

FINAL TECHNICAL REPORT
November 1, 2002, through April 30, 2003

Project Title: **AEROMAGNETIC AND SURFACE SEISMIC SURVEYS FOR
DIKE DETECTION IN ILLINOIS COAL SEAMS, SALINE COUNTY,
ILLINOIS**

ICCI Project Number: 02-1/US-2
Principal Investigator: Marc Silverman, Peabody Energy, Inc.
Other Investigators: Andre J. M. Pugin, Illinois State Geological Survey
Timothy H. Larson, Illinois State Geological Survey
Robert J. Finley, Illinois State Geological Survey

Project Manager: Joseph Hirschi, ICCI

ABSTRACT

For over a century, coal mines in northern Saline County, Illinois have been plagued by ultrabasic igneous dikes that intrude into the coal seams, locally altering the composition of the coal and causing operational problems with the mine equipment and mine planning. We conducted tests integrating two high-resolution geophysical techniques in an effort to detect the dikes and map their locations. First, we acquired high-resolution magnetic data in the area where we suspected the dikes to be present. Several very distinct, large magnitude linear anomalies could be directly associated with known dikes. These and other similar anomalies were mapped in the study area. Second, we acquired high-resolution seismic reflection data in a profile that crossed three of these linear magnetic anomalies. The seismic data provides a cross-sectional view of the shallow subsurface, including the igneous dikes.

We also acquired a seismic test profile in an area that both bordered an abandoned longwall mine and crossed the projected path of a known dike. This seismic test was not in the area covered by the magnetic survey, but the dike and mine boundaries were known from mine records. The seismic test successfully identified both the dike and the boundary of the longwall mine.

High-resolution aeromagnetic surveys successfully locate and map shallow magnetic dikes in Saline and Gallatin Counties. Seismic reflection profiles provide additional detail on the depth and orientation of the dikes and can be used to map the edges of abandoned longwall mines. Further testing of the seismic method could demonstrate its utility in mapping the edges of other types of abandoned mines.

EXECUTIVE SUMMARY

OBJECTIVES

This project is intended to demonstrate some of the capabilities of high-resolution geophysical methods in the coal mining districts of southern Illinois. The primary goal is to demonstrate the utility of integrated geophysical methods in mapping igneous dikes known to occur in Saline and Gallatin Counties. Both high resolution aeromagnetic methods and high resolution seismic reflection profiling were tested. Because of the availability of the equipment in the area, the study was extended to investigate the potential of high resolution seismic reflection profiling in mapping the extent of subsurface longwall mining.

BACKGROUND

For over a century, coal mines in northern Saline County have been plagued by ultrabasic igneous dikes (primarily lamprophyre) that intrude into the coal seams, locally altering the composition of the coal. Also, the hardness of the igneous rocks has caused operational problems with the mine equipment and mine planning. Most dikes are only a few feet wide, but some are up to 30 ft wide and one near Eldorado was reported to be 300 ft wide. Detecting the dikes with drill holes is difficult and once detected, only a very closely spaced drilling program can map their extent. However, these igneous rocks contain up to 9 percent magnetite and produce a significant magnetic anomaly. They can be mapped using magnetic methods, provided a sufficiently dense grid of measurements can be obtained. Because of the strong density contrast between the igneous and sedimentary rocks, seismic reflection methods should be able to provide 2-D images of the dikes as they intrude into the sedimentary column. Together, the two geophysical methods should produce high-quality maps of the dikes.

Longwall coal mine operations are designed to produce severe disruptions of the overlying rock strata. Fracturing and reduced density are imappable using high resolution seismic reflection profiling. This relatively rapid geophysical method can be employed to determine the edges of mined out regions. We tested this procedure over a longwall mine in Saline County. Seismic images of areas mined by room-and-pillar methods might have some of the same characteristics as those mined by longwall methods, but would lack the extensive fracturing unless the mine supports had collapsed.

The study was conducted in northern Saline and western Gallatin Counties, Illinois, north of Harrisburg and Equality and southwest of Omaha. New high-resolution aeromagnetic data were acquired in three areas: Area A is northwest of Galatia in parts of T. 7-8 S., R. 5 E., Saline County; Area B is northeast of Galatia in parts of T. 7 S., R. 6-7 E., Saline County; and the Willow Lake Area is east of Eldorado and south of Omaha in T. 8-9 S., R. 7 E. of Saline County and T. 8-9 S., R. 8 E. in Gallatin County. Two seismic reflection test lines were also acquired: Coffee Road Line is northeast of Raleigh along the north line of Sections 13 and 14, T. 8 S., R. 6 E., Saline County; and Dickey Ford Road Line is south of Elba in the west half of Section 21, T. 8 S., R. 8 E., Gallatin County.

PROCEDURES

In our aeromagnetic survey the flight lines were 100 m apart and flown at a height of 80 m. Magnetometers with a sensitivity of 0.001 nT and sampling rate of 10 samples/sec were used in this survey. Magnetic data were acquired by Terraquest, Ltd. Data were processed and mapped by Edcon, Inc. The data were corrected to a uniform level and effects from electric power lines were removed from the data set. The standard reduction-to-the-pole processing algorithm was applied to the data set. Finally, low-frequency anomalies associated with deep, regional magnetic sources were removed from the data leaving high-frequency residual anomalies caused by shallow, local magnetic sources.

The CMP reflection data on the two seismic lines were acquired with a 48-channel recording system. An accelerated weigh drop created a seismic source at 10 ft intervals along the lines and the receivers were spaced at 10 ft intervals. Seismic reflection processing used PC-based software and, for the most part, followed standard processing protocols. We applied a specialized routine for static correction analysis and modeling. Part of the processing was done in true amplitude mode to reduce distortions of the signal amplitude. For this part, automatic gain control was not applied and the gain is compensated for the muted parts of the CMP records. The true-amplitude display reveals the large decrease in signal amplitude caused by decreased density in the mined-out areas.

RESULTS

The high resolution residual magnetic anomaly maps show cultural as well as natural features. Cultural features include metal buildings, oil wells, towers and power transformers characterized by isolated circular anomalies; and buried pipelines and underground mine workings characterized by discontinuous linear anomalies. Processing algorithms removed most effects from linear power lines, but in areas where the lines curve or are mounted on large towers, residual effects are still apparent in the final maps. Natural features, primarily the igneous dikes are characterized by continuous linear anomalies generally trending north or northwest. Two linear anomalies were identified in Area A, one of which is associated with a known 10 ft wide dike. Only one small-amplitude, north-northwest trending anomaly located in the western part of Area B may be caused by a dike. The Willow Lake Block, east of Eldorado, includes two major oil fields and many other oil wells as well as coal mines. Anomalies associated with these industrial activities are clearly apparent on the residual magnetic map. Also, several large-amplitude linear anomalies are present in the Willow Lake Block that are either directly in line with or coincide with previously mapped dikes. Continuations of these anomalies are interpreted as other dikes. Anomalies in the southwest part of the Willow Lake Block appear to radiate from a central point tentatively identified as a small magnetic plug or dome similar to the one at Omaha. The largest north to northwest trending linear anomaly in the Willow Lake area is caused by the Cottage Grove Dike, a 30-foot wide lamprophyre dike encountered in surface mining. Several smaller anomalies are parallel to the main anomaly, suggesting several other narrow or deeper dikes. These dikes can be traced northward through the entire Willow Lake area. Presumably, these

dikes are directly related to the Omaha dome igneous sills. The Dickey Ford Road Seismic Line crosses the axis of these parallel anomalies.

Vertical dikes can be observed in both the Dickey Ford Road Seismic Line and the Coffee Road Seismic Line. The dikes are characterized by either diffraction patterns or lateral change of phase over a short length with either a chaotic or a ringing wave pattern. One of the dikes imaged in the Willow Lake Magnetic Map is not as obvious in the seismic data. This dike may be too narrow to be clearly identified by the seismic method. The dikes appear to be wider on the seismic sections than they actually are. The heat produced during intrusion altered the sedimentary rock, creating a wider zone of impedance contrasts (velocity, density variations) and producing a reflective zone wider than the dike itself. Diffraction energy may also contribute to an increase in the width of the dike zone on the seismic sections.

The Coffee Road Seismic Line traversed the boundary of a longwall mine. The mined out area is characterized in the seismic section as a “blank-out” or zone with severe reduction in amplitude of the reflection signal. This effect is apparent in the true amplitude representation of the data, but not as apparent when standard AGC techniques are used for processing. The blanked-out area is total over the first 200 meters of the section, with a 100-m wide transition zone leading to a normal layered stratigraphy which is present in the rest of the section.

CONCLUSIONS

High resolution aeromagnetic techniques are ideally suited for mapping the altered lamprophyre dikes in this study area. The high percentage of magnetite in these altered igneous rocks produces a very large magnetic signature that is evident even within the noise of cultural magnetic sources such as buildings, oil wells and power lines. Quantitative modeling procedures could provide more detailed estimates of depth and thickness.

