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Muting the noise cone in near-surface reflection data: An example from southeastern Kansas

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ABSTRACT

A 300-m near-surface seismic reflection profile was collected in southeastern Kansas to locate a fault(s) associated with a recognized stratigraphic offset on either side of a region of unexposed bedrock. A substantial increase in the S/N ratio of the final stacked section was achieved by muting all data arriving in time after the airwave. Methods of applying traditional seismic data processing techniques to near-surface data (200 ms of data or less) often differ notably from hydrocarbon exploration-scale processing (3–4 s of data or more). The example of noise cone muting used is contrary to normal exploration-scale seismic data processing philosophy, which is to include all data containing signal. The noise cone mute applied to the data removed more than one-third of the total data volume, some of which contains signal. In this case, however, the severe muting resulted in a higher S/N ratio in the final stacked section, even though some signal could be identified within the muted data. This example supports the suggestion that nontraditional techniques sometimes need to be considered when processing near-surface seismic data.

INTRODUCTION

A near-surface common midpoint (CMP) seismic reflection experiment was conducted in southeastern Kansas along the southern border of Woodson County (Figure 1). The site is located approximately 1.5 km southwest of Rose Dome, a feature caused by late Cretaceous ultramafic igneous intrusion. The geologic goal of this experiment was to locate a fault or faults causing 15+ m of stratigraphic offset in subhorizontal Paleozoic bedrock outcrop across an unconsolidated sediment-filled lowland suspected to be associated with the Rose Dome intrusion. The important Paleozoic strata in the study area are the Lansing Group and the Stranger Formation. The Lansing Group contains five members of alternating limestone and shale units, with individual units typically 3–6 m thick. The Stranger Formation in the study area consists of four members of alternating limestone and shale units with thicknesses 5–20 m thick. The geology in the study area consists of fairly regularly spaced limestone and shale interbeds (cyclothems), which we suspect contribute to the "ringy" character of the seismic data.

The geophysical goal of the experiment was to extract as much geologic structural information as possible from a data set containing substantial airwave that interfered with the reflections. We found it best to use a nontraditional approach to seismic data processing, being particularly sensitive to differences between hydrocarbon exploration-scale seismic data processing and near-surface seismic data processing. We demonstrate an increase in signal-to-noise (S/N) ratio by muting a substantial portion of the seismic data—specifically, the postairwave portion of the shot gathers referred to as the "noise cone". Typically in production CMP shallow-data collection, the field geometry is planned according to optimum window recording (Hunter et al., 1984). The optimum window is the range of source-receiver separations that allows the target reflectors to be observed without interference from other coherent noise events: airwave, air-coupled wave, and ground roll. Optimum window recording requires a specific rolling geometry. When time, equipment, and personnel constraints are such that the optimum window recording method is not possible, additional data processing problems arise. For example, these data from southeastern Kansas were collected by walking the source location through a fixed receiver line comprised of four segments that were leapfrogged three times during the experiment. This resulted in variable split-spread CMP gathers with a nominal fold of 35 and a maximum fold of 94. Optimum window geometry was not maintained; thus, the airwave and associated air-coupled wave from the surface Betsy seisgun source are dominant coherent noise in the data. Standard procedures of noise attenuation by filtering in frequency/wavenumber (f-k) or amplitude/frequency domains proved unsuccessful for this particular data set.

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FIELD PROCEDURES

The near-surface seismic reflection data were recorded using a 24-bit analog-to-digital (A/D), 96-channel BISON 24096 seismograph. The data were collected with 500 samples per record at a 0.5-ms sampling interval, resulting in a 0.25-s record length. Based on test shots, a 4-Hz pre-A/D low-cut filter and a 825-Hz pre-A/D high-cut filter were used.

The choice of source and receivers for our experiment was based on what was readily available and on previous knowledge of the region. The source used to acquire the data was an 8-gauge surface Betsy seisgun that fired 3-oz lead slugs into the ground. The surface seisgun had a better S/N ratio than a 30.06-caliber rifle also tested at the site. The receivers used were single Mark Products L40A 100-Hz geophones with a group interval of 1.22 m.

A nominal 35-fold CMP line was acquired with a nonstandard split-spread source-receiver geometry. The source interval was 1.22 m with a total of 232 shotpoints. Four receiver cables with 30 takeouts per cable were leapfrogged three times during the experiment, and the source location was walked through each new cable placement. The data were collected in this manner because of severe time constraints; thus, fold was not consistent throughout the profile.

