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Feasibility of CDP seismic reflection to image structures in a 220-m deep, 3-m thick coal zone near Palau, Coahuila, Mexico

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ABSTRACT

The common-depth-point (CDP) seismic-reflection method was used to delineate subsurface structure in a 3-m thick, 220-m deep coal zone in the Palau area of Coahuila, Mexico. An extensive series of walkaway-noise tests was performed to optimize recording parameters and equipment. Reflection events can be interpreted from depths of approximately 100 to 300 m on CDP stacked seismic sections. The seismic data allow accurate identification of the horizontal location of the structure responsible for a drill-discovered 3-m difference in coal-zone depth between boreholes 150 m apart. The reflection method can discriminate folding with wavelengths in excess of 20 m and faulting with offset greater than 2 m at this site.

INTRODUCTION

Faults and folds can be compensated for during mine planning and engineering if their location and displacement or geometry is known before the mining operation begins. The effectiveness of the shallow-seismic technique is extremely near-surface dependent. With the exception of scale, the common-depth-point (CDP) seismic-reflection methodology employed here to study a 3-m thick coal zone was similar to the method as applied to petroleum exploration.

The CDP seismic-reflection method has been successfully used to delineate near-surface structures in a variety of geologic settings (Myers et al., 1987; Treadway et al., 1988; Miller et al., 1990). The parameters and equipment for mapping targets shallower than 200 m with the seismic-reflection method must be optimized for depth of interest and near-surface conditions (Knapp and Steeples, 1986). The source must be capable of generating a consistent, high-frequency, acoustic impulse with energy levels appropriate for the depth of interest. Receivers must have a high level of sensitivity and a flat response to energy to at least 400 Hz. A seismograph with a large instantaneous dynamic range and selectable low-cut filters is critical in most shallow recording environments.

High-resolution seismic-reflection techniques have been successful in locating and quantifying faults representing obstacles to subsurface coal-mining operations in areas with a shallow water table and fine-grained near-surface materials (Gochioco and Cotten, 1989). Extensive and expensive drilling programs have been the primary source of data possessing detail necessary to map shallow structures significant to most mining operations. Evaluation by drilling generally offers limited horizontal resolution. The comparatively continuous subsurface sampling possible with the CDP seismic-reflection method has the potential to allow identification of subsurface anomalies significantly smaller than mineral exploration or evaluation drill-hole intervals. The high-resolution seismic-reflection technique cannot replace drilling, but used in conjunction with a well-planned drilling program, it can significantly increase knowledge of subsurface geology in less time and at a decreased cost.

GEOLOGIC SETTING

The study area is within the Coahuila Coal District (Sabinas-Monclova) in the east-central part of the state of Coahuila, Mexico, in the Coahuila Basin and Range physiographic province (Figure 1). The Sabinas-Monclova Coal District consists of extensive plains and bolsons within which coal-bearing sub-basins occupy synclinal structures separated by steeply dipping anticlinal limestone ranges (Galicia, 1991). This seismic survey was conducted near an active mining area at the northwest end of the Sabinas sub-basin.

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The coal deposits in the Sabinas sub-basin are irregularly distributed, appearing in lenticular layers within synclinal structures developed in the sedimentary rocks. The coal lenses consist of a series of seams ranging from a few centimeters to 2 m thick, interbedded with carbonaceous shales, siltstones, and sandstones at the base of the Upper Cretaceous Olmos Formation. The coal zone ranges in thickness from 3 to 30 m across the sub-basin. The number of coal seams within the coal zone ranges from 15 to 2. The reduced number of seams in some areas is probably associated with ancient distributary paleochannels where extensive erosion of the coal and deposition of sandstone has occurred.

The near-surface material along the survey line consists of a thick limestone conglomerate overlain by a layer of basalt and an alluvial soil. The water table at this site was approximately 5 m deep at the time of acquisition. The conditions in the upper meter permitted acceptable source and receiver coupling along 90 percent of the line.

DATA ACQUISITION

Data for this study were acquired on an EG&G Geometrics 2401 seismograph. The seismograph amplifies, filters (analog), digitizes the analog signal into a 15-bit word, and stores the digital information in a demultiplexed format. The selected low-cut filters have an 18 dB/octave rolloff from indicated −3 dB points. The production line was acquired with 50 Hz analog low-cut and 500 Hz analog high-cut filters. The 1/5 ms sampling interval resulted in a 5000-Hz sampling frequency and a record length of 409 ms. The dynamic range of the seismograph was more than adequate to record quality reflection information in the presence of high-amplitude source-generated noise and the highly attenuative near-surface at this site.

Walkaway-noise tests

The production seismic profile was preceded by an extensive series of tests. Proper matching of high- and low-cut filters for the acoustic characteristics and targets at this site allowed optimization of the seismograph's dynamic range. Source-to-receiver offsets on walkaways ranged from 5 to 355 m with receivers spaced at 5-m intervals (Figure 2). Source and receiver testing included various high yield explosive and downhole shotguns as sources and groups of three high-output 40 Hz geophones and downhole hydrophones as receivers. Reflections, refractions, ground roll, air-coupled waves, and mode-converted energy can be identified on walkaway data recorded with 50 Hz or greater low-cut filters. Determination of source, receivers, source-to-receiver offsets, and analog filter settings was based on a combination of qualitative and quantitative analyses of test data.

