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The Multiwell Experiment Geophysics Program Final Report

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THE MULTIWELL EXPERIMENT GEOPHYSICS PROGRAM
Final Report

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ABSTRACT

Two Vertical Seismic Profile experiments and a Three-Dimensional Surface Seismic experiment were conducted at the Multiwell Experiment site in central Colorado to assess the applicability of seismic methods to mapping lenticular sand bodies of the Mesaverde group in the Piceance Basin. The data from these experiments were analyzed in conjunction with synthetic seismograms computed from well logs and additional geological data. This analysis demonstrated that the producing zones can be delineated once the seismic character of these zones is determined but the morphology of individual sand lenses cannot be mapped at the Multiwell Experiment site. Additionally, the extended vertical seismic profile technique was demonstrated to provide a very high resolution seismic technique for investigation of the region adjacent to an existing well.

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Introduction

The Multiwell Experiment (MWX) was initiated by the Department of Energy as part of the Western Gas Sands Subprogram to evaluate the gas resource in the tight lenticular gas sands of the Mesaverde group in Western Colorado. The Multiwell Experiment plan has two primary objectives: (1) the characterization of low permeability, lenticular gas sands and (2) the evaluation of state-of-the-art and developing technology for production stimulation (Northrop et al., 1984). A site 6 miles southwest of Rifle, Colorado, was chosen for the Multiwell Experiment investigation.

The two primary MWX goals were achieved in part by analysis of data obtained during drilling, coring, logging, and subsequent production of three close-spaced wells through the formation of interest. Additional information obtained from outcrop studies and adjacent wells helped to further the achievement of the stated goals. These methods, however, are limited in that the information is either very localized as in the case of the well data or inferred and not a direct characterization of the properties of the sands being produced. To overcome these limitations required a method to investigate the lenticular sands in situ.

The characterization of the lenticular sands and the features to be determined affect the geophysical techniques that can be expected to provide the desired information. The sand lenses in the Mesaverde group being investigated by the Multiwell Experiment are typically thin (10 ft - 50 ft), of limited lateral extent (100 ft - 2000 ft), and relatively deep (4000 ft - 7500 ft) (Lorenz, 1983).

Due to the small size of the lenses being investigated, "wave" methods with short wavelengths are required. "Potential" methods such as gravity surveys and electrical potential measurements are limited to providing data with an inadequate resolution for these problems or information only in the immediate vicinity of the access wells.

Propagating wave methods fall primarily into two categories, electromagnetic methods and seismic methods (Telford et al., 1976). Both of these methods involve propagating waves through the medium. Changes in properties in the medium (the lenticular sands for this investigation) modify or reflect these waves. The recorded signals resulting from reflection or transmission of these waves are analyzed to determine where the changes in properties occurred. This information is then used to infer material properties and physical characteristics of the material. The primary difference between the two methods is the type of wave and consequently the properties which affect the recorded signal.

Electromagnetic wave methods as applied to the Multiwell Experiment are limited by attenuation to investigations in the immediate vicinity of the well. These techniques may also have potential for use in crosswell investigations.

Seismic methods involve transmitting an acoustic pulse through the ground where changes in the density, bulk modulus and shear modulus of the material affect the waves. These properties usually change with different rock types and fluid properties and hence seismic methods can also be used to infer geologically significant boundaries. The distance a seismic signal can propagate is determined by the anelasticity of the medium. Since the attenuation, a measure of anelasticity, is usually low enough to allow seismic waves with wavelengths short enough to be affected by the sand lenses to propagate, these techniques provide the best investigation tools for remote characterization of the lenticular tight gas sands as part of the Multiwell Experiment.

Within the objectives of the Multiwell Experiment a seismic program was developed to determine how well the discontinuous sands and adjacent formations could be mapped using seismic techniques. The seismic program consisted of three separate surveys, each targeted to a different aspect of the overall MWX goals: a three-dimensional survey to investigate areal extent and interrelationship over the entire estimated production area, a vertical seismic profile to provide depth control and investigate the lenses pierced by the wells, and a cross borehole survey to investigate at a higher resolution the regions between the MWX wells. Additionally, synthetic seismograms based on well logs were used for depth control and correlations between seismic surveys and the site geology in the analysis of the data.

The discussion contained herein will concentrate on assessing the three-dimensional and vertical seismic profile seismic techniques as to their ability to provide information about the areal extent and morphology of the lenticular sands at the MWX Experiment site. A summary of each survey is included; however, the details are only provided where they either significantly affect the results or are necessary to understanding the experiment. Additional information and data are available for all of these experiments in the respective final reports (see references). The cross well seismic survey is a separate investigation coordinated by Los Alamos National Labs and information pertaining to these experiments is contained in Albright and Terry (1984).

1.0 Seismic Theory

Seismic wave propagation is a consequence of the relationship between a periodic stress and strain in the material through which the wave is propagating. If the material behaves as an elastic material (a good approximation for most earth materials subjected to the small stresses of seismic waves) the seismic wave propagation is completely determined by the density, the shear modulus, and the Lame parameter of the material. An abrupt change in any of these properties creates a boundary for the seismic wave. At a boundary, much as in optics, a portion of the wave energy is reflected and the remaining energy of the wave is transmitted through the interface. Consequently, in an ideal system with a single reflection, a short pulse introduced into the ground at the surface will be returned to the surface at a time corresponding to the time it took the wave to propagate to the interface and return. This is termed the two-way travel time. Similarly, a group of stacked boundaries will produce a series of reflection pulses with each pulse occurring at a time corresponding to the two-way travel time to an interface. In this manner a single sand sandwiched between two identical shales will produce a pair of primary reflections corresponding to the top and bottom of the sand and, in addition, several later peaks will result from multiple reflections within the sand as shown schematically in Figure 1.1. With a more complicated structure, as is generally true in the earth, the primary and multiple reflections from all interfaces sum together to give the measured seismogram. The analysis of seismic data strives to invert this process to recover the interface information from the seismogram.

The amount of information that can be recovered from a seismogram is determined by the relationship between the wavelength of the seismic source impulse (source wavelet) and the distance between reflectors. If the distance between reflectors is greater than one-half the wavelength of the highest frequency in the source wavelet, all the information about reflector locations can theoretically be recovered. When the reflectors are separated by less than one-half the wave length, the seismic wavelet acts as a low pass filter and some information about reflector locations is lost and hence no longer recoverable from the seismogram.

