Evaluation of Fault Scarp at Harlan County Lake, Harlan County, Nebraska using High Resolution Seismic Reflection Surveying

Richard D. Miller
Kansas Geological Survey
1930 Constant Avenue
The University of Kansas
Lawrence, KS 66047-3726

Donald W. Steeples
Department of Geology
The University of Kansas
Lawrence, KS 66047-2424

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Kansas Geological Survey
The University of Kansas
1930 Constant Avenue
Lawrence, KS 66047-3726

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SUMMARY

Shallow high resolution seismic techniques were used in an attempt to delineate the subsurface expression of a fault-like displacement exposed in a loess cliff on the Harlan County Lake, a reservoir in south-central Nebraska. Regardless of data-processing flows designed to compensate for a very irregular bedrock surface, it appears one or more faults may have offset consolidated rocks between 70 and 500 m of depth immediately north of the scarp expression in the wave cut shoreline. Seismic reflection data in a CDP format were acquired along the base of the cliff within 20 m of the scarp. The seismic line ran along the water's edge, which for the past three years was at the base of the cliff as the Corps of Engineers maintained the water at near record levels for irrigation and flood control. Preliminary walkaway tests at the site included using several different types of sources and source configurations, which were limited by access problems and extremely wet near-surface conditions. Test data were evaluated for resolution, signal-to-noise ratio, depth range of imaging, and optimum equipment and parameters for effective profiling of a fault with offset as small as a couple meters. Based on CDP processed data and on exposure studies of the fault plane, the fault seen in loess at the surface does not connect in an obvious way to the faults in the subsurface. The subsurface faulting could be primarily normal or reverse, although the reverse interpretation seems to fit the seismic reflection data better.

INTRODUCTION

Shallow high-resolution seismic techniques possess the necessary resolution potential within the saturated loess that borders Harlan County Lake to detect any abrupt displacement of around 3 m or more in otherwise continuous reflectors at depths between 70 and 500 m (Miller et al., 1992; Miller and Steeples, 1991). Shallow P-wave reflection surveys have routinely been successful in imaging faulted rock at shallow depths (< 100 m) as well as within overlying unconsolidated sequences (Miller et al., 1992; Treadway et al., 1988; Myers et al., 1987).

A single 48-fold CDP seismic-reflection line was acquired along the face of the east-facing cliff marking the western perimeter of Bone Cove (Figures 1, 2). The data were collected to take advantage of the multifold redundancy and therefore the noise suppression potential of CDP data processing techniques (Mayne, 1962). The line was located so equal portions of the profile were north and south of the surface trace of the fault in the cove. The abnormally high reservoir level limited the potential lateral extent of the seismic profiles. Meaningful correlation of two-way travel time reflections on CDP stacked sections to specific geologic units requires an accurate average velocity that only a surface-to-borehole or borehole-to-surface acoustic survey can provide, so our results are lacking absolute depth accuracy.

DATA ACQUISITION

Several different types of sources and recording parameters were employed to optimize the acquisition parameters for the CDP production survey. Test data were acquired on a Geometrics 2401X, 48-channel seismograph that amplifies, filters (analog), digitizes the analog signal into a 15-bit word, and stores the digital information in a demultiplexed format. Analog filters have an 18 dB/octave roll-off from the selected -3 dB points. At the time the test data were collected, the lake level was so high that it was not possible to lay out the geophones in the configuration to cross the scarp. Consequently, about two years passed while we waited for the water level to drop long enough for the surface to dry sufficiently to support a seismic survey.

A 96-channel Geometrics StrataView seismograph was used to acquire the production CDP data. The StrataView amplifies, digitizes the analog signal into a 24-bit word, and stores the digital information in a demultiplexed format very similar to the 2401X. The most significant difference between the two seismographs used for this study is the increased dynamic range and number of recording channels of the StrataView model. A variety of analog low-cut filters were tested to allow determination of the optimum analog filter necessary to maximize the instantaneous dynamic range of the seismograph. Ultimately, the data were recorded without analog filtering.

The very site-dependent nature of P-wave source characteristics (Miller et al., 1994) prompted comparison of three types of sources, including the 30.06 downhole rifle (projectile), the 12-gauge auger gun (downhole explosive), and a 5.5 kg sledge hammer (weight drop). Each of these sources was used during the walkaway testing and, due to favorable characteristics, a soft-ground version of the auger gun (Healey et al., 1991), a one-of-a-kind drive gun, with a downhole black powder load was used during the acquisition of P-wave CDP data. The significant attenuation of energy, extremely difficult access, and the very soft, saturated near-surface made selection of the 8-gauge drive gun the best choice at this site under these conditions. The sources selected for testing comprise a good cross-section of low-to-medium energy impulsive P-wave sources.

Receivers tested for this study included single Mark Products L-40A 100 Hz geophones and Mark Products L-28E 40 Hz geophones in groups of three in series. The target interval and resolution requirements dictated the use of relatively high natural frequency geophones, as well as good coupling and small geophone spacing. High quality receivers are essential for cleanly recording the high frequency, low amplitude signals characteristic of shallow seismic surveys.

The production CDP data that resulted in the stacked section displayed in this report were acquired with an 8-gauge black-powder drive gun, three L28E 40 Hz geophones in series per channel, and a 96-channel StrataView recording without analog filters. The drive gun allowed placement of an 8-gauge shotgun shell at a depth of around 0.5 m. The receivers were deployed with 14 cm spikes deeply planted into firm portions of the saturated loess, although some short segments of line crossed sand-bars. The 96-channel seismograph was set up to record with a 0.5 msec sampling interval and over 1 second of data.

Data quality assurance/quality control (QA/QC) were critical and continuous throughout acquisition and processing. Near-surface soil and seismic velocity variations, boat noise, jet aircraft noise, the extremely narrow and changing optimum recording window, and high moisture conditions made establishing QA/QC guidelines and meticulous monitoring of data an absolutely essential aspect of the data acquisition. Based on subtle changes in the near-surface, minor adjustments to some parameters (e.g., source to near-offset geophone) were necessary to maintain the optimum recording window (Hunter et al., 1984). The seismograph CRT display, nearly real-time digital filtering, and real-time graphical display of noise levels permitted instantaneous monitoring of not only cultural, air traffic, and watercraft noise, but also cable-to-ground leakage and geophone plant quality. After each geophone was planted, it was tested to insure a cable-to-ground resistance greater than 1000K ohms and an individual geophone continuity of 1130 ohms (±20 ohms). As well, each geophone underwent a modified tap and twist test. No shot was recorded if background noise voltage levels on active geophones was greater than 0.05 mV. The ability of the seismograph to monitor real-time noise levels, signal quality (through digital filtering), and unacceptable geophone plants, and the roll-switch's built-in earth leakage and continuity meters assisted in maintaining high quality data in the field.

DATA PROCESSING

Data from this study were processed on an Intel P-class microcomputer using *Eavesdropper* and *WinSeis*, both commercially available algorithms. Display parameters were determined based on scale of existing data sets, optimum exaggerations, and workable formats. During this study, the only operations or processes used were those that enhanced the signal-to-noise ratio and/or resolution potential as determined through evaluation of high-confidence reflections identified on field files.

