A Seismic Analysis of Reefs in the Traverse Limestone of Allegan County, Michigan

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A SEISMIC ANALYSIS OF REEFS IN THE TRAVERSE LIMESTONE
OF ALLEGAN COUNTY, MICHIGAN

by

William Charles Henderson

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Geology

Western Michigan University
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A seismic reflection study was performed across the Diamond Springs oil field in Allegan County, Michigan. The horizon of interest was the Middle Devonian Traverse Limestone located 1,700 feet in the subsurface. Within the Traverse Limestone are scattered patch reefs which characterize a targeted reservoir. The use of high-resolution, shallow seismic reflection techniques are useful for defining detailed subsurface porosity zones within the patch reef reservoirs.

Common source-offset profiling utilizing high-frequency sources and proper determination of field parameters are important in obtaining the desired optimum reflection. Also, the use of synthetic seismograms for modeling waveforms is essential for identifying the desired reflections. Finally, to prepare the reflection for interpretation, seismic processing by static and normal move-out corrections are applied. The final seismic cross-section can then be viewed with small porosity zones defined by "elliptical" shaped waveforms created by diffractions.
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William Charles Henderson
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A seismic analysis of reefs in the Traverse Limestone of Allegan County, Michigan

Henderson, William Charles, M.S.
Western Michigan University, 1988
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CHAPTER I

INTRODUCTION

Statement of the Investigation

The Middle Devonian Traverse Group of Michigan has produced a prolific amount of hydrocarbons since the 1920s. By 1978, 99% of the Traverse production was from the Traverse Limestone (Lilienthal, 1978). Most oil and gas production within the Traverse Limestone is developed through the location of small reef masses. The Diamond Springs oil field is an example of a small reef mass which has produced 500,000 barrels of oil and gas since its discovery in 1938.

Modern exploration techniques and advanced equipment have increased the production of oil and gas in recent years. One specific exploration technique, seismic prospecting, has been used extensively to locate reservoirs. High resolution shallow seismic reflection methods can be employed to define the boundaries and high porosity zones of a reef mass. Dobrin (1976) states that reefs are sometimes revealed on seismic records by subtle changes in reflection quality, including the interruption of reflections, and possibly by diffraction effects. Through understanding the geologic environment for reef
development, the basic seismic theory, seismic reflection methodology, and seismic analysis, one can begin to differentiate high porosity zones within a specific oil and gas reservoir. This study examines the feasibility of shallow seismic reflection techniques using a portable seismograph for the location of small reef masses. A known producing field, the Diamond Springs oil field was surveyed to determine if features associated with oil production could be identified by such techniques.

Some advantages of shallow seismic reflection techniques are the decreased time and money involved with a portable survey. Two geophysicists can collect one mile of seismic data in two field days. Another advantage is the increased detail of data collection on the target horizon. A shallow seismic reflection survey with idealized spread lengths and geophone spacings allows for increased reflection sampling points on the targeted horizon. This increases the amount of information collected from the subsurface so small changes in the reflected waves can be observed. Lastly, the portability of a small seismograph in a shallow reflection survey allows for the collection of data in any condition and without large environmental impacts.

Location

The Diamond Springs oil field is located at the
intersection of four townships in Allegan County. Salem (sec 31, TYN, R13W), Overisel (sec 35, 36, T4N, R14W), Monterey (sec 6, T3N, R13W), and Heath (sec 1, T3N, R14W) townships incorporate the field study area (Figure 1).

Stratigraphic Formations

Glacial outwash deposits next to the Wisconsinan Lake Michigan moraine form the overburden in the study area (Lilienthal, 1978). Drillers' logs in the area show interbedded sand and gravel layers with a few clay stringers. The sand and gravel beds are 10 to 20 feet thick and incorporate 5-foot clay stringers. The total thickness of the outwash is 101 feet in the north and ranges to 139 feet in the south. There are 97 feet of outwash in the east and 120 feet in the west. The ground surface topography is relatively flat except for a few rolling hills. These hills have 20 feet of relief near the center of the field area.

The following formations may be seen on the stratigraphic column of Michigan (Figure 2). The Coldwater Formation underlies the glacial deposits and is bedrock in southwest Michigan. The Coldwater Formation is predominantly a grey to blue-grey shale and contains varying amounts of limestone (Lilienthal, 1978). The Coldwater Formation ranges in thickness from 630 feet to 715 feet throughout the study area. Directly beneath the
Figure 1. Location Map of Field Study Area.
Figure 2. Lithology of the Michigan Basin.

Coldwater Formation is the Ellsworth Formation. The Ellsworth Formation is predominantly a green shale that grades into a light brown shale near the Antrim Formation contact (Lilienthal, 1978). The Ellsworth Formation ranges in thickness from 360 feet to 500 feet. Below the Ellsworth Formation is the Antrim Formation. Lilienthal, (1978) describes the Antrim Formation as a brown, hard, thin-bedded brittle, carbonaceous shale interbedded with grey shale in the lower part. Drillers' logs recorded in the field area correlate directly with the above lithologic descriptions. The Antrim Formation ranges in thicknesses from 125 feet to 260 feet in the study area.

The Traverse Formation lies directly beneath the Antrim shale. This unit is composed of grey shale in the upper portion and gradually grades to a more calcareous shale and argillaceous limestone near the base (Lilienthal, 1978). Drillers' logs describe a green to grey shale grading into a brown lime. The Traverse Formation is found in thicknesses of 50 feet in the southeast increasing to 100 feet in the northwest. Underlying the Traverse Formation is the Traverse Limestone. The Traverse Limestone consists of 80 percent limestone and 20 percent dolomite which grades from a brown to a grey limestone. The Traverse Limestone represents the major unit of investigation for this study. The Traverse Limestone is approximately 235 feet thick in the study area.
area and overlies the Dundee Limestone. The Dundee Limestone is predominantly a buff to brownish grey, fine to coarsely crystalline dolomite (Lilienthal, 1978).

Geologic Environment

The Traverse Group is divided into three units, the Traverse Formation, the Traverse Limestone, and the Bell Shale. The Traverse Group has a maximum thickness of 875 feet near the Saginaw Bay with general thicknesses ranging from 800 feet in the north to approximately 100 feet in southwest Michigan. The depositional model for the Traverse Group is an open shelf, carbonate platform which experienced some minor uplift or buildup of sediment that created local barrier shoals (Figure 3) and lagoonal environments (Gardner, 1974). Runyon (1976) describes this lithofacies pattern as a carbonate shelf facies on the west interfingering with a shale on the east. Gardner (1974), Lilienthal (1978) and Runyon (1976) suggest that an influx of clastic sediment originated from an eastern source. Carbonate and clastic lithofacies patterns reflect this eastern source area. The Traverse Group was thought to have undergone a non-continuous transgression which was interrupted by regressive pulses (Gardner, 1974). A north-to-south trending barrier is postulated on the western side of the state (Runyon, 1976). This barrier creates a lagoonal
Figure 3. Map Locating Traverse Fields With Restricting Barrier.

type environment with restricted sea water influx. Reef complexes are commonly encountered on the western edge of the barrier.

Another concept of patch reef development which will only be mentioned, is the growth of patch reefs along a salt collapse edge on the western side of the state from the A2 anhydrite formation deep below the Traverse Limestone (Daniels, 1986). The reefs developed along the salt collapse edge grow in a linear north-to-south trending pattern. The Diamond Springs patch reef, along with many other patch reefs, have developed off the linear trend. Therefore, a detailed discussion of patch reef development along the salt collapse edge is not warranted.

The area of the Diamond Springs oil field is approximately one square mile. Figure 4 shows the size of the oil field as defined by the location of production wells. This base map of the Diamond Springs oil field has two cross-sections, one east to west (A-A') and one north to south (B-B'). The cross-sections show representative lithologies to the top of the Traverse Limestone (Figures 5, 6). One noticeable feature associated with the cross-sections is the slight doming of the Traverse Limestone. The overlying beds are not structurally associated with the doming which suggests that the doming occurred during Middle Devonian time or
Diamond Springs N-S Cross Section.

Figure 6. Lithologic Cross Section B - B'.
earlier. Constructing the structure contour map of the area (Figure 7) indicates an elliptical shape similar to that of some patch reefs. The map also shows relief in the producing horizon as a maximum of 70 feet, but averages about 30 feet. This amount of relief is also consistent with patch reefs in quiet, lagoonal settings.