2.0 3-D Seismic Survey

2.1 Background

Conventional seismic investigation consists of using a series of sources and receivers in a line perpendicular to the general geological structure of a region. The resulting seismic displays give a "picture" of the subsurface equivalent to vertically slicing the ground along the line of the survey. While this technique works well for locating regional structures and trends, it provides no information as to the extent of the structure out of this cross sectional plane. Since the target of investigations at MWX was known to be of limited lateral extent, conventional seismic surveys would only provide very limited information about the primary target. Recovering information about both the areal extent and morphology of the target sands requires a spatial array of both sources and receivers on the surface in what is termed a three-dimensional (3-D) seismic geometry.

The 3-D seismic method uses an array of sources and receivers to generate equivalent vertical seismograms over an area. This gives a seismic picture of the subsurface that corresponds to a block diagram of the region investigated. This data can be used to provide 3-D information about reflections. This block of data is synthesized by treating each source-receiver pair as a separate experiment and then summing the results. In the case of a flat-layered earth, the seismic wave for this experiment would be reflected from the point, called the common mid-point (CMP), halfway between the source and receiver, as shown schematically in Figure 2.1a. If the source and receiver had both been positioned at the CMP, the seismogram would show the reflectors in their true relative positions. The measured seismogram can be made to approximate the vertical seismic experiment by adjusting the time scale to account for the distance between the source and receiver. After this correction, called the normal moveout correction or NMO, is applied, all seismograms with the same CMP can be compared directly, regardless of the source-receiver separation. Consequently, if two different source-receiver combinations share the same CMP, the time-corrected seismograms can be added to improve the signal-to-noise ratio. This summation of independent seismic experiments called "stacking" improves the signal since the reflections will be the same in both records and add constructively while the noise will be uncorrelated and will average to zero if enough records are summed. The number of source-receiver pairs with a common CMP added together for more reduction is called the fold density of the CMP and the larger the fold density, the higher the ratio of signal to noise.

The field configuration for a 3-D survey often does not provide multiple source-receiver pairs with exactly the same CMP. Consequently, the survey is divided into a series of bins by placing a grid over the survey and summing all seismograms having a CMP within the boundaries of a bin. The bin size is arbitrary, with larger bins providing a better signal-to-noise ratio and smaller bins giving better lateral resolution for the survey.

While the NMO correction eliminates the effects of the source-receiver separation (offset) from the data, this is still a very important parameter for the seismic survey. Figure 2.1b schematically shows a point imaged in a seismic experiment at three different offsets. If the imaged point is moved slightly, the three different offsets will have different sensitivities to the change. The short offset seismogram will be very sensitive to changes in reflector depth while a change in lateral position will be essentially undetected. The long offset seismogram will have the reverse sensitivities of the short offset seismogram. Consequently, the best imaging of the point by a single experiment (i.e., a single source/receiver pair) is when the offset is comparable to the depth of the point imaged. A range of offsets, both less than and greater than the depth to the image point will provide the best constraints for locating the reflection point.

Additionally, it is important to have waves propagate through the CMP bin in a number of different directions. This range of azimuths of vertical planes containing the path along which the reflected wave travels is necessary both to determine variations in seismic velocity with propagation direction and to correct for reflections from dipping layers.

The necessity for a high fold density and a range of offset and azimuth values mentioned above is incorporated into the design of the source and receiver arrays for the survey. Additionally, a survey site may impose other constraints on the specific survey geometry used.

The initial processing of the data from the 3-D survey is very similar to conventional 2-D processing. The additional data, however, make the 3-D processing more time consuming and consequently, more expensive. Likewise, the vertical seismic sections through the survey area are essentially equivalent to conventional seismic sections. The advantage of 3-D seismic data, however, comes from displaying the data from the same time for each CMP bin generating planes parallel to the ground surface in a constant time section or "time slice." The time slices are equivalent to a series of topographic maps, each showing only a single contour line. Hence multiple time slices allow one to see a plan map view of the subsurface. Using these displays, lateral variations in addition to vertical changes in geology can be inferred. A diagram showing schematic examples of time sections for a dipping layer and a simplified channel are shown in Figure 2.2. The long seismic wavelengths, relative to the channel size, will broaden the reflections and possibly obscure the separation between the reflections for the real survey data. This, coupled with the presence of many overlapping channels in the subsurface, will cause the actual survey to be much less clear than these examples.

2.2 Data Acquisition

The 3-D seismic survey of the MWX site was run during September 1981 by the Colorado School of Mines (Fried 1983). The survey was conducted using three subparallel receiver arrays with 314 source positions as shown in Figure 2.3. The receiver arrays consisted of 48 single 10 Hz geophones arranged in a rectangular array 1,265 ft long by 55 ft wide with a 55-ft separation between adjacent geophones. Each of the source locations was occupied three times, once for each receiver array. The seismic source used for the survey was a Vibroseis[R] truck. At each source location a series of ten linear sweeps from 18 Hz to 102 Hz, each with a 12 second duration were used. This surface arrangement and the resulting subsurface seismic coverage are shown in Figure 2.4.

Figure 2.4a shows that the subsurface CMP coverage overlaps the area of interest, but as indicated in Figure 2.4b, this coverage is very nonuniform. The periodic variation in fold density east-west across the area covered by the survey is a consequence of the source receiver geometry used. The original field design did not have these problems, but land use constraints, surface topography, and rock exposures, which restricted geophone positioning, required that the field configuration be modified. The uniformity of the coverage from the modified survey configuration was not investigated prior to the data acquisition. As a consequence, the signal-to-noise level is not constant across the survey. This feature of the survey geometry may cause lateral continuity breaks in the low signal-to-noise ratio zones.

2.3 Data Processing

The data from this experiment were processed by the Colorado School of Mines using a 3-D seismic processing package developed by Compagnie Generale de Geophysique (CGG). The complete processing sequence and the parameters used for the processing are discussed in the final report from the Colorado School of Mines (Fried, 1983).

The final results as provided by the Colorado School of Mines were of limited use in investigating the applicability of this survey to the MWX goals. The majority of the problems with this data were a direct result of the field configuration problem mentioned previously, but several difficulties resulted from computer processing limitations at the Colorado School of Mines.

The source-receiver configuration used for the survey provided only a limited range of offsets and azimuths for each CMP bin. The limited azimuthal coverage within the line may affect the resolution of the results, should horizontal velocity anisotropy exist, since the velocity function cannot be well characterized as a function of azimuth. The limitation of offset coverage is, however, a more serious limitation for the MWX survey goals since the location error for edges of discontinuous reflectors will be significant at depths greater than the maximum offset. This implies that location problems may occur in this survey throughout the zones of interest since the maximum offset is about 3000 ft and this is achieved only for a very few source-receiver combinations.

