HIGH RESOLUTION GEOPHYSICAL INVESTIGATION OF LATE QUATERNARY DEFORMATION IN THE LOWER WABASH VALLEY FAULT SYSTEM

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ABSTRACT OF THESIS

HIGH RESOLUTION GEOPHYSICAL INVESTIGATION OF LATE QUATERNARY DEFORMATION IN THE LOWER WABASH VALLEY FAULT SYSTEM

Seven and a half kilometers of high-resolution SH-wave seismic reflection profiles were collected across the Mt. Vernon graben, a 35 km by 3 km graben (bounded by the Wabash Island (WIF) and Hovey Lake faults (HLF)) in the southern Wabash Valley fault system (WVFS) of southern Indiana. Forty-six discrete faults were imaged that displaced Quaternary horizons in the vicinity of the WIF and HLF. The structural styles associated with faults include: 1) normal displacement, 2) reverse displacement and other compressional features, 3) varying magnitudes of slip along fault planes, and 4) different senses of slip along individual fault planes. Carbon 14 dating of displaced horizons suggests movement between approximately 26,000 and 42,000 YBP.

The style and timing of Quaternary deformation within the WVFS, the close association of soil faults to documented post-Pennsylvanian bedrock faults (HLF and WIF), and focal mechanism studies of current seismicity in the Wabash Valley seismic zone are all direct evidence that the extensionally-formed faults of the WVFS are being transpressionally reactivated: a manner consistent with the current east-northeast – west-southwest regional compressive stress field.

KEYWORDS: Seismic Reflection, Seismic Hazard, Quaternary Geology

Frederick Alexander Rutledge III

September 7, 2004

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HIGH-RESOLUTION GEOPHYSICAL INVESTIGATION OF LATE QUATERNARY DEFORMATION IN THE LOWER WABASH VALLEY FAULT SYSTEM

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THESIS

Frederick A. Rutledge III

The College of Arts and Sciences

University of Kentucky

2004
HIGH-RESOLUTION GEOPHYSICAL INVESTIGATION OF LATE QUaternary deformation in the lower Wabash Valley fault system

THESIS

A thesis submitted in partial fulfillment of the requirements of the degree of Master of Science in the College of Arts and Sciences at the University of Kentucky

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2004

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Finally, I’d like to thank my wife Amanda for her unwavering support through my long hours spent on this project, and my daughter Alexis who has inspired me to achieve great things.
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Chapter One

1.0 Background

1.1 Introduction

The Wabash Valley seismic zone (WVSZ), with the exception of the New Madrid seismic zone, is the most seismically active region between the Appalachian and Rocky Mountains (Wheeler and Ravat, 2002). Consequently, the identification of potential source structures within this basin is important for accurate seismic hazard evaluation. The boundaries confining seismogenic sources used for seismic hazard analysis have many economic and developmental implications for a given region (i.e., building codes), and need to be accurately defined.

There are contemporary, historical, and paleoseismic records of earthquake activity in and around a system of faults in the southernmost Wabash River Valley of the central United States, called the Wabash Valley fault system (WVFS). Paleoseismic studies have verified that at least eight large earthquakes (5.5–7.5 M) have occurred in this region during the Holocene (Obermeier, 1998). Earthquake focal mechanisms in the region have shown that the depths of recent seismic events range from approximately 4 to 22 km, and the type of fault motion is predominantly reverse and strike-slip (Taylor et al., 1989; Kim, 2003). The studies of this region, however, have not been able to correlate the regional seismicity with discrete structures of the WVFS. A lack of structural correlation to recent seismicity in the WVFS is a result of (1) sparse seismic network coverage, leading to high epicentral/hypocentral uncertainty, (2) thick alluvial deposits (10–40 m) in the Wabash and Ohio River valleys that have much lower shear strengths than the underlying bedrock, and tend to deform in a more ductile manner, and/or (3) the low recurrence intervals of large events coupled with the alluvial environment of the Illinois Basin, which could erode and cover surface deformation. Based on seismic reflection data, McBride et al. (1997) suggested that a deeper reactivation of Grenville-aged blind thrust faults, which do not extend into the Phanerozoic cover, are the source of some WVSZ events. They also observed that although the faults of the WVFS do not extend into the deformed basement zone, they often correlate to deeper structures within the basement rock.
The objective of this study is to assess the Mt. Vernon graben, a prominent structure located in the southern WVFS of southern Indiana, for neotectonic reactivation. The Mt. Vernon graben is approximately 35 km long and ranges from 2 to 3.5 km in width. It is bounded by the Wabash Island (WIF) and Hovey Lake faults (HLF), two high-angle normal faults that intersect within the upper Precambrian basement, at a depth of approximately 5.5 km (Rene and Stanonis, 1995). Seven and a half kilometers of high-resolution SH-wave seismic reflection profiles were collected across the Mt. Vernon graben. This study targets the Quaternary sediment overlying the Mt. Vernon graben, and images 46 discrete faults of late Quaternary age.

1.2 Geologic Background

1.2.1 Central United States

The Wabash Valley fault system (WVFS) lies within one of the most structurally complex regions in the Midcontinent (Hildenbrand and Ravat, 1997) (Figure 1.1). The WVFS, Cottage Grove Fault System, St. Genevieve Fault Zone, Fluvorspar Area Fault Complex, and several smaller fault systems are bounded by or extend from the intersection of the Reelfoot Rift and the Rough Creek Graben (failed Precambrian to early Proterozoic rifts) (Hildenbrand and Ravat, 1997). Several deep crustal features are also spatially related to these rifting events, including the Commerce Geophysical Lineament, the South-Central Geophysical Lineament, and the Paducah Gravity Lineament. The Commerce Geophysical Lineament has been noted as a possible source structure for the current seismicity in the Wabash Valley seismic zone (Langenheim and Hildenbrand, 1997; Hildenbrand et al., 2002) (see section 1.2.6).

1.2.2 Wabash Valley Fault System

The Wabash Valley fault system (WVFS) is located in the Wabash River Valley of southern Illinois and Indiana. It is bounded by White and Gallatin Counties on the west and the Ohio River on the east, near the confluence of the Ohio and Wabash Rivers. It extends as far north as Wabash County, Ill. and its southern terminus is near the middle of Gallatin County, Ill. just north of the Shawneetown fault zone and Rough Creek fault system junction (Figure 1.2).
The WVFS is a linear, northeast–southwest-trending band of narrow grabens that are roughly coincident with the Wabash River valley of southern Indiana and Illinois (Bristol and Treworgy, 1979; Treworgy, 1981; Ault and Sullivan, 1982; Ault et al., 1985; Rene and Stanonis, 1995). Hovey Lake fault and Wabash Island fault, major faults imaged in this study, are oriented north–northeast (~018–022°). Drilling and deep geophysical soundings have characterized the WVFS as a series of high-angle, normal faults (Bristol and Treworgy, 1979; Sexton and Jones, 1986; Bear et al., 1997). Nelson and Lumm (1987) originally suggested that the faults do not extend to the Precambrian basement; however, more recent seismic investigations (Rene and Stanonis, 1995) imply that the Hovey Lake and Wabash Island faults intersect within the Precambrian basement rocks. Displacements along individual faults can be as great as 146 m, and decrease toward the northern- and southernmost portions of the WVFS (Bristol and Treworgy, 1979).

Considerable uncertainty remains about the origin of the WVFS and its relation to other geologic structures in the region (Fluorspar Area Fault Complex, Rough Creek Fault Zone, Reelfoot Rift, Shawneetown fault zone, Commerce Geophysical Lineament, etc.). Braile et al. (1982, 1986, 1997) indicated that the Reelfoot Rift, Rough Creek Graben, two additional arms called the St. Louis Arm and the Southern Indiana Arm, and the WVFS are all tectonically and geologically related and form a large rift complex. Others, however, believe the WVFS is a structural feature, which formed as a result of stress accommodation near a bend in the Reelfoot–Rough Creek rift system (Hildenbrand et al., 1982; Kolata and Nelson, 1991; Thomas, 1993; Hildenbrand and Hendricks, 1995; Hildenbrand and Ravat, 1997). Kolata and Nelson (1991) hypothesized that compressional stresses during a late Paleozoic continental collision arched this region and produced the extensionally formed Wabash Valley Fault system at its crest.

1.2.3 Regional Stress Field

The WVFS lies within the Midcontinent Stress Province as defined by Zoback and Zoback (1980). This province extends from the Great Plains states eastward to the Appalachian Mountains, and the Gulf Coast states northward into Canada. This region is characterized by east- to east–northeast-trending (~77°) maximum compressive stress (Nelson and Bauer, 1987;
Kolata and Nelson, 1991). The WVFS is located approximately 100 km northeast of the NMSZ, an area in the Midcontinent Stress Province with anomalous stress orientations.

Zoback and Zoback (1980) discussed two processes as the dominant causes of horizontal stress in the Midcontinent Stress Province: asthenospheric drag and ridge push. Asthenospheric drag is caused by a moving lithosphere over a relatively stationary asthenosphere. Frictional shearing stress at this boundary will produce forces opposite the direction of plate motion. Ridge push is caused by lateral density and thickness variation within and between plates. A change in density or thickness results in a buoyance force oriented normal to the density boundary. The vertical component is relieved isostatically, leaving a net horizontal stress.

Push and drag vectors compared in the midcontinent have a statistically significant relationship with the greatest principal stress vectors. This directional correlation between maximum principal compressive stresses and stresses caused by drag and push (Zoback and Zoback, 1980) suggest these forces play a major role in the current Midcontinent Stress Province. Asthenospheric drag, however, has a better statistical correlation with the greatest principle stress than ridge push does; implying drag is the dominant driving force.

Small thrust faults and joints with displacements of a few inches to a few feet have been observed in mines and outcrops of Pennsylvanian and Mississippian rocks in the WVFS. Although some of the small-scale thrust faults could be a result of sedimentologic processes, Ault et al. (1985) suggested most of these joints and thrusts are indications that the Midcontinent Stress Province affects the WVFS.

1.2.4 Regional Seismicity

1.2.4.1 Paleoseismicity

The southern halves of Indiana and Illinois are exposed to a significant level of earthquake hazards (Wheeler, 1997), as documented by historical and recent seismicity (Rudman et al., 1997; Street et al., 2002) (Figure 1.3). In addition, at least eight paleoliquefaction features of Holocene age have been recognized in the region surrounding the study area (Obermeier, 1992, 1998; Munson et al., 1997; Pond and Martin, 1997), which represent significant seismic events (> 6.0 m_b). From calculations based on paleoliquefaction evidence and carbon dating of
the largest events, Obermeier (1998) suggested an event of M~7.5 occurred along the Wabash River approximately 6100 +/-100 years BP, and another of M~7.1 occurred 12,000 +/-100 years BP.

1.2.4.2 Historical Seismicity

Over the past 200 years, a large number of small to moderate earthquakes have occurred in the region surrounding the study area. Since 1820, 18 earthquakes with Modified Mercalli intensities between VI and VII have occurred in the Wabash Valley seismic zone (WVSZ) (Figure 1.4) (FMSM Engineers, 2002). Of these, five events took place within 50 km of the study area before the 1962 installation of the World-Wide Standard Seismograph Network (WWSSN) (Table 1.1). Estimated magnitudes for these events ranged from 4.1 to 4.8 \( m_{fa} \), where \( m_{fa} \) is a body-wave magnitude empirically calculated from the felt area.

1.2.4.3 Contemporary Seismicity

A majority of 60 seismic events recorded in a recent WVSZ study were congregated around the New Harmony Fault, which is located 10 km NW of the study area (Rudman et al., 1997). The largest earthquake to take place anywhere in the WVSZ since the creation of regional seismic networks was on November 9, 1968 [5.5 \( m_{b,Lg} \)], and occurred near the southwestern boundary of the WVFS (Figure 1.3). This event is the largest 20\(^{th}\) century earthquake to occur in the central United States. The most recent notable earthquakes are a 5.0 \( m_{b,Lg} \) in Darmstadt, Ind., on June 18, 2002, as well as a 3.1 \( m_{b,Lg} \), occurring less than 10 km from the study area on January 3, 2003 (Figure 1.3).

