01 Apr 1995

Vertical Resolution of a Seismic Survey in Stratigraphic Sequences less than 100 m Deep in Southeastern Kansas

Richard Daniel J. Miller

Neil Lennart Anderson
Missouri University of Science and Technology, nanders@mst.edu

Howard Randall Feldman

Evan K. Franseen

GEOPHYSICS, VOL. 60, NO. 2 (MARCH-APRIL 1995); P. 423–430, 7 FIGS.

Vertical resolution of a seismic survey in stratigraphic sequences less than 100 m deep in southeastern Kansas

Richard D. Miller*, Neil L. Anderson‡, Howard R. Feldman*, and Evan K. Franseen*

ABSTRACT

A 400-m long, 12-fold high-resolution common depth point (CDP) reflection seismic profile was acquired across shallow converging Pennsylvanian strata in the Independence area of southeastern Kansas. One of the principal objectives was to determine practical vertical resolution limits in an excellent shallow seismic-data area with borehole control.

The dominant frequency of the CDP stacked data is in excess of 150 Hz based on peak-to-peak measurements. Interference phenomena observed on stacked seismic data incorporated with models derived from log and drill-hole information suggest a practical vertical resolution limit of about 7 m, or one-third of the dominant wavelength. This practical resolution is slightly less than the predicted (theoretical) resolution limit of 5 m based on the generally accepted one-quarter wavelength axiom. These data suggest conventional rules of thumb describing resolution potential are not accurate when reflectors on shallow, narrow bandwidth data converge rapidly across horizontal distances less than the Fresnel Zone.

INTRODUCTION

A high-resolution seismic-reflection profile was acquired in the Independence area of Montgomery County, southeastern Kansas. The geologic objective was to conclusively establish that the shallow Pennsylvanian-age Winterset Limestone and Mound Valley Limestone converge due to the associated thinning of the Galesburg and Stark shales (Figure 1). The geophysical goal was to empirically determine practical limits of resolution along converging high-amplitude seismic events in an area where well control was available and seismic-data quality was known to be excellent.

The 12-fold common depth point (CDP) profile was designed to image geometric changes greater than 2 m at depths from 25 to 100 m in a depositional shelf-to-basin environment dominated by limestones, sandstones, and shales (Feldman and Franseen, 1991). The integration of cores, electric logs, check shot survey data, synthetic seismograms, and modeling of the seismic reflection data was used to verify the geologic interpretation. Comparisons of synthetic seismograms and real data were used to estimate the practical resolution of the seismic-reflection data at various depths. These comparisons indicate that practical resolution in the study area is on the order of one-third wavelength and that greater resolution such as that reported by Gochioco (1991, 1992) might be unrealistic in situations such as the one studied here.

RESOLUTION

Classically the measure of the resolving power of seismic reflection data has depended, for the most part, on the dominant frequency of the recorded reflection wavelet and average acoustic velocity of the material (Widess, 1973). Since velocity is generally not considered to be variable, improved resolution has generally come from increasing the dominant recorded reflection frequency. Increasing the dominant frequency of a recorded reflection signal has generally involved increasing the frequency of the source pulse by varying the source configuration, type, and total energy (Knapp and Steeples, 1986). Empirically, for shallow reflection data, higher frequency and relatively broadband-reflected wavelets are more easily recorded in areas with high saturation and where unconsolidated near-surface sediment are relatively thick, well-sorted, and fine-grained.

Resolution also depends on the phase of the recorded wavelet (Koefoed and Voogt, 1980). The wavelet phase of most low energy impulsive surface seismic sources is hybrid

Manuscript received by the Editor March 8, 1993; revised manuscript received July 13, 1994.
*Kansas Geological Survey, 1930 Constant Ave., Campus West, University of Kansas, Lawrence, KS 66047.
‡Formerly Kansas Geological Survey, Lawrence, KS 66047; presently Dept. of Geology and Geophysics, 125 McNutt Hall, University of Missouri-Rolla, Rolla, MO 65401.

minimum phase (mixed phase) with some dependence of that phase on near-surface conditions (Miller et al., 1986, 1992). Since a zero phase wavelet possesses the highest resolution potential (Schoenberger, 1974), phase filtering or deconvolution is commonly used to collapse the source wavelet to nearly a spike with zero phase. Deconvolution requires a minimum-phase wavelet, a reflectivity series with a white spectrum, high signal-to-noise ratio, and a uniform power spectrum (Yilmaz, 1987). The relatively few reflection events, narrow bandwidth, and notoriously noisy nature of shallow reflection data sets (Steeples and Miller, 1990) make it rarely possible to improve resolution through deconvolution without significantly reducing the signal-to-noise ratio over portions of the stacked data set. Because of the inherent difficulties associated with wavelet processing of shallow-reflection data (<100 m), the emphasis, measure, and assertions of resolution potential have generally focused on dominant reflection frequencies.