Using high resolution seismic reflection techniques we have demonstrated that it is possible to resolve sedimentary layers as thin as 4 meters (12 ft). Primary sedimentary features such as sandstone channels can be observed. Narrow igneous dikes are sometimes difficult to observe with the reflection technique, but the wider ones are characterized by diffractions and lateral phase changes. Areas mined with the longwall method can be observed as “blanked out” zones with severely reduced seismic amplitude. This reduction in amplitude is likely caused by absorption of the seismic energy by gas migrating in the intensely fractured rock in and above the collapsed longwall panels. Further testing would be required to fully demonstrate the procedure for the different conditions (flooded, collapsed, etc) of abandoned room and pillar mines. Based on these tests, we recommend that when using the seismic reflection technique to image mined-out areas or igneous dikes, a seismic acquisition system with a minimum of 48 channels should be used and geophones and shots should be spaced at a maximum of 3 meters (10 ft).

OBJECTIVES

This project is intended to demonstrate some of the capabilities of high-resolution geophysical methods in the coal mining districts of southern Illinois. The primary goal is to demonstrate the utility of integrated geophysical methods in mapping igneous dikes within the study area. Both high resolution aeromagnetic methods and high resolution seismic reflection profiling are tested. Because of the availability of the equipment in the area, the study was extended to investigate the potential of high resolution seismic reflection profiling in mapping the extent of subsurface longwall mining.

INTRODUCTION AND BACKGROUND

For over a century, coal mines in northern Saline County have been plagued by ultrabasic igneous dikes that intrude into the coal seams, locally altering the composition of the coal. Also, the hardness of the igneous rocks has caused operational problems with the mine equipment and mine planning (Cady, 1919; Padgett et al., 2002). Dikes have been documented in a narrow band from Eldorado, south to Carrier Mills. Igneous rocks with similar composition occur as sills or plugs in the Omaha area, northeast of Eldorado, resulting in local doming of the sedimentary rocks and an important oil reservoir. A few bore holes in western Gallatin County, east of Eldorado and south of Omaha, as well as recent underground mining southeast of Eldorado, and surface mining in west central Gallatin County, have encountered similar igneous rocks, suggesting that the dike swarm may extend further east than previously mapped. Unfortunately, some of the dikes do not extend to the ground surface and those that do, weather rapidly. Consequently, there is no surface expression of these dikes in Gallatin County. Although some of these dikes are up to 30 ft wide (Cady (1919) reported one reached 300 ft wide near Eldorado) most are thin and nearly vertical. Detecting the dikes with drill holes is difficult and once detected, only a very closely spaced drilling program can map their extent. However, the igneous rocks at Omaha contain up to 9 percent magnetite and produce a significant magnetic anomaly. Presumably the dikes in Gallatin County have similar compositions and could also be mapped using magnetic methods, provided a sufficiently dense grid of measurements can be obtained. Because of the strong density contrast between the igneous and sedimentary rocks, seismic reflection methods should be able to provide 2-D images of the dikes as they intrude into the sedimentary column. Together, the two geophysical methods should produce high-quality maps of the dikes.

Mining has been hampered by the presence of sandstone channels that locally replace the coal. In Saline County, a large sandstone channel interrupts the Springfield Coal and smaller ones interrupt the Herrin Coal. Because of the sinuous nature of these deposits, they have been very difficult to map using boreholes. High-resolution geophysical techniques have been successful in mapping narrow features such as these channels, provided a sufficient contrast exists between the target deposit and the surrounding rock. In this case, the sandstone channels contrast in density with both the coal and surrounding shale, suggesting that seismic reflection methods should be able to image the channels. However there may not be a sufficient contrast in magnetic properties to map them with magnetic methods.

High-resolution seismic reflection methods could also have utility locating mined-out areas in mature coal fields, such as the southern Illinois coal mining district. The longwall mining method produces severe disruption of the overlying strata. This disruption should be detectable in reflection profiles that cross over unmined to mined-out areas, providing a quantitative and objective tool to map the edge of mined-out areas. Abandoned room-and-pillar mines could vary from air-filled voids, to water-filled voids, to debris-filled collapsed zones depending on post-mine conditions in the coal seam. In theory, each of these conditions should present a zone of reduced density that could create either a distinctive seismic reflection or diffraction or reduction in seismic signal amplitude.

The study was conducted in northern Saline and western Gallatin Counties north of Harrisburg and Equality and southwest of Omaha (Figure 1). Data were collected in parts of Townships 7, 8, and 9 South and Ranges 5, 6, 7, and 8 East. New high-resolution aeromagnetic data were acquired in three areas: Area A is northwest of Galatia in parts of T. 7-8 S., R. 5 E., Saline County; Area B is northeast of Galatia in parts of T. 7 S.; R. 6-7 E., Saline County; and the Willow Lake Area is east of Eldorado and south of Omaha in T. 8-9 S., R. 7 E., Saline County and T. 8-9 S., R. 8 E., Gallatin County. Two seismic reflection test lines were also acquired: Coffee Road Line is northeast of Raleigh along the north line of Sections 13 and 14, T. 8 S., R. 6 E., Saline County; and Dickey Ford Road Line is south of Elba in the west half of Section 21, T.8 S., R. 8 E., Gallatin County.

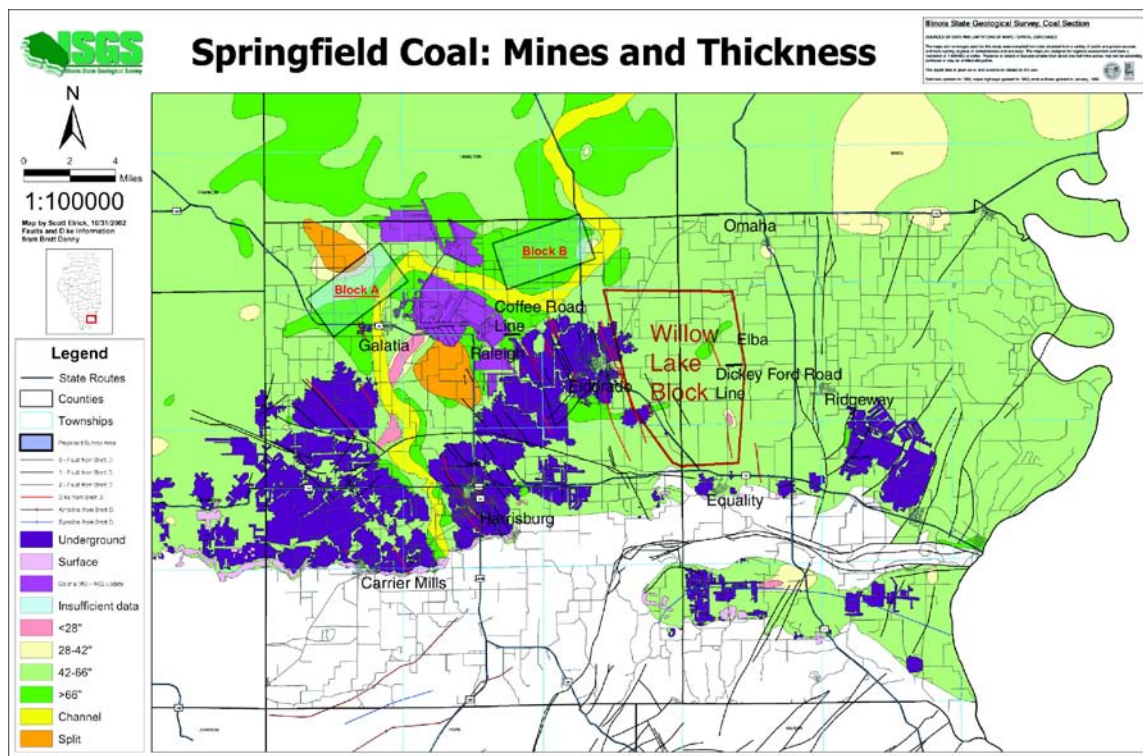


Figure 1. Location of the three magnetic survey blocks and two seismic profiles in Saline and Gallatin Counties. .

The study area lies in the southeastern part of the Illinois Basin coal fields, immediately north of the Cottage Grove Fault Zone and west of the Albion-Ridgeway Fault. The Omaha Dome is on the northeast corner of the study area. Historically, the primary coal seams mined in this area are the Springfield No. 5 Coal (older reports refer to this as the Harrisburg No. 5) and the Herrin No. 6 Coal which lies 100 to 125 feet above the Springfield. Both are Members of the Carbondale Formation of Pennsylvanian age. The Springfield Coal is up to 7.5 feet thick in the Eldorado area, but thins to about 3-5 feet thick to the east. The Herrin Coal is about 5 ft thick. Both coals crop out in the southern part of the study area and then dip northward to a depth of about 780 ft in Hamilton County. Rock between the Springfield and Herrin Coals is mostly sandy shale or sandstone and a prominent sandstone channel replaces the Springfield Coal in parts of the area. Documentation of the structure, composition and thickness of these coal beds has been provided in numerous reports (Cady, 1919; Cady et al., 1951; Hopkins, 1968). About 60 to 90 ft above the Herrin Coal is the Danville No. 7 Coal, near the base of the Shelburn Formation. Where present it is usually about 2 ft thick. (Pullen *in* Cady et al., 1951).