Despite the numerous historic, prehistoric, and contemporary events that have occurred in the WVFS, no primary, coseismic deformation has been documented for these events (Bristol and Treworgy, 1979; Ault and Sullivan, 1982; Ault et al., 1985; Nelson and Lumm, 1987; Rene and Stanonis, 1995; Bear et al., 1997). This lack of known Quaternary deformation or surface expression of faulting in the WVFS is likely the result of the thick alluvial deposits (often greater than 30 m) that accommodate surface strain, and the relatively small displacements that occur in these moderately sized, low-recurrence earthquakes.
1.2.5 Focal Mechanism Studies in the Wabash Valley Fault System

Focal mechanism analysis has been conducted on several moderately sized earthquakes in the Wabash Valley seismic zone (Figure 1.5). Taylor et al. (1989) described three earthquakes west and north of the study area. The November 9, 1968, 5.5 m_w event occurred 35 km west of the study area, and is described as having almost pure reverse motion along a moderately dipping fault striking north–south at a depth of 22 km. The second earthquake was the April 3, 1974, event (M_n 4.7) that occurred approximately 80 km north of the study area. This event produced almost pure right-lateral strike-slip motion, with near vertical nodal planes striking northeast–southwest, and a hypocentral depth of 15 km. The third earthquake was the June 10, 1987, event (m_b 4.9) that occurred approximately 90 km north of the study area. This earthquake was mostly right-lateral strike-slip, with a small compressional component. Nodal planes were near vertical and oriented northeast–southwest, and the event occurred at a depth of 10 km. More recently, Kim (2003) discussed the June 18, 2002, earthquake (M_W 4.6), which occurred 30 km northeast of the study area (approximately 5 km from the northern terminus of Hovey Lake Fault). The event is described as producing mostly right-lateral strike-slip motion with a small extensional component. Nodal planes were near vertical and oriented northeast–southwest, and the event occurred at a depth of 18 km.

1.2.6 Commerce Geophysical Lineament

The Commerce Geophysical Lineament (CGL) is characterized as a linear magnetic and gravity anomaly that extends from Arkansas to Indiana over a distance of 600 km (Langenheim and Hildenbrand, 1994, 1997; Hildenbrand and Ravat, 1997; Hildenbrand et al., 2002) (Figure 1.1). The CGL runs parallel to the Reelfoot Rift and is offset approximately 40 km to the northwest of the failed Precambrian rift structure (Langenheim and Hildenbrand, 1997). Modeling suggests the geophysical anomaly is a swarm of mafic dikes, and its spatial relation and orientation suggest that it is geologically related to the Reelfoot Rift, which has undergone episodic igneous activity (Langenheim and Hildenbrand, 1997). The CGL extends beyond the northern terminus of the Reelfoot Rift and continues along the western edge of the WVFS, eventually crossing the fault system near its northern boundary.
The five large paleoseismic epicenters described by Obermeier (1998) lie near a bend in the CGL (Obermeier, 1998; Hildenbrand et al., 2002) suggesting that it was a potential source for the large prehistoric and historic events. Nevertheless, if the CGL, or other deep structure, is a source for these events, then recent near-surface faulting in the WVFS could indicate the WVFS is a weak crustal zone that accommodates the stress released by the deeper seismic events.

1.2.7 Site Geology

The bedrock consists of mostly late Pennsylvanian sandstone, shale, coal (with underclays), and occasional interbedded carbonates (Rene and Stanonis, 1995). U. S. Geological Survey maps suggest the bedrock is overlain by up to 40 m of unlithified Pleistocene to Holocene sediments, consisting of relatively thin clays underlain by a fining-upward sand sequence. Four soil borings collected from the study area corroborate this characterization (Figures 1.6 and 1.7).

1.3 Related Studies

The Wabash Island Fault (WIF) and Hovey Lake Fault (HLF), forming a 3-km-wide by 40-km-long graben, were originally delineated by petroleum boreholes and subsequently imaged by Rene and Stanonis (1995) with deep seismic-reflection surveys. They concluded that the WIF is composed of several branches in a quasiplanar zone, and primary offset at depth is high-angle, north–northeast- to northeast–trending normal displacement. Displacements on the lower fault branch increase with depth, whereas the displacements on the upper fault branch decrease with depth. The HLF, which lies 3 km to the east, is listric, and displacements along the fault decrease with depth. The two faults intersect within the Precambrian basement rocks. Data based on Rene and Stanonis’s study (1995) suggest the faults propagated through the late Pennsylvanian bedrock but not the Quaternary sediment (Pleistocene and Holocene). This interpretation, however, was based on poor-quality, low-resolution data from early in the time section, because the Quaternary sediment was not their primary target. The higher-resolution seismic surveys conducted in this study were specifically designed to test the validity of their findings by imaging the near-surface sediments. This study’s surveys have found that fault
propagation extends from the Pennsylvanian bedrock into the Quaternary sediments of the Illinois Basin.
Table 1.1: Historical earthquakes occurring within 50 km of study area, before the 1962 installation of the World-Wide Standard Seismograph Network.

<table>
<thead>
<tr>
<th>Date</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Magnitude (mL)</th>
<th>Distance from study area (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/05/1927</td>
<td>38</td>
<td>-87.5</td>
<td>4.8</td>
<td>40 east</td>
</tr>
<tr>
<td>7/27/1927</td>
<td>37.9</td>
<td>-87.5</td>
<td>4.1</td>
<td>45 east</td>
</tr>
<tr>
<td>11/27/1922</td>
<td>37.8</td>
<td>-88.5</td>
<td>4.8</td>
<td>47 NNE</td>
</tr>
<tr>
<td>4/27/1925</td>
<td>38.2</td>
<td>-87.8</td>
<td>4.8</td>
<td>42 east</td>
</tr>
<tr>
<td>9/27/1925</td>
<td>37.8</td>
<td>-87.5</td>
<td>4.6</td>
<td>42 east</td>
</tr>
</tbody>
</table>
Figure 1.1: Significant structural features of the Midcontinent (modified from Kolata and Nelson, 1991). The light-gray shaded region represents the Jackson Purchase, which defines the northeastern terminus of the Mississippi Embayment, an area where faults are covered by alluvial sediment. The dotted gray line represents the Commerce geophysical lineament (Hildenbrand and Ravat, 1997; Harrison et al., 1999). The east-northeast–west-southwest trending arrows represent the current state of stress in the WVFS (Zoback and Zoback, 1980).
Figure 1.2: Faults of the Wabash Valley fault system, surrounding the study area. The green shaded rectangle confines the study area. The Hovey Lake fault and Wabash Island fault were both imaged in the near surface (Figures A-8, A-9, and A-11).
Figure 1.3: Seismicity of the Wabash Valley seismic zone, showing major fault locations. Dashed lines represent epicentral uncertainty. The January 3, 2003, event is located adjacent to the study area.
Figure 1.4: Epicenters of the 18 damaging earthquakes (Modified Mercalli VI or greater) occurring since 1820 in the Wabash Valley seismic zone (modified from FMSM Engineers, 2002). Numbers in parentheses indicate number of events.
Figure 1.5: Focal mechanisms and locations of earthquakes in the vicinity of the Wabash Valley fault system.
Figure 1.6: $^{14}$C dating results and soil classification from WI-1, WI-2, and WI-3. Inverted aged dates (WI-2) could be a result of contamination from uphole organics. More detailed soil descriptions can be found in Appendix C.
Figure 1.7: $^{14}$C dating results and soil classification from HL-1. More detailed soil descriptions can be found in Appendix C.
Chapter Two

2.0 Methodology

2.1 General

P-wave seismic reflection methods have traditionally been used to image near-surface neotectonic deformation in the water-saturated sediment-fill of the central United States river valleys (Sexton and Jones, 1986; Schweig et al., 1992; Williams et al., 1995; Odum et al., 1998; Stephenson et al., 1999). CDP surveys using horizontally polarized shear-waves (SH-mode) have been found to be better suited for imaging near-surface neotectonic deformation of the sediment, however (Woolery et al., 1993, 1996; Harris, 1996; Harris et al., 1998). SH-waves are framework waves, and therefore not affected by the presence of water in saturated sediments. P-waves are influenced by water, which can mask sediment deformation. In addition, there is no mode conversion of SH-waves (unlike SV-waves) at the idealized impedance boundary.

P-wave methods can also be problematic in imaging near surface features, because of their naturally higher velocities relative to S-waves. The result of these higher velocities is a relatively small spatial and temporal window that can be used for making interpretations about the subsurface (Figure 2.1). S-waves, however, are often one-fifth to one-tenth the velocity of P-waves, thereby increasing the size of the optimal windows. An increased spatial optimal window permits application of increased fold without introducing adverse wide-angle reflection effects, whereas a larger temporal window can help better identify reflection boundaries due to increased separation between signal and coherent noise events (Figure 2.1). Although P-waves have frequencies two to three times higher than S-waves, the lower velocity of S-waves relative to P-waves means that resolution can be increased by a factor of 2 to 3 (Woolery and Street, 2002).

2.2 Equipment and Data Collection

The locations of the high-resolution SH-wave seismic profiles were selected using existing low-resolution P-wave profiles from the WVFS (Rene and Stanonis, 1995). Eleven
profiles totaling 7.5 km were collected in the vicinity of the Mt. Vernon graben (Figure 2.2, Appendix A).

Data were collected with a 48-channel Geometrics Strata Visor seismograph, which is a 24-bit system with an instantaneous dynamic range of 115 db and internal hard drive. Two inline spreads of 24 Mark Products 30-Hz horizontally polarized geophones with 7.5-cm spikes were used for the collection of seismic data. One, two-, and four-meter geophone spacings were used, depending on target resolution and depth of survey interest. The seismic data was collected at either 0.5 or 0.25 ms sampling interval. The optimal digital acquisition filter includes a 15-Hz low-cut filter with the high-cut filter out and an occasional 60-Hz notch filter when power lines were present.

The most effective energy source was a steel H-pile set in the ground and struck horizontally with a 1.4-kg hammer. The hold-down weight of the H-pile is 70 to 80 kg, including the weight of the hammer swinger and H-pile section. The H-pile is set in prepared slit trenches, with its flanges struck perpendicular to the geophone spread (Figure 2.3). This orientation of the H-pile relative to the geophone spread will generate SH-mode waves. The trenches provide an efficient couple between the H-pile and the earth, thus improving energy input. The most effective energy couple occurred when the H-pile was set against the edge of road asphalt. The energy source was struck on both sides, and polarity reversals were used to provide accurate identification of the SH-wave energy. During production acquisition, polarity reversal was not used when data quality was good. To obtain a sufficient signal-to-noise ratio, hammer blows were stacked four to nine times per shotpoint. Table 2.1 contains acquisition parameters for Lines 1 – 11.

2.3 Data Processing Procedure

A Pentium 4 microcomputer with VISTA 7.0 (Seismic Image Software, 1995) was used for processing the seismic data. Although certain processing parameters varied from line to line, the processing procedure for all SH-wave data was relatively consistent. DAT field files were transferred from seismograph to computer and converted to SEGY format. Applicable 24-, 12-, and 6-channel files were extracted from 48-channel field files to provide 12-, 6-, and 3-fold data sets. SEGY files were then combined end-to-end by shot location. Spherical divergence gain,
mean, bandpass filter, and automatic gain control (AGC) were then applied sequentially. A geometry header was constructed for each line (including elevation statics when necessary) and applied to the combined files. Bad traces were then discarded, and top and surgical mutes of refraction, direct wave, and noise were implemented to ensure a coherent stack. Velocity picks were obtained by an offset sort, offset stack, and semblance analysis. Once the velocity analysis was complete, a normal move-out (NMO) correction was applied. The data was then sorted and stacked by common depth point (CDP). A frequency-wave number (FK) filter and additional AGC were then applied to the stacked profile to brighten reflection horizons of interest. Refer to Appendix B for detailed Vista 7.0 processing commands for all lines.

Deconvolution, a procedure often used in deeper seismic reflection surveys, is often omitted when processing shallow seismic data (Woolery and Street, 2002). Random reflectivity series and a high signal-to-noise ratio are basic assumptions of the deconvolution process, but shallow reflection data often do not meet these criteria (Baker, 1999). In addition, any digital operator or filter applied to a seismic data set will inherently produce noise. Therefore, any processing procedure that does not significantly improve the quality of the data is not used.