Additionally, the MWX field site for the survey had a very high ambient noise level as a result of drilling activity and the close proximity of a high-voltage power line. The high noise level necessitated the use of reduced gains and a 60 Hz notch filter during data recording. The resulting data have a significantly reduced frequency band and a low signal-to-noise ratio.

During processing, the low signal-to-noise ratio made it difficult both to remove the constant timing shifts (static corrections) for individual records resulting from small variations in the seismic velocity of the surface layers and to determine the velocity structure used for the NMO corrections. These difficulties were further compounded by processing the data in small blocks due to limited computer memory.

2.4 Data Interpretation

The resulting displays were extremely difficult to interpret since it was difficult to separate artifacts of the processing from the actual seismograms. An example of this is shown in Figure 2.5. The features in this figure that tend to align with the grid lines are probably processing-induced features and not the signature of any north-south or east-west geologic structure. From this figure it is also difficult to determine the data noise level because it cannot be separated from processing-induced effects.

The variations causing the grid aligned features are not apparent in the vertical (east-west and north-south) displays through Well MWX-3 shown in Figure 2.6 because of the display scale. The vertical slice displays, however, primarily provide information about vertical structure and are consequently only of limited use for the analysis of lense morphologies at the MWX Experiment site.

At the completion of the data-processing by the Colorado School of Mines, the question as to whether this survey could provide information regarding the areal extent and morphology of the lenticular sands at MWX was still largely unanswered. Consequently it was decided to reprocess the data from this experiment in a manner that would eliminate the processing-induced noise in the previous results.

2.5 3-D Survey Reprocessing

The seismic data and field survey data recorded by the Colorado School of Mines were provided to Prakla-Seismos GMBH in January 1984 for reprocessing starting with the original field data (Dannenberg et al., 1984). During the reprocessing of the data, several inconsistencies in source and receiver positions with the previous processing were noted. These inconsistencies were not large, but the field survey data could not be made to match the previous site map. Corrected versions of both the site map and CMP coverage map were created and are shown in Figure 2.7. Additionally, since the starting azimuth for the survey data was unclear in the field notes, the north arrow for all maps and displays from Prakla-Seismos is rotated 25.5° W of N relative to true north at the site.

The initial processing sequence was similar to that performed previously with the exception that residual statics and velocity analyses required for normal moveout correction and surface correction could be performed with access to the entire data set at one time. Additionally, several processing steps designed to remove the effects of the recording equipment and enhance the signal-to-noise ratio were also included. Prakla-Seismos encountered several problems when running the residual statics correction and the velocity analysis resulting from the low signal-to-noise ratio of the data. To improve the situation the data were rebinned using a rectangular grid with square bins 55 ft on a side for static corrections and stacking velocity determination. Following the evaluation of these corrections, the data were again rebinned at the 27.5-ft grid size used previously for the remainder of the processing.

The displays resulting from the first 3-D stack were extremely noisy. As a consequence of this, several additional processing steps and filter tests were run to improve the signal-to-noise ratio and determine the ultimate utility of the data.

The first step which showed any significant improvement involved a five trace compaction scheme. This method includes summing each trace with its four immediately adjacent neighbors with the central trace having a weight three times that of the outer traces. This reduces the noise level by adding in additional information and at the same time reduces the variation in fold density across the survey. This method, however, also has the effect of slightly smearing the edges of reflectors.

2.6 Reprocessed 3-D Data Interpretation

The constant time sections or "time slices" for the reprocessed data show many small features, but no linear or sinuous features that could correspond to abandoned river channels are apparent. Figure 2.8 shows the time slices corresponding to the red and yellow sands in the coastal zone (6000 ft - 6600 ft) with the geological interpretations of these sands determined by Lorenz (1984) overlain on the display. While the correlation appears to be quite good, it may also be random as is shown by the geologic overlay from the yellow C sand on a time slice from a very different depth (Figure 2.9).

The vertical plane seismic displays shown in Figure 2.10 also show very few reflectors that have a significant lateral extent even in the marine blanket sand zone. This lack of lateral coherence is primarily a result of the overall low signal-to-noise ratio of the survey though the thick surface weathered layer and the fine structure both laterally and vertically for this site may also contribute to the effect. The final results of the reprocessing show the data to be extremely noisy and, in this form, of limited use for identifying and mapping lenticular sands at the MWX field site. Filter tests and migration tests on the final data both showed some visible improvement in the signal-to-noise ratio, but it is unlikely that applying these processing steps to the entire data set will provide displays that are useful for the kind of interpretation desired. Consequently, further analysis of the 3-D seismic data is not warranted.

3.0 Vertical Seismic Profile Experiments

3.1 Background

The Vertical Seismic Profile (VSP) is a seismic technique that allows the wave field to be sampled along a vertical line, as opposed to the horizontal line used in surface techniques. The VSP is run using a source at a single surface location usually near a well and recording the seismic signal at regular intervals down the well. The seismograms recorded at each level are then displayed as a function of depth in order to give a picture of the seismic wave field both as a function of depth and time. This is shown schematically in Figure 3.1.

The primary advantages of this method over surface seismic techniques are: (1) the ability to directly correlate the seismic data with depth and, consequently, other information such as well logs and core and (2) the ability to duplicate a low-noise vertical seismogram at the well for direct comparison with surface seismic surveys in an area of interest. This ability to link surface seismic data to well measurements was the impetus for incorporating the VSP survey in the MWX seismic investigations.

Two types of VSP surveys were conducted at the MWX field site, both as joint Sandia-USGS experiments (Lee, 1984-a; Lee and Miller, 1985). The first, a conventional VSP, was run to provide a direct tie between the time of arrival and the depth to an interface for use in interpreting the other seismic data. The second VSP survey, while it did include a conventional VSP, also used several additional source locations positioned at greater distances and different directions from the well to extend the VSP seismic data away from the well. This method allows for a high resolution seismic investigation of the region adjacent to the well (Lee, 1984b).

3.2 Data Acquisition

3.2.1. The 1982 VSP Survey

The first VSP was run during the spring of 1982, and is described in detail in Lee 1984-a. This experiment consisted of four VSP surveys. Two surveys were run for each of the MWX-1 and MWX-2 wells, one with the source offset approximately 200 ft from the well and a second with the source offset 1900 ft as shown in Figure 3.2. The seismic records, generated by a 410 cu. in. Bolt land airgun, were recorded using a locking triaxial borehole seismometer. Both wells were surveyed from 8000 ft to the surface at 25-ft intervals for both VSPs.

