High-Resolution Seismic Reflection to Delineate Structures at the Northern Extreme of the Nemaha Ridge/Humboldt Fault in East-Central Nebraska

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Executive Summary

High-resolution seismic-reflection data allowed delineation of complex structural features associated with multiple episodes of faulting, uplift, and erosion beneath the Lyman-Richey Sand and Gravel Plant #8 located at the northern extreme of the Nemaha Ridge and Humboldt fault system in east-central Nebraska immediately north of Plattsmouth, Nebraska, in Cass County. The three 2-D seismic profiles that comprise this study imaged the features responsible for a 400+ ft (125+ m) discrepancy in the interpreted top of the Mississippian in two boreholes located less than three-quarters of a kilometer apart (Figure 1). A relatively narrow uplift feature, bounded by a large zone of faulting on the west and a series of normal fault blocks stepping down to the east, defines a more than 1625-ft- (500-m)-wide structurally altered area clearly responsible for the vastly different rocks retrieved from the two coreholes.

This generally north/south-trending, complex structural zone, regionally consistent with the northern extreme of the Nemaha Ridge/Humboldt fault system and strike change in the Midcontinent Geophysical Anomaly (MGA) can be seismically correlated from the southern boundary of the Lyman-Richey Plant, across the Platte River to La Platte Road. For the seismic data to correlate across the Platte River, a major right-lateral strike-slip (wrench) fault with a strike approximately parallel to the three seismic profiles and a slip component of approximately 1 km must be present between line 2 (northern boundary) and line 3 (La Platte Road). Considering the geologic setting and structural complexity of both the basement and overlying Paleozoic rocks in this area, a strike-slip fault is consistent with the subsurface data and provides a reasonable explanation for the regionally unique meander pattern of the

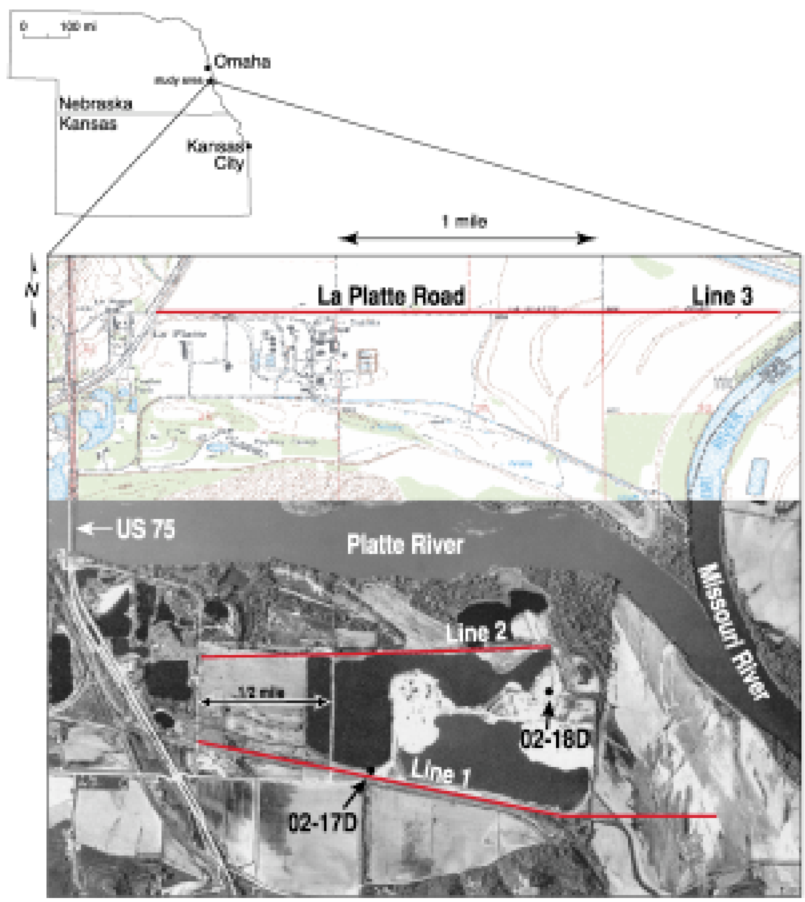

Figure 1. Site map with proposed lines along the north and south property boundaries of the Lyman-Richey Plant #8.

modern Platte River valley. Confidence in the location of and displacement along this strike-slip fault is based on the interpretation of a locally northwest-plunging anticline clearly evident on all three seismic lines. Extrapolating the hinge of the fold north-northwest along its strike, the only possible structural geometry that fits the current orientation and location of this anticline requires approximately 1 km of right-lateral movement between lines 2 and 3. With the plunging nature of the anticline, it is not possible to confidently distinguish if and how much dip-slip component exists and, therefore, none is interpreted along this fault plane.

From basement and lower Paleozoic studies of eastern Nebraska, general trends in faulting and basement lithology appear to be predominantly northeasterly (Carlson, 1967; Lidiak, 1972). Immediately south and west of this site (a distance of less than a few kilometers), major changes in both basement composition and density of structural features have been interpreted from well and regional geophysical studies. Faults and folds interpreted on seismic data from this study—and inferred from line-to-line correlations—which at first glance strike north to north-west, appear to be somewhat contradictory to documented regional trends. However, this apparent discrepancy is easily explained by placing a right-lateral wrench fault beneath the Platte River valley, thereby providing a stress/strain environment that supports localized block rotation and is consistent with the seismically-defined strike of the anticline.

Structures associated with the uplift as interpreted on these seismic data are consistent with those seen on similar studies associated with the Nemaha Ridge further south in Kansas. Large offset and rotated blocks controlled by relatively small displacement, normal faults make up zones accounting for as much as 400 ft (150 m) of uplift at this site. Unfortunately the two southern lines (1 and 2) did not extend east far enough to image rocks that have not been altered in some way by this uplift feature and therefore it is not possible to confidently determine the overall dimensions of the anticline. Borehole 02-18D was drilled directly into an area with an abbreviated or possibly missing Mississippian section. Correlating rocks encountered in 02-18D with 02-17D is complicated and may not be possible for the entire section due to the complexity of the structures each appears to be sampling. An apparent relationship (possibly correlation) between minor faults interpreted on the west flank of the anticline is strong evidence supporting longitudinal faulting. This interpretation is consistent with those made by researchers studying features associated with the Nemaha Ridge in Kansas (Berendsen and Blair, 1995; Gay, 1999).

Considering the highly altered nature of the subsurface in this area, correlating geology observed in boreholes to reflections on seismic lines is done only in a very general way. A combination of data quality and highly variable reflection geometries observed on seismic data permit only general correlations of borehole interpretations from 02-17D to seismic line 1. The generalized geology from 02-17D is the basis for reflection-to-reflector matching on these seismic data. With borehole 02-18D located in an area defined by large normal fault blocks and offset off-line more than 200 m from line 2, it is not reasonable to attempt matching reflections on line 2 with potential reflectors identified in 02-18D. To our knowledge, borehole interpretations to date have not clearly determined whether the boring 02-18D encountered any Mississippian rocks at all. It is possible that no Mississippian rocks were penetrated at all and that the Devonian might be unconformably in contact with the Pennsylvanian. With enhanced analysis of these two cores, it will be possible to provide a more conclusive interpretation of the rock types observed on the seismic data.

Associated with the major features interpreted and inferred from the seismic sections are line-specific structures difficult to confidently correlate from line to line. While they are not particularly significant to the overall geology of this area, they would be devastating to underground mining activities. Small offset (<10 m) faults and folds with only minor curvatures (changes in layer elevation of 10 or so ft [a few meters] over distances of 325 ft [100 m]) interpreted on the flanks of the anticline have little or no effect on the overall quality or quantity of minable limestone but they do represent major obstacles to the mining process. Several normal faults, generally bounding minor folds, are evident within the trough on the western flank of the anticline. Borehole 02-17D penetrates a competent, thick Mississippian limestone section within this zone of folds and faults on the western flank. Therefore, the rock analysis is good, but volumetrically, mining from this point to near the western property boundary would be problematic due to abrupt lateral variations in rock elevations and possibly water associated with faults and folds.

An unusual and somewhat troubling drop in signal-to-noise ratio spanning about a half-kilometer dominates the western end of line 3. There seems to be two possible explanations for this feature: it is either a major basement structure, which could be interpreted as either an uplift (ridge) or major fault zone (reflections have been correlated across the feature, but with the limited amount of high-quality data on the western end of the seismic profile it is not possible to say those correlations are made with high confidence), or alternately this extreme drop in signal-to-noise ratio could be related to an area of high seismic-energy attenuation associated with a recent river meander that has silted full, or simply changes in the near-surface soils. This feature is not observed on either line south of the river, but it could be a portion of the Midcontinent Rift suggested to be following US 75 highway, offset to the east by the Platte River fault. It is possible this chaotic zone is the Humboldt fault previously mapped several kilometers west of this site (Carlson, 1967; Lidiak, 1972). Considering how high up in the section the data appears disturbed by this feature, if it is tectonic in origin then it was active well into the Late Pennsylvanian and seismic data provides no evidence to suggest it has not been active in the Quaternary.

Minability of Mississippian limestones in this area is likely greatest north and northeast of La Platte Road and east of the Lyman-Richey Plant #8 property line. Assuming rock quality, from a mining perspective, is relatively consistent in this general area (~10 km_), the seismic data suggest acceptable layer thicknesses and lateral continuity exist along the western and northwestern property boundaries of the Lyman-Richey Plant and to a greater extent north of La Platte Road. Based on the seismic data and what is assumed to be understood about the geology, if the uplift feature interpreted on line 3 has a strike and plunge consistent with interpretations of lines 1 and 2, then several square kilometers of good, minable rock is likely present immediately north and east of line 3 and along the eastern extreme of line 3. Any underground mining beneath the Lyman-Richey plant would need to concentrate at the far western end of the property or under the extreme east boundary and into the Schilling State Wildlife Area. It is not known how far west or east the very uniform, undisturbed Mississippian section extends beyond the property boundaries. If the chaotic zone interpreted on the western end of line 3 has been offset in a fashion similar to the anticline, then it is likely this same chaotic data area will be encountered less than a half-kilometer west of the western property boundary.

The primary goal of this study was to map the uppermost Mississippian limestone and the basal Pennsylvanian contact. Detailed mapping of this contact was critical for a reasonable description of the feature and determination of the most likely structural process that produced the feature responsible for the apparent inconsistency between coreholes 02-17D and 02-18D. Of secondary interest was the delineation of any thin chert, quartz, and shale stringers that might be present within the massive (over 10-ft-thick) Mississippian limestone encountered in hole 02-17D around 650 ft (200 m) below the ground surface. With the MGA—also called the Midcontinent Rift—and the Humboldt fault immediately west of the study area, and the northern edge of the Nemaha Ridge immediately south of the study area, extreme structural and depositional features were known to be locally possible. The primary objective was accomplished and, considering the complexity and short wavelength nature of the structures and associated movement, the geologic setting of this ~6 mile^2 (~10 km_) study area is, in general, reasonably well described and consistent with all drilling and published literature. Unfortunately, the data quality was not sufficient to tackle the secondary objective: delineating stringers of chert, quartz, and shale within the Mississippian limestone of interest.

As proposed the project consisted of a testing and production phase. The testing phase required an initial trip to evaluate the effectiveness of impulsive sources along a portion of the southern property boundary suspected to possess average near-surface conditions. Based on that testing, the acquisition equipment and field design were modified to include an IVI minivib. A third line was added north of the Platte River after preliminary analysis of the two originally proposed lines showed a major structure beneath the Lyman-Richey property. Data processing concluded with the production of CMP stacked sections representative of an earth cross section. Interpretations focused on a strong reflecting event located at a time-depth approximately equivalent to the expected base of the massive Mississippian limestone targeted by this study.

Seismic images and the resulting geologic interpretations of those seismic images are optimized for the interval between the base of the Mississippian limestone of interest and the lower several hundred feet (hundred or so meters) of the Pennsylvanian section in this area. This optimization required a high degree of confidence correlating the high-resolution reflection data and existing ground truth (borings 02-17D and 02-18D).