Resolution of thin-bed sequences generally relies on interference observations as evidenced by distortion of reflection waveforms (Ricker, 1953; Rüter and Schepers, 1978). Many of these interference characteristics are directly applicable to the resolution of converging reflectors. Amplitude and frequency tuning to form complex waveforms can be indicative of either a thinning bed or variations in reflector sequences (Gochioco, 1991). Modeling studies of reflection

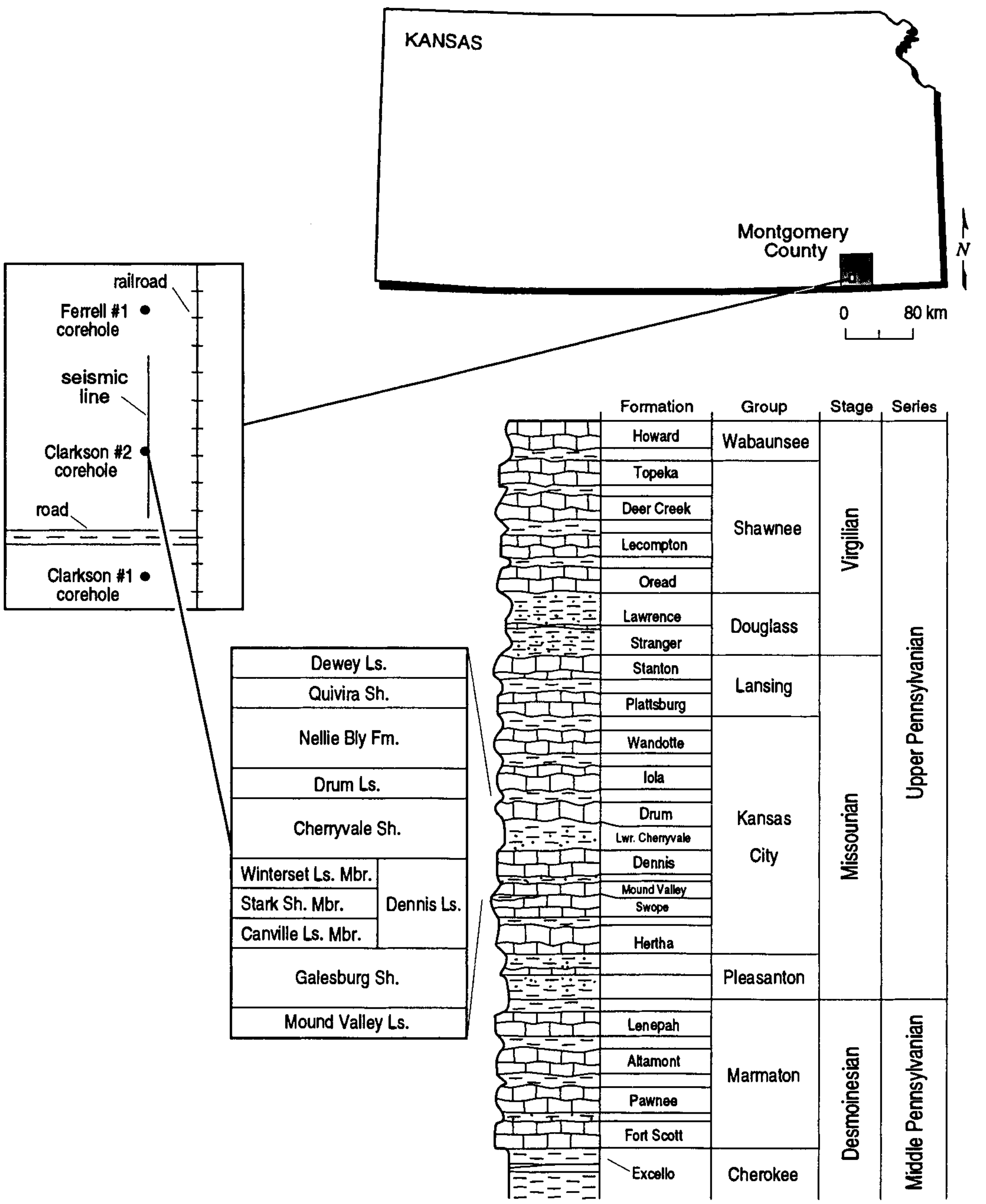

FIG. 1. Location map of study area near Independence, Kansas, with stratigraphic section (after Heckel, 1977).

interference effects suggest beds as thin as one-fortieth the predominant wavelength can produce a distinct, detectable reflection signal (Gochioco, 1992). The ringy nature of multiple reflector sequences complicate the modeled response, making the amplitude and frequency criteria for detecting beds less than one-quarter the dominant wavelength (tuning frequency) nearly impossible with nonzero phase wavelets and interbed multiples (Knapp, 1990). Limited bandwidth, interbed multiples, nonzero phase wavelets, lateral variations in source wavelet, marginal signal-to-noise ratio, and relatively few reflection arrivals complicate detection of, or geometric changes in, reflectors separated by less than one-quarter the dominant wavelength.

FIELD PROCEDURES

The high-resolution seismic reflection data were acquired with a 15-bit EG&G Geometrics 2401 seismograph. Production lines were acquired with a 1/2 ms sampling interval, 100-Hz analog low-cut filter (18 dB/octave rolloff from their indicated −3 dB point), and 500-Hz analog high-cut filters. The dynamic range of the seismograph was more than adequate to record high-quality reflection information in the presence of source-generated and cultural noise at this site.