Several problems were discovered during the data processing that were not detected during the field phase of the surveys. A problem with the 1982 survey resulted from a malfunctioning recording system. The other problems were related to the airgun used as a seismic source. The result of both of these problems was to degrade the recorded seismic signal available for processing.

The recording system problem manifest itself as an additional nondata record written in the middle of the seismic data record. Removing this gap from the data record introduced a small (± 2 ms) unknown timing error into all data following the gap in the 1982 survey. This additional record gap did not occur in the 1984 survey.

The VSP data for MWX-2 from the 1982 survey shown in Figure 3.3 has two undesirable characteristics, both of which are attributable to the source. First, the source waveform has a duration in excess of 0.5 seconds. Analysis of the source monitor records indicates that the three elements of the airgun source were not properly synchronized, giving the increased wavelet length. This has the effect of smearing out the reflections and, at the same time, reducing the high frequency power in the signal.

The second problem was a change in source waveform that resulted from moving the source 15 ft to 20 ft during the survey as the ground under the source became unstable. This occurred only once at about 6000 ft for the 1982 survey. Due to this change in source waveform, the optional processing parameters are different for the upper and lower portions of the survey. Preliminary processing tests indicated that the differences were small enough so as to be insignificant on the processed sections.

Also apparent in Figure 3.3 are the arrivals of a low velocity wave propagating up and down the casing-fluid interface called a "tube wave". Tube waves are generated by surface waves emanating from the source hitting the well.

Although these signals occur late in the record, they have a large amplitude compared to the reflected signal and consequently mask some of the reflection information.

Though several problems were encountered during the data acquisition which resulted in a signal degradation, the data provided a good base from which to evaluate the effectiveness of VSP for mapping and or identifying lenticular sands.

3.2.2. The 1984 VSP Survey

The second VSP, produced during the spring of 1984, was very similar to the first with the exception of the source configuration and the depth range covered (Lee and Miller, 1985). This survey consisted of four VSPs for each of the MWX-2 and MWX-3 wells. The four VSP's consisted of three from long source offset positions and one from a near offset position in the configuration (Figure 3.2). Due to the unavailability of the lower portion of MWX-2 and the shallower bottom hole depth of MWX-3, these VSP surveys covered only depths from 7000 ft to 2000 ft, again at 25-ft intervals.

The 1984 VSP was run during the spring of an exceptionally wet year. Consequently, the airgun source could only be operated at one position for between 20 and 40 pulses. The effect of both the unstable ground and the frequent source repositioning is shown by the apparent horizontal banding in Figure 3.4. The difference in waveform between adjacent source positions is so large for these surveys that it required a special statistical approach to the processing. This technique successfully overcame these source variations, eliminating the need to process each record independently (Lee, 1985).

With the exception of the ground stability problems, the data from this survey were very good. There were no tube waves in the records due to the increased source effect from MWX-3 and more surface land fill at MWX-3.

3.3 Data Processing

The data from both VSP surveys at the MWX field site were analyzed and processed by the USGS using a combination of software developed in-house at the USGS and the DISCO system processing software from Digicon. A summary of the processing sequence used for both VSP surveys is given in Table 3.1.

The first step after stacking the multiple records recorded at each level is the separation of the waves propagating upward toward the surface and the waves propagating down or away from this surface which allows the two portions of the signal to be processed separately. The downgoing portion of the waveform provides the information necessary to determine the formation acoustic velocities and to compute a time-depth table for use with conventional surface seismic data. The separated downgoing waveforms and the corresponding time-depth table from the first survey are shown in Figure 3.5 and Table 3.2, respectively. These data are also used to compute bulk rock properties for the region surrounding the well. Bulk rock value of Poisson's ratio and compressional-to-shear wave acoustic velocity ratio data as computed from the 1982 VSP are shown in Figure 3.6.

The upgoing portion of the waveform is the portion that would be recorded by surface seismic instrumentation. This portion of the waveform provides the information as to reflector location. It can also be summed together to provide a very low noise equivalent surface seismogram for comparison with surface seismic data for identification of the various reflection arrivals.

After the two pieces are processed separately, the data are recombined to give the more conventional VSP display shown for both surveys in Figure 3.7. This display shows the locations of the reflectors as the apices of the "Vs" formed by the intersection of the direct and the reflected arrival. This display is then interpreted as in Figure 3.7 to identify the primary reflectors in the zones of interest. Comparing these displays with the sonic and density logs, also shown in Figure 3.7, it is evident that the seismic impulse has a wavelength that is too long to separate all reflectors and that the reflections observed in the record generally do not coincide with density and/or velocity changes in the well. Reflections are returned from each interface, but what is observed is a sum of all reflections which is essentially a low-pass filtered version of the formation characteristics. In regions such as the paludal zone (6600 ft to 7500 ft) where many high contrast reflectors are separated by less than one-half wavelength, the seismogram is a series of interference figures, whereas in regions where the reflectors are reasonably well separated like in the marine zone (7500 ft to 8200 ft), the reflections align reasonably well with the geologic features. The lack of reflections in the fluvial zone (4400 ft to 6000 ft) indicates either that there is no significant contrast between layers, or the separation between reflectors is so small that the zone behaves acoustically as a homogeneous unit.

The data recorded using an extended horizontal separation between the source and the well can also provide some additional information about the subsurface velocity structure. The larger the angle to the source as measured relative to vertical from the receiver, the greater the shear wave component in the seismic records resulting from the vertical motions of the source. Since the shear waves are only affected by changes in density and shear modulus as indicated by the expression for shear wave velocity in Table 3.3 and not by changes in the bulk modulus, the shear wave and compressional wave response may differ significantly. A comparison of the shear wave VSP in Figure 3.8 and the compressional wave VSPs in Figure 3.7 shows that this is true at the MWX field site. The shear wave data appear to be far more sensitive to lithologic changes in the fluvial zone than the vertical motion compressional VSP.

Additionally, the long offset VSP data contain information about the lateral extent of reflectors between the well and one-half the source offset in a vertical plane containing the source and the well. Resampling the VSP data as a function of depth and time to align reflection points produces a common depth point (CDP) section similar to that produced by surface seismics from the long offset VSP data. These VSP-CDP sections for the source position west, north, and east of the well are shown in Figures 3.9a, b, and c, respectively. The change in reflector character away from the well is a result of lateral variations in rock properties.

3.4 VSP Interpretation

The zones being investigated as part of the MWX are indicated on the interpreted sections in Figure 3.9. The most prominent zone is again the paludal with what appear to be large continuous reflectors. These reflectors are, however, interference figures resulting from closely spaced interbedded coals. Similarly, the marine sands appear relatively continuous with the variations most likely resulting from local variations in thickness or silt/sand ratios.