Drillers' logs, structure contour maps and initial production maps give evidence to the existence of a patch reef as the Diamond Springs oil field. An initial production map was constructed (Figure 8) and was compared to a structure contour map (Figure 7). Evidence supports a patch reef setting due to the high initial production zones in small structural features which are adjacent to dry holes. Viewing the structure contour and initial production maps of nearby oil fields presents a similar type of situation that exists in the Diamond Springs Field (Cline, 1986). High initial production zones or high porosity zones are scattered throughout the structure with low initial production and low porosity zones adjacent to high production zones.

Evidence collected for a Western Michigan University, Kalamazoo, Michigan core lab workshop shows representative samples of Traverse reef core from three separate locations in the state (Figure 9), W.M.U. Core Lab Workshop (1985). Studying these cores helps identify the porous zones found in reef masses which contains high
Figure 7. Structure Contour Map of the Traverse Limestone.
Figure 8. Initial Production Map of the Diamond Springs Oil Field.
Figure 9. Location of Traverse Cores.
production. This information supports the seismic reflection data interpretation and gives physical evidence to the existance of patch reefs in the surrounding area. Unfortunately, there were no cores or core cuttings from within the study area to give direct evidence for patch reef existence.

Two possible interpretations for the initial production zones are offered. First, facies controlled reservoir areas within the patch reef give rise to varying porosity zones. Second, a diagenetically controlled patch reef might create scattered porosity zones due to the deposition and composition of the sediments. In either interpretation information suggests a patch reef environment during Middle Devonian time.

Previous Seismic Investigations

Published research on high-resolution, shallow seismic reflection methods is limited. Most shallow seismic reflection methods were developed in recent years. Work done by Knapp and Steeples (1986b) describes high-resolution, common depth point, seismic reflection profiling through the use of modern instrumentation and field acquisition parameter design. Hunter et al. (1982c) examined common offset profiling and the use of a walk-away noise test to define targeted reflections. Seismic source analysis for shallow seismic reflection
profiling was introduced by Nunn (1977) and Mooney (1984). Some excellent case studies involved shallow reflection seismics for placer-tin-reserve evaluation and mining by Singh (1983) and high-resolution, seismic profiling for coal by Ziolkowski and Lerwill (1979). The authors illustrated shallow reflection methodology for locating various seismic events. Earlier work on high resolution, shallow seismic methods includes Dobrin (1952), Meidav (1969), and Ricker (1953).
CHAPTER II

SEISMIC THEORY

Elasticity

The theory of elasticity gives background knowledge for the basic physical principles governing the propagation of seismic waves in earth materials. The relation between stresses and strains for a particular material enables us to describe the elastic properties of the material as well as the characteristics, such as velocity, of waves propagating therein (Dobrin, 1976). To understand the relationship between stress and strain, Telford, Geldart, Sheriff, and Keys (1976) state that when an elastic body is subjected to stresses, changes in shape and dimensions occur. These changes, which are called strains, can be resolved into certain fundamental types. The two types of strain examined by Telford et al. (1976) were normal strains and shearing strains. In the three dimensional analyses of a body, the components of displacement of point P (x,y,z) are (u,v,w) (Figure 10). The equations for normal strains and shearing strains are then written as follows:

Normal strains: \[ \varepsilon_{xx} = \frac{du}{dx}, \]
Figure 10. Dimensional Analysis of a Body Due to Normal and Shearing Strains.

Shearing strains:

\[ \varepsilon_{yy} = \frac{dv}{dy}, \]
\[ \varepsilon_{zz} = \frac{dw}{dz}; \]

Shearing strains:

\[ \varepsilon_{xy} = \varepsilon_{yx} = \frac{dv}{dx} + \frac{du}{dy}, \]
\[ \varepsilon_{yx} = \varepsilon_{zy} = \frac{dw}{dy} + \frac{dv}{dz}, \]
\[ \varepsilon_{zy} = \varepsilon_{xz} = \frac{du}{dz} + \frac{dw}{dx}; \]

Earth material is also subjected to simple rotation about the three axes. The rotation is represented by the following equation (Telford et al., 1976):

\[ \Theta_x = \frac{dw}{dy} - \frac{dv}{dz}, \]
\[ \Theta_y = \frac{du}{dz} - \frac{dw}{dx}, \]
\[ \Theta_z = \frac{dv}{dx} - \frac{du}{dy}. \]

For small deformations involved in seismic-wave propagation, stress is proportional to strain. This relation is expressed by Hooke's law (Telford et al., 1976):

\[ \nabla_i = \lambda \Delta + 2 \mu \varepsilon_{ii}, i = x, y, z \]
\[ \nabla^2 j = \mu \varepsilon_{ij}, j = x, y, z, j \]

where \( \lambda \) and \( \mu \) are Lame's constants. \( \mu \) is the measure.
of the resistance to shearing strain and is called the shear modulus.

Wave Equation

The general wave equation describes how compressional and shear deformation are incorporated in earth materials. The wave equation is derived from Newton's 2nd Law and uses Hooke's Law to obtain an expression containing only displacements. The wave equation assumes deformation in three directions with each component of stress associated with strain in more than one direction (White, 1965). The three dimensional wave equation for compressional deformation is:

\[
\frac{d^2\Theta}{dx^2} + \frac{d^2\Theta}{dy^2} + \frac{d^2\Theta}{dz^2} = \frac{\lambda}{\lambda + 2\mu} \frac{d^2\Theta}{dt^2}
\]

where \(\Theta\) is the cubical dilatation. For shear deformation the wave equation is (Dobrin, 1976):

\[
\frac{d^2\alpha}{dx^2} + \frac{d^2\alpha}{dy^2} + \frac{d^2\alpha}{dz^2} = \frac{\lambda}{\mu} \frac{d^2\alpha}{dt^2}
\]

where \(\alpha\) is the shear strain. With the three dimensional wave equations known, the velocity \(V_p\) for compressional waves is (Dobrin, 1976):
Seismic prospecting uses propagating elastic waves through the earth to determine subsurface geology. The earth materials are assumed to be layered, isotropic, and homogeneous, and the passage of elastic waves are of constant velocity propagating throughout each medium.

Seismic Waves

Wave Types

Three basic types of seismic waves are found in exploration. These waves are known as the P-wave, S-wave, and Rayleigh surface wave. Each of these distinct types of waves travels with a different velocity. In any material, the P-wave travels at the highest velocity of the three types of waves. The S-wave travels at roughly one-half (.577) of the P-wave velocity in well sorted rocks or at a rate of 0.45 of the P-wave velocity in poorly sorted material (Mooney, 1984). Rayleigh surface waves travel at approximately 0.9 the velocity of S-waves.

The P-wave is commonly defined as a compressional,

\[ v_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} \]

and the velocity \( v_s \) for shear waves is (Dobrin, 1976):

\[ v_s = \sqrt{\frac{\mu}{\rho}} \]
dilatational, longitudinal or irrotational wave (Telford et al., 1976). The P-wave is a body wave which propagates along the surface, or into the subsurface, and returns to the surface by reflection or refraction. P-waves cause slight momentary displacements of earth material as they pass through it. The waves cause a back and forth (compressional) motion which is parallel to the direction in which the wave is travelling (Mooney, 1984). The direction of motion for a spherical P-wave is seen in Figure 11a.

The S-wave, or shear wave, is also referred to as a transverse or rotational wave (Telford et al., 1976). The S-wave, like the P-wave, is a body wave which propagates into the subsurface and returns to the surface by reflection or refraction. S-waves generate a to-and-fro (shear) motion which is perpendicular to the direction of propagation (Dobrin, 1976). Figure 11b shows the motion during propagation of an S-wave. Telford et al. (1976), illustrates that when a wave arrives at point P, it causes the medium in the vicinity of P to rotate about the axis z'z" (parallel to the z-axis) through the angle \( \varepsilon \). Since we are dealing with infinitesimal strains, \( \varepsilon \) must be infinitesimal, and we can ignore the curvature of the displacements and consider that points such as \( P' \) and \( P" \) are displaced parallel to the y-axis to the points of \( Q' \) and \( Q" \).
Figure 11. a) Motion of a Spherical P-Wave, b) Motion During Propagation of an S-Wave, c) Motion of a Rayleigh Wave.

the wave travels along the x-axis, the medium is displaced transversely in the direction of propagation. Since there is transverse motion, the wave is called a shear, or S-wave.