The source and receivers for the production survey were selected after an extensive series of walkaway noise tests. The spectral and total energy characteristics of the downhole .50-cal. seismic source (Steeples et al., 1987) made it the source of choice at this site for this geologic target. The receiver array for the production survey consisted of three Mark Products L28E 40 Hz geophones equally spaced over approximately 1 m and centered on each station. Acquisition parameters and available equipment were optimized for site conditions.

The nominal 12-fold CDP production line was acquired using an end-on source/receiver geometry. The optimum recording window possessed a source-to-nearest-receiver offset of 12.5 m and a source-to-farthest-receiver offset of 70 m for a total spread length of 58 m and a station spacing of 2.5 m (Hunter et al., 1984). A large component of direct and refracted wave energy inhibited closer source-to-receiver offsets and, therefore, the recording of the more desirable near-vertically incident reflected energy. The primary target reflector is approximately 70 m deep with the secondary target around 35 m deep.

DATA PROCESSING

The 24-channel data were processed into a CDP stacked section at the Kansas Geological Survey using commercial software. Extreme care was taken during the editing process to ensure removal of as much nonreflection energy as possible. Velocity analysis incorporated iterative constant velocity stacking with detailed, one-fifth wavelength, surface-consistent statics to improve the accuracy of the velocity model and the frequency content of the reflected wavelets. Designation of NMO stretch of less than 15% was necessary to minimize spectral and amplitude deterioration of the shallower reflections (Miller, 1992). Prestack analysis was emphasized during the processing of this data set.

Differentiating reflection energy from seismic noise on field files is essential for confident and consistent interpretations on shallow seismic stacked sections (Figure 2). Refraction arrivals, present as first breaks on seismograms, were meticulously removed. Ground roll was easily attenuated with the prestack digital filter. The air-coupled wave arrived outside the optimum recording window and presented no problems. The 60 Hz and higher mode (180 Hz) electrical noise from pipelines and power lines strongly affected files from the north end of the survey, inhibiting optimization of the digital filter. Identifying each unique energy arrival on field files improved the accuracy of selected acquisition and processing parameters and therefore the resolution potential of the stacked section.

All raw field files have at least one confidently identifiable reflection event. The Winterset Limestone reflection is interpreted at approximately 60 ms (Figure 2). The reflection at 35 ms is evident on filtered field files and is interpreted as the top of the Nellie Bly Formation or the unnamed sandstone. The dominant frequency of reflection energy on field files ranges from 150 to over 250 Hz (based on peak-to-peak measurements). After CDP stacking (Figure 3) the dominant frequency of the 35 ms reflection event uniformly decreased by as much as 30 percent and the 60-ms event showed about a 20 percent drop in dominant frequency. This poststack drop in dominant frequency is related to NMO wavelet stretch.

MODELING

A geologic cross-section (Figure 4), a corresponding 2-D geologic model (Figure 5), and a synthetic seismogram (Figure 6) were all derived from core and from logs recorded in holes drilled along the seismic line (Clarkson #2 [CDP #494] and Clarkson #1). The geologic model is based on the geologic cross-section with structural and stratigraphic features between the wells based on interpretations of the CDP stacked section. The geometric detail suggested on the geologic model is characteristic of the Missourian strata in the study area. The overall structural and stratigraphic detail, as well as velocities and densities incorporated into the 2-D geologic model (Figure 5), are based on and designed to be consistent with the CDP stacked section, the check shot survey, and the geologic cross-section.

The 2-D synthetic seismogram (Figure 6) was generated from the geologic model using Geophysical Micro-Computer

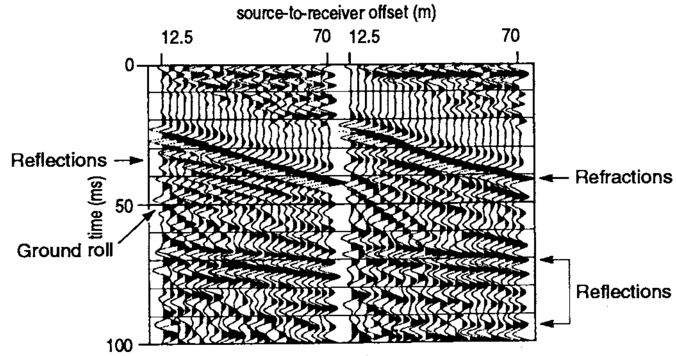

FIG. 2. Two digitally filtered and scaled field files from different locations along the line, each processed identically.