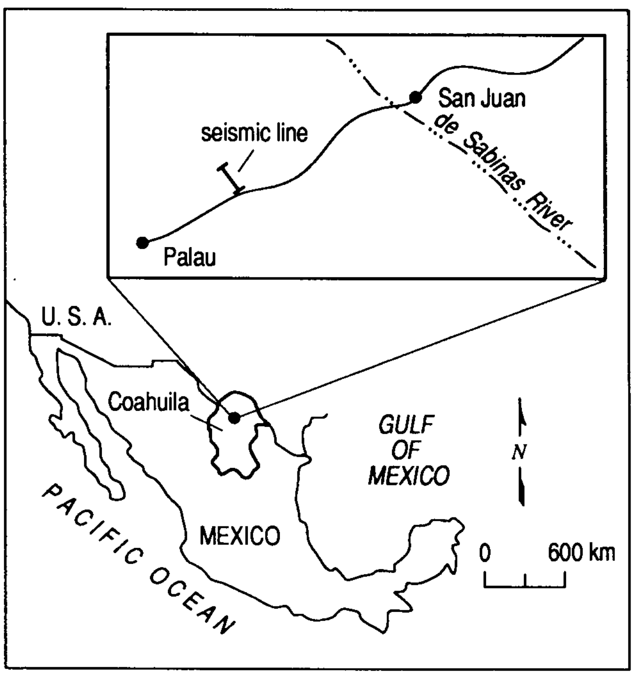

FIG. 1. Site map.

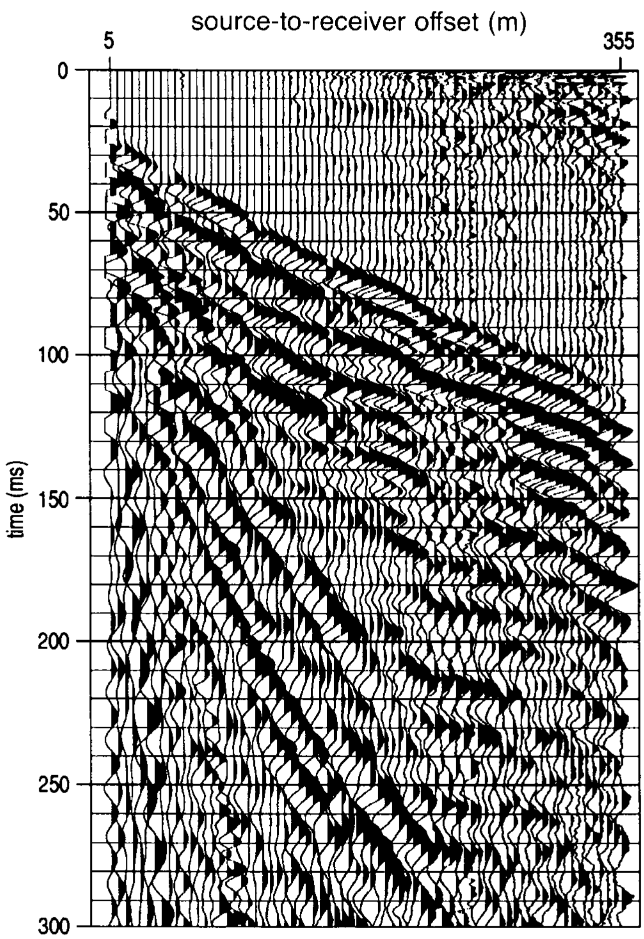

FIG. 2. Seventy-two-trace walkaway with 50-Hz analog low-cut filter, 8-gauge downhole shotgun, and 40-Hz geophones. Indications of higher frequency events with unique arrival curvature are present at source-to-nearest offsets of approximately 100 m and times around 130 ms.

Production data acquisition

Production field parameter selections were based on analysis of appropriate walkaway-noise tests. The downhole 8-gauge shotgun and three, 40-Hz geophones per string were comparatively best suited for the conditions, geologic target, and economics of this study. The receivers were placed in an in-line array with the three geophones equally spaced across a 1-m interval. Station spacings and source-to-receiver offsets were based on walkaway testing and rules of thumb relating optimum subsurface spacing with desired horizontal resolution, depth window of interest, and available recording channels (Hunter et al., 1984).

For production data, the combined total spread length was 220 m with two source-to-nearest-receiver offsets (5 and 105 m) and a 5 m receiver interval. Three different source and receiver configurations were used during recording of the data. The primary geometry was end-on with the source pushing the spread from east to west and a source-to-closest-receiver offset of 105 m. Secondary configurations consisted of end-on geometries, one with the source pushing the spread from east to west and a source-to-closest-receiver offset of 225 m, and the other with the source pushing the spread from west to east and a source-to-closest-receiver offset of 105 m. This recording configuration resulted in an apparent 72-channel asymmetric split-spread geometry with nominal 36-fold coverage.