The Rayleigh wave is the main type of surface wave of importance to seismic exploration. Rayleigh waves travel only along the surface of a solid material. They cause an elliptical kind of motion, part of which is parallel to the surface of the earth along which the wave is travelling and part of which is perpendicular to the surface. Rayleigh surface waves include a horizontal and a vertical component of surface displacement (Mooney, 1984). The amplitude of Rayleigh waves tend to die out with depth as most of the energy is propagated along the surface. Rayleigh waves are believed to be the principal component of groundroll (Telford et al., 1976; Dobrin, 1976; Mooney, 1984). Groundroll represents the low-velocity, low-frequency, high-amplitude surface wave which often obscures reflections on a seismic record. Figure 11c shows the motion of a Rayleigh surface wave.

In shallow seismic exploration, nearly all the work is based upon the P-wave. The P-wave is the first seismic arrival and is easily recognized and timed. The S-wave, on the other hand, appears later on the waveform and is more difficult to recognize than the P-wave. The low velocity Rayleigh surface wave is easy to recognize.
as a large-amplitude, low-frequency signal found later on the record. Groundroll represents all surface waves usually present on shallow seismic exploration records.

Wave Characteristics

In understanding seismic waves it is important to define the general wave characteristics on a seismic record. Frequency, phase, and waveform shape are the major wavelet characteristics defined below.

One characteristic of the seismic wave is frequency. It is defined by the number of times any event recurs in a given period of time. The seismic wave is a result of the superposition of many sinusoidal waves differing in frequency. Many different frequencies are produced from a seismic source and recorded by geophones. The frequencies recorded can be analyzed or digitally filtered on a seismograph. These specific frequency ranges are recorded so an optimum seismic record is generated.

Another characteristic of the seismic wave is phase. The phase of a seismic wave is a function of the frequency. Phase is related to the wave in that all surfaces of a seismic wavefront which have the same proportional wavelength value are in-phase. Surface that do not have the same value are out of phase. Changes in
the phase caused by subsurface layers can be identified on the seismic record as a reversed waveform.

Waveforms are another wavelet characteristic of the seismic wave. The typical waveform shape is referred to as a Ricker wavelet (Dobrin, 1976). Dobrin found that the shape of the wave resembled observed waveforms. Waveforms are derived from impulse signals traveling through subsurface material. The waveforms are generated from a surface source and are dependant upon the frequency of the signal. The waveforms are recorded and shown on a seismic record. Changes in the waveform shape indicate differing features in the subsurface.

Change of Amplitude With Distance

Amplitude is the relative measure of energy created from a source and recorded through receivers. Amplitude is another characteristic of the waveform. Seismic waves change their amplitude with the total distance the wave has traveled. This change of amplitude is seen through divergence, absorption, and energy partitioning.

As a source generates a wave of energy a spherical wavefront diverges from the source point. This spherical divergence directly affects the amplitude of a wave due to the decrease of intensity and energy density of the wave as it increases in distance from the source. Thus,
the amplitude of a seismic wave decreases as it propagates down through the subsurface.

Another factor that affects amplitude with distance is absorption. Absorption is the process where wave energy is absorbed by the subsurface layers. Telford et al. (1976) notes as a wave passes through a medium, the elastic energy associated with the wave motion is gradually absorbed by the medium, reappearing in the form of heat. Absorption is then responsible for the loss of amplitude of the wave and the complete disappearance of the wave motion as it passes through many layers and increases in distance from the source.

Energy partitioning is another factor that causes a decrease in amplitude and energy of a wave with distance. Energy partitioning occurs when a seismic wave intersects a boundary layer with contrasting properties. When a propagating wave encounters a boundary the wave becomes reflected or refracted. The reflected and refracted waves have their own amplitudes. These amplitudes decrease each time the corresponding reflected or refracted wave becomes partitioned at a boundary.

Waves at a Boundary

Seismic waves originating at the surface propagate through the subsurface as reflections and refractions. As a wave encounters a change in elastic properties, such
as at the surface separating two beds, part of the energy is reflected back into the same medium as the original energy, while the balance of the energy is refracted into the lower medium with a change in direction of propagation occurring at the surface separating the two beds.

Reflections and refractions occur when there is a change in acoustic impedance between two layers. Acoustic impedance is defined as the product of density and velocity for a given layer.

Many authors confirm that density fluctuations between layers are minor and usually only the velocities are of importance to acoustic impedance. In some cases there is such a small velocity contrast between layers that a reflection cannot be detected.

A P-wave incident on an acoustic impedance boundary produces a reflected and refracted P-wave and a reflected and refracted S-wave. In shallow seismic exploration the reflected and refracted P-wave are of primary concern (Figure 12). For the reflected wave Snell’s law states that the angle of incidence $\Theta_i$ is equal to the angle of reflection $\Theta_i'$ (Figure 12), (Telford et al., 1976). The P-wave, the incident ray in seismic prospecting, is reflected back to the surface at the angle of incidence.

Reflections are the principle event of interest for seismic exploration, while refractions are used in static
Figure 12. Effects of a P-Wave on a Boundary.

correcting for the shallow horizons. Reflections are identified on the seismic record by the distinguishable alignment of arrival times. As a wave is reflected off a surface or boundary the wave is received at the geophones at a distance from the source point. The arrival times are recorded by the seismograph with a certain arrival time interval between each receiver. A seismic reflection can then be identified by the typical curvature of arrivals on a time-distance plot.

Refractions occur when an incident P-wave strikes an interface and travels into the lower medium (Figure 12). Snell's law represents the law of refraction as

\[
\frac{\sin \Theta_1}{\sin \Theta_2} = \frac{V_1}{V_2}
\]

where \( \Theta_1 \) is the angle of incidence, \( \Theta_2 \) is the angle of refraction, \( V_1 \) is the velocity of the upper medium, and \( V_2 \) is the velocity of the lower medium. When \( \sin \) equals the so called "critical angle" \( \Theta_2 \) equals 90°. In this case the refracted wave does not travel through the interface but travels along the interface between the two layers at the velocity of the lower layer. This critically refracted wave generates waves which propagate into the upper layer at the critical angle.

Refractions are identified on the seismic record as the first coherent waveform event on the record. They are generally termed the first arrivals. Refractions, as
with reflections, have a distinguishable alignment of arrival times. These arrival times, for one given layer, increase with distance from the source and are linear events on the seismic record.

Another type of seismic wave produced when a P-wave strikes an interface at an irregularity, such as a corner or a point where a sudden change of curvature exists, is a diffraction. Dobrin (1976) describes these irregularities as point sources which radiate waves in all directions (Figures 13a, b). The radiating waves are diffractions. Diffractions are identified on the seismic record in a similar manner to reflections except that they form a more pronounced hyperbolic shape of the arrival times. With this type of situation it may be difficult to distinguish a diffraction from a reflection. One way to differentiate between the two events is by identifying the reflection and distinguishing any variations in the arrival times which could be caused by a diffraction. The variations are usually in the form of an elliptical bending seen by earlier arrival times on the seismic record.

Noise

Noise on the seismic record is defined as everything on a seismic record that does not denote or signal a specific event from which information is desired.
Figure 13. a) Relative Intensity of Diffracting Wavefront  
b) Diffractions from a Point Source.

Seismic noise is divided into coherent noise and incoherent noise. Coherent noise is common across a few recorded traces and can be easily identified as noise. Incoherent noise or random noise is dissimilar on the recorded traces and cannot be predicted as to what it will look like. Most of the noise found on the seismic records is associated with the source and may originate from various waves travelling along the surface, near surface structures. Other common sources of noise are automobiles, airplanes, wind, and people. A large portion of the noise on a seismic record can be removed by proper recording and data processing procedures. Two of the most important ways of reducing noise on a seismic record is by field filtering the data during the survey and by frequency filtering the resultant recording.

Resolution

In order to locate small structural features a high seismic resolution is required. Resolution is a function of both the frequency content of the data and the velocities of the beds. One way to increase resolution of the seismic record is to achieve an optimum amplitude and wavelength such that individual wavelet shapes can be identified. Rayleigh (1917) found that two peaks may be resolved as distinct provided the distance between the individual wavelets is greater than or equal to the peak
to trough distance of the wavelet. If this does not occur then the wavelets become combined and are not seen on the seismic record. Since shorter wavelengths have a higher resolving power, one way to obtain higher resolution is to increase the frequency. The limit of resolution that is generally used is called the tuning thickness. The tuning thickness represents a limit that is one quarter of the wavelets' wavelength and is the thinnest bed resolvable. Work by Sheriff (1978), Widess (1973), and Woods (1956) show a resolving power of 1/8 to 1/4 that of the wavelength was sufficient to locate a layer as a reflection event.

