2 2 2</td>
</tr>
</tbody>
</table>

Table 5.2 Recording parameters of the shots made in the source test.

* Exp.: Explosive; Det.: Detonator.
seismograph and 12 geophones (Geo Space model K, 14 Hz) were used to collect the seismic data, which were recorded on a G-724S digital magnetic tape recorder at 10 bit accuracy, with five (12 trace) files per tape. The data were later transferred to a BBC microcomputer, via an RS-232 port, and saved on floppy discs. These data were used for the amplitude and spectral studies. Geophones were placed 10 m apart and were normally planted on the ground (with 7.5cm spikes pushed directly into a firm soil). Figure 5.1 shows the seismic profile (10) with the relative positions of the geophones and shots. Nineteen seismic records were made at the different shotpoints, though an explosive record at 22m depth and a hammer record made at shotpoint 3 were corrupted on tape and could not be used for later processing.

An example of the seismic records shot in the field site is shown in Figure 5.2. The record was made by the weight drop at shotpoint 3 and shows different types of wave generated by the seismic source. These include: the low frequency, large amplitude ground roll with its prolonged wave train which extend across the record with velocities up to approximately 550m/s; a high-frequency air-wave with a velocity of about 337m/s; and the compressional headwaves with a velocity of about 1800 m/s, refracted from within the Triassic overburden.

Explosive and surface source records made at shotpoint 1, which have larger offsets, showed headwaves with velocities between 3 to 4.5 m/ms, probably refracted from the Charnian basement. On the surface source records of shotpoints 1 and 2, the maximum amplitude of the ground roll has a velocity of about 450m/s.

P-wave reflections were not clearly visible on any of the seismic records with the exception of those shot updip, where the basement surface dips towards the source (Figure 5.1), at shotpoint 3 in the time window between the first arrival and the ground roll (Figure 5.2).

The low amplitude of the reflection signals on these seismic records is probably due to the recording system, in which high frequencies were not emphasized. Application of a low-cut filter prior to A/D conversion, normally used to attenuate low frequency source-generated noise, was not
possible on the Nimbus. Also, the receivers were low-frequency geophones (14 Hz), not suited for high-resolution work. As such, the available dynamic range of the recording system was mainly occupied by the large amplitude low frequency seismic waves (ground roll and headwave).

Seismic sources used in this trial were examined and compared for the energy output and the frequency content of the seismic signals. The comparison was based on the compressional headwaves.

(1) Total energy

The amplitude of the first and the second cycles of the compressional headwaves were measured from the seismic traces for the 17 records made by the various sources. The measured amplitudes were standardized for a single shot and a constant gain. These values were plotted on semi-log axes against shot-geophone offsets for each shotpoint. Figures 5.3a, 5.3b, and 5.3c represent the plots of the (second cycle) p-wave amplitudes versus distances at shotpoints BH-1, 2, and 3, respectively. A similar pattern was also obtained from (first cycle) headwave plots. Because the amplitude of the second cycle was comparatively large, calculation errors are less than 10%.

It is clear from the amplitude comparison (Figure 5.3a) that the energy produced by the explosive sources is much greater than that from the non-dynamite sources. The amount of the seismic energy generated by the explosive charges increases with the depth of the burial. This is most likely due to the increase of the confining pressure on the charges with depth. Also, shortening of the refracted wave propagation path, with increased depth of burial, results in less attenuation of the seismic energy. Furthermore, the excitation of ground roll and the effect of the air-wave generated by the blast are reduced with increasing depth of source. The energy produced by the 18 m deep explosive is approximately 13 times as much as that from the 4 m deep explosive.

With regard to the surface seismic sources, the lower part of Figure 5.3a clearly shows that the energy generated from the Buffalo gun is greater than that produced by other
Figure 5.3 Comparison of headwave seismic amplitudes produced by: a) explosives at the borehole and surface sources at shotpoint 1, b) surface sources at shotpoint 2, and c) surface sources at shotpoint 3.
non-dynamite sources (see also 5.3b and 5.3c). Table 5.3 lists the average ratio of the seismic energies of the Buffalo gun and other sources at the different shotpoints. Different refracted phases may be received at the same geophone position from shots at different depths and offsets (e.g. BF, EXP4).

Seismic records from the explosive charges showed a decrease in the amplitude of the ground roll with increased depth of charge burial. The ground roll was almost absent in the 18 m deep explosive record. The average (p-wave/surface wave) energy ratios were approximately 9 for the 4m deep explosive charge and 1.7, 1.6, 0.9, 0.8 and 0.5 for the Buffalo gun, hammer, Betsy gun, weight drop and detonator, respectively (Figure 5.4).

The air-wave was present on most surface source records with the exception of some of the Buffalo gun shots. This is probably because of this gun's coupling to the ground, eliminating air blast escape. The air-wave was also not shown on any of the explosive records, the boreholes being well tamped.

(2) Spectral content

The BBC-microcomputer was used to perform a Fourier transform (Program S.SPECAN; Appendix F.2a.) on the seismic data. Spectral examination of the seismic records showed that noise, whether source-generated or random, seriously affected the useful seismic energy spectrum, especially for the surface sources. Ground roll had a dominant frequency between 10-70 Hz, energy peaks around 40 Hz, and was not significantly affected by changing the shot-geophone offset.

The random noise (winds or traffic) peaked around 15 Hz with no energy above 40 Hz. It had negligible effect on any of the explosive seismic records even at the largest offset (157 m). However, it seriously influenced the spectra of some of the surface source records especially at large distance (>80 m), because of the spreading losses and high attenuation of the seismic waves (see Figures 5.5 and 5.6; Table 5.5).

Normalized spectra of the 4 and 18 m deep explosive shots, measured at offsets of 47 and 157 m, indicate the high frequency content of the seismic energy from the deeper shot
<table>
<thead>
<tr>
<th>SHOT NO.</th>
<th>COMPARED SOURCES**</th>
<th>DISTANCE (m)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&lt; 10</td>
<td>10-40</td>
<td>&gt;50</td>
<td>AVERAGE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ENE</td>
<td>dB</td>
<td>ENE</td>
<td>dB</td>
<td>ENE</td>
<td>dB</td>
<td>ENE</td>
<td>dB</td>
</tr>
<tr>
<td>3</td>
<td>BF/WD</td>
<td>3.1</td>
<td>4.9</td>
<td>4.1</td>
<td>6.1</td>
<td>2.9</td>
<td>4.6</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3</td>
<td>-5.0</td>
<td>4.7</td>
<td>6.7</td>
<td>3.6</td>
<td>5.5</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>BF/BH</td>
<td>13.2</td>
<td>11.2</td>
<td>4.4</td>
<td>6.4</td>
<td>11.8</td>
<td>10.7</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>BF/WD</td>
<td>5.9</td>
<td>7.7</td>
<td>2.4</td>
<td>3.8</td>
<td>5.1</td>
<td>7.1</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>BF/BH</td>
<td>1.0</td>
<td>0.0</td>
<td>7.1</td>
<td>8.5</td>
<td>7.2</td>
<td>8.6</td>
<td>7.1</td>
</tr>
<tr>
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<td>BF/DT</td>
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<td>-0.4</td>
<td>9.6</td>
<td>9.8</td>
<td>5.8</td>
<td>7.6</td>
<td>7.1</td>
</tr>
<tr>
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<td>BF/HM</td>
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<td>12.0</td>
<td>16.0</td>
<td>12.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BF/WD</td>
<td>3.0</td>
<td>4.8</td>
<td>3.0</td>
<td>4.8</td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>BF/BH</td>
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<td>4.6</td>
<td>2.9</td>
<td>4.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BF/EXP4</td>
<td>2.7*10^-4</td>
<td>-35.5</td>
<td>2.7*10^-4</td>
<td>-35.5</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>EXP4/EXP18</td>
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<td>-11.2</td>
<td>7.6*10^-2</td>
<td>-11.2</td>
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<td></td>
</tr>
</tbody>
</table>

Table 5.3 Summary results of comparison of the seismic energies produced by the different sources to that of the Buffalo gun.

** HM : Hammer; WD : Weight drop; BF : Buffalo gun; BT : Betty gun; DT : Detonator; EXP4 : Explosive 4m deep; EXP18 : Explosive 18m deep.
Figure 5.4 Plots of (P-wave/ground roll) maximum amplitude ratios against distance for the 4m deep explosive charge and five surface sources (shotpoint 2).
Figure 5.5 Headwave normalized energy spectra of five surface sources (shotpoint 2) measured at 110m offset.

Figure 5.6 Normalized energy spectra of four surface sources (shotpoint 1) and the 4m deep explosive measured at offsets of 148m and 157m, respectively; the two notches in Buffalo gun's P-wave spectrum may be caused by ghost effects.
Figure 5.7a. The figure also shows that the spectra of the two shots are apparently shifted to the higher frequency with increased offset. For the shallow shot, the energy peaks at frequencies of about 20 and 35 Hz at the short and large offsets respectively, while it peaks at frequencies of about 80 and 115 Hz for the deeper shot. The shift of the spectra to higher frequencies with increased offset and depth is related to the effect of ground roll and the differences in the ray-paths and headwave phases. Table 5.4 summarizes the results of the spectrum comparison.

The effect of the depth and offset on the explosive spectra of Figure 5.7a can be clearly understood on the absolute amplitude spectra shown in Figure 5.7b. A direct comparison can be made between the spectra since the gain (for both recording and displaying) was kept fixed (adjusted to 38 dB) for the four seismic traces. The ratios of the p-wave energy between the two shots and between the two traces of each shot, measured from the absolute amplitude spectra of Figure 5.7b, are in reasonable conformity with that of Figure 5.3a. The deep to shallow explosive energy ratio is approximately 14 and 12 dB at the 47 and 157 m offsets, respectively, as compared to about 11dB at both offsets indicated by the total energy measurement (Figure 5.3a).

Direct comparison between the explosive and the surface sources, however, was not possible because of the great differences in the level of their energies. Instead, only the normalized spectra of these sources were compared. Figure 5.6 shows the normalized energy spectra, measured at geophone 1, of the 4m deep explosive and four surface sources of shotpoint 1. The figure may first suggest that the explosive is the least rich, with the exception of the Betsy gun, in high frequencies. However, bearing in mind that the explosive energy is about 35 dB greater than that of the Buffalo gun (Figure 5.3a), the small peak on the explosive spectrum with frequencies between 100 and 150 Hz may actually have an energy level several times as large as that of the peak frequency of the Buffalo gun. The problem with the explosive charge is that its output is so large that the available dynamic range of the recording system is occupied mainly by
Figure 5.7 Spectra of two explosive charges (4 and 18m deep) measured at 47m (Trace 12) and 157m (Trace 1) offsets:
   a) normalized energy.
   b) absolute amplitude.
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<thead>
<tr>
<th>SOURCE TYPE</th>
<th>OFFSET (m)</th>
<th>NOISE TYPE</th>
<th>FREQUENCY Hz</th>
<th>ENERGY dB</th>
<th>P-WAVE FREQUENCY Hz</th>
<th>ENERGY dB</th>
<th>REMARKS</th>
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<td>ground roll</td>
<td>0-30</td>
<td>*</td>
<td>30-50 6.0</td>
<td>55-95 4.0</td>
<td>P-wave is mainly headwaves from overburden. Ground roll is the dominant frequency. No energy above 100 Hz.</td>
</tr>
<tr>
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<td>EXP4</td>
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<td></td>
<td></td>
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<tr>
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<td>157</td>
<td>mostly random</td>
<td>0-20</td>
<td>11.0</td>
<td>20-55</td>
<td>*</td>
<td>55-90 5.6</td>
</tr>
<tr>
<td></td>
<td>EXP18</td>
<td>Negligible</td>
<td>50-100</td>
<td>*</td>
<td>100-200 4-8.5</td>
<td></td>
<td>P-wave is mainly headwaves from overburden. Insignificant energy beyond 350 Hz (not shown on the plot).</td>
</tr>
<tr>
<td></td>
<td>157</td>
<td>Negligible</td>
<td>95-145</td>
<td>*</td>
<td>60-90 3.5</td>
<td>150-190 3.5</td>
<td>200-250 8.0</td>
</tr>
</tbody>
</table>

Table 5.4 Summary results of energy spectrum comparison of two explosive charges (based on the plots shown in Figure 5.7).

* Represent the dominant frequency (energy peak) against which other energy spectrum levels are measured.
the large amplitude low frequencies. The relatively low-amplitude high frequencies are lost in the limited dynamic range. The gain setting of geophone 1 was 20 dB greater for the surface sources than for the explosives.

Comparison of the surface source spectra (Figure 5.6) clearly indicates the advantage of the Buffalo gun over the other sources. The figure shows that most of the Buffalo gun’s energy is shifted towards higher frequencies with a dominant frequency peak at between 100-150 Hz. Results of the energy spectrum comparison are summarized in Table 5.5.

Comparison of the absolute energy spectra of the surface sources also shows the advantages of the Buffalo gun in terms of energy output. These results agree with those obtained from direct amplitude measurements (see preceding section, Table 5.3).

The steep cutoff of high frequencies on the amplitude spectra (e.g. Figure 5.5) was due to the effect of the 14 Hz geophone (Appendix D.1). Lepper (1981) noted the limitations of this particular type of geophone in high-resolution work. He attributed this to inefficient coupling between the active elements of the geophone and its case which are separated by silicone rubber. The 14 Hz geophones were abandoned and not used in further work.

5.2.2 Comparison of reflected waves

The previous sections demonstrated the superiority of the Buffalo gun over the other types of source using compressional headwaves. Here, reflection signals produced by the Buffalo gun, using the standard cartridge (see Section 5.3.2), are compared to those of the sledge hammer. Figure 5.8 shows split-spread records of the hammer (8 stacks) and the Buffalo gun (2 stacks) made at the NW end of the test site using the Bison Geopro 8024 seismograph and 24 (8 Hz) geophones with 3m geophone spacing. A programmed gain of 6 dB per 30ms and a sampling rate of 2500 Hz were used. A 350 Hz low-cut filter, prior to A/D conversion, was applied to emphasize high frequencies.

Comparison of the two records, where corresponding geophones have equal recording and displaying gain setting, indicates the superiority of the gun over the hammer in
<table>
<thead>
<tr>
<th>SEISMIC SOURCE</th>
<th>NOISE TYPE</th>
<th>FREQUENCY Hz</th>
<th>ENERGY -dB</th>
<th>P-WAVE FREQUENCY Hz</th>
<th>ENERGY -dB</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF **</td>
<td>mostly random (peaks at 10)</td>
<td>&lt; 40</td>
<td>4.0</td>
<td>40-85</td>
<td>100-150</td>
<td>150-200</td>
</tr>
<tr>
<td>HM</td>
<td>mostly random (peaks at 15)</td>
<td>&lt; 40</td>
<td>*</td>
<td>40-140</td>
<td>150-200</td>
<td>6.0-16.0</td>
</tr>
<tr>
<td>WD</td>
<td>mostly random (peaks at 20)</td>
<td>&lt; 35</td>
<td>3.0</td>
<td>35-105</td>
<td>110-150</td>
<td>6.0-12.0</td>
</tr>
<tr>
<td>BT</td>
<td>mostly random (peaks at 15)</td>
<td>&lt; 35</td>
<td>*</td>
<td>50-100</td>
<td>120-160</td>
<td>14.0</td>
</tr>
<tr>
<td>EXP4</td>
<td>mostly random (peaks at 10)</td>
<td>&lt; 20</td>
<td>11.0</td>
<td>20-55</td>
<td>55-90</td>
<td>95-140</td>
</tr>
</tbody>
</table>

Table 5.5 Summary results of energy spectra comparison of four surface sources and the 4m deep explosive charge (based on the plots shown in Figure 5.6).

* Represent the dominant frequency (energy peak) against which other energy spectrum levels are measured.

** The two notches (45-85 and 100-150 Hz) of Buffalo gun's P-wave spectrum may be due to ghost effects (multiple reflections from the surface of the ground). A similar phenomenon can also be observed on the spectrum of the deep planted (0.6m) geophone in Figure 5.17.
Figure 5.8 Comparison of two seismic field records made by: a) hammer, and b) Buffalo gun; Field recording parameters were identical for both records (a 350 Hz analogue low-cut filter was used).
resolving shallow reflections and recording useful high-frequency energy. The hammer record is badly contaminated and dominated by both the low frequency ground roll at short offsets and the high-frequency air-wave at further offsets. In contrast, the Buffalo gun's record is strongly dominated by several reflections, the most pronounced of which is at 75ms, probably from the basement. No hint of air-wave is shown on the record and the ground roll is strongly suppressed.

The high energy output and high-frequency content of the signal generated by the Buffalo gun may be caused and augmented by several factors. The most important of these are: release of energy below the top-soil (usually the major cause of energy loss and attenuation of high frequencies); and firing below the surface of the ground to give good coupling between the source and the ground, thus helping to eliminate the air-wave and reducing the ground roll energy.

Although, by definition, the Buffalo gun is not a repetitive source in the sense that it creates a cavity and requires the gun to be either pushed further down (about 10 cm) or fired in adjacent holes, seismic data from the Buffalo gun indicated that its energy stacks well (Figure 5.8).

5.3 DEVELOPMENT OF THE BUFFALO GUN

5.3.1 Change in gun

The Buffalo gun which was used in the source test consists of three component parts:

(1) The main part is a tube 0.8m in length, 3.5cm in diameter with a stout metal pad at the top end and a cartridge chamber attached to it at the bottom end. A robust metal cross-handle is fixed to the main tube just below the top end while the bottom end is threaded internally to allow the cartridge chamber to be screwed in.

(2) The cartridge chamber is a 7cm long steel cylinder machined internally to house a 12-gauge shotgun cartridge and fitted to the gun's main tube by a screw thread. Cartridges up to 7cm in length can be used with this chamber.

(3) The firing pin is a thin steel rod inserted inside the main tube where its pointed tip rests on the primer cap
of the cartridge. Firing can be done either by a gentle tap on the pin with a light wooden mallet or dropping the firing pin down the main tube onto the cartridge.

A conventional impact switch, of the kind used with the sledge hammer, is taped to the gun's main tube or the cross-handle providing a means of triggering the seismic recorder.

The gun, with its chamber loaded with a blank 12-gauge shotgun cartridge, is deployed in a previously prepared 0.5m deep hole, drilled using a 4cm diameter hand auger. A heavy hammer was then used to drive the gun deeper into ground. This ensured a gas tight seal in the hole and a good coupling between the chamber and the ground. The cartridge is set off by the firing pin.

In this study, the Buffalo gun has undergone continuous modification and development of the gun itself, the way it is deployed and coupled to the ground, and the type of the shotgun cartridges used to provide the seismic energy. These modifications are discussed below. The main objectives behind the development were to maximize the energy and the frequency content of the generated seismic signals and to make the gun simpler to operate and safer to use.

Modifications to the gun were directed at the main tube and cartridge chamber. Guns up to 1.3m long were made to produce seismic energy deeper in the ground and hence increase the seismic efficiency. An auger thread was added to the main tube of the gun to help to drive it a little deeper into the ground to ensure a good coupling and to prevent recoil. A cylindrically shaped impact switch was adapted to fit this auger-fitted gun by inserting it into the end of the tabular cross-handle.

The cartridge chamber was adapted from an open end to a pointed end chamber. The upper part of the chamber houses the cartridge while the lower part is solid and cone shaped. The middle part of the pointed chamber is machined internally and has 3-4 ports to allow gas release. The pointed chamber has a total length of about 19cm. Figure 5.9 shows diagrams of the modified Buffalo gun and the open and pointed cartridge chambers.

The pointed chamber facilitates deployment of the gun in
Figure 5.9 Schematic diagrams of the "auger-fitted" Buffalo gun and two types of chamber:
   a) pointed.
   b) open end.
the ground. The solid cone at the end of the chamber seems not to affect the seismic efficiency of the gun. The pointed chamber size and design was built following a test made to determine the size of cavity caused by the Buffalo gun firing a 12-gauge cartridge housed in the open end chamber which was 0.7m below the ground surface. An investigation hole was made to reveal the cavity created (Figure 5.10).

The cavity made by the gun is a relatively smooth sphere with a radius of approximately 6cm. The bottom end of the gun was about 3cm above the centre of the sphere. This may either be caused by the recoil of the gun or suggest the semi-downward directional nature of the source. As such, obstruction caused by the cone of the pointed chamber is judged to be insignificant.

The use of the modified long Buffalo guns was accompanied by the use of a petrol powered drill to attain maximum efficiency in multifold shallow reflection recording. The Atlas Copco Cobra Hammer Drill, mounted on a two-wheeled trolley was adapted for this purpose. It can accommodate a 1.2m bit and makes approximately 25 holes, 1m in depth and 5cm in diameter, per hour.

5.3.2 Change in cartridge

In this study, a new type of shotgun cartridge, the blank 12-gauge Remington "Popper-Load", was adopted for shallow reflection work. It contains 30gr smokeless powder with 75gr filler and is commercially available. The Popper-Load was field tested and compared with the previously used "Belgrave" cartridge (a type with about 3cm wad). It was found that the reflected energy, from the basement, produced by the Popper-Load was four times as much as that from the "Belgrave". The seismic energy from both cartridges had fairly similar frequencies. Descriptions of cartridge types are given in Table 5.6 while the cartridges and cartridge chamber are shown in Figure 5.11.

The potential of different types of shotgun cartridges in resolving shallow seismic reflection was tested at the same field trial site, the Popper-Load being used as a standard against which to measure other types of cartridge. The effect of confinement of the cartridge was also examined.
Figure 5.10 Photograph showing the Buffalo gun and the cavity it creates.
<table>
<thead>
<tr>
<th>NAME (ID)</th>
<th>POWDER TYPE</th>
<th>POWDER WEIGHT (gr)*</th>
<th>FILLER WEIGHT (gr)</th>
<th>WADS LENGTH (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgrave</td>
<td>Smokeless Nitrocellulose</td>
<td>25</td>
<td>0</td>
<td>3.0</td>
</tr>
<tr>
<td>Popper-Load</td>
<td>Nitrocellulose</td>
<td>30</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>Nitrocellulose</td>
<td>40</td>
<td>75</td>
<td>0.1</td>
</tr>
<tr>
<td>F</td>
<td>Black powder</td>
<td>80</td>
<td>?</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 5.6 Description of the different types of shotgun cartridge used in this study.

* gr (grain) = 0.0648 gm (gram).
Thus some of the cartridges had their bottom end glued with Araldite. The Popper-Load, glued Popper-load, C-shell, glued C-shell, and F-shell were tested. These shells differ in the amount and type of the propellant powder (Table 5.6). The C and F shells are also 12-gauge and were especially made for this test by a local gunsmith.

This test was part of a larger trial in which the type of geophone and geophone plant were also examined (see Section 5.4). The survey line was shot at the NW end of the field.

Figure 5.11 Photograph showing different types of cartridge and cartridge chamber: A) 410-gauge; B, C, and D) 12-gauge; E) 10-gauge; and F) 8-gauge cartridges.
Thus some of the cartridges had their bottom end glued with Araldite. The Popper-Load, glued Popper-Load, C-shell, glued C-shell, and F-shell were tested. These shells differ in the amount and type of the propellant powder (Table 5.6). The C and F shells are also 12-gauge and were especially made for this test by a local gunsmith.

This test was part of a larger trial in which the type of geophone and geophone plant were also examined (see Section 5.4). The survey line was shot at the NW end of the field site where a grid of shots were made at position C of seismic Profile 10 in Figure 5.1. The plan of the seismic test, which includes geometry, type of geophones and other relevant information, is shown in Figure 5.12. The Bison Geopro 8024 24-channel seismograph was used and a 35Hz pre-recording low-cut filter (filter out is not available on the Bison) and a programmed gain of 6dB per 30ms were applied.

Seismic data from the geophones at the arc (Figure 5.12) were used for energy and spectral analysis and comparison. At the arc, the source-generated noise (the ground roll and the air-wave) became a late event on the seismic record (>110ms). As such, no interference occurs between this noise and the main reflection signals which come from the Charnian rockhead. First arrivals coming from within the Triassic overburden were also used in the analysis.

Figures 5.13a and 5.13b show first arrival and reflection energies, respectively, versus the geophones (8 and 100 Hz) at the arc produced by the various cartridges. The variation in the energy level for each shell at the different geophone positions is related to the type of geophone and geophone plant (Section 5.4). These plots clearly indicate the high energy produced by shell-C as compared to other cartridges. Its reflected energy is about 5 and 10 times as much as that produced by the Popper-Load for the 100 and 8 Hz geophones, respectively. Confining cartridges, whether for the Popper-Load or shell-C, showed a slight increase in energy (<20%), only observed on the refracted energy.

Figure 5.14 shows that confining the cartridges increased the bandwidth of useful energy. This is most evident on the C-shell where the useful reflected energy
Figure 5.12 A plan of the seismic source and geophone test made in the field site showing the relative positions of shots and geophones.
Figure 5.13 Comparison of seismic energies (Amplitude$^2$) produced by different types of shotgun cartridge for:
  a) headwave, and b) reflected wave.

Figure 5.14 Reflection (Input voltage) spectra of different types of shotgun cartridge measured by a 100 Hz geophone (No.12).
is shifted by between 20-100 Hz to the high-frequency end of the spectrum. For the Popper-Load, the shift was no more than 20 Hz. This is because the Popper-Load was already packed in a closed plastic case while the C-shell consisted of hard paper with a thin wad closing its end. Shell-F has a lower frequency content.

These features were observed on the other geophones used as well as on the headwave spectra.

The results of the test indicated the superiority of the glued C-shell to other cartridges in terms of both the energy output and the frequency content of both the reflected and refracted signals. The attributes of energy produced by the cartridges are dependent on the type and amount of the powder used in making the cartridges, the way it is fired, and the degree of the confinement of the shells.

5.4 SEISMIC DETECTOR

5.4.1 Type of geophone

Two types of geophone were investigated with the newly developed system. These were the Mark Products, Models L-10B and L-40A-2, with natural frequencies of 8 and 100 Hz, respectively. The aim was to record high-resolution shallow seismic reflection data in the frequency range of approximately 150-600 Hz. The 8 Hz geophones were tried because of their high output voltage (0.236 V/cm/s), almost double that of the 14 Hz geophone. It has a flat amplitude response up to 150 Hz. Available frequency response curves and other geophone specifications, provided by the manufacturers, are found in Appendix D.1.

In this study, the sensitivity of the Mark Products 100 Hz geophones was computed at 0.14 V/cm/s and their resistance was measured at 500 Ohms. Lepper (1981) found that these types of geophones were very effective in eliminating low-frequency noise (due to their cutoff rate of 5.5 dB/octave below 100 Hz), and had a flat spectrum from 100-600 Hz. However, he noticed a scattering of the mechanical resonant peaks in some of these geophones; unsatisfactory resonance as low as 674 Hz was observed and attributed to inefficient assembly of the geophone. The 8 Hz and 100 Hz
geophones have opposite polarities.

The Mark Products geophones were tested in two ways: 1) to compare the total energy and input voltage spectra of the P-wave measured by the two types of geophone at an offset where there is no interference from the source-generated noise, and 2) to examine the effectiveness of the geophone attributes in recording high-frequency reflection in a normal field layout where seismic records are usually swamped by the source-generated noise.

Figure 5.12 shows the plan for the first test in which pairs of 8 and 100 Hz geophones were similarly planted along the line. This geometry ensures a large time-window for uncontaminated reflections for the geophones at the arc (see Section 5.3.2). Figures 5.13a and 5.13b clearly indicate the higher energy recorded by the 8 Hz geophones as compared to the 100 Hz geophones for the various types of shotgun cartridge. Here, for uniformity, only the data from the confined C-shell is used. Comparison of the two figures indicate that the average headwave energy is about 4.4 and 4.7 times as much as that of the reflection for the 8 and 100 Hz geophones, respectively. These two values are quite comparable if we allow for about 5% error in amplitude measurement.

The P-wave energy (both refracted and reflected) measured by the 8 Hz geophones was approximately 2.8 times that of the 100 Hz geophones. The low signal recorded by the 100 Hz geophone is due to its lower sensitivity and the effect of its natural frequency which acts as a low-cut filter, eliminating energy below 100 Hz.

One can measure the actual geophone input voltage on previously recorded data on the Bison Geopro (Section 5.5.1). Figure 5.15 shows the input voltage spectra of the 8 Hz geophones 13 and 14 and the 100 Hz geophones 11 and 12. Spectra of geophones 12 and 13 are typical for the normally planted geophones at the arc (Figure 5.12). Spectra of geophones 11 and 14 (as well as 9) are rather complicated (Section 5.4.2).

The 8 Hz geophone has a higher output voltage level than the 100 Hz geophone at all frequencies (Figure 5.15). The peaks of the spectra from both type of geophones are between
Figure 5.15 Input voltage spectra measured by different geophones (11-14) and geophone plants at the arc (see Figure 5.12).
20-140 Hz, these being dominated by the headwave energy. These spectra are strongly influenced by the geophone response (clear on the 100 Hz geophone) and the Bison (35 Hz, 12 dB/octave) low-cut filter (clear on the 8 Hz geophone). The second frequency peaks of 140-465 Hz (8 Hz geophone) and 140-590 Hz (100 Hz geophone) are mostly from p-waves (see Figure 5.14). Beyond these frequencies, the spectra are affected by spurious noise which may be caused by a combination of mechanical and geophone-ground coupling resonance.

It is surprising that the spurious noise appears to occur at such high frequencies for the 8 Hz geophone. Lepper (1981) indicated that a broad flat spectrum is obtainable from an efficiently assembled low frequency geophone. However, the uncertainty of its response at high frequencies and the possibility of distortion at these frequencies make this type of geophone unsuitable for high-resolution work. The highest voltage measured by the 8 Hz geophone is about 0.16 mV while the lowest useful voltage is about 4 µV. These correspond to particle velocities of approximately 6.78x10^{-4} and 1.69x10^{-5} cm/s which are reasonable for a normal ground motion at this offset. Lepper (1981) indicated that particle velocities in the range of 10^{-3} to 10^{-6} cm/s are usual in seismic work. He pointed out, however, that an output voltage of about 0.5 mV is desirable.

With respect to the 100 Hz geophone output voltage, it is high (about 95 µV) at low frequencies and about 1 µV at approximately 600 Hz. The particle velocity of 6.78x10^{-4} cm/s (measured from the 8 Hz geophone) was used to calculate the sensitivity of the 100 Hz geophone. The computed sensitivity value is approximately 0.14 V/cm/s which seems reasonable for this type of geophone. Although the level of the 100 Hz geophone output is low, it should not cause a serious problem since (1) these measurements were made at an offset usually representing the far-field in a shallow reflection survey, and (2) the Bison extended dynamic range (Section 5.5) should compensate for the drop of voltage with time, and the electronic noise of the seismic recorders is usually very low.