The principal utility of a walkaway noise test is to expedite and improve equivalent comparisons of various source, receiver, and instrument settings and configurations as they relate to overall improvements in the signal-to-noise ratio and frequency content. Walkaway tests are ideally suited to the identification of individual events within the full wavefield. Phase velocity and wave types are probably the most important pieces of information extractable from walkaway seismograms. Their importance is related to the dependence of velocity and wave type on spread geometries and offsets (Pullan and Hunter, 1985). The level of testing is dependent on the objectives of the project and degree of difficulty in obtaining the required resolution. Processing of walkaway data for this study was limited to trace organizing, gain balancing, and digital filtering. Walkaway data from each source configuration or comparison parameter are displayed in a source-to-receiver order.

For most basic shallow high-resolution seismic reflection data, CDP processing steps are a simple scaling down of established petroleum-based processing techniques and methods (Yilmaz, 1987; Steeples and Miller, 1990). The processing flow for the CDP stacked sections was similar to that used for routine petroleum exploration (Table 1). The main distinctions relate to the conservative use and application of correlation statics, precision required during velocity and spectral analysis, and the accuracy of the muting operations. A very low (by conventional standards) allowable NMO (normal moveout) stretch (< 20%) was extremely critical in minimizing contributions from the very shallow reflected energy at offsets significantly beyond the critical angle. Limiting wavelet stretch through muting maximizes resolution potential and minimizes distortion in the stacked wavelets (Miller, 1992). Variability in time arrival of the first refraction from linear was as much as 30 msec across a single shot gather, suggesting sufficient changes in depth to bedrock to require compensation. Operations such as refraction statics were unsuccessful compensating for this depth variability. Common offset statics were the only statics correction technique that proved effective in removing the artifacts of an extremely variable bedrock surface. Processing used on these data has been carefully executed with no *a priori* assumptions. Extreme care was taken to enhance through processing only what could be identified on raw data and not to create artificial coherency on stacked sections.

Most processing operations applied to shallow high-resolution seismic reflection data sets during the generation of CDP stacked sections are a simple scaled-down version of established processes developed for petroleum exploration. Some processes have assumptions that are violated by most shallow reflection data sets and application of these processes could dramatically reduce data quality or worse, generate artifacts. In particular, with processes such as deconvolution and some forms of trim statics there is an assumption of a large number of reflections with a random reflectivity sequence and high signal-to-noise ratios (Yilmaz, 1987). Migration is another process that, due to non-conventional scaling, many times appears to be necessary when geometric distortion may be simple scale exaggeration. With extremely low near-surface velocities, migration corrections may be minimal (Black et al., 1994). The low-pass nature and coherency enhancing tendency of f-k migration improves geometric accuracy but reduces resolution potential of reflections on CDP stacked sections. It can also increase aliasing problems in coherent noise such as the air-coupled wave and ground-roll. Consistency in arrival and apparent orientation of individual reflections after each process was critical to ensuring the authenticity of reflections on the final stacked sections.

Table 1
Processing Flow

Primary Processing

format from SEG2 to KGSEGY
preliminary editing (automatic bad trace edit with 10 msec noise window)
trace balancing (50 msec window)
first arrival muting (direct wave and refraction)
surgical muting (removal of ground roll based on trace-by-trace arrival)
assign geometries (input source and receiver locations)
sort into CDPs (re-order traces in common midpoints)
velocity analysis (whole data set analysis on 100 ft/sec increments)
spectral analysis (frequency vs amplitude plots)
NMO correction (station dependent ranging from 1200 [S-wave] to 4500 [P-wave] ft/sec)
correlation statics (2 msec max shift, 7 pilot traces, 100 msec window)
digital filtering (bandpass 75-150 500-750)
secondary editing (manual review and removal of bad or noisy traces)
CDP stack
AGC scale (100 msec window)
display

Shallow seismic reflection is a method that lends itself to over-processing, inappropriate processing, and minimal human-involvement processing. Interpretations 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. Identification and confirmation of reflection hyperbolae on field files is essential and best accomplished through mathematical curve fitting, incorporating borehole-derived velocity structure and comparison of file-to-file consistency.

RESULTS

Field files from this survey all have a very irregular refraction arrival event that seems to be traceable in other arrivals deeper in time on individual files (Figure 3). F-k filtering (slope filter) was a reasonably effective method of removing ground roll energy (Figure 4). The careful tracking through all processing steps of reflection events interpretable on raw field files allows significant confidence in interpretations of stacked sections.

The stacked section possesses very good quality data with several coherent reflections between 100 and 300 msec across about 80 percent of the line (Figure 5). The critical area of interest for this study unfortunately is within the 20 percent of the section that represents a challenge to confidently interpret. Depending on interpretation tendencies, the coherent reflection events could depict a zone of faulting or a region with broken coherency in the stacked reflections. The interpretation that requires only minimal speculation puts a fault between statiosn 540 and 590. The fault scarp was located at station 490 on the ground surface.

Figures 6 and 7 show palinspastic reconstructions resulting from the cutting and pasting of the section in Figure 5. The reverse-fault reconstruction in Figure 6 gives an excellent fit of data at reflection times between 150 and 250 msec. The two reverse faults at stations 517 and 550 fit particularly well. The fault reconstruction at location 585 is not as good.

Figure 7 is a normal-fault reconstruction with the fault projecting to the surface at location 527. The normal-fault reconstruction does not possess the evident in the reverse-fault reconstruction. Consequently, we favor the reverse-fault reconstruction of Figure 6, which was used to develop the interpretation of the seismic section in Figure 5.

We do not have a definitive tie of specific events interpreted on the seismic section to specific stratigraphic units. From the literature, we know the top of the Dakota is at about 460 m elevation relative to sea level (Jewett and Merriam, 1959; Merriam, 1957a), which would put it at a depth of about 135 m below the Earth's surface beneath the seismic line. The same literature sources suggest the Permian-aged Stone Corral anhydrite should be present, but no Permian-aged salt. Ray Burchett of the Nebraska Geological Survey provided us with a deep well log from about 4 km to the southwest (Sec. 30, T1N, R17W), and it shows only a few meters of Stone Corral anhydrite and no salt. Based on horizontal extrapolation from this well, the Stone Corral is at a sea-level elevation of about 105 meters at the location of the seismic line. The Stone Corral is commonly flat on the scale of ten kilometers in this region, so horizontal extrapolation for a distance of 4 km is reasonable.

Our previous experience with seismic reflection data recorded about 100 km to the south (Steeples et al., 1986; Knapp et al., 1989) leads us to suspect that the reflector at about 250 ms is the Stone Corral. If the event at 250 ms is the Stone Corral, the deep well indicates that reflection time would correspond to a depth of about 490 m.

At several locations examined in Knapp et al. (1989), faulting in the Stone Corral and shallower units was related to dissolution of salt a hundred meters or so below the Stone Corral. We have no evidence for the presence of salt at this site. Consequently, we have no reason to ascribe the deeper faulting to dissolution of Permian evaporites.

Some tectonic fault activity evident between stations 517 and 590 could have occurred in the time interval between the late Permian and the late Cretaceous, or possibly into Ogallala time. There is evidence suggesting the presence of the basal Ogallala at the north end of the cliff, at or just a few feet below the topographic level of the seismic line. Several blocks of basal Ogallala that each weigh a ton or more are present at this location. Our very first walkaway seismic line collected at the waterline suggested that a near-surface high velocity layer (possibly Ogallala) truncated near the horizontal location of the offset paleosol in the cliff.