The study area is bounded on the east and south by two major faults – the Albion - Ridgeway Fault to the east and the Cottage Grove Fault Zone (Nelson and Krausse, 1981; Nelson and Lumm, 1987; Nelson, 1995) to the south. The Albion Ridgeway Fault is the westernmost major fault in the Wabash Valley Fault Zone (Bristol and Treworgy, 1979), a series of generally north-trending high-angle mostly normal faults fanning away from the east-west trending strike-slip Cottage Grove and Shawnee Town Fault Zone (Nelson and Lumm, 1987). Many subsidiary faults have been documented in the coal fields since the work of Cady (1919). Most of these subsidiary faults also are north-trending normal faults similar to the Wabash Valley Fault System (Nelson and Krausse, 1981).

A series of mostly north or northwest trending igneous dikes intrude into the Springfield No. 5 Coal at several coal mines in the study area. These dikes which vary from a few feet wide up to 300 ft wide, were first described by Cady (1919) with maps, drawings and photographs. Most of the documented dikes occur in a zone at the east end of the Cottage Grove Fault Zone from Eldorado southwest toward Carrier Mills. Emplacement of the dikes was apparently synchronous with subsidiary faulting (Cady, 1919; Nelson and Krausse, 1981; Nelson and Lumm, 1987). Similar igneous rocks have been encountered by a few drill holes scattered in the rest of the study area, particularly east of Eldorado as well as in recent underground mining southeast of Eldorado, and surface mining in west central Gallatin County. It is likely that more dikes are present in the eastern part of the study area (Clegg and Bradbury, 1956), but the number and extent of these eastern dikes cannot be determined from drill holes alone. Igneous rocks also occur as sills in the Omaha area (English and Grogan, 1948) in the northeast corner of the study area and as explosion structures and dikes, south of the study area in Hardin and Pope Counties (Bain, 1905; Clegg and Bradbury, 1956). Petrographic studies and age determinations of the igneous rocks at Omaha, dikes in the coal mines near Eldorado and Harrisburg, and in dikes and plugs in Hardin and Pope Counties suggest that they are all from the same magma source and were emplaced during Permian time (Nelson and Lumm, 1987;

Nelson, 1995, Hildenbrand and Ravat, 1997). These dikes are the northern extent of the Tolu Arch, a northwest-trending Permian structure (Fifarek et al., 2001). The dikes and sills are generally composed of dark green lamprophyre. The rocks are highly altered with most of the primary olivine altered to serpentine (Sparlin and Lewis, 1994; Denny et al., 2002). Some samples contain up to 9 percent magnetite (Sparlin and Lewis, 1994) or 15 percent iron (Denny et al., 2002). They weather rapidly and have no surface expression.

The study area lies at the extreme southern edge of the area covered by Illinois Episode glaciers. Only thin, discontinuous tills from this glaciation are present in the area (Frye et al., 1972). However, virtually all the upland surfaces in the study area have been mantled by Wisconsin Episode loess, up to 8 ft thick (Willman and Frye, 1970) that is assigned to the Peoria Silt (Hansel and Johnson, 1996). Fine-grained sediments as much as 100 ft thick were deposited in the lowland parts of the study area by a backwater lake, Lake Saline, associated with Wisconsin Episode glacial meltwater (Frye et al., 1972).

Because the igneous rocks in the study area have a high iron content, they are a likely target for mapping using magnetic methods. Based on a regional aeromagnetic map (Kucks, 1990) and new ground-based point magnetic measurements, Sparlin and Lewis (1994) were able to map the intrusives associated with the Omaha Dome. The dikes south of the Omaha Dome are too narrow to be resolved on a regional aeromagnetic map. Hildenbrand and Ravat (1996) conducted a high resolution magnetic survey that included the eastern part of the study area. Their study used flight lines that were spaced 457 m apart and 152 m above ground. This is the first study to clearly map dikes in western Gallatin County, east of Eldorado. They demonstrated that north-northeast trending dikes exist both north and south of the Omaha dome. They calculated that some of the dikes north of Omaha may be only a few feet thick, are essentially vertical in orientation, and extend to within a few hundred feet of the ground surface. These conclusions are consistent with observations of dikes encountered in coal mines in the Eldorado and Harrisburg area. Although their study was designed to investigate neotectonic features in the area, they pointed out that the high resolution magnetic mapping technique could be useful in planning shallow coal mines.

Hensen and Sexton (1991) demonstrated the resolving power of the high resolution seismic reflection method in several test profiles just west of our study area. They were able to map channel sandstones that interrupt the Herrin No. 6 Coal and to distinguish between shale and limestone roof rock overlying the Herrin Coal. These methods are applicable to mining operations in the Springfield as well as the Herrin Coal in our study area.

Subsidence related to modern longwall coal mine operations of the Herrin Coal in Saline County was documented by Van Roosendaal et al. (1997). Geotechnical instrumentation, drilling and *in situ* testing were used to characterize an area before and after longwall mining. At the subsidence site, Herrin Coal about 6 ft thick and 400 ft deep was extracted from 2 adjacent longwall panels. Van Roosendaal et al. (1997) calculated a long term ratio of subsidence to mined-out height to be 60 to 72 percent. They also documented an

increase in high angle fractures in bedrock units overlying the coal. The fracturing resulted in a decrease in seismic velocity and bulk density. Decreases were most notable in sandstone units where the seismic velocity decreased as much as 35 percent. More commonly, seismic velocity decreased in the range of 1 to 13 percent, averaging about 8 percent. Bulk density decreased about 7 to 8 percent. The subsidence test site was located 3 miles west of our Coffee Road Seismic Line in Section 17, T. 8 S., R. 6 E. in another area of the same mine imaged beneath the Coffee Road Line. The mining activity imaged beneath the Coffee Road Line was longwall mining in the Springfield Coal and we expect that similar fracture processes with reduction in density and seismic velocity would be present beneath the Coffee Road Line.

EXPERIMENTAL PROCEDURES

High Resolution Aeromagnetic Methods

Following the suggestion of Hildenbrand and Ravat (1997) we conducted a test of high resolution magnetic methods to map igneous intrusions in the study area (Figure 1). Our study employed a higher resolution survey than that conducted by Hildenbrand and Ravat (1997). They created a grid using flight lines at about ½ km intervals and 152 m height. In our survey the flight lines were only 100 m apart and flown at a height of 80 m. Magnetometers with a sensitivity of 0.001 nT and sampling rate of 10 samples/sec were used in this survey. Magnetic data were acquired by Terraquest, Ltd. Data were processed and mapped by Edcon, Inc. Simple processing techniques were used to enhance the visual interpretation of the data. The data were corrected to a uniform level and effects from power lines were removed from the data set. To enhance the symmetry of the anomalies so that they align with seismic data, the data were transformed to the anomalies that would be observed if the magnetization and regional field were vertical (as if the anomaly was measured at the north pole). Hence this procedure is called “reduction to the pole” and results in the anomalies more nearly centered over their respective causative bodies (Dobrin and Savit, 1988; Baranov and Naudy, 1964). Finally, low-frequency anomalies associated with deep, regional magnetic sources were removed from the data leaving high-frequency residual anomalies caused by shallow, local magnetic sources.

Although many local magnetic sources, such as power lines, were removed from the data set, others remained. Visual inspection of the maps and comparison with topographic maps, road maps and field verification revealed that most of the small, circular anomalies could be confidently attributed to various cultural sources, particularly buildings and oil wells. Some linear anomalies could also be attributed to cultural sources such as buried utility lines or power lines that had not been completely masked by the initial processing procedure. After these circular and linear anomalies had been accounted for, some large amplitude, linear anomalies remained. Some of these remaining linear anomalies are directly associated with previously mapped igneous dikes. Other remaining linear anomalies have similar features and are interpreted as igneous dikes. Some of the dikes interpreted by Hildenbrand and Ravat (1997) are also observable in our data set, but at greater resolution.

We have conducted a simple visual inspection and interpretation of the magnetic data. Quantitative interpretations, such as forward modeling of the data could also be applied to advantage. These methods could provide estimates of the depth and thicknesses of the igneous rocks. Hildenbrand and Ravat (1997) and Sparlin and Lewis (1994) give examples of these quantitative interpretations for similar magnetic data sets in this region. Instead of calculating a magnetic model of the dikes, we used the magnetic data to target a test area for acquiring a 2-D seismic reflection profile. The 2-D seismic profile provides a direct image of the dikes.

High Resolution Seismic Reflection Methods

Seismic methods have been developed over the past half-century to image subsurface conditions at depths varying from a few meters to several kilometers. Hensen and Sexton (1991) demonstrated the utility of the seismic reflection method in imaging channels and facies changes in the sediments surrounding the coal seams in the Harrisburg area. In this study, we extend this method to image the narrow igneous dikes that intrude into the coal seams and to image mined out areas. The shallow seismic reflection method is based on the measurement of travel times of acoustic waves in layered media. Bulk density and seismic velocity of the rock layers are the primary properties that influence the sound propagation through the ground. A seismic pulse traveling through the ground is reflected at layer boundaries where the velocity and density of the adjoining rock layers have contrasting values. The combined contrast of the layer velocities and densities is called the impedance contrast. A controlled energy source is used to impart seismic energy into the ground and very sensitive receivers detect the sound as it is returned to the ground surface.