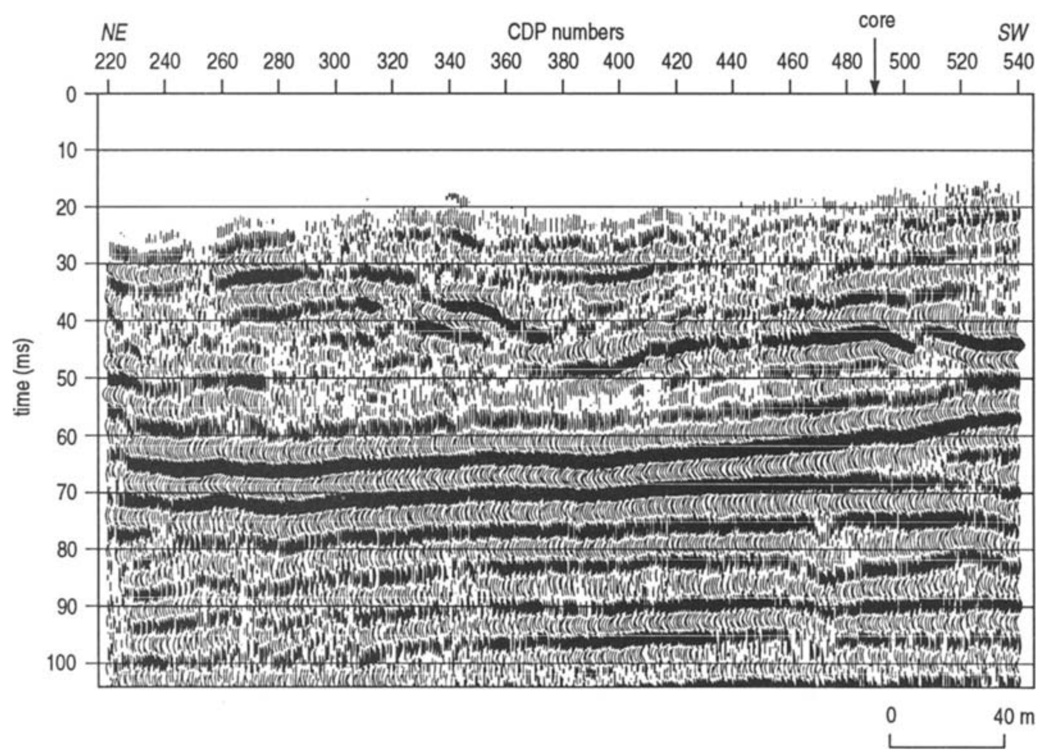

FIG. 3. Uninterpreted high-resolution seismic line. These data were acquired with an EG&G Geometrics 2401 seismograph using a downhole .50-cal. seismic source and receiver arrays consisting of three 40 Hz geophones equally spaced over approximately 1 m and centered on each station. 1024 samples were recorded per trace at a sampling interval of 0.5 ms. Length of seismic line is about 0.4 km (0.25 miles).

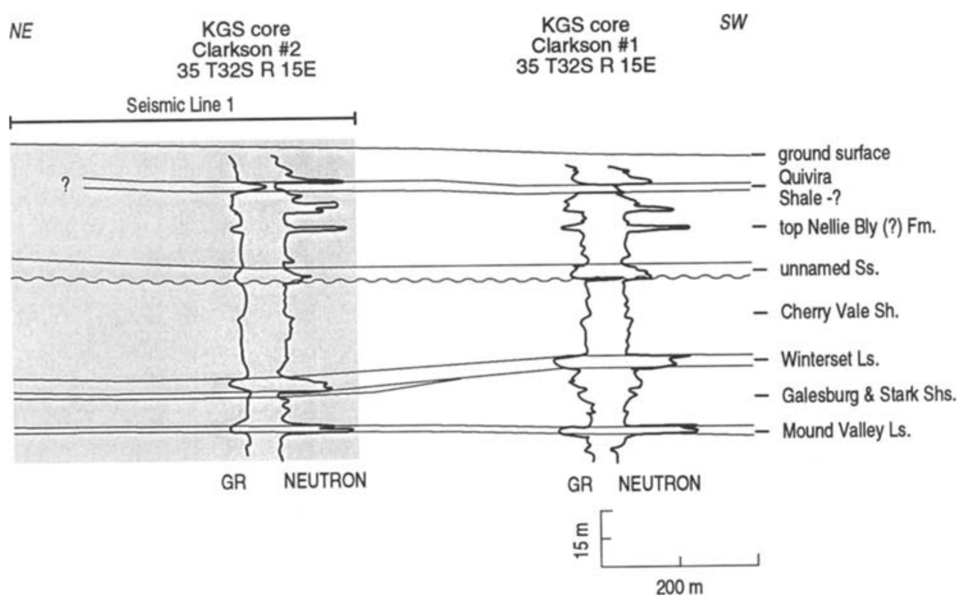

FIG. 4. Geologic cross-section along seismic line based on KGS cores. Shaded box indicates approximate location and thickness of interval models for the synthetic seismic line.