The coastal zone only shows two reflections; one at the base and one near the top. These appear from analysis of well log data to be the top and bottom of the coastal sands. The bottom reflector appears to be relatively small with boundaries at 400 ft west, 200 ft north, and 400 ft east of MWX-3. These positions are not inconsistent with the work of Lorenz (1984). However, since only three points on the channel boundary are constrained, any channel having these points on the edge will satisfy the data. Consequently, these data say nothing regarding channel directions. The fluvial zone appears to be relatively devoid of laterally coherent reflections. However, there is an indication of laterally discontinuous reflectors away from the well.

The VSP survey was included in the seismic program primarily to establish a relationship between reflectors as observed in surface seismic data and the geology at MWX as determined from well log and core analysis. The 1982 VSP provided this information and additionally the long offset source indicated the potential for the VSP to provide more information about lense geometries. The resolution improvement over surface seismic data was a result of the close proximity of the receiver to the lenses being investigated. The 1984 VSP survey was designed to take maximum advantage of the long offset source and to provide maximum information about the fluvial, coastal, and possibly the paludal zones. Even though there were severe noise problems in the data resulting from ground instability, the VSP-CDP sections provided the highest resolution seismic data available for the site. These sections indicated the presence of lateral variations in properties in the fluvial and coastal zone, but the wavelength is only sufficient to identify major boundaries. Additionally, the two vertical sections, east-west and north from the well provide sufficient information only to define boundaries and not the complete areal configuration of the discontinuous lenses.

Mapping the complete morphology of lenses would require sections recorded at several additional azimuths from the well. Additionally, the use of multiple offsets at a single azimuth would provide the information necessary to correct for diffraction effects. This type of survey would involve a substantially increased field effort over previous studies and is not warranted considering the small impedance contrasts and close spacing for the lenses in the zones of interest, as discussed further in the following section.

4.0 Synthetic Seismic Analysis at MWX

4.1 Background

The solution to the general seismic problem, determining geologic structure from returned seismic signals, is non-unique. That is, there may be many different geologic structures which yield the same seismic response. Consequently, any available additional information about the existing geological structure at a site being investigated can be used to provide a better interpretation of the seismic data. Data from well logs can be used for this application, but the relationship between the well logs and the observed seismogram must be established. One method used to determine this relation is to tie depth and seismic arrival time as was done in the VSP. While this technique does give a correlation, it was also shown (Fig. 3.7) that features on the well logs do not necessarily match with seismic arrivals. A second method is to use the well logs to model the vertical seismogram. This technique has the advantage that the synthetic seismogram can be computed to correspond to any type of survey since the source parameters in the model can be varied. The resulting estimated seismic response is also directly correlated to depth in a known manner so that the seismic response corresponding to a specific geological boundary can be identified. Additionally, when the targets of interest are identified, it is possible to determine the source parameters necessary to identify these features using the seismic method.

A synthetic seismogram, since it is computed directly from well logs, is only as accurate as the well logs. Any problems with the sonic and density logs such as cycle skips, washout effects, etc., will all result in apparent boundaries and consequently will show up as reflections on the synthetic seismogram. Similarly, any significant deviation of a well will result in a measured depth along the well being different from the actual depth. Consequently, comparisons with actual seismic data (3-D and VSP) may not provide a perfect match but may require a nonlinear compression of the time scale for the synthetic relative to the true seismic record since it will be longer while covering the same depth range. Even with these limitations, however, the synthetic seismogram provides a very useful means for interpreting surface seismic and VSP data.

Computation of a full synthetic seismic record containing primary and multiple reflections, refractions and attenuation is an extremely complicated and computationally intensive process involving solution of the 2-D or 3-D wave equation or ray propagation equations. While this does provide a more accurate result, it is far more than is required for this analysis. The approach used here was to compute a one-dimensional synthetic seismogram that does not account for multiple reflections, refractions, or attenuation, but does locate the primary reflectors at their true time positions as determined from the sonic log.

4.2 Theory

The reflectivity, or portion of energy reflected at an interface, is determined by the seismic impedance (velocity x density) above and below the interface. If the impedance log is treated such that each value represents an individual layer, the reflectivity, C_i, of the i^{th} such layer can be computed by the relation

$$C_i = \frac{Z_{i-1} - Z_i}{Z_{i-1} + Z_i}$$

where Z_i is the impedance of the i^{th} layer. This is approximated by the relation

$$C = \Delta \log [\rho v/2]$$

where Δ is a difference function and ρ and v are density and velocity, respectively (Sheriff, 1980). This approximation allows the reflectivity to be computed in the time domain and also is less sensitive to noise in the well logs.

The approximation used for the above relation breaks down if the impedance change across any boundary is comparable to the impedance of either layer. The well log data from MWX show no boundaries that approach this limitation.

A synthetic seismogram is computed by evaluating the convolution of a seismic source function (wavelet) with the reflectivity as determined from well logs. Since the wavelet will remain constant only as a function of time and not depth, it is necessary to first transform the well logs to functions of time using the time-depth table determined by integrating the sonic log. The result then is a seismogram with amplitude versus time. The same time-depth table can then be used to convert the seismogram to a function of depth for comparison with other well data.

4.3 Interpretation

The acoustic impedance log as computed for MWX-3 is shown in Figure 4.1. The primary zone of interest in this figure is the region from 4000 ft to 7500 ft. Within this zone, there are several significant variations; however, the region from 5000 ft to 6000 ft appears quite constant. Similarly, the interval from 6000 ft to 6400 ft is also relatively constant indicating that the geologic features are not well represented as seismic features.

Using the method described above, this impedance log was used to compute both a reflectivity series for MWX-3 and a synthetic seismogram using a 40 Hz Ricker wavelet as shown in Figure 4.2. Peaks corresponding to significant reflections are noticeably absent from the 0.8 to 1.05 second zone (4000 ft - 6500 ft) with structure both above and below this zone. Figure 4.3 presents the lower portion of the seismogram as a function of depth. This shows that the region with essentially no reflections is the fluvial and coastal zones. The larger reflections below this are from the coals in the paludal zone.

Seismograms for the fluvial, coastal, and paludal zones are presented with well logs and geologic interpretations from Lorenz (1984, 1985) in Figure 4.4. These comparisons clearly demonstrate that the structure at MWX is too fine and the impedance contrast between layers too low to be adequately resolved in the seismic section. The gross structure such as identifying the fluvial-upper coastal zone, the base of the coastal zone, or the thickness of the coal, sand and shale sequence in the lower coastal and paludal zone can be clearly determined from these seismic records. Additionally, the uniform sine wave character of the record within these zones is indicative of an existing fine structure which cannot be resolved.