Introduction

As locally available outcrops of high-quality limestone suitable for construction aggregate become harder to come by, development of underground resources may become the only way to continue supplying sufficient raw material for Omaha and the state of Nebraska. An alternative to expensive underground mining requires transporting cheaper-to-extract bulk product from distant surface mines. Transportation costs for raw materials could easily exceed economically viable limits. In searching for future raw material, exploratory drilling beneath the Lyman-Richey Sand and Gravel Plant #8 unearthed an unexpected and dramatic inconsistency in rock recovered from two coreholes physically separated by less than 1 km (Figure 1). A difference of more than 325 ft (100 m) in the top of a massive (250-ft [60-m]-thick) Mississippian limestone unit was observed in core retrieved from these two holes. This 650-ft (200-m)-deep Mississippian limestone was classified as an excellent potential source of raw material. Using all available data, explorationists were not able to settle on an explanation for this discrepancy. High-resolution seismic reflection was determined to be the most practical approach and possess the greatest potential to unravel this subsurface geologic puzzle.

This seismic-reflection study focused on 1) applying minimal to noninvasive, high-resolution seismic techniques in this alluvial near-surface setting, 2) maximizing the resolution potential (both horizontal and vertical) in this potentially complex structural setting, 3) optimizing source and acquisition geometries for resolution and survey economics, 4) correlating seismic data with borehole data, 5) delineating intra-limestone beds as thin as a few feet at over 700 ft (215 m) below ground surface, 6) determining the 3-D geometry of the feature responsible for the discontinuity between the two coreholes on the Lyman-Richey Plant #8, and 7) establishing analogies and possible chronologies as they relate to structures observed on seismic profiles studying faulting near the Nemaha Ridge in north-central Kansas.

Initially two lines were proposed (lines 1 and 2) running parallel to the north and south property lines (Figure 1). After data along those lines were acquired and preliminary processing completed, it became clear that the geologic feature responsible for borehole inconsistencies was large, complex, and underlaid most of the sand-plant property. Initial interpretations suggested this feature consisted of a major uplift block and multiple bounding faults along both flanks of the uplift. This scenario is not conducive to the operation of an underground mine. A third line was then proposed to investigate the subsurface immediately north of the Platte River in hopes these structures were localized and an area more conducive to underground mining might be found not too far from core hole 02-17D where high-quality resource was known to exist.

Geologic and Geophysical Setting

The study area lies immediately north of the Nemaha uplift (Ridge) and within an area that has been strongly influenced by the tectonic activity associated with the Precambrian Mid-continent Rift System (MGA) (Steeples, 1995) (Figure 2). The Nemaha Ridge is a buried granite mountain range that formed about 300 million years ago near the end of the Mississippian and beginning of the Pennsylvanian. From subsurface data alone, it is

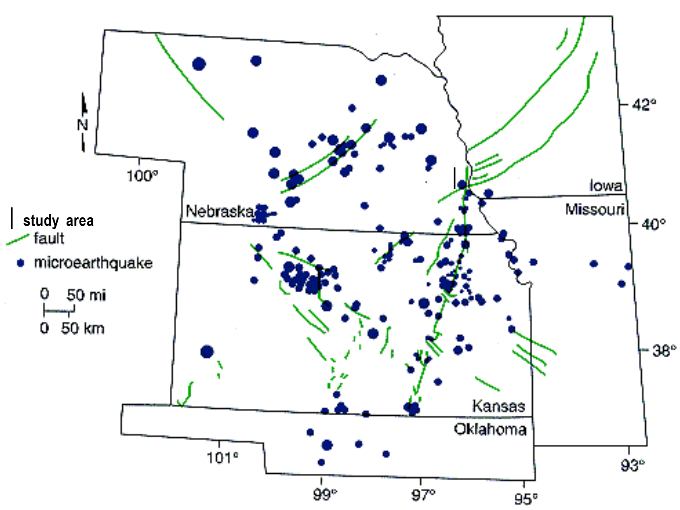

Figure 2. Microearthquakes recorded by the Kansas Geological Survey between August 1977 and August 1989 are size-coded by local magnitude. The largest event had a magnitude of 4.0 and the smallest had a magnitude of 0.8 on the Richter Scale.

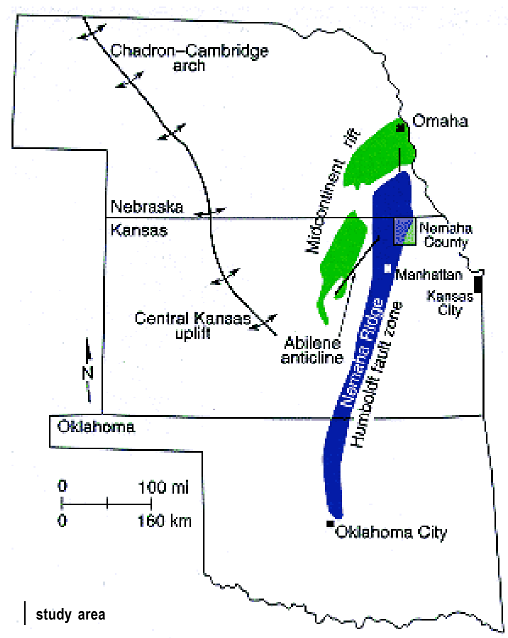

Figure 3. Major regional tectonic features that are apparently related to earthquake activity. Nemaha County is the locality where the Nemaha Ridge was discovered by drilling in the

currently interpreted to extend from roughly Omaha to Oklahoma City (Figure 3). In some places along the eastern front of this mountain range, elevation changes of over 2000 ft (600 m) across horizontal distances less than 3 miles (5 km) have been documented (Cole, 1976; Geier, 1999). The faults that bound the ridge are still slightly active today, especially the Humboldt fault zone that forms the eastern boundary of the Nemaha Ridge.

About 50 miles (70 km) west of the Nemaha Ridge in Kansas, the MGA is a zone of the earth's continental crust that was ripped apart and filled with oceanic-type crust (basaltic rocks) about 1.1 billion years ago. This rift zone extends from central Kansas northeast across Nebraska, Iowa, and Minnesota, and into the Lake Superior region. Why the rifting stopped after only spreading about 30 to 50 miles (45 to 70 km) is not known; however, if it had not stopped, the United States would have likely separated into two different continents with the present-day Kansas split by an ocean providing beach front property near present-day Salina, Kansas.

Considering the proximity of the study area to the intersection of the MGA and Nemaha Ridge, regional faulting, folding, and fracturing of mid-Pennsylvanian and early rock layers would not be unexpected. The majority of documented basement geologic features trend northeasterly with the closest most significant feature a major basement fault approximately 3 miles (5 km) west of the study area and a valley of sedimentary Precambrian rock less than a mile (1.5 km) south (Figure 4). Within about a six-county area, including this site and extending to the west and south, the MGS possesses a bend or change in strike from north-northeast to northeast. This dramatic change is consistent with the intersection of two major midcontinent faults: Humboldt and the Thurman-Redfield Structural Zone. These faults intersect about 20 miles (30 km) immediately south of this site.

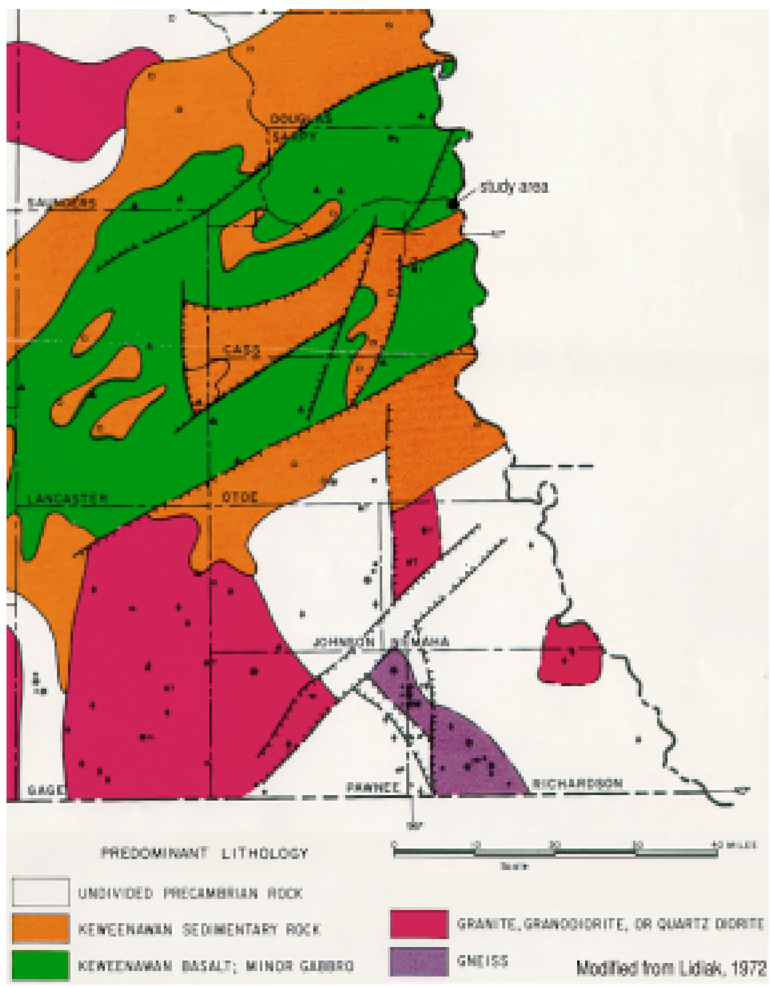

Figure 4. Basement lithology and interpreted structures from drill

Two coreholes located within a half-mile (0.75 km) of each other were drilled to provide preliminary source rock chemical and volumetric analysis at this site (Figure 1). Rocks encountered in the two boreholes were interpreted to be dramatically different below about 400 ft (125 m) (Joeckel et al., 2002; Nichols, 2003). This difference was most obvious in rocks from hole 02-18D interpreted to be below the thick Pennsylvanian shale that rests unconformably on a Mississippian limestone in hole 02-17D at about 570 ft (175 m) (Figure 5). In corehole 02-18D, thick Mississippian limestone is replaced by at least 400 ft (125 m) of what appear to be cyclic Pennsylvanian sequences. Based on a very limited amount of subsurface data, local basement topography is suggested to dip gently to the east and possess no distinguishable features (Figure 6). Therefore, faulting was not expected nor an obvious mechanism suggested from drill data to account for this apparent offset in the top of the Mississippian limestone.

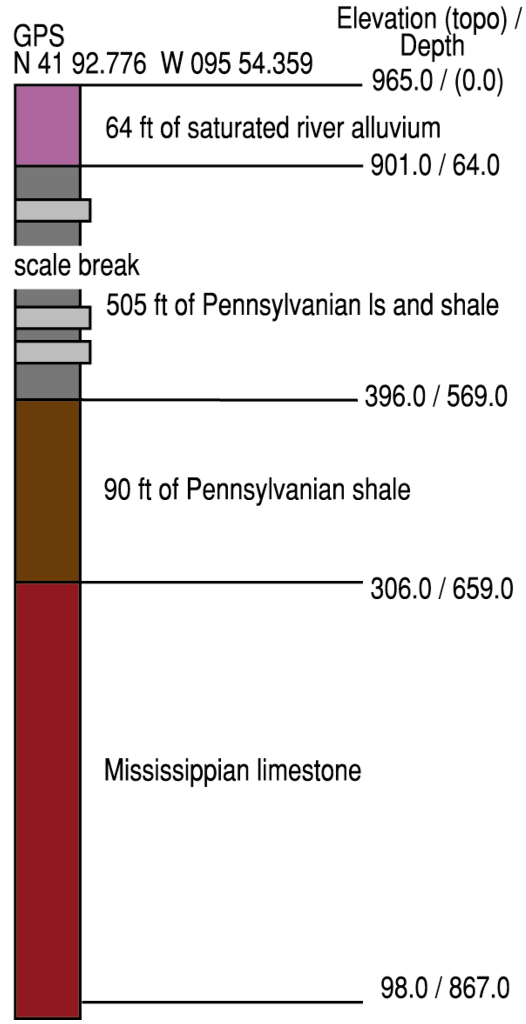

Figure 5. General log of hole 02-17D (Nichols, 2003).