NOISE ATTENUATION/MUTING

The goal of processing seismic reflection CMP data at any scale is to increase the S/N ratio. Many techniques of displaying, filtering, and correcting for statics improve the S/N ratio (Robinson and Treitel, 1980; Waters, 1987; Yilmaz, 1987). Display and static correction techniques enhance the coherency of reflections, whereas filtering techniques generally separate reflection data from coherent and/or incoherent noise. Although the techniques for processing and noise attenuation in hydrocarbon exploration-scale and near-surface seismic data are the same, the application of the techniques is typically dissimilar (e.g., Miller, 1992; Black et al., 1994).

The basis of all filtering techniques is that in some domain, signal and noise are distinct and separable, and the noise can be attenuated without substantially negatively affecting signal. Two main digital filtering techniques applied to near-surface data are done in the frequency/wavenumber (f-k) domain and the frequency/amplitude (frequency) domain. When attenuating linear noise with a different spatial slope than the reflections, f-k filtering is most applicable—whether in shot, receiver, CMP, or stacked space. Frequency filtering is most applicable when filtering noise with a different frequency content than the reflections. Another domain in which noise and signal are separable is the time-offset (t-x) domain, or the shot domain of seismic data. Muting in this domain is not typically thought of as filtering, but the same care must be taken in identifying noise and signal, determining the best mute to apply to enhance the S/N ratio, and selecting the mute taper to avoid introducing unwanted artifacts.

The main components of spatially limited coherent noise in near-surface reflection data are refractions, ground roll, airwave, and air-coupled wave. Filtering in the t-x domain, or muting, is a straightforward way to separate (remove) noise from signal. Muting of refracted and direct-wave energy is typical of both exploration-scale and near-surface data and is necessary on most data sets to ensure the noise does not appear coherent on CMP stacked sections and result in geologic misinterpretation. Although care must be taken to identify refractions and reflections correctly, the muting process itself is straightforward.

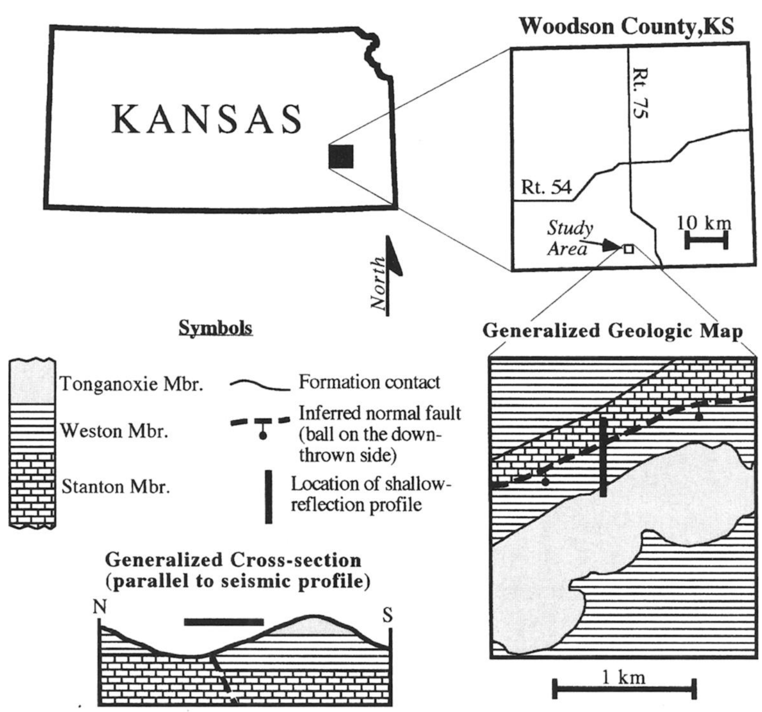

FIG. 1. The location of the study area in south-central Woodson County, Kansas. In the area of the seismic profile, the exposed thickness of the Weston Member on the downthrown block between the Tonganoxie and Stanton Members is about 15 m less than the expected regional thickness of the Weston.