A second method to increase resolution is to produce single fold data where high frequencies are recorded. Collecting single fold data is accomplished by conducting a common source-offset seismic survey where the targeted subsurface horizon is sampled and recorded once by each geophone. Common depth point surveying on the other hand collects data by sampling and recording each point on the targeted horizon a multitude of times.

Field filtering is another way to increase the resolving power of the seismic record. A field filter is a low-cut filter designed to counter the natural low-pass character of the earth. A field filter will allow the recording of frequencies greater than a fixed frequency. Field filtering the data helps counter the earth’s
natural high-frequency attenuation. Knapp and Steeples (1986b) stress the importance that the filter cutoff frequency not be so high, and the rolloff slope so steep that all of the signal is filtered away; but it is also important that cutoff frequency be high enough to attenuate high-amplitude, low frequency signal and low frequency noise that might swamp the digitizing system, leaving no trace of the high frequency reflections.
CHAPTER III

SHALLOW SEISMIC REFLECTION METHODOLOGY

Equipment

One aspect of a high-resolution shallow seismic survey is the use of modern high-technology equipment. A 12 or 24-channel portable seismograph is employed in a seismic survey. These units have many superior field parameter functions with user friendly implementation and advanced memory storage. 12 or 24, 60 to 100 hertz frequency geophones aligned in series are used as receiving devices. Sources applied in a survey to produce energy are commonly a sledge hammer, shotgun, or dynamite. Power for a seismograph is provided by a 12-volt portable battery.

Seismic Sources

There are several factors to consider when selecting a seismic energy source for shallow reflection surveys. They are cost, convenience, amount of energy needed, environmental damage, and safety. The two types of shallow seismic sources discussed herein are the sledge hammer and the 12-gauge shotgun.

The sledge hammer is the least expensive seismic
source. Depending on size, the purchase price ranges from $20.00-$60.00. A sledge hammer is virtually indestructible. Mooney (1984) states the hammer provides adequate energy for shallow seismic work and is by far the fastest source with which to carry out a survey. A metal plate must be used in conjunction with the sledge hammer to create a higher frequency spike impulse and thus more pronounced resolution. For maximum effectiveness, the sledge hammer must strike the plate perpendicularly rather than at angle. A heavier hammer is more effective seismically (Mooney, 1984). This is due to the increased weight of the hammer producing more energy than a smaller hammer. There is virtually no environmental damage with the hammer source. Safety with the hammer is of minimal concern, but one should wear safety glasses.

The shotgun source, on the other hand, is more expensive than the sledge hammer. The average cost to construct the gun is $50.00 and the average cost of shotgun slugs is 5 slugs for $3.00. The shotgun is buried 2 feet beneath the surface of the ground to minimize the effects from a loose unconsolidated soil and fires a 12-gauge slug to create a point source. The shotgun produces a lesser amount of higher frequencies than the hammer but has greater energy. Like any firearm, if the shotgun were pointed in the wrong
direction, a potential safety hazard could exist; but with common sense, accidents are easily avoided. Environmentally the shotgun creates small caverns, but does not have permanent damaging effects.

Common Source-Offset Surveying

Common source-offset surveying samples the targeted reflection once at any particular point on a given horizon. A common source-offset survey is set up with a fixed source-offset and a constant geophone interval. Hunter et al. (1982b) state that a common source-offset survey increases the resolution of the seismic record.

When conducting any seismic survey it is advisable to construct a raypath diagram to understand the seismic wave path. A raypath diagram models the path taken by the seismic wave as it propagates through the subsurface. The raypath diagram indicates the incident and transmitted angles as the seismic wave crosses a change in lithology. The total spread length, the source-offset distance, and the depth to a given layer are factors which determine the incident angle on a layer. The equation

\[
\frac{\sin \Theta_1}{\sin \Theta_2} = \frac{V_1}{V_2}
\]
determines the angle of incident and the angle of transmittance into the lower medium at every interface, or the angle that the reflected ray reflects off the interface.

Knowing the travel path of a seismic wave from a raypath diagram gives the geophysicist an idea of how much of the targeted subsurface horizon will be sampled with a common source-offset and geophone spread length. This ensures that when conducting a common source-offset survey the targeted subsurface horizon will be sampled at the desired interval on its surface.

Optimum Window

The optimum window technique is a useful method to view the desired reflection events. This technique is accomplished by calculating the assumed arrival time for the desired reflection event and instituting a correct seismic spread length to record that time range. Once the value has been calculated the desired reflection should arrive within the optimum window. The optimum window is located on a seismic record between the groundroll and the refraction arrivals (Fig. 14). To locate the area regarded as the optimum window a walk-away noise test should be conducted.

When initiating a seismic survey in the field, it is common to begin with a walk-away noise test. Knapp and
Figure 14. Location of Optimum Window for Overburden Reflection.

Steeples (1986a) explain that a walk-away noise test has several advantages. It is an actual test of field conditions. There are no estimates or guesses of what the response will be. It is possible to determine the arrival of events, true amplitudes, and evaluate the effectiveness of source and geophone arrays.

The walk-away noise test is conducted by providing energy at increasing intervals of source offset with geophones in a fixed location. This provides for a large range of seismic responses at a large number of source-to-receiver offsets. The ideal way to conduct a walk-away noise test is to begin with zero offset and a fixed geophone spread length. The offset is then increased incrementally by a distance equal to the spread length for as great a distance as desired. The general importance of the walk-away test is to define the optimum window where desirable reflections are located and to examine the depths and velocities of the reflected, refracted, and groundroll seismic events. Knapp and Steeples (1986b) suggest that the minimum offset in the walk-away noise test be close to zero for at least two reasons. First, for velocity and timing control, it is most effective to have a near zero offset measurement. Second, in processing the data, it is useful to have first-arrival (refraction) information near the source for statics and datum correction. Hunter et al. (1982a)
explains that for optimum velocity and intercept time
determination, one should attempt to obtain a window in
an area as close as possible to the leading edge of the
groundroll, spanning a zone where the reflector shows
maximum curvature yet not extending the window into the
wide-angle zone where possible interference may occur.
In an effort not to overextend the window, Hunter et al.
(1982a) suggests as a rule of thumb not to exceed a total
spread length of 1.5 times the depth to the targeted
horizon. The maximum optimum window distance value is
calculated using the equation
\[ 2Z\tan(i_c) = \text{maximum optimum window value} \]
where \( Z \) is the depth to the target horizon and \( i_c \) is the
arc sin of \( V_1/V_2 \). \( V_1 \) is the upper boundary velocity and
\( V_2 \) is the lower boundary velocity. The maximum optimum
window distance value defines the location where the
reflections are not masked by refractions found on the
seismic record (Figure 14). The minimum optimum window
distance value is the value that must be obtained before
any reflections can be observed on the seismic record.

Seismic Field Parameters

One of the most instrumental aspects of a shallow
seismic reflection survey is the definition of field
parameters. Experimenting with field filtering, gains,
sweep, sampling rate, notch filters, geophones, and
source-offset enhances the clarity and resolution of the seismic record. Field parameters are critical to the acquisition of seismic data.

Field filtering of the seismic wavelet at the recording instrument helps obtain high frequencies while large amplitude, spurious signals, such as low frequencies, are minimized. Field filtering removes the undesired noise and phase distortions from seismic data before it is recorded. While details vary, most seismic amplifiers permit selection of upper and lower limits of the band-pass. The lower limit of the band-pass or high-pass filter can selectively attenuate the lower frequencies and thereby increase the proportion of high frequencies. Typical low-cut filter settings are 100-200 hertz.

Knapp and Steeples (1986b) explain that in high-resolution work, application of low-cut filters prior to analog-to-digital conversion is critical for several reasons. First, the seismic noise environment (wind, traffic, etc.) tends to be low frequency (below 100 hz). Because high-resolution sources do not have sufficient energy to overcome the magnitude of low-frequency noise, the noise must be attenuated by filtering. Second, seismic sources tend to have more low-frequency energy than high-frequency energy. This imbalance is accentuated by the third factor—that the earth attenuates high
frequencies more severely than low frequencies, i.e., the earth is a low-pass filter. This situation is especially common in drift covered areas. The poorly sorted, loosely compacted drift attenuates most of the desirable frequencies. It is therefore important to filter out the low frequencies so the majority of high frequency signals are recorded.