DATA PROCESSING

Data were processed on an Intel 80386-based microcomputer. The processing flow was similar to those used in petroleum exploration. Data characteristics and scale, unique to shallow reflection data, required a conservative approach to correlation statics, velocity and spectral analysis, and trace-by-trace muting and deconvolution.

Extreme variability in the thickness and composition of near surface material resulted in significant static anomalies on CDP stacked data. These static anomalies inhibited realistic interpretations of subsurface structures on brute stacked seismic sections. A common-offset-statics operation reduced the effects of near-surface irregularities and allowed an accurate interpretation of the stacked data.

Digital bandpass filtering greatly enhanced reflection energy. Low-frequency noise identified on amplitude spectra ranged from 10 to about 60 Hz. A digital band-pass filter with zero percent points at 80 and 220 Hz was applied to the data. The dominant frequency of most reflection energy was between 80 and 110 Hz. The bandwidth and dominant frequency of the reflection signal allowed ground roll energy to be effectively attenuated.

Deconvolution sufficiently decreased reflection coherency and signal-to-noise (S/N) ratios so that reflection events previously coherent were no longer interpretable across the expanse of the section. For deconvolution to operate properly the S/N ratios must be high, several primary reflection events must be present, and wavelet characteristics of all reflections must be consistent (Yilmaz, 1987). Inconsistency in wavelet characteristics and low S/N ratios inhibited effective suppression of the source wavelet using the deconvolution operation.

RESOLUTION

Vertical and horizontal resolution are improved by increasing the dominant frequency and broadening the frequency spectrum of recorded reflection energy (Widess, 1973; Knapp, 1990). Increasing the frequency of recorded energy can often result from increased low-cut filtering, optimized field equipment and procedures for existing conditions, and care during data processing. Severe low-cut filtering attenuates lower frequency information (ground roll and ringy refraction/direct wave), effectively balancing the reflection spectrum toward higher frequencies (Steeples, 1990). Attenuating high-amplitude, low-frequency information allows increased analog amplification (fixed or floating point), which in turn boosts the percentage of useable signal in the digital word. The resolving power of seismic data depends on the dominant reflection frequency, bandwidth surface station spacing, timing accuracy, and accuracy of the velocity function.

Horizontal resolution is based on the effective radius of the first Fresnel zone, which is a factor of $\sqrt{2}$ smaller than the actual radius (Sheriff, 1991). Subsurface spacing for the CDP data is 5 m, and the dominant frequencies range between 80 and 120 Hz, providing seven to nine sample points within the effective radius of the first Fresnel zone at 200 m of depth and 11 to 15 sample points within the effective radius of the first Fresnel zone at 300 m of depth. Analysis of stacked data empirically suggests that the practical horizontal resolution limit of this survey is approximately three to five sample points at 220 m, or about $\frac{1}{2}$ of the effective radius of the first Fresnel zone.

Vertical bed resolution for reflectors less than 200 m deep ranges between 2 and 3 m depending on dominant frequency, average velocity, and validity of the $\frac{1}{8}$ wavelength criteria (Widess, 1973). For reflectors imaged on this survey deeper than 250 m, the vertical bed resolution will range between 3 and 4 m. Accuracy or limit of bed offset determinations for any single reflection is based on timing accuracy, time uncertainty related to near-surface variability, and accuracy of the velocity function. Comparison of calculated vertical change between boreholes 33 and 34 is consistent with actual offsets as calculated from change in reflection arrival time and average velocity. Empirically, vertical offsets of 2 m or more at 200 m of depth should be discernible in this area. Resolution limits of CDP data are a function of dominant reflection frequencies and average velocity.

RESULTS

Unequivocal identification of reflection energy on field files is essential for accurate interpretation of CDP stacked sections. Most raw field files from this data set have at least one confidently identifiable reflection event (Figure 3). Reflections can be interpreted on close offset data as shallow as 80 ms and as deep as 240 ms (Figure 3a, b, c, d). On long offset data, a high confidence set of reflections is interpreted within a time window from approximately 130 ms to 280 ms (Figure 3e, f). The dominant frequency of reflection energy is approximately 70 Hz and independent of time and offset distance. Reflections interpretable on field files strongly support the interpreted reflections on CDP stacked data.

Analysis of processed field files improves confidence in interpretations of CDP-stacked sections (Figure 4) (Steeples and Miller, 1990). Digital filtering, first arrival muting, appropriate trace balancing, bad trace editing, and common offset statics were key to improving the prestack appearance of reflections interpretable on raw field files. Effects of processing (including increased S/N ratio, apparent reflection coherency, and subtle increase in dominant reflection frequencies) are evident when raw field files (Figure 3) are compared to moved-out and processed field files (Figure 4). Indications of near critical-angle reflection energy on processed field files necessitated a careful and a conservative approach to interpreting reflections shallower than 100 ms.