In our case study, the target of interest, the dikes, are composed of lamprophyre. The large density contrast between Paleozoic shale and the unweathered lamprophyre dikes suggests a strong potential for producing reflections. Furthermore, the heat produced by the intrusion is known to have altered the shale, increasing its velocity. However, unlike the sills found in the Omaha area, the dikes in the Harrisburg area are nearly vertical. This causes a difficulty in imaging the dikes using the seismic reflection technique, because layer interfaces greater than 45 degrees in angle can not be observed. The vertical dikes still may produce a detectable, though indirect, acoustic signal through changes and disruptions of the horizontal layers and diffractions induced by geometrical irregularities in the dike. The Dickey Ford Road Seismic Line (profile 29/3) traverses three linear magnetic anomalies interpreted as igneous dikes in the Willow Lake Block (Figure 2). The Coffee Road Seismic Line (profile 29/4) crosses one or two dikes known from previous mining operations (Figure 3).

In some cases, P-wave reflection seismic surveys can detect changes in shallow subsurface density conditions that are created by subsiding underground mine workings. Two different criteria can be used to detect the changes: 1) decrease in P-wave velocity, and 2) decrease in signal amplitude. However, the signal associated with these changes may not be sufficiently strong in all material types to be consistently reliable.

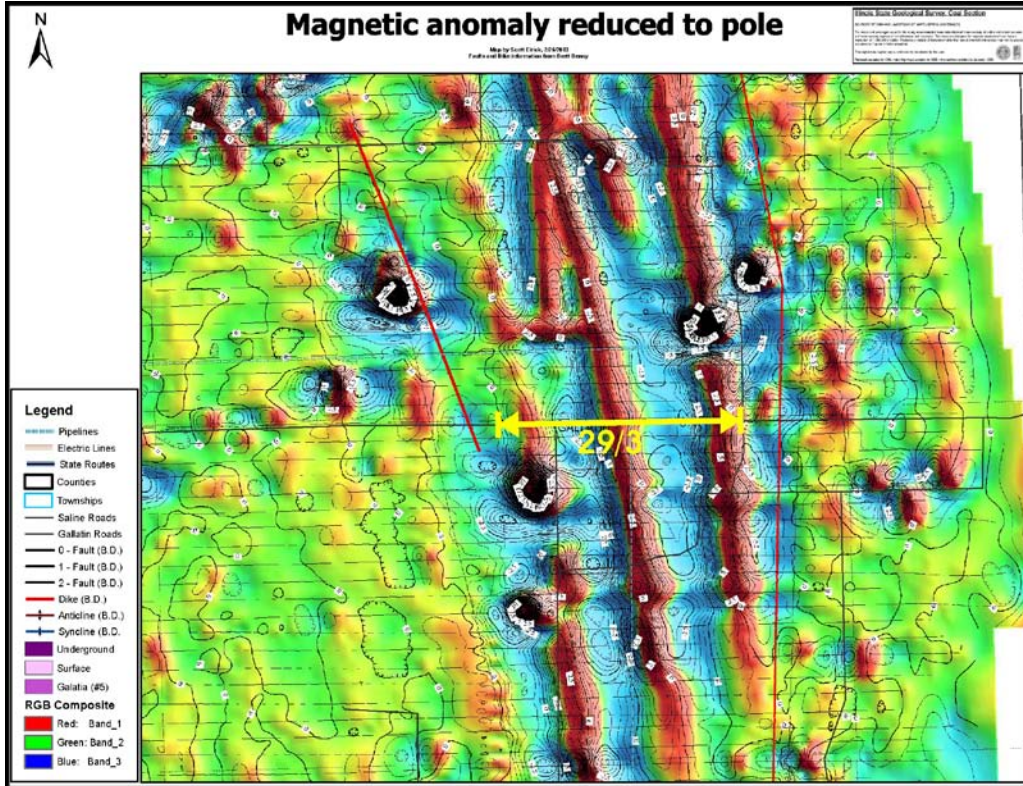


Figure 2. Location of Dickey Ford Road Seismic Line (line 29/3) in relation to magnetic anomaly map. Position within the study area is shown in Figure 1.

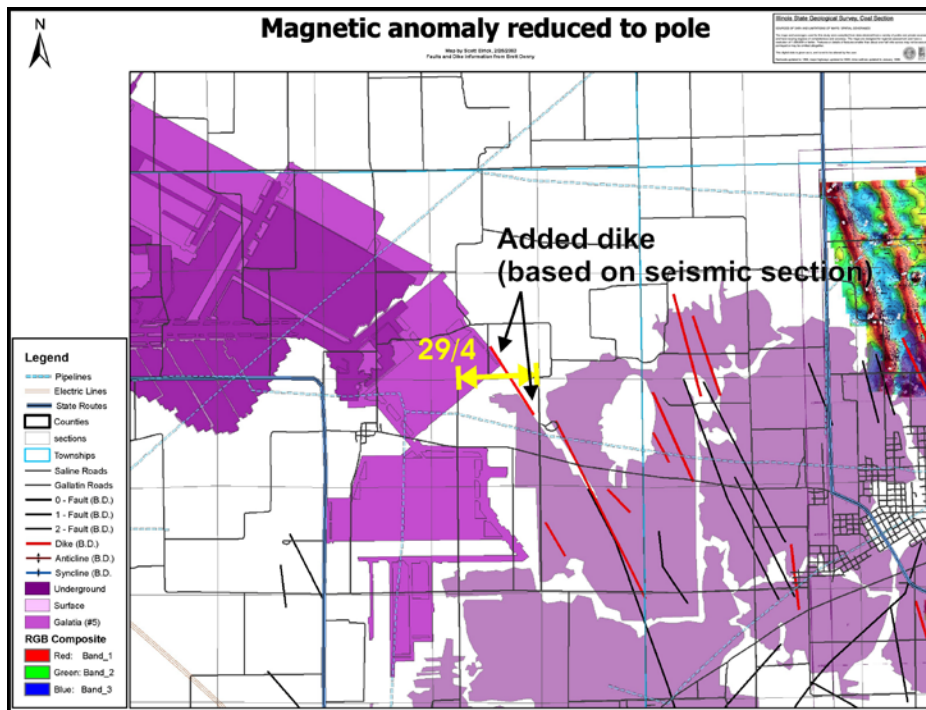


Figure 3. Location of Coffee Road Seismic Line (line 29/4) in relation to previously mapped dikes (red lines) and mined out areas (in purple). Position within study area is shown in Figure 1.

Theoretically, underground voids, such as room and pillar mine workings or collapsed mine workings, exhibit very strong impedance contrasts with surrounding rock and have good potential for being observed by the reflection method. Longwall mining operations do not leave voids, but areas of highly shattered and fractured rock above the mine panel have significantly reduced density. These areas should be observable by the reflection method. The impedance contrast of Quaternary sediments or weathered bedrock (both having low velocity and density) with unweathered bedrock (having high velocity and density) is also very strong. In practice, irregularities in the shallow sediments (thickness and material type) introduce strong distortions in the reflection images that may lead to erroneous interpretations of voids where none exist. Special attention has been given to the correction of this problem. The Coffee Road Seismic Line (profile 29/4) begins in a mined out area and continues into an unmined area (Figure 3). This line was designed to test whether the high resolution seismic method could distinguish longwall mined and unmined areas.

The presence of loess, wind-blown glacial silt, at the ground surface often decreases the frequency of the reflected compressive acoustic waves. In effect, this surface material produces a natural high-cut filter on the signal. This effect could diminish the resolution of the seismic data, but we did not observe this effect even with several feet of loess present in some parts of the profiles.

The reflection data on the two seismic lines were acquired with a 48-channel recording system. An accelerated weight drop created a seismic source at 10 ft intervals along the lines and the receivers were spaced at 10 ft intervals.

Acquisition tool	Multi-channel planted spiked phones
Recording channels	48
Roll along switch box	Geostuff, 96 input 48 output
Geophones/array	1
Nominal offset	10 ft
Receiver interval	10 ft
Geophone type	40 Hz
Shot interval	10 ft
Source	Accelerated weight drop, 100 lb, Digipulse.
Stack	1
Bin size	5 ft
Max. fold	24
Recording system	Geometrics Strataview
Sampling rate	0.25 ms
Record length	512 ms
Input filters	Low cut 35 Hz

Table 1. Acquisition parameters

Seismic reflection processing used PC-based software and, for the most part, followed standard processing protocols. Because of the severe shallow distortions, we applied our own routines for static correction analysis and modeling (operations 3, 4 and 8 in Table 2; for further information see Pugin and Pullan (2000)). This near-surface correction process involves a very careful measurement of the initial arrival of the seismic signal (the first break) at each of the 48 channels in each shot record. Part of the processing was done in true amplitude mode to reduce distortions of the signal amplitude. For this part, automatic gain control was not applied and the gain is compensated for the muted parts of the CMP records. The true-amplitude display reveals the large decrease in signal amplitude caused by decreased density in the mined-out areas. For more information on the technique see Pugin (2002).