The above comparison raises the question as to what frequency would be required to adequately resolve the desired features. The reflectivity function shown in Figure 4.2 is essentially the impulse response of the subsurface. That is, it corresponds to the seismogram that would be generated by a delta function source. Consequently, it is not possible to have a seismogram with better resolution. Since the units of interest are not clearly defined in this display, seismic methods will probably not provide much more than general structure information at this site. This same conclusion can be drawn from the seismic impedance plot in Figure 4.1. The impedance is relatively constant with small random variations throughout the fluvial and coastal zones with the significant steps occurring above the fluvial and in the paludal zone. There is also a smaller step occurring at the top of the basal sand interval in the coastal.

The synthetic seismogram provides a useful tool to assess the applicability of seismic methods to the specific goals of MWX. While the results do not look promising for identifying and mapping individual lenses, it does appear the general structure can be determined. The results of this synthetic seismic analysis can also be used in the interpretation of both the existing VSP and 3-D seismic data from the MWX field site. Additionally, it should be noted that the inability of the seismic method to resolve and map lenticular channels at this site is primarily a result of the local rock properties. Increasing the frequency content of the seismic source will help somewhat, but will still not make it possible to map individual lenses. The seismic technique may be applicable at another site where the rock property variations are larger, but a synthetic seismic investigation of the proposed site using nearby well logs if they are available is recommended to assess the potential of the seismic method.

5.0 Discussion

The VSP - CDP sections and the comparable West-East section from the 3-D seismic survey compared in Figure 5.1 show only a very poor correlation at best. Also included in this comparison are the synthetic seismograms constructed using the Ricker wavelet which most closely approximates the respective survey (40 Hz wavelet to match the VSP and a 23 Hz wavelet to match the 3-D data). These comparisons with the synthetics indicate that some of the difference is a result of the higher frequency content in the VSP data. Recognizing the difference in frequency content, the two surveys still give very different pictures, specifically in the horizontal length of reflectors. Since the average fold density for the VSP - CDP is much higher than that for the 3-D survey, it is reasonable to assume that these discrepancies are a result of noise in the 3-D survey data. Consequently, the results of the 3-D survey should only be used with great caution.

The other feature of the comparisons in Figure 5.1 is the lack of any significant reflections throughout the 0.7 sec to 1.0 sec zone which covers the majority of the fluvial and coastal zones. The synthetic seismic analysis demonstrated that at least at well MWX-3, both the property contrasts between reflectors and the thickness of individual reflectors were small and consequently, these produce at most a series of interference figures. The seismic sections indicate that this is generally true of the region surrounding the wells. There is, however, an indication of seismic structure in the zone to the north and east of the wells from the VSP-CDP plots (Figure 3.9). It is very difficult to interpret anything in this region from the 3-D survey plots since the noise level is quite high. There are some laterally coherent reflections to the west of the well which lend some additional support to the presence of significant reflectors north and west of the wells. This interpretation must be held with some caution, however, as the VSP source position east of the well encountered the most serious ground stability problems and consequently will have the largest degradation of all VSP-CDP lines.

6.0 Conclusions

The seismic data acquired as part of the Multiwell Experiment provided a good base from which to evaluate the applicability of seismic techniques to the characterization of lenticular sands. The analysis of these data demonstrated:

1) The complete morphology of individual lenses or channels in the coastal and fluvial zones cannot be determined at the MWX site using existing surface seismic techniques.
2) Zones with similar geologic characteristics such as the paludal - lower coastal zone and the upper coastal-fluvial zone have a recognizable seismic character in both the VSP and the 3-D seismic data.
3) The extended VSP technique provides the highest resolution seismic picture of the region adjacent to a well.
4) Synthetic seismograms provide a means to determine the success potential of seismic methods prior to executing the survey.

The ability of seismic methods to identify only zones and not individual lenses or channels is due largely to the local rock properties. While these properties are most likely indigenous to the tight lenticular sand formations, it is possible that similar areas exist where the lenses are larger (or shallower) and the rock property variations are larger and the seismic techniques will work quite well.

The 3-D method and the VSP method both have the potential to map spatial features of interest, provided the features are of sufficient size and contrast sufficiently with the surrounding medium so as to be resolvable. For field development in a lenticular sand region such as MWX, it appears the VSP method provides the best picture in that it extends known information away from the existing well. For these surveys at least one long source offset is required; however, using both multiple azimuths and multiple source efforts for each survey will provide essentially 3-D coverage of the region adjacent to the well. A more regional view will require a 3-D survey. When this survey is performed, care must be taken to assure uniform site coverage and as high a returned signal frequency as possible.

7.0 Recommendations

The long offset VSP data provided an indication that shear waves were more sensitive to the boundaries of interest. This, coupled with a wavelength roughly half that of the compressional waves for the same frequency, may provide the resolution and contrast required to map the zones on a much smaller scale than the conventional high resolution methods. This should be investigated further to determine the full potential of this method for defining the areal extent and morphology of lenticular sands.

Table 3.1

Basic VSP Processing Sequence
1. Demultiplex Field Record
2. Sort, Edit, and Mute Data
3. Stack the data from different shots at the same level
4. Apply deconvolution operators to compress the source wavetrain
5. Separate upward and downward propagating waveforms
6. Merge the upward and downward propagating waves and increasing the amplitude of the upward propagating portion to increase the visibility of this portion of the signal
7. Display VSP record

Table 3.2

Time Depth Table from the 1982 VSP

Depth (Feet)	Travel Time (ms)	Depth (Feet)	Travel Time (ms)
600	91	4400	391
800	108	4600	405
1000	126	4800	419
1200	143	5000	435
1400	159	5200	449
1600	176	5400	465
1800	192	5600	479
2000	208	5800	493
2200	224	6000	508
2400	239	6200	525
2600	255	6400	540
2800	271	6600	556
3000	287	6800	572
3200	301	7000	590
3400	317	7200	608
3600	331	7400	628
3800	347	7600	646
4000	361	7800	660
4200	377	8000	672

+ Depths are referenced to a surface elevation of 5359 feet.

++ Times are one way travel accurate to ± 2 ms corrected for a source offset of 265 feet.