The effectiveness of the high-frequency geophones in
recording shallow reflections is seen when shooting a normal (small) spread of geophones. Figure 5.16 shows three field records made by the 8 and 100 Hz geophones at the NW end of the test site. These records were collected by a downdip shooting of an end-on spread (12 geophones, 3m apart). Comparison of the lower records (b and C) shows the advantage of the 100 Hz geophone in suppressing source-generated noise and emphasizing high-frequency reflections (from the basement at 75 ms). This type of geophone was found, when accompanied with a 200 Hz low-cut filter, to be very effective in recording high-frequency data (Figure 5.16a). Three shallow reflections, from within the Triassic overburden, are visible on this record where they were obscured on the other records (b and c). Finally, the records show opposite polarity for the two types of geophones.

5.4.2 Type of geophone plant

In this study, both geophone burial and the use of long spikes were tried in attempting to plant the geophone on a firm medium.

First, a 69m split-spread was shot at the NW end of the field site using 24 (8 Hz, 7.5cm spike) geophones, 3m apart. Alternative geophones were either normally planted (directly pushed to the ground) or buried in a shallow (0.1m) hole. At two positions, geophones were planted in a relatively deep (0.6m) hole. A significant improvement was made to the quality of the data with the shallow burial of geophones with higher frequencies being recorded. With deep hole plant, an even better result was achieved (Figure 5.17). Besides the excellent coupling attained this plant also reduced the attenuation of high frequencies by the top soil. However, the signal amplitude was smaller, as expected, than those obtained by surface planted geophones by about 6 dB.

As regards length of the geophone spikes, the 13cm spike was found to be very effective in securing a good coupling to the ground by a normal plant on a firm soil. The high-frequency records (a and b) in Figure 5.16 were obtained using (100 Hz) 13cm spike geophones. Krohn (1984) and Knapp and Steeples (1986a) reported an improvement to data quality by using this type of spike which they attributed to an
Figure 5.16 Comparison of three seismic field records shot by the Buffalo gun, using 8 and 100 Hz geophones (3m spacing); Field recording parameters were identical except for the low-cut filter.
Figure 5.17 A seismogram recorded by a (0.6m deep, 15m offset) 8 Hz geophone and its spectrum (T15); Superimposed are the spectra (T12 and T18) of adjacent 'surface planted' geophones (12 and 18m offsets).

Figure 5.18 Seismograms recorded by the geophones at the arc (see Figure 5.12) shot by a confined Popper-Load cartridge.
increase in the coupling resonant frequency.

However, these and other investigators, in their recommendations to use longer spikes, did not set a maximum limit to spike length. Therefore, very long spikes were tried in this study. The 100 and 8 Hz geophones (9, 11, and 14) on the arc (Figure 5.12) were mounted on 0.45 and 0.6 m spikes. The total energy and the input voltage spectra of these geophones were compared to that of the 13cm spiked geophones in Figures 5.13a and 5.13b, and 5.15, respectively. The energy plots (Figures 5.13a and 5.13b) show the low energy level achieved with such a plant. The spectra show phase distortion and reduction in the input voltage of the geophones (Figure 5.15). The coupling resonant frequency is lowered to approximately 375 Hz. Such distortion degraded the seismic signals and formed a complex wavelet (Figure 5.18); this was most likely caused by destructive interference between the seismic waves which travelled (with a high velocity) through the long steel spike and those propagated through the low velocity surface materials. Use of long spikes was therefore abandoned.

5.5 RECORDING EQUIPMENT

A seismograph-field computer system was developed as the core of the newly developed high-resolution shallow seismic reflection system. Such a setup has three purposes: 1) to provide a cheap data storage facility, 2) to provide immediate quality control and preliminary processing of the data in the field and 3) to be used, in the laboratory, for further processing to obtain a reasonable subsurface image.

Although most of the modern engineering seismographs incorporate useful features such as signal enhancement and digital filtering, the output is usually in the form of a paper record. A field computer, therefore, becomes a significant step towards cost efficiency by storing data on magnetic discs for playback. Besides, it furthers the seismograph processing capabilities by providing additional features such as spectral analysis and velocity analysis. Preliminary processing which includes the construction of a constant offset seismic section from multifold records can also be easily made in the field. Such steps are helpful to
optimize field recording parameters and techniques.

5.5.1 Seismic recorder

The 24-channel Bison Geopro 8024 seismograph was used. It is a microcomputer controlled device having an 8 bit analogue to digital converter with a 48 dB dynamic range. A programmed gain function effectively extends this, in steps of 6 dB with time, up to 78 dB by a programmed gain control (PGC). It records 959 samples per channel with an 8 bit sample resolution for the input memory and 16 bit for the enhanced memory. The samples are stored in a fixed point format in the input memory and in a block floating point format in the enhanced memory. Data stored in either type of memory can be transferred to the computer via an RS 232 port. In this study, seismic data in the enhanced memory were usually transferred to the computer for recording.

An important feature of the Bison for high-resolution reflection recording is its analogue filter capabilities. Three types of filter, low-cut, high-cut, and notch, can be applied to the data (geophone input voltage) before being sampled by the A/D converter and stored in a digitized form. These filters are used to suppress source-generated interfering noise and prevent aliasing of high-frequencies. Filters of 35 Hz low-cut, 1000 Hz high-cut, and notch out are normally preset on the Bison. However, a variety of filter values can be used as required. The low-cut and high-cut filters have a cutoff rate of 12 dB/octave pass. Frequency response curves of some of the filters incorporated in the Bison are found in Appendix D.2.

It is possible to determine the actual geophone input voltage from data previously recorded by the Bison. Geophone input voltage is calculated as follows:

\[
\text{Input voltage} = -5 \frac{A 2^e}{S 2^{(g/6)}}
\]

where the input voltage is in volts (V), A is sample value, e is exponent, g is gain in dB, and S is scale factor (128 for 8-bit, 32767 for 16-bit). The effect of the filter is not considered in this calculation.

The Bison can display a 24-trace seismogram on a (228
mm) CRT and as a paper record. Also, it provides many other displaying and processing features such as digital frequency filtering. The Bison is powered by a 10–14 volts, 7–8 Amps source. A more detailed description can be found in the Bison Instruments instruction manual (1984).

5.5.2 Field computer

The BBC-B microcomputer was used as a field (as well as office) processor in the shallow reflection system. It is a modified, portable version using a 6502 second processor to increase memory and computing speed. Using a double density disc filing system, a maximum of 24 seismic data (24-trace) files, 28.5 Kbyte each, can be saved on each disc. The RS 232 interface is used to transfer data from the Bison to the BBC. The BBC was adapted to run from a 12-volt car battery.

The BBC was chosen because it is cheap, easy to interface, and because of the flexibility of its hardware and software. It can be used for both storing and processing data, and, has shown to be robust in rough field conditions. Its software has been written, in BASIC, specifically for this project. These programs are described in more detail in Chapter 6. Processing is somewhat slow on the BBC, but is quite useful for quality control in the field and for small scale surveys. The SEG-Y format is used for data files allowing straightforward transferral of data to a larger mainframe computer for further processing using a commercially available seismic processing package.

5.6 FIELD ACQUISITION TECHNIQUES

5.6.1 Recording parameters

In the seismic reflection surveys, the Buffalo gun, using confined Popper-Load blank shotgun cartridges (Section 5.3), was employed to provide high-frequency energy. One shell was usually fired at each shotpoint at a depth of about 1 metre below the surface of the ground. 100 Hz geophones, with 13cm spikes normally planted on the surface, were regularly used. In areas with poor ground conditions 0.2 to 0.3 m holes were made to improve coupling. Only single geophones have been used.
The field conditions determined the preemphasis filters applied. Under favourable conditions, such as the presence of a thin and firm soil, a shallow water table, and a large velocity contrast, a 200 Hz (12 dB/octave) low-cut filter was normally applied prior to A/D conversion. This was found to be very effective in recording high-frequency records (Figure 5.16a). When the field conditions were less good (e.g. disturbed soil, deep water table), low-cut filters were dropped down to as low as 100 Hz to maintain reasonable signal level.

A 192ms record was normally made. This time length was suitable for the shallow scale of survey (target depth <100m) and ensured a sampling rate of 5000Hz on the Bison Geopro. The Bison records were usually resampled when transferred to the BBC for recording to half the sampling rate (0.4ms for sample interval). This provided signals with a Nyquist frequency of 1250Hz, which was well above the frequency range of interest (150-600 Hz). Aliasing of high frequencies was corrected by an anti-alias filter. An 825Hz (-12dB/octave) high-cut filter was usually applied during recording.

5.6.2 Geometry

Hunter's optimum methods (the window and constant offset techniques) were first employed to record a single fold seismic section in the field site along Line 8 (see Figure 7.1). Initially, the optimum window technique was used by updip shooting of the line at 3 locations using a 69m end-on spread with 24 (8 Hz) geophones, 3m apart. A time-space window was established where reflections were not contaminated by source-generated noise. The time window was found to occur at 24 and 27 m offsets and so the entire line (177m) was updip shot with these offsets to record a constant offset section. Thirty shots (0.5m deep, 6m interval) were fired along the line in which 2 traces were recorded for each shot. 24-trace files were made of these traces and saved on a floppy disc. Figure 5.19 shows the constant offset seismic section which was shot along the line. Alternate traces were time shifted to compensate for change in offset. No weathering correction was applied.

The seismic section is a high quality record where a
Figure 5.19  Seismic reflection section recorded along Line 8 using the constant offset technique; Offsets of 24 & 27m, 8 Hz geophones and 200 Hz low cut-filter were used; Traces are 3m apart.
satisfactory S/N ratio was obtained from single fold coverage and is rich in high frequencies. Several reflectors are visible on the record. The deepest of these is the one from the unconformity at the top of the Charnian. It varies in time from approximately 80 to 40 ms from the NW end to the SE end of the section. The shallow reflections seen at about 60 and 50 ms are most likely from sandstone layers within the Triassic overburden; they seem to be fairly continuous. Other discontinuous reflections can be seen on the record.

Such optimum techniques of seismic recording were later abandoned, because they only proved useful in areas with good field conditions. The common mid-point (CMP) method was adopted in order to improve the signal to noise ratio. The CMP method took no greater effort to conduct in the field than the previous method. It was later used to construct single fold seismic sections with different offsets (constant offset sections). In areas with good field conditions, such constructed sections were adequate to give reasonable subsurface images where the S/N ratio was satisfactory.

A seismic reflection line with 12-fold CMP coverage was recorded in the field site along (refraction) Line 10 (Figure 5.1). A 24 (100 Hz, 13cm spike) geophone spread (end-on), with 2m geophone spacing, was rolled along the line. Zero offset shots were fired every 2 metres. This geometry was used to provide information about near-surface materials which were deduced from uphole time and headwave data.

The use of 2m geophone spacing (and the subsequent 4m spacing in the CMP gather) resulted in a horizontal sampling of 1m, and was adequate to avoid spatial aliasing of ground roll. The first Fresnel zone and the wavelength of the ground roll are generally estimated to be > 10m along this line (Sections 3.3.3, 5.2.1). Mixing (i.e. binning; see Section 6.7.2) of two adjacent CMP gathers before stacking, however, was required for other lines in this area (see Section 7.5) in order to suppress ground roll by increasing the fold of cover, without reducing the resolution.

To illustrate the effect of the CMP technique, Figure 5.20 shows a comparison between single fold and multifold (4-9) seismic sections across the field site. No elevation corrections were applied because the site is essentially
Figure 5.20 Seismic Profile 10:

a) constant-offset section constructed from the CMP data with 24m shot-geophone offset; Traces are 2m apart.
b) 4-9 fold CMP stacked section; CMPs are 1m apart.
flat. Statics only included weathering corrections which were made to the depth of the source (the base of the Buffalo gun which was about 0.8m below the surface of the ground).

A noticeable feature on these sections is the severe deterioration to data quality at the SE end of Line 10 (beyond CMP No. 153). Line 10 ran across a cultivated field at a distance of 162m, where the soil was badly disturbed, while the soil was relatively undisturbed along Line 8. The degradation in the quality of the seismic data across the farm was in both the S/N ratio and the frequencies. The signal level dropped markedly and the transmission of high frequencies was unsatisfactory. Field records from this end of the line were swamped with low frequency large amplitude ground roll which had a very high velocity (about 1200m/s) as compared to about 550m/s at the NW end.

An attempt to overcome this problem, planting of the geophones in 0.1m holes across the farm, made no improvement. Geophones planted in deeper holes (about 0.25m) led to some signal to noise improvement. There was still an absence of visible reflected energy on the records.

Figure 5.20b does show the improvement made to S/N ratio of the seismic section by processing. A noticeable improvement was made in the farmfield though definition remained reduced. The stacked section gives a clear and a satisfactory image of subsurface. A detailed description of all the processing steps and geological interpretation of the section is found in Chapter 7.

5.7 CONCLUSION
Field tests indicated the following combinations gave optimum results:

1) Seismic source
   a) 12-gauge Buffalo gun.
   b) Popper-Load or "C" shell.
   c) Depth of ≈1m below ground surface.

2) Seismic detector
   a) 100 Hz geophone (Mark products).
   b) 13cm spike.
c) Surface or ¼m hole plant depending on firmness of topsoil.

3) Seismic recorder

Field setup of a seismograph-microcomputer (i.e. Bison-BBC) for providing extended processing capabilities as well as instant quality control of data (e.g. producing constant-offset sections and performing spectral analysis).

4) Recording parameters
   a) Low-cut analogue filter (i.e. 200 Hz).
   b) Sample interval of 0.4ms.

5) Geometry
   a) 12-fold CMP recording.
   b) 46m (24 geophones) end-on spread.

It must be emphasized that the field trials were carried out in an area where the water table is shallow and high frequencies are transmitted from considerable depth.
CHAPTER 6
SHALLOW SEISMIC REFLECTION DATA PROCESSING TECHNIQUES

6.1 INTRODUCTION
The aim of data processing techniques is to produce an interpretable cross-section of subsurface geology from seismic field records which may commonly be noisy. Hence, the object of processing is to enhance seismic data quality. In general, quality enhancement can be divided into three categories:

1) increasing the signal to noise ratio,
2) improving the resolution of the reflection record, and
3) repositioning of data to compensate for spatial distortion.

Discussion of the different types of processing applied in reflection seismology (marine and land) can be found in Sheriff and Geldart (1983), Hatton et al (1986) and Yilmaz (1987).

In this study, processing was used to increase the signal to noise ratio (e.g. CMP stacking) and to improve the resolution of seismic data (e.g. deconvolution). Both preliminary and standard processing procedures were applied using different processing systems (both hardware and software). Figure 6.1 shows a typical preliminary processing sequence that was performed on a BBC microcomputer (see Section 6.10). A standard seismic data processing package, the Seismic Kernel System (SKS) by Merlin Geophysical Limited (see Section 6.11), was used on a mainframe computer to perform extensive processes including velocity spectrum analysis, residual statics, band-pass filtering and deconvolution.

6.2 DATA EDITING AND GAIN RECOVERY

6.2.1 Data editing

1) Edit trace headers
On the BBC, details of shots and geophones (e.g. X, Y coordinates) are inserted into the trace headers of the seismic field records. On the SKS, these data are written into a database file (Section 6.11).

2) Edit trace samples
Plots of seismic traces and their spectra are usually
FIELD RECORDS

EDITING
*Input shot & geophone data

STATIC DETERMINATION
*Uphole time
*Refraction

GAIN RECOVERY

Reflection Velocity Determination

CMP GATHER

NMO Correction and Muting

CMP Stacking

TRACE SORTING

DISPLAY
Constant-offset and CMP Stacked Sections
*Mixed/unmixed traces
*Different modes
*Different scale
*Pass-band filter
*Amplitude spectrum

CONSTANT-OFFSET FILE

Figure 6.1 Flow chart of a typical preliminary processing sequence on the BBC microcomputer.
produced to examine the quality of the seismic data. Spectral analysis (Section 6.7.3) and wiggly trace plots of seismic data are useful to determine the characteristic of signal and noise and to check the polarity of the data traces, which can be reversed upon request.

Very noisy and spiky traces which cannot be made useable by further processing (e.g. frequency filtering) need to be zeroed, otherwise they can degrade the quality of the results. Muting (Section 6.4) is an example of trace sample editing.

3) Sort traces

Field records, which are shot ordered, are used to determine near-surface velocity structure and compute field statics using first break data (Chapter 4; Section 6.3).

In Chapter 3 (Section 3.3.3), the recording aspect of the CMP method was discussed. Processing of seismic reflection data starts with the rearrangement of the seismic traces of the field records into files containing traces having a common mid-point, which are known as CMP gathers (Figure 3.3).

6.2.2 Gain recovery

Adjustment of gain is an important step which is normally made during processing to recover the true amplitude of the reflection wave. The reflection amplitude, besides being decided by the acoustic impedance contrast (see Section 6.8.1), is affected by other processes during propagation in the earth such as attenuation (Section 3.2.2) and spherical divergence (discussed below). Also, it is dependent on the amplification gain of the recording system. The latter can be easily adjusted since its value is known (Section 5.5.1).

A seismic wave undergoes a reduction in amplitude due to geometrical spreading. The total energy ($E$) associated with an expanding spherical wavefront is constant; however, its intensity ($I$) decreases away from the source as follows:

$$I = \frac{E}{4\pi r^2}$$  

where $I$ is energy per unit area of wavefront and $r$ is the distance from the source point. The amplitude ($A$) of the seismic wave is inversely proportional to $r$, since $E \sim A^2$ (Telford et al, 1976).
The mechanism of spherical divergence does not involve actual loss of energy, only distribution of energy over an increasingly large wavefront. It is independent of the characteristics of the medium.

Correction of spherical divergence is distance dependent requiring the use of the velocities with which seismic waves propagated. For simplicity, however, the spherical divergence correction can be approximated by a time-dependent linear scaling factor since time \( t \) is related to distance:

\[
\text{Amplitude } \sim \frac{1}{t}
\]

This approximation may be reasonable for shallow reflection work with structural evaluation objectives (Mooney, 1984).

Another gain function is of the type \( t^2/V_o^2 \) which can be used to correct for spherical divergence. This is usually applied once the velocity structure of the subsurface geology is determined. An exponential function can also be used to counter the effect of attenuation (Section 3.2.2), if a suitable function can be estimated from the data.

Gain functions can be applied to seismic data at any stage of processing. Their effects can be removed by using reversed functions. Gain recovery is important in attaining the assumption of the stationarity of the source waveform before applying deconvolution (Section 6.8).

6.3 FIELD STATICS

A detailed refraction interpretation method was discussed in Chapter 4. Field statics obtained by this method were applied to the seismic data processed on the SKS. A method for statics computation from first breaks, which was applied on the BBC processed seismic data, is discussed below.

Uphole time measurement

This is a straightforward method for static corrections based on the assumption that shots are fired below the weathering layer. Figure 6.2 shows a simple weathering problem with the uphole times being used for static corrections. The datum is chosen according to the topography of the near-surface layer. If the base of the weathering is smooth and shots are placed consistently at or just below it, a simple static
Figure 6.2 Uphole time measurement.
correction can be calculated with the base as a datum:

\[ \text{Total static} = t_g = -\frac{d_s}{V_w} \] .... (6.2)

where \( t_g \) is the geophone static correction.

This correction is equivalent to placing the geophones at shot positions. Alternatively, the datum can be chosen at the surface of the ground and the weathering layer is replaced by an equivalent layer having subweathering layer velocity:

\[ \text{Shot static} = t_s = \frac{d_s}{V_{sw}} \]

\[ t_g = -\frac{d_s}{V_w} + \frac{d_s}{V_{sw}} = -\frac{d_s}{V_w} + t_s \] .... (6.3)

However, when the base of the weathering layer is irregular, a datum can be chosen within the subweathering layer but as close as possible to the base of weathering (Figure 6.2) and static corrections can be made as follows:

\[ t_s = -\frac{(E_s - d_s - E_d)}{V_{sw}} \]

\[ t_g = -\left\{ \frac{d_s}{V_w} + \frac{(E_s - d_s - E_d)}{V_{sw}} \right\} \] .... (6.4)

This equation can also be manipulated in a similar way to that of Equation 6.3 if the datum is chosen at the surface of the ground. It should be mentioned here that errors due to the assumption of vertical reflection travel paths in near surface materials are neglected.

6.3.1 Picking of first arrivals

First arrival times are usually picked manually either by hand using paper records or on the computer screen by a moving cursor. In effect, the two types of picking are similar in their dependence on the eye in identifying the first departure of seismic signal from the background noise. Because the accuracy of picking is dependent on the signal amplitude and S/N ratio, a constant phase on the first pulse needs to be picked consistently on the different traces. The peak amplitude or the inflection point are usually exploited for this purpose. Manual picking on the screen has the advantage of speed, while hand picking on paper allows cross correlation of the first pulse which can be useful for determining the first kick accurately at large offsets where S/N ratio is low.

Alternatively, first arrivals can be picked automatically by the computer. Picking algorithms are generally based on the
assumption that the shape of the first pulse does not change along the seismic profile. In general, there are two types of picking methods: 1) the cross-correlation method (Peraldi and Clement, 1972) and 2) the coherence method (Coppens, 1985). However, because the pulse shape does change from one trace to another, especially in shallow seismic surveys, these methods may not be accurate in picking. It should be mentioned, however, that Coppens (1985) used the coherence method on common-offset traces where changes in pulse shape were expected to be insignificant.

Gelchinsky and Shtivelman (1983) proposed a method where the constancy of the pulse shape along the line is not necessary. It is based on noise suppression and spatial correlation of the signal. Hatherly (1980, 1982), on the other hand, used two independent techniques of picking to support each other. These are a correlation and a least squares prediction methods which are used on a single trace.

In this study, some of the procedures proposed by Hatherly (1980) were used for the BBC automatic picking routine. This was used to determine the uphole time from uphole geophones. Because these geophones were at zero or very small offset the S/N ratio was very high and was used as the criterion for picking. A description of the picking routine is found in BBC Program S.UPTIME (Appendix F.2a).

6.4 NORMAL MOVEOUT CORRECTION

Assuming a constant velocity medium and straight raypaths, a reflection event on all the CMP traces falls on a hyperbola (Figure 3.3). Correcting the two-way slant time into two-way vertical time flattens the reflection into a perfect alignment (constant time on all traces in the gather) resulting in signal enhancement upon stacking (Section 6.7.1). This reduction in time is known as normal moveout 'NMO' correction. In reality, this situation is seldom met; the earth consists of many velocity layers. This makes the assumption of a straight raypath invalid. The common depth point assumption may also be violated when reflectors are not horizontal.

Therefore, in order to achieve perfect NMO correction the exact raypath and velocity distribution need to be used (Cressman, 1968). However in practice, the velocity used in NMO
correction is derived empirically since the data needed to achieve perfect correction is never known in advance. It is called the stacking velocity and is the one which gives the best stacking (see next section). For any trace-sample, the NMO is computed and the sample shifted in time as follows:

\[ T_c = T - \Delta t_n \]  

where

\[ T_c \] is the NMO corrected time for the sample,
\[ T \] is the original time, and
\[ \Delta t_n \] is the computed NMO (Figure 3.3).

Since the computed NMO varies with time down the record, even with a constant velocity, it is also called the dynamic (time-dependent) correction.

Levin (1971) indicated that although reflections from the same horizon in a CMP gather may not be coming from the same point where dip is present, it is still possible to flatten the reflection, even for steep dip, by the use of the stacking velocity. The dip causes the stacking velocity to be higher than the actual velocity with which the seismic energy propagates.

However, because NMO corrections are traveltime dependent, reflection pulses are distorted (stretched). Dunkin and Levin (1973) pointed out that the spectrum of the NMO corrected pulse is a linearly compressed version of the spectrum of the pulse before NMO correction. The compression is dependent on the reflection two-way vertical time, shot geophone offset, and the velocity. Because NMO is larger at large offsets and at shallow depths, the signal distortion is much more severe at short travel times and on long-offset traces. Hence, these parts are usually muted during processing.

**Muting**

Muting is a process of assigning zero values to parts of the trace. Muting is usually applied before stacking to prevent the strong direct and refracted arrivals at large offsets from masking shallow reflections when stacking is carried out. It is also used to avoid the pulse stretch distortion caused by the NMO correction. Muting can be applied on stacked traces too.

A gradual linear taper is usually applied at the edge of
the mute zone to smooth the change from live to zero trace, preventing a sudden increase in amplitude and a consequent adding of high frequencies at this point.

6.5 VELOCITY DETERMINATION FROM CMP GATHERS

Velocity determination methods used in data processing are based on the hyperbolic time-distance relationship (Figure 3.3). Although this assumption is only valid for a single uniform layer, it is made because of the simplicity of its implementation. The velocity determined from these methods is known as the stacking velocity.

The stacking velocity is an apparent velocity, being a function of stratification and dip, and has no physical significance. It is generally used as a first approximation to the time-weighted rms velocity (Brown, 1969; Al-Chalabi, 1979) which is defined as follows:

\[ V_{rms} = \left( \frac{\sum_{k=1}^{n} V_k t_k}{T_0} \right)^{\frac{1}{2}} \] .... (6.6)

The rms velocity is related to the average velocity and their difference is dependent on the heterogeneity of the ground (Al-Chalabi, 1979). From the rms velocities, interval velocities \( V_i \) can be derived using Dix's Equation:

\[ V_i = \left( \frac{(V_2^2 T_2 - V_1^2 T_1)/(T_2 - T_1)}{T_2 - T_1} \right)^{\frac{1}{2}} \] .... (6.7)

where \( V_1 \) and \( V_2 \) are the rms velocities at the top and the bottom of the interval and \( T_1 \) and \( T_2 \) are the vertical travel times.

The average velocity is defined as follows:

\[ V_a = \left( \frac{1}{T_0} \right) \sum_{k=1}^{n} V_k t_k \] .... (6.8)

where

- \( V_a \) is the average velocity to the base of the nth layer,
- \( V_k \) and \( t_k \) are the velocity and two-way traveltime within the kth layer, and
- \( T_0 \) is the zero offset (total) reflection time.

The average velocity is normally used for time-depth conversion.

For a dipping reflector beneath a homogeneous overburden, the stacking velocity \( V_s \) is higher than the overburden
velocity \((V_o)\):

\[ V_s = \frac{V_o}{\cos \alpha} \quad \quad (6.9) \]

where \(\alpha\) is the dip component in the direction of the profile. The dip of the reflector affects the relation between the velocity and the NMO (Levin, 1971; Al-Chalabi, 1979).

6.5.1 Stacking velocity

Estimation of the stacking velocities, which are used in NMO correction, is an important part of the seismic data processing sequence. A simple method to determine velocity is finding the hyperbolic curve which best fits reflection times across the traces of a CMP gather. Constant velocity gather panels are another way of obtaining the best stacking velocity. Here, a CMP gather is corrected for NMO using a range of constant velocities. The velocity which best lines up the reflection on the gather is used for stacking. This and the above mentioned method are dependent on NMO only. They have poor resolution and require seismic records with high S/N ratio and visible and strong reflectors.

Another velocity determination method is the constant velocity stacks 'CVS' method. Here, a number of CMP gathers are stacked using a range of constant velocities producing several CVS panels. Stacking velocity is estimated on the basis of the stacked reflection amplitude and continuity. This method is important where complex subsurface structure is present though it requires high S/N ratio.

Other velocity analysis techniques which are widely used in conventional reflection and normally performed on a mainframe computer are known as velocity spectrum methods. Here, the velocity which can produce the maximum coherency in the primary reflection on the CMP gather is the objective (Al-Chalabi, 1979). Different methods are used for coherency measurement such as the optimum summation method (Garotta and Michon, 1967), 'dynamic' unnormalized correlation method (Schneider and Backus, 1968), normalized correlation method (Neidell and Taner, 1971) and semblance method (Taner and Koehler, 1969; Neidell and Taner, 1971). The semblance technique of velocity spectrum determination is the most common, and was used in this study on the SKS.
The traces within a gather are NMO corrected using a trial velocity function. The semblance is calculated over a time-window, which slides in steps with time down the record, as follows:

\[ C(v,t) = \frac{\sum_{i=1}^{n} (\sum_{j=1}^{m} a_{ij})^2}{m \sum_{i=1}^{n} \sum_{j=1}^{m} a_{ij}^2} \]  

where

- \( C(v,t) \) is the semblance value at time \( t \) using velocity \( v \),
- \( n \) is the number of samples in a time-window,
- \( m \) is the number of traces in the gather, and
- \( a \) is the sample amplitude.

Semblance represents the normalized output-to-input energy ratio. Its value range is \( 0 \leq C \leq 1 \).

Semblance effects a good resolution in time and velocity. It is sensitive to amplitude variation. For two identical traces with only different scaling factors, the semblance value is not perfect (\( C \neq 1 \)) while their normalized cross-correlation is unity. The width of the time-window, time step, time and velocity ranges are specified by the user.

The computed semblance value as a function of time and velocity is displayed "contoured" on a time-velocity plot "velocity spectrum". Scaled maximum Semblance and maximum amplitude are also plotted with time beside the spectrum to help in picking velocities of primary reflections. Figure 7.6 (Chapter 7) shows an example of a velocity spectrum display.

The resolution of the velocity spectrum analysis is dependent on several parameters: the spread length, number of traces in the CMP gather, S/N ratio, bandwidth of data and departure from hyperbolic assumption of normal moveout.

Lack of large offsets reduces resolution, especially at large two-way time where there is only small moveout. Lack of small offsets degrade velocity spectra especially at shallow depths. Increasing stack fold increases the accuracy of velocity picking. The accuracy of the spectrum is limited when the S/N ratio is poor. Band-pass filtering and automatic gain control help to improve the resolution. Residual statics corrections reduce the random noise and improve resolution. Reduction of peaks of random noise can also be achieved by averaging the semblance of several CMP gathers. The number of
CMPs is limited by the dip of the reflection horizon which otherwise smears the peaks. This is more evident for shallow events because of large moveouts.

6.6 RESIDUAL STATICS

Field statics remove a significant part of the traveltime distortion caused by long spatial wavelength statics (Chapter 4), but do not correct for short wavelength statics caused by rapid changes in elevation, thickness and velocity of near-surface layers, the residual statics. When stacking high frequency signals (i.e. 200 Hz) static errors need to be less than 1.25ms to avoid destructive stacking.

Statistical estimates of residual statics can be obtained by automatic procedures which make use of the multiplicity of data generated by CMP recording. Residual static corrections involve: 1) picking of the reflection traveltime, 2) decomposing the picked time into its components. After field statics and normal moveout applications the apparent reflection traveltime is comprised of residual shot static (RSS), residual receiver static (RRS), residual normal moveout (RNMO), vertical two-way time (TWT) and indeterminate noise (Hileman et al 1968; Disher and Naquin, 1970).