2.4 Migration Analysis

Migration of shallow SH-wave seismic data (depths of 2 to 50 m), unlike data from deeper surveys, is often unnecessary. This is a result of the close proximity of the reflectors to the source and receivers, and the much lower velocities of near-surface reflectors and SH-waves. A flow chart developed by Black et al. (1994) based on the “migrator’s equation” was used to determine the need for migration. The steepest dipping reflector of the study was used in the migration analysis (Line 11, CDP 150–220). The reflector has an apparent dip of 0.0033 s/m. Equations from Black et al. (1994):

\[ d_x = (v^2 D_{ut} / 4), \]
\[ d_t = t \left\{ \left[ 1 - \left( \frac{v D_{ut}}{2} \right)^2 \right]^{1/2} \right\} \]

were used to determine \( d_x \) and \( d_t \), which are the maximum distances a point will move in the horizontal or vertical direction during migration, respectively. \( D_{ut} \) is the dip (s/m), \( v \) is the rms velocity, and \( t \) is the two-way travel time of the reflector. The calculations yielded a \( d_x \) of 6.5
m, and a $d_t$ of 11.2 ms (1.28 m at 229 m/s), values that are less than the horizontal and vertical resolution limits of the survey. These calculations were conducted using the steepest dipping reflector of the study, and migration was therefore deemed unnecessary for the remainder of the seismic sections.

2.5 Seismic Resolution

Seismic resolution is defined as the minimum distance between two features (e.g., a bedding plane, a fault) such that both can be observed on a seismic record (Sheriff, 1977). All vertical resolutions reported in this study are calculated by the one-quarter wavelength criteria, as defined by Sheriff and Geldart (1989), where wavelength is equal to velocity divided by frequency. This type of resolution is known as the observable limit, meaning the top and bottom of the feature can be resolved. The detectable limit, however, is the minimum thickness a feature can be and still produce a seismic reflection, even though the entire feature cannot be resolved. The detectable limit can be as small as $1/10 \lambda$ to $1/20 \lambda$ (Sheriff and Geldart, 1989).

The horizontal (spatial) resolutions reported in this paper are based on the radius of the first Fresnel zone. A Fresnel zone is defined as the area of reflected energy that differs in phase by less than a half cycle, meaning it is constructively interfering (Sheriff and Geldart, 1989). The first Fresnel zone radius ($R_t$) is a function of wavelength and depth, and can be calculated using Sheriff and Geldart’s (1989) relation:

$$R_t = \left(\frac{V}{2}\right)(t/f)^{1/2}$$

where $V$ is the average velocity, $t$ is the two-way travel time, and $f$ is the frequency. A feature smaller than the first Fresnel zone will more likely diffract energy than reflect it.
### Table 2.1: Acquisition parameters for Lines 1 - 11

<table>
<thead>
<tr>
<th>Line #</th>
<th>Near Offset (m)</th>
<th>Shot Interval (m)</th>
<th>Geophone Spacing (m)</th>
<th>Record Length (s)</th>
<th>Sample Interval (ms)</th>
<th>Acq. Filter - Low Cut (Hz)</th>
<th>Acq. Filter - High Cut (Hz)</th>
<th>60 Hz Notch Filter</th>
<th>Geophone (Hz)</th>
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<td>2</td>
<td>2</td>
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<td>No</td>
<td>30 Hz</td>
</tr>
<tr>
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<td>4</td>
<td>4</td>
<td>4</td>
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</tr>
</tbody>
</table>
Figure 2.1: P- (left) and SH-wave (right) field files collected along the same spread. Notice the increased temporal and optimum window of the SH-wave seismogram. Because the P-waves have a much higher velocity and a smaller temporal window, reflectors R1 and R2 are not imaged in the P-wave field file (from Woolery and Street, 2002).
Figure 2.2: Locations of Lines 1 through 11. The orange line represent a 1-m group interval, the red lines represent a 2-m group interval, and the yellow lines represent a 4-m group interval. Numbers represent line number. The blue circles represent borehole locations of WI-1, WI-2, WI-3, and HL-1. The black dotted lines are the locations of deeper seismic-reflection profiles that imaged Hovey Lake fault and Wabash Island fault at depth (Rene and Stanonis, 1995). Another reflection survey conducted by Rene and Stanonis is located just west of Line 8.
Figure 2.3: Relative orientations of spread, sensor, and hammer swing. Steel H-pile and horizontally polarized geophone are located bottom right.
Chapter Three

3.0 Interpretation

3.1 General

Fault and structural interpretations were based on the high-resolution near-surface SH-wave stacked reflection profiles. Bedrock and soil layers imaged in Lines 1 through 11 are often complexly deformed. Consequently, only prominent and coherent features that are well within the resolvable limits will be interpreted on the figures and discussed in the text. Deformation above bedrock is the most important, because it reveals the nature of the most recent tectonic activity. In order to discriminate between structure and nontectonic features, anomalies had to be exhibited over multiple horizons. Orientations and location of seismic lines are displayed in Figure 2.2. Uninterpreted sections are shown in Appendix A.

3.2 Soil-Bedrock Interface

Depth to bedrock was determined from borehole logs WI-1 and HL-1 (Appendix C). The top-of-bedrock reflector was determined from its high-amplitude signal that resulted from the high impedance contrast between the loosely compacted soil and consolidated bedrock (Figure 3.1). To ensure that the suspected reflector on east–west Lines 1, 2, 6, and 8 was the soil-bedrock interface, a depth calculation was completed using the stacking velocities obtained from the semblance analysis and the Dix equations. The calculation yielded a depth of 32.3 m (106 ft), which is within 5 percent of the borehole-derived depth of 34 m (112 ft). The discrepancy is likely due to irresolvable near-surface velocity variations, or the visual distinction between sediment and bedrock (recorded by core logger) might not correlate with the change in elastic properties (seismic reflection) due to the weathered-bedrock zone that often exists at this boundary. The soil-bedrock interface reflector was coherent across the seismic sections adjacent to the boreholes.

The geophone spreads used in Line 11 (1-m spacing) were not long enough to obtain a robust sampling of the hyperbolic reflection curves for an accurate semblance velocity model.
Therefore, a refraction analysis was conducted to better constrain velocities (Appendix D). The velocities obtained from refraction data were used to calculate depth to bedrock. Results showed bedrock to be at a depth of 11 m on the southeast end of Line 11 (footwall of Hovey Lake Fault) and 22 m on the northwest end (hanging wall). Bedrock was at a depth of 10.85 m in borehole HL-1 (southeast end of Line 11), which is a 1 percent difference from refraction-derived data.

### 3.3 Deformation Interpretation

Faults were interpreted based on reflector offset, diffractions, deformation/bulging in reflectors, and loss of coherency. In general, soil reflector deformation is often not as apparent as bedrock deformation. This could be a result of the low shear strengths of the soils, the lower impedance contrast between intra-alluvial reflectors, or the soil having undergone less deformation. The low shear strength of soils means that small to moderate slip along a preexisting bedrock fault would be more likely to bend the overlying unconsolidated material than sharply offset it, especially in saturated soils.

### 3.4 Vertical Exaggeration

In order to display seismic sections, vertical exaggeration is necessary. Vertical exaggeration (VE) varies with depth because of velocity fluctuations. VE’s in this study will be reported for each line, but are only applicable to the soil reflectors. This is because the exaggeration changes abruptly below the soil-bedrock interface as a result of the high impedance contrast. VE’s reported are based on a constant, average soil velocity from surface to bedrock. Only two VE’s are reported (2.5 and 5.3) because of the similarity of soil velocities from line to line. All lines with 4-m geophone spacings will be displayed with a VE of 5.3, and lines with 1- and 2-m geophone spacings will be displayed with a VE of 2.5.

An apparent consequence of vertically exaggerating a section is an increase in fault and reflector dips. Apparent fault dips reported in the text are adjusted for vertical exaggeration (Figure 3.2), but not for out-of-plane effects such as oblique transects across faults. Notice in Figure 3.2 that with a vertical exaggeration of 5.3, an exaggerated 85° dip translates into an unexaggerated dip of 65°.
3.5 Seismic Line Interpretation

3.5.1 Line 1 interpretation

SH-wave seismic reflection profiles for L-1 total 1.4 km in length. Source wave input for this line was often a higher frequency than for L-3 through L-10, because the H-pile in this case was placed directly against the road asphalt. This road couple reduced movement of the plate when struck with the hammer, resulting in higher frequency and, therefore, higher-resolution data.

A comparison of L-1 and L-6 reflection profiles and frequency spectra verifies this phenomenon (Figures 3.3 and 3.4). L-1 and L-6 are parallel, collinear, and less than 30 m apart. Acquisition parameters and equipment are identical; however, L-6 was collected on a gravel road, so a stiff couple could not be accommodated. There is also a slight variation in energy input from L-1 to L-6 because of the inherent variation in hammer swing magnitude. Frequency analysis of L-1 yields an average soil frequency of 50 Hz (vertical resolution of 1.0 m and horizontal resolution of 4.7 m) and an average bedrock frequency of 40 Hz (vertical resolution of 1.5 and horizontal resolution of 9.5 m), whereas L-6 has an average soil frequency of 40 Hz (vertical resolution of 1.1 m and horizontal resolution of 4.3 m) and an average bedrock frequency of 30 Hz (vertical resolution of 1.9 m and horizontal resolution of 11.1 m). This difference in reflection frequency between L-1 and L-6 results in a noticeable resolution difference between the two lines.

Interpreted profiles for L-1 are displayed in Figures 3.5 through 3.9. The average bedrock depth along L-1 is approximately 33 m. The location of borehole WI-1 (CDP 571 of Figure 3.6) is shown on Figure 2.2, and the borehole description is in Appendix C.

3.5.1.1 Zone 1

Fault Zone 1 consists of two near-vertical faults that extend well into the Quaternary overburden (Figure 3.5). The westernmost fault has an apparent dip of 88° to the east, and the easternmost fault has an apparent dip of 88° to the west. The faults were interpreted based on the loss of bedrock coherency, diffraction patterns, and bedrock offsets in the footwalls of the faults.
(~4.5 m of displacement across a 32 m fault zone). This loss of bedrock coherency is likely because of diffraction interference and a fractured fault zone, which makes identifying slip direction and magnitude between the faults difficult. Coherent soil reflections, however, exhibit compressional antiformal features bounded by the faults as shallow as ~18 m. The easternmost fault was extended upward to a depth of 10 m based on the series of diffractions that terminate at that depth.

3.5.1.2 Zone 2

Fault Zone 2 spans approximately 160 m of L-1 and contains five high-angle faults with apparent dips ranging from 78 to 85° (Figure 3.6). Total bedrock displacement across 90 m of the fault zone (CDP 400–490) is ~6 m. Maximum bedrock displacement on a single fault is ~2.5 m (CDP 575) in a reverse motion. Soil is displaced ~2 m in a reverse motion at a depth of ~16 m (CDP 500). Bedrock is at a depth of 34 m on either side of the fault zone, but within the faulted region bedrock is uplifted to a depth of 28 m.

3.5.1.3 Fault 3

Fault 3 (Figure 3.7) is a small-offset normal fault with an apparent dip of 73° extending up to a depth of 18 m. The displacement observed on Fault 3 is ~1 m, and it can be consistently recognized from 175 to 360 ms. The combination of consistent offset in bedrock and soil layers and strong diffraction patterns was used to delineate this fault. Although the fault shows net normal displacement, bedrock layers directly on the fault bulge upward in the hanging and footwalls, implying this fault has been reactivated in a compressional sense.

3.5.1.4 Fault 4

Fault 4 (Figure 3.8) is a high-angle discontinuity with an apparent dip of 88° to the east. It is similar to Fault 3 in that net displacement across the fault is minimal, strong diffractions are present up to 150 ms two-way travel time, and bedrock is uplifted ~1 m in the hanging and
footwalls of the fault. A loss of coherency in soil and bedrock reflections further indicates deformation.

3.5.1.5 Zone 5

Zone 5 (Figure 3.9) consists of four high-angle reverse and normal faults, with apparent dips ranging from 74 to 83°. Reflector displacement, positive and negative folds, and strong diffractions evidence the faults. The fault farthest to the west exhibits reverse motion and the most displacement within this zone; deformation extends as shallow as ~17 m. Maximum soil displacement across this fault is ~2.5 m over a 24-m fault zone (CDP 1270–1294). Bedrock elevation across this fault is displaced ~1.5 m over a 20-m fault zone (CDP 1270–1290). The three easternmost faults all show normal displacement within the bedrock, but one fault shows reverse motion in the soil up to a depth of ~18.5 m (CDP 1305) (Figure 3.9).