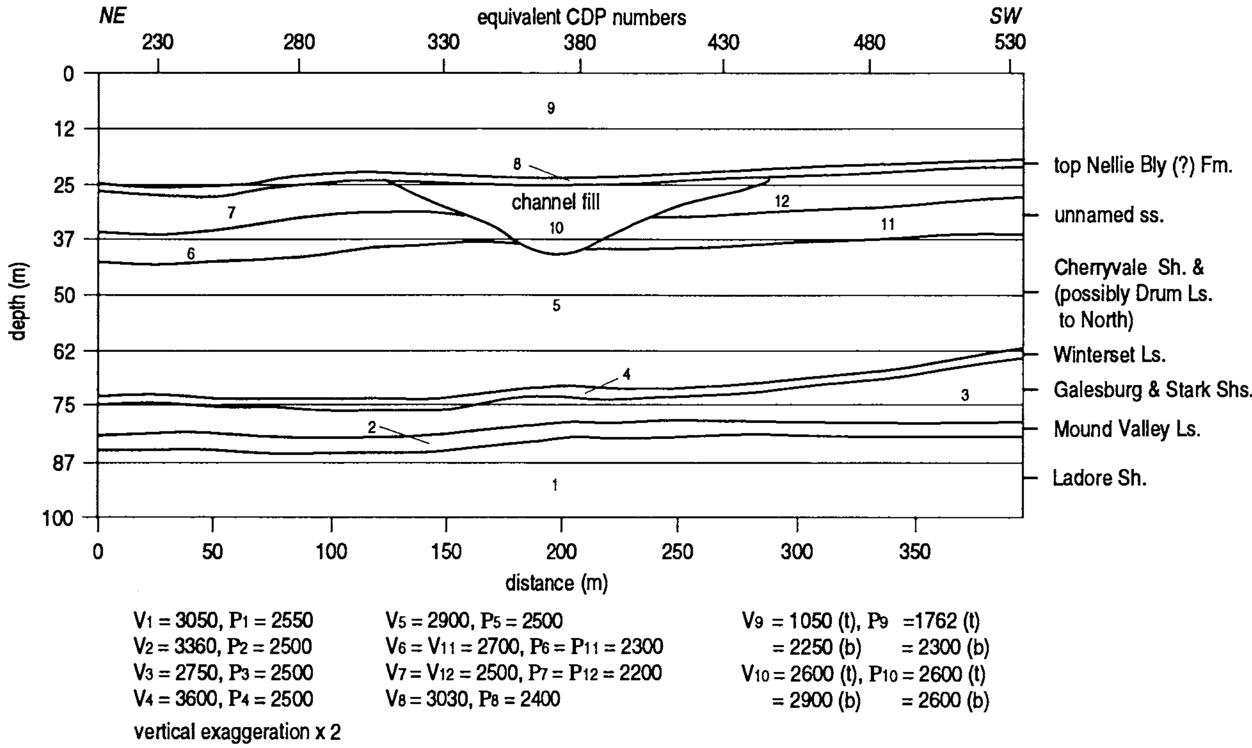

FIG. 5. Two-dimensional geologic cross-section. The geologic cross-section is structurally consistent with well control (Clarkson #2 core) at trace 494 (Figure 3). The velocities and densities incorporated into the model are consistent with the lithologies encountered in the Clarkson core, check shot survey data at the same well site, and stacking velocity control. This cross-section is presented as a reasonable representation of that portion of the subsurface imaged by the seismic control and illustrates some of the geometric details that characterize the Missourian age strata in the study area. For this model, velocity (V = m/s) and density (P = kg/m^3) are defined at each interface and at the top (t) and base (b) of the channel fill.