Picking of reflection traveltime

Cross-correlation function between traces is used in picking traveltimes, which can be achieved using different approaches (Hileman et al 1968; Disher and Naquin, 1970; Taner et al, 1974). The most widely used method of time picking is known as the pilot scheme, which was used in this study on the SKS. A CMP stacked trace is cross correlated with the traces of the CMP gather. Here, picking of the traveltime is CMP consistent where traces in each CMP gather are aligned to obtain the optimum stacked trace (Taner et al, 1974).

The time shift ($\tau$) between the pilot trace $f_1$ and a trace $f_2$ in a CMP gather is determined by the maximum cross-correlation function:

$$C_\tau = \frac{\sum f_1(t) f_2(t+\tau)}{\sqrt{\sum f_1^2(t) \sum f_2^2(t)}}$$ \hspace{1cm} (6.11)

where $C_\tau$ is the normalized cross-correlation amplitude. The
maximum normalized amplitude is used as a measure of similarity between traces, and can also be used as a reliability factor of statics computation.

Cross-correlation is made over a selected time window, which should be centred on the peak primary energy. A maximum correlation time shift is usually specified to prevent cycle skipping in the cross-correlation. Scaling of the cross-correlation function can be used to reduce the possibility of cycle skipping. The correlation window should cover the time zone where primary events are dominant with large S/N ratio and should be sufficiently large to include several primary reflections and reasonably deep to minimize differential RNMO between primaries.

It is quite normal to apply frequency filtering and deconvolution to the seismic data before picking residual statics to improve S/N ratio. This helps to estimate a reliable time shift that corresponds to the peak cross-correlation value. Several passes of residual statics are usually made to the seismic data to improve the quality of traveltime picking. Usually, velocities used in normal moveout correction are refined between the passes.

**Decomposition of the picked time**

The earth is approximated by a simple model where the near-surface effects are assumed to be time-invariant and surface consistent (Taner et al, 1974). Time-invariant means a constant time shift "static" for all reflections from deeper subsurface layers. Surface consistency implies that the static shift is dependent on shot and receiver positions on the surface and not on raypaths in the subsurface. Raypaths in the near-surface are assumed vertical regardless of shot-geophone offset due to refraction at the base of this low-velocity layer. Vertical raypaths between a reflection point on an interface in the subsurface and a reference datum near the surface are simulated by correcting seismic traces for normal moveout (Section 6.4). The stacked section is used as a model for subsurface geology.

The picked residual static $T_{ijh}$ can be approximated by the following terms:
\[ T_{ijh} = S_i + R_j + G_{kh} + M_{kh} X_{ij}^2 \quad \ldots \quad (6.12) \]

where

- \( S_i \) is RSS at shot position \( i \),
- \( R_j \) is RRS at receiver position \( j \),
- \( G_{kh} \) is difference in TWT at a marked point (i.e. CMP 1) and traveltime at CMP position \( k \) (i.e. \( i+j/2 \)) for reflector \( h \); it is referred to as structural term, and
- \( M_{kh} X_{ij}^2 \) is RNMO for CMP \( k \) and reflector \( h \).

Surface consistent solution is achieved by decomposing the picked time \( T_{ijh} \) into the four terms using the least-squares method (Yilmaz, 1987). The sum of the least-squares error energy \( E \) between the picked time \( T_{ijh} \) and the modelled time \( T_{ijh} \) must be minimized:

\[ E = \sum (T_{ijh} - T_{ijh})^2 \quad \ldots \quad (6.13) \]

Because of the large number of equations involved, Gauss-Seidel iteration is used to converge into correct solutions. A threshold value, based on the rate at which solutions change after each iteration, is used to terminate computation (Wiggins et al, 1976).

The statistical reliability of the solution is increased by increasing the CMP multiplicity. For less than 3-fold, CMP data are not adequate to solve the static problem. The surface consistent solution cannot solve for long wavelength statics components. These are usually modelled as part of the structure term. The static solution is nonunique, because of the problem of fewer independent equations than unknowns. Restrictions of spatial variation of statics, moveout and structure may be used to counter the problem.

6.7 METHODS TO IMPROVE SIGNAL-TO-NOISE RATIO

### 6.7.1 Stacking CMP traces

CMP stacking is a multichannel filtering technique exploiting the criterion of the existence and absence of trace to trace correlation in the signal and noise, respectively. As such, the CMP horizontal stacking technique is used to improve signal to noise ratio (Mayne, 1962). Stacking itself is simply the process of composing a trace from a number of traces.
usually done (digitally) by summing together the corresponding samples of the traces and averaging the summed samples:

$$A(t) = \frac{1}{n} \sum_{i=1}^{n} a_i(t) \quad \ldots \quad (6.14)$$

where

- $A(t)$ is the mean sample value,
- $n$ is the number of traces (stack fold), and
- $a$ is a single sample value.

This type of stacking is a linear process in which individual frequency components are retained (Hatton et al, 1986).

Stacking CMP traces is normally done after reflection record-times are reduced to two-way vertical times with respect to a datum plane (static and dynamic corrections; Sections 6.3 and 6.4). In order to have perfect reflection alignment, the above mentioned corrections need to be optimum. In such a case the signal to noise ratio enhancement is proportional to the square root of the stack fold ($\sqrt{n}$), which is the highest achievable improvement (Hatton et al, 1986). The primary reflection is linearly enhanced while the amplitude of the random noise is reduced by $\sqrt{n}$. This requires signal pulses to be identical. However, because of the stretching due to NMO correction (Section 6.4), pulses on the different traces in the CMP gather are not identical resulting in a smaller than $\sqrt{n}$ signal to noise improvement (Dunkin and Levin, 1973).

The stretching of the pulse caused by the NMO correction, inaccuracy of static and dynamic corrections, non-hyperbolic moveout, and pulse broadening caused by earth filtering of high frequencies (which increases with increased offset especially at shallow depths), tend to reduce the resolution of the stacked trace.

Because non-reflection events (i.e. multiples which usually have larger moveout) do not line-up with NMO correction, they tend to be attenuated by stacking (Mayne, 1962). This, however, is strongly dependent on the NMO velocity contrast between the primary and multiple reflections (Cressman, 1968). Thus, stacking is ineffective in attenuating multiples if there are little differences between primary and multiple reflections velocities. In Section 6.8, suppression of multiples by deconvolution is discussed.
Stacked trace normalization

The amplitude of the stacked trace in Equation 6.14 is normalized by the factor $n^{-1}$, which is commonly used in scaling the stacked CMP trace. Improvement of S/N rms amplitude ratio by $\sqrt{n}$ can only be achieved by optimal stacking where the noise is purely random. This means that the S/N ratios and signal amplitudes of the n CMP traces in the stacked trace should be equal (Robinson, 1970).

Other types of normalization such as the weighted mean (the weight may, for example, depend on trace offset) and the median are sometimes used, particularly for multiple attenuation (Hatton et al, 1986). The Nth-root stack (McFadden et al, 1986) is another type of stacking in which the average of the Nth root of each sample is raised to the power N. It is particularly useful in reducing the effects of noise spikes and sharpening the signal (enhancing S:N contrast) though it causes signal distortion.

6.7.2 Mixing traces

Trace mixing is a multichannel frequency filtering technique generally used to improve the signal coherency and continuity though it reduces resolution. It is done by summing adjacent traces from different shots and is usually made on the final section (stacked or constant offset) as a cosmetic step. It can improve S/N ratio by: 1) attenuating high-frequency noise though often random noise may be organised after mixing (Hatton et al, 1986) and 2) suppressing coherent arrivals with large apparent dip such as refraction, diffraction and side-swipes from off-line reflectors.

Trace mixing is most effective where the reflector over which the summation is made is relatively horizontal or when the width of the summed reflection points is smaller than the first Fresnel zone (Section 3.3.3); otherwise resolution is reduced. A three-trace mixing with a weighting scale of 1:2:1 is often used. Its application on the stacked section can produce a more easily interpretable section.

Mixing of traces (i.e. Binning) can also be done before stacking. This is very important where the S/N ratio is low. Adjacent CMP gathers can be combined together to produce a single gather, changing the spatial sampling along the line.
without loss of data. This effects better velocity estimation and increases S/N ratio by increasing the fold of cover. The effect of mixing on the ground is similar to that of an array, attenuating ground roll and reinforcing reflections because of their long apparent wavelengths (Section 3.3.2).

6.7.3 Frequency filtering

Frequency filtering is a single channel technique used to discriminate against some of the undesirable seismic energy with frequency being the discriminator. It is used to increase S/N ratio and improve temporal resolution. It can be made at any stage of the processing sequence (before and after stacking) and even in the field during recording. The most common type of filter is the band-pass filter. This can be used to filter out noise from data though its efficiency is dependent on the extent of separation between their spectral peaks. Hence, their spectra need to be determined first in order to design a suitable filter (see next section).

An ideal band-pass filter is a zero-phase which passes a certain bandwidth without modifications and rejects the remaining part of the spectrum of the seismic trace:

\[
A(f) = \begin{cases} 
1, & f_1 < f < f_2 \\
0, & \text{elsewhere,} 
\end{cases} 
\]  

(6.15)

where \( A(f) \) is the "boxcar" amplitude spectrum, \( f_1 \) and \( f_2 \) are the low and high cutoff frequencies.

In practice, slopes are introduced at both ends of the boxcar and a trapezoid passband is used. Steep slopes result in a spectrum with a ringy character (Yilmaz, 1987). The width of the passband should not be too narrow and the slopes not too steep, otherwise they can lead to instabilities in the filter. Band-pass filtering can be achieved in the time domain by convolving the coefficients of the filter (time samples) with those of the input seismic trace (see Appendix E.1).

Normally, a series of filter panels are used to decide the optimum band-pass filter for the trace or for the different parts (time-variant) of the trace. This is very important since the signal frequency band tends to shift to lower frequencies
with increasing time. However, in order to preserve the signal bandwidth and have an interpretable wavelet, 2-3 octaves of bandwidth centred over the dominant frequency are required. Also, the ringing effect caused by the steepness of the slope of the filter must be reduced to a minimum level (Hatton et al, 1986).

Application of band-pass filtering before deconvolution is important to suppress the low-frequency ground roll and attenuate the high-frequency ambient noise which otherwise might contaminate the signal autocorrelation (see Section 6.8). A narrow band-pass filter can sometimes be useful to obtain better results from cross-correlating between traces (e.g. Residual statics). A band-pass filter (or a time-variant band-pass filter) is usually applied to the final stacked section. The effects of applying band-pass filters to the seismic data can be seen in Chapter 7.

Spectral analysis

The Fourier transform has a great importance in seismic data processing (see Appendix E.2). In this study, it was used for spectral evaluation of the seismic data and was applied to final stacked sections and field records.

6.8 DECONVOLUTION

6.8.1 The convolutional earth's model

The earth is assumed to be composed of layered strata with different physical properties. The contact between any two layers represents a discontinuity in the physical characteristics. For seismic work the relevant property is the acoustic impedance which is the product of the velocity and density of the medium. Part of the energy carried by the p-wave is reflected in the upper layer and the remaining energy is transmitted into the lower layer. The ratio of the reflected wave amplitude $A_r$ to the incident wave amplitude $A_i$ (i.e. unity), for a plane wave at normal incidence, is dependent on the reflection coefficient associated with the interface:

$$\frac{A_r}{A_i} = R = \frac{(\rho_2 V_2 - \rho_1 V_1)}{(\rho_2 V_2 + \rho_1 V_1)} \ldots \ldots (6.16)$$
where $R$ is the reflection coefficient (or reflectivity) for pressure wave; $\rho_1$, $\rho_2$ are the density of upper and lower layers; $V_1$, $V_2$ are the velocity of the upper and lower layers, respectively. The quantity $1-R$ represents the transmission coefficient (Telford et al., 1976).

For simplicity of the model, the angular dependency of the reflection coefficient is ignored as is the mode conversion at the interface (i.e. S-wave). Since the contrasts in velocity and density are usually small at the geological boundaries, or interfaces, the reflected energy amounts to only a small fraction of the incident energy.

For a zero-offset trace, the time series of the reflection coefficients of the model's layered interfaces is called the reflectivity series. It is the recorded seismogram at the surface if the seismic source is a unit-amplitude spike (Figure 6.3). This represents an idealized case while the real situation is as follows:

1) the earth response does not include primary reflections only (i.e. reflectivity series); for every primary there are many multiples,
2) amplitude of primary events are reduced due to transmission losses, and
3) amplitude decay due to geometrical spreading and attenuation.

The earth model is further simplified by ignoring the effects of the transmission losses because reflection coefficients are very small, and by replacing the multiples associated with each interface with a common multiple train for the entire model "section multiple train" (Robinson, 1981). Accordingly, the recorded seismogram consists of events each of which is associated with a primary reflection coefficient and a section multiple train. Mathematically, this can be represented as follows:

$$s(t) = e(t) = r(t) \ast m(t) \quad \ldots \quad (6.17)$$

where $s(t)$ is the recorded seismogram, $e(t)$ is the earth impulse response, $r(t)$ is the reflectivity series, $m(t)$ is the section multiple train, and $\ast$ denotes convolution.

In this equation $s(t)$ is equal to $e(t)$ because the seismic source is assumed a spike. In reality, the pressure wave
<table>
<thead>
<tr>
<th>(a) Geological Layer Sequence</th>
<th>(b) Graph of Acoustic Impedance ($pV$) with Depth</th>
<th>(c) Reflection Coefficient (R) Log &amp; i.e. Reflectivity Depth Function</th>
<th>(d) Reflection Coefficient Log with Transmission Losses (TL)</th>
<th>(e) Reflection Log with Transmission and Spreading Losses (TSL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>$pV$ Log</td>
<td>R Log</td>
<td>R+TL Log</td>
<td>R+TSL Log</td>
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</table>

Figure 6.3 The convolutional earth model:

a) geological layer sequence,
b) graph of acoustic impedance ($pV$) with depth,
c) reflection coefficient (R) log i.e. reflectivity depth function,
d) reflection coefficient log with transmission losses (TL), and
e) reflection log with transmission and spreading losses (TSL); (After Anstey, 1970).

Conversion of the reflection coefficient depth function into time series "reflectivity series", using velocity information and a specified time sampling interval, is equivalent to a spike-source hypothetical seismogram; convolution of a source waveform with the reflectivity series results in a realistic seismogram.
generated by the seismic source (e.g. dynamite) has a band-limited wavelet of finite duration. The recorded noise-free seismogram of the earth model using a source wavelet $w(t)$ can be written as follows:

$$s(t) = w(t) * e(t) = w(t) * r(t) * m(t) \quad \ldots \quad (6.18)$$

Here, the seismic wavelet replicates itself and is scaled by the reflection coefficients. A more realistic seismogram can be represented by adding random ambient noise $n(t)$:

$$s(t) = w(t) * r(t) * m(t) + n(t) \quad \ldots \quad (6.19)$$

This equation represents a 1-dimensional convolutional model of a zero-offset seismogram (Yilmaz, 1987). An example of representing a convolutional process in a discrete form can be seen in Appendix E.1.

The source waveform in the convolutional model is assumed to be stationary. In fact, however, the waveform undergoes continuous modifications through propagation in the earth where the amplitude decays due to geometrical spreading (Section 6.2.2) and high frequencies are attenuated due to absorption (Section 3.2.2). Compensation for the non-stationarity of the source waveform is usually done by correcting the recorded seismogram for spherical divergence and attenuation (Section 6.2.2).

The process to recover the reflectivity series $r(t)$ from the recorded seismogram $s(t)$ is called deconvolution (Peacock and Treitel, 1969). This is accomplished by removing the effects of the source wavelet and multiples. If the source wavelet is known (e.g. air-gun signature), then the solution to the deconvolution problem is deterministic. If the source wavelet is not known, as is the case in this study, then the solution is statistical. Spiking deconvolution is used to compress the source wavelet into a spike and predictive deconvolution is used to suppress multiples. The differences between the different techniques are in the mathematical methods of formalization.

6.8.2 Spiking deconvolution

The aim of spiking deconvolution is to improve the temporal resolution of seismic data by removing the effects of
the source wavelet by compressing it into a spike. To do this, a filter, which when convolved with the source wavelet produces a spike, needs to be designed. This requires that the basic wavelet must be known.

The random noise component \( n(t) \) in Equation 6.19 is assumed to be zero. Pure random noise has a white spectrum, containing equal energy at all frequencies. The autocorrelation of white noise is a spike at zero lag and zero at all other lags. Sources of noise include wind, traffic, geophone, recording equipment and others. Therefore, we can start with Equation 6.18 and two assumptions are made here:

1) the seismogram \( s(t) \) is a stationary process, the autocorrelation \( ss(\tau) \) of \( s(t) \) is consistent from any time window.
2) the earth impulse response is a random process (white and stationary). Its autocorrelation \( ee(\tau) \) is a spike at zero lag and zero at all other lags.

It follows that:

\[
ss(\tau) = p \; ww(\tau)
\]  \hspace{1cm} (6.20)

where \( p \) is the autocorrelation of the earth response (which is proportional to the power of the white noise). The autocorrelation of the source wavelet \( ww(\tau) \) is a scalar multiple of the autocorrelation of the seismogram, except for the zero-lag coefficient. Therefore, the shape of the autocorrelation of the wavelet is obtained from the recorded seismogram itself (Robinson and Treitel, 1967).

Once the basic wavelet is estimated, then the coefficients of the deconvolution operator filter can be determined using the Wiener filtering method.

**Optimum Wiener filter**

This method is based on the least-squares criterion. The objective is to minimize the energy of the difference between a desired output \( z(t) \) and the actual output \( y(t) \):

\[
E = \sum_{t} [z(t) - y(t)]^2
\]  \hspace{1cm} (6.21)
E is error energy which should be minimum. If E is zero, then a perfect spike is obtained. The actual output is the result of convolving the input \( x(t) \) with the operator filter \( f(t) \), which has a finite number (\( n \)) of coefficients:

\[
y(t) = x(t) \ast f(t) = \Delta t \sum_{\tau=0}^{n-1} f(\tau) x(t-\tau) \quad \cdots \quad (6.22)
\]

for \( f(t) = f_0, f_1, \ldots, f_{n-1} \). \( \Delta t \) is the time increment and is assumed to be unity. Substituting \( y(t) \) in Equation 6.21 gives:

\[
E = \sum_{t} \left[ z(t) - \sum_{\tau=0}^{n-1} f(\tau) x(t-\tau) \right]^2 \quad \cdots \quad (6.23)
\]

\( E \) is minimized by setting the partial derivatives of \( E \) with respect to each coefficient of \( f(\tau) \) equal to zero:

\[
\frac{\partial E}{\partial f_j} = 0 \quad \cdots \quad (6.24)
\]

for \( j=0, 1, 2, \ldots, n-1 \). This results in a system of \( n \) linear simultaneous equations:

\[
\sum_{\tau=0}^{n-1} f(\tau) \phi_{xx}(j-\tau) = \phi_{zx}(j) \quad \cdots \quad (6.25a)
\]

or

\[
\sum_{\tau=0}^{n-1} f(\tau) \sum_{t} x(t-\tau) x(t-j) = \sum_{t} z(t) x(t-j) \quad \cdots \quad (6.25b)
\]

for \( j=0, 1, 2, \ldots, n-1 \). \( \phi_{xx} \) and \( \phi_{zx} \) are the autocorrelation of the input time series and the crosscorrelation of the desired output and the input data. These equations are known as the normal equations and are used to find the coefficients of the operator filter. Equations 6.25a,b can be written in matrix notation as follows (Peacock and Treitel, 1969; Yilmaz, 1987):

\[
[\phi_{xx}][f] = [\phi_{zx}] \quad \cdots \quad (6.26a)
\]

or

\[
\begin{bmatrix}
| & | & & | & | & |
| r_0 & r_1 & r_2 & \cdots & r_{n-1} & | f_0 & | g_0 |
| | & | & | & | & |
| r_1 & r_0 & r_1 & \cdots & r_{n-2} & | f_1 & | g_1 |
| | & | & | & | & |
| r_2 & r_1 & r_0 & \cdots & r_{n-3} & | f_2 & | g_2 |
| | & | & | & | & |
| \vdots & \vdots & \vdots & \ddots & \vdots & | \vdots & | \vdots |
| r_{n-1} & r_{n-2} & r_{n-3} & \cdots & r_0 & | f_{n-1} & | g_{n-1} |
\end{bmatrix}
\]
where
\[ r_0, r_1, \ldots, r_{n-1} \] are the input autocorrelation coefficients, 
\[ f_0, f_1, \ldots, f_{n-1} \] are the Wiener filter coefficients, 
\[ g_0, g_1, \ldots, g_{n-1} \] are the desired output and input 
crosscorrelation coefficients.

For spiking deconvolution, the desired output \( z(t) \) is 
represented by the series coefficients 1, 0, 0, ..., 0 and its 
crosscorrelation with the input \( x(t) \), therefore, can be 
represented by the series coefficients \( g_0, 0, 0, \ldots, 0 \). 
Equation 6.26b is then reduced to:

\[
\begin{bmatrix}
  r_0 & r_1 & r_2 & \ldots & r_{n-1} \\
  r_1 & r_0 & r_1 & \ldots & r_{n-2} \\
  r_2 & r_1 & r_0 & \ldots & r_{n-3} \\
  \vdots & \vdots & \vdots & \ddots & \vdots \\
  r_{n-1} & r_{n-2} & r_{n-3} & \ldots & r_0 \\
\end{bmatrix}
\begin{bmatrix}
  f_0 \\
  f_1 \\
  f_2 \\
  \vdots \\
  f_{n-1} \\
\end{bmatrix}
= \begin{bmatrix}
  g_0 \\
  0 \\
  0 \\
  \vdots \\
  0 \\
\end{bmatrix}
\quad \ldots \quad (6.27)
\]

The input series \( x(t) \) represents the recorded seismogram (i.e. 
\( s(t) \) in Eq. 6.18).

In order to minimize the error \( E \) to zero, an infinite 
length filter needs to be used. In practice, a perfect spike 
can never be achieved because the filter must have a limited 
number of coefficients. Another important factor in the 
performance of spiking deconvolution is dependent on the input 
wavelet, which has to be minimum phase (i.e. has the least 
energy delay). Because the operator filter is in effect the 
inverse of the wavelet, having a minimum phase wavelet results 
in a minimum delay filter (i.e. stable filter), whose 
coefficients decay with time until they vanish at \( t=\infty \) (i.e. 
convergent series).

The amplitude spectrum of the operator filter is 
approximately the inverse of the amplitude spectrum of the 
input wavelet. If there are zeros in the latter (e.g. band-pass 
filtered data), then the operator tries to raise the absent 
frequencies which leads to poor results (spikes accompanied 
with high-frequency noise). This problem rarely occurs in 
reality since there is always noise in the recorded seismogram 
which is additive in both frequency and time domains. However, 
to ensure numerical stability of the operator filter, a little 
white noise is usually introduced to the system before
designing the filter. This is achieved by adding a constant \((\lambda)\) to the zero lags of the autocorrelation function (i.e. \((1+\lambda)r_0\)). This is called pre-whitening.

If the input wavelet is not a minimum phase (e.g. mixed phase), then a delayed spike rather than a zero delay spike should be obtained. The former gives less error \((E)\) than the latter. Here, the desired output is defined as a delayed spike that results in the least error. Then the actual output from the Wiener filter using the optimum delayed spike should give the most compact possible results. This process is called wavelet shaping. In fact, the zero-lag spike and minimum-phase are a special case of the general wavelet shaping process (Yilmaz, 1987).

6.8.3 Predictive deconvolution

The aim of predictive deconvolution is to improve the temporal resolution of seismic traces by predicting and suppressing multiple reflections. This method is based on the assumptions that multiples are periodic and therefore predictable while primaries are random and therefore unpredictable. This means that the earth impulse response \(e(t)\), which was assumed to be a random process in Section 6.7.2, is actually composed of the uncorrelated reflection component \(r(t)\) and the correlated multiple component \(m(t)\). Thus, assumption 2 in Section 6.7.2 may not be quite correct since \(\hat{w}(\tau)\) may be disturbed by \(p\). On the other hand, the reflectivity and wavelet components \(w(t) * r(t)\) are assumed to represent a random process (i.e. reflectivity series). The objective of predictive deconvolution is to extract this reflectivity series by the decomposition (deconvolution) of seismogram \(s(t)\) in Eq. 6.18.

To achieve this, a filter which can predict the values of an input \(x(t)\) at a future time \(t+\alpha\) from the values at the present time \(t\), is designed. \(\alpha\) is the prediction distance (or lag). Then, the difference between the true values at \(t+\alpha\) and the predicted values at \(t+\alpha\) gives an error series which represents the unpredictable component of the input trace (i.e. the reflectivity series). If the true values at lag \(t+\alpha\) are \(x(t+\alpha)\) and the predicted values are \(\tilde{x}(t+\alpha)\), then the error series \(r(t+\alpha)\) is given by:
The predicted values are obtained by convolving a prediction operator filter \( f(t) \) with the input data \( x(t) \) as in Eq. 6.22. The error series (Eq. 6.28) can be rewritten as follows (Peacock and Treitel, 1969):

\[
 r(t+\alpha) = x(t+\alpha) - \bar{x}(t+\alpha) \quad \ldots \quad (6.28)
\]

The coefficients of the prediction operator filter can be obtained by using the Wiener least-squares method, similar to that used in spiking deconvolution (Eq. 6.21). Here, the desired output \( z(t) \) represents the true values \( x(t+\alpha) \) and the actual output \( y(t) \) represents the predicted values \( \bar{x}(t+\alpha) \).

Since the predicted values are a time-advanced version of the input data \( x(t) \), the terms on the right hand side of Eq. 6.25b are replaced by the crosscorrelation between the input data and its \( \alpha \)-lag replica. Equation 6.25b is rewritten as follows:

\[
 \sum_{\tau=0}^{n-1} f(\tau) x(t+\alpha) x(t-\tau) = \sum_{\tau=0}^{t} x(t+a) x(t-j) \quad \ldots \quad (6.29)
\]

and Equation 6.26b is rewritten:

\[
 \sum_{\tau=0}^{n-1} f(\tau) x(t+\alpha) x(t-j) = \sum_{\tau=0}^{t} x(t+a) x(t-(\alpha+j)) \quad \ldots \quad (6.30)
\]

Here, only the autocorrelation function of the input data is required and only \( \alpha+n \) lags of the autocorrelation are computed and used to estimate the operator filter.

The coefficients of the prediction operator filter (i.e. \( f_0, f_1, \ldots, f_{n-1} \)) obtained from Eq. 6.31 can then be used in Eq. 6.29 to give the prediction error (i.e. reflectivity series). This series can also be obtained, directly, by the use of a prediction error filter \( a(t) \), which is derived from the prediction operator \( f(t) \):
\[ a(t) = (1, 0, 0, \ldots, 0, -f_0, -f_1, \ldots, -f_{n-1}) \]

Convolution of this prediction error operator with the input \( x(t) \) data results in the error series. This is called prediction error deconvolution. If the prediction lag \( \alpha = 1 \), then the prediction error operator reduces to:

\[ a(t) = (1, -f_0, -f_1, \ldots, -f_{n-1}) \]

which contracts the source wavelet into a spike. Therefore, the prediction error deconvolution with a unit prediction lag is similar to the spiking deconvolution except for a scale factor (Peacock and Treitel, 1969; Yilmaz, 1987).

The performance of the prediction filter is determined by the following parameters: the prediction lag \( \alpha \), the length of the operator \( n \), the length of the autocorrelation window \( G \) and the pre-whitening constant \( \lambda \). Besides these factors, the effectiveness of the predictive deconvolution is related to the \( S/N \) ratio.

The prediction lag \( \alpha \) can be used as a means to control the resolution of the deconvolved seismic data. Since the crosscorrelation between the desired output and the input is zero between \( \alpha \) and \( \alpha + n - 1 \), the first lags are preserved and the second lags are zeroed; the desired wavelet therefore cannot be longer than \( \alpha \). The highest resolution is obtained when \( \alpha \) is unity. This is equivalent to spiking deconvolution. This is, however, not always desirable since it boosts high frequency noise. It also requires the wavelet to be minimum-phase, otherwise it does not produce a spike but a complicated high-frequency wavelet. Two zero crossing (or more) lags are usually used instead. This is useful for short period multiple attenuation.

The length of the operator is chosen according to the objective of deconvolution. For wavelet compression and short period multiple suppression, \( n \) is selected so that \( (n + \alpha) \) is equal to the basic wavelet length on the autocorrelogram. Better results are obtained by choosing a long operator though improvement is not indefinite since more spurious noise may be introduced by increased length. For multiple suppression the length \( n \) is chosen according to the window to be deleted which may include one or more orders of multiples. Obviously, \( \alpha \) is
chosen to by-pass the first part of the autocorrelogram which represents primary reflections. However, it is quite possible that primary reflections may be unintentionally predicted and suppressed. This may happen if the reflectivity series is not white and stationary where strong correlations may exist between primaries.

The autocorrelation function is an important tool for both the optimum design of the filter and the examination of the effectiveness of the deconvolution on the seismic data. Deconvolution test panels, using different filter parameters, are usually made and verified by the autocorrelogram. The data time-gate from which the autocorrelation is obtained should be carefully chosen so as not to include noise. It should be large enough to include the reflection signal and exclude the first part of the trace (i.e. first arrival) and the late part of the trace (i.e. ambient noise). The gate G should be longer than 8αΔt (Yilmaz, 1987).

The pre-whitening constant λ is usually applied only to ensure numerical stability of the filter. Only a minute amount of pre-whitening (0.1 to 1.0%) is normally used since random noise is always present in seismic data.

The presence of noise is harmful to the deconvolution operator. Its effect is similar to that of pre-whitening on the zero-lag coefficients of the autocorrelation function of the input data and it also might slightly affect the non-zero coefficients. Deconvolution of data with low S/N ratio causes the S/N ratio to be even lower. It is important therefore to improve S/N ratio before deconvolving the data. Band-pass filtering and stacking may be useful in this respect.

Predictive deconvolution, whether it is aimed at wavelet compression or multiple suppression, can be applied on both unstacked and stacked data.

Deconvolution before stacking

a) Wavelet compression before stacking is useful to improve resolution of seismic data and thus improve the accuracy of velocity determination and residual statics.

b) Multiple suppression may not be effective since the periodicity of the multiples is preserved only with "normal incidence" zero-offset data.
Deconvolution after stacking

a) Useful to improve resolution of the final stacked data by compressing the wavelet and removing short period multiples.

b) Suppression of multiples since CMP stack is a zero-offset trace. A disadvantage is that amplitude relationship between multiples may be altered by stacking due to velocity differences between primaries and multiples.

In this study, predictive deconvolution was applied, using the SKS, on seismic data before and after stacking. The results are shown in Chapter 7.

6.9 SEISMIC SECTION DISPLAY

The display of the stacked seismic section is the final step in the processing and is the end product of all other stages. Since the interpretation depends on the human eye, it is affected by the way the section is displayed. Section display includes the type of the displaying modes, horizontal and vertical scales and the amplitudes of the signal waveforms. For shallow seismic reflection work, since structural evaluation is the objective, a small scale display with emphasis on the continuity of the reflectors is sufficient. On the BBC, seismic plots are obtained using Programs S.WIGPIC, S.WIGOFF and S.FILPIC (Appendix F.2a). Hard copies of the seismic data processed on the SKS are produced on the Versatec plotter.