The seismic data indicate there is clearly some faulting at depths of 50-500 meters. Most of it is in the northern third of the line, about 100 meters or so north of the offset in the loess. Most of the faulting is probably reverse; in addition there is some possible flower structure as interpreted in Figure 5. We cannot resolve any reflectors shallower than about 50 meters. It is unlikely that the deeper faults interpreted in Figure 5 are directly related in a first order way to what we see at the surface, although our data do not preclude that. The dips would have to be 45 degrees or more to the north, and the observed sense of motion on the fault in the loess would be opposite in both dip and direction of offset to our preferred interpretation from Figure 5 and the reconstructions of Figures 6 and 7.

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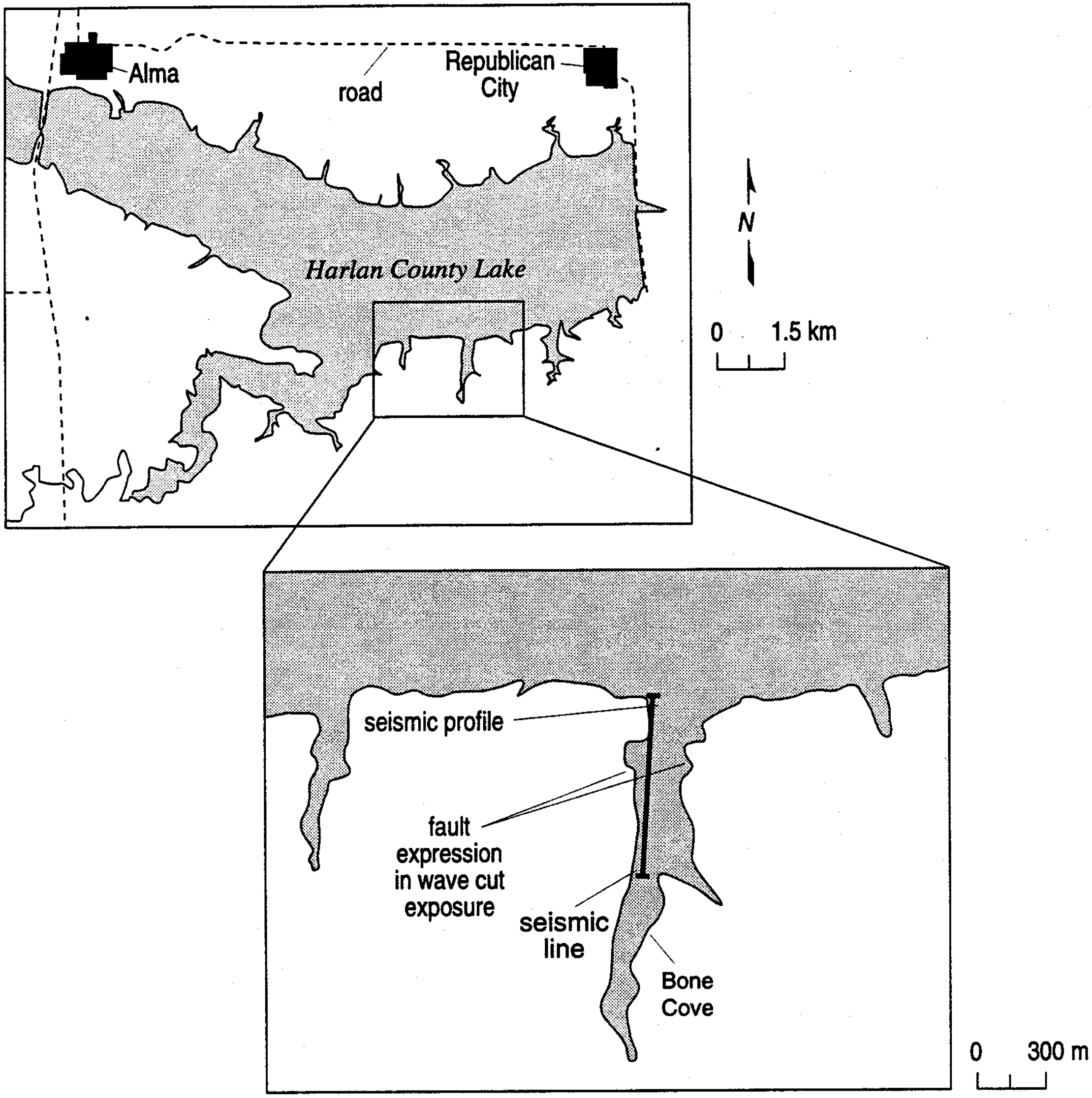


Figure 1. Map of study area.

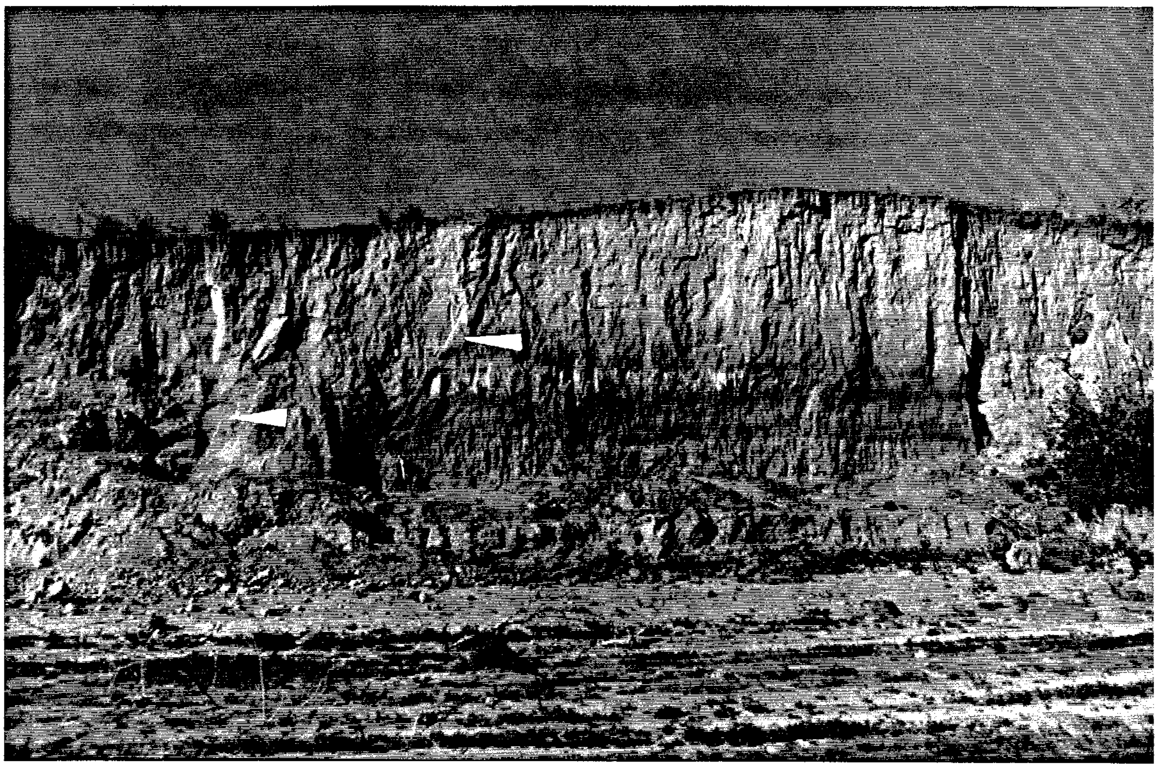


Figure 2. The wave-cut exposure of the loess and slip planes. The arrows indicate the location of the slip planes. The left (south) side is downthrown, offsetting the buried soils of the Gilman Canyon Formation by 1.8 m.