3.5.2 Line 2 Interpretation

Reflection profiles of L-2 are contained in Figures 3.10 and 3.11. L-2 is an extension of L-1 that begins ~40 m east of the terminus of L-1 and continues 0.5 km east to Hovey Lake (Figure 2.2). Reflection coherency and resolution in L-2 are very similar to that of L-1 because of the close proximity of the two lines, and an efficient energy couple was maintained. L-2 has an average soil frequency of 40 Hz (vertical resolution of 1.1 and horizontal resolution of 4.5 m) and an average bedrock frequency of 30 Hz (vertical resolution of 1.9 and horizontal resolution of 9.7 m).

Fault Zone 6 (Figure 3.10) consists of four high-angle faults with apparent dips ranging from 71 to 83°. The two easternmost faults merge at a depth of 45 m, and exhibit compressional strain within the branched fault zone. All bedrock displacements appear to be normally offset directly on the fault, but exhibit antiformal deformation in the footwalls and hanging walls, sometimes enough to produce net reverse motion across the fault. Maximum bedrock displacement is ~2 m across a 22-m fault zone (CDP 110–132). The soil directly above this deformed bedrock is displaced ~3 m across a 38-m zone (CDP 110–148). Fault interpretations
were based on abrupt dip changes that are consistent from depths between ~10 m and ~42 m, a loss of soil coherency, and diffractions.

### 3.5.3 Line 3 Interpretation

The location of L-3 (Figure 2.2), a 350-m east–west-trending survey, was chosen based on the surface projection of the HLF, as imaged by a deeper P-wave seismic reflection survey (Rene and Stanonis, 1995). HLF was targeted because it defines the eastern boundary of the Mt. Vernon Graben. Data was collected on an unimproved road; the soil was not firm enough to achieve a good energy source couple relative to Lines 1 and 2. Although the profile exhibits relatively high-frequency reflections, the coherency of bedrock and soil reflections are the poorest of the 10 lines, possibly because of weak impedance boundaries between soil horizons and poor energy coupling.

Shown at CDP 70 (Figure 3.12), Fault 7 is a normal fault with an apparent dip of 70° to the west. The bedrock displacement on the fault as shown is ~3.5 m. This fault is interpreted to be Hovey Lake fault or a fault closely associated with it, based on several factors. First, the fault exhibits high-angle, normal displacement with the hanging wall to the west, which is consistent with the sense of motion and orientation of the previously characterized post-Pennsylvanian HLF (Rene and Stanonis, 1995). All other faults imaged in the immediate area are west of Fault 7 (see Line 4), and have the opposite sense of motion, or the magnitude of displacement is too small. Second, the location of Fault 7 is approximately 500 m east of the location at which Rene and Stanonis (1995) projected the HLF to the surface. Because of the low resolution and poor coherency of this line, the identification of slip magnitude is difficult. Consequently, this feature cannot definitively be labeled as HLF.

### 3.5.4 Line 4 Interpretation

L-4 (Figures 3.13 and 3.14) is the westward extension of L-3, totaling 1.05 km in length, and was collected on a stiffer road surface than for L-3. This change in surface stiffness improved the energy couple, providing better quality data than L-3. Although the data for L-4 is more coherent, and higher resolution than for L-3, the continuity of reflections in L-4 is poor
because of the extensive deformation in the soil and bedrock, and possibly weak impedance contrast between horizons. L-4 has an average soil frequency of 40 Hz (vertical resolution of 1.2 m and horizontal resolution of 4.0 m) and an average bedrock frequency of 40 Hz (vertical resolution of 1.4 m and a horizontal resolution of 8.9 m). The average bedrock depth across L-4 is ~25 m.

3.5.4.1 Zone 8

Zone 8 is a series of three faults (Figure 3.13) with normal displacement below bedrock, and reverse movement in the soil. The faults change dip at the soil-bedrock interface, from east-dipping in the bedrock (75° to vertical) to west-dipping in the soil (23° to 30°). Bedrock displacement on the easternmost fault (CDP 310) is ~4 m over a 110-m fault zone, and the fault is upwarped in the footwall ~2.5 m between CDP 320 and CDP 375. The middle fault in Zone 8 (CDP 390) has ~2 m of bedrock displacement over a 28-m fault zone, and ~2 m of soil displacement over a 30-m fault zone. Because of a lack of coherency below the soil-bedrock interface, fault dips in the bedrock were inferred. The structural style of bedrock in L-4 suggests that bedrock is displaced normally with high-angle faults.

3.5.4.2 Zone 9

Zone 9 (Figure 3.14) is a graben consisting of two normal faults, the eastern fault (CDP 200) having an apparent dip of 70° to the west and the western fault (CDP 220) having an apparent dip of 75° to the east. Bedrock displacement across the eastern fault is ~2.5 m, and soil displacement is ~1.5 m. The faults were identified from an abrupt change in bedrock coherency, offset bedrock and soil layers, and small diffractions.

3.5.5 Line 5 Interpretation

The location of L-5 (Figure 2.2) was chosen based on the surface projection of the WIF, as reported by Rene and Stanonis (1995). L-5 (Figure 3.15) is 620 m in length, has an average soil reflector frequency of 35 Hz (vertical resolution of 1.1 m and horizontal resolution of 4.6 m),
and an average bedrock reflector frequency of 40 Hz (vertical resolution of 1.5 m and horizontal resolution of 10 m). Bedrock is at an average depth of ~30 m.

The soil-bedrock interface is coherent and variation in depth is minimal. The absence of bedrock displacement in L-5 demonstrates that the surface projection of the WIF (Rene and Stanonis, 1995) in this part of the study area is poorly defined. Soil reflectors are difficult to interpret because of low reflector coherency. No tectonic deformation can be observed in the soil or bedrock with any certainty, and therefore no interpreted faults are discussed.

3.5.6 Line 6 Interpretation

L-6, located less than 30 m to the west of L-1 (Figure 2.2), extends L-1 to the west and is 600 m in length. L-6 has an average soil frequency of 40 Hz (vertical resolution of 1.1 m and horizontal resolution of 4.3 m) and an average bedrock frequency of 30 Hz (vertical resolution of 1.9 m and horizontal resolution of 11.1 m). Bedrock is at an average depth of ~33 m.

3.5.6.1 Zone 10

Zone 10 (Figure 3.16) is a series of normal and antithetic faults with apparent dips ranging from 54° to 80°. There is a loss coherency in the hanging walls of the two westernmost faults of Zone 10, but bedrock is displaced ~3.5 m in the footwalls of the faults over a 25-m fault zone (CDP 105–130). Maximum soil displacement is on the western branch of the antithetic fault, and is ~1.5 m over a 20-m fault zone (CDP 170–190). In Zone 10, as in many other fault zones in the study area, some bedrock and soil reflections exhibit antiformal features in the hanging and footwalls of these normal faults, implying a compressional component to the strain. Soil is upwarped ~ 3 m from a depth of ~16.5 m to ~13.5 m between CDP 150 and 140; this exceeds the maximum soil displacement across any fault in this zone.

3.5.6.2 Zone 11

Zone 11 (Figure 3.17) consists of three high-angle normal faults with apparent dips ranging from 78 to 85°. All faults normally displace Quaternary overburden. Bedrock
displacement (R4) across the easternmost fault (CDP 595) is ~2 m, and R1 on the same fault is normally displaced ~1.5 m. R3 on this fault shows less than 0.5 m of displacement, however. This is most likely a result of oblique fault slip displacing dipping soil reflectors (out-of-plane effect). R1 is also displaced ~1.5 m across a 14-m fault zone on the westernmost fault (CDP 541–555).

Although all faults and reflectors exhibit normal displacement directly on the fault, antiformal uplift of layers is apparent. All soil reflectors in the hanging wall of the westernmost fault are uplifted to a two-way travel time greater than or equal to that of the footwall (less than 25 m from the fault).

A large diffraction can be seen at CDP 615 at the end of L-6. The diffraction was not associated with any fault because it does not correlate to any offset reflection. There may be bedrock and/or soil displacement between L-6 and L-1, however.

3.5.7 Line 7 Interpretation

L-7 (Figures 3.18 and 3.19) is a north–south-oriented line beginning near the east end of L-2 and extending 440 m to the south. This line is oriented only 20° from the strike of the major faults in the area, and therefore the dips, offsets, and style of faulting imaged in L-7 will be skewed. Although the orientation of the line was not ideal, the data was collected to complete the transect across the Mt. Vernon graben, and connect the east–west-trending lines to the west (Lines 1, 2, 6, and 8) with the northwest–southeast trending lines further to the southeast (Lines 9, 10, and 11). Soil reflectors have an average frequency of 45 Hz (vertical resolution of 1.1 m and horizontal resolution of 4.7 m) and bedrock reflectors have an average frequency of 40 Hz (vertical resolution of 1.5 m and horizontal resolution of 9.0 m). Bedrock is at an average depth of ~27 m.

3.5.7.1 Zone 12

Zone 12 is made up of two near-vertical faults extending to 140 ms two-way travel time (Figure 3.18). Net bedrock displacement across the two faults is ~3.5 m (CDP 55–120), and both soil and bedrock exhibit monoclinal folding in the hanging wall of the southernmost fault. Net
soil displacement is ~2 m across the same two faults. The combination of small offsets, bold
diffraction patterns in the sediment, and abruptly changing dips at the soil-bedrock interface
suggests tectonic deformation. The apparent offset across the fault zone is likely less than the
true offset. This is because of the subparallel orientation of the profile to the regional fault strike
(~20°).

3.5.7.2 Fault 13

Fault 13 is located at CDP 240 of L-7 (Figure 3.19). It exhibits normal displacement and
has an apparent dip of 64° to the north. Based on previous fault-related studies (Rene and
Stanonis, 1995), the orientation of the fault is more likely north-northeast–south-southwest,
making the true dip greater than the apparent dip imaged in L-7. The bedrock has an apparent
vertical displacement of ~2.5 m across a 32-m fault zone (CDP 245–277). Soil is normally
displaced ~1 m over a 20-m fault zone (CDP 250–270). Pronounced uplift of bedrock is
observed between CDP 250 and CDP 420. This results in the northern and southern ends of the
line having approximately the same bedrock depth (~27.5 m), but the middle segment is uplifted
to a depth of ~24.5 m.

3.5.8 Line 8 Interpretation

L-8 (Figures 3.20 and 3.21) is a westward extension of L-6 (Figure 2.2) and is the
westernmost line in the study area. L-8, 800 m in length, was collected to image the primary
strand of the Wabash Island Fault (WIF) in the near surface. This location was chosen from the
projection of the fault previously imaged and characterized at depth by Rene and Stanonis
(1995). The average soil reflection frequency of L-8 is 50 Hz (vertical resolution of 0.8 m and
horizontal resolution of 4.3 m) and the average bedrock reflection frequency is 40 Hz (vertical
resolution of 1.3 m and horizontal resolution of 8.1 m). L-8 has an average bedrock depth of ~26
m.
3.5.8.1 Zone 14

Zone 14 (Figure 3.20) consists of one normal fault and an antithetic fault with normal displacement on the rooted fault and reverse displacement on the antithetic part. The western fault dips 60° to the east and the primary segment of the antithetic fault dips 79° to the west. The western fault in Zone 14 (CDP 100) has the greatest displacement: bedrock and soil displacements are ~6 m and ~1.5 m, respectively. The faults were interpreted based on large offsets, diffraction patterns, and abrupt loss of coherency.

The western fault in this zone (CDP 100) is interpreted as the WIF. Several indicators corroborate this interpretation: (1) the fault has the same dip direction and sense of motion that the WIF has at depth, (2) the magnitude of displacement is larger than most in the area, implying it could be associated with a primary structure, (3) the location of the fault is less than 350 m from the Rene and Stanonis (1995) surface projection of the WIF, and (4) the relative density of surface faults in the vicinity of Line 8 with significant displacements is greater than that of the interpreted structures to the east, also suggesting a relation to a primary structure.

3.5.8.2 Zone 15

Zone 15 (Figure 3.21) consists of two normal faults and one antithetic fault with apparent dips ranging from 57 to 75°. The middle fault in Zone 15 branches at the soil-bedrock interface and exhibits reverse soil displacement on the antithetic part and normal displacement along the rooted fault in soil and bedrock. The eastern fault (CDP 225) exhibits normal displacement and dips to the west, whereas the western fault (CDP 325) is normally displaced and dips to the east. Bedrock and soil are at approximately the same depth on either side of the fault zone.