Notch muting the airwave—muting the data along a narrow region containing coherent airwave energy—is performed occasionally on hydrocarbon exploration-scale data. However, the apparent phase velocity of the airwave in hydrocarbon-scale data is slow compared with reflection phase velocity. With larger receiver spacings and target depths, the airwave phase usually arrives too late to contaminate the signal. Additionally, in hydrocarbon exploration-scale data, the airwave amplitude is typically of similar order of magnitude to reflections and can be attenuated successfully during stacking. With near-surface data, however, the airwave typically is significant in terms of an invasive relationship to signal and in high amplitude relative to reflections (e.g., Figure 2). This is an even more significant problem if optimum window recording is not used (Mooney and Kaasa, 1962; Knapp, 1986). One method of removing the airwave is f-k filtering; however, the airwave is often spatially aliased at the frequencies of interest in shallow reflection data.

A method of noise attenuation for near-surface CMP data mentioned in the literature is to mute everything arriving later than the airwave when no signal is identified in that region (Miller et al., 1990). This region is referred to as the noise cone and occasionally is expanded to include the air-coupled wave. The noise cone was muted from the southeastern Kansas data, even though some reflection energy is identifiable within the noise cone. The resulting CMP gathers look untraditional; however, the S/N ratio within the noise cone is substantially lower that the S/N ratio outside of the noise cone. Noise cone muting is a very simple technique that increases the S/N ratio of the stacked CMP data by about 50%, based on peak phase-amplitude calculations.

DATA PROCESSING

The 96-channel CMP data were processed at the University of Kansas using Seismic Processing Workshop, a commercial processing package. The two main concerns of processing this particular data set were (1) identification of reflections and (2) removal of airwave and air-coupled wave. Figure 2 shows two of the near-surface shot gathers with the reflections and coherent noise identified. Reflections were identified in detail by analyzing fit of hyperbolas to coherent phases in statics-corrected CMP gathers, with cross-checking by shot-gather comparisons. Standard processing—removing noisy traces, correcting for elevation statics, applying refraction statics to correct for long-wavelength variations in the very near surface, detailed muting of refractions, velocity determination by iterative analysis of constant-velocity stacks and velocity semblance, NMO corrections with stretch mute, and stacking—was applied to the data.

For this particular data set with its below-average S/N ratio compared to other near-surface reflection data collected in the area, removal of the airwave by conventional filtering techniques was not successful. The f/k filtering was unsuccessful because the balance between the removal of spatially aliased airwave energy and generation of artifacts, tested at a wide variety of parameters, was unacceptable. Additionally, the airwave is spatially aliased at the same frequency range in which signal occurs and with a similar spatial orientation; thus, f-k filtering does not remove the aliased portion of the airwave without degrading signal.

Frequency filtering was partially successful in attenuating some coherent and incoherent noise, but the separation of

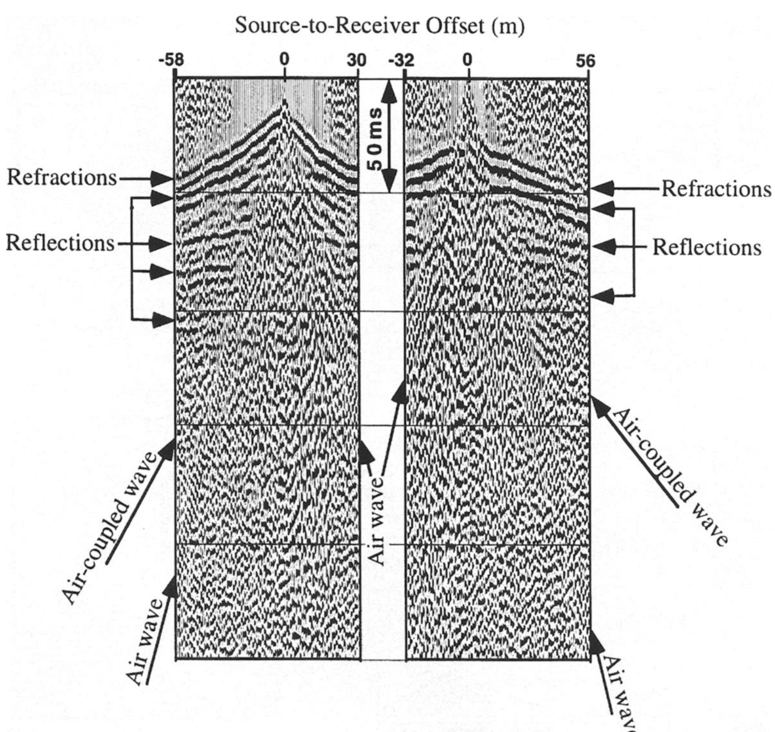

FIG. 2. Two digitally filtered and scaled field files from different locations along the seismic profile, each processed identically, with identifiable phases labeled. The dominant frequency of the reflections determined by peak-to-peak measurements is 180 Hz.