1. Format conversion SEG2 to KGS
2. Geometry editing
3. First-break picking
4. First-break modeling for static corrections
5. Band-pass filter 80, 110, 300 350 Hz
6. CMP sort
7. Residual ground-roll and guided-wave mute
8. Application of refraction-based static corrections
9. Velocity analysis
10. Normal move-out
32 ms - 5500 ft/s; 52 ms - 7000 ft/s; 72 ms - 8500 ft/s
11. Stretch mute
12. AGC scaling, 220 ms (not applied for true amplitude section)
13. Stack
14. Plot of the section
15. Migration
16. Fold balancing (on true amplitude section only)
17. Depth conversion (2350 m/s)
18. Plot of the section

Table 2. Processing parameters

RESULTS AND DISCUSSION

Results of High Resolution Aeromagnetic Surveys

Residual magnetic anomalies in Area A are shown in Figure 4. The many small, circular anomalies are caused by buildings. A curvilinear anomaly on the western edge of the area is a residual effect of sources associated with a curving highway. The most prominent remaining linear residual anomaly is a north-northwest trending anomaly in the center of the area (Figure 4). This large-amplitude anomaly is probably caused by a shallow dike. Just west of this linear anomaly is a second linear anomaly that is smaller in amplitude. However, this anomaly has been confirmed as being caused by a 10 ft wide dike in a mine (R. Jacobson, oral communication, 2003). Two smaller linear anomalies which occur further west in the area also may be caused by igneous dikes.

Residual magnetic anomalies in Area B are shown in Figure 5. An east-northeast series of large-amplitude circular anomalies in the southeast part of this area is probably caused by a buried pipeline. No other prominent linear residual anomalies are present in this area. A small amplitude, north-northwest trending anomaly in the western part of the area may be caused by a small dike. This tentative interpretation is highly uncertain.

The large Willow Lake Block (Figure 6) is east of Eldorado and includes areas that contain mapped igneous dikes (Nelson and Krausse, 1981). Hildenbrand and Ravat (1997) included a portion of this area in their earlier high resolution magnetic study. Two major oil fields and many other oil wells produce clusters of circular anomalies on this map. Despite this clutter, large amplitude linear anomalies are clearly present that are either directly in line with, or coincide with, previously mapped dikes. The actual coincidence is probably closer than that shown on Figure 6. Continuations of these anomalies are interpreted as other dikes. Anomalies in the southwest part of the Willow Lake Block appear to radiate from a central point which Hildenbrand and Ravat (1997) tentatively identified as a small magnetic plug or dome similar to the one at Omaha. Adding to the complexity of the anomalies in this area are some which are caused by metal structures in underground mines (written communication, M. Silverman, 2003) that happen to be coincident with this igneous intrusion. Even after accounting for the mine-related anomalies, several linear anomalies probably related to dikes remain. These anomalies generally have a northwest trend, similar to the other dikes in the area. The large north to northwest trending linear anomaly in the southeast part of the Willow Lake area is caused by the Cottage Grove Dike (Paggett et al., 2002; Denny et al., 2002), a 30-foot wide lamprophyre dike encountered in surface mining. Several smaller anomalies are parallel to the main anomaly, suggesting several other narrow or deeper dikes. These dikes can be traced northward through the entire Willow Lake area. Presumably, these dikes are directly related to the Omaha dome igneous sills (English and Grogan, 1948; Sparlin and Lewis, 1994). The Dickey Ford Road Seismic Line crosses the axis of these parallel anomalies.

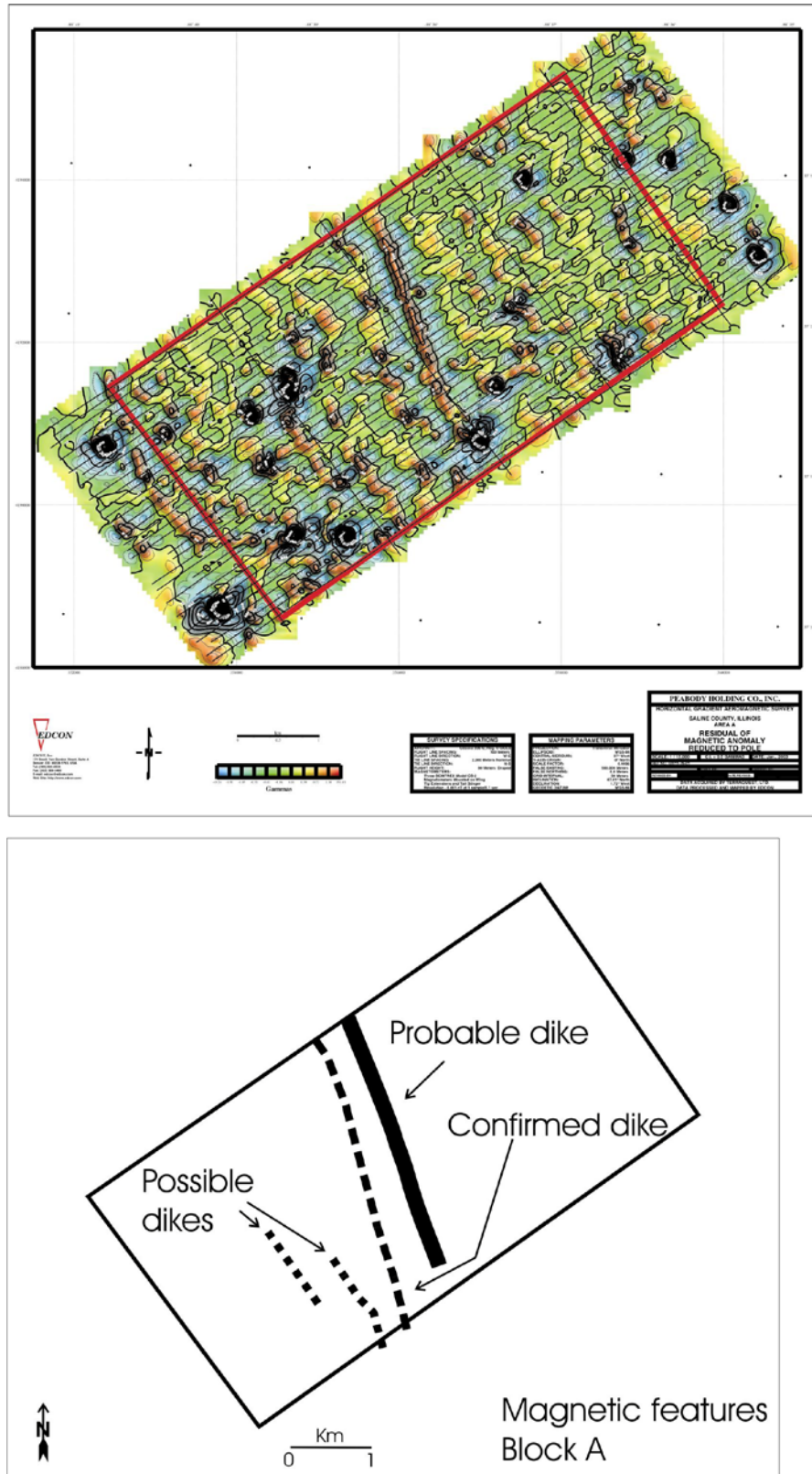


Figure 4. (a) Reduced-to-pole residual magnetic anomaly map of Area A. (b) Interpreted igneous dikes in Area A.