Coherent reflections can be interpreted across the entire CDP stacked section (Figure 5). The CDP stacked section has a nominal fold of 36 (the 36 fold resulted from the multipass acquisition technique described previously). The stacking velocity across most of the line is within ±150 m/s of 2750 m/s. The coal reflection is interpreted to be present at approximately 175 ms. Reflections interpreted to represent acoustic interfaces at or near the coal depth have a subtle eastward dip between boreholes 42 and 34 with approximately 6 to 7 m (5 ms two-way) of relative depth difference.

Subtle stratigraphic features can be interpreted on many parts of the section (Figure 6). Variations in amplitude and frequency of the coal (175 ms) reflection could indicate changes in bed thickness or lithologies. As with the 175 ms event, apparent horizontal changes in frequency and amplitude of reflections between 120 and 160 ms are likely related to stratigraphic variations. The significance of these stratigraphic features, and many others on the stacked section cannot be completely ascertained without more subsurface geologic information.

A monocline or normal fault can be interpreted between boreholes 33 and 34 at the approximate depth of the coal (Figure 6). This structure accounts for about 3 m (about 2 ms two-way time) of vertical change in the coal elevation. Approximately 3 m (2 ms) of difference in reflection elevation across this structure is consistent on all events interpreted between 100 and 300 m of depth. The apparent structure associated with the coal is not consistent with other reflections in a vertical or horizontal sense. Variability

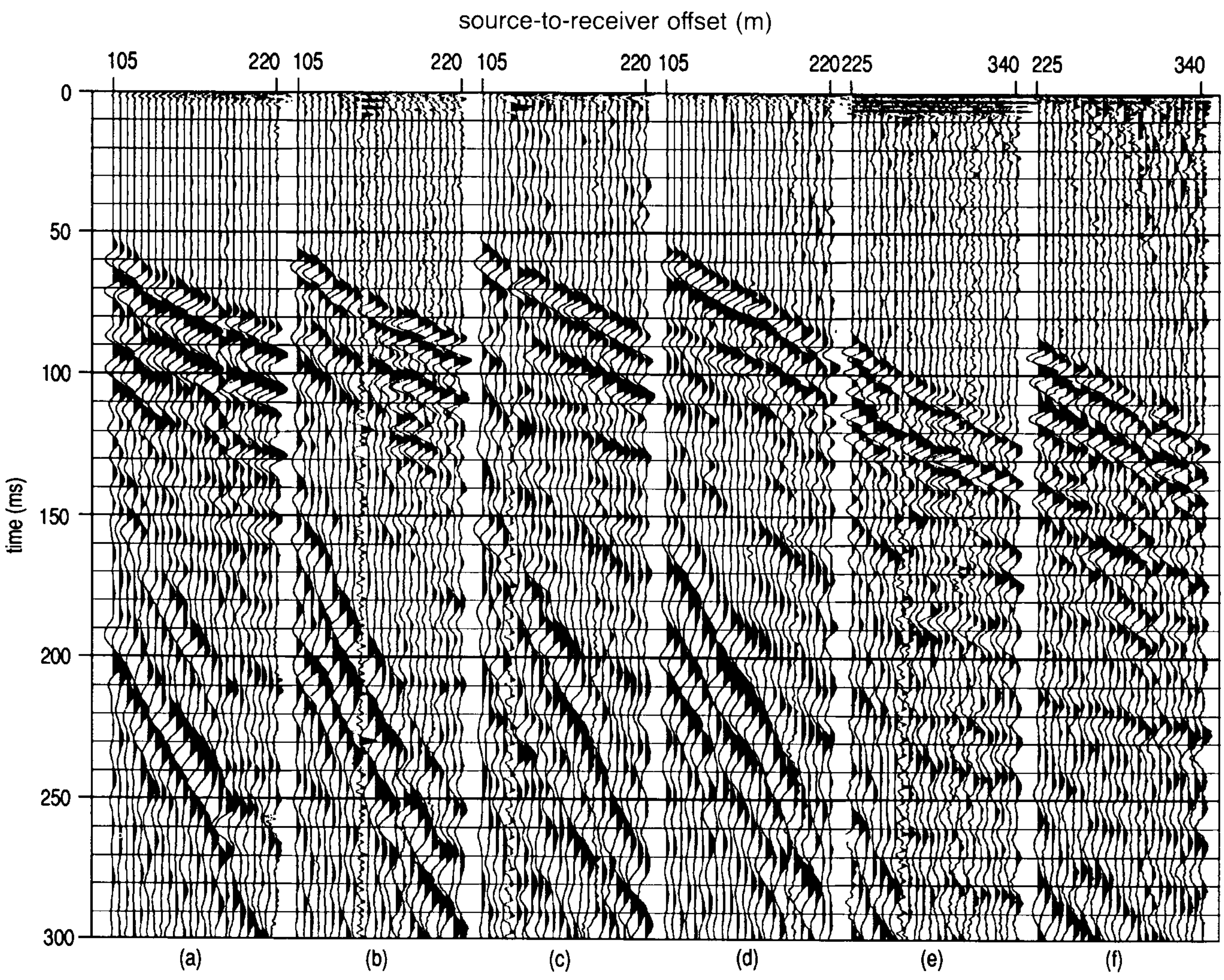

FIG. 3. Selected unprocessed field files. Subtle indications of reflection energy can be interpreted on all six files. Files a-d were collected with source-to-closest-receiver offset of 105 m and e-f were collected with source-to-closest-receiver offset of 225 m.