Offset soil and bedrock reflectors, diffractions, and abrupt loss of coherency were primary indicators of the faults. Maximum bedrock displacement across a single fault is ~2 m over a 44-m fault zone (CDP 273–295). Maximum soil displacement is ~1.5 m over a 72-m zone (CDP 299–335), and soil is displaced in a reverse sense ~1 m at CDP 291.
3.5.9 Line 9 Interpretation

L-9 (Figures 3.22 and 3.23), 880 m in length, was collected to locate and image Hovey Lake Fault, thereby completing an almost continuous set of lines across the graben formed by the Wabash Island fault and Hovey Lake fault (west to east: Lines 8, 6, 1, 2, 7, 10, and 9). The soil-bedrock interface of Hovey Lake fault was successfully imaged; however, the shallower soil reflectors (less than 10 m) could not be resolved because shot and geophone spacings were 4 m each, resulting in direct-wave interference within the optimum soil-reflector window. Part of this line, therefore, was reshot (Line 11) at 1 m shot and geophone spacing, with a 0.25 ms sampling interval, and a smaller source (2 lb hammer and smaller aluminum plate) was used. L-9 interpretations are displayed in Figures 3.22 and 3.23, but discussion of this fault zone will be confined to Line 11 (section 3.5.11), where soil and bedrock deformation can be observed together.

3.5.10 Line 10 Interpretation

L-10 (Figure 3.24) is an east–west-trending line starting at the first shot of L-9 and continuing westward for 215 m (Figure 2.2). Soil layers were not imaged because of direct-wave interference with soil reflections. A smaller sampling interval, tighter geophone spacing, higher frequency input, and a higher low-cut acquisition frequency would likely correct this problem. Line 10 has an average bedrock reflection frequency of 50 Hz (vertical resolution of 0.5 m and horizontal resolution of 3.2 m).

Zone 16 (Figure 3.24) contains two near-vertical normal faults ~28 m apart, with apparent dips ranging from 75 to 85°. The calculated apparent dips on these faults are uncertain, because of the lack of multiple horizons (i.e., the soil-bedrock interface reflector is the only reliable reflector). The greatest displacement is on the eastern fault (CDP 35), and it is displaced ~1 m. The faults were identified by reflector displacement and diffractions.
3.5.11 Line 11 Interpretation

L-11 (Figure 3.25) images part of L-9 (the first 290 m) across Hovey Lake Fault. A reduced aperture sampled a shallower depth. Shot and geophone intervals were decreased from 4 m (L-9) to 1 m (L-11), the sampling interval was decreased from 0.5 ms to 0.25 ms, and a smaller (2 lb) rock hammer was used. Using these acquisition parameters, reflectors as shallow as 60 ms were obtained across the 300-m profile (Figure 3.25, Appendix E—Line 11), while L-9 yielded no reflectors above 100 ms (Figures 3.22, 3.23, and Appendix E—Line 9). The average soil reflector frequency of L-11 is 50 Hz (vertical resolution of 1.1 m and horizontal resolution of 5.1 m). L-11 has an average bedrock reflector frequency of 45 Hz (vertical resolution of 5.1 m and horizontal resolution of 22 m). Because of the large number of faults in L-11, all faults are numbered.

L-11 exhibits a total bedrock displacement of ~10.5 m across a 200-m fault zone (CDP 0–400). At the steepest displacement gradient (CDP 150–230), bedrock is displaced ~5 m. Across fault 3, the uppermost soil reflector is normally displaced ~2.5 m over a 13-m fault zone, and is bulged in the hanging wall. This reflector is at a depth of ~6.5 m in the hanging wall of the fault. Apparent fault dips range from 75 to 88°. The sediment layers thicken to the west, and several soil reflectors terminate as they are traced east. Faults 2 through 8 are normally displaced, and soil and bedrock reflectors often show varying magnitudes of displacement along the same fault (Faults 2 through 5). Fault 1, however, exhibits reverse displacement in the bedrock and bottom two soil reflectors, and normal displacement in the uppermost soil reflector affected by the fault. The variable displacement across single faults (Faults 2 through 5) and the opposite sense of motion seen across a single fault (Fault 1) are both likely due to out-of-plane effects. If these faults have a component of strike-slip motion, then a two-dimensional model of displacement magnitude and sense of motion is insufficient to describe the character of the faulting.

Although most faults in L-11 show normal displacement, compressional deformation, such as upwarped bedrock and sediment, is present over the entire line. Antiformal folding of sediment and bedrock can be seen from CDP 50 to 130 and CDP 400 to 430. Bedrock is upwarped from CDP 150 to 290, as well as sediment from CDP 25 to 50 and CDP 50 to 120.
Figure 3.1: Raw and AGC field files from Line 3. Diffraction pattern, offset-bedrock reflector, and soil reflector are labeled in partially processed field file.
Figure 3.2: The relationship between unexaggerated and exaggerated dips at vertical exaggerations (VE) of 2.5 and 5.3. All stacked seismic sections with a 1- or 2-m group interval are displayed with a VE of 2.5, and stacked sections with a group interval of 4 m are displayed with a VE of 5.3.
Figure 3.3: Frequency versus amplitude plot of Line 1 soil reflections (stiff energy couple).
Figure 3.4: Frequency versus amplitude plot of Line 6 soil reflections (poor energy couple).
Figure 3.5: First interpreted section of Line 1. Green indicates soil/bedrock interface.
Figure 3.6: Second interpreted section of Line 1. Yellow indicates soil reflections. Green indicates soil/bedrock interface.
Figure 3.7: Third interpreted section of Line 1. Green indicates soil/bedrock interface.
Figure 3.8: Fourth interpreted section of Line 1. Green indicates soil/bedrock interface.
Figure 3.10: First interpreted section of Line 2. Yellow indicates soil reflection. Green indicates soil/bedrock interface.
Figure 3.12: Interpreted section of Line 3. Green indicates soil/bedrock interface.
Figure 3.13: First interpreted section of Line 4. Yellow indicates soil reflections. Green indicates soil/bedrock interface and intra-bedrock reflection.
Figure 3.14: Second interpreted section of Line 4. Yellow indicates soil reflections. Green indicates soil/bedrock interface and intra-bedrock reflection.
Figure 3.16: First interpreted section of Line 6. Yellow indicates soil reflections. Green indicates soil/bedrock interface.
Figure 3.17: Second interpreted section of Line 6. Yellow indicates soil reflections. Green indicates soil/bedrock interface and intra-bedrock reflector.
Figure 3.18: First interpreted section of Line 7. Yellow indicates soil reflections. Green indicates soil/bedrock interface.
Figure 3.19: Second interpreted section of Line 7. Yellow indicates soil reflection. Green indicates soil/bedrock interface.
Figure 3.20: First interpreted section of Line 8. Yellow indicates soil reflections. Green indicates soil/bedrock interface.
Figure 3.22: First interpreted section of Line 9. Green indicates soil/bedrock interface.
Figure 3.23: Second interpreted section of Line 9. Green indicates soil/bedrock interface.
Figure 3.24: Interpreted section of Line 10. Green indicates soil/bedrock interface.
Figure 3.25: Interpreted section of Line 11. Yellow indicates soil reflections, and green indicates soil/bedrock interface.
Chapter Four

4.0 Discussion

4.1 Structural Style of Deformation

The near-surface deformation observed between the Hovey Lake and Wabash Island faults of southern Indiana is varied in structural style and extent throughout the study area. Forty-six discrete Quaternary faults were imaged over the 7.5 km of seismic line collected. Of these faults, 23 exhibited normal displacement, 11 reverse displacement, eight were indeterminate due to loss of coherency around the fault, and four showed different senses of motion along a single fault. Fifteen compressional features (i.e., antiformal folds or uplifts) associated with soil and bedrock faults were observed in the seismic data, and three of the 46 faults exhibited varying apparent magnitudes of slip within Quaternary sediment. The average bedrock displacement at the soil-bedrock interface (for all calculated displacements, L-1 to L-11) is ~3.4 m (range of 1 to 10.5 m), and the average soil displacement is ~1.7 m (range of 1 to 3 m). Previous work in the WVFS (Rene and Stanonis, 1995), indicates that bedrock faults imaged in this study are likely oriented north/northeast–south/southwest, and because most faults that offset soil horizons are near-surface projections of bedrock faults, their orientations are likely parallel.

An example of different types of slip along a single fault is shown in Figure 3.17. The middle fault in Zone 11 exhibits reverse displacement at R1 and normal displacement at R2. Another example of this can be seen in Line 11 (Figure 3.25), where Fault 4 exhibits normal displacement in the bedrock reflector and soil reflector directly above bedrock, but exhibits reverse displacement in the next two shallower soil horizons.

4.2 Tectonic Implications

The wide range of deformation types observed in the near-surface faults of the WVFS suggests a complex relationship between the current regional stress field, regional crustal anomalies (i.e., ancient bedrock faults), and prehistoric to contemporary seismicity. All bedrock
faults imaged in this study are high angle and interpreted to be originally formed under an extensional stress regime. The majority of soil-penetrating faults are also high angle and normally displaced; however, a substantial amount of compressional deformation is observed in the form of reverse faults and uplift of soil and bedrock. Normal faults, reverse faults, and uplifted sediment all within a 200-m fault zone, are not uncommon. The existence of these varied styles suggests the structures are acting in a predominantly transpressional manner within the study area.

Nearly all faults that offset soil horizons are near-surface projections of bedrock faults. This implies the Quaternary deformation events identified in this study are not the result of surficial processes (slumps, collapse, etc.), and the style of faulting observed in the soil is partially a result of the preexisting bedrock structure. The high-angle, north/northeast–south/southwest-trending bedrock faults of the WVFS are currently under an east/northeast–west/southwest-oriented compressive stress (Zoback and Zoback, 1980). The diffuse seismicity throughout the WVFS indicates there are seismogenic faults within or beneath the WVFS, particularly in the relatively deeper crust. If the existing bedrock faults of the WVFS are being reactivated under the current regional compressive stress field, they should undergo net oblique-compressional strain. This type of strain, when acting on high-angle faults in dipping bedrock and soil, can produce a complex set of structural features that are difficult to accurately delineate in a two-dimensional survey (Figure 4.1). The sense of motion along individual fault planes imaged in two dimensions can only be resolved by precisely knowing the site-specific fault orientation and dip, stratigraphic dip direction and magnitude, the apparent type of fault slip and magnitude (obtained from the seismic record), and the orientation of the survey line. Consequently, the description of any two-dimensional cross-sectional fault image will yield only apparent slip magnitude and direction, because of the geometric factors outside of the imaged plane. As a result of the out-of-plane effect, a series of two-dimensional surveys in an area experiencing transpressional (or transtensional) strain along high-angle faults, would likely image a wide range of apparent slip types over a relatively small area. The wide range of apparent slip types observed in the near-surface faults of the southern WVFS, and focal mechanism studies of contemporary seismicity occurring in the region, suggest that transpressional strain has been affecting the WVFS since the late Quaternary.
Focal mechanism studies of the WVFS have shown that the primary slip type associated with moderate earthquakes from 1965 to the present is right-lateral strike-slip (Taylor et al., 1989; Kim, 2003). The November 9, 1968, event (35 km west of the study area) (Figure 1.3), however, yielded almost pure reverse motion. Deep reflection profiles conducted by Rene and Stanonis (1995) demonstrated that the Hovey Lake fault (HLF) and Wabash Island fault (WIF) intersect within the Precambrian basement rocks at a depth of ~5.5 km, and the WIF continues into the basement rock (Figure 4.2). The December 7, 2000, event (3.9 m$_b$), which took place approximately 5 km from the north end of HLF, occurred at a focal depth of approximately 5 km. The March 6, 2000, event (2.7 m$_b$), which occurred just north of Evansville, Ind., also had a focal depth of 5 km. In addition, the June 10, 1987, event, which occurred approximately 20 km north of the WVFS at a focal depth of about 10 km, had eight aftershocks, which occurred at depths of less than 5 km (Figure 4.3). Earthquakes occurring at depths in this range (within the boundaries of the WVFS) are most likely occurring on the faults of the WVFS. In addition, small thrust faults in Mississippian and Pennsylvanian rocks with displacements of a few inches to a few feet have been identified in mines within the WVFS; many of these faults are thought to be formed tectonically (Ault et al., 1985). These studies further substantiate the idea that the faults of the WVFS are affected by the Midcontinent Stress Province, and are being transpressationally reactivated under the current east/northeast–west/southwest regional stress field.