Mode of display

In general, four types of trace display are commonly used. These are: 1) wiggle trace, 2) variable-area, 3) wiggle and variable-area, and 4) variable density. The first three of these modes are used in this study. The third type which is made by blacking-in one side of the wiggle trace is commonly used for final section display.

Scale of display

The choice of the horizontal and vertical scales is determined by the details sought from the section. This can be quite different from that used in conventional reflection. A unity scale ratio may be required to prevent the distortion of
subsurface structural features. However, this may result in losing the continuity of the reflection across the section. A horizontal exaggeration may be needed to preserve the continuity. This is especially important for the single fold data.

Trace equalization

Amplitude equalization on a trace-by-trace basis is usually used to increase the interpretability of the seismic sections by minimizing the amplitude variations along the section and improving the continuity of reflection events laterally. This is usually applied on the final section only if lateral amplitude variations, which may be considered in stratigraphical interpretation, are considered not important.

Trace equalization is achieved by computing and applying a time-variant data dependent amplitude balancing scalar (Instantaneous AGC). A specified sliding time-gate is moved down the record one sample at a time. The mean absolute amplitude value over the time-gate is measured. The ratio of a constant scalar (i.e. 1.1) to the measured mean is then used as a balancing factor for the first sample in the time-gate.

The IAGC results in a constant average absolute amplitude level over the whole trace. This type of trace scaling is critical since it can destroy the signal character and degrade the S/N ratio. It is dependent on the size of the chosen time-gate. The IAGC was applied on the SKS processed seismic sections (see Chapter 7).

On the BBC, the gain of each trace is manually set to ensure overlapping of reflections and establish continuity along the seismic section.

Resolution of the print

The quality of the record is determined by the dynamic range of the plot, which is controlled by the screen in the case of the BBC micro-computer. However, because of the limited resolution of the screen (640 x 256 squares) and in order to obtain high quality records, seismic sections need to be divided into small portions each of which is plotted on A4 size paper. These portions are then pasted together and reduced (photographically) producing a high quality record.
High quality plots can be obtained for the SKS processed seismic sections. A Versatec plotter with a resolution of 80 dots/cm is used to produce hard copies.

6.9.1 Constant-offset section

A single fold seismic section with a constant-offset can be used for preliminary evaluation or as a final interpretable section of subsurface geology. This is entirely based on the quality of the recorded seismic data. In this case, minimum processing effort is required. Static corrections can be avoided if weathering is not a serious problem. Normal moveout correction is not essential since traces have common shot-geophone offset, though for depth conversion NMO as well as velocity determination are required.

6.10 IMPLEMENTATION ON THE BBC MICROCOMPUTER

The BBC-B microcomputer with the 6502 second processor, which is used to provide storage as well as processing facilities to the shallow reflection system (chapter 4), has a total memory of 128 K including that of the second processor (64 K each). The memory of the BBC-B is divided between ROM (Read Only Memory) and RAM (Random Access Memory) while the memory of the second processor is only in RAM. The memory of the first device is entirely used by the system itself for utilities such as disc filing system (DFS), screen display, and operating system. On the other hand, the second processor provides 44 K of user memory, which can be used to accommodate data (seismic) and BASIC programs with its dynamic variables, as shown in Figure 6.4. The remaining 20 K is used for BASIC and the operating system.

For this series of programs, the user memory of the microcomputer is divided into two parts: 1) an upper part with 28.5 K of memory space used to store seismic data, and 2) a lower part with 15.5 K of memory reserved for the BASIC program and its dynamic variables. The division of memory is done by resetting the value of HIMEM to 4600 Hexadecimal (Figure 6.4). This division is important since it allows operation (load to memory and save on disc) with either part separately from the other.
Figure 6.4 Memory map of the 6502 second processor of the BBC-B microcomputer (memory address is in Hexadecimal).
6.10.1 Data filing format

Seismic data are filed in a close approximation to the SEG-Y format. An exact SEG-Y format (Barry et al., 1980) was not followed because of the limited memory of the field computer. Nevertheless, the format used still allows almost straightforward transferral of data to a larger mainframe computer if further processing, using a commercially available package, is sought. The length of the data file for a 24-trace seismic field record is 29180 bytes of which 164 bytes are used for file header and 29016 bytes for trace information. The latter is made up of 185 and 1024 bytes for the header and data of each trace, respectively. The location of the file components in memory and the memory allocation of the file and trace header are found in Appendix F.1.

6.10.2 Software programming

A seismic software package, written in BASIC, has been developed for the shallow reflection system. The package is designed to run on the BBC microcomputer and to provide facilities for data recording and some preliminary processing procedures. The software package is divided into a series of programs to cope with the memory limitation of the BBC. These programs are menu driven and can be loaded to the computer reserved memory (15.5K) independently (Figure 6.4). The limitation in memory space has also caused the BASIC programs to be written as compactly as possible avoiding the use of remarks for procedure description.

The software package consists of 15 major programs grouped into three modes which are used for data recording, editing, and processing. These programs are called from a TOPMENU using the "CHAIN" command. A flow chart of the package programs is shown in Figure 6.5. A brief description of these programs and their listings are found in Appendix F.2. The results of using these programs to process seismic data are presented in Chapters 5 and 7.

6.11 STANDARD SEISMIC REFLECTION PROCESSING PACKAGE

A commercially available 2-dimensional seismic data processing package, the Seismic Kernel System (SKS) of Merlin Geophysical Limited, was also used in this study. SKS includes
115 processors for both marine and land seismic data. These are used for editing, geometry, gain scaling, velocity analysis, filtering, stacking, residual statics, migration, display and others (Merlin Geophysical Limited, 1989). SKS operates on the Leicester University mainframe computer (Vax 8650). A Versatec plotter was used to plot seismic data.

Seismic field records are transferred from the BBC microcomputer to the Vax mainframe computer via the standard file transfer package Kermit. On Vax, seismic data are reformatted into a single file with a special "Merlin Geophysical" Format. Database files are used to store geometry, statics and other relevant information. Setup files are written in a special "Merlin geophysical" language (MGL), which is translated into FORTRAN by the system.

The results of using the SKS to process seismic data are presented in Chapter 7.
CHAPTER 7
SHALLOW SEISMIC REFLECTION DATA PROCESSING—CASE STUDY

7.1 INTRODUCTION

Shallow seismic reflection surveys were carried out at two sites in Bardon Hill Quarry in the Charnwood Forest area in the summer of 1986. The first site was as used for previous experiments (Sports ground; Chapter 5) and the second was termed the southern farm fields (Figure 7.1). Five seismic profiles were shot at the two sites, Profiles 8, 9 and 10 at the first site and Profiles 11 and 12 at the second site. In both sites, the main aim was to record reflections from the Triassic-Charnian unconformity using the CMP method.

In this chapter, the results of analysing these seismic data, using the various processing techniques (Chapter 6), are discussed. Both the BBC preliminary processing and the SKS standard processing packages were used. On the BBC, only Lines 10 and 12 were CMP stacked while on the SKS Lines 8, 9, 10, and 11 were analysed in detail. The geophysical and geological interpretation of these seismic sections are presented here.

The geology of the field sites and data acquisition parameters are discussed first. Seismic Line 10 is then used as a detailed example of processing. Comparison is made with the processing and results of Lines 8 and 9, which have similar high quality data, and also with Lines 11 and 12, which have low quality data. The effect of near-surface material on the quality of the seismic signal is discussed.

7.1.1 Geology of field sites

The geology is basically the same at both sites; Triassic sediments unconformably overlying low-grade metamorphosed Charnian basement (Section 5.1.1). At site 2, borehole calibration of a plus-minus refraction interpretation of the basement along Line 12 had indicated that the basement is much deeper than was revealed by refraction (Figures 7.1, 7.2; Appendix G.1).

The near surface layers at site 2 are strongly weathered and the water table is expected to be deeper than in the first site. This was indicated during the shooting by the holes (up to 1.1m below the surface of the ground) which were drilled
Figure 7.1 Map of Bardon Hill showing the layout of seismic Profiles 8, 9, 10, 11 and 12, and some boreholes (BH) in the area (values in brackets are the depths (m) to the basement; see Appendix G.1).
Figure 7.2 Geological cross-section along Line 12 based on a plus-minus refraction interpretation.
for the shots. The topsoil is dry and loose and the entire area was cultivated.

7.2 DATA ACQUISITION

The CMP acquisition technique (Figure 3.3) was used to collect seismic data along the five profiles with CMP intervals of 1m. 467 shots were fired along these profiles, at 2m intervals, using a 46m end-on spread (24 geophones, 2m apart) and provided a total of 825m of 12-fold coverage. The recording system and the spread geometry were identical for all profiles though some of the field recording parameters differed depending on the local field conditions. Table 7.1 contains the relevant data of the field records for all the profiles while Figures 7.1 shows the field layout of the profiles. Lines 9 and 10 of site 1 run into a farm field where the soil is cultivated.

The first site is known from previous experiments (Chapter 5) to have field conditions favourable for reflection recording, except where lines extend into cultivated farm fields. At site 2, field records were, generally, dominated by low-frequency, large amplitude source-generated noise, especially the headwaves, which were strongly reverberant swamping most of the record along with the ground roll (see Appendix G.2). The transmission of seismic energy was variable along the two profiles and the transmission of high frequencies was low; weak reflections from the basement can be observed only on some of the shot records.

Field work at these sites also included surface elevation measurements along the profiles.

7.3 PROCESSING OF SEISMIC PROFILE 10 (SITE 1)

Seismic Profile 10 has been chosen for detailed study and processing because of the following:

(1) The high quality of its reflection data. This was essential to develop and test the BBC processing software.

(2) The opportunity to investigate the sudden deterioration in the quality of the data when part of the profile (the SE end) runs into a cultivated farm field (see Section 7.10).

(3) The opportunity to make a comparison with the plus-minus refraction interpretation method which was made along the same
(a) Common parameters:

Recording system : Bison Geopro 8024
Geophone type : 100 Hz, 13 cm spike
Source type : Buffalo gun; glued Popper-Load Cartridge
Geometry : CMP; end-on spread, 46 m in length
No. of geophones : 24; geophone spacing = 2 m; shot interval = 2 m
Shot-geophone offset : 0; normal offset = 0.2 m
Fold of cover : 12; CMP interval = 1 m
Record length : 192 ms; sample interval = 0.4 ms
Programmed gain : 6 dB/20 msec; High-cut filter = 825 Hz; Notch = out.

(b) Detailed data:

<table>
<thead>
<tr>
<th>PROFILE NO.</th>
<th>PROFILE LENGTH(m)</th>
<th>NUMBER OF SHOTS FIRED</th>
<th>NOMINAL SHOT DEPTH (m)</th>
<th>GEOPHONE PLANT</th>
<th>LOW-CUT FILTER (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>226</td>
<td>91</td>
<td>0.8</td>
<td>Normal (on the surface of the ground).</td>
<td>200</td>
</tr>
<tr>
<td>9</td>
<td>156</td>
<td>56</td>
<td>0.8</td>
<td>Normal for G1-44; In 0.2-0.25m holes for G45-79.</td>
<td>200</td>
</tr>
<tr>
<td>10</td>
<td>228</td>
<td>92</td>
<td>0.8</td>
<td>Normal for G1-82 (soilis ground); For S 60-75: G83-98 (farm field) were normal; For S 76-82 :G83-105 were in 0.1m holes; For S 83-92: G83-115, were in 0.2-0.25m holes, except G98 &amp; 99 (0.1m holes).</td>
<td>200</td>
</tr>
<tr>
<td>11</td>
<td>240</td>
<td>98*</td>
<td>1**</td>
<td>Normal.</td>
<td>150</td>
</tr>
<tr>
<td>12</td>
<td>316</td>
<td>130*</td>
<td>1**</td>
<td>Normal.</td>
<td>150 for S 1-79 100 for S 80-136</td>
</tr>
</tbody>
</table>

Table 7.1 Field recording data of seismic records.

* S : Shot; G : Geophone. S 56 of Line 11 and S 23, 26-29 and 70 of Line 12 were missed due to obstacles.
** Depths are varied for some shots (see Appendix G.7).
Seismic Line 10 was processed on both the SKS and the BBC microcomputer. Processes performed on the SKS included:

- Geometry details input
- Field statics
- Sorting traces into CMP gathers
- Trace editing and polarity reversal
- Gain recovery
- Velocity analysis
- NMO corrections and muting
- CMP stacking
- Residual statics
- Band-pass filtering
- Predictive deconvolution
- Trace equalization
- Section display

This sequence of processing was not strictly followed. Some of these processes can be used in any order (pre-stack or post-stack) and can often be repeated. Parameters used in processing are displayed on the processed seismic sections.

The sequence of processing Line 10 on the BBC is shown in Figure 7.3.

a) Geometry details input

Shot and geophone geometry information were written into a database file for SKS processing of Line 10 (Section 6.11). On the BBC, these data were inserted into the trace headers using Program S.HEADUP (Appendix F.2a).

b) Field statics

(1) Near-surface velocity structure

First break data obtained from reflection field records were used to determine the near-surface velocity structure along the profile. First arrival times were hand picked with a picking error of <1 ms. The number of picked traces for the shot files varied along the line: all traces for shots 1-60, the near 20-11 traces for shots 61-74 and the near 10-7 traces
FIELD STATICS: Geophone statics (datum is 0.8m below the surface of the ground)

GAIN RECOVERY: Removal of programmed gain (6dB/20ms)

GAIN FUNCTION: Linear 180dB/s

CONSTANT-OFFSET GATHER:
Offset: 24m
Display:
1) Horizontal exaggeration
2) Variable-area and wiggly traces
3) Mixed traces 1:2:1

CMP GATHER:
Velocity analysis: At CMPs 21, 45, 76, 100, 120, 121, 151, 180, 187, and 195
NMO correction: Velocity-time functions (see Figure 7.7)
Muting: 20–26 ms
Stacking: 4–9 fold
Display:
1) Horizontal exaggeration
2) Variable-area and wiggly traces
3) Mixed traces 1:2:1

Figure 7.3 BBC Processing sequence of seismic Line 10.
for shots 75-92. This variation was caused by the reduction in the S/N ratio of the seismic data in the cultivated farm field (Section 5.6.2). The results of the plus-minus refraction interpretation using Program REFRAC (Chapter 4), which revealed two velocity layers, are shown in Figure 7.4.

The velocity of the upper layer (VL1) ranged between approximately 420 to 665 (±50)m/s and the thickness of this layer (Z1) varied between approximately 0.9 to 1.8 (±0.2) m. The velocity decreased gradually along the line (NW to SE), though it increased at the SE end of the line (in the farm field). The latter increase was most likely due to the deep plant (0.2-0.25m) of the geophones. This layer represents the topsoil of weathered material.

The velocity of the lower layer (VM2) ranged between approximately 1400 to 1820 (±100)m/s. The layer had a fairly high and consistent velocity at the NW half of the profile. Then, it gradually decreased along the line towards the farm field and dropped suddenly some 300 m/s within a short distance (20m; shots 70-80). This layer is most likely the saturated overburden sediments and its surface is the water table.

The changes in velocities, both of upper and lower layers, suggest lateral changes in the lithology of near-surface materials (see Section 7.10).

(2) Data reduction

The results of the plus-minus interpretation (Figure 7.4) were used to model the near-surface structure for static corrections of Line 10 on the SKS. Long refraction records (Section 5.2.1) were used to determine the depth and the velocity of the subweathering layer, which were estimated at 5.0m and 1.9 m/ms, respectively. A horizontal plane at a height of 180m O.D., which represents the surface elevation at Station 79 (Figure 7.4), was chosen as a datum.

It can be seen later (Section 7.3-f; Figure 7.6) that near-surface velocities determined by refraction methods are higher than stacking velocities from reflections deeper than the datum. This may be caused by anisotropy of the Triassic sediments. The effect of the differences in these velocities on processing as well as on the timing reflections is
RESULTS OF REFRACTION INTERPRETATION
Datafiles: line10.mtx
Title: Bardon Hill, Line 10, smoothed (7,9) points
Plots of Velocity (VL, VM), Depth (Z) and Statics (ST)

Figure 7.4 Near-surface structure along Line 10 interpreted from first arrival times using Program REFRAC:

VL1 was extrapolated for Stations 92 to 115;
VM2 was extrapolated for Stations 1 to 4 and 91 to 115;
Z1 was determined by:
   a) intercept times at Stations 1 and 2,
   b) modified geophone delay times at Stations 93 to 101, and
   c) plus times at Stations 3 to 92;
ST1 is geophone statics; Stations are 2m apart.
negligible (< sample interval).

Comparison of the SKS stacked sections (Figures 7.5a,b) shows that field statics effected a minor improvement to the quality of the stack. This can be observed, for example, on shallow reflections (20-35 ms) between CMPs 38-42 and 105 to 130 where the continuity of the reflectors seems to have improved. However, the continuity of the main reflector (around 40ms) between CMPs 143 and 149 appears to be disturbed by field static corrections. This may suggest that the refraction solution (Figure 7.4) may not be accurately determined across the fence into the cultivated farm field due to the reduced multiplicity of the plus and minus times calculations (Section 7.3-b1). Another factor may be the varying depths of certain geophones for different shots in the farm field (Table 7.1). For simplicity of implementation on the SKS these geophones were given a fixed depth (0.1m). At the SE end of the profile (beyond Station 101; Figure 7.4), the effect of statics was only traveltime reduction since statics had an extrapolated constant value which was estimated from nearby stations.

On the BBC, statics applied to Profile 10 included only those associated with the geophones. The base of the Buffalo gun (0.8m below ground surface) was used as a datum and data were reduced to this level. Hence, compensation was only made for lateral velocity variations in the uppermost 0.8m along the line.

The BBC first arrival picking program S.UPTIME (Appendix F.2a) was used to determine geophone statics. Zero offset (uphole) geophones could not be used for uphole time measurement due to picking difficulties (see Section 7.8-al; Appendix G.5). The second nearest geophone (2m offset) was used instead for first arrival time picking and the velocities of the top 0.8m of the soil were determined. These velocities, after being smoothed, were used to calculate what would have been uphole times (geophone statics) at all shot positions (Appendix G.3). For the geophones beyond the last shot (92), an average geophone static based on the last five shots was used. Errors due to first arrival time picking and smoothing of velocities were within a sample interval (0.4ms).
c) Sorting traces into CMP gathers

Seismic traces of the shot ordered field records were sorted into CMP gathers with CMP intervals of 1m. A maximum fold of cover of 12 was achieved except towards the ends of the line where the fold of cover is gradually reduced to one. On the BBC, sorting field traces into CMP gathers (as well as into common shot-geophone offset) was done using Program S.SORT (Appendix F.2a).

d) Trace editing and Polarity reversal

On the SKS, three near traces (offsets < 11m), which were strongly dominated by refracted waves and ground roll, were zeroed to prevent contamination of shallow reflections. Noisy traces along the line, especially across the cultivated farm field, were also rejected. The maximum number of live traces in CMP gathers was reduced to 9 and 6 outside and inside the farm field, respectively.

On the BBC, the rejection of noisy traces, such as those due to weak shots, bad geophones (e.g. ringing traces), overloaded and interfering source-generated noise, was made interactively during stacking using Program S.STACK (Appendix F.2a) where each gather was plotted on the screen. In addition to this selective rejection of traces, three of the near traces (offsets < 11m) were systematically and automatically excluded from the stack, reducing the maximum stack fold to no more than 9 for CMPs 11-170. At the SE end of the line (beyond CMP 170), where ground roll extends further, swamping most of the record, three additional traces (offsets < 23m) were rejected making the maximum number of live traces in CMP gathers no more than six.

Polarity of the traces was reversed in accordance with the SEG convention of representing the onset of a P-wave as a trough.

e) Gain recovery

The recording programmed gain (6dB/20ms) was first removed. For the SKS processed data, an exponential gain function of 200 dB/s was used and correction for geometrical spreading was applied using the relevant stacking velocity-time functions.
A linear time-dependent function of 180dB/s was the only compensation for the amplitude decay used on the BBC.

f) Velocity analysis

On the SKS, constant velocity stack panels and velocity semblance spectra were used to determine the stacking velocities at certain points along the line. CMP gathers used in the analysis were band-pass filtered and gain recovered. Velocities were obtained after the application of field statics and were refined between passes of residual statics, which improved resolution. Semblance results were by far the easiest to pick. A semblance function averaged over five CMP gathers gave the optimum result, reducing noise level without smearing the reflection peaks.

Velocity spectrum analysis was made at several CMPs along the line. The final picks of velocities were obtained from CMPs 25, 62, 78, 140 and 183. Figures 7.6 is an example of a velocity spectrum showing that the resolution of velocity picks decreases with increased time down the record because of the small moveout (Section 6.5). Stacking velocity change along the line is controlled by the structure. Velocity functions used in stacking are shown on the stacked sections.

On the BBC, velocity-time functions were determined at key points along the line using Program S.NMOCOR (Appendix F.2a). Constant velocity gather panels were made for the CMP gathers at each of these points, which included CMPs 21, 45, 76, 100, 120, 121, 151, 180, 187 and 195. Examples of these panels, which can be found in Appendix G.4, show the difficulty of obtaining a unique stacking velocity from a certain reflection. Figure 7.7, which represents velocity-time functions derived from some of the panels, indicates the poor resolution of such analysis. Stacking velocity can be varied some ±100m/s quite easily without being noticed by the analysis and sometimes up to ±250m/s without serious consequences to the quality of the stacked data. The range of the spread in the stacking velocity is greater for deeper reflectors and for lower frequency data. The velocity-time functions, which were approximated by a single straight line at each gather, were used for the NMO corrections.

The poor resolution in velocity determination can be
Figure 7.6 Picking of stacking velocities from semblance spectrum averaged from semblance function of 5 CMP gathers (60-64).

SKS processing parameters

2) Exponential gain: 200dB/s
Band-pass filter: 150Hz/24dB - 600Hz/24dB
Residual statics

2) Number of traces: 12
Start of analysis: 0.0ms
End of analysis: 212ms
Time increment: 2.4ms
Time window: 4.8ms
Minimum velocity: 1000m/s
Maximum velocity: 4000m/s
Velocity increment: 20m/s
Low semblance contour value: 35%
High semblance contour value: 95%
Number of contour lines: 12
Figure 7.7 Velocity-time functions determined, using the BBC, at some CMPs along Line 10. The solid horizontal line represents the range of the determined velocity to a certain reflector while the dashed line indicates the limit in velocity beyond which the quality of stacking may be seriously affected.
attributed to two factors: 1) the velocity determination method itself, in the case of the BBC, where coherency is estimated by the visual inspection of the data and 2) the noise level, which may include time shifts due to static errors, anisotropy, wave shape change due to different attenuation and raypaths, stretching of the pulse due to NMO correction and differences in source and receiver couplings.

Figure 7.8 shows the tolerance to variations in the stacking velocity used for NMO corrections. Assuming an error of 0.4ms (sample interval) in NMO calculations, an error of ±100m/s in the stacking velocity is negligible at the furthest offset (46m) while at shorter offsets (say 30m, for example) an error of about ±200m/s in velocity has negligible effect. This is true for velocities > 2000m/s and TWTs > 60ms. For smaller TWTs (e.g. 40ms) the above mentioned errors in velocity are caused by an error of about two sample intervals in NMO calculations.

g) NMO Corrections and muting

On the SKS, the determined stacking velocities at the key points were extrapolated and interpolated and used in NMO corrections. A mute function, which varied with trace offset (10ms,10m to 35ms,46m), was applied on the stacked section shown in Figure 7.5c. This function was determined by producing a suite of stacks using different mute functions. A 5.0ms taper was used. Comparison between this figure and Figure 7.5b shows effect of muting in improving the resolution of shallow reflectors.

On the BBC, the NMO correction for Profile 10 was made using Program S.NMOCOR (Appendix F.2a). Velocity-time functions derived from the velocity distribution shown on Figure 7.7 were used in the correction. The early part of the traces (0-25ms) was muted after NMO correction.

h) CMP stacking

On the SKS, a trace normalization factor of $n^{-0.75}$ was used. The effective stack fold ranged between 6 and 9 for CMPs 23 to 184 and decreased progressively towards the ends of the line down to one. Figure 7.5 shows examples of stacked sections processed on the SKS.
Figure 7.8. Plots showing NMO as a function of velocity, offset and two-way reflection time.
On the BBC, CMP gathers were stacked using Program S.STACK (Appendix F.2a). Each gather was plotted on the screen and the gains of the traces were changed so that the amplitude of the main reflection (of the basement) appeared to be roughly equal on all the traces of the gather. Also, plotting the traces made it possible to examine the quality of the data, allowing for the rejection of any trace from the stack (Section 7.3-d). The effective fold of stack along this line ranged between 4-9.

Improvement in S/N ratio brought about by CMP stacking of the seismic data can be clearly seen on Figure 7.9. The greatest improvement was made away from the two ends of the profile due to the larger stack fold.

i) Residual statics

Two passes of residual statics were applied on Line 10 using the SKS. Initially, field statics corrected data (NMO corrected CMP gathers and stacked "pilot" traces) were used to determine residual statics. Two narrow time-windows (15ms), centred on the 50 and 60ms TWT (shallow reflections) were selected for CMPs 7 to 95. For CMPs 95 to 203, a wider time-window (20ms) centred on the main reflector (TWT=40ms) was used. A maximum time shift of 5.0ms was used to prevent cycle skipping during cross-correlation, whose function was scaled down by 80% (Section 6.6). The seismic data were band-pass filtered to improve picking.

A second pass of residual statics was made using data corrected for the first residual statics and refined velocities. The effect of residual statics on the quality of the seismic data can be seen in Figure 7.5. Comparison between Figure 7.5c and Figure 7.5b shows the considerable improvement to the quality of the stack achieved by application of residual statics.

j) Band-pass filtering

On the SKS, bandpass filtering was used before and after stacking to discriminate against noise and to improve S/N ratio. Filter panels were used to select the most suitable filter parameters. A band-pass filter of 200Hz/24dB and 800Hz/24dB was applied to the final stacked section.
Figure 7.9 Seismic sections along Profile 10 (processed on the BBC; three adjacent traces are mixed 1:2:1):

a) constant-offset section constructed from the CMP data with 24m shot-geophone offset; Traces are 2m apart.

b) 4-9 fold CMP stacked section; CMPs are 1m apart.
Predictive deconvolution

Deconvolution was applied, using the SKS, to seismic Line 10 before, after, and before and after stacking with the objective of improving the temporal resolution (Section 6.8). Deconvolution tests were carried out on the stacked CMP traces 20-40 and 110-130. Parameters such as the prediction lag $\alpha$, the autocorrelation window $G$ and the operator length $n$ were examined. The percent pre-whitening $\lambda$ was kept constant at 1%.

Figure 7.10 shows panels of deconvolved data using constant $G$ of 80ms and $n$ of 20ms and variable $\alpha$. A lag of 2.8ms was considered as a compromise between a moderate resolution and a good S/N ratio. Figure 7.11, which represents deconvolved panels with constant $n$ of 20ms and $\alpha$ of 2.8ms and variable $G$, indicates the importance of the latter for the optimum filter design. The autocorrelograms at the bottom of the figure show that the periodical events were highly suppressed by the use of the (20-100ms) time-window. Operator lengths of 20 and 30 ms were tested with no apparent difference on the deconvolved data and their autocorrelograms.

The results of the deconvolution tests on the stacked CMP traces 110 to 130, where the main reflector is shallow, were not satisfactory because of the narrow time-window.

The operator filter, which was designed from CMPs 20-40 using $\alpha$ of 2.8ms, $n$ of 20ms and $G$ of 80ms, was convolved with the entire section. Figures 7.12a,b represent the stacked sections without and with deconvolution applied after stacking. These figures show the considerable improvement to the quality of the data achieved by deconvolution which compressed the basic wavelet into a short pulse and removed a significant part of the reverberated energy as can be seen on the autocorrelograms. Figure 7.13a shows the deconvolved section with band-pass filter and AGC applied.

The results of applying deconvolution before stacking is shown in Figure 7.13b, where parameters similar to that of Figure 7.13a were used. Comparison of these figures indicates that deconvolution after stacking was more effective than before stacking in improving resolution (notice the second peak of the 60ms TWT reflection between CMPs 7-60). This may be attributed to the improvement in the S/N ratio achieved by stacking. However, application of deconvolution before and
<table>
<thead>
<tr>
<th>Time Shift (ms)</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4 ms</td>
<td>1.2 ms</td>
</tr>
<tr>
<td>3.6 ms</td>
<td>2.8 ms</td>
</tr>
</tbody>
</table>

**Figure 7.10** Decostoration test of prediction plot for selected CMP traces 20-40 (Line 10):

- Figure 7.2C without AGC.
- Figure 7.2D shows autocorrelation window (20-100ms), 20ms.
- Figure 7.2E shows deconvolved traces using variable prediction filters (shown on original trace) (processing parameters are similar to those of...
Figure 7.11 Decimation test of autocorrelation window for stacked CMP traces 20-40 (Line 10):

(a) original stack (processing parameters are similar to those of
(b) deconvolved stack (shown on top of panels). 2.8ms prediction lag - 2.8ms operator
length and 1% pre-whitening.
Figure 7.12 Comparison of two CMP stacked sections (Line 10) and their autocorrelograms (below) showing the effect of deconvolution:

a) original section.

b) deconvolved section (after stacking) using 20ms operator filter,

2.8ms prediction lag, 1% pre-whitening and 80ms autocorrelation window (20-100ms) designed from CMP traces 20-40.

SKS PROCESSING PARAMETERS

1) Pre-stack
   Trace edit: Offset < 11m
   Field statics
   Residual statics
   Stacking velocity: Shown on Figure 7.14
   Geometrical spreading
   Exponential gain: 200dB/s
   Band-pass filter: 200Hz/24dB - 800Hz/24dB
   Mute: 10ms, 11m, 35ms, 45m

2) Stack and post-stack
   Stack fold: 1-9
   Band-pass filter: 200Hz/24dB - 800Hz/24dB
   Deconvolution: (for seismic section b)
   Design: CMPs 20-40, start time 20ms, auto-correlation window 80ms
   Operator length: 20ms
   Prediction lag: 2.8ms
   Pre-whitening: 1%
   Apply: CMPs 7-200, start time 10ms

3) Display
   Scale: Approximately two-fold horizontal exaggeration
   CMP interval: 1m
after stacking produced optimum results (Figure 7.13c).