Indicative of the unique evolution of this rift/ridge area is the presence of Pennsylvanian clastic basal strata near the eastern Nebraska-Kansas border on the eastern flank of the Nemaha uplift. The coarse, feldspathic sandstones and conglomerates derived from Proterozoic granitic basement of the Nemaha uplift that make up these strata show upward transitions from coarse, poorly sorted, clay-cemented, feldspathic sandstones into shales and/or mudstones with paleosols (Joeckel et al., 2002). Once the lithologic interpretation of the core from 02-18D is complete, the number of possible scenarios relating to the unique geologic setting to lithologies and structures in very close proximity to the borehole location should be reduced.

All three lines were located within the Platte River valley on Quaternary alluvium, which likely makes up the upper 20 to 70 ft (6 to 20 m) of sediment at this site (Figure 7). Lines 1 and 2 were located in Cass County while line 3 was in Sarpy County. Water-table depths at the time of the surveys were estimated to be around 20 ft (6 m) for lines 1 and 2 and around 30 to 40 ft (9 to 12 m) for line 3, based on ponds and river elevations.

Experimental (Testing) Phase

Experimentation revolved around a series of tests designed to evaluate a variety of acquisition methods and parameters. The intent of these experiments was to determine the characteristics and associated potential of seismic data recorded with several different configurations of sources at different source locations using a single fixed spread of receivers to delineate the possible structure responsible for the discrepancy between coreholes 02-17D and 02-18D. From these data determination of properties like resolution potential, signal-to-noise ratio, and penetration depths provided a solid estimate of how well the method would work answering the key geologic questions.

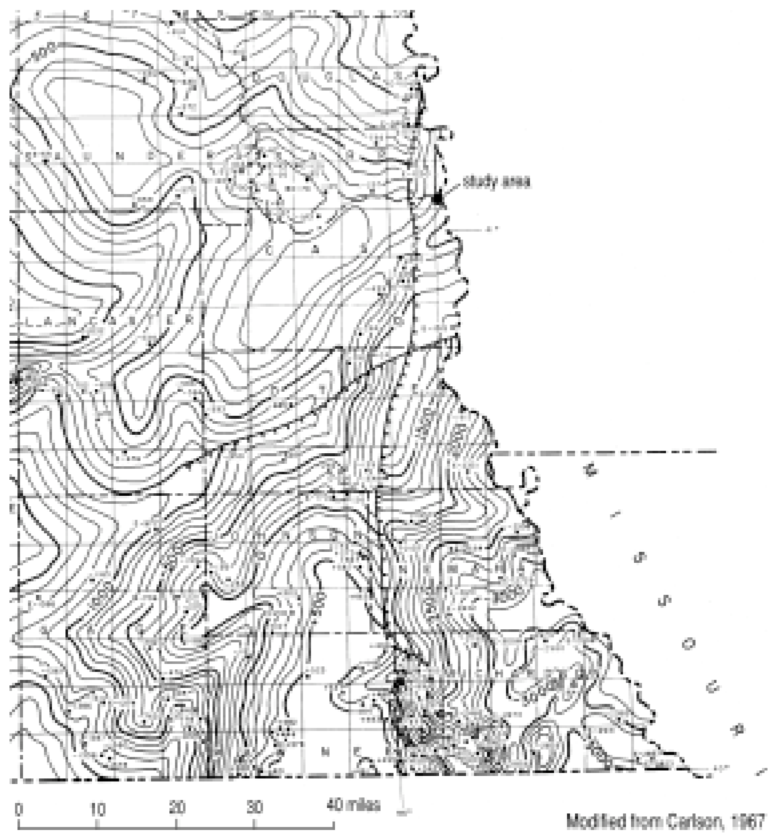

Figure 6. Basement topography interpreted from drill data.

All test data were recorded by a spread of receivers located along the southern property boundary in the ditch north of the railroad tracks (Figure 8). A large dynamic range seismograph with a low noise threshold is imperative to obtaining the highest possible quality data. For this study all data were recorded on a 24-bit, 240-channel Geometrics StrataView seismograph and StrataVisor NZC controller (Figure 9). The test spread was located along the far west end of line 1 partially in a cultivated field and partially in the railroad ditch. Based on the best subsurface data available at that time, the test line was thought to overlie uniform, relatively undisturbed subsurface material, far enough away from the highway and active sand-mining operations to minimize the recorded vehicle and machinery noise. In hindsight, the railroad ditch turned out to be one of the poorest data areas on this site due to fill material in the ditch and the underlying trough with faulted and folded rocks. However, decisions made based on testing in this lower quality data site, such as dramatically increasing the source power, proved critical to the success of the survey.

Walkaway testing included source-to-receiver offsets ranging from 8 ft (2.5 m) to approximately 1900 ft (600 m). The receiver interval for this testing was 16 ft (5 m) with half-interval source points providing a pseudo 8 ft (2.5 m) receiver spacing. The 8-gauge Auger Gun (Healey et al., 1991) (requiring only class C explosives) (Figure 10), 50-cal. downhole (Figure 11), and IVI Minivib high-frequency vibrator (Figure 12) were tested for spectral characteristics, attenuation (signal-penetration depths), and overall signal-to-noise properties. Contrary to original predictions, the gun sources (50 cal. and downhole 8-gauge) proved unacceptable for this survey. Surprisingly low signal levels and a high ratio of surface wave to body wave energy were observed (Figure 13). These characteristics are indicative of a very attenuative, loosely compacted, dry near surface, something that is uncommon in an alluvial setting with a relatively shallow water table. Vibratory sources are usually superior in areas with a hard (elastic) surface material/covering. The greatest loss going to a vibratory source from an impulsive source is in spectral characteristics. However, for this site the vibrator was selected to increase the amount of seismic energy delivered to the ground rather than optimizing wavelet characteristics through use of high-velocity projectile sources.

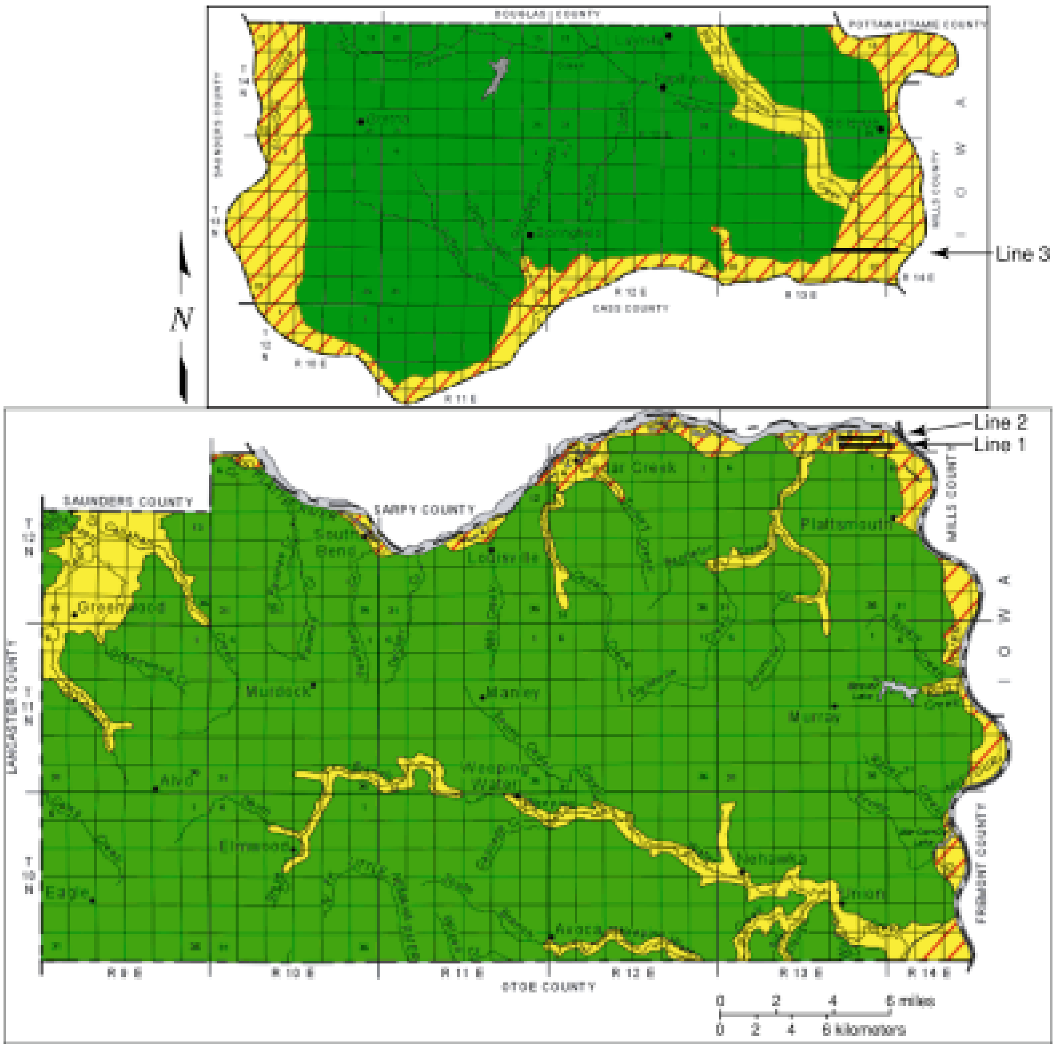

Figure 7. Cass and Sarpy county maps highlighting alluvial and upland areas (maps from Nebraska Survey website, http://csd.unl.edu/pestguides/cass.asp, http://csd.unl.edu/pestguides/sarpy.asp).

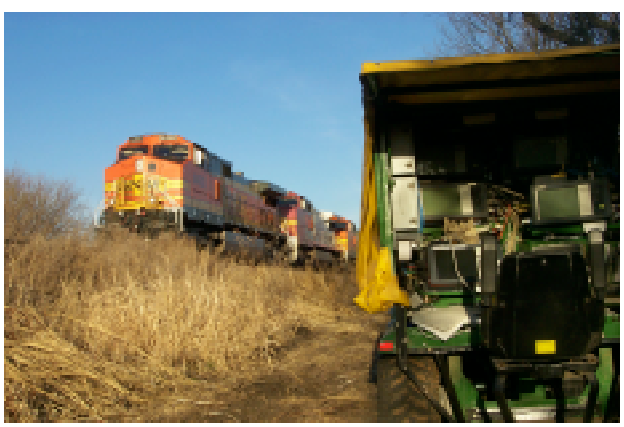

Figure 8. Test line was located in north railroad ditch.

Figure 9. 240-channel Geometrics StrataView with StrataVisor controller mounted on a 6-wheel John Deere Gator.

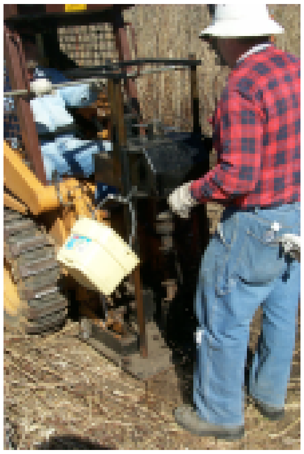

Figure 10. 8-gauge auger gun.

Figure 11. 50-caliber downhole.

Figure 12. IVI minivib I.