signal in the frequency domain from the airwave and air-coupled wave, especially within the noise cone, was not possible (Figure 3). A Butterworth band-pass filter from 160 to 200 Hz with ramps of 12 dB/octave gave the best results, mainly by filtering out most of the low-frequency component of ground roll and air-coupled wave and the high-frequency component of airwave and background noise. We were careful not to introduce additional ringy character to the data and concluded that the 40-Hz wide passband filter, centered on the dominant signal frequency, was as narrow as possible without introducing additional signal distortion.

We determined that the best method to remove the remainder of the airwave and air-coupled wave, which overlap in frequency with the reflections, was to mute the noise cone. Figure 4 shows an unmuted and muted shot gather. The removal of a substantial portion of the low-quality data from the CMP gathers by muting the noise cone generated an improvement in the final stacked section (Figure 5). Removing reflection data contained within the noise cone did not decrease coherency of reflections in the final product.

Of note with the data is the ringy character of the reflections. This is considered a factor of both the geology and near-surface conditions. Convention suggests deconvolution will help to attenuate true multiples. However, several of the basic assumptions underlying deconvolution (Yilmaz, 1987) are violated. First, the convolution model is based on the assumption that the source generates a compressional-plane wave that impinges on layer boundaries at normal incidence. Our near-surface reflection data consist of wide-angle reflections where the depth of the reflector is not substantially greater than the cable length; thus, the normal incidence condition is violated. A second assumption of the convolutional model is that the reflectivity series of the subsurface is spatially random. However, our near-surface reflection data consist of only four significant reflectors. Additionally, the geologic layering is repetitive in space. Both of these conditions suggest the reflectivity is not random. Because both of the major assumptions in the convolution model are invalid for our near-surface reflection data, it is not surprising that suppression of multiples by deconvolution is not possible for our data and in fact only serves to degrade the quality.