1) Trace equalization

Application of AGC was important in bringing up weak reflections and improving the continuity along the line (see Figures 7.12b and 7.13a). A time-gate of 30ms was used. AGC was only available on the SKS.

m) Section display

SKS processed sections (e.g. Figure 7.13) were plotted with a horizontal scale of 6 traces/cm and a vertical scale of 100 cm/s using the versatec plotter (Section 6.11). These scales ensured approximately two-fold exaggeration in the horizontal scale, which made it easy to identify and preserve the continuity of reflections on the seismic section (Section 6.9). Figure 7.14 shows a final deconvolved seismic section plotted without horizontal exaggeration which was used in the interpretation.

BBC records (Figures 7.9) were plotted with a two-fold exaggeration in the horizontal scale. The improved vertical (time) resolution of the stacked section (Figure 7.9a as compared to the constant-offset section (Figure 7.9b) was because the length of the traces in each portion of the printed section was 50ms for the former section and 100ms for the latter section. Also, the number of traces per unit length on the stacked section was double that of the constant-offset section which enhanced the quality of the former seismic section (Section 6.9).

7.4 PROCESSING OF SEISMIC PROFILE 8 (SITE 1)

Seismic Line 8 was processed on the SKS only. However, a constant-offset section was previously shot along this line (Chapter 5; Figure 5.19). Figure 7.15 shows the type of processes that were applied to Line 8.

Figures 7.17a,b are initial stacked sections without and with field statics applied, respectively. Comparison of these figures shows that field statics has affected considerable improvement to the quality of the stacked data. This is strongly evident between TWT=10-30ms where the S/N ratio and the continuity of the reflections were improved.
The accompanying (1) and the Trace sections provided without horizontal exaggeration: CWP

![Diagram](image)

**SWS PROCESSING PARAMETERS**

**LINE 10**

<table>
<thead>
<tr>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
</table>

*Note: Diagram and trace sections shown in the accompanying text.*
are in part (deconvolved before and after stacking).

The monochromatic (c) and the filtered section (d) without horizontal deconvolution: CMPs

**Figure 7.14** A final deconvolved CMP stacked seismic section (line 10) showing reflections from

**CMP NUMBER**

**SE PROCESSING PARAMETERS**

**LINE 10**
Geometry details input: Database file.
Field statics: Computed from refraction interpretation (Figure 7.16);
Subweathering layer velocity = 1.9 m/s;
Subweathering layer depth = 5.0 m;
Datum = 180 m O.D. = surface height at Station 7.
Sort into CMP gathers: CMP interval = 1 m; Maximum fold of cover = 12.
Edit (zero) traces: 11 m > offset > 43 m for CMPs 1-140; 15 m > offset > 43 m
for CMPs 141-169; 15 m > offset > 39 m for CMPs 170-204.
polarity reversed: P-wave onset is trough.
Gain recovery: 1) Removal of programmed gain 6 dB/20 ms; 2) Apply
exponential gain function of 200 dB/s; 3) Apply
geometrical spreading function.
Velocity analysis: 1) Constant velocity stacks; 2) Semblance (averaged
over 5 CMPs) at CMPs 25, 50, 100, 120 and 170.
NMO corrections: Using interpolated and extrapolated stacking velocity functions.
Muting: Offset-time functions 11 m, 10 ms to 46 m, 35 ms; Taper = 5.0 ms.
CMP stacking: Normalization factor = $n^{-0.75}$; Stack fold = 1-12 for
initial stack, and 1-9 for final stack.
Residual statics: 1) Window (15 ms) centred at:
a) 60 ms between CMPs 7-70,
b) 50-40 ms between CMPs 7-120 and
c) 45-35 ms between CMPs 120-200;
2) Maximum shift = 5.0 ms; 3) Crosscorrelation scalar = 80%.
Band-pass filtering: 1) 150 Hz/24 dB to 600 Hz/24 dB for initial stacks;
2) 200 Hz/24 dB to 800 Hz/24 dB for final stacks.
Deconvolution: 1) Design CMPs 20-50, start time 20 ms; 2) Autocorrelation
window 80 ms; 3) Operator length 20 ms; 4) Prediction
lag 2.8 ms; 5) pre-whitening 1%; 6) Apply
CMPs 7-200, start time 10 ms.
Trace equalization: AGC window 30 ms.
Section display: 1) Horizontal scale 6 traces/cm;
2) Vertical scale 100 cm/s; 175 cm/s for final
section; (sections have been photographically
reduced for this thesis).
RESULTS OF REFRACTION INTERPRETATION

Datafiles: line08.mix

Title: Bardon Hill, Line 08, smoothed (7,9) points

Plots of Velocity (VL, VM), Depth (Z) and Statics (ST)

---

Figure 7.16 Near-surface structure along Line 8 interpreted from first arrival times (almost all traces were picked) using Program REFRAC:

VL1 was extrapolated for Stations 91 to 114;
VM2 was extrapolated for Stations 1 to 4 and 90 to 114;
Z1 was determined by:
   a) intercept times at Stations 1 and 2,
   b) modified geophone delay times at Stations 92 to 114, and
   c) plus times at Stations 3 to 91;
ST1 is geophone statics; Stations are 2m apart.
Figure 7.17 CMP stacked seismic sections along Line 8 showing the effect of statics and deconvolution: a) without statics, b) with field statics, c) with residual statics and d) deconvolved before and after stacking.

LINE 11

SKS PROCESSING PARAMETERS

1) Pre-stack
   Trace edit:
   Field statics:
   Residual statics
   Stacking velocity:
   A single time-velocity function
   20ms, 1.8m/ms - 75ms, 2.1m/ms
   (Velocities for sections c, d are shown on Figure 7.18)

   Geometrical spreading
   Exponential gain:
   Band-pass filter:
   150Hz / 24dB - 600Hz / 24dB (for sections a, b)
   200Hz / 24dB - 800Hz / 24dB (for sections c, d)
   Mute:
   10ms, 11m - 35ms, 45m (for sections c, d)
   (for seismic section d)
   Deconvolution:
   Design:
   CMPs 20-50, start time 20ms.
   Autocorrelation window 80ms
   Operator length:
   Prediction lag:
   Pre-whitening:
   Apply:
   Band-pass filter:
   CMPs 7-200, start time 10ms
   200Hz / 24dB - 800Hz / 24dB (for section d)

2) Stack and post-stack
   Stack fold:
   Band-pass filter:
   Exponential gain:
   CMPs 20-50, start time 20ms.
   Autocorrelation window 80ms
   Operator length:
   Prediction lag:
   Pre-whitening:
   Apply:
   Band-pass filter:
   CMPs 7-200, start time 10ms
   200Hz / 24dB - 800Hz / 24dB (for section d)
   Trace equalization:
   30ms AGC window

3) Display
   Scale:
   CMP interval:
   Approximately two-fold horizontal exaggeration
   1m
Comparison between Figure 7.17c, which represents the stacked section with residual statics (second pass) applied, and Figure 7.17b shows the significant improvement achieved by residual statics application.

Deconvolution was applied to Profile 8 before, after and before and after stacking. As in Line 10, deconvolution before and after stacking gave best results. Figure 7.18 is a final seismic section deconvolved before and after stacking.

7.5 PROCESSING OF SEISMIC PROFILE 9 (SITE 1)

A constant-offset section was produced for seismic Line 9 on the BBC (Figure 7.19); traces are plotted from right to left opposite to SKS plot orientation. The types of process applied to Line 9, using the SKS, are shown in Figure 7.20.

Seismic traces with small offsets were rejected (Figure 7.20) because they were dominated by strong ground roll and refracted waves while traces with large offsets were rejected: 1) to avoid near-critical reflection in the NE part of the section where the main reflector is shallow, and 2) because these traces had high ambient noise in the SW part of the section (the cultivated farm field).

Therefore, adjacent CMP gathers were mixed before stacking to increase the fold of cover. For this particular spread geometry, mixing two adjacent gathers resulted in a new gather in which each trace has a unique distance from the source (Section 6.7.2). The effect of mixing on resolution is negligible since the first Fresnel zone is estimated to be >10m, for a velocity of 2.0m/ms, a frequency of 200Hz and traveltimes between 20 to 60ms (Section 3.3.3).

Figure 7.22 shows a final deconvolved (after stacking) seismic section with field statics applied, which improved the continuity of the reflections, especially between CMPs 30 to 60 (TWT= 25ms). Deconvolution seems not to be as effective on Line 9 as on Lines 8 and 10 which may be related to the lower quality of seismic data (S/N ratio) along the former line and the narrow autocorrelation time-window.

7.6 INTERPRETATION OF SEISMIC PROFILES 8, 9, AND 10

(1) Seismic interpretation
Figure 7.18 A final deconvolved CMP stacked seismic section (Line 8) showing reflections from the unconformity (U) and the Triassic sediments; plotted without horizontal exaggeration; CMPs are 1m apart; (deconvolved before and after stacking).
Figure 7.19 Constant-offset (24m) section (Line 9) constructed from field files using the BBC; arrows point to the reflection from the unconformity; traces are 2m apart and are not corrected for statics.
FIGURE 7.20 SKS PROCESSING SEQUENCE OF SEISMIC PROFILE 9

Geometry details input: Database file.

Field statics: Computed from refraction interpretation (Figure 7.21); Subweathering layer velocity = 1.9 m/s; Subweathering layer depth = 5.0 m; Datum = 180 m O.D. = surface height at Station 44.

Sort into CMP gathers: CMP interval = 2 m (mixing two adjacent CMP gathers); Maximum fold of cover = 24.

Edit (zero) traces: 19 m > offset > 39 m.

Polarity reversed: P-wave onset is trough.

Gain recovery: 1) Removal of programmed gain 6 dB/20 ms; 2) Apply exponential gain function of 200 dB/s; 3) Apply geometrical spreading function.

Velocity analysis: 1) Constant velocity stacks; 2) Semblance (averaged over 5 CMPS) at CMPS 25 and 100.

NMO corrections: Using interpolated and extrapolated stacking velocity functions.

CMP stacking: Normalization factor = $n^{-0.75}$; Stack fold = 1-14 for initial stack, and 1-10 for final stack.

Band-pass filtering: 200 Hz/24 dB to 800 Hz/24 dB.

Deconvolution: 1) Design CMPS 90-120, start time 10 ms; 2) Autocorrelation window 60 ms; 3) Operator length 20 ms; 4) Prediction lag 2.8 ms; 5) pre-whitening 1%; 6) Apply CMPS 10-131, start time 10 ms.

Trace equalization: AGC window 30 ms.

Section display: 1) Horizontal scale 6 traces/cm; 2) Vertical scale 100 cm/s; 175 cm/s for final section; (sections have been photographically reduced for this thesis).
RESULTS OF REFRACTION INTERPRETATION

Title: Bardon Hill, Line 09, smoothed (7,9) points

Plots of Velocity (VL, VM), Depth (Z) and Statics (ST)

Figure 7.21 Near-surface structure along Line 9 interpreted from first arrival times using Program REFRAIC:

1) picked traces were as follow:
   all traces for shots 1 - 21,
   near traces 23 - 20 for shots 22- 25,
   near traces 19 - 15 for shots 26- 31,
   near traces 14 - 12 for shots 32- 35,
   near traces 9 - 5 for shots 36- 45, and
   near traces 12 - 14 for shots 46 - 56.

2) VL1 was extrapolated for Stations 56 to 79;
   VM2 was extrapolated for Stations 1 to 4 and 55 to 79;
   Z1 was determined by:
   a) intercept times at Stations 1 and 2,
   b) modified geophone delay times at Stations 57 to 69, and
   c) plus times at Stations 3 to 56;
   ST1 is geophone statics; Stations are 2m apart.
are in apart (deconvoluted after stacking). (b) and the Pwiss sections: plugs without horizontal exaggeration: CMFs.

Figure 7.22 A full deconvoluted CMP stacked seismic section (line 9) showing reflections from

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**Line 6**

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**Line 10**

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**Line 14**

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**Line 22**

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**Line 24**

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**Line 25**

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**Line 26**

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**Line 28**

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**Line 30**

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**Line 32**

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**Line 34**

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**Line 36**

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**Line 40**

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**Line 42**

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**Line 74**

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**Line 80**

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**Line 82**

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**Line 84**

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**Line 86**

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**Line 88**

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**Line 90**

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**Line 92**

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**Line 94**

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**Line 96**

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**Line 98**

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**Line 100**

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Figure 7.22 A final convolved CMP stacked seismic section (line 9) showing reflections from CDP 99-120, with time line 10.

**S3S PROCESSING PARAMETERS**

**LINE 9**

- **Source window:**
  - Zone 7: 1007/24dB - 8000 Hz/24dB
  - CDPs: 10-120

- **Trace configuration:**
  - 2-zone A/D window
  - 1007/24dB - 8000 Hz/24dB
  - 2 CDPs
  - 200 Hz/24dB - 2000 Hz/24dB

- **Display:**
  - Band-pass filter
  - Black levels
  - Time scale
  - Trace number

- **Time移民:**
  - L1 > 200 Hz < 250 Hz

- **Event migration:**
  - Event time

- **Time scale:**
  - L1 > 200 Hz < 250 Hz

- **Display window:**
  - Zone 7A

- **Event migration:**
  - Event time

- **Time scale:**
  - L1 > 200 Hz < 250 Hz

- **Event migration:**
  - Event time
Although the primary objective of the interpretation is in mapping subsurface structure, it is also possible to take advantage of the seismostratigraphic interpretation technique (Sheriff, 1980). Assumptions were made with regard to the shape of the reflection pulse and the plan for the seismic interpretation:

1) The source pulse was assumed to be a minimum-delay pulse.
2) Reflections were identified by the line-ups of strong and clear peaks (blacked-in) though with some reservations; which include multiples, diffraction hyperbolas, residual source-generated noise which survived processing, and accidental line-up of random noise.
3) Continuity, correlation and tying of reflections at the intersection of the sections were used as criteria for reliable interpretation.

The deconvolved sections (Figures 7.14, 7.18 and 7.22) were used in the interpretation. Seismic horizons which are identified as genuine reflections are marked on the stacked seismic sections. Two units, with an onlap pattern, can be immediately recognized on the section. These units appear to be bounded by an unconformity surface (U) characterized by its angularity and amplitude predominance (MacQuillin et al, 1984).

Reflections recognized in the upper unit, especially on Profiles 8 and 10 where the quality of data is high, include:

T1- Continuous and gently dipping reflections with angular discordance with the underlying unconformity. They are also characterized by their high frequency and amplitude and their smoothness.
T2- Continuous to discontinuous reflections which are fairly parallel to reflections T1. They are fairly smooth with high to moderate frequency and amplitude. These reflections may have been unintentionally attenuated by deconvolution.
T3- Continuous to discontinuous reflections characterized by their moderate amplitude and high frequency.

Besides these reflections, there are some short and weak alignments which might be reflections. An example is the moderate-frequency and low-amplitude reflection B, which is
down dip divergent with respect to the unconformity.

The unconformity appears to have a fairly regular surface in the right-hand part of the sections and dips steeply towards the left and the surface becomes very irregular. The continuity of the surface is broken and the reflections are abruptly displaced at certain locations along the profiles. This is strongly evident on Lines 9 and 10 where diffraction hyperbolas appears to have developed (for example see the undeconvolved section in Figures 7.12a).

Reflections on the three seismic sections, which make a triangle, appear to tie fairly well at their intersection points with the exception of that between Lines 8 and 9 where the main reflector on the later section could not be easily identified around CMP 10 (Figure 7.22).

(2) Geological interpretation

The reliability of interpretation of a seismic section is influenced, to a large extent, by recording and processing specifications and restrictions:

1) The amplitude and frequency of the seismic signal vary (decrease vertically) with record time due to geometric divergence and attenuation.
2) The S/N ratio may vary laterally along the section due to the varying degree of coverage.
3) The accuracy of velocity determination. In Section 7.3-f, it was found that processing does not require precision in velocity measurement. Interpretation, on the other hand, is very sensitive to velocities for two purposes: a) depth conversion, and b) interval velocity (which is an expression of rock property) determination. However, the only available velocities are the stacking velocities (Figures 7.14, 7.18 and 7.22), which were not accurately determined, are controlled by stratification and dip, and are affected by the variable quality of the seismic data along the profile. Hence, these velocities need to be averaged and smoothed to reduce error. An estimated value of about 2020m/s is considered to be a good approximation of the average velocity to the unconformity. This was obtained from the refined stacking velocities (by residual statics) at CMPs 25, 62, 78, 140 and 183 along Line
10 (Figure 7.14) using Equations 6.8.

4) The resolution of the seismic section is decided by the frequency content of the seismic signal which determines the minimum thickness of beds to be resolved as separate reflections. Beds with thickness less than the resolvable limit, though they may not be distinguished as separate events, have a significant effect on the shape of the seismic pulse. Assuming a dominant frequency of approximately 250 Hz (on the deconvolved sections) and an average velocity of approximately 2000m/s, the resolvable limit is around 2m.

In order to obtain more accurate and reliable interpretation, advantage was taken of the available geological information on the area (Section 5.1.1). The reflections above the unconformity (T1, T2 and T3) are most likely caused by thin bed(s) of sands and sandstones, compact mudstones and bands of fine breccia. However, it is not possible to correlate these reflections because no 'continuous' cores of the Triassic sediments are available along these lines.

The prominent reflection U represents a surface of unconformity which separates the Triassic sediments from the underlying Charnian basement. The surface of the unconformity is irregular (broken) towards the wadi, where a layer of breccia is also present (possibly reflection B). This, however, may explain the complexity of the waveform (shown on the undeconvolved sections) especially towards the wadi (Section 5.1.1). Further complexity of the waveform is caused by the Triassic sediments which constitute a reverberant system and significantly affect the waveform by adding trailing cycles to the reflected wavelet.

Using the average velocity of 2.02m/ms, the calculated depth to the basement along Line 10 ranges approximately between 82 (±5) to 32 (±3)m at CMPs 10 and 175, respectively. These errors are caused by time picking errors (±1 ms) and errors in velocity (±0.1 m/ms). The determined depth at CMP 10 seems to be reasonable as compared with the basement depth (100m) indicated by BH-2 (Figure 7.14), bearing in mind that this borehole is located about 10m (downdip) from CMP 10 and that the seismic section was not migrated.
The depth to the basement at CMP 175 cannot be checked since the borehole at this locality (BH-3; Figure 7.14) terminates at 22m within the Triassic sediments.

7.7 PROCESSING OF SEISMIC PROFILE 11 (SITE 2)

Constant-offset sections along Line 11 were produced using the BBC (Figures 7.23a,b); traces are plotted from left to right. These sections show the low quality of seismic data along this line (Section 7.2). Strong reverberant headwaves with a dominant frequency of about 100Hz dominate the seismic section, especially at small offsets.

The types of process applied to Line 11, using the SKS, are shown in Figure 7.24.

Refraction interpretation of first arrival times revealed two velocity layers along Line 11 (Figure 7.25). The velocity of the upper layer (VL1) ranged between approximately 580 to 1160 (±100) m/s and the thickness of this layer varied along the line between approximately 3 to 9 m (±1m). This layer represents the topsoil and weathered sediments (Appendix G.1). The velocity of the lower layer was determined by the minus time method (VM2) and 'forward' least-square method (VL2). Velocities determined by the former method ranged between 1640 to 2050 (±100) m/s while for the latter method velocities ranged between 1560 to 2175 (±100) m/s. This layer represents the subweathering sediments.

The accuracy of refraction results is dependent on the method of interpretation and the quality of first arrival picking (Chapter 4). Velocities obtained from the minus times for Stations 28 to 85, which were extrapolated to both ends of the line, were used for depth conversion for all stations. The accuracy of the measured depths at Stations 25-87 is expected to be higher than those measured by other methods, especially those at Station 88-121 (Figure 7.25). This may be related to: 1) the multiplicity of the plus times calculations for the first case and 2) the lack of reversed coverage, which was caused by the large depth to the refractor and by the reduction in the effective length of the spread towards the end of the profile, in the second case. First arrival times could not be picked from traces with offsets >30m for shots 78 to 98 (Stations 101-121).
Figure 7.23  Constant-offset sections (Line 11) constructed from field files using the BBC; arrows point to reflection from the unconformity; traces are 2m apart:

a) offset = 24m, mixed traces.
b) offset = 36m, programmed gain (6dB/20ms).
FIGURE 7.24 SKS PROCESSING SEQUENCE OF SEISMIC PROFILE 11

Geometry details input: Database file.

Field statics: Computed from refraction interpretation (Figure 7.25); Subweathering layer velocity = 2.05m/ms; Subweathering layer depth = 10.0m; Horizontal datum = 195m O.D. = surface height at Station 121; Floating datum = ground surface (179-195m; Stations 1-121).

Sort into CMP gathers: CMP interval = 2m (mixing two adjacent CMP gathers); Maximum fold of cover = 24.

Edit (zero) traces: offsets < 14m.

polarity reversed: P-wave onset is trough.

Gain recovery: 1) Removal of programmed gain 6dB/20ms; 2) Apply exponential gain function of 250 dB/s; 3) Apply geometrical spreading function.

NMO corrections: Using a time-velocity function of 20ms, 1.8m/ms - 75ms, 2.1m/ms (obtained from Line 10).

CMP stacking: Normalization factor = n^-0.75; Stack fold = 1-16.

Residual statics: 1) Window (40ms) centred at: a) 45ms between CMPs 1-30, b) 45-50ms between CMPs 20-55 and c) 05-55ms between CMPs 50-104; 2) Maximum shift = 5.0ms; 3) Crosscorrelation scalar = 80%.

Band-pass filtering: 1) 150Hz/40dB to 600Hz/24dB.

(before & after stack)

Deconvolution: 1) Design CMPs 60-80, start time 20ms; 2) Autocorrelation window 80ms; 3) Operator length 25ms; 4) Prediction lag 4.4ms; 5) pre-whitening 1%; 6) Apply CMPs 1-104, start time 10ms.

(after stack)

Trace equalization: AGC window 30ms.

Section display: 1) Horizontal scale 3 traces/cm; 2) Vertical scale 100cm/s; 165cm/s for final section; (sections have been photographically reduced for this thesis).
RESULTS OF REFRACTION INTERPRETATION
Data files: LN11-6.MIX
Title: Bardon Hill, Line 11, smoothed (7,9) points
Plots of Velocity (VL, VM), Depth (Z) and Statics (ST)

Figure 7.25 Near-surface structure along Line 11 interpreted from first arrival times using Program REFRAC:

1) picked traces were as follow:
   all traces for shots 1 - 55 and 57 - 77, and
   near traces 16 - 9 for shots 78 - 98.

2) VL1 was extrapolated for Stations 1 to 16;
   VL2 was extrapolated for Stations 1 to 3 and 111 to 121;
   VM2 was extrapolated for Stations 1 to 27 and 86 to 121;
   Z1 was determined by:
   a) intercept times at Stations 88 and 121,
   b) modified geophone delay times at Stations 2 to 24, and
   c) plus times at Stations 25 to 87;
   ST1 is geophone statics; Stations are 2m apart.
The calculated depth to the base of the weathering layer at Station 73 was approximately 6.2m whereas the actual depth, indicated by borehole data (BH-12, Appendix G.1), is about 5.5m. The relatively large thickness of the weathering layer may be the cause of the attenuation of high frequency seismic energy in this site.

The results of refraction interpretation (Figure 7.25) were used for statics computation (see also Figure 7.24). Comparison between Figure 7.26a and Figure 7.26b, which represent stacked seismic sections without and with field statics, show that the effect of field statics on the quality of the seismic data (amplitude and continuity of reflections) cannot be easily assessed. However, it is evident that statics affected the curvature of reflections between CMPs 45 and 95. The apparent structure "fold" of the reflections (TWT 50-80ms), which might have been caused by the effect of near-surface material, was removed by field statics.

Stacking velocity functions could not be determined, whether by semblance or constant velocity stacks, because of the low quality of the data (low frequency and low S/N ratio). A single time-velocity function, which was obtained from Line 10, was used for stacking Line 11 (Figure 7.26c). Comparison between this figure and Figure 7.26b indicates that stack quality is not affected by large changes (+200m/s) in the stacking velocities. It also shows that residual statics (Figure 7.26c) affected no (or little) apparent improvement to the quality of stack. Here, a crucial factor was the selection of a time window for the time picking by cross-correlation.

Deconvolution tests were applied to the stacked seismic section of Line 11. An autocorrelation window of 80ms, operator length of 25ms and a prediction lag of 4.4ms gave compromise results between resolution and S/N ratio (Figure 7.26d). Comparison between this figure and Figure 7.26c shows that deconvolution has increased resolution though it reduced the quality of the stacked seismic data (S/N ratio).

Figure 7.27 shows a final undeconvolved seismic section which was used in the interpretation.

7.8 PROCESSING OF SEISMIC PROFILE 12 (SITE 2)

Seismic Profile 12 was processed on the BBC only. A flow
SBS PROCESSING PARAMETERS

LINE 11

- (d) Decayed after stacking.
- (e) Residual effects applied.
- (g) No effects applied.
- (h) Without stacking.

Figure 7.26 CDP stacked seismic sections along Line 11 showing the effect of stacking and
Figure 7.27 A final undeconvolved CMP stacked seismic section (Line 11) showing reflections from the unconformity (U) and the Triassic sediments: plotted without horizontal exaggeration: CMPs are 2m apart.
chart of the types of process applied to this profile is shown in Figure 7.28.

a) Field statics

1) Near-surface velocity structure

Figure 7.29a shows topsoil velocities along Line 12 determined from the second nearest geophone (2m) using Program S.UPTIME (see Appendix G.5).

Near-surface structure was determined at some points along the line using Program S.REFRAC, which assumes a plane-layer earth structure (Appendix F.2a). In general, two velocity layers were revealed while a third layer was interpreted at some shots at both ends of the line, where data quality permitted first arrivals to be picked at further offsets (Appendix G.8). The velocity of the upper layer varied between approximately 450 to 760 (±100) m/s which was basically similar to the uphole velocities (Figure 7.29a) though less accurately determined. The velocity of the second layer varied between approximately 780 to 1800 (±100) m/s (Figure 7.29b). With regard to the third revealed layer (for shots 1, 7, 129 and 132; see Appendix G.8), its velocity is within the upper range of the second layer velocity.

The upper layer, with a thickness between approximately 1.0 to 2.5 (±0.3) m, most likely represents the dry topsoil. The surface of the second layer is probably the water table and the large lateral variations in velocity might be caused by lithological changes along the line (e.g. saturated weathered mudstone and gravel to saturated and compact mottled mudstone). The second interface (for shots 129 and 132, for example) may separate an upper layer of saturated mudstone and gravel and a lower layer of saturated and compact mudstone.

The upper and second layers may correspond to the upper "weathered" layer for Line 11 (Figure 7.25).

2) Data reduction

Field statics applied to seismic Profile 12 included only those associated with the geophones. The base of the Buffalo gun was used as a datum and data were reduced to this level (Appendix G.5c). Hence, compensation was made only for lateral
FIELD STATICS: Geophone statics (datum = 0.8-1 m below the surface of the ground)

GAIN RECOVERY: Removal of programmed gain (6dB/20ms)

GAIN FUNCTION: Linear 180dB/s

CONSTANT-OFFSET GATHER:
   Offset: 30 and 36m
   Display:
      1) Horizontal exaggeration
      2) Variable-area and wiggly traces
      3) Unmixed traces
      4) Statics applied/not applied

CMP GATHER:
   Velocity analysis: None
   NMO correction: Velocity-time function of CMP 21
      of Line 10 (Figure 7.7)
   Muting: 15 ms
   Stacking: 8 fold
   Display:
      1) No horizontal exaggeration
      2) Variable-area and wiggly traces
      3) Unmixed traces

Figure 7.28 BBC Processing sequence of seismic Line 12.
Figure 7.29  Near-surface velocities along Line 12 determined by BBC Programs S.UPTIME and S.REFRAC; arrows indicate missing shots:

a) uphole velocity.
b) subweathering velocity.
velocity variations of the uppermost =0.8-1.0m along the line (Figure 7.29a).

This reduction of data is not sufficient to solve the statics problem since the datum is within the weathering layer. However, because of the low quality of the data first arrival times could not be picked from traces with offsets >24m except for a few shot records (Section 7.8-a1).

b) Constant-offset section

Figures 7.30a,b represent, respectively, constant offset sections along Line 12 with 30 and 36 m shot-geophone offsets. Reflections are not easily identifiable on the sections, which were swamped by reverberant headwaves along with ground roll.

NMO correction and CMP stacking

The low quality of the seismic data in this site prevented velocity analysis. A single stacking velocity-time function, obtained from Line 10 (CMP 21 in Figure 7.7), was used for NMO correction of the entire line. The stacking program (S.STACK; Appendix F.2a) was made fully automatic; hence, it was not possible to observe CMP gathered records on the screen. Subsequently, it was not possible to equalize the gain of the CMP traces or to selectively reject noisy traces from being stacked. However, pre-set rejection of traces was made along the entire line (4 traces with offsets <15m) to avoid surface waves, reducing the maximum fold of stack to 8.

Comparison between the stacked seismic section (Figure 7.31) and the single-fold section (Figure 7.30) suggests that CMP processing has made some S/N improvement though this was not very significant. The quality of the stacked section is low; it is dominated by source-generated noise and random noise and is of low frequency. Band-pass filters available on the BBC (Program S.FILPC; Appendix F.2a) are narrow and therefore cannot be used to produce an interpretable section.

7.9 INTERPRETATION OF SEISMIC PROFILES 11 AND 12

The same assumptions and procedures used in the interpretation of Lines 8, 9 and 10 (Section 7.6) were followed in the interpretation of Lines 11 and 12. However, interpretation of the latter lines is more difficult because
Figure 7.30 Constant-offset sections (Line 12) constructed from field files using the BBC; arrows point to reflection from the unconformity, traces are 2m apart:
   a) offset = 30m, statics and additional gain function of 120 dB/s are applied.
   b) offset = 36m, statics are not applied.
Figure 7.31  CMP stacked seismic section (Line 12) showing reflection from the unconformity (U); plotted without horizontal exaggeration by dropping alternative CMP traces; CMPs are 2m apart;(processed on the BBC).
of the low quality of the stacks. Seismic interpretation is not reliable without incorporating the available geological information along the profile (BH-12 and refraction data; Figures 7.1 and 7.2).

For Line 11, several seismic horizons (U, T1, T2, and T3) may be identified as genuine reflections (Figure 7.27) while only one horizon (U) may be identified for Line 12 (Figure 7.31). The stacked section of Line 11 has a higher quality (S/N ratio and resolution) than that of Line 12. This is because of the extensive processing (on the SKS) applied to the former line and because its original field records were of better quality.

Reflection U may represent the surface of the unconformity which separates the Triassic sediments and the underlying basement. It is distinguished by its angularity and moderate amplitude. Reflections T1, T2 and T3 are most likely caused by thin beds of sands and bands of fine breccia (BH-12; Appendix G.1). However, it is not possible to correlate these reflections because of the difficulty of marking the onset of the reflections.