in reflection slope, inconsistency in the apparent relative two-way time separation, and coherency of reflections between CDP's 35 and 55 suggests the interpreted structure is not the result of an improper static correction.

Time-depth conversions necessary to construct the interpretive cross-section were based on stacking velocities (Figure 7). Vertical and horizontal variations interpretable in shallow stratigraphic units (less than 150 ms) between CDP 40 and 60 are not observable deeper than the coal. This suggests that variations in velocity associated with stratigraphic/structural changes above the coal did not appreciably affect the structural cross-section derived from stacking velocities and two-way times. Folding of the magnitude and irregularity observed here is consistent with interpretations of folding and faulting or fault zones on shallow seismic data from other areas (Treadway et al., 1988; Miller et al., 1990).

The seismically interpreted generalized structure of the coal zone is consistent with the structural cross-section generated from drill information (Figure 7). The stratigraphic precision possible with drill data is not generally possible with seismic data. The 13-m thick stratigraphic section derived from drill data represents slightly less than $\frac{1}{2}\lambda$ of the dominant reflection energy and is therefore within the resolution limits of this survey. The top and bottom of the 3-m thick coal zone is not resolvable with data from this survey.

The seismically derived structural interpretation possesses significantly more horizontal resolution and detail between boreholes than the cross-section produced by interpolating between boreholes. Empirically, the seismic-derived structural cross-section seems to possess horizontal resolution on the order of 15 to 25 m (or ± 7 to 12 m, about $\frac{1}{2}$ the actual radius of the first Fresnel zone).

The major fault zone (the primary target of this survey) must be present at or beyond the eastern limits of the imaged subsurface. Drill information has suggested approximately 16 m of difference in the coal-seam depth between boreholes 42 and 36. The zone of reduced coherency on the east end of the line from 150 ms to the bottom of the section in part is probably related to low fold yielding a reduced S/N ratio. Some indication of diffracted/scattered energy could be interpreted as radiating from the fault zone associated with the 16 m of displacement. The interpreted diffraction and the