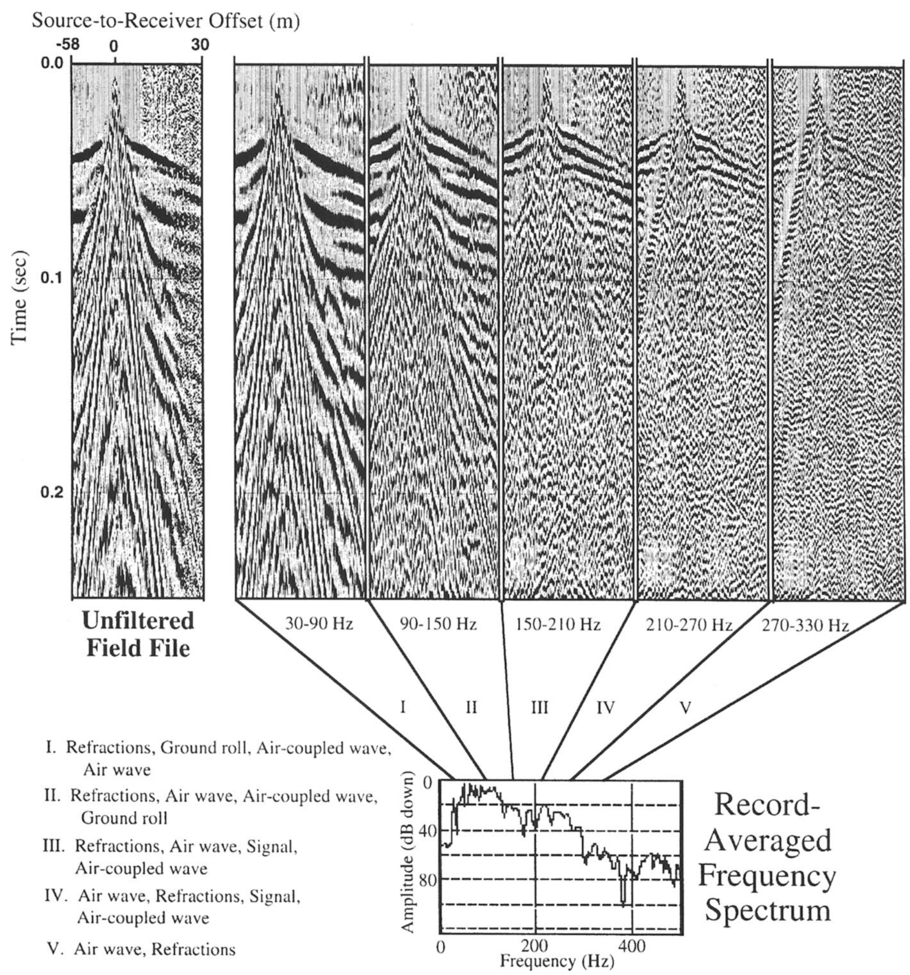

FIG. 3. Filter panels of a typical digitally filtered field file, using a Butterworth filter with 16 dB/octave for all ramps. All records are AGC scaled after filtering with a 50-ms window. The roman numerals are keyed to the coherent phases observed in the data, in decreasing order of power. The filter panels are tied to a representative amplitude versus frequency spectrum. For these data, signal is not separable from noise by frequency filtering, except for low-frequency (<120 Hz) ground roll, air-coupled wave, and airwave. Note that airwave is present at all frequencies and aliased at higher frequencies. Also note the frequency range dominated by signal does not correlate to a dominant peak or series of peaks on the amplitude spectrum.

SEISMIC DATA INTERPRETATION

The geologic goal of acquiring the CMP stacked section was to accurately locate a substantial (15+ m of throw) normal fault(s) not exposed at the surface. The identification of stratigraphic offset is based on near-horizontal bedrock exposures on either end of the study site. The two dramatic features of the final stacked section (Figure 6) are the cyclicity of the reflections and noticeable reflection discontinuities/diffractions. The cyclic reflections are typical of southeastern Kansas cyclothemic deposition and are a result of the interbedded limestone and shale units in the region which have been identified by drilling (Miller et al., 1995). The discontinuities and/or associated diffractions are interpreted as faults.

Figure 7 is an uninterpreted and interpreted shot gather, showing the presence of truncated reflections and associated diffractions. These events were noticed in the field and during data processing; they correspond with the largest offset fault observable in the stacked seismic section near 55 m offset from the north end of the profile. We similarly cross-checked the other interpreted faults with CMP gathers and shot gathers for confirmation and restored offset across faults to ensure wavelet character was consistent for the proposed offsets (Figure 6).

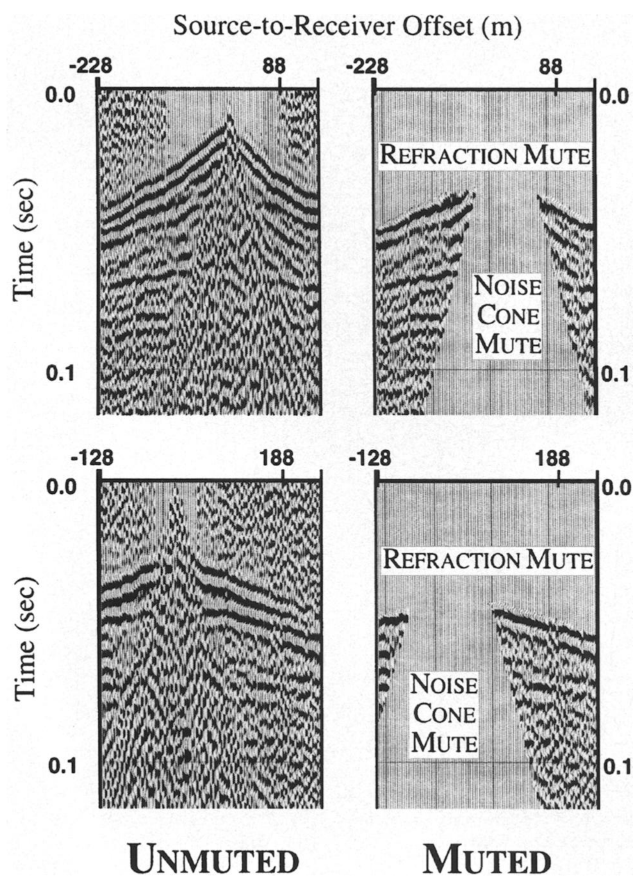

FIG. 4. Two typical unmuted and muted digitally filtered and scaled split-spread field files. The low S/N ratio region, referred to as the noise cone, is preferentially muted. Muting this region improves the overall S/N ratio of the final stacked section. Additionally, refractions are muted. A 4-ms taper was used at the edges of all mute regions.