The calculated depth to the basement, using the same average velocity (2.02 m/ms) that was used for Site 1, is approximately 70 (±5)m at the intersection point of Line 11 and 12 (CMPs 61 and 158). Picking errors can be as high as 5 ms. This determined depth correlates reasonably well with the actual depth of the basement (≈82m) indicated by BH-12 (Appendix G.1).

7.10 EFFECT OF NEAR-SURFACE MATERIAL ON SIGNAL QUALITY

Seismic Profile 10 provides a good opportunity to analyse the factors which cause areas to be labelled as "good" or "bad" for seismic reflection recording. This line runs across two adjacent areas (Figure 7.1) where the quality of the recorded seismic data changes from high to low.

Figure 7.32 shows velocity and amplitude variations along Line 10 for: a) headwaves, b) reflected waves, and c) surface waves. The bars on the different plots represent calculation errors and the arrow (at a distance of 162m) points to the fence which separates the sports ground (to the left) from the farm field (to the right).
Figure 7.32 Plots of lateral variations in velocity and amplitude (Line 10) of: a) headwaves, b) reflected waves, and c) surface waves. \( V_u \), \( V_{sw} \), \( V_{st} \) and \( V_{gr} \) designate the upper, subweathering, stacking and ground roll velocities, respectively. \( A_{18} \) and \( A_{24} \) refer to amplitudes measured at offsets of 18 and 24 m from the shots.
Headwave velocities included upper layer velocity $V_u$ and subweathering velocity $V_{sw}$, which were obtained from Figure 7.4. These headwaves were from within the overburden since the cross-over distance for the basement refraction is much greater than the spread length ($\approx 240$ to $100 \pm 10$m between the NW and SE ends of the line). Amplitudes of the headwaves were measured from the first peak-second trough and do not necessarily represent the maximum headwave amplitudes, especially in the farm field.

Stacking velocity $V_{st}$ was obtained from semblance analysis of some CMP gathers (Figure 7.14). The amplitude of the reflection, which is from the basement, represents the maximum peak-trough amplitude.

Ground roll velocity $V_{gr}$ is measured for the onset surface waves. The amplitude is of the onset wave too and does not necessarily, especially in the sports ground, represent the maximum amplitude.

The plotted variables are the results of complex geological conditions and diverse acquisition and geometrical parameters and relationships. In order to establish relationships between the these parameters, the effect of the various factors were checked; first along the line in the sports ground and, then, at the both sides of the fence.

The headwaves velocity curves indicate a lateral change in lithology along the left part of the profile starting at a distance of about $130 \pm 10$m, which is well before the farm field (Section 7.3-b). This may correspond to changes from saturated mudstone to saturated mudstone and gravel. This change in velocity is also observed on the $V_{gr}$ curve. Gravel was found in the farm field below the topsoil ($>0.2$m) where holes were dug for the geophones. The effect of lithology changes can also be seen on the amplitude curves (e.g. around 130m) for the surface waves while it is less obvious on the reflection amplitude curves. This supports the hypothesis of lithological change in near-surface layers through which these waves (headwaves and surface waves) mainly propagate.

Other factors which might cause variations of amplitudes along the line are the variability of the shotgun cartridges and the coupling of the gun with the ground and the geophone ground coupling. The effects of source and geophone ground...
couplings cannot be differentiated because of lack of reversed data. However, source coupling may be indicated by the strength of the air-wave on the record (Figure 7.32). A weak air-wave may suggest good coupling while bad coupling may be indicated by a strong air-wave.

The effect of geophone ground coupling on the amplitude is variable, in particular in the farm field because:

1) the deep plant, which improved coupling, also reduced the amplitude by being away from the free surface,

2) the presence of gravels in the soil made it difficult to ensure firm and consistent geophone ground coupling, and

3) the gravels in the soil caused scattering of the seismic energy.

The effect of the geophone ground coupling is discussed later in this section.

The general increase in the reflected amplitude (in the sports ground) towards the SE may be due to the decrease in the depth to the basement. Hence, there is less energy loss (due to geometrical spreading and attenuation) and increased reflection amplitude due to the angle of incidence approaching the critical angle (critical distances = 70-35 ±10m between the NW and SE ends of the sports ground). Since the effects of these are positive on the reflection amplitude, they are not thought to have caused the deterioration of the seismic data across the fence into the farm field. The reflectivity of the basement is also not considered because the change in the overburden and basement velocities across the fence is not significant. The variations in the stacking velocity Vst and basement velocity (Chapter 2) are caused by structural effects.

The remaining 'different' factors across the fence are reduced to: 1) the relationship (spatial and time) between the various types of wave, and 2) the geophone ground coupling.

The presence of a window in time for the recording of reflections was very important. Although reflection amplitude was low in the left end of the line, it was still recorded because an uncontaminated window was present, which was ensured by the ground roll being late on the trace. The increase in the velocity of the ground roll towards the SE and the decrease in the velocity of the headwaves and the depth to
the basement resulted in narrowing the window. As reflections were overridden by the ground roll at the 18 and 24 m offsets in the farm field, they were still visible at further offsets as observed on some of the field records. Further into the farm field, however, the ground roll velocity increased completely swamping the last few records (Appendix G.4). Ground roll velocity varied from approximately 250 to 700 and up to 1200 m/s between the NW end, fence and SE end of the line, respectively.

Bredewout and Goulty (1986) indicated that at a shallow overburden/bedrock interface the ground roll tends to travel faster, contaminating most of the seismic record. Such velocity variation was also observed along Line 8 (between approximately 250-700 m/s) and Line 9 (up to 1200-1400 m/s). The fact that both lines (9 and 10) run across the farm field suggests that the change in ground roll velocities is also related to the changes in the characteristics of the near-surface materials across the fence. This is also supported by the fact that the depth of the basement increases further into the farm field. The wavelengths of the ground roll increase towards the farm field (Figure 7.32); hence it propagates deeper in the ground. Basically, these wavelengths were determined using the filtered seismic data (low cut= 200 Hz). If the dominant frequency (=40 Hz) of the ground roll, which was determined from unfiltered records in this area (Section 5.2.1), is to be used the wavelengths would have been between 6-30 m along the line.

The geophone ground coupling is perhaps the most important factor which is responsible for the deterioration of the seismic data in the farm field. This is not only because it affects the recording of high frequencies but (as can be seen on plots a & c near the fence in the farm field) also because of the level of the total seismic energy (signal to 'random' noise ratio). This is seen to change (in the farm field) towards the SE end as deeper geophone plants where used. Since the water table does not change across the fence and since the lithological changes in the near-surface materials occur before the farm field, the decrease in the frequency of the seismic records in the farm field is believed to be caused mainly by the bad geophone ground coupling since
this is determined by the conditions of the topsoil which varies significantly (from firm to loose) across the fence in the farm field. This conclusion is also supported by the better quality data (in the farm field) along Line 9 (Figure 7.19) because all the geophones in the farm field where deep planted (=0.25m) for this line.

Krohn (1984) observed a shift in the geophone ground resonant coupling frequency from 340 Hz to 120 Hz by crossing from a firm soil into a ploughed garden. This was also accompanied with a shift in damping from 60% to 44% of critical damping, respectively.

7.11 CONCLUSION

The results of processing shallow seismic reflection data indicated the following:

1) The effectiveness of all types of process (e.g. velocity analysis, deconvolution, residual statics, stacking) was highly dependent on the quality of the seismic field data.

2) The quality of the seismic field records was found to be strongly influenced by the physical properties of near-surface materials. Here, two factors were important: a) the thickness of the weathering layer which controlled the transmission of high frequencies and b) the firmness of the topsoil which affected the geophone ground coupling. The presence of a thin weathered layer (water table =1-2m) in Site 1 made it possible to record high frequency (around 200Hz) reflection data.

3) Field statics computed, using Program REFRAC, from first break data obtained from the multifold reflection records made a significant improvement to the quality of the stack, especially for very shallow reflections (TWT <30ms), in Site 1.

4) An important factor in the application of residual statics was the selection of a time-window for time picking by crosscorrelation. In Site 1, where the data were of high frequency, a narrow window of 15-20ms centred on a single reflection achieved remarkable results in enhancing reflections. For the low-frequency data of Site 2, the
selection of the time-window was a major difficulty. Hence, the use of a large window (40ms) was necessary though residual statics affected minor improvement to the quality of the stack. The poor quality of residual statics in this site can be demonstrated by the mean of the normalized crosscorrelation peaks for Line 11 which was 0.4, and the rms error of the solution, which was 1.1ms compared to 0.75 and 0.7ms for Line 8 (Site 1), respectively.

5) Deconvolution was very useful in increasing resolution of the shallow seismic sections. Its effectiveness, however, was dependent on the following crucial factors: a) a wide autocorrelation time-window, b) the presence of a number of reflections, and c) high quality of the original data. In Site 1, an autocorrelation window of 80ms, filter length of 20ms and prediction lag of 2.8ms gave the optimum result, significantly improving the resolution of the seismic section (resolvable limit around 2m).

6) The quality of shallow seismic data was enhanced by stacking CMP traces which increased S/N ratio. In Site 1, reflections from horizons as shallow as 20m or less, which were not visible on the field records, were obtained by stacking. In Site 2, where the quality of seismic data was low, mixing two adjacent CMP gathers before stacking was useful in suppressing ground roll and enhancing reflections.

7) The CMP stacked section of Line 10 indicates that a preliminary processing sequence using a simple microcomputer can be adequate to produce a satisfactory image of shallow subsurface structure provided that field seismic records are of high quality as shown in Figure 7.9.
8.1 CONCLUSIONS

1) Seismic reflection and refraction methods

The results of this study demonstrate the potential of the seismic reflection method for shallow depth applications (i.e. engineering scale problems). This method has shown significant advantages over the seismic refraction method in obtaining a more detailed image of subsurface structure. However, success with the method was dependent on several factors (see Section 8.1-2), illustrating the need for great attention to detail in preserving high-frequency energy. This study was conducted at two sites, with different near-surface field conditions representing two extremes, in Bardon Hill Quarry (Charnwood Forest area) where Triassic sediments unconformably overlie low-grade metamorphosed Charnian basement.

Site 1

Here, field conditions (thin 1-2 m weathered layer, shallow water-table and firm topsoil) were favourable for reflection recording and high quality stacked seismic reflection sections (along Profiles 8, 9 and 10) were produced. Strong reflections from the surface of the unconformity 'basement' and from horizons within the Triassic sediments, as shallow as 20m or less, were obtained. The plus-minus refraction interpretation method, on the other hand, detected the main feature of the geology (the basement) though it smoothed its topography and underestimated its depth. Borehole calibration of seismic refraction and reflection results along Line 10 indicated the superiority of the latter method. The estimated depths to the basement revealed by refraction and reflection were approximately 65 and 85m, respectively, while the actual depth was approximately 100m (Figure 7.14).

Site 2

Field conditions were not favourable for the
transmission and recording of high frequencies in this site; the weathered layer was ≈ 2 to 4 times as thick as that in Site 1, the water-table was deep and the topsoil was cultivated. The stacked seismic reflection sections (along Profiles 11 and 12) were of low quality (low frequency and low S/N ratio) though reflections from the unconformity were obtained. Comparison between refraction and reflection results shows the advantage of the latter method. The estimated depths to the basement were approximately 50 and 70m determined by the refraction and reflection methods, respectively, while the actual depth indicated by BH-12 is 82m (Figure 7.1).

2) High-resolution system development

Seismic energy source
The Buffalo gun, equipped in this study with a 12-gauge Popper-load blank cartridge and fired at ≈1m below the ground, showed greater advantages over other types of surface source (i.e. hammer, weight drop, Betsy seisgun, and detonator) in providing high-frequency energy required by the shallow scale of survey. It was also characterized by reduced ground roll energy, the latter being a serious problem in shallow reflection work.

Seismic detector
The 100 Hz (Mark products) geophone was an important element in the recording of high-resolution data. It was very effective in suppressing low-frequency source-generated ground roll and resolving shallow reflectors. The coupling of the geophone with the ground was a critical factor and was strongly influenced by variations in the physical properties of near-surface materials. In areas of firm soil (i.e. the sports ground in Site 1), a normal plant of the geophone (with 13cm spike) was found to be adequate to record high frequencies. Deep planting (≈4m) of the geophone was necessary to improve the coupling in areas of loose soil (the cultivated farmfield in Site 1). However, a 'very' long (≈5m) spike was found to be ineffective because of signal distortion which may be caused by interference between the
seismic waves travelling through the spike and surface materials.

Recording equipment

The facility to provide extensive quality control of data in the field, which was achieved by incorporating a seismograph-field computer system, was beneficial. This allowed data to be monitored continuously and enabled plans on the progress of the survey to be made while the field work was under way. Processes such as spectral analysis, velocity analysis and the construction of a constant-offset seismic section from multifold records were easily performed in the field.

Field acquisition techniques

The geometrical relationship between the various types of wave which can provide a window in time for uncontaminated reflection recording was an important factor. This was dependent on the geological structure and field conditions (i.e. thickness of overburden and depth of water-table). Shot-geophone offsets between 10 to 20 m were used in both sites (in processing by zeroing these traces) to prevent the strong ground roll and reverberant headwaves dominating the seismic record.

Application of a severe (i.e. 200 Hz; Site 1) analogue low-cut filter was essential to attenuate low-frequency source-generated ground roll and enhance the high-frequency content of the signal.

Data processing on the microcomputer

The results of processing seismic Profile 10 indicate that a preliminary processing sequence using a simple ‘micro’ computer can be adequate to produce a satisfactory image of shallow subsurface structure (e.g. constant-offset section and CMP stacked section) provided that field seismic records are of high quality (i.e. visible reflections). CMP stacking of seismic data provided an improved image of subsurface structure achieved by enhancing reflections by increasing the S/N ratio. However, this process was fairly slow on the BBC because of memory and speed limitations.
3) Field statics

Computation

Field statics were computed from first break data by Program REFRAC. The results of interpreting synthetic data showed the reliability of this program in accurately mapping very shallow sub-surface layer structure by using both forward and "fabricated" reversed arrival times. For real data, this method was found to be fairly reliable provided that reversed coverage of first arrivals could be established (see below). The calculated thickness of the weathered layer at BH-12 was 6.2m while the actual thickness was 5.5m.

Application

Application of field statics, which were computed from first break data picked from the multifold reflection records using Program REFRAC, had a significant effect on the shallow seismic reflection data. In Site 1, where the weathered layer was thin and hence the reflection spread was long enough to provide reversed coverage of first arrival times (especially along Line 8), field statics were accurately determined; this was shown by the remarkable enhancement of the quality of the stacked section, especially of the very shallow reflections (<30ms TWT). The effect of long as well as medium wavelengths statics was removed and the continuity of these reflections was improved.

In Site 2 the weathered layer was thick, and reversed coverage of first arrival data could not be provided along most of the line. Hence, the computation of field statics was not expected to be as accurate as in Site 1. However, application of field statics to Line 11 showed the removal of long wavelength statics which had influenced the shape of reflections from the basement as well as from the Triassic sediments. Improvement to S/N ratio achieved by field statics could not be examined because of the low quality (low frequency) of the data.

Application of field statics becomes very important for shallow seismic data especially if the facility for residual statics is not available (e.g. on a microcomputer).
4) Standard reflection data processing package

The results of processing shallow seismic data on the mainframe computer using a standard seismic reflection package (the SKS) resulted in a significant improvement to the quality of the seismic data. In Site 1, reflections from horizons as shallow as 20m or less, which were not visible on the field records, were obtained by stacking. In Site 2, where the quality of seismic data was low, mixing two adjacent CMP gathers before stacking was useful in suppressing ground roll and enhancing reflections.

In addition to the advantage of large memory, great computation and manipulation power, flexibility, a large number of processes and the higher quality of the plots, there were two particular procedures which were of special interest in shallow reflection data and were different from processing on the BBC. These are residual statics and deconvolution.

Residual statics

The selection of a time-window for time picking by crosscorrelation was a critical factor in the application of residual statics. In Site 1, where the data were of high frequency, using a narrow window of 15-20ms centred on a single reflection achieved remarkable results in enhancing reflections, especially at very shallow depths. For the low-frequency data of Site 2, the selection of the time-window was a major difficulty and hence a large window (40ms) was used. Here, residual statics effected minor improvement to the quality of the stack.

Deconvolution

The effectiveness of deconvolution in improving the resolution of the shallow seismic sections was dependent on the following crucial factors: a) a wide autocorrelation time-window, b) presence of a number of reflections, and c) high quality of original data. In Site 1, the deconvolution operator was designed from a few traces where a wide time-window containing several reflections was available. An autocorrelation window of 80ms, filter length of 20ms and prediction lag of 2.8ms gave optimum results, significantly
improving the resolution of the seismic section (resolvable limit around 2m). These results were achievable since the main aim of deconvolution was to compress the basic wavelet.

Finally, the effectiveness of these and all types of process including those performed on the BBC was highly dependent on the quality of the seismic field records, which was strongly influenced by the physical properties of near-surface materials. Here, two factors were important: a) the thickness of the weathering layer which controlled the transmission of high frequencies and b) the firmness of the topsoil which affected the geophone ground coupling.

8.2 RECOMMENDATIONS

In the light of the results of this study the following recommendations are suggested:

1) A major problem with the shallow seismic reflection method is the source-generated noise (i.e. ground roll) because of its large amplitude and prolonged wave train. Reducing the amplitude of this type of wave is useful in enhancing the high-frequency content of the signal. Therefore, a lower-energy source (perhaps 0.38-calibre or even 0.22-calibre cartridges) should be investigated.

2) The use of analogue low-cut filters to discriminate against and attenuate the low-frequency ground roll has been useful in emphasising high frequencies and recording useful data. However, the effectiveness of such a technique is dependent on the extent of separation between the spectra of the different types of wave. Therefore, the potential of 3-component recording to allow identification and removal of unwanted phases should be investigated.

3) The field computer (the BBC-B) should be replaced by a more powerful model (> 1 Mbyte of user memory) with a large hard disc (~40 Mbyte). This is essential to augment both the storage as well as the processing capabilities of the system.

4) Software for simple automated processing such as the
construction of constant offset section or CMP stacking (with a view to 'real time' operation) should be developed. This would help to improve the efficiency of the shallow reflection system.

5) Program REFRAC needs to be further developed by:

a) incorporating an automatic procedure of first arrival time picking,
b) screen plotting of time-distance graphs, which is useful for identifying types of arrivals,
c) improving the minus times velocity determination, and
d) performing depth error analysis and correction.
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APPENDICES
Appendix A

Application of shallow seismic reflection methods to site investigation

I. A. Hill and J. W. Ali

Synopsis
The conventional approach to site investigation is to perform systematic drilling to the depths of interest. Drilling is essential to the geologist in providing measurable specimens of the rock materials at depth. The disadvantage of drilling is that it provides detailed geological knowledge at the site of the borehole, but does little to establish the geological structure between boreholes. Interpolation is usually done by geological insight and with extra boreholes sunk in ambiguous areas. A method of providing continuous and detailed interpolation of geological features between boreholes is highly desirable. It could reduce the density of the initial borehole grid and the requirement for follow-up drilling. Seismic reflection, resistivity and electromagnetic surveys are already used for this purpose with some success, but all have resolutions that are insufficient to obviate problems of correlation with borehole data. Each is subject to limitations in the range of geological situations for which it will be effective. Seismic reflection in suitable circumstances can provide depth determination accurate to ±10%, but is unreliable where geological boundaries have steep dips or seismic velocity decreases with depth. The results of these methods can be presented as graphs and contour plans.

The conventional approach to site investigation is to perform systematic drilling to the depths of interest. Although useful results have been reported in several case histories, the method has not gained general acceptance. The major reasons are that the applicability of the method in a wide range of geological environments has not been established and that the costs of such surveys can exceed the drilling costs in a more conventional approach.

The developments necessary to produce a practical shallow seismic system and the progress made in implementing these ideas are reported. The essential requirement is to generate and record seismic waves with frequencies of more than 200 Hz. These high-frequency waves have short wavelengths and, hence, produce good spatial resolution of the order of a few metres. A description is given of a combination of seismic source and high-frequency geophones that allows such recording. Data handling and processing are demonstrated with quite cheap seismographs and computers. Results over a known, simple geological structure are presented. Although this illustrates the advantages of the method, its applicability to a wide range of geological environments remains to be proved. This objective is being pursued in current work with encouraging results.

The attractions of the seismic reflection method are that it has potentially the highest resolution of any of the geophysical methods (excluding radar, which has a very limited depth of investigation) and can be applied to a wide range of geological problems. Another great attraction of the method is that the end-product supplied to the geologist for interpretation is an image of the subsurface with a great similarity to a geological section. The application of the method in shallow investigation forms the subject of the work presented here.

Principles of seismic reflection method

A seismic source at or just below the surface of the ground produces P, S and surface waves that radiate outwards. Surface waves do not penetrate deeply into the solid earth and their use for near-surface geological investigations is limited. Both P waves and S waves propagate throughout the solid earth, undergoing refraction and reflection at interfaces and being attenuated by the media through which they travel. Both may yield useful information, and a study of both types of waves can be a powerful way of determining certain physical properties of the transmission media—most importantly, of finding values of Poisson's ratio. In the present discussion only the transmission of P waves is considered.

At any interface a proportion of the energy incident on it will be reflected back into the transmitting medium. Seismic reflection is governed by the same simple laws as apply to optical reflection. The amplitude and phase of the reflected wave, however, vary with the angle of incidence. The simplest case is for normal incidence, where the reflected amplitude is simply determined by the contrast between the acoustic impedances of the two media. The relationship holds approximately for all angles up to the critical angle, at which all relationships become much more complex. Within the area of sub-critical reflection the reflection amplitude depends, to a first approximation, only on the contrast of density and acoustic velocity between the two media. This simple fact indicates two strengths of the reflection method when compared with seismic refraction. First, wave reflection will occur whether the acoustic impedance increases or decreases with depth; and, second, even if the velocity is constant between two media, a change in density alone may produce a reflected wave. These two points, combined with the inherent requirement of the refraction system for quite gradual lateral changes in structure, show the potential advantages of reflection measurements. The same points drove the hydrocarbon industry to change from refraction to reflection methods.

The problem with the reflection method is that the reflected waves are more difficult to detect since they are never the first to arrive at any point on the surface (Fig. 1). Since each seismic wave is of an oscillatory nature, the ground vibration due to each wave will last for a finite time-interval. When two waves arrive at the detector (geophone) at the same time they will interfere and separation of the two effects will be complex. Seismic reflection measurements to large depths can be made relatively easily since the returning reflected waves will arrive at the geophones after the refracted waves have passed, and the surface waves can be filtered out by the use of large
arrays of geophones on the surface. As the depth of investigation decreases the arrival time of the different wave types become increasingly close. Separation of the different waves can be aided if the wave pulse from each lasts for the shortest possible period—that is, if the waves are of high frequency and are generated by a source that is as 'impulsive' as possible. The geophone arrays used to attenuate surface waves also attenuate such high-frequency reflections, making the use of such arrays undesirable. The earth, particularly the poorly compacted near-surface layers, absorbs seismic energy at a rate that depends on frequency, the highest frequencies being attenuated most. For this reason deep seismic surveys use seismic frequencies in the range 20–100 Hz. For shallow surveys the highest possible frequencies must be recorded—preferably > 200 Hz. Even at these frequencies the range of distances between source and geophones within which the reflected waves arrive well separated in time from the other wave types is limited. This range is often referred to as the 'optimum window'. The extent of this detection window for reflected waves can be extended by carefully suppressing the response of the recording system to other interfering wave types—in particular, the air wave and 'ground-roll' (surface wave).

**Fig. 1** Time-distance graph showing arrival times of direct, reflected, refracted and surface waves for simple two-layer earth structure

The requirements for a shallow seismic reflection system can, thus, be summarized as comprising a high-frequency source; transducers capable of registering high-frequency seismic signals; a recording seismograph with adequate dynamic range and sampling interval; and computer processing. These components will be discussed in turn, the first three being the essential hardware components of a field system for the recording of data and the last being the software for extracting the maximum information from the field records. Only those factors which have led to the development of the present system are discussed here since comprehensive reviews of shallow seismic reflection equipment and techniques can be found elsewhere.

### Practical recording of seismic reflection data

The first essential is a source that generates an adequate proportion of its energy at high frequencies and is in a position where near-surface attenuation is minimized. The source should be reliable, environmentally acceptable and efficient in field use, as well as inexpensive and safe. Many have been proposed for this type of work, and comparisons of some have been recently reported. Such sources can be broadly divided into three groups—surface impact, subsurface projectile and subsurface explosive.

The surface impact sources include the simplest possible source, the sledgehammer. It combines a reasonable signal with great convenience, but lacks the power of signals generated at high frequencies that is necessary for highly attenuative near-surface conditions. The factor that gives the greatest convenience—that of acting on the ground surface—is the most fundamental disadvantage in that the severest attenuation occurs in the uncompacted near-surface layers. The projectile sources—essentially, modified large-calibre guns—offer the convenience of a surface source with the advantages of avoiding near-surface attenuation. A heavy lead slug is fired into the ground and penetrates as deep as 1 m, generating seismic waves as it decelerates. The source does have potential for very high-frequency content, as demonstrated by Steeple's, but it has some disadvantages. One, which it shares with the surface-impact sources, is the generation of large surface waves and air-coupled waves that interfere with the returning reflected waves. Another serious, though non-scientific problem is the licensing of such devices in Europe, where firearm regulations are strict.

The preferred source for this study is the 'buffalo gun'. It consists of a length of stout metal pipe machined to hold a 12-gauge cartridge at one end and to take a long, central firing pin to contact the primer cap of the cartridge. The pipe can be inserted into a pre-drilled borehole to any required depth. Blank cartridges, having no lead shot, form a convenient small explosive package. Since the charge is completely confined, there is little air-coupled wave generation and the surface wave is minimized. Additionally, the source is below the least consolidated and, hence, most highly attenuating layer. A firing depth of 1 m has been found to provide the optimum balance between the effort required for drilling and seismic efficiency. The characteristic energy and frequency content of the source can be adjusted by the judicious choice of cartridge. Both the quantity and type of the powder charge, as well as the containment of the charge by wadding and cartridge case, affect the radiated seismic signal. Blank cartridges of any type can be made easily and cheaply by gunsmiths and require no licensing for possession or use in Britain.

As a quantitative test of the assertions made above a field trial was carried out in which reflections were recorded for a variety of sources of each type. Surface impact sources were represented by a weight drop and a sledgehammer, projectile sources by the Betsy Seisgun (a commercially marketed, modified 8-gauge shotgun) and subsurface explosive sources by the buffalo gun, seismic electric detonators and small blasting gelatin charges. The amplitude of the seismic waves, averaged over several measurements, was plotted against distance from the source, the results being shown in Fig. 2. It is clear that the buffalo gun has a very good signal amplitude. The high-frequency content of the signals from the detonator and the buffalo gun is also better than in those from the other sources. This advantage is increased by the reduction in air-coupled and surface waves generated with the buffalo gun when compared with surface or projectile sources. The buffalo gun can be built in a day at a reasonably equipped workshop without special tools or materials, and use of the device has no adverse environmental effects, being quiet and leaving no ground damage. For all reflection work reported here the buffalo gun source was used. Experiments with different charges in the cartridges revealed that the source obeys the established relationship of frequency of radiated...
seismic waves to charge size. Although it is quite possible to manufacture very powerful cartridges, the high-frequency content is rapidly lost with charge sizes much in excess of that commonly used for commercially available blank cartridges.

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The choice of detector for the seismic waves is equally critical. Geophones in common use for conventional seismic work have a resonant frequency in the range 8–30 Hz—usually at the low end of this range. This ensures that they detect with minimum distortion the usual seismic frequency band of 20–100 Hz. At frequencies of more than about ten times their resonant frequency a parasitic mechanical resonance occurs that gives the geophones an unpredictable response. A schematic response curve for a geophone is shown in Fig. 3. Also shown is the ideal response for an accelerometer. This instrument has a regularly increasing sensitivity to high frequencies, which is very useful in recovering the low amplitudes of high-frequency waves caused by the frequency-dependent absorption by the ground materials. Unfortunately, no well-proven field instruments of this type are yet available, although several manufacturers are developing them. In the absence of a suitable accelerometer a high-quality, high-frequency (100-Hz) geophone was selected (Mark Products L-40A-2). Geophones of this type are relatively insensitive to frequencies of less than 50 Hz and have a flat response from 100 to at least 700 Hz. The important effects of filtering at the geophone and the recording instrument are illustrated in Fig. 4, in which identical shots with different geophone and filter combinations are recorded. The contribution of the geophone to improving the high-frequency content of the signal and attenuating the low-frequency ground-roll can be seen to be important, but not sufficient without the aid of additional, analogue, low-cut filters.

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geophones at the same time as the much lower-amplitude reflected waves. One solution is purely financial: equipment used by the hydrocarbon industry overcomes this problem at a cost of five to ten times the price of the engineering seismograph. This cost increase may be prohibitive for site investigation work. The problem can be relieved more simply by applying severe high-pass filtering to the seismic data before digitization. The predominantly low-frequency surface waves are heavily attenuated, but the high-frequency reflected energy is unaffected. Another useful facility is to change the amplification of the input signal with time during recording. This allows the maximum use to be made of the limited dynamic range as the signal amplitudes decrease with time. To speed fieldwork and aid correlation of the data the seismograph should record 24 channels. In the present work a Bison Geopro 8024 was used—a 24-channel engineering seismograph with all the essential features described above. To preserve the digital data they are passed to a portable computer in the field and written on floppy disk. The computer is a repackaged BBC B micro with a second processor and double-density disk interface. The BBC was chosen for its combined virtues of easy interfacing to other instrumentation, ease of programming and low cost. Its deficiency is that its computing power is at least one order of magnitude below that necessary for complex processing of the data.

Data are collected by use of the CMP reflection geometry. Geophones are connected via 'roll along' cables to a 'roll switch', at which any group of 24 geophones can be selected from as many as 120 distributed along the seismic line. The chosen 24 geophones are connected via the switch to the seismograph, where the signals are recorded. Recording of the seismic data is initiated by an electrical pulse supplied by an impact source, in this case a buffalo gun source. The field equipment is shown diagrammatically in Fig. 5. The system is very similar in principle to that used by the hydrocarbon industry. The seismograph stores the data in computer memory and these are transferred via RS232 interfacing to the BBC B computer. The software running in the BBC computer formats the data to a close approximation of SEGY format and enters all necessary header data. The data are stored in computer memory in binary form and can be dumped to floppy disk, each disk holding 24 data files of which each contains one 24-trace seismic record.

**Computer processing of data**

Computer processing of the data has two rather separate aspects. The first is a requirement to analyse the data for quality-control purposes as recording takes place. This must be fulfilled by the field computer. Typical requirements are to view the data at variable amplifications, compute the spectrum of the data traces and apply a frequency filter. The second aspect is the rigorous geometrical correction and signal processing needed to produce a multi-fold seismic section for a given seismic line. These operations require computing power beyond that of any portable microcomputer available at the time of writing, though the speed of development in the microcomputer market indicates that the situation will soon change. For the purposes of the present research the problem was solved by transferring the data to a DEC Vax 8600 mainframe and using a commercially available seismic processing software package. Processing by this system is still under development and will be reported elsewhere.