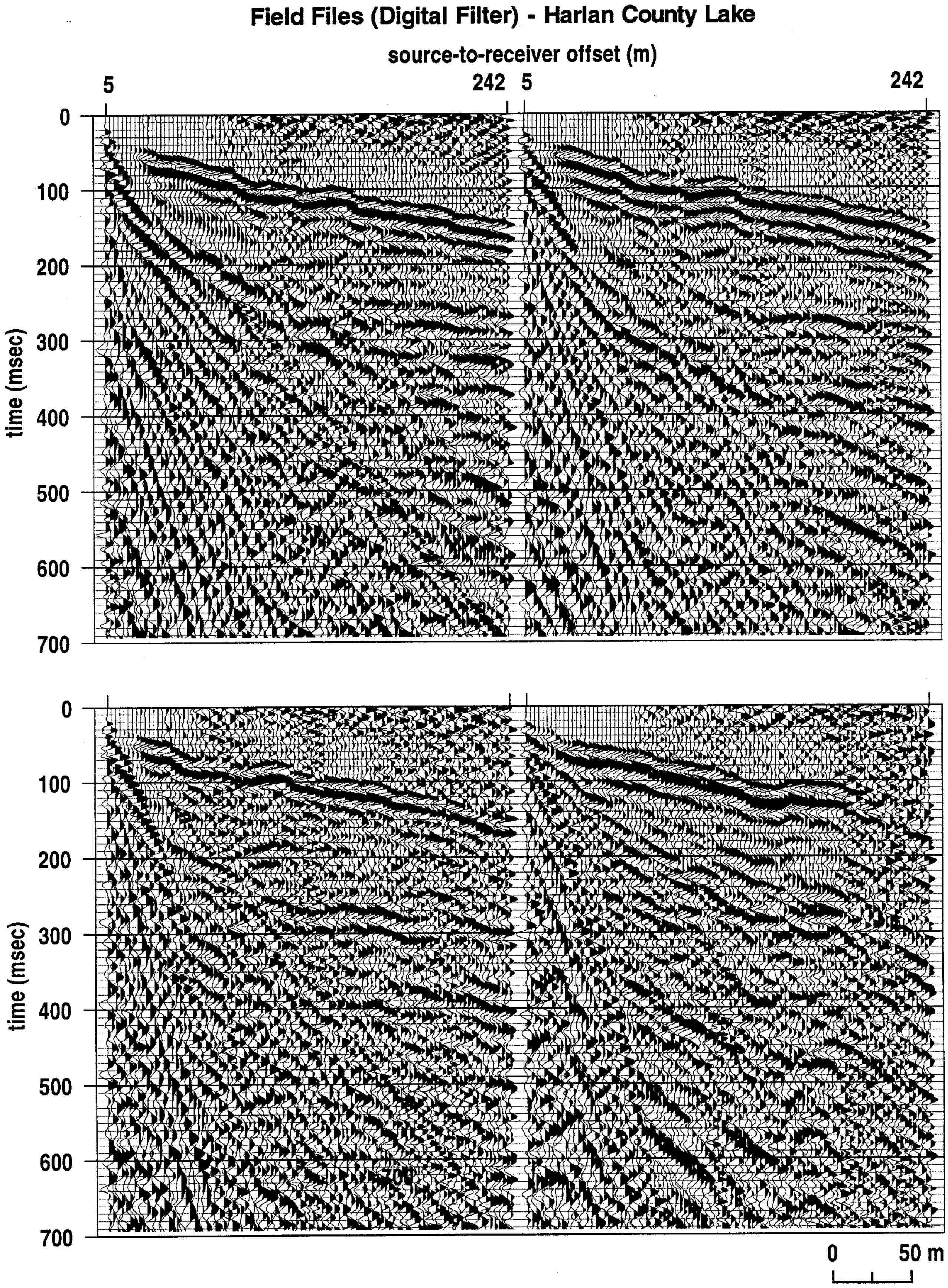


Figure 3. Digitally filtered field files. Reflections can be seen at times between 250 and 300 msec. Depths at 250 msec 2-way reflection time are probably about 490 m.