Rene and Stanonis (1995) imaged the WIF and HLF (comprising the Mt. Vernon graben) at depth. The Mt. Vernon graben formed in extension; however, there is a broad anticline bounded by the WIF and HLF from the surface to a depth of ~4 km (Figure 4.2). Rene and Stanonis (1995) interpreted this anticline to be the result of reverse-drag folding during the extensional formation of the Mt. Vernon graben. The extensive near-surface deformation imaged in this study between the WIF and HLF, the orientation of the current regional stress field, and regional focal mechanism studies, indicate that this anticline may have formed due to, or was accentuated by, transpressional stresses after the formation of the Mt. Vernon graben.

Although evidence suggests the Midcontinent Stress Province is affecting the faults of the WVFS, the Commerce geophysical lineament (CGL) (Figure 1.1 and section 1.2.6), which passes through the northern edge of the WVFS, could be a major contributor to the current seismicity observed in the WVFS. Displacements as young as Holocene age have been observed
on faults overlying the CGL (Harrison et al., 1999), suggesting a possible relationship between the basement structure and near-surface faulting events (Harrison and Schultz, 1994). In addition, at least five large prehistoric earthquakes occurred near the surface projection of the CGL (Hildenbrand and Ravat, 1997). McBride et al. (1997) show that the hypocenter of the November 9th, 1968 event (M 5.5) (Figure 1.3) coincides with basement reflectors of the CGL. The exact relationship between the CGL and WVFS is unknown, however.

### 4.3 Seismic Hazard Implications

Carbon-14 dating conducted on organics obtained from four wells in the study area confirms that soil horizons that range between 26,840 ±150 YBP and 41,040 ±740 YBP have been displaced (Figures 1.6–1.7). These dated horizons are not the shallowest imaged reflectors, but represent ages at depths between 8 and 10 m. The shallowest imaged displaced reflector (Line 11, Fault 3) is at a depth of 6.5 m. The U. S. Army Corps of Engineers and the U. S. Nuclear Regulatory Commission classify faults on which movement has occurred in the last 35,000 years as “capable.” The age of the faults imaged in this study, therefore, have significant design implications for critical structures in the region.

Obermeier (1998) described paleoliquefaction features found in and around the WVFS with calculated magnitudes of M~7.5 and M~7.1, occurring 6100 ±100 YBP and 12,000 ±100 YBP respectively. Other paleoliquefaction features of Holocene age have been identified in the region (Munson et al., 1997; Pond and Martin, 1997), which represent significant seismic events. The combination of late Quaternary imaged faults, paleoseismicity, and contemporary seismicity in the WVFS suggests that the southern WVFS is a source zone for seismic hazard evaluation. The imaged structure in this study cannot characterize strain or slip rates, or the minimum depth of displacement/deformation, however. Therefore, additional study is required to define magnitude and recurrence estimates.

Although no surface expression of late Quaternary earthquakes is known in the WVFS (i.e., fault scarps, pronounced lineaments), the potential to produce sizeable earthquakes is not diminished. More compressive uplifting is associated with faults observed in this study than reverse motion along fault planes. This is likely the result of the thick, unconsolidated, water-saturated sediments of the Illinois Basin being more likely to experience ductile deformation.
than brittle faulting (i.e., scarps) when undergoing compressive stress. In addition, the regional alluvial environment (i.e., Ohio and Wabash Rivers) would likely erode any scarps or bluffs associated with Holocene and Quaternary faulting, given the low recurrence intervals of large events. Therefore, geomorphic processes and the ductile nature of the sediment will significantly mask surface expression of these low-recurrence seismic events.

To better constrain the timing of these modern faulting events, a more detailed study of the upper 8 m of soil needs to be completed. Micro-seismic surveys (0.25–1 m group interval) could be used to better constrain the style and timing of faulting in the nearer surface. Ground-penetrating radar (GPR) should also prove to be an effective exploration technique, because of the low clay content in the soils of this study area. Locations for GPR surveys can be selected over deformation zones of interest in Lines 1 through 11. If shallow targets are identified with GPR profiles, paleoseismic trenching locations can be used to resolve recurrence intervals, slip rates, and magnitudes of these events.

The majority of 60 seismic events recorded in the Rudman et al. (1997) study were congregated around the New Harmony Fault (NHF), which is located approximately 5 km west of the Wabash Island fault, and approximately 10 km northwest of the study area. This seismicity clustering in the vicinity of the NHF, and its close proximity to the Quaternary deformation associated with the Wabash Island fault, also make it a potential site for further study of recent faulting within the WVFS.
Table 4.1: Histogram of focal depths of the microearthquakes in the Wabash Valley seismic zone that were located by St. Louis University between 1985 and 1995. Focal depths of the aftershocks of the June 10, 1987 earthquake are shaded red. The focal depths of the four events in the box are shown along the top of the plot for comparison.

1. December 7, 2000
   38.02° N/87.68° W
   $m_b = 3.9$

2. June 10, 1987
   38.71° N/87.05° W
   $m_b = 5.2$, strike-slip

3. April 3, 1974
   38.55° N/88.07° W
   $m_b = 4.7$, strike-slip

4. November 9, 1968
   37.91° N/88.37° W
   $m_b = 5.5$, thrust
Figure 4.1: The complex three-dimensional nature of high-angle faults undergoing oblique-compressional strain (Roberts, 1983).
Figure 4.2: Structure associated with the Wabash Island fault (left) and Hovey Lake fault (right) beneath the current study area. The reflectors shown (from shallowest to deepest) are the Ste. Genevieve Limestone, the New Albany Shale, the Maquoketa Group, the Knox Group, the Eau Claire Formation, and the acoustic basement. Cross-section displayed with 2x vertical exaggeration. Modified from Rene and Stanonis (1995).
Chapter Five

5.0 Conclusions

Seven and a half kilometers of high-resolution, SH-wave seismic-reflection profiles from southern Indiana image deformation in the Quaternary sediments of the southern Wabash Valley fault system. Forty-four of the 46 faults that offset or deform soil horizons are extensions of high-angle bedrock faults, confirming that these features are tectonic in origin and not a result of surficial processes that can produce similar features (e.g., slumps, collapse features, etc.). The average bedrock displacement at the soil-bedrock interface is approximately 3.4 m (range of 1 to 10.5 m), and the average soil displacement is approximately 1.7 m (range of 1 to 3 m).

The Quaternary deformation imaged in the WVFS exhibits several styles of deformation: (1) apparent normal fault motion, (2) compressional features, such as antiformal folding of soil layers in the hanging and footwalls of faults and apparent reverse motion along faults, (3) opposite sense of motion across individual faults, and (4) varying slip magnitude across individual faults.

Varying types of slip and magnitude of slip along single faults suggests an oblique component to the fault motion out of the imaged plane, producing an out-of-plane effect that can distort the true slip direction and magnitude in a two-dimensional survey. When dipping layers or layers with varying thicknesses are offset laterally or obliquely, a false sense of motion can be imaged in two dimensions.

The seismic profiles suggest soil and bedrock layers are folded or uplifted by components of compressional stress, rather than solely undergoing reverse-motion slip along high-angle faults. Apparent normal displacements observed in the Quaternary sediment can result from localized areas of tension (or transtension) that occur in a transpressional fault zone (Sanderson and Marchini, 1984), out-of-plane effects, and/or hinge-parallel extension resulting from compressional uplift and folding of the bedrock and soil (Teyssier and Tikoff, 1998).

Carbon-14 dating of displaced horizons suggests movement between approximately 26,000 and 42,000 YBP (Figures 1.6–1.7). The imaged structures are the only known primary coseismic deformation of late Quaternary age within the WVFS. Therefore, these faults are
considered capable by the U. S. Army Corp of Engineers and the U. S. Nuclear Regulatory Commission (movement within the past 35,000 years), and will affect critical facilities in the area.

The style and timing of Quaternary deformation within the WVFS, the close association of soil faults to documented post-Pennsylvanian bedrock faults (Hovey Lake fault and Wabash Island fault), and focal mechanism studies of current seismicity in the Wabash Valley seismic zone are all direct evidence that the extensionally formed faults of the WVFS are being reactivated in a manner consistent with the current east/northeast– west/southwest regional compressive stress field.
Appendix A

Uninterpreted SH-wave reflection profiles collected in this study. These profiles are displayed at the same scale and vertical exaggeration as their interpreted counterparts.
Appendix B

Vista 7.0 processing commands and sequence for Lines 1 – 11.

Standard Processing Procedure

1) Convert DAT files to standard SEG-Y format
2) Retrieve applicable 24-, 12-, and 6-channel files from 48-channel field file
3) Combine end to end by shot location
4) Apply spherical divergence gain
5) Mean combined file
6) Apply bandpass filter
7) Apply automatic gain control (AGC)
8) Construct geometry header
9) Apply header to combined file
10) Kill bad traces
11) Top mute refraction and surgical mutes when applicable
12) Perform velocity analysis which includes:
   a. Sort by offset
   b. Stack by offset
   c. Semblance analysis
   d. Pick velocities
13) Apply normal move-out correction with constructed velocity profile
14) Sort data by common depth point (CDP)
15) Stack data by CDP
16) Apply frequency-wave number (FK) filter
17) AGC stacked profile
Detailed Processing Procedure of SH-Wave Seismic Data

The following commands are for 24-channel data sets only. Twelve and six-channel data sets underwent very similar processing steps, and therefore are not included in this section. Most final stacks displayed in the appendix are compiled from 6 and 12 channel data sets.

**Line 1 – Processing Commands for Vista 7.0**

<table>
<thead>
<tr>
<th>Line</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>MACRO spec.mac (convert DAT files to SEG-Y)</td>
</tr>
<tr>
<td>2)</td>
<td>MACRO 48-24.mac (convert 48-channel data to 24-channel data)</td>
</tr>
<tr>
<td>3)</td>
<td>COMBINE put a 24chan.cmb</td>
</tr>
<tr>
<td>4)</td>
<td>GAIN a put b 8</td>
</tr>
<tr>
<td>5)</td>
<td>MEAN b put c 1.0</td>
</tr>
<tr>
<td>6)</td>
<td>FILTER d put e 20 40 80 100</td>
</tr>
<tr>
<td>7)</td>
<td>AGC e put f 150 1.0</td>
</tr>
<tr>
<td>8)</td>
<td>GEOM Geowvf24.sgy Geowvf24</td>
</tr>
<tr>
<td>9)</td>
<td>HEAD Geowvf24.sgy put f</td>
</tr>
<tr>
<td>10)</td>
<td>IKIL f 24</td>
</tr>
<tr>
<td>11)</td>
<td>IMUT f 24 → 24mut.sgy</td>
</tr>
<tr>
<td>12)</td>
<td>DEL a</td>
</tr>
<tr>
<td>13)</td>
<td>MOVE f put a</td>
</tr>
<tr>
<td>14)</td>
<td>DEL f</td>
</tr>
<tr>
<td>15)</td>
<td>SORT a[1-576] put b offset ….put c[16128-16752] offset</td>
</tr>
<tr>
<td>16)</td>
<td>STACK b put j offset</td>
</tr>
<tr>
<td>17)</td>
<td>SEMB j put r 100 1000 50</td>
</tr>
<tr>
<td>18)</td>
<td>VPICK j and r put vlin1-24.dat</td>
</tr>
<tr>
<td>19)</td>
<td>DEL b to y</td>
</tr>
<tr>
<td>20)</td>
<td>NMO a put b vlin1-24.dat m20</td>
</tr>
<tr>
<td>21)</td>
<td>SORT b put c cdp</td>
</tr>
<tr>
<td>22)</td>
<td>STACK c put d cdp</td>
</tr>
<tr>
<td>23)</td>
<td>FKFIL d put e 20 100 –24 1.0</td>
</tr>
<tr>
<td>24)</td>
<td>AGC e put f 100 1.0 → 24stack.sgy</td>
</tr>
</tbody>
</table>
25) DEL a to z
26) READ 24mut.sgy put a
27) NMO a put b vel24.dat m 15
28) SORT b put c cdp
29) READ 24stack.sgy put d
30) MCORR c with d put e and f 100 600 10 20 40 80 100 line1.st1
31) ITERATE line1.st1 line1.st2 3
32) ASTAT c put g line1.st2
33) STACK g put h cdp
34) FKFIL h put i 20 100 –24 1.0
35) AGC i put j 100 1.0
Line 2 – Processing Commands for Vista 7.0