Whereas complex processing will greatly enhance data quality, for areas with good data quality it is not essential. In such locations a geologically useful section can be produced by displaying a 'constant offset' section. This merely requires the selection of all recorded data traces from any one line with the same shot–geophone distance (offset) and their display as parallel traces in shot order along the line. The result is enhanced by the addition of static corrections to compensate for near-surface velocity variations, frequency filtering and trace mixing to increase continuity across the section.

Additionally, the ability to analyse the 'moveout' on shot records, or, more correctly, on CMP gathers, allows the derivation of stacking velocities that can be used for approximate time–depth conversion.

A library of programs has been written for the BBC microcomputer so that it can perform all of these functions and process good-quality data to produce seismic sections. Since the hardware used is the same as that used for data recording, sections of this type can be produced in the field. The ability to view the data in processed form in the field is of great advantage to the user of this method. It allows planning decisions on the progress of the survey to be made during data acquisition and enables follow-up surveys of particular features of the data to be conducted immediately. The limited facilities of the BBC computer are not regarded as a problem. As soon as a suitably powerful portable computer becomes available it is intended that the present BBC software be transported to such a machine and the more complex processes that are currently restricted to the mainframe processing system be emulated on the field machine.

**Case history**

The utility and geological application of the system can be demonstrated best by a short case history. Near Leicester low-grade metamorphic rocks of late Precambrian age outcrop to form the hills of Charnwood Forest. The Charnian rocks are unconformably overlain by Triassic siltstones and mudstones with sandy lenses of Keuper age. The unconformity surface resulted from arid-climate erosion in Triassic time, the Charnian rocks forming a local massif dissected by eroded wadis, which were gradually filled by locally derived clastic sediments. The local topography of the erosional surface is very uneven with wadis several tens of metres deep. The detection of the form of this surface beneath the
Triassic cover is of interest to the minerals industry as several major quarries operate in the Charnian rocks. The interface is a good geophysical target, presenting a clear contrast in most physical rock properties—notably, density, seismic velocity, porosity and resistivity.

Geophysical surveys to determine the unconformity surface have been conducted by various operators using dc resistivity, electromagnetic (EM34) and seismic refraction techniques. Because of the excellent contrast in resistivity between the lithologies separated by the unconformity both dc resistivity and electromagnetic surveys produce useful results. Resistivity depth sounding very clearly shows the interface, but, because of the large horizontal scale of the measurements (>100 m), relative to the wavelength of the topography on the unconformity, the depths produced are lateral averages and topographic detail is not resolvable. Electromagnetic surveys provide a very good semi-quantitative guide to the unconformity topography, higher resistivities corresponding to smaller depths to the interface. The results may be calibrated by boreholes, but the relationship of sampled resistivity values to depths is not simple owing to lateral resistivity variations in drift, Trias and the Charnian itself. The EM technique represents a very cost-effective, qualitative reconnaissance mapping method, but it cannot provide detailed, calibrated information on the fine structure of the interface at scales of less than about one quarter of the depth of burial.

The seismic refraction technique provides a more accurate quantitative estimate of depth, generally to an accuracy of ±10 m, but the steep topography on the wadi structures and the occurrence of thin high-velocity layers within the wadi-fill sediments create conditions in which the assumptions made in the standard interpretation methods (plus-minus or generalized reciprocal method) are violated and accuracy decreases.

A test reflection survey was conducted over an area of essentially flat surface topography where the depth to the unconformity was known from borehole data. Resistivity and seismic refraction data have been collected in the same test area and reveal the approximate structure, subject to the difficulties outlined above. Fig. 5(a) shows the geology beneath the test line as inferred from borehole data: the line was chosen to run across a wadi structure approximately perpendicular to its axis. The depths to the unconformity vary from just over 100 m at the left-hand end of the wadi to about 30 m at the right-hand end of the section. In the axis of the wadi a layer of breccia up to 15 m thick overlies the unconformity. The seismic refraction results (Fig. 5(b)) systematically underestimate the true depths, partly because of the increase in velocity with depth of the sediments and partly because of the complexity of interpreting seismic waves that are travelling essentially horizontally through a laterally varying structure. Depth sounding by dc resistivity (Fig. 5(c)) gives only a general average depth to the interface. Detailed resistivity traversing with interpretation by computer modelling could generate more informative results, but such data were not collected for the present investigation.

The seismic reflection survey was conducted with the equipment described above, geophones and shots both being spaced at 2-m intervals to give reflection points from the subsurface at 1-m spacing. The survey line slightly exceeded 200 m in length. For each shot 24 geophone traces were recorded with analogue filters set at 200–825 Hz pass band. This geometry gives 12 separate reflected wave measurements from each reflection point (spaced at 1-m intervals), each measurement with a different shot–geophone offset. For the reasons described above certain offsets will produce data that represent reflection more clearly than others. A search of the

![Diagram](image-url)
more simple form, making discrimination of individual, closely spaced reflecting horizons much clearer. These processing techniques are not novel and can be accomplished with readily available software. The purpose of this case history is to illustrate that even without such complex processing a clear and useful image of the subsurface geology can be derived. Fig. 8 demonstrates the effect of signal to noise improvement brought about by a stack of the twelvefold data traces for part of the line shown in Fig. 7; the processing was carried out on the field computer system. Most stacked traces are the sum of between four and eight field traces, selected as those with the best combination of offset distance and signal to noise ratio in each common reflection point (CMP) gather. The unconformity reflection has been strongly enhanced in relation to the noise, which in this case is mostly generated by the source—that is, wave types from the source other than reflected P waves. Waveform processing is beyond the computing power of the present field computer system and is not demonstrated here.

**Discussion**

The barriers to the wider use of shallow seismic reflection in site investigation are threefold. The first is the doubt about whether such measurements can be made at a useful variety of geological sites. The propagation of the high-frequency waves used is dependent on the attenuation in the near-surface materials. The exact limitations can only be determined by a much wider variety of field trials, which are in progress at present. The second is the question of cost-effectiveness. This method gives a much more detailed subsurface image than other geophysical methods. The qualitative contours of electromagnetic surveys are certainly useful for reconnaissance investigations, and the data are acquired quickly and cheaply. It is where detailed geological information is required—for example, in quarry design or reserve volume estimation—that the reflection method would be appropriate. The collection of data for a research project with the use of an experimental system does not permit representative survey...
costing. However, it is worth recording that the data were collected by a field party of four men in less than one working day, using equipment with a capital cost of less than £50 000. The constant-offset section can be produced with a further two hours' work. Complex computer processing would currently add a significant amount to the cost owing to the need to use a large, mainframe computer. As pointed out above, this situation is likely to change very rapidly with the increasing power of small computers.

The exciting future for shallow seismic reflection lies not only in the present capability of the method but also in the host of new technical developments in prospect that will enhance it. These can be summarized as improved signal detection through the use of accelerometers rather than geophones, improved signal recording through the development of cheap, faster analogue to digital converter circuits and the improved processing capabilities of small computers. These, of course, must be accompanied by the development of suitable processing procedures and appropriate software. Although the processing aims are essentially similar to those achieved by commercial hydrocarbon industry operators, the rather peculiar nature of shallow reflection data requires careful rethinking of 'standard' operations. The concept of static corrections is difficult to apply to these data since the whole data record may correspond to less than the 'weathered layer' of more conventional work. Waveform processing also presents a challenge in that the normal statistical methods used for operator design in deconvolution are unlikely to be valid for these data.

Acknowledgement

Sites for field trials were kindly provided by various companies, which also supplied geological control information—in particular, borehole records and cores. The data were collected with the help of various members of the geophysics group at Leicester University. J.W.A. was supported for the duration of this work by a scholarship from the Iraqi Government. Continuation of the work is funded by the Mineral Industry Research Organisation (MIRO).

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Authors
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J. W. Ali, who graduated in Baghdad, Iraq, in 1977, worked for the Directorate General for Geological Survey and Mineral Investigation, Baghdad, before continuing his studies at the University of Windsor, Ontario, Canada, where he obtained the degree of M.Sc. in geology and geophysics in 1983. He is currently completing a doctorate at Leicester University, England.
APPENDIX B  Seismic refraction data for Line 10.

Appendix B.1  Raw seismic data for Line 10.

(Information about the weight of the explosive charges and the type of geophones used in the refraction survey are not available)

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**Title:** BARDON HILL - JULY 1984 - LINE 10

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23.0 | 440.0 | 0.0 | 179.4 | 152.5 | 112.0 | 75.1 | 33.1 | 44.6 | 76.2 | 110.1
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**Shot Details:**

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Appendix B.2 Corrected seismic data for Line 10.
Appendix B.3 Seismic data for the short hammer survey.

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Appendix B.5 Depths and elevations of subsurface layers obtained from seismic Profiles A-F.

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APPENDIX C Description of program REFRAC

Appendix C.1 The main program

Several options are available on the program which need to be specified by the user. These include the interval (in stations) at which velocity (by the least square method) is determined, type of smoothing of velocity and depth, type of averaging used in TP and TM calculations and other options concerning plotting of results.

The program starts by reading data from a formatted file (see Appendix C.3). Error messages are printed out if data are wrongly formatted or if the read data are unexpected. Data are stored in arrays, referenced by their station numbers. Information about geophones, shots and first arrival times can be printed out for verification.

The process of interpretation starts with the determination of $V_j$ by subroutine FORVEL. This is done by fitting a regression line through a set of time-distance pairs using the least square method. Next, forward refractor velocities $V_2$ and $V_3$ are determined using the same subroutine. These velocities are measured for each shot record or for records at the specified interval. The velocity values are assigned to stations in the middle of the projection of the segment of the corresponding time-distance curve on the surface of the ground. Correlation coefficients of the time-distance fit and intercept times (for $V_2$ and $V_3$) are also determined.

Once forward velocities are obtained, the process of true velocity measurement by subroutine TRUEVEL begins by correcting arrival times (if shots where fired below the surface of the ground) using subroutine SHOTCOR. Then, data are reduced to a plane datum close to the surface of the ground at the lowest geophone height. True velocity is determined from a forward shot record and a constructed reverse profile using the Hobson-Overton least square method by subroutine LEASQUR (see Section 4.4.2). Standard error of the travel times is measured too. The determined true velocity and forward velocity are used to calculate the dip of the refractor.
The true velocity determination process covers the seismic line at the specified shot spreads. These velocities then overwrite the forward velocities in the arrays. If reverse profiles cannot be constructed from the forward arrivals, the forward velocities are used for subsequent calculations. The useable velocities are then linearly interpolated between stations and extrapolated at the end of the line by subroutine VELPOLATE. A table with the results which includes the velocities, standard errors and correlation coefficients is printed out.

The process of shot correction of the raw data (subroutine SHOTCOR) is then repeated using the newly determined velocities. The correction times for all the shots along the line are saved into arrays and a list of these times is printed out.

Then, subroutine DELAYCAL is used to calculate the plus times. Selection of the stations (shots and geophones) which construct the required raypath configuration is carried out. The calculated plus times for each shot-receiver station are averaged (using either the mean, trimmed mean or median). The averaged values are saved into arrays and a table containing these values and their standard deviations is then printed out.

The process of minus time determination then follows, using subroutine VELMINUS. This process is fairly similar to the previous subroutine in constructing the raypath configuration and determining the minus time. Minus times measured over the same raypath are averaged out (using either the mean, trimmed mean or median) and are used to obtain the velocity of the refractor which is assigned to the station in the middle of the raypath (Figure 4.1). Then, velocities are interpolated and extrapolated using subroutine VELPOLATE. A list containing the minus velocities and their standard deviations is printed out.

The next step is depth determination using subroutine DEPTHCAL. The depth is calculated for each station where the plus time was measured. For stations where TP was not obtained, intercept times and modified geophone delay times are used. Depth conversion normally uses velocities determined from the minus times, but true velocities are used
if the number of points at which they are determined is greater than twice the number of points of those obtained by the minus time. If neither true velocities nor minus velocities can be obtained, forward velocities are used.

Statics for subsurface layers are then calculated at each station along the seismic line. A print out of the determined layer thicknesses along the line is then produced.

Smoothing, if required, can be applied to velocities and layer thickness using subroutine SMOOTH from within subroutine DEPTHCAL. Velocities are always smoothed before commencing depth calculation. Then, once the depths to the first interface are obtained, they are smoothed before they are used in the calculation of the depths to the second interface. Smoothing (filtering) can be done in two ways:

1) By using the weighted average (binomial) mean. This is obtained over 5 points using different weighting factors (5-1). The value of the mean is assigned to the station with the highest weight.

2) By using the running mean. It is obtained by averaging, with equal weight, over a certain "odd" number of points after rejecting the highest and the lowest values. The mean value is assigned to the middle station. Seven or nine smoothing points can be chosen. In the case of velocity smoothing only, the chosen number of points are used for smoothing $V_2$ while for $V_1$ smoothing is made over a lower (by 2) number of points. On the other hand, smoothing for $V_3$ is made over a higher (by 2) number of points. This filter has a steeper slope on the short wavelength response than the binomial mean.

The increased severity of the filter with depth is quite justified since: a) the lateral variation in velocity may be expected to decrease with layer depth and b) the picking errors on the furthest offset traces are expected to be higher than for the nearer geophones.

The results of the interpretation which include layer thickness, least-square velocity, minus velocity, statics and dip are printed out for each station along the line. Statistical measures of the results are also printed.
Notification is given of the types of velocities and times used in depth calculation and of the type of smoothing of velocity and depth. These results are also written into a datafile.

Finally, the results are written into a graphical output file using subroutine PLOTS. Plots of velocities, depths and statics are made available.
Appendix C.2 Subroutines used in program REFRAC

**RORVEL**
This subroutine measures $V_1$ from direct arrivals and $V_2$ and $V_3$ from forward refractor arrivals. It uses subroutine REGLIN to calculate these velocities as well as their correlation coefficients. It, then uses subroutine VELPOLATE for velocity interpolation and extrapolation.

**REGLIN**
This subroutine computes velocity and intercept time by fitting a straight line through a set of arrival times received by geophones and the distances of the geophones from the shot using the least square method. Subroutine DATATYPE is used to identify the type of the arrivals received by the set of geophones.

**TRUEVEL**
This subroutine uses FORVEL to obtain forward $V_2$ and $V_3$ and subroutine SHOTCOR for shot correction. It then calls subroutine LEASQUR to compute the true velocity and dip of the refractor. These velocities are then interpolated and extrapolated by subroutine VELPOLATE.

**LEASQUR**
This procedure starts by reducing the arrival times to a datum plane at an elevation equal to that of the lowest geophone in the shot spread. Refracted arrival times are identified, using subroutine DATATYPE, and the corresponding geophone stations are marked. Reversed arrival times are then produced from combinations of the last geophone in the forward shot record and different shots located at the marked geophone stations. True velocity is then computed using the Hobson-Overton least square method. The standard error of fit of the geophone set is also determined. Reversed velocity is obtained and the dip of the refractor is calculated.

**VELPOLATE**
This subroutine uses linear interpolation of velocities between stations and extrapolates velocities for stations at
the end of the line. Extrapolation is done by assigning a constant velocity to these stations. This velocity is obtained by averaging out velocities at 5 nearby stations.

**DATATYPE**

This process is used to identify live geophones with the same type of arrivals. Type 1, 2 and 3 are used for the direct, refracted from the second layer and refracted from the third layer arrival times, respectively. Zero type is used for dead geophones and type -1 for missing shots.

**SHOTCOR**

This subroutine determines the time needed for the arrival times in order to correct for the shot not being at the surface (or precisely at the position and height of the geophone at the shot-geophone station).

**DELAYCAL**

This and subroutine VELMINUS are the most important processes in the program. DELAYCAL starts by searching for the shot-geophone combinations which construct the required raypath configuration and having the same data type. Plus times are calculated at the reference shot-geophone station and their average (which can be either the mean, trimmed mean or median) and the standard deviation is determined (by subroutine STATISTICS) and assigned for that station.

**VELMINUS**

This procedure is fairly similar to that of subroutine DELAYCAL in terms of establishing the required raypath configuration. It determines minus times over a segment of the refractor and uses subroutine STATISTICS to find their average (mean, trimmed mean or median) and their standard deviation. The average minus time is converted into velocity which is assigned to the station in the middle of the segment.

**DEPTHCAL**

This subroutine uses the determined velocities, plus times and intercept times to determine the thickness of the
layers. It calls subroutine GEOPHDEL to calculate the modified geophone delay time for stations which do not have plus or intercept times. Subroutine SMOOTH is used to smooth velocities before thickness calculation and afterward to smooth the thickness itself.

GEOPHDEL
This procedure is used to measure the difference between refracted arrival times (modified delay time) at successive geophones. These geophones are usually located at the end spread of the end-on recording geometry; the last spread where geophones lead the shots along the seismic line and the first spread where the shots lead the geophones.

SMOOTH
This subroutine is used to smooth velocities and depths by averaging over a certain number of stations. It employs two types of filtering procedure: 1) binomial weighted average over 5 points, 2) running mean over 7 or 9 points with the rejection of the maximum and minimum values in that interval.

STATISTICS
This subroutine is useful for determination of statistical measures. These include the mean, 10% trimmed mean, median, mean deviation, standard deviation and the minimum and maximum values.

PLOTS
This subroutine produces a grid file of velocity, depth and statics plots. It sets the border lines, captions and the scaling of these plots. It uses subroutine GRAPH to draw these plots.

GRAPH
This procedure is used at each time to plot the values of either velocity, depth or statics along the seismic section.

Modifications of Subroutines GRAPH and PLOTS are used in program MIXPLOT.
Appendix C.3 Datafile format

Refraction data deduced from the CMP reflection recording are read into the Fortran program REFRAC from a datafile (e.g. LINE01.DAT). The data are written in a list-directed format where each record is typed in a separate line in the following order:

1) LINE 1 contains (2 numbers):-
   Number of stations (STATION), Station interval (STINT).

2) "STATION" OF LINES, each contains (4 numbers):-
   Station number (STNO), Height (HEIGH), normal offset (GNOFF), Depth (GDEPT).

3) NEXT LINE contains (2 numbers):-
   Number of subsurface layers 'earth model' (MODEL),
   Minimum number of channels 'or gap' which receive direct wave arrival (GAP).

4) NEXT LINE contains (3 numbers):-
   Number of spreads (NSPRD), Number of channels (NCH),
   Type of recording (GFLAG).

5) "NSPRD" OF LINES, each contains (4 numbers):-
   Spread number (SPRDN), First geophone-source offset (GlSOFF),
   Geophone spacing (STSPC), Gap between geophone 12-13 (MIDGAP).

6) NEXT LINE contains (3 numbers):-
   Number of shots (NSH), Shot interval (SHINT), Nominal offset (OFFSET).

7) "NSH" OF BLOCK OF LINES, each contains:--
   a) A LINE contains (2 numbers):-
      Shot station (SHST), Spread number (SPRDN).
   b) NEXT LINE contains (3 numbers):-
      Shot normal offset (SNOFF), Shot depth (SDEPT),
      Uphole velocity (UPTIME).
   c) "NCH" OF LINES, each contains (4 numbers):-
      Geophone number (GEONO), Arrival time (ARTIM),
      Arrival type (DT), Difference between nominal geophone depth and that used for a particular shot (DEPDF).
Units of measurement

(1) Shots and geophones are referred to by stations.
(2) Station 'geophone' height, normal offset, depth and spacing are measured in metres.
(3) Shot depth and normal offset are measured in metres.
(4) Shot and geophone depths and differences in geophone depths (below or above a certain datum or level) are positive downward and negative upward.
(5) Arrival time is measured in ms.
(6) Velocity is measured in metre/ms.
(7) GFLAG refers to type of recording:
   0 is used for end-on spread, geophones leading.
   1 is used for end-on spread, geophones tailing.
(8) DT refers to type of arrival data:
   -1 is used for missing shot.
   0 is used for dead geophone.
   1 is used for direct wave.
   2 is used for refraction from second layer.
   3 is used for refraction from third layer.
(9) The format of data in the datafile is as follows:

   Arrival time (F5.1).
   Distance (F5.2).
   Height (F6.2).
   Velocity (F5.3).
   Thickness (F5.2).
   Statics (F4.1).
Appendix C.4 Listings of Programs REFRAC and MIXPLOT.

Appendix D.1 Frequency response curves and geophone specifications get:
1) the 6 lb. geophone.
2) the 14 lb. geophone.

PROGRAM REFRAC

11/10/89 11:48:43 01

Vertical hardness: 150 psi. 
Chemical age resistance
Resistance: 100 psi. 
Certified for: 100 psi. 
Cement: 100 psi. 

For more information, please refer to the manual.
APPENDIX D  Recording equipment specifications

Appendix D.1  Frequency response curves and geophone specifications of:

a) the 8 Hz geophone.

b) the 14 Hz geophone.

(a) Standard Specifications of the 8 Hz Geophone

- **Frequency Range, Hz**: 4.5-10
- **Frequency Tolerance**: ±0.5 Hz
- **Standard Coil Resistance, Ohms**: 138/215/374
- **Resistance Tolerance, %**: 5 / 5 / 5.5
- **Maximum Distortion @ 0.7 in/s**: 0.2%
- **Transduction Constant, V/in/s**: 0.031 V/Rc
- **Open Circuit Damping, ±10%**:
  - **Coil Current Damping**: f
  - **Suspended Mass, Grams**: 17.00
  - **Power Sensitivity, mW/in/s**: 1.67
  - **Case-to-Coil, Motion, in. p-p**: 0.080
  - **Basic Unit Diameter, in.**: 1.25
  - **Basic Unit Height, in.**: 1.4
  - **Basic Unit Weight, oz.**: 5.0

(b) Standard Specifications of the 14 Hz Geophone

- **Natural frequency, Hz ±5%**: 14, 20, or 28
- **Standard coil resistance @ 25°C, Ω ±5%**: 215
- **Optional coil resistances, Ω**: 20 to 1450
- **Total moving mass, oz (g)**: 0.195 (5.54)
- **Intrinsic voltage sensitivity, V/in/s (V/m/s)**: 0.29 (11.4)
- **Intrinsic power sensitivity, mW/in/s (W/m/s)**: 0.392 (0.61)
- **Voltage/weight ratio @ 215 Ω, V/in/s oz (V/m/s/g)**: 0.161 (0.022)
- **Power/weight ratio, mW/in/s oz (W/m/s/g)**: 0.218 (0.012)
- **Normalized transduction constant, V/in/s (V/m/s)**: 0.0198 V/Rc (0.78 V/Rc)
- **Maximum coil excursion P-P, in (cm)**: 0.06 (0.15)
- **Damping constant**:
  - **with 215 Ω coil**: 130.91, or 65
  - **with 215 Ω coil**: 1 (2.54)
- **Height, in (cm)**: 0.875 (2.22)
- **Diameter, in (cm)**: 1.8 (51)
Appendix D.2 Frequency response curves of analogue filters on the Bison Geopro 8024 seismograph.
APPENDIX E Mathematical background

Appendix E.1 Convolution

Convolution is a mathematical operation with a wide range of application in the time domain. Convolution of two continuous functions, e.g. \( f(t) \) and \( g(t) \), is defined as follows:

\[
h(t) = \int_{-\infty}^{\infty} f(\tau) g(t-\tau) \, d\tau \quad \ldots \quad (E.1)
\]

It is usually expressed by:

\[
h(t) = f(t) * g(t) \quad \ldots \quad (E.2)
\]

where \( h(t) \) is the convolution product (Sheriff and Geldart, 1983).

For discrete functions \( f_i \) and \( g_i \), convolution can be written as follows:

\[
h_j = \sum_{i=0}^{m} f_i \, g_{j-i} \quad \ldots \quad (E.3)
\]

This equation shows that one function is reversed and swept along the time-axis an integer at a time (assuming sampling period of unity). At each shift position, corresponding elements of both functions are multiplied and summed to produce a point of convolved output function. An example of this is frequency filtering where the seismic signal and a filter operator may be convolved in time domain. The seismic signal itself can also be considered as the convolution of the source wavelet and the reflectivity series with time (Hatton et al, 1986).

The process of convolution of functions in the time domain is equivalent to multiplication of the Fourier transforms of the functions in the frequency domain. This represents the convolution theorem:

\[
f(t) * g(t) \leftrightarrow F(\omega) \cdot G(\omega) \quad \ldots \quad (E.4)
\]

This relationship is of a great importance in seismic data processing because it allows processing to be done in the most suitable domain.
Appendix E.2 Fourier transform

The Fourier transform (FT) is a mathematical operation which provides a means of converting a function from one domain to another such as transforming a time domain function (seismogram) into a frequency domain function (spectrum) and vice versa. It is based on Fourier series where any function can be represented as a simple trigonometric series. For a periodic continuous function of time \( g(t) \) with a period \( \tau \), \( g(t) \) can be expanded in an infinite series as follows:

\[
g(t) = a_0/2 + \sum_{n=1}^{\infty} \left[ a_n \cos(2\pi nt/\tau) + b_n \sin(2\pi nt/\tau) \right] \quad \text{(E.5)}
\]

where

\[
a_n = \frac{2}{\tau} \int_{-\frac{\tau}{2}}^{\frac{\tau}{2}} g(t) \cos(2\pi nt/\tau) \, dt \quad \text{(E.6)}
\]

\[
b_n = \frac{2}{\tau} \int_{-\frac{\tau}{2}}^{\frac{\tau}{2}} g(t) \sin(2\pi nt/\tau) \, dt
\]

for \( n = 0 \) to \( \infty \); \( 2\pi/\tau = \omega_0 \); \( 2\pi n/\tau = \omega \) is the angular frequency of the \( n \)th term.

The three constants \( a_0 \), \( a_n \), and \( b_n \) are known as Fourier coefficients. Their derivation can be found in Camina and Janacek (1984). Equations E.5 and E.6 indicate that the periodic function \( g(t) \) can be represented by an infinite number of sinusoidal waves whose frequencies are integral multiples of that of the function \( g(t) \). The angular frequency \( 2\pi/\tau \) is the fundamental and its integral multiples are the harmonics \( (n2\pi/\tau) \). The transformation from time domain to the frequency domain is called Fourier analysis (Sheriff and Geldart, 1983).

Fourier series of the periodic function \( g(t) \) can also be written in exponential form with the aid of Euler formula (\( e^{i\theta} = \cos \theta + i\sin \theta \)) as follows:

\[
g(t) = \sum_{n=-\infty}^{\infty} c_n e^{in\omega_o t} \quad \text{........ (E.7)}
\]

where
\[ c_n = \frac{1}{\tau} \int_{-\frac{\pi}{\tau}}^{\frac{\pi}{\tau}} g(t) e^{-i n \omega t} \, dt \]

\[ = \frac{1}{\tau} \int_{-\frac{\pi}{\tau}}^{\frac{\pi}{\tau}} g(t) \cos(n \omega t) \, dt - i/\tau \int_{-\frac{\pi}{\tau}}^{\frac{\pi}{\tau}} g(t) \sin(n \omega t) \, dt \]

\[ i = -1; \quad c_n = \frac{1}{2}(a_n - i b_n) \quad \text{for } n > 0; \quad \text{for } n < 0, \]

\[ c_n = \frac{1}{2}(a_n + i b_n). \]

For a transient function, Fourier series are replaced by Fourier integrals to represent these functions. As the period \( \tau \) approaches infinity, the fundamental frequency \( 2\pi/\tau \) approaches zero resulting in a continuous frequency spectrum and the summation in Equation E.7 can be replaced by integrals and the transient function \( g(t) \) is as follows:

\[ g(t) = \int \left[ \int g(t) e^{-i \omega t} \, dt \right] e^{i \omega t} \, d\omega / 2\pi \quad \ldots \quad (E.8) \]

This equation can be written:

\[ g(t) = \int_{-\infty}^{\infty} G(\omega) e^{i \omega t} \, d\omega / 2\pi \quad \ldots \quad (E.9) \]

where

\[ G(\omega) = \int_{-\infty}^{\infty} g(t) e^{-i \omega t} \, dt \quad \ldots \quad (E.10) \]

\( G(\omega) \) is known as the Fourier transform of \( g(t) \) and \( g(t) \) the inverse Fourier transform of \( G(\omega) \). These constitute a Fourier pair and are represented by the notation:

\[ g(t) \leftrightarrow G(\omega) \quad \ldots \quad (E.11) \]

Further, the quantity \( G(\omega) \) can be expressed as:

\[ G(\omega) = [a^2(\omega) + b^2(\omega)]^{1/2} e^{i\phi(\omega)} \quad \ldots \quad (E.12) \]

where

\[ |G(\omega)| = [a^2(\omega) + b^2(\omega)]^{1/2} \]

\[ \phi(\omega) = \tan^{-1} \left[ b(\omega)/a(\omega) \right] \]

The modulus \( |G(\omega)| \) is known as the amplitude spectrum of \( g(t) \), \( \phi(\omega) \) is the phase spectrum, \( a(\omega) \) is the cosine spectrum and \( b(\omega) \) is the sine spectrum.

So far, \( g(t) \) was considered as a continuous and infinite
function. In practice, however, functions representing data (such as seismograms) are usually of finite length and stored in digital form which may cause spectrum distortion due to the truncation effect and aliasing, respectively. A discussion of these effects can be found in Hatton et al (1986) and Sheriff and Geldart (1983).