CONCLUSIONS

The nontraditional method of filtering a substantial portion of the data in the *t-x* domain by muting the noise cone increases the S/N ratio by eliminating the portion of the data in which the S/N ratio is low, even though identifiable signal is present. In the near-surface seismic profile in southeastern Kansas, the increase in S/N ratio allows for a more detailed interpretation of the final stacked seismic section. The interpreted final stacked section identifies the targeted faults. The stratigraphic offset of the faults agrees with the field data: a total offset of 15+ m

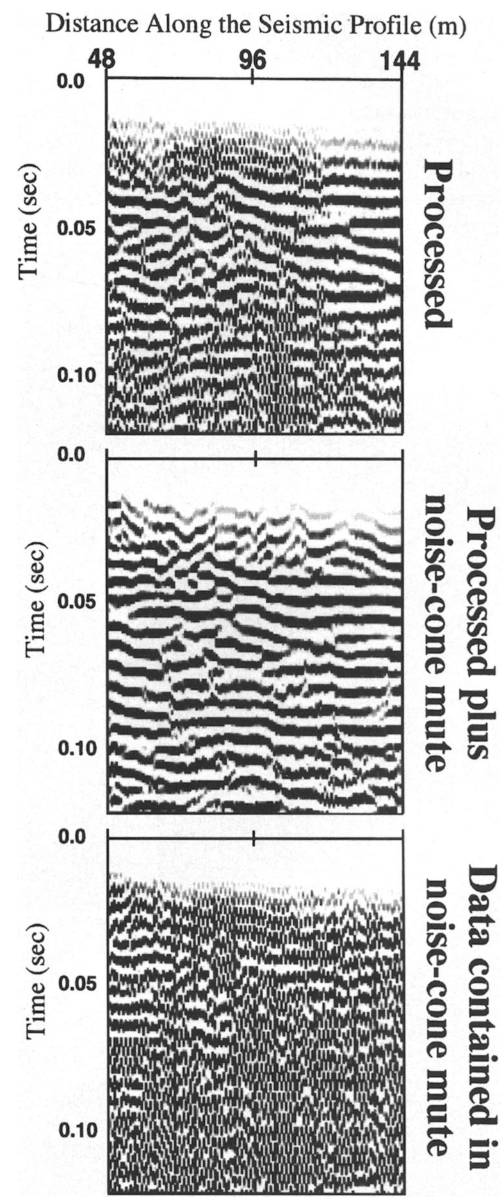

FIG. 5. A representative portion of stacked section from the Woodson County data. The top section is processed by the standard procedures described in the text. The middle section is generated with an identical processing flow, with the additional step of muting the noise cone in the shot gathers (see Figure 4). Note the improvement in S/N ratio from the top section to the middle section. The bottom section is created by CMP stacking of the data contained in the noise cone mute (i.e., data removed from the top section to get the middle section).