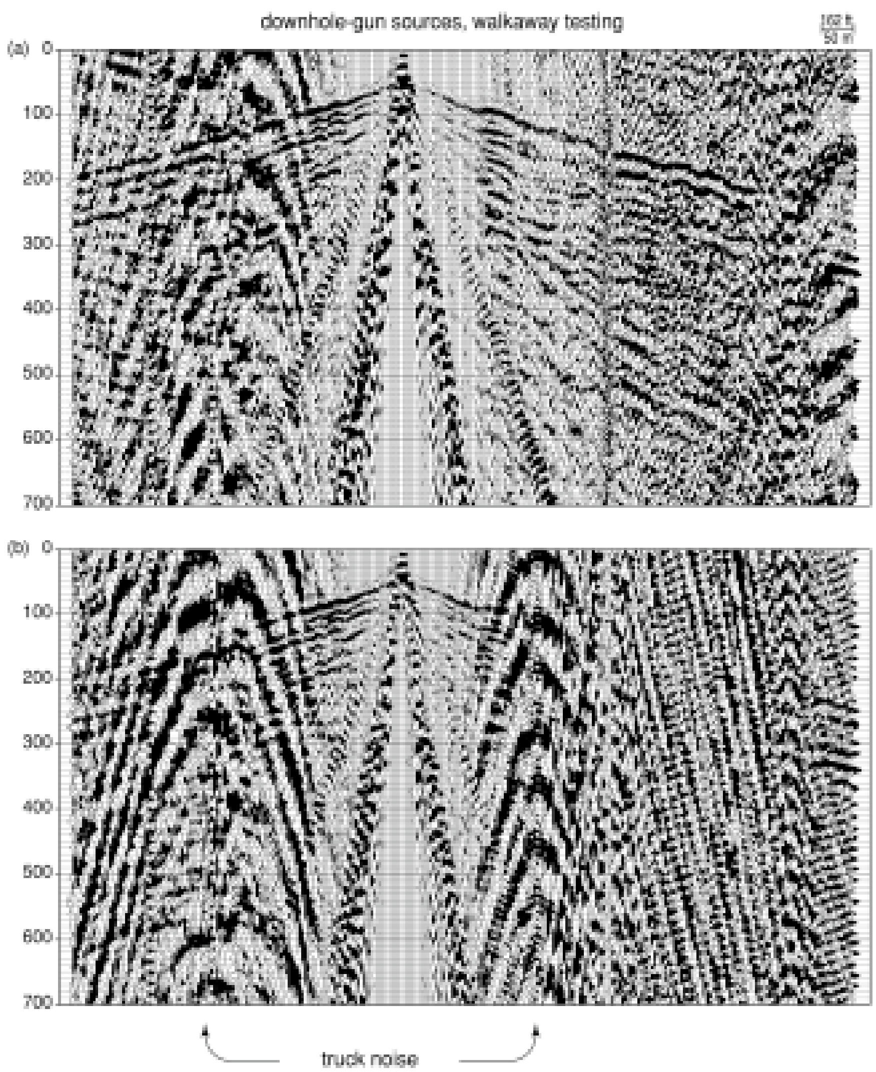

Figure 13. Walkaway-test data from gun sources.

Both double 40-Hz Mark Products L-28E geophones and triple 10-Hz Mark Product U2w geophones wired in series were tested. The need for a strong signal from geophones with a high spurious noise threshold is paramount, and from previous experience it is known that lower-quality geophones will not produce the desired output within the desired frequency band. Based on receiver output recorded by the seismograph, the lower than expected source energy observed, and the need for more high-frequency components of the spectra, the 40-Hz geophones were selected for production (Figure 14). Prior to on-site testing, the 10-Hz geophones were expected to outperform the 40-Hz phones based on site geology and previous experience. However, like many of the expectations of and pre-survey concepts about data potential and optimum recording equipment and parameters at this site, the receivers selected for production were not the ones thought likely during planning.

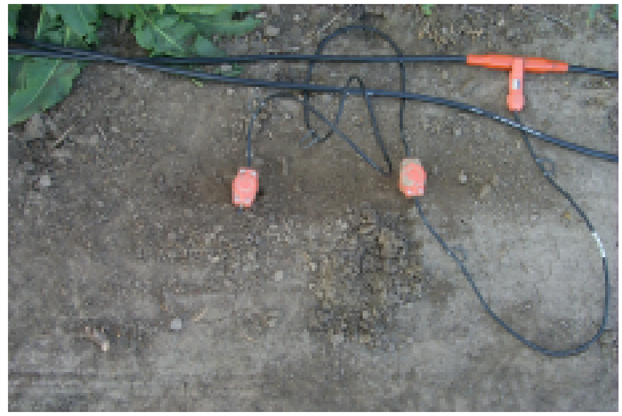

Figure 14. Two 40-Hz high-output geophones

Production Acquisition

Data were acquired on three 2-D profiles subparallel to and approximately centered on the Platte River (Figure 1). The same data acquisition parameters and equipment were used for all three lines. A 240-channel fixed array with 16-ft (5-m) receiver and 32-ft (10-m) source intervals provided shot gathers with near offsets around 32 ft (10 m) and far offsets ranging from 1950 ft (600 m) to over 2900 ft (900 m). Three uncorrelated sweeps, 10 seconds long, with a spectra that linearly increases in time from 20 to 250 Hz, were individually recorded at each shot station. Recording data uncorrelated and unstacked provides excellent opportunities for spectral and signal-to-noise enhancements only possible after careful analysis of each shot's properties (Doll and Çoruh, 1995). The IVI minivib used to produce seismic energy for this survey was specially outfitted with a prototype Atlas rotary valve designed to deliver more than four times the peak force at 200 Hz compared to standard valves. More than 30 gigabytes of data were recorded during this survey.

Preliminary line layout was based on optimized subsurface coverage and property access. Once the survey was underway, the line locations changed only slightly due to obstacles and ground conditions. Attempts were made to acquire data in such a way as to maintain consistent surface conditions and to minimize potential velocity or elevation anomalies that could complicate data processing. Unfortunately, it was not possible to avoid recording non-source generated noise with the proximity of the active sand and gravel mining operations and during fly-overs by aircraft from Offutt Air Force Base just 3 miles (5 km) to the north. As a result of excellent cooperation by the sand and gravel mine foreman noticeably reduced the background noise levels when certain mining operations were halted while active receivers were nearby. Major noise sources included the dredge (Figure 15), separators (Figure 16), pumps, truck traffic (hauling from the stockpiles), aircraft, and rail traffic. For intermittent noise sources like trucks, trails, and planes, acquisition was stopped until these moving noise sources were sufficiently offline for noise levels to drop below predetermined maximum thresholds.

Figure 15. Sand dredge work in south end of pond.

Figure 16. Sandpiles around separators (sieves) and conveyors.

The fold (redundancy) and sampling frequency (spatial and temporal) were greater than purely sufficient. A larger than "standard" number of data traces available for each shot provides insurance that signal-to-noise ratio of stacked traces could be optimized, data would not alias, and resolution will not be compromised. Spectral-balanced, correlated shot gathers possess dominant frequencies around 150 to 180 Hz for shallower events (<150 ms) and 120 to 150 Hz for the interval of interest (200 to 400 ms) (Figure 17). At these frequencies (assuming high enough signal-to-noise ratios) and target depths (600 ft [185 m] below ground surface), it should be possible to detect bed offsets or material changes at theoretical horizontal (Bruhl et al., 1996) and vertical (Widess, 1973) resolution limits on the order of 120 ft (37 m) and 15 ft (4.5 m), respectively. In practice however, estimates of the vertical resolution limit of these data are closer to 25 ft (7.7 m) (Miller et al., 1995). Spatial sampling was at the maximum recommended at 15 per radius of the theoretical Fresnel Zone (Steeples and Miller, 1990).

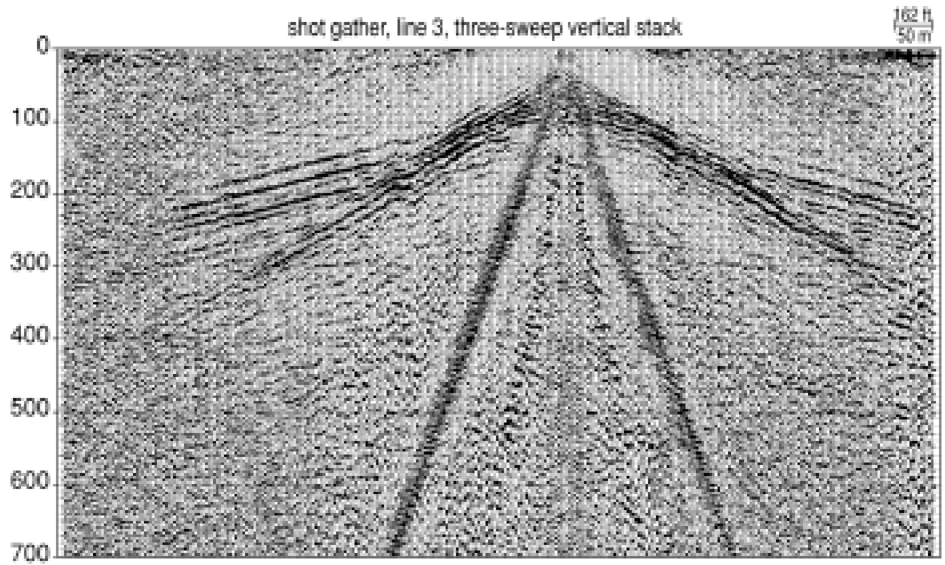

Figure 17. Spectral-balanced shot gather showing entire seismic wavefield.

Data were acquired using a CMP-fixed rolling-spread technique which, once processed, results in nominal 30-fold CMP stack sections with trace or subsurface sample spacing of 8 ft (2.5 m). Conceptually this acquisition approach provides greater flexibility in choosing offsets beyond the estimated optimum spread for the target. With the abundance of traces available during processing, variable offset gathers can be produced which optimally stack traces (as few as two) from time depths across a much larger range than possible with smaller traditional rolling spreads. If all available traces from this data set were stacked, the nominal fold would be 60. Having a nominal fold of 30 means half the available traces have been deleted in pursuit of higher signal-to-noise ratios without compromising the offset-dependent nature of reflected energy. Asymmetric split-spread geometries also provide the added benefit of enhanced continuity and increased velocity and dip control in comparison to strictly end-on or symmetric split-spread configurations. Our 240-channel data set is processed to extract the optimum 120-channels of data for each shot with individual trace selections based on noise and velocity variations unique to each station.

QA/QC

Data were acquired and processed on this survey to ensure the highest quality and most accurate acoustic representation of the geologic setting possible. Most important to verification of seismic-interpretation accuracy is display of representative shot gathers for all lines. This provides sufficient supporting information for independent evaluation of the legitimacy of processes and processing parameters used and interpretations made on CMP-stacked sections.

Equipment and recorded data were continuously monitored during acquisition to ensure the production of the highest quality CMP-stacked section. Response amplitude of receivers was monitored using a modified tap test performed after planting each geophone or group of geophones. Continuity and leakage of each active station was observed and maintained at acceptable levels using group-specific metering techniques. Real-time noise monitoring provided another method of finding receivers that were improperly planted or not responding in an acceptable fashion. Each problem receiver group was investigated and exchanged if the problem could not be resolved. Shooting was halted when noise thresholds exceeded a set level (established based on average background noised measured at this site). Ground force signal was recorded uncorrelated on channel 1 for each sweep and used to qualitatively evaluate coupling, vibrator performance, amplitude/frequency relationship, and sweep characteristics. The system underwent a series of pre-acquisition tests designed to ensure the integrity of analog filters, consistency in system noise, and precision in digitally stored data. Visual analysis of general signal-to-noise ratio, environmental noise, DC bias, and variations in the optimum recording window was performed on every sweep.

Production Processing

High-resolution seismic-reflection data, by its very nature, lends itself to over-processing, inappropriate processing, and minimal involvement processing. Interpretation of high-resolution shallow-reflection data must take into consideration not only the geologic information available, but also each step of the processing flow and the presence of reflection events on raw unprocessed data. Data processing included only operations and parameters that enhanced signal-to-noise-ratio and/or resolution as determined by effect on high-confidence reflections interpreted directly on shot gathers (Figure 18). For the most part, processing of high-resolution shallow-reflection data is a matter of scaling down conventional processing techniques and methods; however, without extreme attention to details, conventional processing approaches will produce undesirable artifacts. In-field processing at this project was performed for quality-control purposes.