Field Files (F-K Filter) - Harlan County Lake

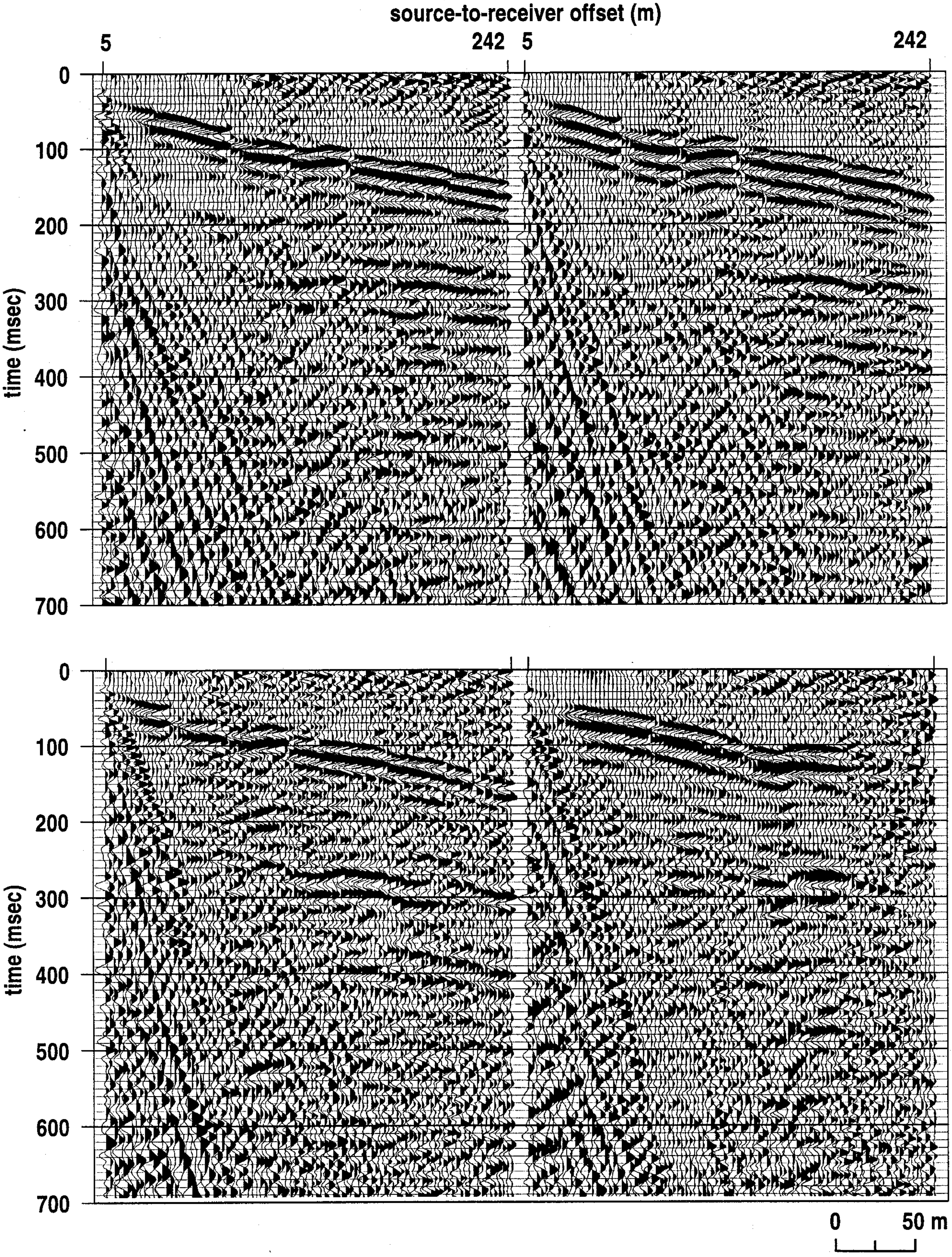
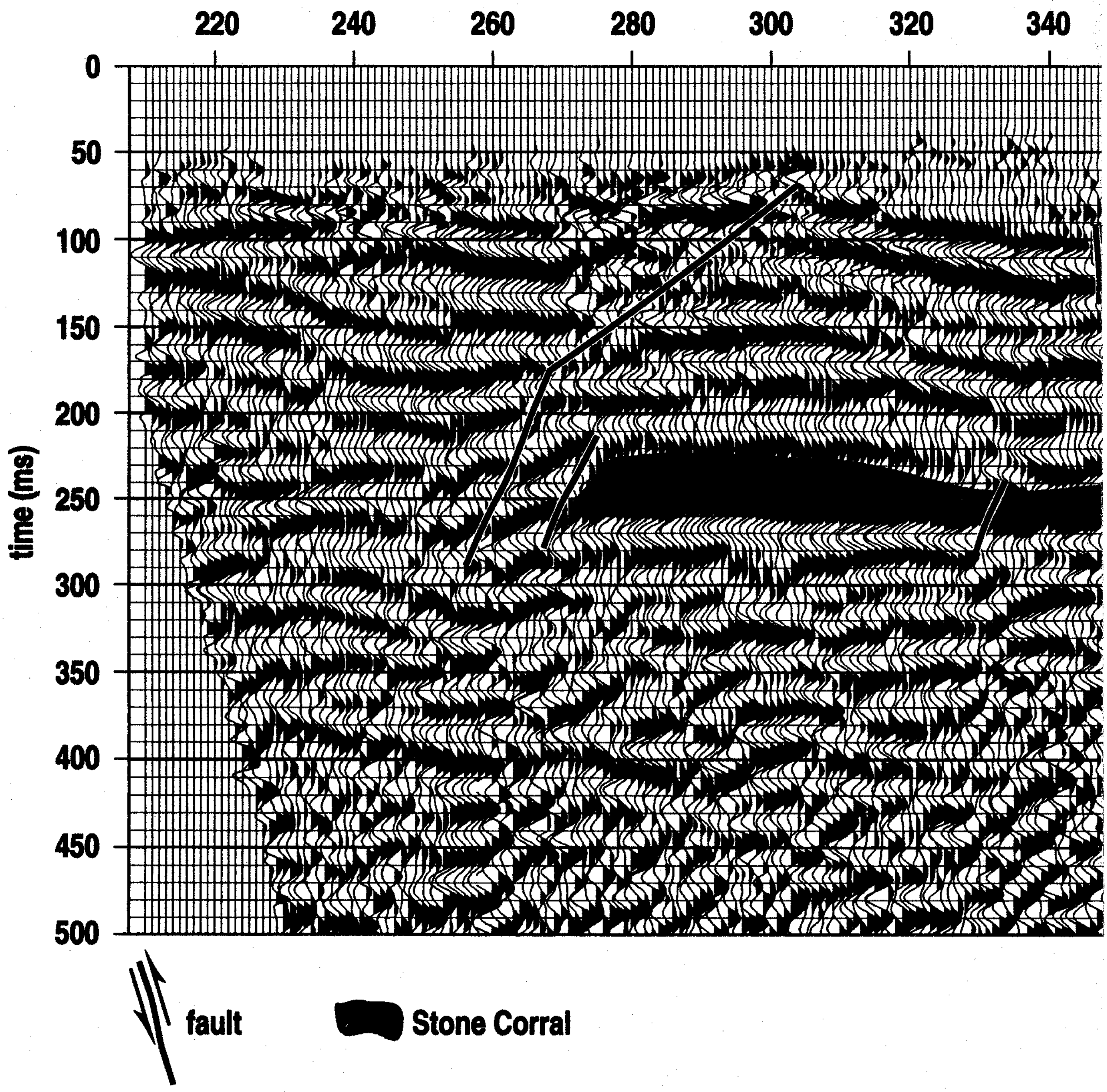


Figure 4. Field files after f-k filtering. Reflections can be seen at times between 100 and 200 msec after filter was applied to the same files that are shown in Figure 3.