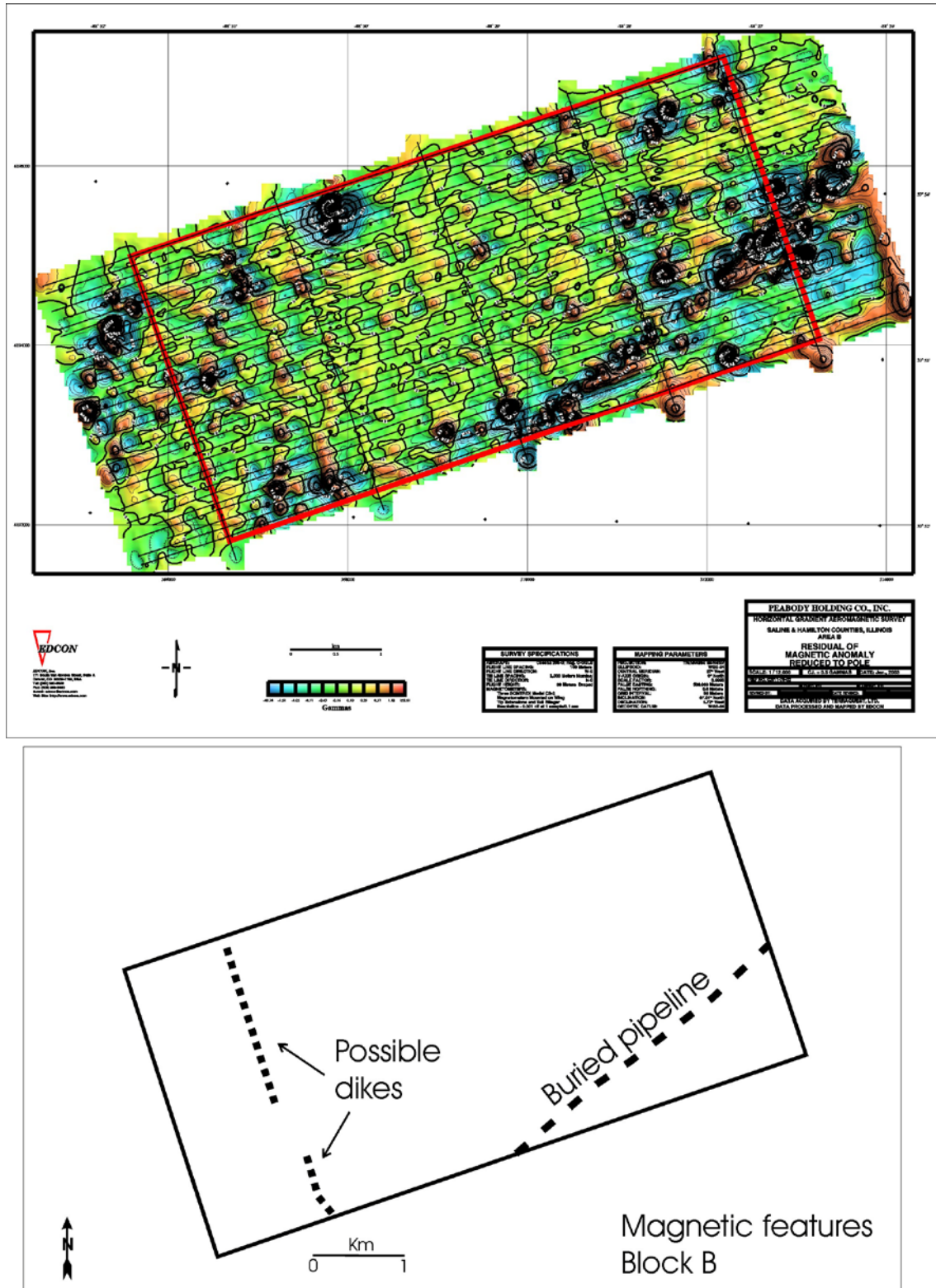


Figure 5. (a) Reduced-to-pole residual magnetic anomaly map of Area B. (b) Interpreted magnetic features in Area B.

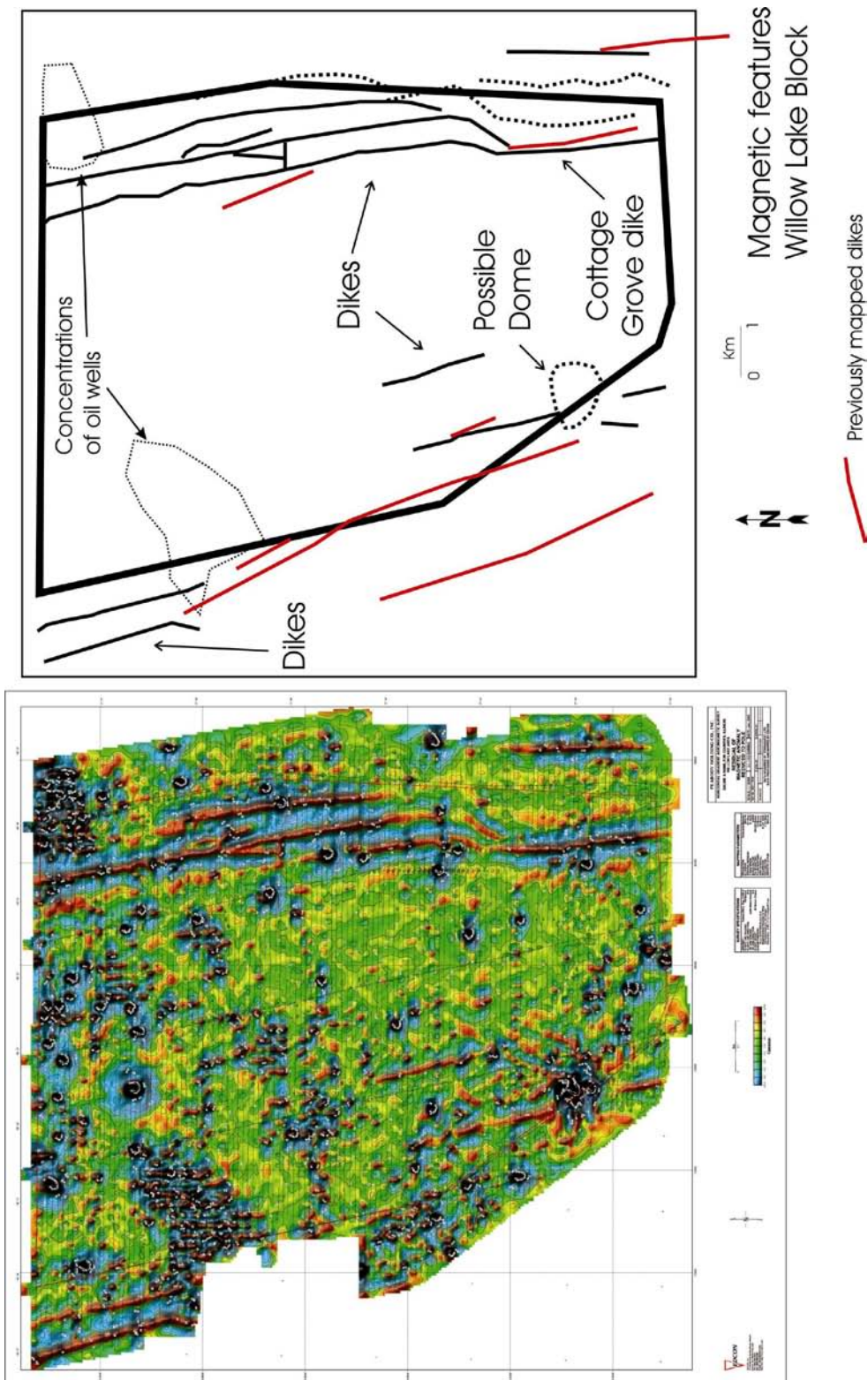


Figure 6. (a) Reduced-to-pole residual magnetic anomaly map of Willow Lake Block. (b) Interpreted magnetic features in Willow Lake Block. Actual coincidence of magnetic anomalies and previously mapped dikes is closer than shown on this figure.

Results of High Resolution Seismic Profiling

The processed seismic profiles acquired in this study are shown in Figure 7 (Dickey Ford Road Line, profile 29/3) and Figure 8 (Coffee Road Line, profile 29/4). These two profiles illustrate different aspects of this test survey. The Dickey Ford Road Line provides a good example of stratigraphic imaging while also imaging several igneous dikes. The Coffee Road Line traverses both mined-out and unmined areas and images one or two igneous dikes.

The Dickey Ford Road seismic section (Figure 7) displays good penetration of sound waves with a broad-band frequency spectrum in the bedrock. Even with a simple processing sequence using only an automatic gain control and a band pass filter to enhance the signal, the upper part of the section shows remarkably continuous phases, however the resolution is diminished by a ringing effect which is produced by reverberations occurring in the shallow weathered zone. This reverberation can be removed by using a deconvolution digital filter (Figure 7, second section). The effect of this tool is to increase the resolution for stratigraphic observations, with the side-effect of increasing the background noise in the section. With an average frequency spectrum of 180 Hz and a P-wave velocity of 2800 m/s the theoretical resolution (1/4 of wavelength) is approximately 4 m (12 ft). This operation demonstrates the potential of the method for detailed analysis of coal bed stratigraphy, using borehole calibration, similar to that conducted by Henson and Sexton (1991). Due to the high noise level, deconvolution processing was not applied for structural analysis such as dike observation. On this section three major reflections are visible at depths of 60 m, 100 m and 150 m. We are not able to confidently assign these reflectors to stratigraphic horizons without a calibration borehole and an associated Vertical Seismic Profile (VSP). A downward curved reflection may be associated with a channel feature at a depth of 120 m, at the distance coordinate 600 m – 1200 m.

Vertical dikes can be observed in both the Dickey Ford Road Line (Figure 7, dikes 1 to 3) and the Coffee Road Line (Figure 8, dikes 4 and 5). These features have multiple characteristics. Dike 3 clearly shows diffraction patterns. Dikes 1, 3, 4 and 5 are observed through a lateral change of phase over a short length with either a chaotic or a ringing wave pattern. This is especially observable with dikes 4 and 5 in the paraphase display in Figure 8. Dikes 1, 3 and 4 are associated with vertical fault displacements on both sides of the dikes. A synclinal fold with amplitude of about 15 m can be observed between dikes 2 and 3. The presence of dike 2 is obvious in the magnetic anomaly map (Figures 2 and 6) but is not as obvious in the seismic data. This dike may be too narrow to be clearly identified by the seismic method. The dikes appear to be wider on the seismic sections than they actually are. The heat produced during intrusion altered the sedimentary rock, creating a wider zone of impedance contrasts (velocity, density variations) and producing a reflective zone wider than the dike itself. Diffraction energy may also contribute to an increase in the width of the dike zone on the seismic sections.