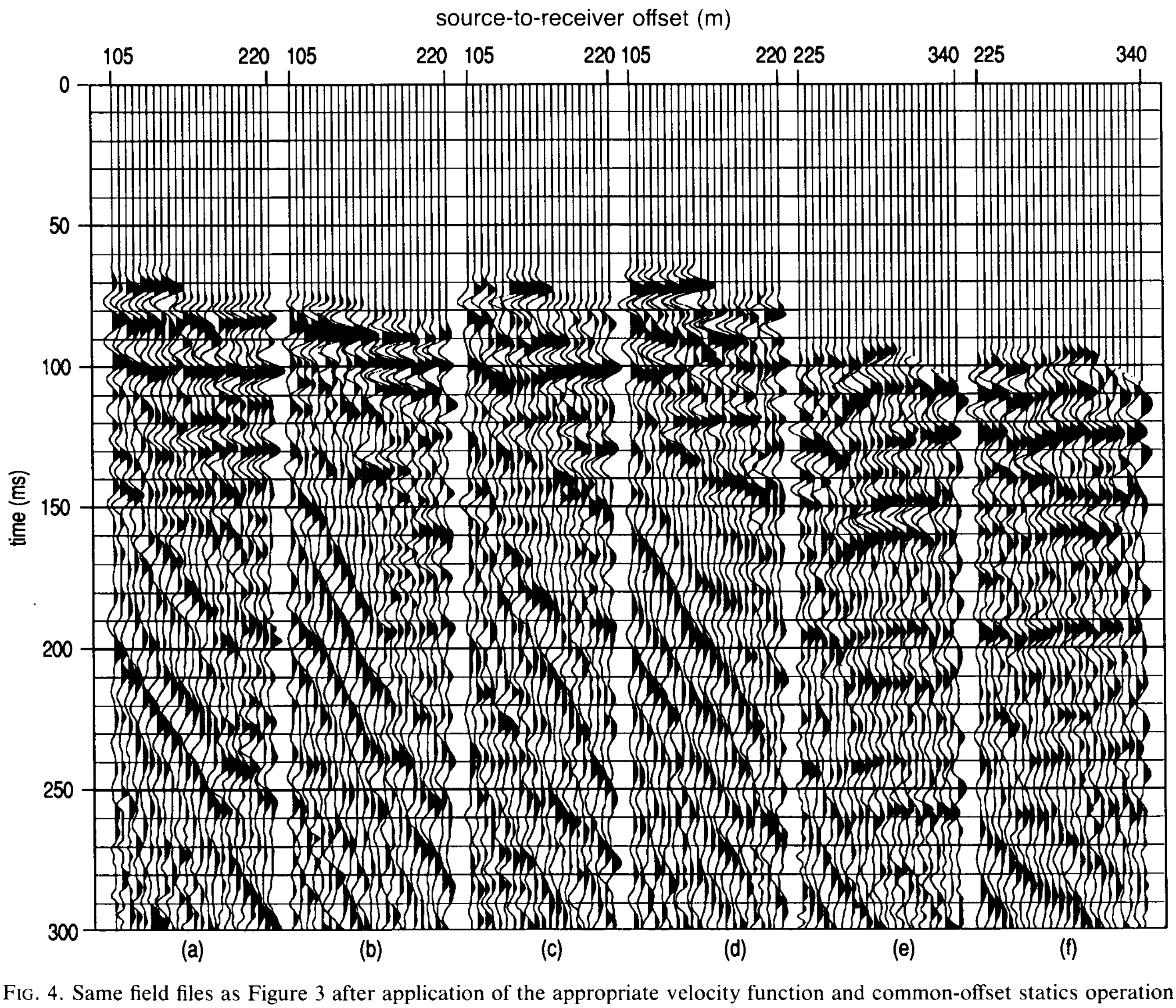

FIG. 4. Same field files as Figure 3 after application of the appropriate velocity function and common-offset statics operation.

apparent drop in S/N and coherency is deeper than 150 ms in two-way traveltime and is most likely related to faulting present east of station 10. Extension of the line to properly image the subsurface east of station 10 was not practical because a heavily traveled highway intersected the road about 10 m east of station 0.

CONCLUSIONS

The seismic-reflection technique imaged shallow subsurface structures significant to the longwall mining of coal in the Palau area. The relative topography variation of geologic layers at or near the depth of the coal can be determined within about 20 m (±10 m) horizontal ($\frac{1}{2}$ radius of the first Fresnel zone) and 7 m vertical ($\frac{1}{4}\lambda$). Timing and velocity accuracy are sufficient (as verified by drilling) to detect faulting with displacement of 2 m or more and folding with relative amplitudes of at least 2 m, and wavelength of 20 m or more using the CDP seismic-reflection method.

The primary target of the seismic survey was an undelineated structure responsible for approximately 16 m offset in the coal. Due to cultural problems (i.e., heavily traveled road) the primary target was not directly detected by the seismic survey. No determination could be made as to the source (i.e., fault or fold) of the 16-m relative elevation difference in the coal.

A secondary target was a drill-interpreted offset accounting for approximately 3 m of relative difference in the coal depth between boreholes 33 and 34. The seismic survey was able to image a structure that accounted for the 3 m of interpreted displacement between boreholes 33 and 34. The structure can be interpreted as either folding or faulting.