The amplitude gain and program gain are two parameters which, when used correctly, can create a seismic record with equal amplitude. The amplitude gain measures the average output signal level over a short interval and adjusts the gain to keep the output consistent regardless of the input level. The program gain on the other hand increases the output level at a constant interval of time across a trace. The amplitude gain is set for every geophone at a level in which the seismic signal is strong but not distorted. When used in conjunction with the program gain, a seismic record is analyzed for minor changes in waveform character on a record with equal amplitude.

The sampling rate controls how often the continuous waveform is sampled by a digital recorder. If the sampling rate is too large, omission of minor details in the seismic record can occur. A sampling rate from 0.2 ms to 2.0 ms produces a detailed record. The smaller the
sampling rate and the more waveform sampled, the better the detail of the seismic record.

In recording a seismic waveform, a notch filter must be implemented to eliminate the common cultural frequencies. Telford et al. (1976) explains that the use of a notch filter will eliminate the recording of high voltage lines which contain a frequency of 50 or 60 hertz.

The use of high-frequency, 60 to 100-hertz geophones helps enhance the resolution of the high-frequency seismic signal. Many authors suggest the use of high-frequency geophones. These geophones act as a low-cut filter; and the operating characteristics of a high-frequency geophone with high-frequency data achieve better records than those of a low-frequency geophone that records the same ground motion. Knapp and Steeples (1986b) suggest the use of 100 hertz geophones for shallow, high-resolution surveys in the 75-100 hertz band pass range.

In addition to an increase in high-frequency geophone resolution, the geophone-to-ground coupling can increase the resolution of the signal. Krohn (1984) believes that because the firmness of the soil increases with depth, burial of the geophones or the use of long spikes can increase the coupling resonant frequency. Knapp and Steeples (1986b) state that a bad geophone
plant reduces the area of contact and can introduce additional mechanical factors into the geophone ground coupling-response function, both of which are detrimental to the system response.

The source-offset distance will allow for the examination of reflections at various depths. As the source-offset distance increases, the arrival time to a particularly targeted reflector will increase. Therefore, the optimum window for a large source-offset will increase the optimum zone for targeted reflections.

The effects of field parameters on a shallow reflection survey can help enhance the resolution of the signal recorded. Developing precise field parameters is extremely important. Losing optimum results of a seismic survey is possible unless testing of the field parameters is perfected. With an increased knowledge of the field parameters, a geophysicist can initiate a common source-offset survey.

Seismic Processing and Analysis

The acquisition of field data is the first step in obtaining a final seismic cross section. The second step is processing and analysis. Synthetic seismograms, digital filtering, static and normal move out corrections, velocity and noise analysis are all
integrated in the complex process of analyzing a seismic record.

**Synthetic Seismograms**

Synthetic seismograms are calculated models simulating the data expected from the actual seismic records. A synthetic seismogram approximates arrival times and velocities of given layers. They also give an approximation of the normal move out correction applied to each individual record. Synthetic seismograms are a useful "tool" in helping to define various conditions encountered in the subsurface. The synthetic seismogram is created using velocities and thicknesses of individual horizons. These velocities and thicknesses may be calculated from sonic and gamma ray neutron logs respectively. The sonic log is a measure of the average velocity across a large horizon in the subsurface. The gamma ray neutron log gives a measure of the contacts between horizons and thus gives an estimate of the horizon thickness. The velocities and thicknesses calculated from the logs give estimated values for use in the synthetic seismogram.

**Velocity Analysis**

One method to check the validity of a model is by a velocity analysis. The arrival times for a given layer
are plotted on a time-squared, distance-squared graph. The data is then entered into a computer program or plotted on graph paper to calculate the slope of the best fit line through the graphed points. A least squares, linear regression, computer program calculates the slope. The velocity of the given layer is then calculated by taking the square root of the inverse of the slope. The calculated velocity value is then compared to the velocity value obtained from the sonic log to determine the validity of the model. If the two velocity values are comparable then the model chosen for seismic processing was accurate.

Seismic Filtering

One method used to "clean up" or "filter out" noise in a seismic record is to apply a digital filter. Dobrin (1976) states that the main objective of digital filtering in seismic reflection work is to remove undesired signals (collectively referred to as noise) from the record, leaving, ideally, only primary reflections having geological meaning. Filtering allows only a certain frequency range to be passed through the filter. This effect helps discriminate noise on the seismic record and enhances the remaining reflections.

Another method to eliminate noise on a seismic record is by field filtering. Field filtering the data
allows for the reduction of certain noise bands that can attenuate the data. This is generally the case with low frequency noise from cultural sources.

Frequency filtering on the other hand allows for the reduction of noise by reducing some of the unwanted noise bands from the record after the data has been collected. This type of noise attenuation will increase the desired signal and reduce the unwanted noise.

**Static Corrections**

One step in processing seismic records is that of static correction. Static corrections are a time correction to reduce the effects of near surface layers on the reflected arrivals. A static correction is performed on each record to negate the effects of near surface weathered layers and changes in elevation. A common technique to derive the static correction is to "flatten" a layer. To get accurate corrected values the horizon from which the static correction values are derived must be a reasonably flat, homogenous layer. This layer must be identifiable and consistant on all the records. Static correction values may be calculated using the refracted event for this layer. Arrival times are adjusted such that the layer appears as a flat horizon on the seismic record. This time adjustment forms the static correction for the seismic record.
Normal Moveout Corrections

Normal moveout corrections are applied after the static corrections have been completed. The normal moveout correction accounts for the time difference in reflection arrivals due to the varying distances between the source and the geophones. The time values for a normal moveout correction are calculated from a synthetic seismogram. Specifically, the arrival time differences from each of the traces are extrapolated from the targeted reflection. Once the normal moveout correction has been applied, small differences in arrival times can be compared and interpreted. The normal moveout correction is applied to each record to allow for the arrival time difference between the traces. A normal moveout correction aligns the true arrival times of the reflected event across the record. A normal moveout correction is applied to a seismic record by subtracting the specified time value obtained on each trace in the synthetic seismogram from the actual trace arrival time. Telford et al. (1976) explains the concept of normal moveout as extremely important. It is the principle criterion used to determine whether an event observed on a seismic record is a reflection.
CHAPTER IV

SEISMIC REFLECTION SURVEY

Equipment

The seismograph instrumentation employed in this study was a 12-channel Bison Geopro Seismograph, Model 8012A. This unit has many superior field parameter functions with user-friendly implementation and an advanced memory storage unit to store 30 field records. Twelve, high frequency geophones aligned in series were used as receiving devices. Sources applied to produce the seismic energy were a shotgun source adaption to fire 12-gauge shotgun slugs into the earth and a 16-pound sledge hammer which impacted a 4-inch-square steel plate. A two-conductor wire was used as the offset cable between the source and the first geophone. Power for the seismograph was provided by a Bison 12-volt portable battery.

Method of Study

The seismic survey was performed using a shotgun source. A source-offset of 918 feet was measured from the first geophone. There was a 30.5-foot spacing between 12 geophones giving a total spread length of
1,253.5 feet. A common offset profile was implemented using the above parameters to obtain sampling on the surface of the Traverse Limestone every 15.25 feet. Two seismic cross-sections were constructed, one north to south and the other east to west. Field parameters were chosen by direct experimentation in the field. Modeling was performed using the New Jersey Geological Survey "HRASSD" synthetic seismogram program. Implementation of these "tools" describes the method for the research.

Reflected and Refracted Horizons

There were three subsurface horizons which were found to have a sufficient acoustic impedance contrast to reveal reflections. Two of these reflections are from within the Antrim and Dundee formations while the third is the Traverse Limestone. Figure 15 identifies the reflections and is corrected for statics and normal moveout. The reef bearing Traverse Limestone is the target in the seismic study.

Refractions also played an important part in the study. Figure 16 displays the first breaks or refraction arrivals for the first three subsurface layers. Refractions are important in the determination of velocities from the near surface layers. These velocities were used for static corrections to the base of the refracted horizon to eliminate weathering effects,
Figure 15. Reflections Corrected for Static and Normal Move-out.
Figure 16. Results of "HRASSD" Refraction Program from a Walkaway Survey.
and as drift velocities in the synthetic seismogram. Static corrections of the refracted waves reduce the near surface or drift effects and produce a coherent aligned waveform. Since the Traverse Limestone was chosen as the targeted horizon, an in-depth study of the actual field parameters was completed.