The finite discrete Fourier transform (DFT) is a convenient version for machine computation. If the time \( t \) is replaced by \( r d \) where \( r \) is an integer \( (0,1,2,...,n-1) \) and \( d \) is the sample interval \( (T/n) \); then Equations E.9 and E.10 can be written in the form of DFT as follows:

\[
G(v) = \frac{1}{n} \sum_{r=0}^{n-1} g(r) . e^{-2\pi vr/n} \quad \cdots \quad (E.13)
\]

and the inverse DFT:

\[
g(r) = \sum_{v=0}^{n-1} G(v) . e^{2\pi vr/n} \quad \cdots \quad (E.14)
\]

Derivation of the finite discrete Fourier transform can be found in Bracewell (1978), Camina and Janacek (1984), and Hatton et al (1986). The DFT requires \( N^2 \) arithmetical operations of multiplication and addition. The number of calculations can be reduced to the order of \( N \log_2 N \) by the use of the fast Fourier transform (FFT) algorithm which is based on decomposing the series (i.e. time series) sequentially into half-series. This requires that \( N \) must be a power of 2 at each split of the series. The DFT is then obtained by summing the shorter DFTs.
APPENDIX F Description of BBC seismic reflection programs

Appendix F.1 BBC file and trace headers memory allocation

Memory locations (decimal)
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Start of trace 1 header 18084 (46A4 Hexadecimal).
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<td>25337</td>
<td>18</td>
<td>38637</td>
<td>38822</td>
<td>39845</td>
</tr>
<tr>
<td>7</td>
<td>25338</td>
<td>25523</td>
<td>26546</td>
<td>19</td>
<td>39846</td>
<td>40031</td>
<td>41054</td>
</tr>
<tr>
<td>8</td>
<td>26547</td>
<td>26732</td>
<td>27755</td>
<td>20</td>
<td>41055</td>
<td>41240</td>
<td>42263</td>
</tr>
<tr>
<td>9</td>
<td>27756</td>
<td>27941</td>
<td>28964</td>
<td>21</td>
<td>42264</td>
<td>42449</td>
<td>43472</td>
</tr>
<tr>
<td>10</td>
<td>28965</td>
<td>29150</td>
<td>30173</td>
<td>22</td>
<td>43473</td>
<td>43658</td>
<td>44681</td>
</tr>
<tr>
<td>11</td>
<td>30174</td>
<td>30359</td>
<td>31382</td>
<td>23</td>
<td>44682</td>
<td>44867</td>
<td>45890</td>
</tr>
<tr>
<td>12</td>
<td>31383</td>
<td>31568</td>
<td>32591</td>
<td>24</td>
<td>45891</td>
<td>46076</td>
<td>47099</td>
</tr>
</tbody>
</table>

File header memory allocation

<table>
<thead>
<tr>
<th>Byte nos.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CDP% CDP fold of data &quot;nominal&quot; (1-48)</td>
</tr>
<tr>
<td>2-25</td>
<td>CL$ Client (23 characters +1)</td>
</tr>
<tr>
<td>26-49</td>
<td>CO$ Company (23 Chars.+1)</td>
</tr>
<tr>
<td>50</td>
<td>CR% Number of crew (integer 1-255)</td>
</tr>
<tr>
<td>51</td>
<td>L% Line number (integer 1-99)</td>
</tr>
<tr>
<td>52-76</td>
<td>SA$ Survey area (24 chars.+1)</td>
</tr>
<tr>
<td>77-103</td>
<td>MI$ Map I.D. (26 chars.+1)</td>
</tr>
<tr>
<td>104</td>
<td>RE% Reel number (Integer 1-255)</td>
</tr>
<tr>
<td>105-106</td>
<td>JD% Julian day</td>
</tr>
<tr>
<td>107-108</td>
<td>YR% Year (A.D.)</td>
</tr>
<tr>
<td>109-125</td>
<td>OB$ Observer (16 chars.+1)</td>
</tr>
</tbody>
</table>
126-138  KIT$  Instrument manufacturer (12 chars.+1)
139-151  KIT1$  Instrument model (12 chars.+1)
152-162  KIT2$  Instrument serial no. (10 digits.+1)
163     C%  Number of channels of data (1-24)
164     CA%  Number of auxiliary channels (1-24)

**Trace header memory allocation**

<table>
<thead>
<tr>
<th>Byte nos.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td>TSEQ%  Trace sequence number within line</td>
</tr>
<tr>
<td>5-8</td>
<td>TSEQD%  Trace sequence number on disc</td>
</tr>
<tr>
<td>9-12</td>
<td>SNO%   Original field record number</td>
</tr>
<tr>
<td>13-16</td>
<td>TN%    Trace number in original field record</td>
</tr>
<tr>
<td>17-20</td>
<td>ENO%   Energy source point number</td>
</tr>
<tr>
<td>21-24</td>
<td>CMPN   CMP ensemble number</td>
</tr>
<tr>
<td>25-28</td>
<td>TNCMP%  Trace number within the CMP ensemble</td>
</tr>
<tr>
<td>29-30</td>
<td>TCID%  Trace I.D. code</td>
</tr>
<tr>
<td></td>
<td>1=seismic data  2=dead  3=dummy</td>
</tr>
<tr>
<td></td>
<td>4=time break  5=uphole  6=sweep</td>
</tr>
<tr>
<td></td>
<td>7=timing  8=water break</td>
</tr>
<tr>
<td></td>
<td>9=-----N =optional use (32767)</td>
</tr>
<tr>
<td>31-32</td>
<td>SH%    Number of vertically summed traces</td>
</tr>
<tr>
<td>33-34</td>
<td>STA%   Number of horizontally summed traces</td>
</tr>
<tr>
<td>35-36</td>
<td>DUS%   Data use: 1=production, 2=test</td>
</tr>
<tr>
<td>37-40</td>
<td>SGD    Distance from source point to receiver (+ve in direction of increasing shot point numbers.)</td>
</tr>
<tr>
<td>41-44</td>
<td>GHT    Receiver group elevation (-ve B.S.L.)</td>
</tr>
<tr>
<td>45-48</td>
<td>SHT    Surface elevation at source</td>
</tr>
<tr>
<td>49-52</td>
<td>SZ     Source depth below surface (always +ve)</td>
</tr>
<tr>
<td>53-56</td>
<td>DHG    Datum elevation at receiver group</td>
</tr>
<tr>
<td>57-60</td>
<td>DHS    Datum elevation at source</td>
</tr>
<tr>
<td>61-64</td>
<td>WDS    Water depth at source</td>
</tr>
<tr>
<td>65-68</td>
<td>WDG    Water depth at group</td>
</tr>
<tr>
<td>69-70</td>
<td>HDS%   Scaler to be applied to all elevations and depths specified in (41-68), e.g. -100=divide by 100.</td>
</tr>
<tr>
<td>71-72</td>
<td>XYS%   Scaler to be applied to all coordinates (73-88), e.g. +10=multiply by 10.</td>
</tr>
<tr>
<td>Column Numbers</td>
<td>Description</td>
</tr>
<tr>
<td>----------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>73-76</td>
<td>SX Source coordinate - X</td>
</tr>
<tr>
<td>77-80</td>
<td>SY Source coordinate - Y</td>
</tr>
<tr>
<td>81-84</td>
<td>GX Group coordinate - X</td>
</tr>
<tr>
<td>85-88</td>
<td>GY Group coordinate - Y</td>
</tr>
<tr>
<td>89-90</td>
<td>CDU Coordinate units: 1=length (metres or feet), 2=seconds of arc</td>
</tr>
<tr>
<td>91-92</td>
<td>WV Weathering velocity</td>
</tr>
<tr>
<td>93-94</td>
<td>SWV Subweathering velocity</td>
</tr>
<tr>
<td>95-96</td>
<td>UTS Uphole time at source</td>
</tr>
<tr>
<td>97-98</td>
<td>UTG Uphole time at group</td>
</tr>
<tr>
<td>99-100</td>
<td>STC Source static correction</td>
</tr>
<tr>
<td>101-102</td>
<td>GSC Group static correction</td>
</tr>
<tr>
<td>103-104</td>
<td>TSA Total static applied (Zero if not)</td>
</tr>
<tr>
<td>105-106</td>
<td>LTA% Lag time A in ms.</td>
</tr>
<tr>
<td>107-108</td>
<td>LTB% Lag time B in ms.</td>
</tr>
<tr>
<td>109-110</td>
<td>DEL% Delay recording time in ms.</td>
</tr>
<tr>
<td>111-112</td>
<td>MTST% Mute time - start</td>
</tr>
<tr>
<td>113-114</td>
<td>MTED% Mute time - end</td>
</tr>
<tr>
<td>115-116</td>
<td>S% Number of samples in this trace</td>
</tr>
<tr>
<td>117-118</td>
<td>US% Sample interval in us for this trace</td>
</tr>
<tr>
<td>119-120</td>
<td>SGT% Gain type of field instrument: 1=fixed, 2=binary, 3=floating, 4--N=optional use</td>
</tr>
<tr>
<td>121-122</td>
<td>GINC% Instrument gain constant</td>
</tr>
<tr>
<td>123-124</td>
<td>GA% Instrument early or initial gain (dB)</td>
</tr>
<tr>
<td>125-126</td>
<td>CORL% Correlated: 1=no, 2=yes</td>
</tr>
<tr>
<td>127-128</td>
<td>SFST% Sweep frequency at start</td>
</tr>
<tr>
<td>129-130</td>
<td>SFED% Sweep frequency at end</td>
</tr>
<tr>
<td>131-132</td>
<td>RL% Sweep length in ms.</td>
</tr>
<tr>
<td>133-134</td>
<td>ST *Sweep type: 1=linear, 2=parabolic, 3=exponential, 4=other</td>
</tr>
<tr>
<td>135-136</td>
<td>STLS% Sweep trace taper length at start in ms.</td>
</tr>
<tr>
<td>137-138</td>
<td>STLE% Sweep trace taper length at end in ms.</td>
</tr>
<tr>
<td>139-140</td>
<td>TAT% Taper type: 1=linear, 2=cos , 3=other</td>
</tr>
<tr>
<td>141-142</td>
<td>AFF% Alias filter frequency, if used</td>
</tr>
<tr>
<td>143-144</td>
<td>AFS% Alias filter slope</td>
</tr>
<tr>
<td>145-146</td>
<td>NFF% Notch filter frequency, if used</td>
</tr>
<tr>
<td>147-148</td>
<td>NFS% Notch filter slope</td>
</tr>
<tr>
<td>149-150</td>
<td>LO% Low cut frequency, if used</td>
</tr>
<tr>
<td>151-152</td>
<td>HI% High cut frequency, if used</td>
</tr>
<tr>
<td>153-154</td>
<td>LCS% Low cut slope</td>
</tr>
</tbody>
</table>
270

155-156  HCS%  High cut slope
157-158  JD%  Year data recorded
159-160  YR%  Day of year
161-162  HR  Hour of day (24 hour clock)
163-164  MIN  Minute of hour
165-166  SEC  Second of minute
167-168  TBC%  Time basis code: 1=local, 2=GMT, 3=other
169-170  TWF%  Trace weighting factor: defined as 2
            volts for the least significant bit
            (N=0,1,....32,767)
171-172  RSFP%  Geophone group number of roll switch
            position one
173-174  GTF%  Geophone group number of trace number
            one within original field record
175-176  GTL%  Geophone group number of last trace
            within original field record
177-178  GPS%  Gap size (total number of groups
            dropped)
179-180  OVE%  Overtravel associated with taper at
            beginning or end of line: 1=down (or
            behind), 2=up (or ahead)
181      POL%  Polarity (1=+ve, -1=-ve)
182      WHO%  Exponent
183-185  ----  Unassigned- for optional information**

*Bytes 133-134 has been used for source type: 5=Buffalo gun,
6=hammer

**In the exact SEG-Y format (Barry et al, 1980) the
unassigned bytes are bytes 181-240.
Appendix F.2a BBC Programs description

System Menu

(1) S.INTRO
This program is loaded by the auto-boot facility. It checks that the second processor is available and HIBASIC is loaded. If not, it gives instructions for these actions. After successful checks it chains "S.TOPMENU".

(2) S.TOPMENU
This program is the core of the system. It offers a menu for the major facilities available within the whole system and chains the appropriate program as required. It has a main menu where two sub-menus within this program are entered. These are the editing and processing menus which are used to access the respective programs. Data file saving and loading are accomplished within this program and are available as options on both sub-menus. Besides these options, three editing programs and ten processing programs can be chained via their respective menus (Figure 5.5).

Also available on the main menu is an option to chain the programs concerned with the recording of seismic field data as can be seen in the figure.

Recording Programs

(1) S.SEGINIT
This program, first, clears the user memory reserved for field data storage. Then, it prompts for information for the file header and initialises values for the trace headers from which it can build an instruction set for semiautomatic recording of data files. It identifies the following information and store them as system variables which are preserved when the relevant recording program is CHAINed:

<table>
<thead>
<tr>
<th>R%</th>
<th>Recorder type</th>
<th>Data accuracy (bit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bison</td>
<td>16 bit</td>
</tr>
<tr>
<td>2</td>
<td>Bison</td>
<td>8 bit (enhanced)</td>
</tr>
<tr>
<td>3</td>
<td>Bison</td>
<td>8 bit (display)</td>
</tr>
</tbody>
</table>
4 Nimbus cartridge 10 bit.

- **T%** Record time length
- **U%** Initial shot number
- **W%** Shot number increment.

These parameters are passed to the relevant data recording program which is chained at the end of the data input.

This program also issues instructions for setting the baud rates on the recorder in use to ensure the fastest possible data transfer.

(2) **S.RECBIS**

This program provides a data recording facility to be operated in conjunction with a field seismograph. This particular program interfaces to the Bison Geopro 8024, but facilities for other recorders (e.g. Nimbus ES-1210) can be provided by a fairly small modification of one procedure in this program.

The program is chained by program S.SEGINIT, in which the file and header information for the recorded files is initialised. Prompts also given for the type of recorder and data accuracy (see S.SEGINIT for more details).

The program has the procedures to record data from the Bison enhanced memory with 16 bit accuracy, 8 bit accuracy, and from the display memory with 8 bit accuracy. Data are transferred from the Bison to the BBC memory by an RS 232 interface.

The program displays a status page showing:
1) Line number, date, and time.
2) Shot data: number, increment, type, X-Y coordinates, height, and depth.
3) Geophone data: numbers, offsets, spacing, and gap.
4) Disc no., drive no., number of files on disc, free space on disc, and the filename.
5) Trace sequence numbers in line and on disc, and the first geophone position on the roll switch.

Six options are provided on the page. Three (S,G, and T) are used to edit data in 2, 3, and 4-5, respectively. The other three are:

- **R-** Causes data to be recorded from the Bison, stored in
computer memory, and written to disc file. The status page is updated and re-displayed.

P- Causes a screen display of the seismic data in memory.
P- Exits to higher level menu (chains S.SEGINIT).

The program has a facility for data disc management. The free space available on the disc is determined after each data file is saved. Instructions are given to insert a new disc when the current disc is full.

**Editing Programs**

1. **S.HEADED**
   
   This program allows the editing of the header data from the data file currently in memory. It displays all the file headers and has an option for their print. The program also displays 12 values of the trace headers, which are common to all traces, and allows for their editing. However, it has options to print all the values from any trace header or all the trace headers in one data file.

2. **S.HEADUP**
   
   This program provides the facility to edit geophone, shot, and some other data from the trace headers. Its primary purpose is for inserting location data of geophones and shots for a series of consecutive files along a continuous line.

   X-Y coordinates and heights of the geophones and shot, shot-geophone offsets, and the CMP numbers for all the traces in the current file are displayed. Also displayed are the depth and type of shot, trace sequential numbers in line and on disc, and other trace header information. Data can be edited for single traces, or for all traces. Updated shot parameters are automatically written to all trace headers.

   After the displayed data are accepted as correct, the next sequential file along the seismic line can be automatically loaded and the current parameters for all geophones common to the previous edited file are automatically inserted. The program allows for missing shots along the line.

3. **S.WIGPIC**
   
   This program plots seismic traces, from a data file currently in memory, on the screen either as wiggly traces or
in wiggle-variable area mode. It allows gain changes in steps
of 6 dB, static shifts, and has the facility for traveltime
picking. A hard copy of the plot or the picked traveltimes
can be obtained.

The program can produce a statics corrected version of the
data record using the static times stored in the trace
headers which are previously determined by the statics
determination programs. Also, it allows weighted trace mixing
for each three consecutive traces. The static corrected and
the mixed trace files are stored in memory. Hence they can be
saved on disc via the saving facility in program S.TOPMENU.

Processing Programs
(1) S.SORT

This program extracts traces from field records and orders
them into constant-offset files or CMP gathers:

Constant-offset

The program requires a series of field files with
increasing shot numbers along a given seismic line. Field
files are loaded into drives 1 and 3. Files for a specified
range of shot numbers are automatically loaded in turn, and
traces with the required offset selected and saved as single-
trace files on drive 2, but with the correct reload address
to memory to construct constant-offset files. When 24 traces
have been selected, those traces are read back into memory
and saved as a constant-offset file on drive 0. These files
have default filenames CONOFnn, where nn increments
sequentially. Instructions are given to change field file
discs as well as that used to save the constructed files when
are full.

CMP gather

Similar to the previous procedure, drives 1 and 3 are used
to load field data files into memory while drive 2 is used
for temporarily saving of traces of the same CMP number as
single-trace files which are reloaded into memory to
construct a CMP gather file to be saved on drive 0. This
program is rather complicated due to the limited memory of
the BBC. The total number of shots and the maximum number of
CMP fold of cover are fed into the computer. Also, the number of the lowest and highest files on each disc and the number of discs in line are to be given. This is very important so the computer can give the instructions to insert and remove the specific data discs while sorting.

When a field file is loaded into memory, a trace with the required CMP number is selected and saved on drive 2. The next file is loaded automatically and the trace headers are searched for the same CMP number. If present, the trace is selected and saved; if not present or the maximum fold of coverage is exceeded, a CMP gather file from traces saved on drive 2 is constructed and saved on drive 0. The CMP number is incremented and the search for the new CMP trace continues starting again with the first field file on disc and so on. When the updated CMP number becomes greater than those in any field file previously searched, that file is dropped until the whole line is completed. CMP gather files are given default filenames mmGnnnn, derived from the seismic line number (mm) and the CMP number (nnnn).

In both constant-offset and CMP gather sorting procedures accommodation is made for missing shots along the seismic line.

(2) S.UPTIME

An automatic picking of first arrivals can be made using this program. Field data files of a seismic line can be auto-loaded into the computer memory. This program is particularly used to determine uphole time and uphole velocity where an uphole geophone or the second nearest geophone can be chosen for picking. A time-window is selected for the picking and a time limit is set beyond which the picked time may be considered to be caused by either a pre-trigger of the seismograph or by error in picking.

The picking is usually done automatically and a list and a print of the picked time, velocity, and shot depth are made continuously. When the pick is suspect, or when the picked time is greater than the limit set in advance, or when no pick is made, a display is made for the two traces. A confirmation is then required to pass the pick or a manual picking (by moving cursors) can be made when the computer
fails to pick.

The automatic picking looks for the first sample of the first signal pulse and considers all samples before that as noise. A record of the maximum noise level is kept while rejecting samples as noise. The first step in the picking is to correlate the absolute value of the difference between the current sample and the previous one with the difference of the two previous samples. Once the difference is greater, the sample is subjected to further checking. First, the sample and the two following samples are checked for sign and for increasing or decreasing in their values. If the test is passed, the maximum of these values are compared with the maximum noise value. If it is greater by four times, the pick is finally passed. If not, the trace is plotted for confirmation. This simple signal to noise ratio dependent procedure was found to work well since the signal level is very high at these zero or small offset traces.

Once a sample is picked as being the first sample in the pulse, another procedure is performed to determine the accurate time of the kick. First, the r.m.s. of the last (up to five) noise samples is calculated. Then two gradients are determined: one between the picked sample and the one which follows and the second is between the picked sample and the previous one. The largest of these gradients is used to locate the exact kick time by its intersection with the calculated r.m.s. noise level. If the gradients are equal the picked sample time is used directly.

(3) S.REFRAC

This BBC program (not to be confused with Program REFRAC; Appendix C) provides the facility to determine three subsurface velocities utilizing the first arrival data from a field seismic data file. Sequential files can be loaded automatically within this program.

Traces of a data file are displayed and the screen is scaled according to the record time length and the shot-geophone offsets which are read from trace headers. Then, lines controlled by the cursors can be moved around on the screen. Direct and refracted velocities can be determined by fitting these lines to the first breaks on the traces.
The program also allows to determine the depths of up to two interfaces. A plane layer model is assumed in these calculations. For accurate direct (uphole) velocity and depth calculation, when shots are fired below the surface of the ground, the actual direct distance is used. This is done by temporarily fixing one end of the moving line on the screen at a distance from the uphole trace equivalent to the direct shot-geophone distance.

The determined velocities and depths as well as the cross-over distances are listed on the screen and printed.

(4) S.VELAN

This program allows velocity information to be obtained from reflection data file currently in memory. Up to five velocities from reflections can be computed. The velocity to a reflector is determined by picking a reflection at zero or small offset trace and guessing velocities which can give the best hyperbolic curve to fit the reflection event across the traces. Shot-geophone offsets are read from trace headers. A horizontal interface and straight raypath are assumed.

Interval velocities are calculated from the determined (NMO) velocities, which are considered as first approximations to the r.m.s. velocities. The interval and r.m.s. velocities are listed on the screen and a hard copy can be obtained.

(5) S.NMOCOR

This program performs NMO correction for the data traces of a seismic file. Files can be loaded sequentially and automatically from drives 1 and 3. A plot of the traces is displayed before and after the NMO correction with the option of having a hard copy print. NMO corrected files are saved on drives 0 and 2. Alternatively, NMO correction can be made without the plotting of traces on the screen.

The program can accommodate up to six velocity-depth points which are fed in at the start of the procedure. A velocity time function is calculated by interpolating and extrapolating between these points. Also fed in to the computer are the start and the end time of muting for the near and far traces and accordingly mute values are written.
to all traces header by interpolation.

The NMO is then computed for each sample in the trace using the shot-geophone offset (read from trace header) and the sample velocity (derived from the velocity time function). Then the sample is shifted by integer values determined from the NMO and sample interval. Samples beyond the mute time for the trace are zeroed.

Once a file is corrected for NMO it is saved on disc. If files are displayed, then it is possible to repeat the NMO correction using different velocity functions. This allows the best stacking velocity to be determined simply by visually examining the alignment of reflection on the plot (velocity panels). Traces can be either corrected for static (uphole time) or not before NMO correction.

(6) S.GNAJUST

The program allows to adjust the gain of seismic traces. Data files along a seismic line can be loaded (using drives 1 and 3) automatically and sequentially. Three procedures are available in this program:

Programmed gain removal

The programmed gain, which is usually applied in the field during recording in steps of 6 dB per time increment, is read from the trace header. Trace sample values are then divided by a factor which is determined by the corresponding number of increments made along the trace time.

Spherical divergence compensation

Traces that have their programmed gain removed can be corrected for spherical divergence. A time-dependent scale factor is multiplied by the sample value. Four gain functions are available. These increase by a maximum of 24, 18, 12, and 6 dB per 100 ms.

Trace gain standardization

This program allows the gain of all traces within a file to be the same. Here, two options are available: 1) a gain value can be chosen by the user or 2) the program sets the gain to the highest possible value. In either case, the
standardized gain is checked so sample values cannot be higher than can be stored in two bytes.

(7) S.SPECAN
This program performs a Fourier transform (FT) of any data trace from a file currently in memory and plot the spectrum. A whole trace, half a trace and small portions of the trace can be spectrally analysed. The FT program allows plotting of the absolute and normalised energy and amplitude spectra or a logarithmic scaled spectrum of the geophone input voltage. The selected seismogram and its spectrum are displayed on the screen and can be printed upon request. The dynamic range of the amplitude spectrum plot is around 40 dB, based on the maximum vertical size of the plot and the vertical resolution of the printer.

(8) S.FILPIC
This program allows frequency filtering of traces of a seismic data file currently in memory. Five band-pass filters (0-100, 100-150, 150-200, 200-300, and 300-500 Hz) can be applied. The filtered data record is displayed on the screen (in wiggle or wiggle-variable area mode) and can be printed upon request. Values of the filter operators are stored in a separate file on the disc (which is not listed). The input data (seismogram) is convolved with the respective operator after being read to the computer memory from the disc.

(9) S.STACK
The program sums the CMP gathered traces and produces an average stacked CMP trace. CMP gather files are loaded automatically to the computer from drives 1 and 3. The program allows for missing CMP files. Once a CMP file is loaded and stacked, the stacked trace is saved on drive 2 as a single-trace file with the correct reload address to memory. When 24 stacked traces are formed, these traces are loaded back to memory and saved as a CMP stacked file on drive 0. These files have default filenames mmSTKnn, where mm is the seismic line number and nn increments sequentially.

The program plots the CMP gather on the screen and allows changes in the trace gains. Also, it allows the rejection of
any trace (e.g. noisy traces) and automatically avoids the muted parts of any trace from stacking. Alternatively, stacking can be made directly without the plotting of the files which saves processing time. However, traces to be rejected need to be set in advance.

(10) S.WIGOFF

This program plots data traces from a file currently in memory annotating them with trace CMP number, X-coordinate of the CMP point, static, and gain. Trace gains, statics, and display modes (wiggle and variable area) may be changed as required. The main purpose of this program is for plotting constant-offset and CMP stacked seismic sections. The resulting plot can then be screen dumped using the *GDUMP ROM to an FX80 type printer. The plot is orientated so that additional traces can be dumped to form a continuous section.

Major differences from S.WIGPIC are the lack of a time picking facility, the orientation of the traces on the plot, and static corrections and trace mixing can only be done in the plotting procedures and, therefore, cannot be stored in memory.
Appendix F.2b  BBC Programs list
APPENDIX G  Borehole and seismic data for reflection Profiles 8, 9, 10, 11 and 12.

Appendix G.1  Depths to the Charnian basement at 12 boreholes and log of borehole No. 12. (see Figure 7.1 for locations of the boreholes).

<table>
<thead>
<tr>
<th>BH No.</th>
<th>HEIGHT (m)*</th>
<th>DEPTH (m)**</th>
<th>BH No.</th>
<th>HEIGHT (m)*</th>
<th>DEPTH (m)**</th>
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</thead>
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<td>71</td>
<td>2</td>
<td>180</td>
<td>100.5</td>
</tr>
<tr>
<td>3</td>
<td>180</td>
<td>&gt;22+</td>
<td>4-11</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>12</td>
<td>189</td>
<td>81.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Height of the surface of the ground at the borehole; ** Cores were not available for BH 1-11. The depth to the basement was based on the rate of drilling presuming that the drill bit has met bedrock.
+ This hole ends before reaching the bedrock.
++ Data are available to this study but not released for this thesis (data are confidential).

BOREHOLE 12 DATA LOG

<table>
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<tr>
<th>ROCK TYPE</th>
<th>DEPTH (m)</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
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<td>WEATHERED LAYER</td>
<td>5.5</td>
<td>Badly weathered, plastic red mudstone.</td>
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<tr>
<td></td>
<td>16.3</td>
<td>Red mottled mudstone (30cm sandy grey mudstone, large (2cm) cavities)</td>
</tr>
<tr>
<td></td>
<td>17.1</td>
<td>(15cm sandy grey mudstone)</td>
</tr>
<tr>
<td></td>
<td>22.5</td>
<td>(15cm soft red mudstone layer)</td>
</tr>
<tr>
<td></td>
<td>24.0</td>
<td>(30cm reduced mudstone layer)</td>
</tr>
<tr>
<td></td>
<td>29.2</td>
<td>(20cm sand layer)</td>
</tr>
<tr>
<td></td>
<td>34.0</td>
<td>Red mottled mudstone (20cm reduced sandy grey layer)</td>
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<tr>
<td></td>
<td>39.0</td>
<td>Red mottled mudstone (20cm sand layer with cavities)</td>
</tr>
<tr>
<td></td>
<td>43.5</td>
<td>(soft friable clay)</td>
</tr>
<tr>
<td>MUDDSTONE</td>
<td>50.5</td>
<td>Red mottled Mudstone (20cm soft clay layer)</td>
</tr>
<tr>
<td></td>
<td>62.5</td>
<td>Mottled mudstone (solution holes)</td>
</tr>
<tr>
<td></td>
<td>64.0</td>
<td>(Breccia band)</td>
</tr>
<tr>
<td></td>
<td>69.0</td>
<td>(Breccia band)</td>
</tr>
<tr>
<td></td>
<td>71.0</td>
<td>(Mottled sandstone 'green/red')</td>
</tr>
<tr>
<td>BRECCIA</td>
<td>81.7</td>
<td>Gradational contact upwards to red/green banded sandstone.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hard red sandstone matrix. Coarse breccia clasts up to 20cm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clasts become gradually smaller upwards.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Lowest matrix of breccia)</td>
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<tr>
<td>CHARNIAN ROCK</td>
<td>91.0</td>
<td>Fine grained, poorly cleaved mudstone.</td>
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<tr>
<td></td>
<td></td>
<td>End of borehole</td>
</tr>
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</table>
Appendix G.2 Some seismic field records from Site 2:

a) Line 11
Appendix G.3 Calculated uphole times (i.e. geophone statics) using uphole velocities and the depth to the base of the Buffalo gun (0.8m) along Line 10.

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<th>UPHOLE TIME (ms)</th>
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<tr>
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<td>1.538</td>
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<td>1.379</td>
<td>54</td>
<td>1.538</td>
</tr>
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<td>1.379</td>
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<td>1.509</td>
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<tr>
<td>46</td>
<td>1.428</td>
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</table>

* Geophones were planted on the surface except for shots 83-92 where 0.2-0.25m holes were used.
Appendix G-4: Constant velocity panels (MHO corrected) for CMP gathers 45, 100, 130, and 167 along line 180. MS and CD designate gathers without and with saisons correction, respectively. Prior to the MHO correction, the record length is 100 ms.
Appendix G.5  Uphole time measurement for Line 12

The zero offset (uphole) geophones were initially tried for time picking. However, the picked times were found to be widely dispersed and the uphole velocity distribution along the line was highly fluctuating (Appendix G.5a). The reason for this was not only due to the limitations of the picking program (see the periodicity of the picked times) but mostly due to the difficulties of locating the first kick (even by hand) on the zero offset trace. The latter is caused by the inconsistency of the first arrival waveform and presence of noise, which might be caused by the movement of the shooter or recoil of the gun (see Appendix G.6). Therefore, the second nearest geophone (2m offset) was used instead for first arrival picking. The picked times were used to determine uphole velocities, which were smoothed (Figure 7.29a) and used to calculate what would have been the uphole times (Appendix G.7).

A histogram of the calculated uphole times from the second nearest geophones (Appendix G.5b) clearly manifests the improvement (a mean of 1.83ms and a standard deviation of 0.23 ms as compared to a mean of 1.1 ms and a standard deviation of 0.73 ms of Appendix G.5a) that has been achieved by using these geophones and due to the improved accuracy of the current program (S.UPTIME; Appendix F.2a), which was checked by hand picking of the first arrivals. However, in both cases, the picked times were fairly approximated to one sample interval.
Appendix G.5a,b

a) Histogram of times picked from zero offset geophones (mean = 1.1ms, standard deviation = 0.73ms and number of samples 'shots' = 116).

b) Histogram of times picked from the 2m offset geophones (mean = 1.83ms, standard deviation = 0.23ms and number of samples = 116).
Appendix G.6 Field record (Line 12) showing zero and 2m offsets seismic traces (channels 24 and 23).
Appendix G.7 Calculated upheole times using the upheole velocities (Figure 7.29a) and the depth to the base of the Buffalo gun along Line 12 (all geophones were planted on the surface).

<table>
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<tr>
<th>SHOT NO.</th>
<th>TIME (ms)</th>
<th>DEPTH OF GUN (m)</th>
<th>SHOT NO.</th>
<th>TIME (ms)</th>
<th>DEPTH OF GUN (m)</th>
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Appendix G.8 Results of refraction interpretation of some field records along Line 12 using BBC Program S.REFRAC.

NEAR-SURFACE VELOCITY STRUCTURE

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