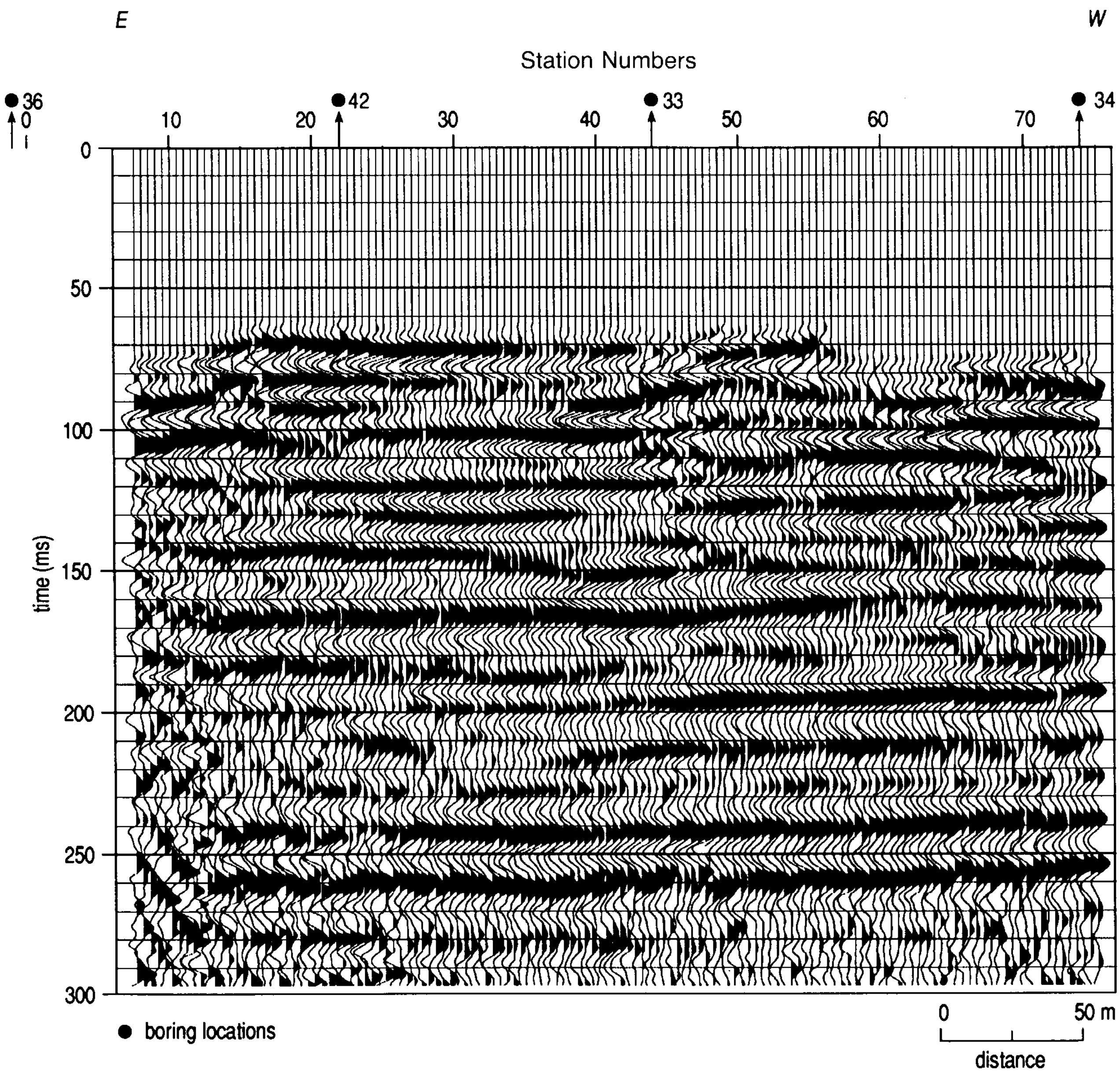

FIG. 5. Nominal 36-fold CDP stacked seismic section. Several coherent events can be interpreted across the line.

The improved resolution provided by seismic reflection in comparison to drilling in this area will allow maximum coal recovery with a minimum of downtime through improved mine planning. Encountering unexpected structural variation of as little as 2 m across an expanse of as large as 50 m can reduce mine efficiency. Abrupt or irregular changes in a coal seam surface require adjustments of the longwall machine several tens of meters prior to contact with an altered area. Without advance notice of subsurface obstacles, mining operations could be significantly hampered for indefinite periods of time, and in severe cases, personal injury and/or damage to equipment could result.

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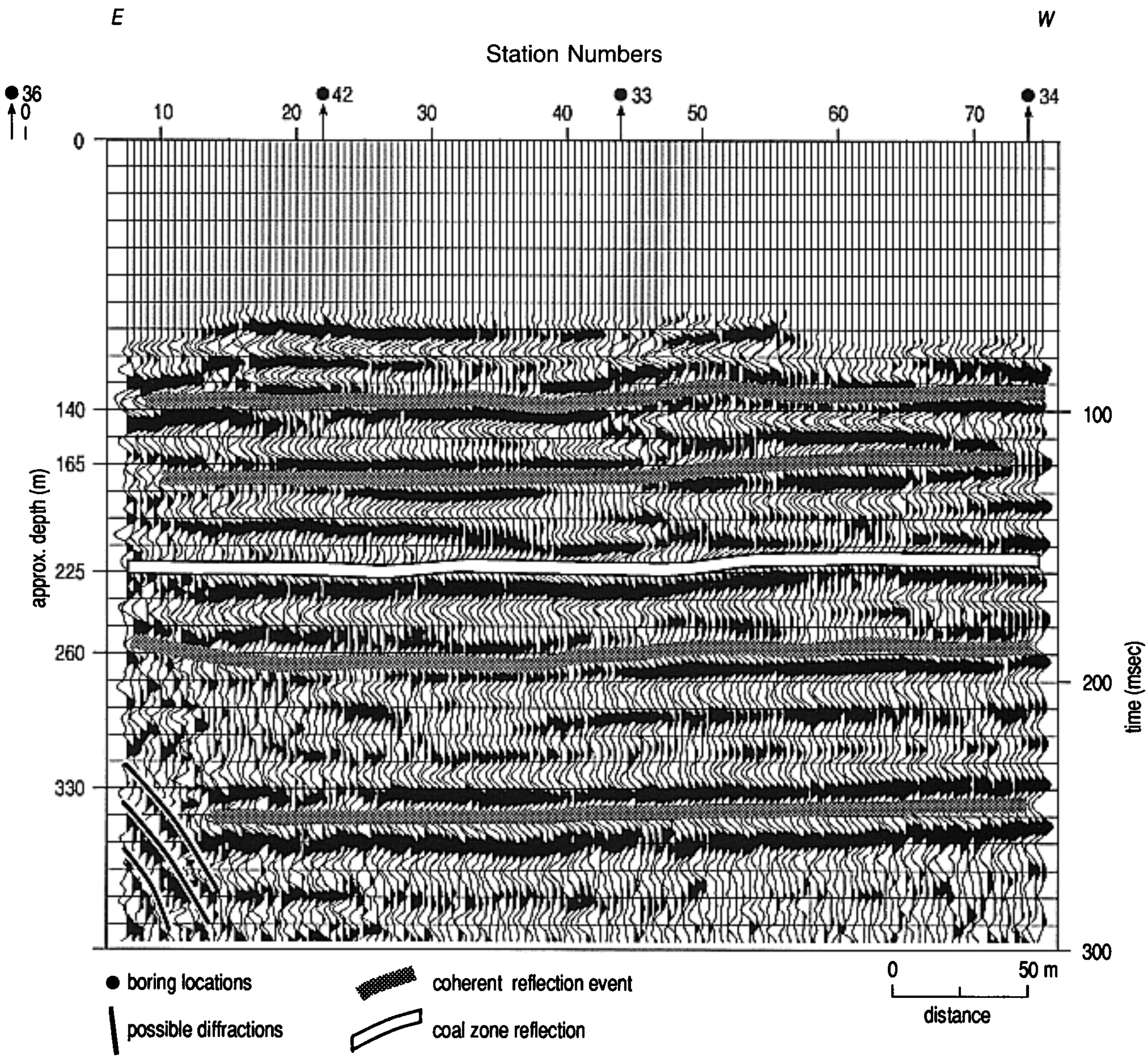