The basic architecture and sequence of processing steps followed during the generation of the final stacked sections were similar to conventional petroleum exploration flows (Yilmaz, 1987). The primary exceptions relate to the step-by-step quality control necessary for the highest confidence interpretations of shallow features and realization of full-resolution potential (Miller et al., 1989; Miller et al., 1990; Miller and Steeples, 1991) (Figure 18). Specific distinctions relate to the emphasis placed on velocity analysis (Miller, 1992), lack of extensive wavelet processing, care and precision placed on muting, step-by-step analysis of effects of each operation on reflected energy, limiting statics operations to maximum shifts no greater than one-quarter wavelength of the dominant reflection energy with large correlation windows, and coincident iterative velocity and statics analysis. Each analysis step in the processing flow is available for critique.

Special emphasis was placed on all the analysis portions of the processing flow. It has been proved necessary and most effective to do velocity and spectral analysis on every CMP (Steeples and Miller, 1990). Variability in near-surface materials and/or surface conditions around this study area required changes in processing parameters across distances as small as 65 ft (20 m). To ensure the highest quality geologically representative stacked section, velocity analysis was performed on every CMP. In association with this point-by-point analysis, care was taken to ensure all coherent events interpreted as reflections on stacked sections are indeed reflections. Biasing processing parameters to enhance events interpreted on stacked sections as reflections that are actually coherent noise was avoided at all cost. Differentiating reflections from direct wave, refractions, air wave, and ground roll in the early portion of a stacked section was extremely difficult and, by design, overly aggressive with respect to muting.

Key processes and parameters included: pre-correlation processing, spectral balancing, fk filtering (direct wave), small shift trace-to-trace correlation statics, optimized fold/near-vertical offset trace only stacks, and migration filtering. Pre-correlation processing improved the spectral characteristics providing better resolution and a more balanced waveform (Doll and Çoruh, 1995). Spectral balancing is a simple band-limited deconvolution and effectively broadens the bandwidth. Trace-to-trace correlation statics involves correlation of a multi-trace stacked pilot with each individual trace so the optimum static shift can be determined that aligns wavelets within the prescribed time window. To avoid artifacts it is critical with this statics technique that the correlation window be large and the maximum allowable static shift be small (less than one-quarter wavelength). Optimized fold/offset is simply an editing process in which only traces within the optimum recording window (Hunter et al., 1984) for each reflecting horizon are retained for inclusion in the CMP-stacked section. Finally, migration filtering is a technique developed at the KGS to suppress high-angle (>80 degrees) coherent noise (Ivanov et al., 1998). These unique processing steps and parameters proved critical to producing an accurate and interpretable stacked section.

Figure 18. Generalized processing flow.

Seismic/Geologic Interpretation

Seismic-data interpretations are principally guided by the interpretation of core data from 02-17D, time to depth conversions based on velocity analysis of these seismic data, documented regional geologic information, reflection coherency, and experience working with high-resolution data across the Nemaha Ridge/ Humboldt fault system in three different locations in Kansas. Coherent events interpreted as reflections have been verified through shot-gather comparisons to be reflections.

Line 1

Overall data quality along line 1 (railroad line) was the poorest of the three data sets collected on this project. Expectations prior to actually acquiring data along this line were that the best data would likely come from this area. Working in ditches generally provides better coupling by putting both source and receiver closer to the water table and in contact with more compacted native soils. However, the railroad ditch along the southern boarder proved to be quite a bit less than ideal and actually very poor. It is assumed this unexpectedly low signal-to-noise area resulted from decades of sedimentation coming from runoff waters as the surrounding area drained into this ditch on its way to the Missouri River.

It is difficult on some shot gathers to identify the reflected energy. Fortunately, sitewide a reflection event from around 800 to 1000 ft (250 to 310 m) below ground surface (200 ms) was consistently recorded on many shot records (Figure 19). This event is significantly older than the target limestone at the top of the Mississippian section. It is characterized by a distinctive change in reflection frequency characteristics with signal arriving above this horizon possessing 25 to 50% higher dominant frequencies. This kind of a frequency boundary is not uncommon on high-frequency broadband data and is usually indicative of a dramatic change in the geology (e.g., unconformity). No long-offset traces (which in this context means time/offsets before the direct wave arrival) were included in the stacked sections.

In general, these data were plagued with static irregularities related to changes in near-surface velocity (Figure 19b-A). Elevation changes were insignificant relative to the observed lateral variability in material velocity. Some of this problem was compensated for by defining a velocity function (V(t)) every 20 CMPs; however, the most noted improvements came with the conservative application of correlation statics. Consistent (present for more than a few traces on consecutive shot records) shallow (<150 ms) reflections range from difficult to impossible to find on shot gathers on the western two-thirds of line 1. The highest quality reflection data on this profile were acquired in the open field east of the eastern property line (in the wildlife refuge).

High noise and limited lateral coherency of reflection events have adversely affected the overall quality of the CMP-stacked data from this line (Figure 20). But even with lower than hoped signal-to-noise, several events can be traced across the entire profile and correlated to borehole 02-17D. Events interpreted in orange are from within the 500+ ft (150 m) thick sequence of Pennsylvanian limestone and shales. Coherency breaks in this event are related to near-surface problems and low signal-to-noise levels. However, considering the processing flow used, good confidence can be generally placed in these interpretations. The top of the Mississippian limestone, the target of this survey, is interpreted in blue and can be distinguished by its

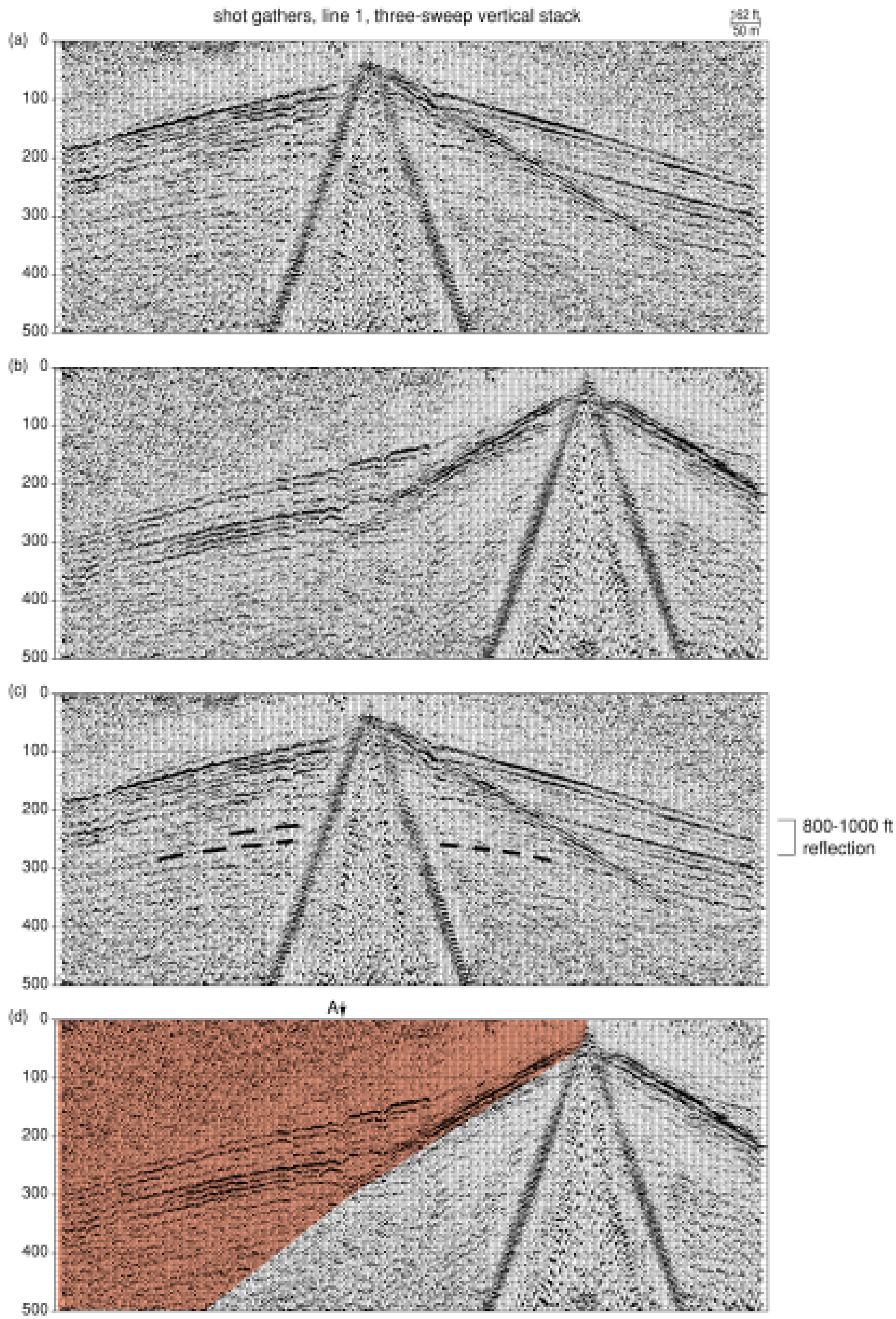

Figure 19. Common shot gathers from two widely separated stations. A = effect of near-surface static.

time/depth and distinctive change in reflection character, especially evident at the extreme west end of line 1. Finally, the highest amplitude and most prominent sitewide event is interpreted in purple and is from a depth of around 800 to 1000 ft (250 to 310 m). This purple event best represents the structural geometries beneath the Pennsylvanian section and likely very similar to basement topography across the entire site.

Without a doubt the 325+ ft (100+ m) uplift clearly evident below station 1380 is the explanation for the discrepancy in borehole data between 02-17D and 02-18D. This feature is generally consistent with structures associated with the Nemaha uplift further south in Kansas and the southeastern extreme of Nebraska. This feature is on the wrong side of the Humboldt fault and too far north to be easily identified as part of the Nemaha Ridge. It is most likely a structure associated with the Humboldt fault and Nemaha Ridge and was active during the same time and under the same stress regime as the Nemaha Ridge (Lidiak, 1972).

It appears the Pennsylvanian section is relatively undisturbed, with the possible exception of the bottom few tens of meters. However, the Mississippian limestone identified in boring 02-17D appears to either pinch out at the uplift-bounding faults or it is extremely thin and below the resolution of this survey. Based on the best possible interpretation of these data, it appears the top of the Mississippian section is missing on the crest of the anticline at the southern property boundary; some of the basal Pennsylvanian limestone and shales may also be missing. This geometry suggests a mound of either Lower Mississippian or Upper Devonian was exposed to the atmosphere into Early Pennsylvanian time.

Faults are interpreted based on reflection offset and diffraction patterns diagnostic of bed terminations. In general, individual faults have very small displacements (~33 ft [10 m] or less), but across what are referred to as fault zones displacement can exceed 325 ft (100 m). Faulting and minor folding on the flanks of the pronounced anticline are consistent with geometries observed on seismic data further south along the Nemaha Ridge/Humboldt fault system (Geier, 1999). The most dramatic fault zone, accounting for 325 ft (100 m) of displacement, marks the western edge of the uplift feature around station 1300. Between this fault zone and the western end of the profile the faults and folds are minor but are laterally persistent out to at least station 1040. This western portion of the line has a complete Mississippian section preserved but is structurally altered from its original layer-cake depositional geometry.

Only a small sampling is available east of the uplift feature. The target Mississippian limestone appears to thicken east of the faults that define the edges of the anticline. Assuming this trend in the Mississippian continues east, a section approximately equivalent in both chemistry and thickness to that observed in borehole 02-17D would be expected east of the Lyman-Richey east property boundary. In the shallow portion of the subsurface in this area, the cyclic Pennsylvanian limestones and shales are coherent and display reflection signatures that were expected and have been observed elsewhere in Kansas, seismically diagnostic of these kinds of repetitious units.