Figure 5 Interpreted seismic section.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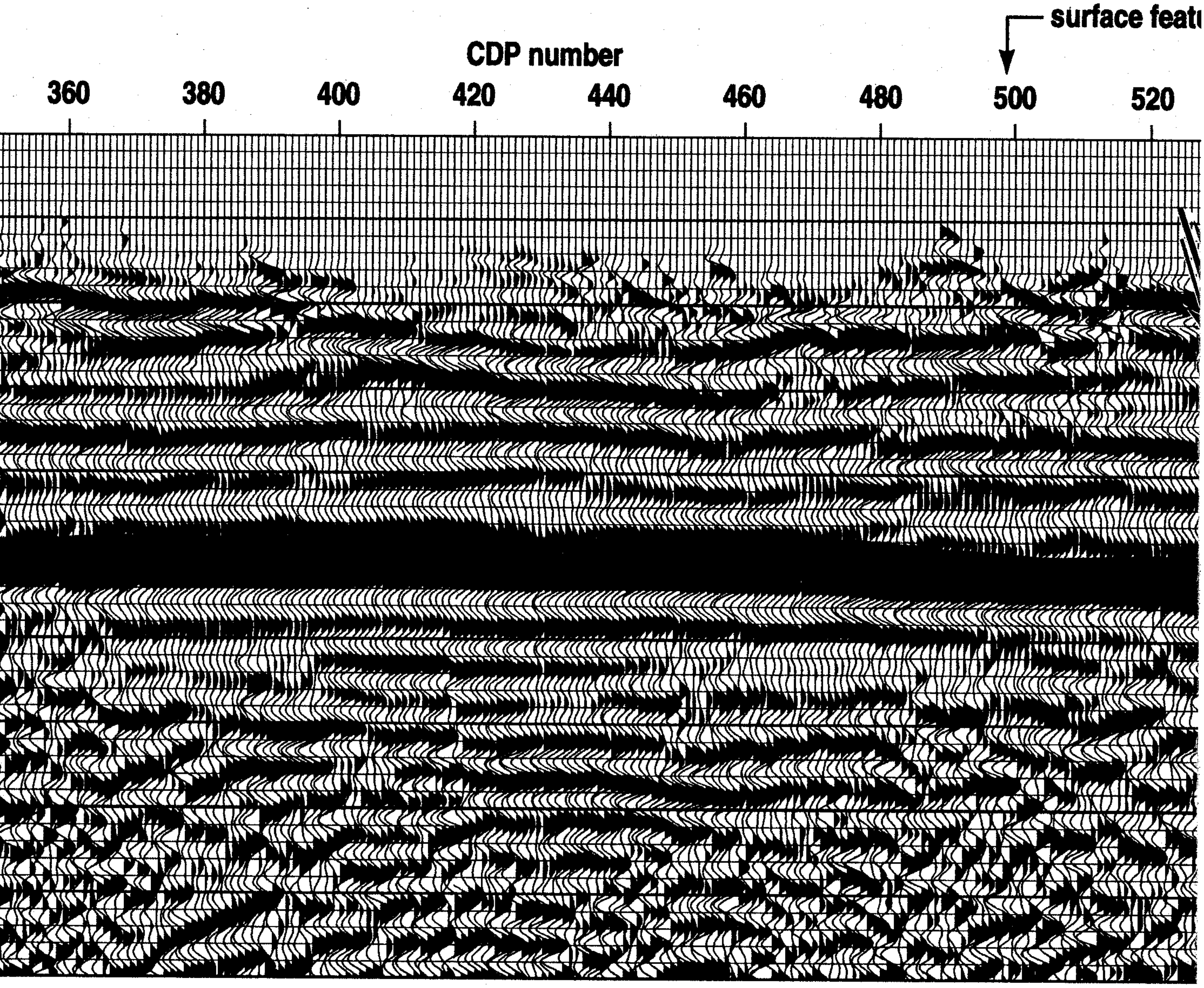
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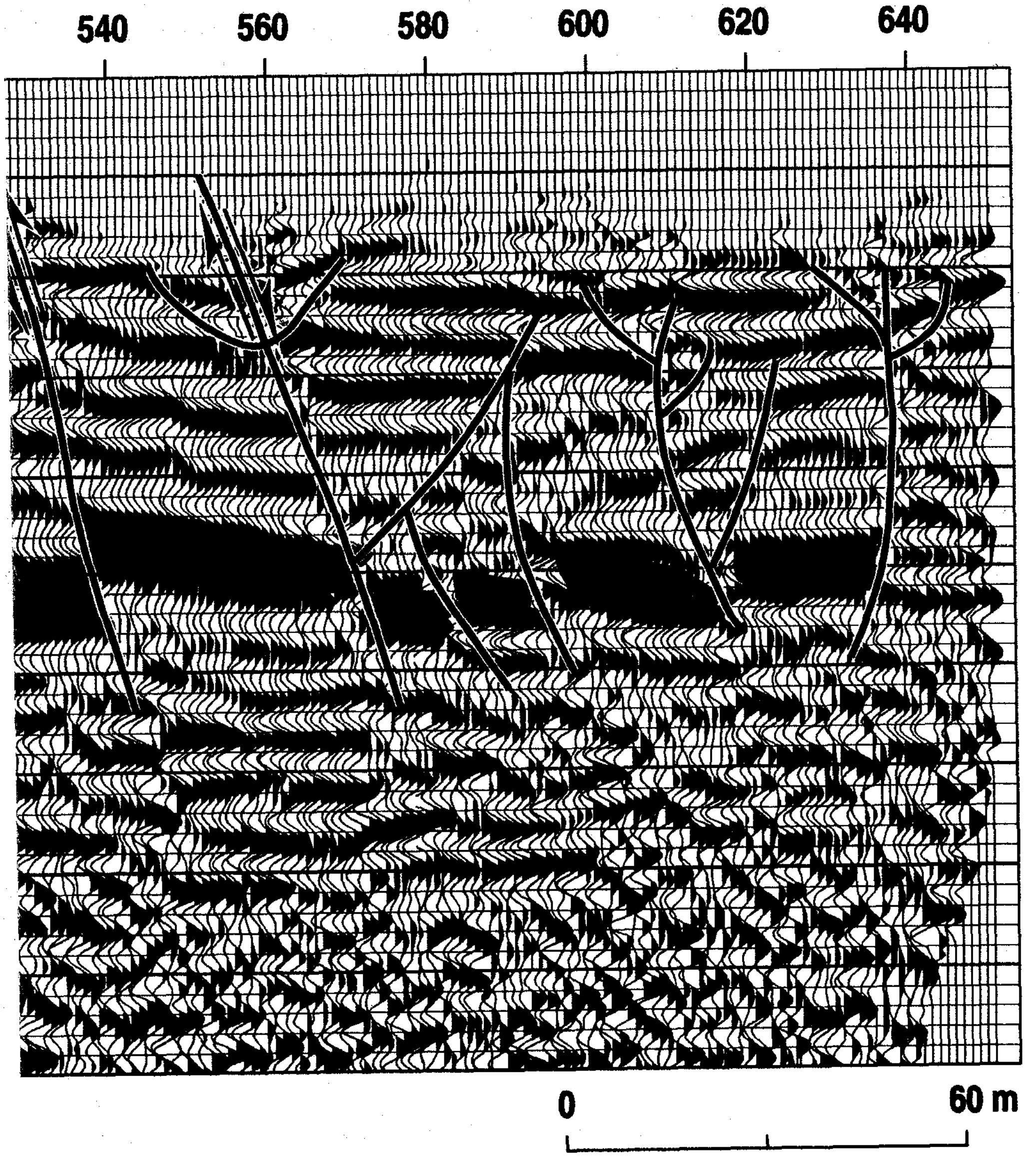
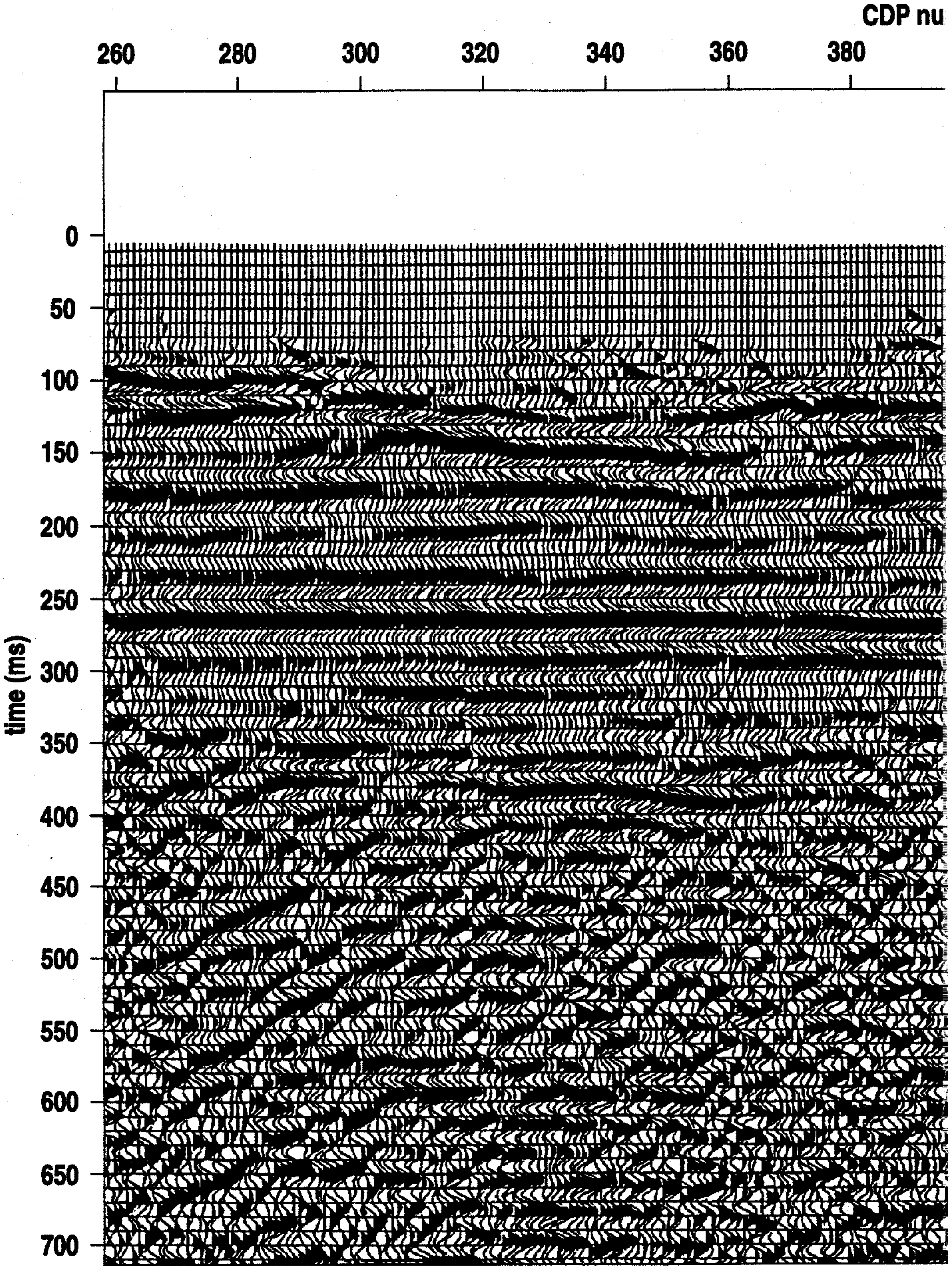