Field Parameters

Walk-Away Noise Test and Optimum Window

In obtaining the most coherent signal from the seismograph a variety of field parameters were examined and the optimum value was chosen for the specific site. In order to select the optimum field parameters a walk-away noise test was conducted and the optimum window calculated to define the location of the Traverse Limestone reflection. A walk-away noise test also gives the geophysicist information on shallow layer velocities and depths. Figure 17 shows the results of a walk-away noise test. The geophone spacing remained at a constant interval of 30.5 feet, while the offset originated at 0 feet and was increased the total geophone spread length of 335.5 feet. The offset was again increased the geophone spread length to obtain a final offset of 671 feet. The direct arrival, two refracted arrivals, several reflectors, and groundroll are interpreted from
Figure 17. Walkaway Noise Test.
the walk-away noise test (Figure 17). The walk-away noise test also indicated an optimum window where the desirable reflections are located (Figure 17). The Traverse Limestone and two unidentified reflections from within the Antrim and Traverse Formations are located in the optimum window. The outer limit of the optimum window was calculated such that the total spread length of the source-offset and geophone array cannot exceed 3,500 feet or the Traverse Limestone reflection will be masked by late waveform arrivals on the record. The inner limit of the optimum window was defined by the first coherent reflected arrival. After the optimum window was determined, experimentation on field parameters was undertaken to obtain the best resolution on the Traverse Limestone reflection.

**Hammer vs. Shotgun Source**

A source comparison was completed using a 16-pound sledgehammer, a shotgun with slugs, and a shotgun with regular 7.5-shot shotgun shells, all at the same location. Figures 18 and 19 show the results of 1 and 2 regular shotgun shells. Figures 20, 21, and 22 are the results of 1, 2, and 3 shotgun slugs, and Figure 23 through 26 are the results of 10, 20, 30, and 40 hammer blows. The regular shotgun shells produced a large amount of noise on each trace. Both 7.5-shot shotgun
Figure 18. Result From 1 Regular Shotgun Shell.
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Figure 19. Result From 2 Regular Shotgun Shells.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 20. Result From 1 Shotgun Slug.
Figure 21. Result From 2 Shotgun Slugs.
Figure 22. Result From 3 Shotgun Slugs.
Figure 23. Result From 10 Hammer Blows.
Figure 24. Result From 20 Hammer Blows.
Figure 25. Result From 30 Hammer Blows.
Figure 26. Result From 40 Hammer Blows.
records have similar frequency ranges but have indistinguishable results. The shotgun slugs produced less noise per record which cleaned up the records for examination. Figure 22 shows a slight energy increase over Figures 20 and 21, but at the cost of shotgun shells, the difference is negligible. The 16-pound sledgehammer registered very little noise and trended toward an equal amount of energy to that of the shotgun slug. In most instances, the energy from the two sources was comparable, but in sandier surface areas the shotgun produced a more consistent energy at greater depths.

The differences between the 10 to 40 hammer blow records is slight, which suggests that 10 hammer blows is as effective as 40. With the targeted horizon at approximately 1,700 feet, the shotgun source with 1 slug provided satisfying results. One slug per shot hole was reasonably affordable and created less bodily stress than pounding the 16-pound sledgehammer. The most significant factor in choosing the shotgun with 1 slug was the repeated successful results. After choosing the seismic source, pre-emphasis filtering was undertaken to record the best possible signal.

**Field Filtering**

Choosing the correct value for a field filter was established by examining different frequency ranges for a
low-pass filter. The experimental field filters were set at frequency ranges from 75-475 hertz (Figure 27), 70-375 hertz (Figure 28), 75-825 hertz (Figure 29), and 75-440 hertz (Figure 30). Each of these frequency ranges was chosen with the field filtering theory in mind. Figures 27, 28, and 30 show no major obvious differences on the seismic record for the frequency filter ranges when compared. However, the frequency range in Figure 29 (75-875 hertz) produced a broader range of signals. Each record shows significant noise associated with a few of the traces. The shaped frequency curve of the seismographs band-pass filter does allow for some low-frequency noise to pass through the receivers and infest the records. This situation is evident from the idealized frequency response curve (Figure 31) of the 7 and 1000 hertz filters which indicates a wide range flat response to signals received between 10 and 900 hertz. On the basis of the similarities in filter ranges a 75-440 hertz frequency range was established to produce the best resolution of the seismic waveforms. The 75-440 hertz frequency range was chosen over the other ranges due to the frequencies identified on the frequency filter analysis. The maximum frequency identifiable through digital filtering on the records was 400 hertz so the frequency ranges of 475 and 825 hertz were not chosen. The next step after pre-emphasis filtering is to set the
Figure 27. Trace Showing a Frequency Range 75 - 475 Hz, 480 ms Sweep Time, and a 990 Foot Source Offset.
Figure 28. Trace Showing a Frequency Range 70 - 375 Hz, and a 192 msec Sweep Time.
Figure 29. Trace Showing a Frequency Range 75 - 825 Hz, a 960 msec Sweep Time, and a 660 foot Source Offset.
Figure 30. Trace Showing a Frequency Range 75 - 440 Hz, a 480 msec Sweep Time, and a 825 foot Source Offset.
Figure 31. Idealized Frequency Response Curve of the 7 and 1000 Hertz Filters.

program gain to record an even amplitude signal across the records.

Program Gain

To increase the amplitude of the recorded signal the program gain was set for 60 millisecond (ms) for each trace, thus increasing the recorded amplitude by 6 decibels (db) every 60 ms. For every 6 db increase in signal, a doubling effect on amplitude occurred. Knapp and Steeples (1986b) explain that with an increase of 6 decibels at every given time in milliseconds, the amplitude is increased by a factor of two. Knowing this factor, one would expect the noise to increase in amplitude across the trace. Thus, noise can distort the seismic signal and obscure the targeted reflections. This was the case on a few of the traces throughout the seismic cross-sections but overall there was no major disadvantage from the use of the program gain. The advantage of using the program gain is that it allows the weaker signals arriving later in time to be amplified so small features on the record can be identified.

Sweep Time

Three separate sweep-time selections were examined in the field survey. Figures 28, 29, and 30 have sweep times of 192 ms, 480 ms, and 960 ms respectively. The
480 ms sweep time was used for the reflection survey due to the time span of recording. The 960 ms sweep time compacted the record making reflections difficult to determine. The 192 ms sweep time could not produce a large enough time coverage to examine the occurrence of the Traverse Limestone. In plotting the time spans of the records, the 480 ms sweep time recorded the optimum window range with enough detail to identify small changes in the reflected waveform. The 192 ms sweep time expanded the plot to view greater detail but did not record the optimum window range. The 960 ms plot recorded the optimum window range but compacted the record so small changes on the seismic record could not be interpreted.

**Sampling Rate**

The sampling rate determines the time interval the waveform is sampled and is directly related to the sweep time. The Bison Geopro seismograph has a built-in sampling interval for the individual sweep times chosen. With a 480 ms sweep time, a sampling interval of 0.5 ms is used to record the seismic waveform.

**Notch Filter**

Besides the implementation of pre-filtering, a notch
filter was implemented in the survey to filter out the high voltage power lines and other 60 Hz noise.

Geophones

Most of the study area is covered by surficial sand and in the areas where sandy soil exists the high frequency content of recoverable signal is reduced. Knapp and Steeples (1986b) strictly advise that using a large spike and planting the geophones firmly and carefully into cleared ground is singularly the most effective means of improving geophone ground-coupling response and increasing the resolution of the signal recorded. All geophones were planted according to this advice. Attempts to improve the response by burying the geophones in the areas of poor reception were not successful. High frequency geophones were used to increase the resolution of the signal.

Source-Offset

Three source-offset distances were initially tried, 660, 825 and 990 feet. Of the three offset distances only the 990 foot offset produced a large optimum window where reflections could be viewed on the same record. In an effort to obtain the large optimum window and increase the speed in conducting the seismic survey a 915 foot
source-offset was implemented. There are two main advantages to using a source-offset of 915 feet.

First, the larger offset produced an optimum window where many reflections were observed on the same seismic record. The Traverse Limestone was identified as one of the reflection events. Second, the 915 foot offset was divided equally by a value of 152.5 feet. The importance of choosing this particular value allows for mobility in moving the geophones and source along a common source-offset line. With a geophone spacing of 30.5 feet, the distance between five geophones is 152.5 feet. In flipping five geophones after every recording, the total source-offset distance is marked by six geophone spread flips or 915 feet. Figure 32 shows a raypath diagram for three geophone spread flips. A total of 33 geophone spread movements covers a total distance of 1 mile sampled on the Traverse Limestone. Therefore, the source offset of 915 feet increases the speed and mobility in conducting a common source-offset survey.