Line 2

Overall data quality on line 2 is the best of the three lines. Reflection arrivals are much more pronounced across the entire profile, especially throughout the time-depth interval of interest (Figure 21). Reflected energy from the Lower Pennsylvanian, which is interpreted to range from bedrock at about 40 ms to 150 ms, has a distinctively higher frequency and layered or cyclic appearance on spectrally balanced shot gathers than deeper reflections. A clear decrease in dominant frequency is evident below about 150 to 170 ms. This change was observed on line 1 and is interpreted to be indicative of the Pennsylvanian/Mississippian contact. It could be inferred that the thin cyclic nature of the Pennsylvanian rocks gives way to the more massive Mississippian units and therefore the more abrupt frequency transition. Processing of these shot gathers included removal of all first arrivals, offset greater than around 490 to 650 ft (150 to 200 m), air-coupled waves, and ground roll (Figure 21c).

Shot gathers from line 2 provide an excellent view of the offset and depth-dependent nature of seismic characteristics at this site (Figure 21c). At long offsets (offsets greater than imaging depth) the reflected energy becomes asymptotic to the first arrivals and appears to be dominated by guided waves. If these longer-offset events are not removed, they will stack coherently and give a completely misleading picture of the subsurface. As well, air-coupled wave and ground roll make up the majority of the energy arriving at close offsets and form a cone originating at the source and extending to the bottom of the record. These arrivals are also removed, leaving a relatively small time and offset window for reflection arrivals retained for CMP stacking, but one that has the highest signal-to-noise ratio potential.

In comparison to CMP stacked data from across the study area, line 2 provides the best images of and therefore insights into the subsurface geology in this area (Figure 22). Cyclic Pennsylvanian limestone and shale sequences are clearly distinguishable down to about 150 ms (approximately 590 ft [180 m]) on the west end of the profile. A distinctive change in wavelet characteristics below 150 ms is interpreted to be the top Mississippian, consistent with interpretations of core from borehole 02-17D. Consistent with shot gathers, the most obvious and distinguishable characteristic of this Pennsylvanian/Mississippian boundary is the marked decrease in dominant frequency and therefore apparent data-resolution potential. Looking deeper into the section and continuing to correlate reflections on the CMP-stacked section with major lithologic changes interpreted from core, another obvious drop in dominant frequency and therefore change in physical properties of the rocks occurs at about 250 ms. This interface is interpreted to be the base of the massive limestone encountered at about 810 ft (250 m). High-quality data allow a great deal of confidence interpreting major changes in geology on seismic data because it is on the west end of line 2.

Without a doubt the most pronounced feature evident on line 2 is the uplift centered on about station 2300 (Figure 22). Reflections directly above the crest of this structure are relatively flat, high frequency, and appear undisturbed. Comparing reflections from the west end of the section to those above the uplift structure suggests most movement on this structure concluded by the beginning of the Pennsylvanian. Truncation of the massive Mississippian limestone against the flanks of the anticline suggests deposition of this massive limestone took place during the later part of this structure's active time period. It is not clear from the seismic data if possibly a very thin veneer of this massive limestone is present across the crest of the anticline. Based on the consistency in the basal contact of the Pennsylvanian between stations

2040 and 2300, it is safe to say that movement on this anticline was clearly active well into Early Pennsylvanian. On the other hand, if no trace of the massive Mississippian limestone observed in borehole 02-17D

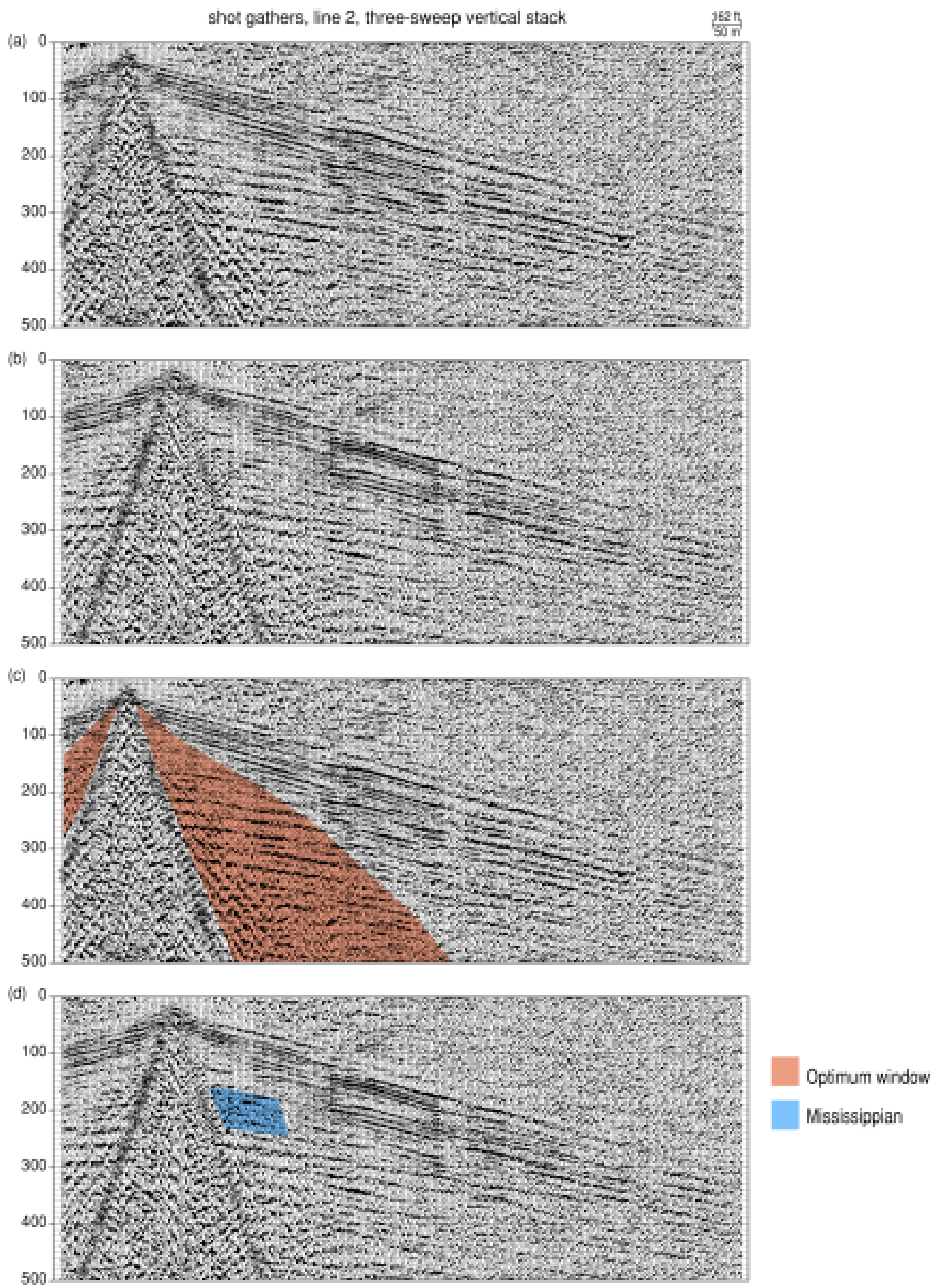

Figure 21. Shot gathers (a) and (b) are representative of line 2 data. Optimum window for record (a) is outlined in (c). Reflections from the Mississippian evident on (b) are highlighted on (d).

exists beneath station 2300, then this uplift feature would have been a topographic high with little to no movement throughout the Later Mississippian and Early Pennsylvanian.

Faulting and associated bed offsets along the flanks of the uplift suggest minor movement well into the Pennsylvanian. Without a clearly distinguishable bedrock reflection continuous across the section, it not possible to determine if faulting has been active as late as the Quaternary. A high-resolution seismic-reflection survey designed to image the upper 325 ft (100 m) along line 2 would answer that question. The fault zone interpreted between stations 2220 and 2280 has a very distinguishable characteristic that can easily be identified on line 1. Extrapolating this feature to line 3 is a bit more difficult, but considering all equivalent structures on line 3 are subdued in comparison to lines 1 or 2, identifying this west-bounding fault zone can be done with some degree of confidence.

Faults are interpreted on the CMP section based on bed offset traceable through all coherent reflection along a straight-line trend. To ensure reflection offsets are not the result of near-surface static, faulting is only interpreted where bed-to-bed offset is non-vertical in nature. That is, the trend or trace of a fault or fault zone as it is tracked contiguously through time from offset reflection to offset reflection is a straight line and dips less than 90 degrees relative to vertical.

Bounding faults east of the uplift, as on line 1, cover a much wider zone than evident on the west side. Much like faulting along the Nemaha Ridge further south in Kansas, the character of faulting (size and makeup of the fault zone) on opposite sides of uplifted blocks are not necessarily similar in nature. Faulting on the west side of this uplift is abrupt with approximately 325 ft (100 m) of vertical displacement measurable across a horizontal distance of about 1000 ft (350 m) with over 260 ft (80 m) of the offset occurring in about 650 ft (200 m). Considering the horizontal resolution at this depth is around 375 ft (120 m), this fault zone is likely less than 650 ft (200 m) wide. Faulting on the east side of the uplift is distributed in blocks with each block being between 325 and 650 ft (100 and 200 m) long and vertically displaced around 65 to 100 ft (20 to 30 m), with an apparent dip of around 20 degrees. Although the entire fault zone on the east side was not imaged by either line 1 or line 2, based on these data, data from line 3, and characteristics of documented faulting further to the south, the total displacement on both sides of the anticline are approximately equivalent, just distributed across a greater distance and more unique fault planes on the east.

Dip is interpreted east of the uplift on the top of the Mississippian and within the Pennsylvanian section. This dip likely indicates growth-type structures, with movement slowing dramatically and likely going dormant during the Later Pennsylvanian. Most of the faults that penetrate the top of the Mississippian could well have seen minor reactivation sometime in the last 300 million years but, based on a total displacement of less than 65 ft (20 m) since the end of the Mississippian, none has seen much activity since the Pennsylvanian.

Reflections and faults can be correlated with confidence between lines 1 and 2. This continuity in seismic interpretation allows a very reasonable geologic picture of the subsurface to be postulated south of the Platte River. The uplift structure is, of course, dominant on both sections. Direct comparison of the two sections suggests this uplift feature narrows slightly and plunges to the northwest at a rate of around 160 ft/mile (30 m/km). The major fault zone that bounds the western side of the uplift narrows slightly to the north, but the faulted and folded zone forming a trough-like feature also west of the uplift has about the same dimensions on both lines. Most of the "minor" faults (displacements suggested to be less than 27 ft [10 m]) can be matched on both lines, but without distinguishing characteristics it is not possible to say with confidence which, if any, of these faults traverse the full half mile (0.75 km) between lines 1 and 2 and which ones terminate or emerge within that unsampled portion of the subsurface.

Line 3

Near-surface conditions for line 3 were completely different from those present on lines 1 and 2. Receivers for line 3 were located in the road ditch while the source was coupled to the asphalt road on the western two-thirds of the profile and to a hardpack gravel road for the eastern one-third (Figure 23). For all three profiles the water table was less than 80 ft (25 m) deep and the unconsolidated material above bedrock was river alluvium. Line 3 lacked the lateral consistency in Pennsylvanian reflections. For some shot stations high-frequency reflections from the upper 490 ft (150 m) were clearly distinguishable from linear first arrival or guided wave

Figure 23. La Platte Road, Sarpy County, Nebraska.

energy, while for other shots all arrivals from reflectors in the upper 490 ft (150 m) were obscured by linear source-generated noise (Figure 24). Hence, it is much more difficult to confidently interpret shallow reflections on line 3 in comparison to the east and west extremes of line 2.

Shot gathers along line 3 possess signal-to-noise ratios that allow identification of reflected energy on about 50% of all records. On some individual shot gathers (25% of total), it is possible to clearly interpret reflection from above and below the Mississippian/Pennsylvanian contact (Figure 24). High-amplitude direct wave and air-coupled waves are dominant along line 3. It is assumed this obvious increase in direct wave energy on line 3 data relative to line 1 and 2 data is related to the presence of the highway roadbed. Useful reflected energy can be isolated from coherent noise sufficiently on most shot records from line 3. Wide-angle reflections, direct wave, and air-coupled wave were removed from the shot records before CMP stacking.