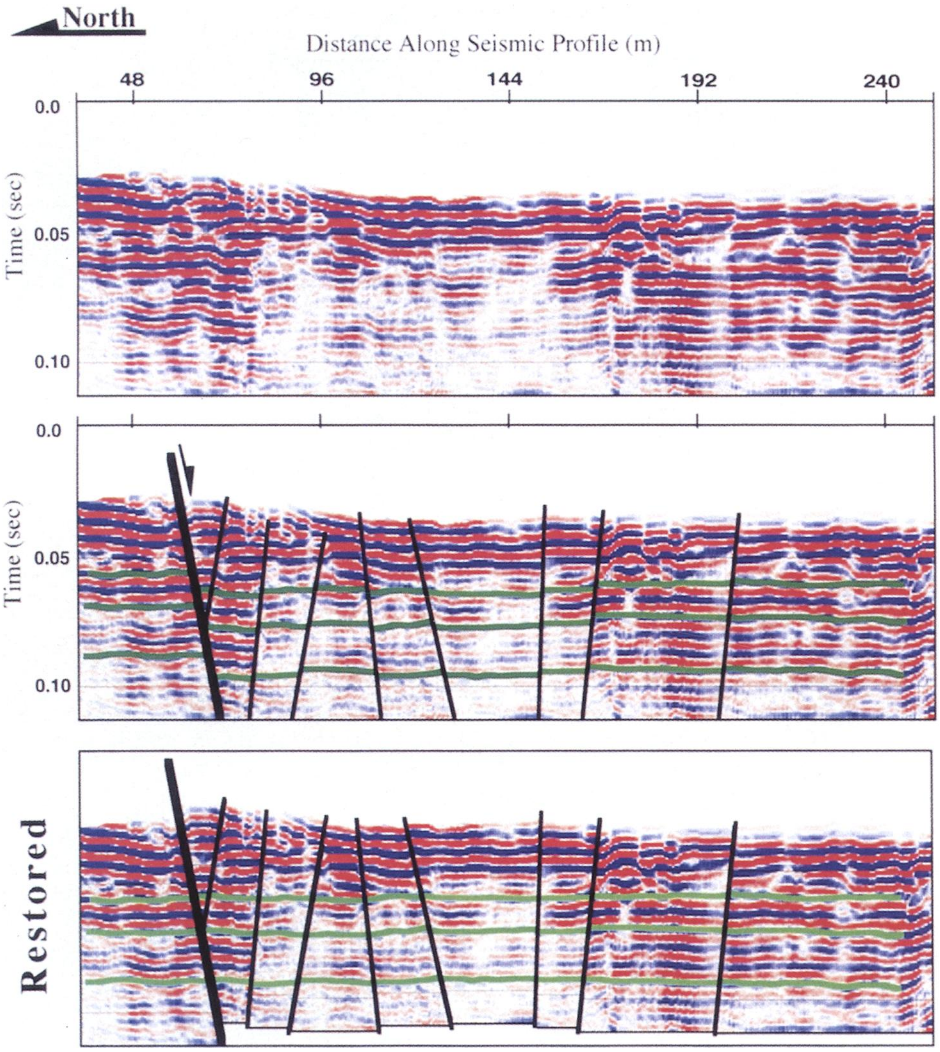

FIG. 6. Uninterpreted, interpreted, and restored near-surface reflection profile from Woodson County, Kansas. These data were acquired with a BISON 24096 system using 100-Hz geophones and an 8-gauge surface Betsy seisgun with a source and receiver interval of 1.22 m. The processing routine is described in the text. The main normal fault, accounting for most of the 15+ m of the throw across the profile, is shown in bold.

from one end of the profile to the other, when converting to depth. Muting the noise cone is a very simple technique which, based on the time and effort required to test it, should be tested on near-surface data sets that have prominent airwave and air-coupled wave problems.

Increasingly, methods of applying seismic data processing techniques in near-surface data (200 ms of data or less) differ in some respects from procedures used in hydrocarbon exploration-scale seismic data processing. If a traditional processing routine were used on the data presented in this paper—specifically, not muting the entire noise cone because it contains identifiable signal—a substantially degraded stacked seismic section would have resulted.

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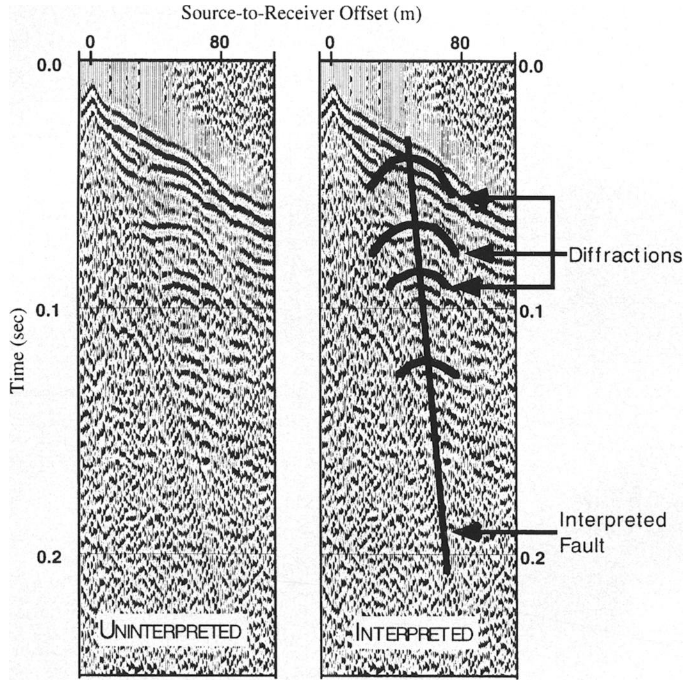

FIG. 7. Identical uninterpreted and interpreted digitally filtered and scaled field file from the north end of the seismic profile. The fault and associated diffractions from the truncated strata are identified. The interpreted fault on this and adjacent field files spatially correlate with the main normal fault on the final stacked section.

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