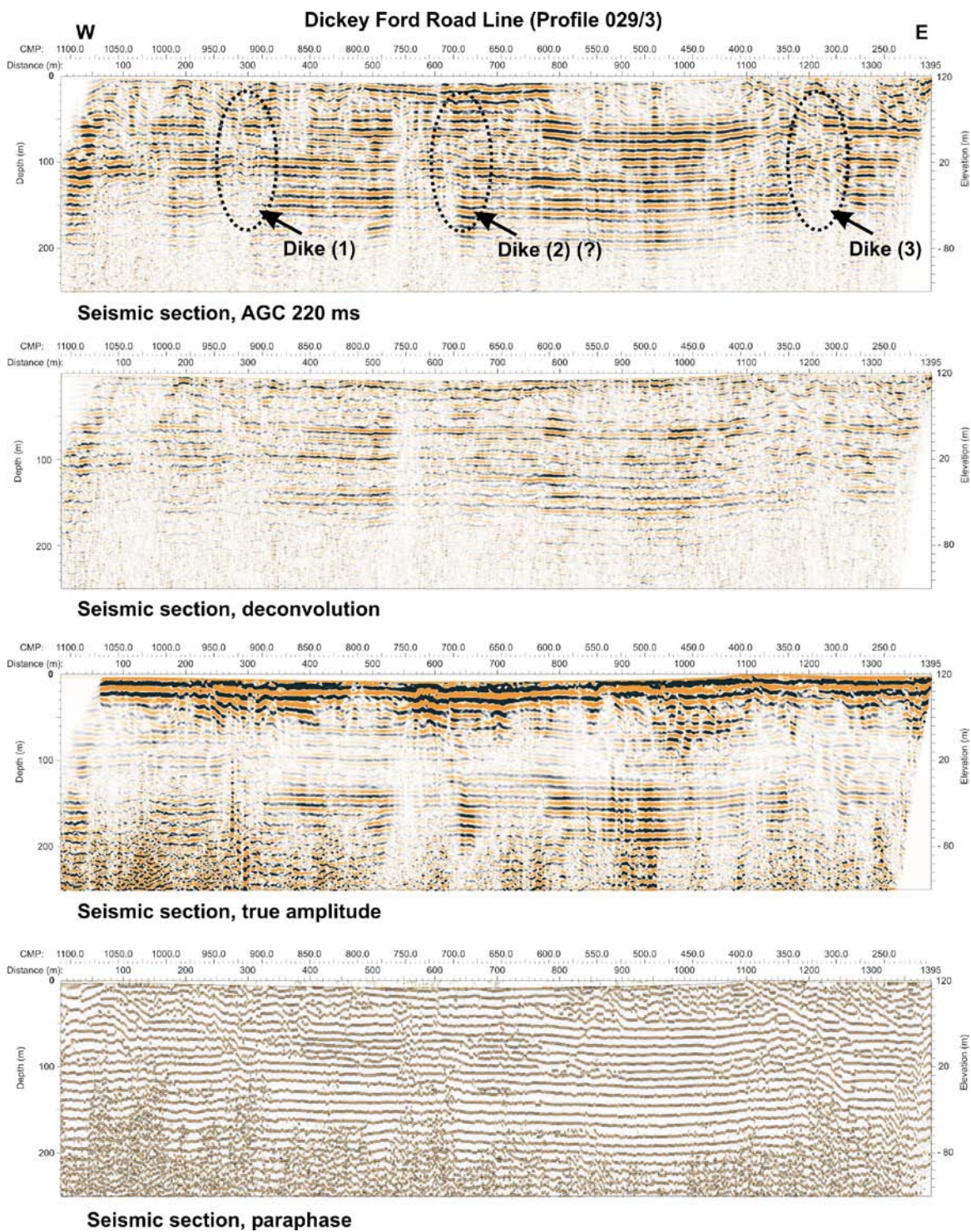


Figure 7. Results of the Dickey Ford Road Seismic Line (profile 29/3). The high-resolution seismic reflection profile traverses three dikes interpreted from the magnetic data (Figures 2 and 6). Location of the section is shown on Figure 1. See text for explanation of the four panels.

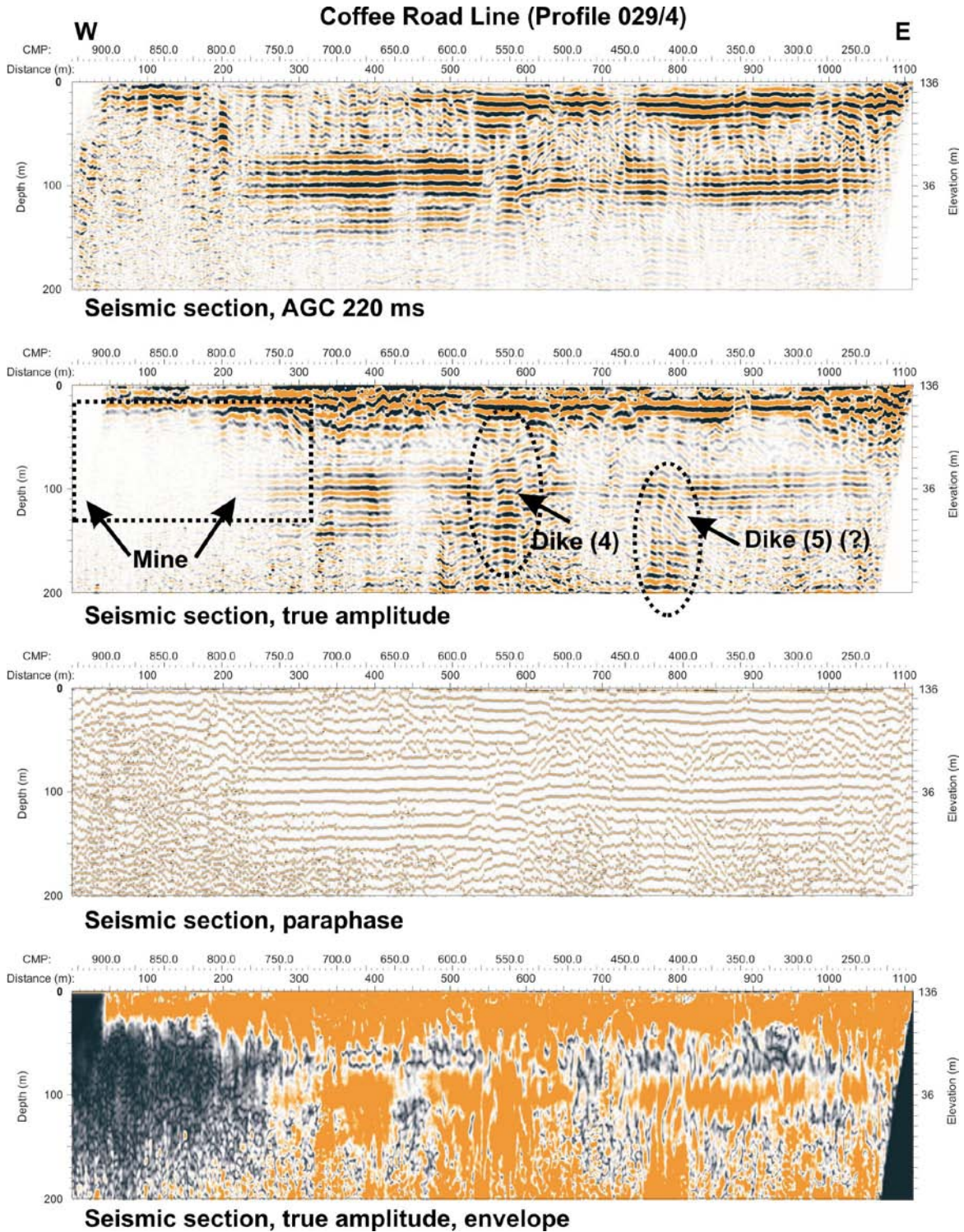


Figure 8. Coffee Road high-resolution seismic reflection profile (29/4). The profile crosses a mined out area and one or dikes. Location of the section is shown on Figure 1. Explanation of the four panels is given in text.

The Coffee Road seismic line (profile 29/4, Figure 8) was designed to acquire data in a mined-out area. If we apply the widely used processing gain enhancement called Automatic Gain Control (AGC), the section looks like the top panel of Figure 8. The amplitudes of the waves are homogenized by the AGC, minimizing the effect of the mined-out section. Although this homogenizing effect may be useful for stratigraphic imaging, it destroys important components of the signal that is caused by the density effects related to the mined-out areas. The reflected signal amplitude is proportional to the density changes occurring underground, so we want to preserve these differences, not eliminate them. For this reason, processing techniques employing AGC should be avoided. Instead, processing routines using true amplitude (Pugin, 2002) preserve the amplitude variations in the section. The result, shown in the second panel of Figure 8, images the decreased densities above the mined-out area as sharply decreased amplitudes.