Table 3.3

The Relationship Between Seismic Velocities and Rock Material Properties

$$V_p = [(\lambda + 2\mu)/\rho]^{1/2} = [(k + 4/3\mu)/\rho]^{1/2}$$

$$V_s = [\mu/\rho]^{1/2}$$

V_p = Compressional wave velocity

V_s = Shear wave velocity

k = Bulk modulus

μ = Shear modulus

λ = Lame's parameter

ρ = Density

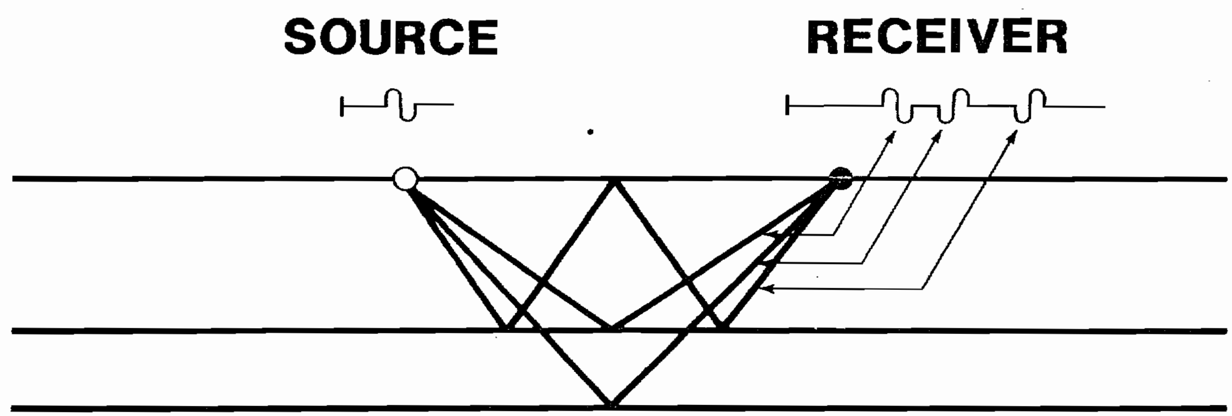


Fig. 1.1. Schematic diagram of the reflection seismogram.

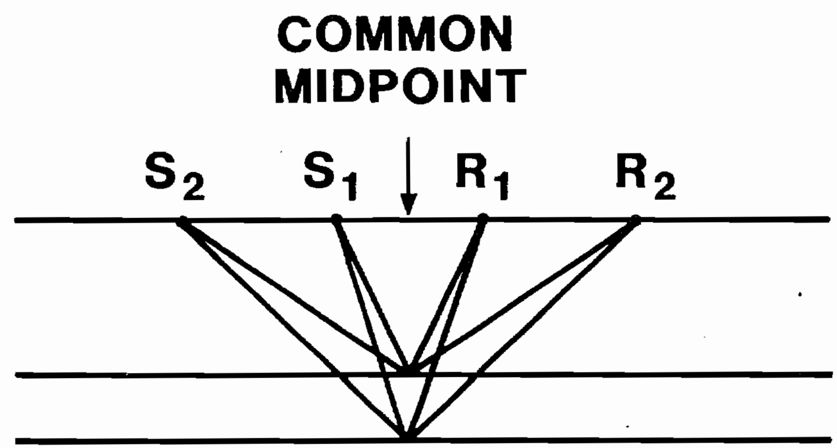


Fig. 2.1a. Schematic diagram of the common midpoint relative to the source and receiver geometry.

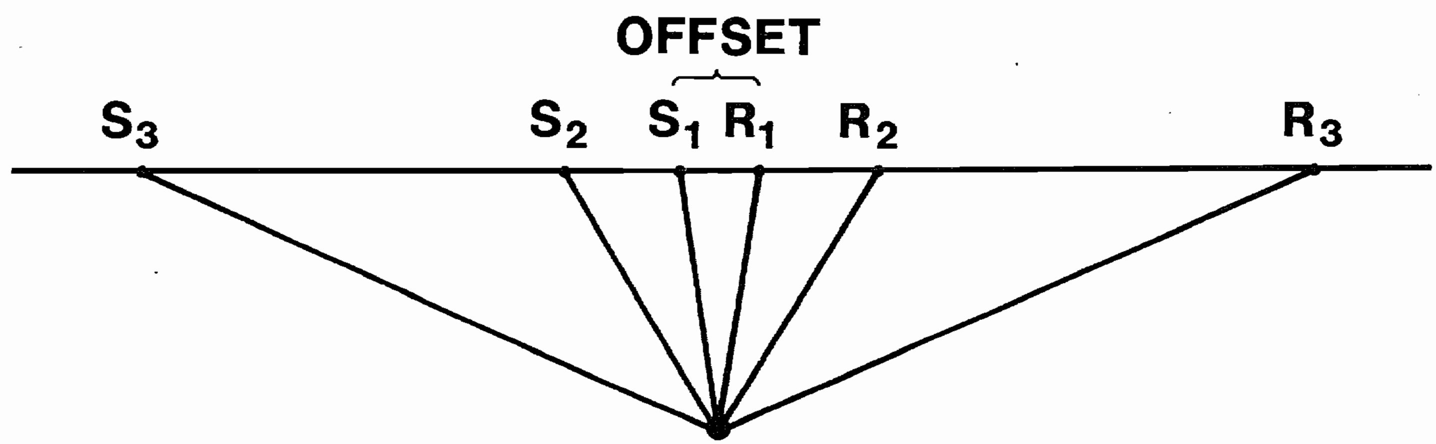


Fig. 2.1b. Reflections from a point using three different Source (S) - Receiver (R) offsets.