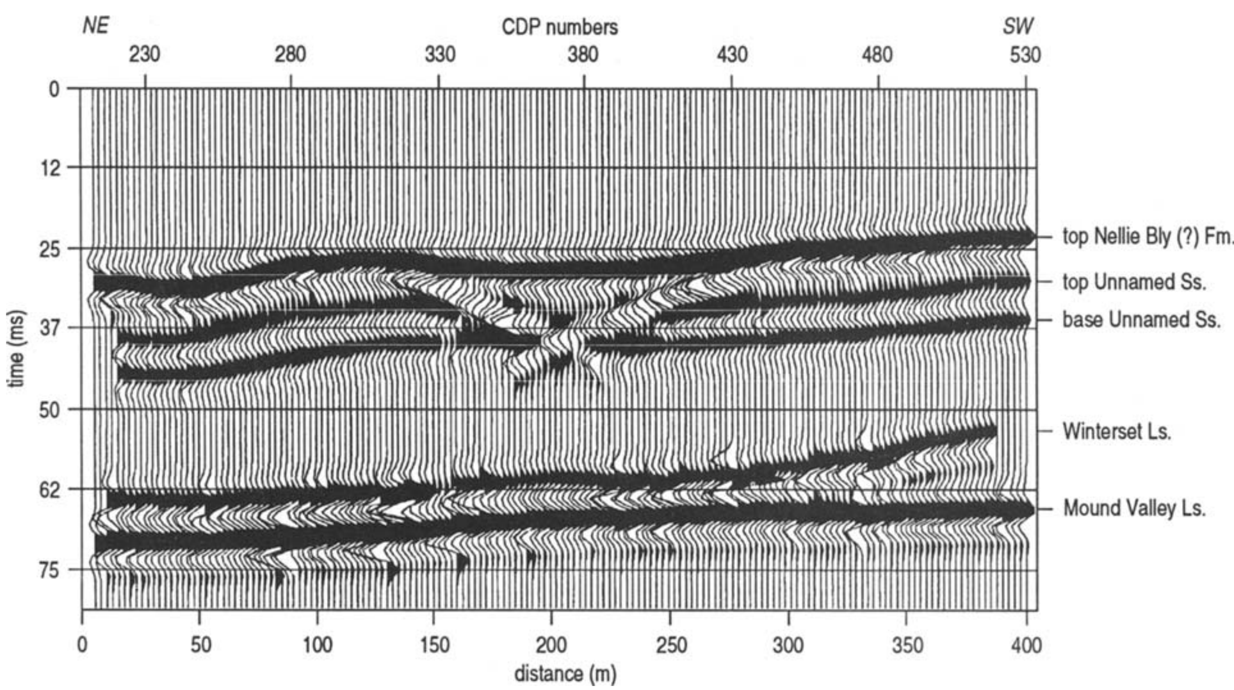

FIG. 6. Two-dimensional synthetic seismogram generated for the geologic cross-section of Figure 5 using Geophysical Micro-Computer Ltd. diffraction modeling software. A 150 Hz, zero-phase, normal-polarity Ricker wavelet was used. More prominent events on the synthetic seismogram have been labeled to facilitate comparisons between the geologic model, synthetic seismogram, and seismic line.

Ltd. diffraction modeling software. The model uses a 150 Hz, zero-phase, normal-polarity Ricker wavelet. The more prominent events on the synthetic seismogram have been labeled to facilitate comparisons between the geologic model, synthetic seismogram, and stacked seismic section.

Of particular interest on the geologic model and the synthetic seismogram is the convergence of the Winterset Limestone and Mound Valley Limestone. At the Clarkson #1 borehole, the separation between the top of the two limestone units is about 12 m or three-fifths wavelength (based on 150 Hz wavelet and 3000 m/s velocity). Wavelet interference effects at this three-fifths dominant wavelength separation are evident on the synthetic seismogram (Figure 6). At trace 400, to the north of the Clarkson #1 borehole, the vertical separation decreases to 5 m (about one-quarter wavelength). On the synthetic seismogram, the apparent response at 7 m reflector separation is nearly the same as that observed at 5-m separation. From a practical perspective it is difficult to visually determine where the two limestone events begin to tune. Based on the zero-phase synthetic seismogram alone, bed separations of less than 7 m (one-third wavelength) cannot be estimated accurately.

The reflection wavelets from the top of the Winterset Limestone within the transition zone (region where the Winterset goes from nearly horizontal to possessing apparent dip) could possess sufficient vertical and horizontal variability to adversely affect both apparent resolution and wavelet suppression techniques. This effect is related to the diffraction modeling method. This subsurface smearing could cause the resolution to be less than predicted near the interpreted convergence.

Further to the north of the Clarkson #1 well, the modeled beds diverge to around 10 m, producing wavelet interference similar to that observed near the borehole. With respect to the interpretation of the synthetic seismogram, both wavelet frequency and wavelet interference are effective interpretation tools down to thicknesses of about one-third the dominant wavelength, but some speculation is necessary to infer bed thicknesses of one-quarter or less the dominant wavelength in this cyclic, thin-bed environment.

SEISMIC DATA

Event identification on the CDP stacked section (Figure 7) is based on correlation at the borehole tie point with the synthetic seismogram (Figure 6). The time positions of identified horizons are consistent with geologic control (Clarkson #2 well site), stacking velocities, and the check shot survey (Clarkson #2).

The two most striking features on the seismic profile are the channel cut-and-fill feature centered on CDP 380 at about 40 msec (45 m) depth and the converging Winterset and Mound Valley limestone reflectors at approximately 65 msec (80 m) depth on the southwest end of the seismic section.

With respect to practical vertical resolution limits, the most significant feature on the seismic section is the convergence of the Winterset and Mound Valley limestone reflectors (Figure 7; at about 65 ms, between CDPs 440 and 520). Interference between the Winterset and Mound Valley events is very pronounced at CDP 490, where the interval thickness is 12 m (about three-fifths wavelength), and farther north where the interval decreases more.