Raypath Diagram

A raypath diagram (Figure 32) was constructed to show the direction traveled by a propagating P-wave into the subsurface and its reflection off the Traverse Limestone. The raypath diagram also displays the amount of subsurface coverage on the Traverse Limestone at every
Figure 32. Raypath Diagram of 3 Geophone Spread Movements and Coverage on the Traverse Limestone.
shot point. Table 1 gives the angle of incidence values with associated velocities. As the raypath diagram shows, there is 165.75 feet of coverage on the Traverse Limestone for each shot point and thus the Traverse Limestone is sampled every 15.25 feet. To ensure complete coverage of the Traverse Limestone between records, the twelfth and first geophones for subsequent shot points were overlapped. This small sampling interval allows for a detailed survey in the shortest possible time period.

Processing and Analysis of Field Data

**Synthetic Seismogram**

To determine the validity and existence of the Traverse Limestone reflection a synthetic seismogram was generated using the data listed in Table 2. Velocities for the synthetic seismogram were acquired from a sonic log approximately 2 miles east-south-east of the Diamond Springs oil field. An average velocity across a particular lithology was chosen to model that horizon. The velocity value for the drift layer was determined by a refraction analysis. The thickness of each particular horizon was chosen from drillers' logs throughout the field. Gamma ray neutron logs were used in conjunction with drillers' logs to support the lithologic thickness
### Table 1

Raypath Values

<table>
<thead>
<tr>
<th>Layer</th>
<th>Velocity (ft/sec)</th>
<th>Incidence Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>5,500</td>
<td>-</td>
</tr>
<tr>
<td>Coldwater Shale</td>
<td>10,000</td>
<td>17</td>
</tr>
<tr>
<td>Ellsworth Shale</td>
<td>9,000</td>
<td>15.3</td>
</tr>
<tr>
<td>Antrim Shale</td>
<td>10,000</td>
<td>17</td>
</tr>
<tr>
<td>Traverse Formation</td>
<td>12,000</td>
<td>20.5</td>
</tr>
<tr>
<td>Traverse Limestone</td>
<td>16,000</td>
<td>27.8</td>
</tr>
<tr>
<td>Dundee Limestone</td>
<td>11,000</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 2

Synthetic Seismogram Values

<table>
<thead>
<tr>
<th>Layer</th>
<th>Velocity (ft/sec)</th>
<th>Thickness (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>5,500</td>
<td>101</td>
</tr>
<tr>
<td>Coldwater Shale</td>
<td>10,000</td>
<td>677</td>
</tr>
<tr>
<td>Ellsworth Shale</td>
<td>9,000</td>
<td>407</td>
</tr>
<tr>
<td>Antrim Shale</td>
<td>10,000</td>
<td>230</td>
</tr>
<tr>
<td>Traverse Formation</td>
<td>12,000</td>
<td>49</td>
</tr>
<tr>
<td>Traverse Limestone</td>
<td>16,000</td>
<td>235</td>
</tr>
<tr>
<td>Dundee Limestone</td>
<td>11,000</td>
<td>-</td>
</tr>
</tbody>
</table>
values. The model incorporates the data and produces idealized reflections. The field parameters inserted into the synthetic seismogram model were a geophone interval of 30.5 feet, a source-offset at 915 feet, a time delay equal to 50 milliseconds, and a sweep time of 480 milliseconds. This data was inserted into the New Jersey Geological Survey "HRASSD" synthetic seismogram program and a model was generated (Figure 33). The model's arrival time for the Traverse Limestone reflection was compared to one corrected seismic record. The actual arrival time for the Traverse Limestone correlated with the model. Table 3 shows the representative arrival times for the Traverse Limestone model and the corresponding actual arrival times on the record. This indicates the existence of a reflection at the actual arrival time for the Traverse Limestone. To check the validity of the model, the Antrim Shale and Dundee Limestone reflection arrival times were examined on a few records to determine correlation with the model. After normal moveout and static corrections the Traverse Limestone, Antrim Shale, and Dundee Limestone indicated actual arrival times correlating to the model arrival times suggesting the occurrence of a reflection that represented those particular horizons. Since the Traverse Limestone reflection was considered valid,
<table>
<thead>
<tr>
<th>Geophone</th>
<th>Synthetic (msec)</th>
<th>Actual (msec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>331.6</td>
<td>332</td>
</tr>
<tr>
<td>2</td>
<td>332.5</td>
<td>333</td>
</tr>
<tr>
<td>3</td>
<td>333.5</td>
<td>333</td>
</tr>
<tr>
<td>4</td>
<td>334.6</td>
<td>334</td>
</tr>
<tr>
<td>5</td>
<td>335.6</td>
<td>335</td>
</tr>
<tr>
<td>6</td>
<td>336.7</td>
<td>336</td>
</tr>
<tr>
<td>7</td>
<td>337.8</td>
<td>337</td>
</tr>
<tr>
<td>8</td>
<td>339.0</td>
<td>339</td>
</tr>
<tr>
<td>9</td>
<td>340.1</td>
<td>340</td>
</tr>
<tr>
<td>10</td>
<td>341.3</td>
<td>341</td>
</tr>
<tr>
<td>11</td>
<td>342.6</td>
<td>343</td>
</tr>
<tr>
<td>12</td>
<td>343.8</td>
<td>342</td>
</tr>
</tbody>
</table>

Figure 33. Synthetic Seismogram Model of a Typical Trace.
digital filtering, static corrections, and normal move-out corrections were applied to the rest of the records.

**Digital Filtering**

A digital filter was applied to all the records upon return from the field. The band pass digital filtering was chosen with a frequency range of 125-200 hertz. The frequency range was selected by conducting a frequency analysis on a single trace recorded from one shotgun blast. The signal was examined from 5-400 hertz in 25 hertz intervals. Figure 34 represents an example of an unfiltered record from shot point 34, of seismic cross-section B-B'. The frequency analysis applied to that record is viewed in Figures 35 through 51 with the optimum frequency range between 125 and 200 hertz. There are frequencies outside the 125 to 200 hertz optimum range but they taper off as the limits are expanded away from this range, where the effects on the record become minimal. An example of frequency band pass filtering from 125-200 hertz is examined in Figure 51. Reflections seen on this record are identifiable, whereas the reflections look obscured on the unfiltered version (Fig. 34). The importance of frequency filtering is obvious as a processing method to distinguish reflections after obtaining the original field data. Once frequency
Figure 34. Unfiltered Trace From Shot Point 34.
Figure 35. Frequency Filtered Trace From 5 - 25 Hz.

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Figure 36. Frequency Filtered Trace From 25 - 50 Hz.
Figure 37. Frequency Filtered Trace From 50 - 75 Hz.

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Figure 38. Frequency Filtered Trace From 75 - 100 Hz.
Figure 39. Frequency Filtered Trace From 100 - 125 Hz.
Figure 40. Frequency Filtered Trace From 125 - 150 Hz.
Figure 41. Frequency Filtered Trace From 150 - 175 Hz.

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Figure 42. Frequency Filtered Trace From 175 - 200 Hz.
Figure 43. Frequency Filtered Trace From 200 - 225 Hz.

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Figure 44. Frequency Filtered Trace From 225 - 250 Hz.

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Figure 45. Frequency Filtered Trace From 250 - 275 Hz.
Figure 46. Frequency Filtered Trace From 275 - 300 Hz.
Figure 47. Frequency Filtered Trace From 300 - 325 Hz.
Figure 48. Frequency Filtered Trace From 325 - 350 Hz.
Figure 49. Frequency Filtered Trace From 350 - 375 Hz.
Figure 50. Frequency Filtered Trace From 375 - 400 Hz.
Figure 51. Frequency Filtered Trace 125 - 200 Hz From Shot Point 34.
filtering was completed static corrections were applied to all the records.

Static Corrections

Static corrections were applied to every record after digital filtering was completed. A consistently picked refraction was chosen for the static corrections. This layer is located at a depth of 235 feet in the uppermost part of the Coldwater Shale. The consistency of the refracted wave makes it possible to achieve a high standard for the corrections.