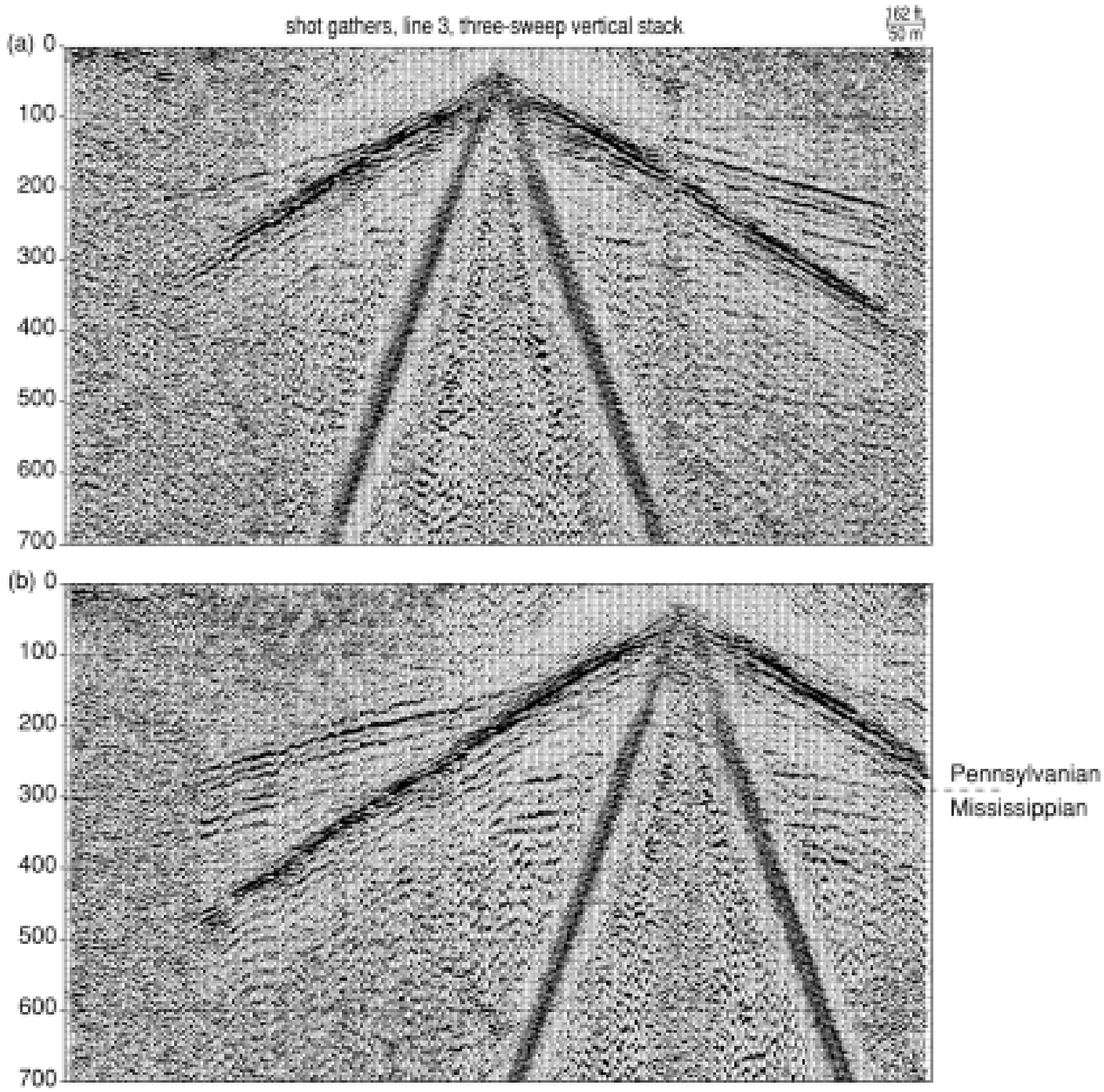

Figure 24. Shot gathers from La Platte Road.

Reflections from Pennsylvanian strata are easily identified in the upper 150 ms on spectral balanced shot gathers as high-amplitude, high-frequency events with hyperbolic curvature at offsets between 162 and 490 ft (50 and 150 m) (Figure 24). The lack of consistency in arrival characteristics is evident and clearly detrimental to the coherent stacking of these shallow high-frequency events on CMP sections. Below this packet of high-frequency reflection is a relatively quiet zone with little in the way of easily distinguishable reflections. This could be related to several factors including lack of sufficient high-frequency energy at these depths to distinguish individual reflections or simply insufficient acoustic contrasts within this part of the geologic section.

On most shot gathers from line 3, reflections can be interpreted from and below what has been identified as the Pennsylvanian/Mississippian contact at around 225 ms (Figure 24). Below this contact several distinctly separable reflections are evident down to time depths of around

500 ms, which is a two-way travel time very near that expected for the top of basement at just over 2100 ft (675 m) below ground surface in this area. Considering these shot gathers have only been spectral-balanced and scaled, data quality is quite good with noticeable signal-to-noise enhancement expected with CMP stacking.

The western one-third of line 3 possesses data characteristics unique from any other observed on the three lines that make up this study (Figure 25). Coherent reflections with an apparent tie to the Pennsylvanian/Mississippian contact and the basal contact of the massive Mississippian limestone encountered in boring 02-17D have been interpreted across the first approximately one-third mile (0.5 km) of profile. NOTE: This interpretation is very tenuous and lacks good confidence. For nearly the next three-quarters mile (1 km) (stations 3100 to 3260), the data possess no reflection energy readily identified on shot gathers. After the data had been run through a full processing suite including CMP stack, coherent events seemed to appear within this poor data region possessing characteristics consistent with stacked reflection on other lines and on the eastern third of this line. Interpretation of these discontinuous events as reflections is done with limited confidence. These interpretations are based on wavelet characteristics and diffraction patterns evident on unmigrated sections. This low signal area could be the expression of a major fault zone associated with basement uplift, or at the other end of the possibilities, it could be completely the result of a very attenuative and disturbed near surface related to an old river meander or other alluvial anomaly. Clearly if faulting and tectonic forces have been at work and are the reason for this poor data area, these faults must have been active sometime immediately prior to or during early deposition of alluvial sediments.

The eastern two-thirds of the line 3 CMP stacked section possesses reflection events with character and arrival times consistent with and, without much difficulty, can be correlated to lines 1 and 2 (Figure 25). Unlike lines 1 and 2, line 3 does not seem to have a segment(s) within the profile where characteristic cyclic Pennsylvanian reflections are prevalent and uniquely distinguishable from the broken coherency seen in the upper 150 ms on most data from this area. Considering the high-quality reflections seen on shot gathers within the upper 150 ms along some stretches of this profile, it is likely the problem getting reflections to stack coherently relates to near-surface static and a very small optimum window. In some cases only one or two traces have reflection wavelets from a particular near-surface interface that are separable from coherent noise within this shallow portion of the section. With such limited data to work with and the reliance of CMP processing on fold and a range of source-to-receiver offsets for accurate velocity and static corrections, it is not surprising that coherent reflections prevalent across large segments of the section are difficult to enhance.

Reflections from above the Pennsylvanian/Mississippian contact lack sufficient coherency for accurate fault mapping through the shallow portion of the section. However, based on the much more uniform bedding apparent below the top of Mississippian and the subdued nature of the uplift feature interpreted on this line, faulting is not expected to be as pronounced in the shallower portion of this section as was evident on lines 1 and 2. From shot gathers and unmigrated stacked data, a zone centered on station 3600 appears highly disturbed with chaotic arrivals prevalent down to time depths in excess of 120 ms. With reflections immediately below this chaotic zone showing no apparent abnormalities or adverse effects that appear related to faulting, it is reasonable to suggest this zone is either an incised valley or associated with extreme variability within the alluvium. Abrupt changes in the bedding patterns within the alluvium would not be unexpected considering the high-energy depositional environment in an old river meander.

Confident geologic interpretations on this line are limited to reflections below the basal contact of the Pennsylvanian and to depths approaching basement at around 2200 ft (675 m) (Figure 25). As on lines 1 and 2, the dominant structure interpretable on line 3 is the anticline centered on about station 3520. This uplift structure has a slightly different geometry on this line than observed south of the Platte River. Beneath La Platte Road the uplift features appear much broader and seem to influence not only the basal rocks of the Mississippian, but also most if not all of the interpretable portions of the Pennsylvanian section. From the base of the massive Mississippian limestone interpreted based on correlations with lines 1 and 2, a total of around 162 ft (50 m) of vertical uplift is present at around 1000 ft (300 m) depth. Moving up the section, the top of the Mississippian section looks to have around 100 ft (30 m) of total vertical uplift. The shallowest Pennsylvanian rocks imaged with these data possess a structure with total vertical movement of around 50 ft (15 m).

Relative to the Mississippian section, the total vertical movement across the uplift feature on line 3 is no more than 162 ft (50 m), with the crest of the uplift buried more than 810 ft (250 m). Structures interpreted on line 3 are consistent with the mid-Pennsylvanian structures interpreted on lines 1 and 2. Only 16 to 32 ft (5 to 10 m) of uplift appears to be unique to the base of the upper Mississippian limestone, while more than 130 ft (40 m) is unique to the same unit on line 2. This association clearly suggests movement this far north was predominantly Pennsylvanian or later with most of the displacement translated throughout the imaged section along fault planes. Further south most of the vertical movement associated with the anticline is pre-Pennsylvanian; however, faults interpreted to penetrate the Pennsylvanian section appear to have similar offset south as those mapped north of the Platte River. With the anticline currently interpreted as plunging to the northwest, the noted reduction in displacement on this basal limestone reflection (purple) north of the Platte River would be expected. Post-Mississippian movement along faults both bounding and adjacent to the uplift is consistent across the entire 6-mile_ (10-km_) study area.

Considering the possible time-to-depth conversion problems in this area due to changes in alluvial materials, dip on layers is difficult to estimate with a great deal of accuracy. Examination of the entire imaged section (from bedrock to possibly basement) suggests most of the rock layers identified as younger than the massive Mississippian limestone have dips greater than 15 percent. Grades this steep are problematic for mine activities. However, the top of the Missis-sippian limestone appears to have little or no dip east of station 3680. An abrupt change in the layer dip west of 3680 likely marks the easternmost fault associated with this structurally altered zone. Based on interpreted structures and wavelet characteristic, it is reasonable to extrapolate this structural boundary (abrupt change from excessive dip [from a mining perspective] to rela-tively flat layers) south to equivalent features beneath and immediately east of the Lyman-Richey property on line 1. The uppermost Mississippian limestone east of this boundary represents viable resource rock considering the likelihood the chemistry will be consistent with 02-17D, layer thickness, layer dip, and proximity to the Lyman-Richey Sand and Gravel Plant #8.