According to existing mine maps, the first (western-most) 300 m of the seismic section traverses an area mined with the longwall method. It produces a “blank-out” or severe reduction in amplitude of the reflection signal. This effect is apparent in the true amplitude representation of the data, but is not as apparent when standard AGC techniques are used for processing. The blanked-out area is total over the first 200 m of the section, with a 100-m wide transition zone leading to a normal layered stratigraphy which is present in the rest of the section. This reduction in seismic amplitude is probably a function of the longwall mining method. Instead of creating actual cavities, as in room-and-pillar mining, the technique purposely causes the roof and surrounding rock to collapse. As a result, the zone of fractured rock surrounding the mine has significantly lower density and seismic velocity (Van Roosendaal et al., 1997). The fracturing may be so intense that coherent reflections are not observable. Furthermore, methane gas and air introduced during the mining operation may absorb some of the acoustic energy.

CONCLUSIONS

High resolution aeromagnetic techniques are ideally suited for mapping the altered lamprophyre dikes in this study area. The high percentage of magnetite in these altered igneous rocks produces a very large magnetic signature that is evident even within the noise of cultural magnetic sources such as buildings, oil wells and power lines. The complex patterns of the dikes would not be easily mapped using drill holes alone, but can be traced over many miles using simple qualitative visual methods. Simple processing procedures such as reduction-to-pole and regional removal are adequate for locating the sources. Quantitative modeling procedures could provide more detailed estimates of depth and thickness.

Using high resolution seismic reflection techniques we have demonstrated that it is possible to resolve layers as thin as 4 m (12 ft). Primary sedimentary features such as sandstone channels can be observed. Thin igneous dikes are sometimes difficult to observe with the reflection technique, but the thicker ones are characterized by diffractions and lateral phase changes. These same igneous dikes are apparent in the aeromagnetic maps, and the seismic reflection surveys provide higher precision in imaging them in multiple dimensions.

Areas mined with the longwall method can be observed through amplitude absorption using a true-amplitude data processing scheme. The mined-out areas appear as “blacked out” zones with severely reduced seismic amplitude. This reduction in amplitude is likely caused by absorption of the seismic energy by gas migrating in the intensely fractured rock in and above the collapsed longwall panels. Further testing would be required to fully demonstrate the procedure for different conditions (flooded, collapsed, etc) of abandoned room and pillar mines. Based on these tests, we recommend that when using the seismic reflection technique to image mined-out areas or igneous dikes, a seismic acquisition system with a minimum of 48 channels should be used and geophones and shots should be spaced at a maximum of 3 m (10 ft).

ACKNOWLEDGEMENTS AND DISCLAIMERS

Scott Elrick, Chris Korose, Blair Tormey, and Steven Sargent of the ISGS contributed to the seismic field operation. Russ Jacobson and Brett Denny provided constructive reviews of preliminary drafts of portions of this manuscript.

This report was prepared by Timothy Larson and Andre Pugin, Illinois State Geological Survey with support, in part by grants made possible by the Illinois Department of Commerce and Community Affairs through the Office of Coal Development and the Illinois Clean Coal Institute. Neither Timothy Larson, Andre Pugin, the Illinois State Geological Survey nor any of its subcontractors nor the Illinois Department of Commerce and Community Affairs, Office of Coal Development, the Illinois Clean Coal Institute, nor any person acting on behalf of either:

- (A) Makes any warranty of representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights; or
- (B) Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring; nor do the views and opinions of authors expressed herein necessarily state or reflect those of the Illinois Department of Commerce and Community Affairs, Office of Coal Development, or the Illinois Clean Coal Institute.

Notice to Journalists and Publishers: If you borrow information from any part of this report, you must include a statement about the State of Illinois’ support of the project.

REFERENCES

- Bain, H. F., 1905. *The fluor spar deposits of southern Illinois*: U. S. Geological Survey Bulletin 255, 70 p.
- Baranov, V., and Naudy, H. 1964, Numerical calculations of the formula of reduction to the magnetic pole: *Geophysics* 29: 67-79.
- Bristol, H. M., and J. D. Treworgy, 1979. *The Wabash Valley Fault System in Southeastern Illinois*: Illinois State Geological Survey Circular 509, 19 p.
- Cady, G. H., 1919. *Coal Resources of District V (Saline and Gallatin Counties)*: Illinois State Geological Survey Coal Mining Investigations Bulletin 19, 135 p.
- Cady, G. H., H. A. Lowenstam, H. L. Smith, M. W. Pullen, M. B. Rolley, and R. Siever, 1951. *Subsurface Geology and Coal Resources of the Pennsylvanian System in Certain Counties of the Illinois Basin*: Illinois State Geological Survey Report of Investigation 148, 123 p.
- Clegg, K. E., and J. C. Bradbury, 1956. *Igneous Intrusive Rocks in Illinois and their Economic Significance*: Illinois State Geological Survey Report of Investigation 197, 19 p.
- Denny, F. B., R. H. Fifarek, R. N. Guillemette, and P. L. Padgett, 2002. Petrographic and microprobe analysis of the Cottage Grove Dike (Saline County, Illinois). *Geol. Soc. Am. Abstracts with programs*. 34(2): A92-93.
- Dobrin, M. B. and C. H. Savit. 1988. *Introduction to Geophysical Prospecting, Fourth edition*: McGraw-Hill, New York, 867 p.
- English, R. M and R. M. Grogan, 1948. Omaha Pool and Mica-Peridotite Intrusives, Gallatin County, Illinois: Illinois State Geological Survey Report of Investigation 130, 24 p.
- Fifarek, R. H., F. B. Denny, L. W. Snee, and D. P. Miggins, 2001. Permian igneous activity in southeastern Illinois and western Kentucky: implications for tectonism and economic resources. *Geol. Soc. Am. Abstracts with programs*, 33(6): A420.
- Frye, J. C., A. B. Leonard, H. B. Willman, and H. D. Glass, 1972. Geology and Paleontology of Late Pleistocene Lake Saline, Southeastern Illinois: Illinois State Geological Survey Circular 471, 44 p.
- Hansel, A. K., and W. H. Johnson, 1996. Wedron and Mason Groups: Lithostratigraphic Reclassification of Deposits of the Wisconsin Episode, Lake Michigan Lobe Area: Illinois State Geological Survey Bulletin 104, 116 p.

- Hensen, Jr., H. and J. L. Sexton, 1991. Premine study of shallow coal seams using high-resolution seismic reflection methods. *Geophysics* 56: 1494-1503.
- Hildenbrand, T. G., and D. Ravat, 1997. Geophysical setting of the Wabash Valley Fault System. *Seis. Res. Let.* 68(4): p 567-585.
- Hopkins, M. E., 1968. Harrisburg (No. 5) Coal Reserves of Southeastern Illinois: Illinois State Geological Survey Circular 431, 25 p.
- Kucks, R. P., 1990. Aeromagnetic anomaly map of the Paducah 1 degree by 2 degree quadrangle, Missouri, Illinois, and Kentucky: U.S. Geological Survey Miscellaneous Field Studies Map MF-2121.
- Padgett, P. L., D. Pilcher, P. R. Ames, J. R. Staub, and F. B. Denny, 2002. Igneous intrusions associated with the Cottage Grove Fault System in southern Illinois: their effects on mine planning: *Geol. Soc. Am. Abstracts with programs*, 34(2): A-103.
- Pugin, A. and S.E. Pullan, 2000. First-Arrival alignment static corrections applied to shallow seismic reflection data. *J. Env. Eng. Geophys.* 5(1):. 7-15.
- Pugin, A. J. M., 2002. Fold balancing to preserve amplitude of land-based shallow seismic reflection: Proceedings of SAGEEP February 10-14, 2002 Las Vegas, Nevada, CD-ROM edition.
- Pullen, M. W., 1951. Gallatin County in Cady, G. H., H. A. Lowenstam, H. L. Smith, M. W. Pullen, M. B. Rolley, and R. Siever, 1951. Subsurface Geology and Coal Resources of the Pennsylvanian System in Certain Counties of the Illinois Basin: Illinois State Geological Survey Report of Investigation 148, 123 p.
- Nelson, W. J., and H.-F. Krausse, 1981. The Cottage Grove Fault System in Southern Illinois: Illinois State Geological Survey Circular 522, 65 p.
- Nelson, W. J., and D. K. Lumm, 1987. Structural Geology of Southeastern Illinois and Vicinity: Illinois State Geological Survey Circular C 538, 70 p.
- Nelson, W. J., 1995. Structural Features in Illinois: Illinois State Geological Survey Bulletin 100, 144 p.
- Sparlin, M. A., and R. D. Lewis, 1994. Interpretation of the magnetic anomaly over the Omaha Oil Field, Gallatin County, Illinois. *Geophysics* 59: 1092-1099.
- Van Roosendaal, D. J., B. B. Mehnert, N. Kawamura, and P. J. DeMaris, 1997. Final Report of Subsidence Investigations at the Galatia Site, Saline County, Illinois: Illinois Mine Subsidence Research Program XI, 59 p.

Willman, H. B., and J. C. Frye, 1970. Pleistocene Stratigraphy of Illinois: Illinois State Geological Survey Bulletin 94, 204 p.