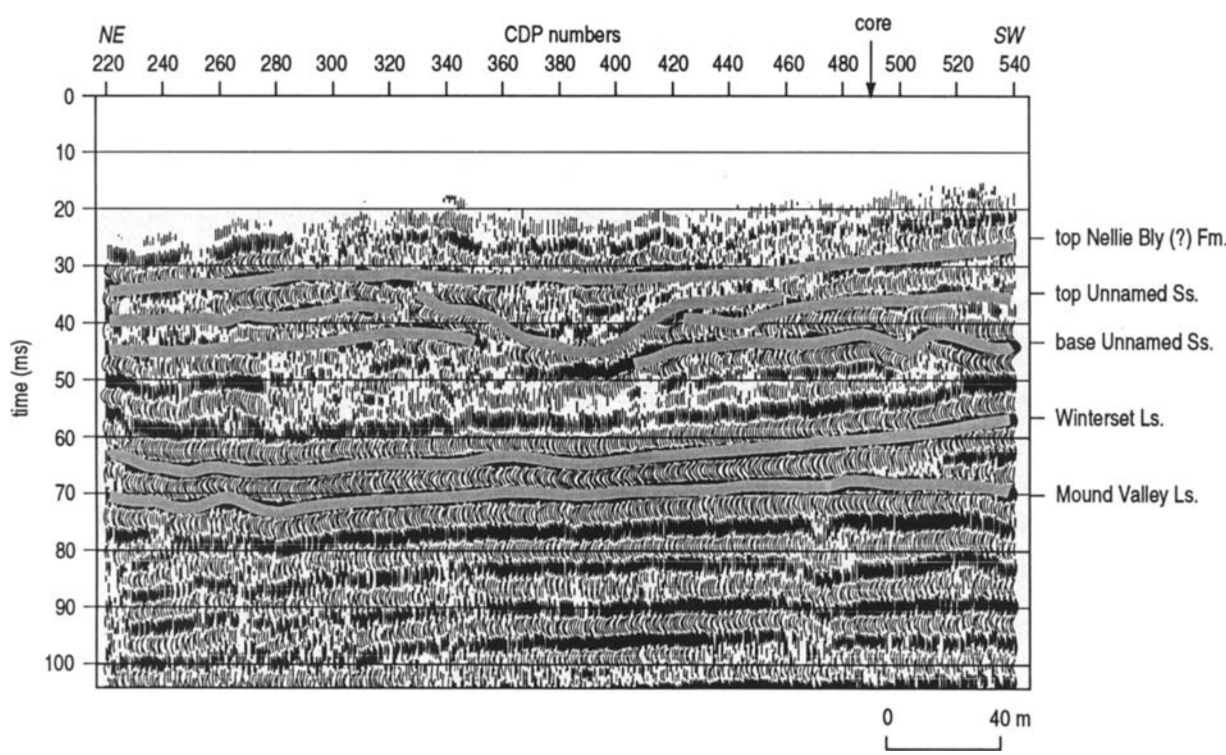

FIG. 7. Interpreted 12-fold CDP stacked section. This is the interpreted version of the section presented in Figure 3. The buried channel and converging beds can be identified easily.

The dominant frequencies of the Winterset and Mound Valley limestone events on the stacked seismic section exceed 150 Hz. The average velocity from the top of the Winterset Limestone to the top of the Mound Valley Limestone is on the order of 3000 m/s. A quarter of the dominant wavelength within this interval is approximately 5 m.

The Winterset Limestone and Mound Valley Limestone reflections tune to varying degrees between CDPs 420 and 480. Optimum tuning seems to occur between CDPs 420 and 446. Without the benefit of well control and associated modeling within this segment, we could assume, based on quarter wavelength interference phenomena, that the Winterset/Mound Valley interval thins to around 5 m. However, the synthetic seismogram exhibits similar tuning when the Winterset/Mound Valley interval is greater than 7 m. This suggests that interpreting convergence (reflector discrimination) less than one-third the dominant wavelength is not a prudent practice for these data at this site.

Based on predicted subtle amplitude and frequency interference effects when reflector separation is less than one-half the dominant wavelength, interpretation of unique reflectors separated by less than one-third the dominant wavelength at this site would require extremely high quality data (i.e., high signal-to-noise and broad bandwidth), vertically and horizontally consistent stacked reflection wavelets, and perhaps even extraordinary subsurface well control for confirmation. Observations on this high quality data set (for shallow reflection data) suggest vertical resolution less than one-third wavelength should not be considered obtainable routinely.

Resolution could have been affected by both the dip of the Winterset Limestone (as suggested during discussion of the model) and by the anomaly associated with the unnamed sandstone unit at approximately 45 ms beneath CDP 500 (Figure 3). The significant change in dip within a Fresnel zone could have been responsible for some wavelet smearing and for a drop in both bandwidth and dominant frequency. Considering the rate of change in dip (10 m vertical in 100 m horizontal) and the diameter of a Fresnel zone at 80 m depth (approximately 50 m), the magnitude of the smearing problem is evident. Of potentially equal significance is the apparent offset in the unnamed sandstone reflector directly above the Winterset Limestone reflector near CDP 500. The change in the velocity function and the interference caused by this interpreted erosional feature could have impacted the resolution around the area of maximum convergence. Without incorporating this erosional feature into the model, correlation between the synthetic and the real data is extremely good within the convergence zone, implying the insignificance of this feature in interpreting fractional wavelength interference effects.

CONCLUSIONS

Seismic-reflection data at this site have the potential to detect stratigraphic features with vertical separation down to about 7 m (one-third wavelength) at a depth of around 70 m. This practical resolution is less than the predicted 5 m quarter-wavelength resolution potential. In our opinion, the principal reason for the difference between the practical and theoretical limits of resolution observed here is that the Winterset and Mound Valley reflectors thin significantly within one Fresnel zone. Additionally, resolution could have been affected by the laterally inconsistent nature of the reflection wavelet, relatively narrow bandwidth reflection wavelet, and the rugosity of the reflecting horizons. The lack of detailed subsurface control precludes direct correlation of observed interference effects (amplitude and frequency variations) with changing interval thicknesses and diminishes the resolution potential of the survey.