1) MACRO spec.mac (convert DAT files to SEG-Y)
2) MACRO 48-24.mac (convert 48-channel data to 24-channel data)
3) COMBINE put a 24chan.cmb
4) GAIN a put b 8
5) MEAN b put c 1.0
6) FILTER d put e 20 40 80 100
7) AGC e put f 150 1.0
8) GEOM Geohlf4.sgy Geohlf24
9) HEAD Geohlf24.sgy put f
10) IKIL f 24
11) IMUT f 24 → 24mut.sgy
12) DEL a
13) MOVE f put a
14) DEL f
15) SORT a[1-288] put b offset ….put f[5761-6024] offset
16) STACK b put j offset
17) SEMB j put r 100 1000 50
18) VPICK j and r put vlin2-24.dat
19) DEL b to y
20) NMO a put b vlin2-24.dat m20
21) SORT b put c cdp
22) STACK c put d cdp
23) FKFIL d put e 20 100 –24 1.0
24) AGC e put f 100 1.0 → 24stack.sgy
25) DEL a to z
26) READ 24mut.sgy put a
27) NMO a put b vel24.dat m 15
28) SORT b put c cdp
29) READ 24stack.sgy put d
30) MCORR c with d put e and f 100 600 10 20 40 80 100 line1.st1
31) ITERATE line1.st1 line1.st2 3
32) ASTAT c put g line1.st2
33) STACK g put h cdp
34) FKFIL h put i 20 100 –24 1.0
35) AGC i put j 150 1.0
Line 3 – Processing Commands for Vista 7.0

1) MACRO spec.mac (convert DAT files to SEG-Y)
2) MACRO 48-24.mac (convert 48-channel data to 24-channel data)
3) COMBINE put a 24chan.cmb
4) GAIN a put b 8
5) MEAN b put c 1.0
6) FILTER d put e 20 40 80 100
7) AGC e put f 200 1.0
8) GEOM lin3geom.sgy lin3geom
9) HEAD lin3geom.sgy put f
10) IKIL f 24
11) IMUT f 24 \(\rightarrow\) 24mut.sgy
12) DEL a
13) MOVE f put a
14) DEL f
15) SORT a[1-288] put b offset ….put h[1729-1917] offset
16) STACK b put j offset
17) SEMB j put r 100 1000 25
18) VPICK j and r put vel24.dat
19) DEL b to y
20) NMO a put b vel24.dat m20
21) SORT b put c cdp
22) STACK c put d cdp
23) FKFIL d put e 20 100 –24 1.0
24) AGC e put f 75 1.0 \(\rightarrow\) 24stack.sgy
25) DEL a to z
26) READ 24mut.sgy put a
27) NMO a put b vel24.dat m 15
28) SORT b put c cdp
29) READ 24stack.sgy put d
30) MCORR c with d put e and f 100 600 10 20 40 80 100 line1.st1
31) ITERATE line1.st1 line1.st2 3
32) ASTAT c put g line1.st2
33) STACK g put h cdp
34) FKFL h put i 20 100 –24 1.0
35) AGC i put j 200 1.0
Line 4 – Processing Commands for Vista 7.0

1) MACRO spec.mac (convert DAT files to SEG-Y)
2) MACRO 48-24.mac (convert 48-channel data to 24-channel data)
3) COMBINE put a 24chan.cmb
4) GAIN a put b 8
5) MEAN b put c 1.0
6) FILTER d put e 20 40 80 100
7) AGC e put f 200 1.0
8) GEOM lin4ch24.sgy lin4ch24
9) HEAD lin4ch24.sgy put f
10) IKIL f 24
11) IMUT f 24 → 24mut.sgy
12) DEL a
13) MOVE f put a
14) DEL f
15) SORT a[1-288] put b offset ….put d[6049-6336] offset
16) STACK b put j offset…. 
17) SEMB j put r 100 1000 25.…
18) VPICK j and r put vel24.dat…. 
19) DEL b to y
20) NMO a put b vel24.dat m20
21) SORT b put c cdp
22) STACK c put d cdp 
23) AGC c put f 100 1.0
24) FKFIL d put e 20 100 –24 1.0 → 24stack.sgy
25) DEL a to z
26) READ 24mut.sgy put a
27) NMO a put b vel24.dat m 15
28) SORT b put c cdp
29) READ 24stack.sgy put d
30) MCORR c with d put e and f 100 600 10 20 40 80 100 line1.st1
31) ITERATE line1.st1 line1.st2 3
32) ASTAT c put g line1.st2
33) STACK g put h cdp
34) FKFIL h put i 20 100 –24 1.0
35) AGC i put j 200 1.0
Line 5 – Processing Commands for Vista 7.0

1) MACRO spec.mac (convert DAT files to SEG-Y)
2) MACRO 48-24.mac (convert 48-channel data to 24-channel data)
3) COMBINE put a 24chan.cmb
4) GAIN a put b 8
5) MEAN b put c 1.0
6) FILTER d put e 20 40 80 100
7) AGC e put f 200 1.0
8) GEOM lin5ch24.sgy lin5ch24
9) HEAD lin5ch24.sgy put f
10) IKIL f 24
11) IMUT f 24 → 24mut.sgy
12) DEL a
13) MOVE f put a
14) DEL f
15) SORT a[1-288] put b offset ….put d[3169-3456] offset
16) STACK b put j offset…. 
17) SEMB j put r 100 1000 25…. 
18) VPICK j and r put vel24.dat…. 
19) DEL b to y
20) NMO a put b vel24.dat m20
21) SORT b put c cdp
22) STACK c put d cdp
23) FKFIL d put e 20 100 –24 1.0
24) AGC e put f 150 1.0 → 24stack.sgy
25) DEL a to z
26) READ 24mut.sgy put a
27) NMO a put b vel24.dat m 15
28) SORT b put c cdp
29) READ 24stack.sgy put d
30) MCORR c with d put e and f 100 600 10 20 40 80 100 line1.st1
31) ITERATE line1.st1 line1.st2 3
32) ASTAT c put g line1.st2
33) STACK g put h cdp
34) FKFIL h put i 20 100 –24 1.0
35) AGC i put j 150 1.0
Line 6 – Processing Commands for Vista 7.0

1) MACRO spec.mac (convert DAT files to SEG-Y)
2) MACRO 48-24.mac (convert 48-channel data to 24-channel data)
3) COMBINE put a 24chan.cmb
4) GAIN a put b 8
5) MEAN b put c 1.0
6) FILTER d put e 10 20 90 100
7) AGC e put f 125 1.0
8) GEOM lin6ch24.sgy lin6ch24
9) HEAD lin6ch24.sgy put f
10) IKIL f 24
11) IMUT f 24 \rightarrow 24mut.sgy
12) DEL a
13) MOVE f put a
14) DEL f
15) SORT a[1-288] put b offset ….put f[7201-7368] offset
16) STACK b put j offset…. 
17) SEMB j put r 100 1000 25…. 
18) VPICK j and r put vel24.dat…. 
19) DEL b to y
20) NMO a put b vel24.dat m20
21) SORT b put c cdp
22) STACK c put d cdp
23) FKFIL d put e 10 100 -24 1.0
24) AGC e put f 75 1.0 \rightarrow 24stack.sgy
25) DEL a to z
26) READ 24mut.sgy put a
27) NMO a put b vel24.dat m 15
28) SORT b put c cdp
29) READ 24stack.sgy put d
30) MCORR c with d put e and f 100 600 10 10 20 90 100 line1.st1
31) ITERATE line1.st1 line1.st2 3
32) ASTAT c put g line1.st2
33) STACK g put h cdp
34) FKFIL h put i 10 100 –24 1.0
35) AGC i put j 75 1.0
Line 7 – Processing Commands for Vista 7.0

1) MACRO spec.mac (convert DAT files to SEG-Y)
2) MACRO 48-24.mac (convert 48-channel data to 24-channel data)
3) COMBINE put a 24chan.cmb
4) GAIN a put b 8
5) MEAN b put c 1.0
6) FILTER d put e 20 40 80 100
7) AGC e put f 125 1.0
8) GEOM lin7ch24.sgy lin7ch24
9) HEAD lin7ch24.sgy put f
10) IKIL f 24
11) IMUT f 24 → 24mut.sgy
12) DEL a
13) MOVE f put a
14) DEL f
15) SORT a[1-288] put b offset ….put e[4897-5184] offset
16) STACK b put j offset…. 
17) SEMB j put r 100 1000 25…. 
18) VPICK j and r put vel24.dat…. 
19) DEL b to y
20) NMO a put b vel24.dat m20
21) SORT b put c cdp
22) STACK c put d cdp
23) FKFIL d put e 20 100 –24 1.0
24) AGC e put f 125 1.0 → 24stack.sgy
25) DEL a to z
26) READ 24mut.sgy put a
27) NMO a put b vel24.dat m 15
28) SORT b put c cdp
29) READ 24stack.sgy put d
30) MCORR c with d put e and f 100 600 10 20 40 80 100 line1.st1
31) ITERATE line1.st1 line1.st2 3
32) ASTAT c put g line1.st2
33) STACK g put h cdp
34) FKFIL h put i 20 100 –24 1.0
35) AGC i put j 125 1.0
Line 8 – Processing commands for Vista 7.0

1) MACRO spec.mac (convert DAT files to SEG-Y)
2) MACRO 48-24.mac (convert 48-channel data to 24-channel data)
3) COMBINE put a 24chan.cmb
4) GAIN a put b 8
5) MEAN b put c 1.0
6) AGC c put d 200 1.0
7) FILTER d put e 20 40 100 120
8) IKIL f 24
9) GEOM lin8ch24.sgy lin8ch24
10) HEAD lin8ch24.sgy put f
11) IMUT f 24 → 24mut.sgy
12) DEL a
13) MOVE f put a
14) DEL f
15) SORT a[1-288] put b offset ….put i[4321-4608] offset
16) STACK b put j offset…..
17) SEMB j put r 25 1000 25….
18) VPICK j and r put vel24.dat…. 
19) DEL b to y
20) NMO a put b vel24.dat m 15
21) SORT b put c cdp
22) STACK c put d cdp
23) FKFIIL d put e 20 120 –24 1.0
24) AGC e put f 200 1.0 → 24stack.sgy
25) DEL a to z
26) READ 24mut.sgy put a
27) NMO a put b vel24.dat m 15
28) SORT b put c cdp
29) READ 24stack.sgy put d
30) MCORR c with d put e and f 100 600 10 20 40 100 120 line1.st1
31) ITERATE line1.st1 line1.st2 3
32) ASTAT c put g line1.st2
33) STACK g put h cdp
34) FKFIL h put i 20 120 –24 1.0
35) AGC i put j 200 1.0
Line 9 – Processing commands for Vista 7.0

1) MACRO spec.mac (convert DAT files to SEG-Y)
2) MACRO 48-24.mac (convert 48-channel data to 24-channel data)
3) COMBINE put a 24chan.cmb
4) GAIN a put b 8
5) MEAN b put c 1.0
6) AGC c put d 125 1.0
7) FILTER d put e 10 25 110 120
8) GEOM lin9ch24.sgy lin9ch24
9) HEAD lin9ch24.sgy put f
10) IKIL f 24
11) IMUT f 24 → 24mut.sgy
12) DEL a
13) MOVE f put a
14) DEL f
15) SORT a[1-288] put b offset ….put c[4896-5184] offset
16) STACK b put j offset…..
17) SEMB j put r 25 1000 25…..
18) VPICK j and r put vel24.dat…..
19) DEL b to y
20) NMO a put b vel24.dat m 15
21) SORT b put c cdp
22) STACK c put d cdp
23) FKFIL d put e 20 120 –24 1.0
24) AGC e put f 200 1.0 → 24stack.sgy
25) DEL a to z
26) READ 24mut.sgy put a
27) NMO a put b vel24.dat m 15
28) SORT b put c cdp
29) READ 24stack.sgy put d
30) MCORR c with d put e and f 100 600 10 10 25 110 120 line1.st1
31) ITERATE line1.st1 line1.st2 3
32) ASTAT c put g line1.st2
33) STACK g put h cdp
34) FKFIL h put i 10 120 –24 1.0
35) AGC i put j 200 1.0
Line 10 – Processing commands for Vista 7.0