Figure 6. Palinspastic reconstruction of Figure 4, assuming reverse faulting caused the truncation of beds between 150 and 250 msec.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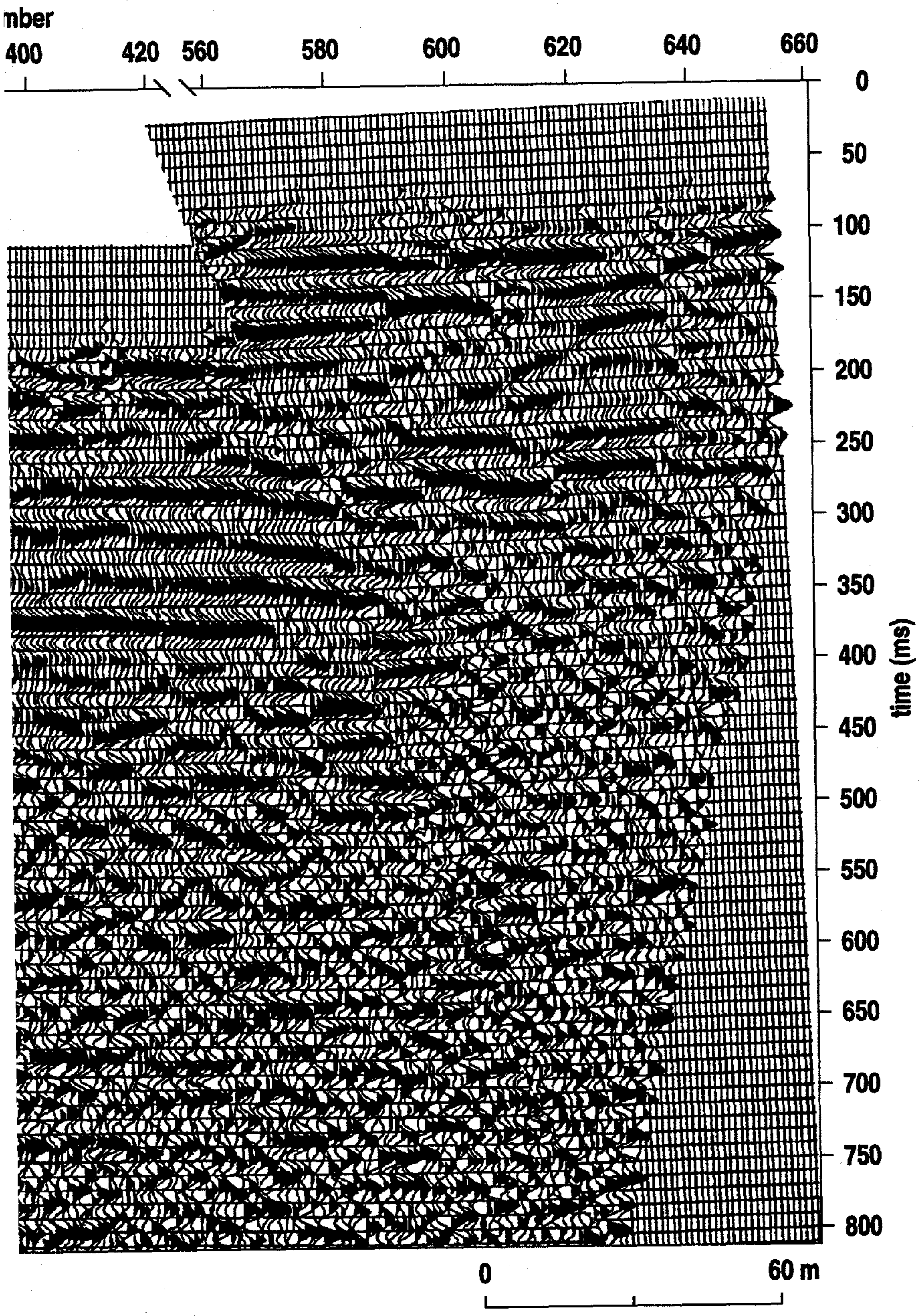
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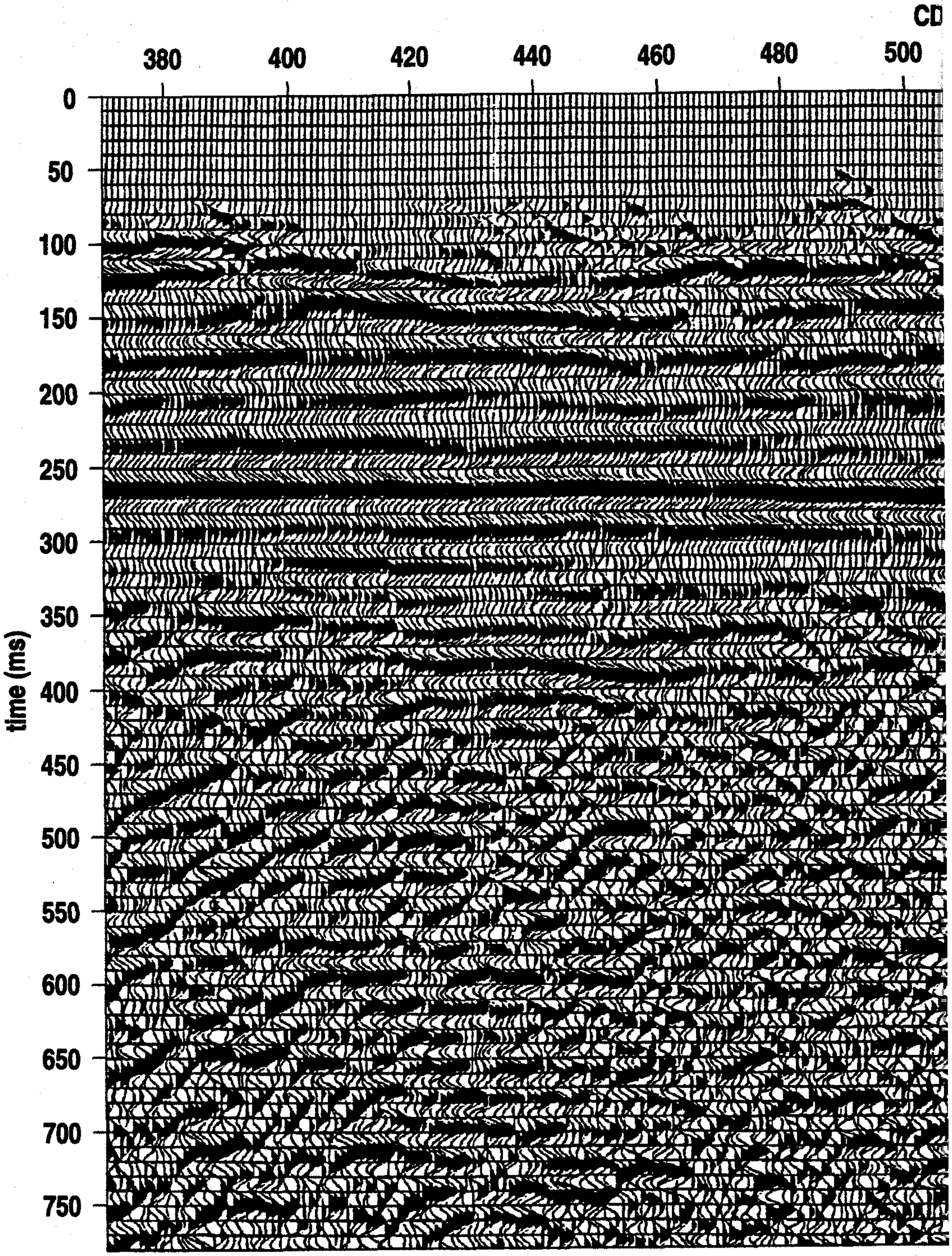
Figure 7. Palinspastic reconstruction of Figure 4, assuming normal faulting caused the truncation of beds between 150 and 250 msec.