Overall

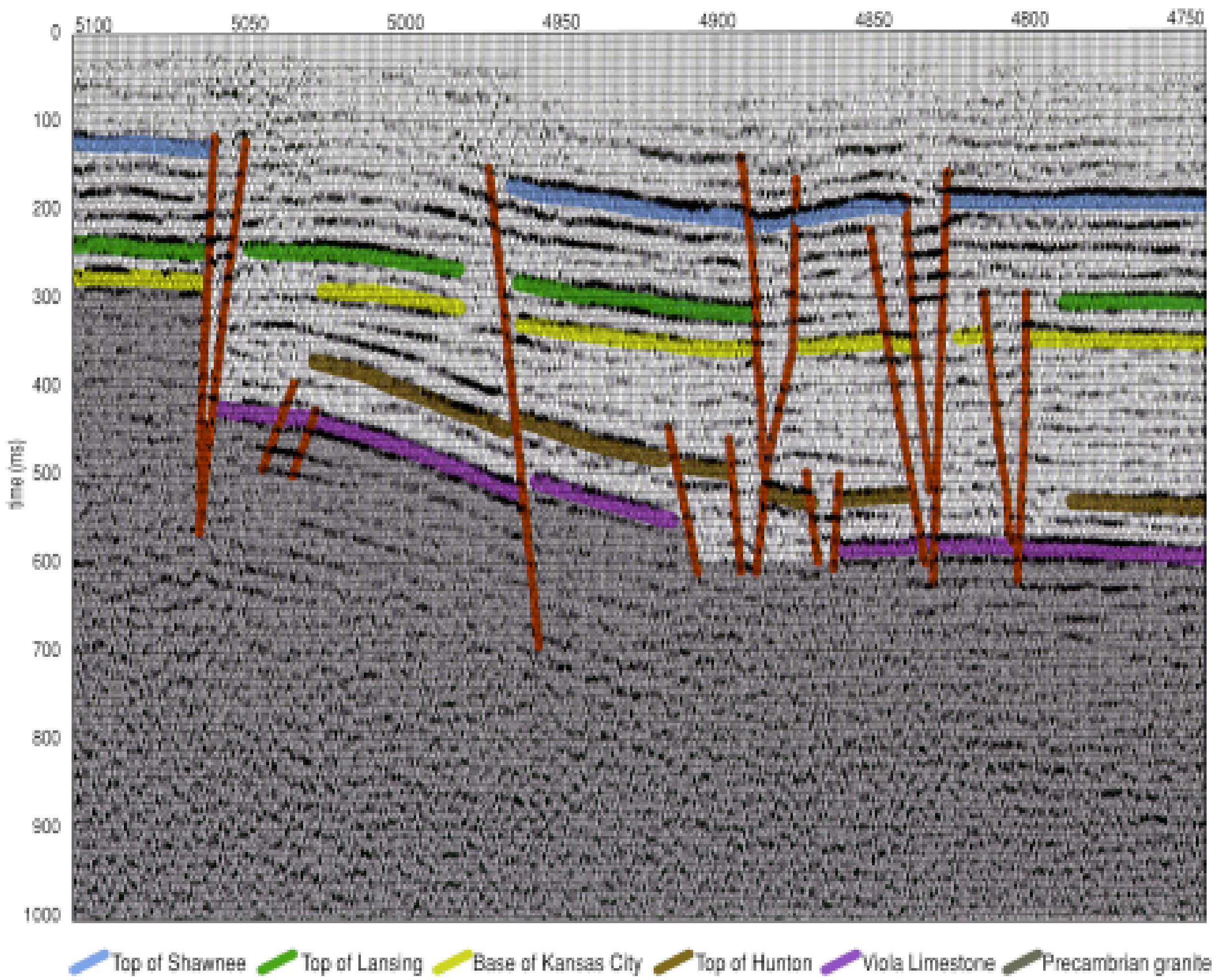

Figure 26. Humboldt fault zone interpreted on seismic data collected between St. Marys and Manhattan, Kansas.

Structural characteristics of this site are in general consistent with those observed at several locations along the Nemaha Ridge/Humboldt fault system in Kansas (Figure 26). Geologic maps of this major midcontinent structure generally do not show the Nemaha Ridge extending north much beyond Johnson County, Nebraska, which is more than 40 miles (60 km) south of this site (Figure 6). Most deep drill hole studies suggest the basement expression of the Humboldt fault (generally possessing over 900 ft [275 m] of offset in this area) extends as far north as Omaha and passes less than 3 miles (5 km) west of this site. Without a doubt, the dominant basement feature within the southeastern corner of Nebraska is the Midcontinent Geophysical Anomaly (MGA). Regionally the overall trend of MGA transitions from predominantly north to more northeast between Omaha and Otoe County, Nebraska, a distance of around 60 miles (100 km) south.

This Lyman-Richey study area sits just north and east of this bend in strike of the MGA, clearly atop the northeast-trending arm of the MGA, immediately north of Nemaha Ridge truncation, and just east of the Humboldt fault. These mapped trends in basement lithologies and structures at first appear to contradict the seismically derived interpretations and local correlations of the uplift feature beneath the Lyman-Richey site. However, a right-lateral strike-slip fault located beneath the modern Platte River channel provides both a mechanism with the appropriate stress/strain regime and a reasonable explanation/justification for correlating the uplift feature across the Platte River between lines 2 and 3 (Figure 27).

By placing a right-lateral strike-slip fault with approximately two-thirds mile (1 km) of displacement beneath the modern Platte River channel, the periodicity observed in the major uplift structure and associated faults and folds correlates extremely well across all three lines (Figure 27). The apparent north-northwest trend of the structures mapped on seismic data, although nearly 45 degrees out of alignment with regional basement features, is consistent with block-rotation scenario common with wrench faulting. Formation of the anticline south of the river took place predominantly in the pre-Pennsylvanian with a limited amount of post-Mississippian growth. This structure is predominantly controlled by faults immediately adjacent to the uplift. With the Pennsylvanian/Mississippian contact generally dipping to the north and the anticline most distinctive and possessing the greatest uplift at the base of the massive limestone beneath the southernmost seismic line, it is difficult to tell if and how much the anticline plunges to the north-northwest.

Reflections from within the Pennsylvanian section have been uplifted and faulted in proximity of the anticline and are most pronounced on lines 1 and 2. Uniformity of folding as interpreted within the Mississippian section is contrasted by the fault-controlled structural high in the Pennsylvanian rocks characterized by its very broken nature. About a quarter of the total vertical displacement associated with the anticline is contained within the Pennsylvanian part of the section. Seismically the discontinuous nature of the Pennsylvanian section in places is, to a large extent, related to faulting, the near-surface conditions, and the dominance of the direct arrivals. Distinguishing where the rocks are truly broken up from faulting and folding and where drops in signal relative to noise are related to near-surface irregularities cannot be determined with confidence.

Recommendations

Minability of the Mississippian limestone is the key question this survey was designed to help answer. Based on the seismic reflection data, published basement geologic information, borehole interpretations, and data from similar settings further south in Kansas, a generalized map indicating areas of good, moderate, and poor potential for underground mining of the Mississippian limestone has been produced (Figure 28). These classifications are based on thickness of target rock, faulting and folding, and projections of interpreted geologic features offline.

Clearly directly over the uplift would be a poor area to attempt underground mining. This is obvious for two reasons: first, the Mississippian limestone is not present on the southern end of the property and is abbreviated along La Platte Road, and second, the limestone has a dip that could exceed 25 degrees in places across the crest. Other poor areas would be through the highly faulted and folded area identified on the west extreme of line 3. The poor data quality in this area compounded with the most pronounced diffraction patterns of anywhere else surveyed are key indicators of a highly altered and rubbled layer.

Areas identified as with moderate potential have reduced thickness of the target limestone or have minor faulting/folding present. Faulting in these areas generally are interpreted to have offsets less than 16 ft (5 m) where the limestone appears to be at least 162 ft (50 m) thick. A potential problem in these areas might be water that gains access to the mine through these faults. Folds are also present in these areas but with minor curvatures, producing dips of less than 10 to

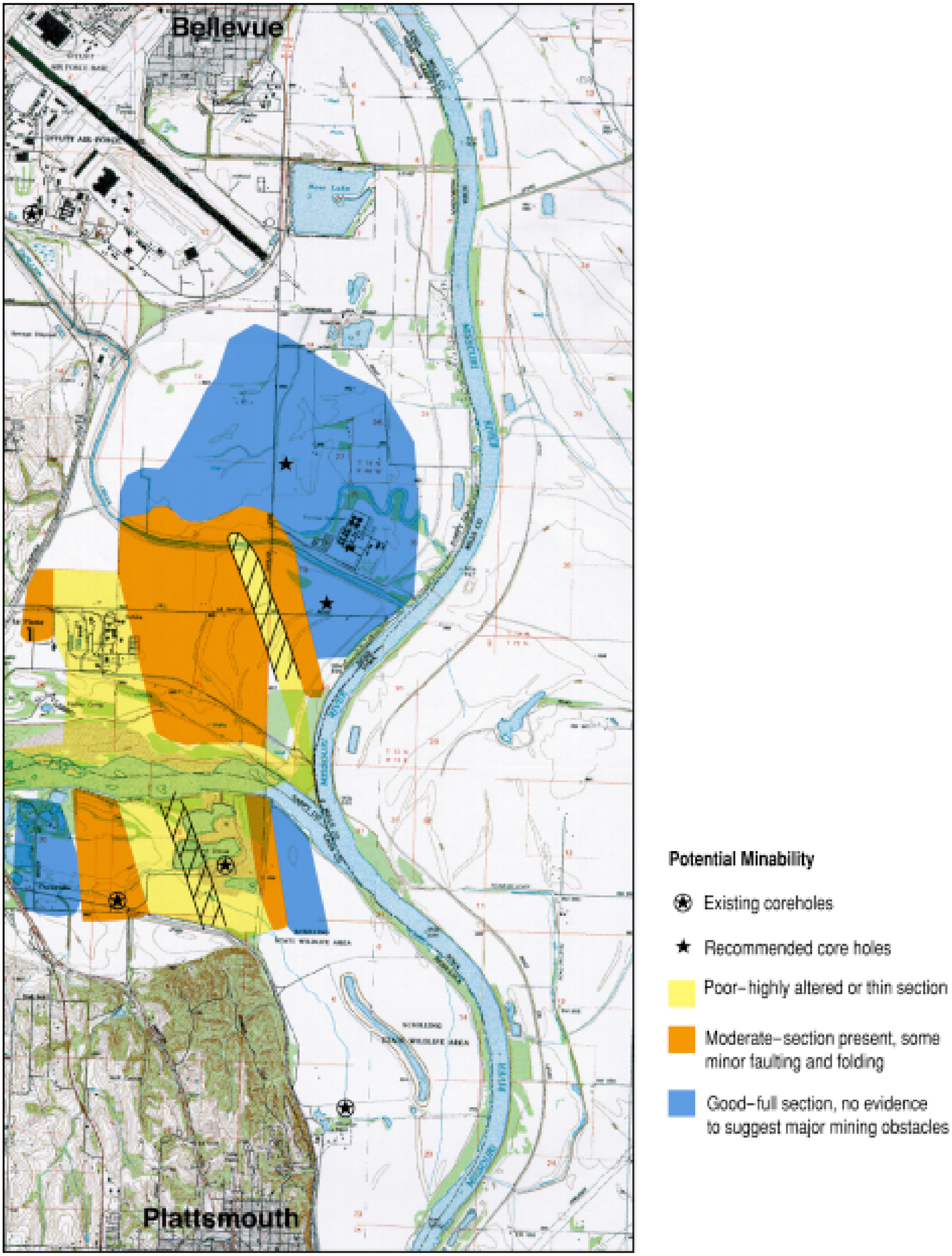
Bellevue
Plattsmouth
Potential Minability
Existing coreholes
Recommended core holes
Poor- highly altered or thin section
Moderate- section present, some minor faulting and folding
Good- full section, no evidence to suggest major mining obstacles

Figure 28.

15 degrees. These may be problematic from a mine-engineering perspective considering the maximum grade for haul trucks is usually around 10 percent.

Locations characterized as good have little or no faulting interpreted, possess what appears to be a full Mississippian section (based on what was discovered in 02-17D), and only regional dips. The most promising areas are at the eastern extreme of the survey area and north of the eastern half of the La Platte line. A small area on the western extreme of the Lyman-Richey property also has excellent data quality and appears to be outside the structurally altered zone. A great deal of unexplored potential lies immediately east and south of the Lyman-Richey plant beneath the Schilling State Wildlife Area.

The only true confirmation of these kinds of data and interpretations comes from boring data. Two locations have been identified which will provide both ground truth for the seismic data and appraise the resource potential in an area inferred from seismic data as good. Drilling priority would be the hole located closest to the La Platte Road seismic line with the northern hole second. The northern hole might even be best belayed until more seismic is acquired in that area to confirm the presence of undisturbed Mississippian rock. Seismic further north might provide a better location and reduce the number of holes necessary to fully appraise the resource.

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