1) MACRO spec.mac (convert DAT files to SEG-Y)
2) MACRO 48-24.mac (convert 48-channel data to 24-channel data)
3) COMBINE put a 24chan.cmb
4) GAIN a put b 8
5) MEAN b put c 1.0
6) AGC c put d 200 1.0
7) FILTER d put e 20 40 120 140
8) GEOM lin10ch24.sgy lin10ch24
9) HEAD lin10ch24.sgy put f
10) IKIL f 24
11) IMUT f 24 → 24mut.sgy
12) DEL a
13) MOVE f put a
14) DEL f
15) SORT a[1-288] put b offset ….put e[865-1152] offset
16) STACK b put j offset….  
17) SEMB j put r 25 1000 25….  
18) VPICK j and r put vel24.dat….  
19) DEL b to y
20) NMO a put b vel24.dat m 15
21) SORT b put c cdp
22) STACK c put d cdp
23) FKFIL d put e 20 140 –24 1.0
24) AGC e put f 200 1.0 → 24stack.sgy
25) DEL a to z
26) READ 24mut.sgy put a
27) NMO a put b vel24.dat m 15
28) SORT b put c cdp
29) READ 24stack.sgy put d
30) MCORR c with d put e and f 100 600 10 20 40 120 140 line1.st1
31) ITERATE line1.st1 line1.st2 3
32) ASTAT c put g line1.st2
33) STACK g put h cdp
34) FKFIL h put i 20 140 –24 1.0
35) AGC i put j 200 1.0
Line 11 – Processing commands for Vista 7.0

1) MACRO spec.mac (convert DAT files to SEG-Y)
2) MACRO 48-24.mac (convert 48-channel data to 24-channel data)
3) COMBINE put a 24chan.cmb
4) GAIN a put b 8
5) MEAN b put c 1.0
6) AGC c put d 50 1.0
7) FILTER d put e 20 30 70 80
8) FKFIL e put f 20 80 –24 1.0
9) AGC f put g 50 1.0
10) GEOM lin11ch24.sgy lin11ch24
11) HEAD lin11ch24.sgy put f
12) IKIL f 24
13) IMUT f 24 \rightarrow 24mut.sgy
14) DEL a
15) MOVE f put a
16) DEL f
17) SORT a[1-288] put b offset ….put e[865-1152] offset
18) STACK b put j offset…..
19) SEMB j put r 25 1000 25….
20) VPICK j and r put vel24.dat….
21) DEL b to y
22) NMO a put b vel24.dat m 15
23) SORT b put c cdp
24) STACK c put d cdp \rightarrow 24stack.sgy
25) DEL a to z
26) READ 24mut.sgy put a
27) NMO a put b vel24.dat m 15
28) SORT b put c cdp
29) READ 24stack.sgy put d
30) MCORR c with d put e and f 30 300 10 20 30 70 80 line1.st1
31) ITERATE line1.st1 line1.st2 3
32) ASTAT c put g line1.st2
33) STACK g put h cdp
Appendix C

Borehole descriptions for WI-1, WI-2, WI-3, and HL-1. Their locations relative to the seismic profiles are displayed in Figure 2.2. Drilling and logging were conducted by Fuller, Mossbarger, Scott, and May Engineers, Inc., Louisville, KY (FMSM, 2002).
<table>
<thead>
<tr>
<th>Lithology</th>
<th>Description</th>
<th>Elevation</th>
<th>Depth</th>
<th>Remarks</th>
</tr>
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<tr>
<td>0.0</td>
<td>Grass</td>
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<tr>
<td>25.0</td>
<td>Drilling without Sampling</td>
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<td>25.4-25.5 trace organics</td>
<td>SAND (USCS: SP), red brown, non-plastic, damp to saturated, loose, medium grained, rounded, poorly graded (visually classified)</td>
<td>25.0-27.0</td>
<td>1.1</td>
<td>1-3-6-6</td>
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<td>32.0 trace organics</td>
<td>SP-2</td>
<td>27.0-29.0</td>
<td>1.3</td>
<td>6-8-9-11</td>
</tr>
<tr>
<td>33.4 trace organics</td>
<td>SP-3</td>
<td>29.0-31.0</td>
<td>1.0</td>
<td>4-7-7-6</td>
</tr>
<tr>
<td>35.0-35.1 trace organics</td>
<td>SP-4</td>
<td>31.0-33.0</td>
<td>1.5</td>
<td>5-8-5-7</td>
</tr>
<tr>
<td>35.6</td>
<td>SAND (USCS: SW), red brown, non-plastic, saturated, loose, medium to coarse grained, rounded, well graded, with fine rounded gravel (visually classified)</td>
<td>35.0-37.0</td>
<td>1.2</td>
<td>3-5-6-8</td>
</tr>
<tr>
<td>42.2 trace organics</td>
<td>SP-5</td>
<td>33.0-35.0</td>
<td>1.2</td>
<td>4-4-5-9</td>
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<td>44.2-44.4 trace organics</td>
<td>SP-6</td>
<td>35.0-37.0</td>
<td>1.2</td>
<td>3-5-6-8</td>
</tr>
<tr>
<td>45.0</td>
<td>No Refusal/Bottom of Hole</td>
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<tr>
<td>Lithology</td>
<td>Description</td>
<td>Overburden</td>
<td>Sample #</td>
<td>Depth</td>
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<td>-------</td>
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<td>Grass</td>
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<tr>
<td>1.5</td>
<td>Topsoil</td>
<td>CS-1</td>
<td>0.0-5.0</td>
<td>2.8</td>
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<tr>
<td></td>
<td>SIPTY CLAY (USCS: CL), red brown, si. plastic, damp, medium stiff to stiff, with manganese concretions (visually classified)</td>
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<tr>
<td>6.3</td>
<td>CLAYEY SAND (USCS: SC), red brown, non-plastic, damp, loose, medium grained (visually classified)</td>
<td>SP-1</td>
<td>5.0-7.0</td>
<td>1.9</td>
</tr>
<tr>
<td>8.0</td>
<td>SAND (USCS: SP), red brown, non-plastic, damp to saturated, loose, medium grained, rounded poorly graded (visually classified)</td>
<td>SP-2</td>
<td>7.0-9.0</td>
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<tr>
<td></td>
<td>9.0-9.9 clay lens, red brown, stiff</td>
<td>SP-3</td>
<td>9.0-11.0</td>
<td>2.0</td>
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<tr>
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<td>11.0-11.8 clayey sand lens</td>
<td>SP-4</td>
<td>11.0-13.0</td>
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<td>11.8-15.6 trace organics</td>
<td>SP-5</td>
<td>13.0-15.0</td>
<td>2.0</td>
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<td>19.0-24.4 trace organics</td>
<td>SP-6</td>
<td>15.0-17.0</td>
<td>2.0</td>
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<tr>
<td></td>
<td>24.4-24.5 clay lens, gray, stiff</td>
<td>SP-7</td>
<td>17.0-19.0</td>
<td>2.0</td>
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<td>24.5-24.6 sand lens, gray, fine</td>
<td>SP-8</td>
<td>19.0-21.0</td>
<td>1.7</td>
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<td>24.6-24.7 clay lens, gray to red brown, stiff</td>
<td>SP-9</td>
<td>21.0-23.0</td>
<td>1.4</td>
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<td>26.0-26.3 trace organics and trace gravel</td>
<td>SP-10</td>
<td>23.0-25.0</td>
<td>1.6</td>
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<td>Elevation</td>
<td>Depth</td>
<td>Lithology Description</td>
<td>Overburden</td>
<td>Sample #</td>
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<tr>
<td>29.0</td>
<td>29.0-31.0</td>
<td>SAND (USCS: SW), red brown, non-plastic, saturated, loose, coarse grained, rounded, well graded, with fine rounded gravel (visually classified)</td>
<td>SP-13</td>
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<td>29.0</td>
<td>31.0-33.0</td>
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<td>SP-14</td>
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<td>33.0-35.0</td>
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<td>SP-15</td>
<td>33.0</td>
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<tr>
<td>35.8-37.0</td>
<td>35.0-37.0</td>
<td>increased fine gravel content (approx. 20%)</td>
<td>SP-16</td>
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<td>37.0-39.0</td>
<td>37.0-39.0</td>
<td>no fine gravel</td>
<td>SP-17</td>
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<td>39.0</td>
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Project No.: LX1998363 Location: J.T. Myers L&D Hole No.: WI-2
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<th>Depth</th>
<th>Rec. Ft.</th>
<th>Blows</th>
<th>Mole. Cont. %</th>
<th>Remarks</th>
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<td>Elevation</td>
<td>Rock Core</td>
<td>RQD</td>
<td>Run</td>
<td>Rec. %</td>
<td>SDI</td>
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<tr>
<td>0.0</td>
<td>Grass</td>
<td>CS-1</td>
<td>0.0-5.0</td>
<td>5.0</td>
<td>--</td>
<td>--</td>
<td>Equipment: OME 85 #1, 3.25-inch HSA, 3-inch split spoon with 300-lb. automatic hammer and 18-inch drop, 5-foot CME continuous sampling tube</td>
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<tr>
<td>1.0</td>
<td>Topsoil</td>
<td>CS-2</td>
<td>5.0-10.0</td>
<td>4.2</td>
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<td>SAND (USCS: SP), red brown, non-plastic, damp to saturated, loose, fine to medium grained, rounded, poorly graded (visually classified)</td>
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</tr>
<tr>
<td>6.6</td>
<td>SILTY CLAY (USCS: CL), red brown, sl. plastic, damp, medium stiff to stiff, with manganese concretions (visually classified)</td>
<td>CS-3</td>
<td>10.0-15.0</td>
<td>3.3</td>
<td>--</td>
<td>--</td>
<td>Super Gel-X drilling mud introduced at 30.0 feet</td>
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<tr>
<td></td>
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<td>CS-4</td>
<td>15.0-20.0</td>
<td>2.3</td>
<td>--</td>
<td>--</td>
<td>Begin 3-inch split spoons at 30.0 ft</td>
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<tr>
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<td></td>
<td>CS-5</td>
<td>20.0-25.0</td>
<td>2.3</td>
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<td>--</td>
<td>30.5 very thin clayey sand lens, 30.5 trace organics</td>
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<td>29.2</td>
<td>SAND (USCS: SW), red brown, non-plastic, saturated, loose, medium to coarse grained, rounded, well graded, with fine rounded gravel (visually classified)</td>
<td>CS-6</td>
<td>25.0-30.0</td>
<td>2.9</td>
<td>--</td>
<td>--</td>
<td>Carbon-14 Age 42,230 ± 850 ypb at 30.5 ft</td>
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<td>30.0 very thin clayey sand lens</td>
<td>SP-1</td>
<td>30.0-32.0</td>
<td>1.3</td>
<td>1-3-4-6</td>
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<td>10-27-100+</td>
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Appendix D

Refraction analysis of the southeast end of Line 11. First-break picks are in the first figure. Soil/bedrock velocities and depths are shown in the subsurface model (second figure).
Appendix E

Representative raw and partially processed field files for each seismic line collected in this study.

Line 1: 48-channel field file—A) Raw, B) AGC

A)       B)
Line 2: 48-channel field file—A) Raw, B) AGC
Line 3: 48-channel field file—A) Raw, B) AGC, bandpass filter
Line 4: 48-channel field file—A) Raw, B) AGC, bandpass filter
Line 5: 48-channel field file—A) Raw, B) AGC, bandpass
Line 6: 48-channel field file—A) Raw, B) AGC

A)       B)
Line 7: 48-channel field file—A) Raw, B) AGC, bandpass filter
48-channel field file—A) Raw, B) AGC, bandpass filter, FK filter
Line 9: 48-channel field file—A) Raw, B) AGC, bandpass filter
Line 10: 48-channel field file—A) Raw, B) AGC, bandpass
13-channel split-spread field file—A) Raw, B) mean, gain, AGC, bandpass filter, FK filter (notice weak soil reflector at 60 ms)
### Appendix F

Range of horizontal and vertical resolutions for Lines 1 – 11.

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References Cited


VITA

F. Alex Rutledge

Education -

-West Virginia University, Morgantown, West Virginia, 1998 - 2002
Bachelor of Science – Geology – Cum Laude

-University of Kentucky, Lexington, Kentucky, 2002 – 2004
Master of Science – Geology (Geophysics) – 4.0 GPA

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-Research Assistant, Kentucky Geological Survey, May 2003 – May 2004
-Teaching Assistant, University of Kentucky, September 2002 – May 2004
-Field Geologist, West Virginia Geological and Economic Survey, May 2001 – August 2001

Honors and Activities –

-Member of Golden Key International Honor Society, 2000 – present
-Field Camp, West Virginia and Maine; 6 week structural geology mapping project, 2002
-Presented undergraduate research findings at the Geological Society of America’s sectional meeting, 2002
-Presented thesis research at the American Geophysical Union national conference, 2003
-Recipient of Graduate School Pirtle academic scholarship, 2003 and 2004