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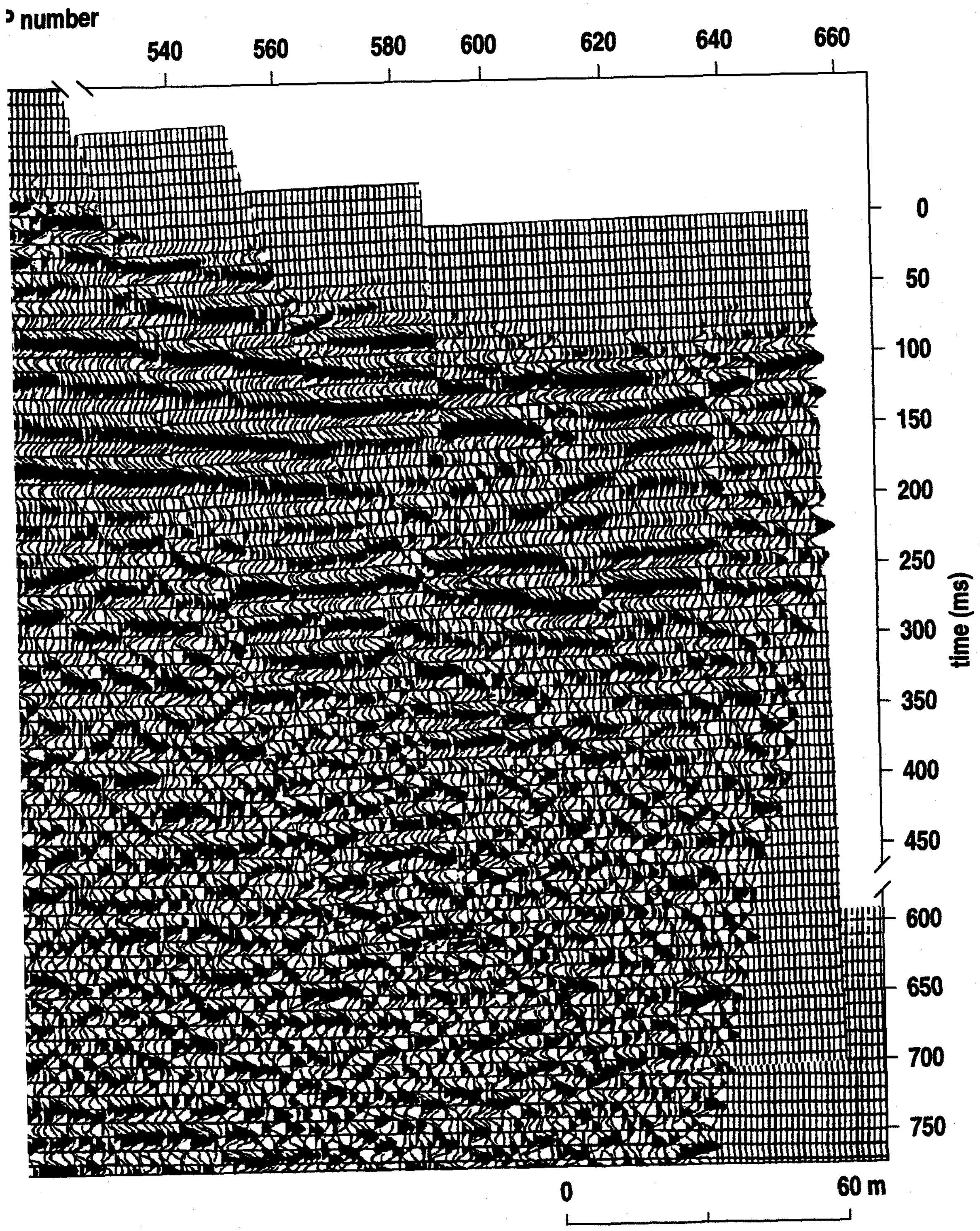
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