The first step in completing a static correction is to define the horizon for the correction. In this case a refraction within the Coldwater Shale was observed on each of the records at approximately the same arrival time. All of the records showed a linear trend in the arrival times from trace 1 to trace 12. In order to obtain correlation of the refracted wave across the records the first and last geophones were overlapped on adjacent records. This correlation verified the linear arrival time trend on each of the records. The second step in completing the static correction is to compute the time difference from trace 1 to trace 12. An average time difference is calculated by averaging the first arrival times from all the records in the survey. The time difference is divided by eleven, the number of
spaces separating traces 1 and 12. The new number is then added successively to each trace to give the static correction value. Each record is then matched to the static correction times by lining up the chosen event for the static correction. A straight line correction should be the final result. Since all the records contained little variation in the arrival times from the refracting horizon, the static corrections eliminated the near surface effects of the overburden layer. In the event of a curved static correction line or a jump in time from a static correction, a poor geophone plant or a change in lithology has influenced the record.

The static corrections greatly enhanced the alignment of the reflected events and negated the near surface noise clouding the records. In a few areas, a poor geophone plant in sandy soil affected the results of static corrections. An example of this type of noise can be seen in Figure 52.

Normal Move-out

Normal move-out corrections were applied to the Traverse Limestone, Antrim Shale, and Dundee Limestone as a final determination of the validity of the reflections (Figure 15). Each lithology was corrected for normal move-out and determined to be a true reflection event due to the consistency of the waveforms across the records.
Figure 52. Seismic Trace Showing Noise From a Poor Geophone Plant.
The Traverse Limestone was then corrected for normal move-out on all the records as the true targeted reflection. To doublecheck the Traverse Limestone reflection a velocity analysis was calculated and the velocities compared.

**Velocity Analysis**

A velocity analysis of the reflections on the seismic records was calculated to correlate to the velocity of the Traverse Limestone in the synthetic seismogram. The velocity value calculated from the "HRASSD" computer program was 15,709 feet per second. This correlated well with the 16,000 feet per second calculated from the seismic records for the Traverse Limestone. These comparable velocity values also justify the validity of the model and the actual Traverse Limestone reflection.

Although processing "cleaned up" the records there was still minor noise associated with the records.

**Noise**

The last and most prevalent effect on the seismic records is noise. Even after digital filtering, static, and normal move-out corrections, noise was still evident on the records. Wind noise affected the seismic records significantly on days when tree roots created an energy
vibration (Figure 53). Pump jacks pumping every other day also produced noise as a spike wavelet, which can be traced across one of the records (Figure 54). Overall, noise did not affect the seismic record significantly. Digital filtering was able to cancel most of the noise on the records and enhance the desired Traverse Limestone reflection.

One specific type of noise not filtered out through processing techniques was a type of reverberation noise. The reverberations (Figure 55) were calculated to have a frequency of 55 hertz. Although notch filters of 60 hertz were used to eliminate noise in the 60 hertz range, they did not encompass the 55 hertz signal which would have eliminated the reverberations. The effects of the 55 hertz signal are present due to the drawbacks of the Bison's notch filter discussed previously. The reverberation at 55 hertz is characterized as noise, but its origin could not be defined.

**Trace Addition**

After processing the seismic records to eliminate unwanted noise, trace addition (summing) was performed to enhance the reflection event off the Traverse Limestone. Trace addition involved adding neighboring traces in sequential order. On a seismic record, trace two would be added to trace one, trace three would be added to
Figure 53. Seismic Trace Showing Wind Noise.
Figure 54. Seismic Trace Showing Pump Jack Noise.
Figure 55. Seismic Traces Showing Reverberation Noise.
trace two, and so forth. The effect of adding neighboring traces was interesting, but the results were not entirely unexpected. Figure 56 illustrates the results of one record with and one record without trace addition. The significant difference between the two records is that the trace added record shows an enhancement of the desired reflections. Combining a few trace added records and comparing them to nontrace added records yields similar results. Although trace addition slightly improved the records, adding a series of records was not feasible on the Bison Seismograph. Due to this limitation and the increase in time for single trace addition, adding consecutive traces was not implemented.

Results

The Traverse Limestone was identified on the seismic records by correlation to a synthetic seismogram and by velocity analysis. The arrival times representing the Traverse Limestone matched the actual arrival times seen on commercial records in the Diamond Springs area. Thus the Traverse Limestone reflection was identified in this thesis.

The Traverse Limestone reflection is the only true reflection verified in the analysis. The Traverse Limestone reflection seen on cross-sections A-A' (Figure 57) and B-B' (Figure 58) indicate a slight doming over
Figure 56. a) Seismic Trace Without Trace Addition. b) Seismic Trace With Trace Addition.
Figure 57. Seismic Cross Section A - A' Along 136th Street.
Figure 58. Seismic Cross Section B - B' Along 36th Avenue.
the whole seismic cross-section. This is attributed to the overall structure of the reef mass. The lithologic cross-sections constructed from well logs showed the maximum relief of the Traverse Limestone as 70 feet. This relief produced approximately 3 milliseconds time change across the seismic cross-sections and verified the existence of a domed structure. This structure along with previous evidence suggests the existence of a domed reef mass.

Static problems did not exist due to the first break method of analysis. The static errors were relatively insignificant in determining the validity of the interpretation. Seismic cross-section A-A' shows similar static results to seismic cross-section B-B' although more noise is associated with cross section B-B' due to the presence of surface sand. Therefore, static correction errors had no significant affect on the seismic record.

Normal moveout corrections applied to each of the records indicate that the Traverse Limestone reflection is influenced by structure and possibly diffractions.

One common feature associated with diffracting events is the normal move-out correction being twice that of a reflecting normal move-out correction. After the normal move-out process was undertaken for the Traverse Limestone, a distinctive separation still existed between
each trace. This arrival time separation was approximately twice that of the reflection normal moveout correction which implies the possibility of a diffracting event. The expected waveform from a diffraction off a point source or the edge of a porosity zone is idealized in Figure 14, where the radial waves shown in the drawing are returning to the surface along the indicated paths. The arrival times from this type of event are such that an "elliptical" shape is created on the seismic crosssection.

The normal moveout correction was identical on all the traces, and in conjunction with the velocity analysis, gives evidence that the "elliptical" bending of the waveform in the seismic cross-sections is a true event.

Within the overall structure of the reef small pockets of high porosity and high production exist. These zones of high production are possibly associated with diffractions. The high production porosity zones act as an irregular point of curvature which change the velocity of the waveform and create a diffraction. The particular zones of production are seen on seismic cross-section A-A' (Figure 57) where the production zones are in direct correlation with the "elliptical" shape of the waveform.

The overall quality of the records is good. Small
changes in the reflected waveform such as the "elliptical" bending correlated to the high porosity zones. The detail of coverage on the Traverse Limestone provided sufficient quality to identify the small porosity zones within the reef mass, and cross section A-A' had excellent quality in data recorded across the section while B-B' was slightly less in quality due to the increased surface sand while recording the data.

Although it is known that diffractions do exist, it is unlikely they can be specifically identified on the records. Because the program gain and amplitude gain were set to create an even amplitude throughout the records, it would mask the signature of a diffacting event on the record. The "ellipsoidal" bending of the waveform could be primarily caused by small structural features represented by the porosity zones, along with the possible diffractions.
CHAPTER V

CONCLUSION AND FUTURE RESEARCH

The Diamond Springs oil field located in Allegan County, Michigan, represents a Devonian patch reef. A seismic survey in the area was completed by developing an east-to-west (Figure 57) and a north-to-south (Figure 58) seismic cross-section. Both seismic cross-sections detail the subsurface geology, in particular the Traverse Limestone.

The Traverse Limestone topography represents a domed structural feature in lithologic cross-section, as well as in seismic cross-section. The seismic cross-sections did show a slight doming over the production zones along with an "elliptical" bending of the waveform. This leads one to believe the porosity zones affect the seismic waveform in a detailed survey. Therefore, a detailed, common offset, shallow seismic survey can produce excellent results when permitted time to analyze all parameters before the final survey is undertaken. High resolution of the waveform was achieved through common source-offset surveying using a shotgun source and high frequency geophones. Finally, it is possible to define shallow patch reefs by locating significant porosity
zones through the use of common source-offset profiling. Continued research is needed before understanding the conditions and implications of high resolution shallow seismic surveys. Information gained through this study sheds light on the use of common offset seismic profiling. To decrease the cost of exploration, the definition of small, shallow structures is necessary to determine the exact emplacement of oil wells. Questions brought to light from the research that need further investigation include: (a) the use of common depth-point surveying to enhance the reflection off the Traverse Limestone and reduce seismic noise, (b) the elimination of reverberations in certain areas of the survey, (c) the use of dynamite as a possible source to increase the energy and resolution at depth, and (d) the correct use of program gain and amplitude gain to better define possible diffractions.
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