We recognize that the resolution limits at this site could be less than one-third wavelength for extremely high quality broad-band data. This would require the qualitative analysis of wavelet interference and characteristics, recording of the actual source signature, and substantial subsurface control (for both confirmation and acoustic measurements). Without ground truth based on several accurately placed coreholes and associated well logs, resolution less than 7 m, or one-third the dominant wavelength, is not feasible in this cyclic thin bed environment. The synthetic section supports the practical resolution limits of the seismic section.

In a practical sense, expectations of vertical resolution less than one-third wavelength may be beyond the potential of most shallow reflection data. This data set possesses bandwidth, dominant frequency, and coherent reflection events consistent with or slightly better than most surveys that target objectives less than 100 m deep in areas where the water table is more than 10 m deep. Some improvement in bandwidth and dominant frequency, and therefore resolution, could be expected where fine-grained, saturated near-surface conditions exist.

ACKNOWLEDGMENTS

The data for this paper were acquired with support from the U.S. Department of Energy (DOE Grant #DE-FG07-90BC14434). However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the DOE. We thank Jesse Clarkson and Warren Ferrell for allowing access to their land for the purposes of coring and seismic acquisition. We would also like to thank Mary Brohammer for assistance in preparing this manuscript, Pat Acker for her quality graphics, and Rex Buchanan for his editorial comments. Special thanks also to Dwain Butler (as Associate Editor he tackled this manuscript at least twice), Richard Adair, Ray Brown, and two other reviewers for their frank and very objective comments.

REFERENCES

Feldman, H. R., and Franseen, E. K., 1991, Stratigraphy and depositional history of the Drum Limestone and associated strata (Pennsylvanian) in the Independence, Kansas, area: A Field Trip Guidebook and Road Log: Kansas Geol. Surv. Open-file report 91-45.

Gochioco, L. M., 1991, Tuning effect and interference reflections from thin beds and coal seams: Geophysics, **56**, 1288–1295.

——— 1992, Modeling studies of interference reflections in thin-layered media bounded by coal seams: Geophysics, **57**, 1209–1216.

Heckel, P. H., 1977, Origin of phosphatic black-shale facies in Pennsylvanian cyclothems of midcontinent North America: Am. Assoc. Petr. Geol. Bull., **61**, 1045–1068.

Hunter, J. A., Pullan, S. E., Burns, R. A., Gagne, R. M., and Good, R. S., 1984, Shallow seismic-reflection mapping of the overburden-bedrock interface with the engineering seismograph—some simple techniques: Geophysics, **49**, 1381–1385.

Knapp, R. W., 1990, Vertical resolution of thick beds, thin beds, and thin-bed cyclothems: Geophysics, **55**, 1183–1190.

Knapp, R. W., and Steeples, D. W., 1986, High-resolution common-depth-point, seismic-reflection profiling: Field acquisition parameter design: Geophysics, **51**, 283–294.

Koefoed, O., and de Voogd, N., 1980, The linear properties of thin layers, with an application to synthetic seismograms over coal seams: Geophysics, **45**, 1254–1268.

Miller, R. D., 1992, Normal moveout stretch mute on shallow-reflection data: Geophysics, **57**, 1502–1507.

Miller, R. D., Pullan, S. E., Steeples, D. W., and Hunter, J. A., 1992, Field comparison of shallow seismic sources near Chino, California: Geophysics, **57**, 693–709.

Miller, R. D., Pullan, S. E., Waldner, J. S., and Haeni, F. P., 1986, Field comparison of shallow seismic sources: Geophysics, **51**, 2067–2092.

Ricker, N., 1953, Wavelet contraction, wavelet expansion, and the control of seismic resolution: Geophysics, **18**, 769–792.

Rüter, H., and Schepers, R., 1978, Investigation of the seismic response of cyclically layered carboniferous rock by means of synthetic seismograms: Geophys. Prosp., **26**, 29–47.

Schoenberger, M., 1974, Resolution comparison of minimum-phase and zero-phase signals: Geophysics, **39**, 826–833.

Steeples, D. W., and Miller, R. D., 1990, Seismic-reflection methods applied to engineering, environmental, and groundwater problems, *in* Ward, S., Ed., Geotechnical and environmental geophysics, Review and Tutorial, 1: Soc. Explor. Geophys., 1–30.

Steeples, D. W., Miller, R. D., and Knapp, R. W., 1987, Downhole .50-caliber rifle—An advance in high-resolution seismic sources: 57th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 76–78.

Widess, M. B., 1973, How thin is a thin bed?: Geophysics, **38**, 1176–1180.

Yilmaz, O., 1987, Seismic data processing, *in* Doherty, S. M., Ed., Neitzel, E. B. series Ed., Series: Investigations in geophysics, no. 2: Soc. Explo. Geophys.