FIG. 6. The interpreted CDP stacked seismic section suggests gentle folding across most of the line with possible intermittent faulting. The low S/N area on the eastern portion of the section is probably related to a fault.

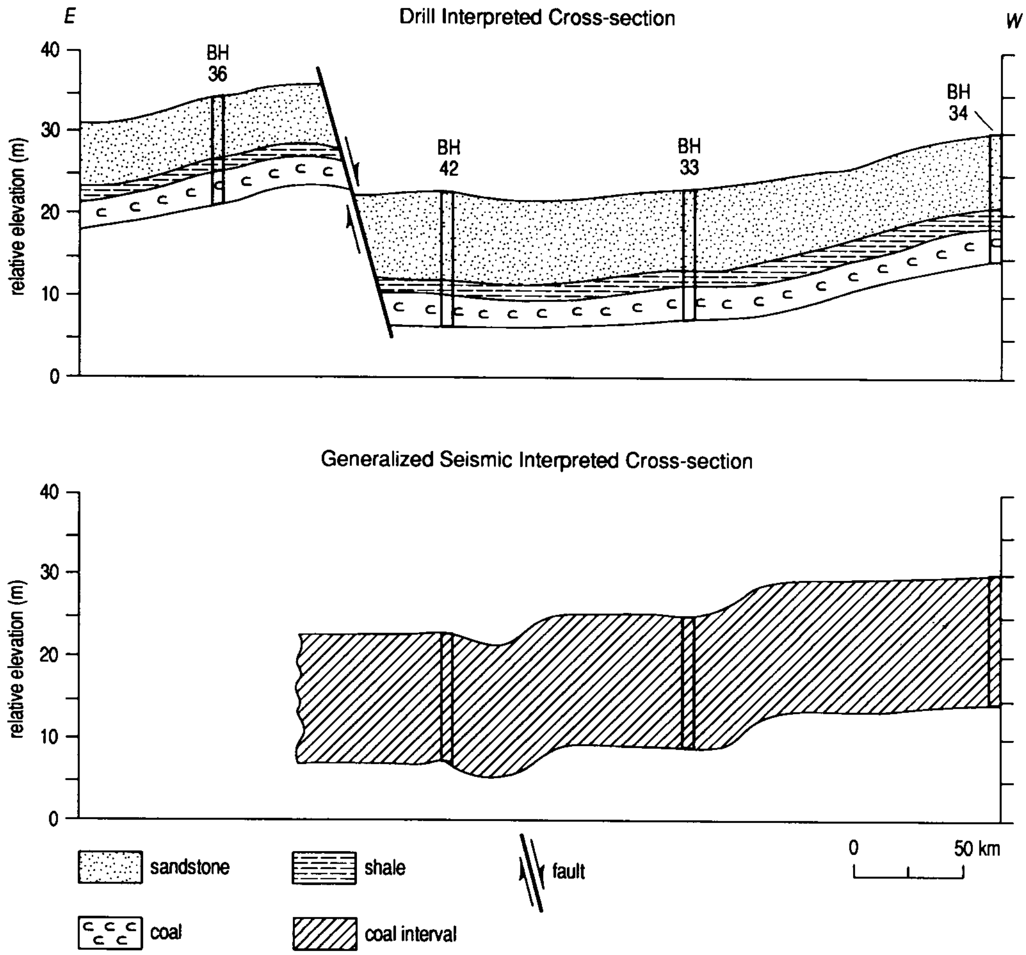

FIG. 7. Two structural cross-sections—one derived from drill information and the other from seismic data.

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