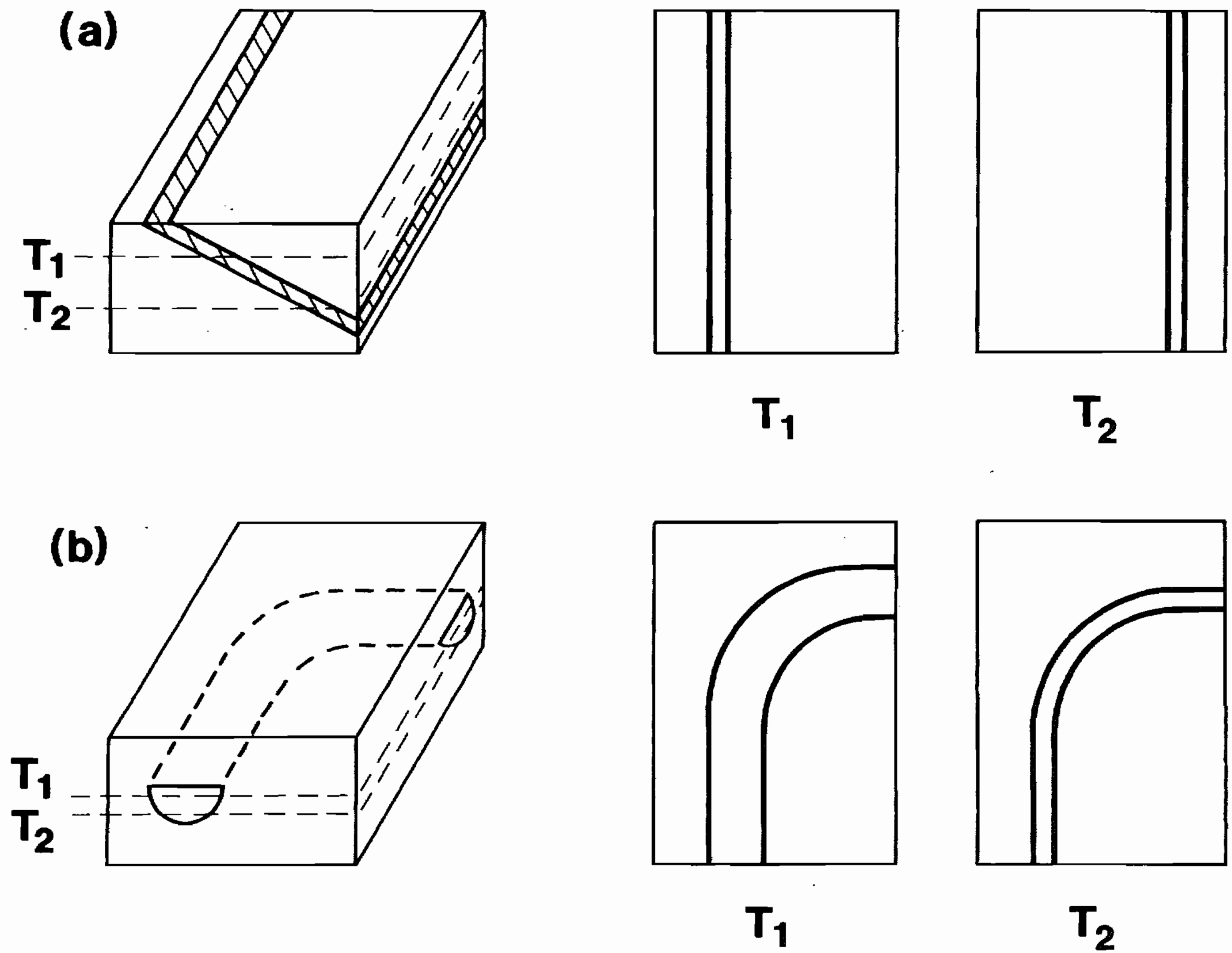


Fig. 2.2. An idealized time slice display for a) a dipping bed and b) a channel.

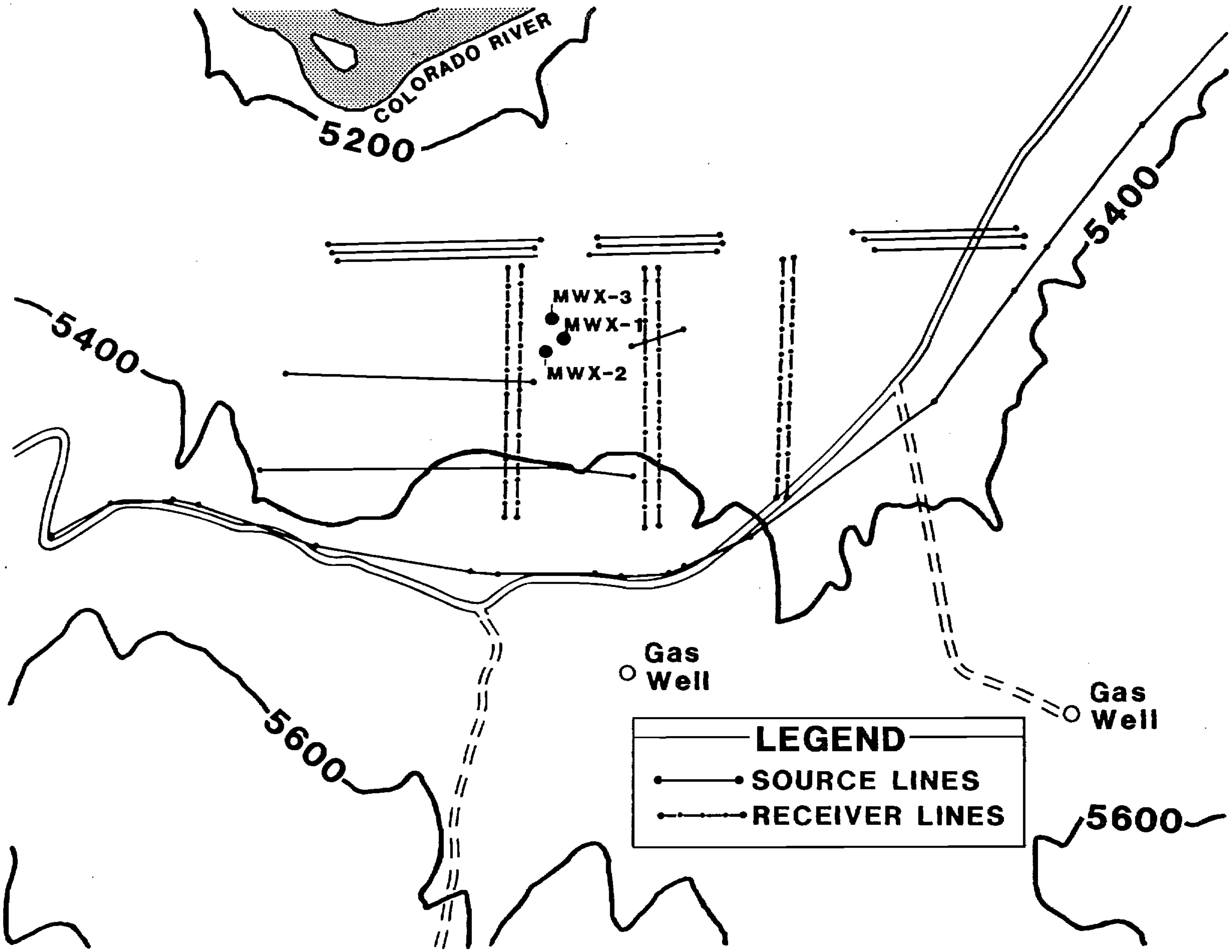


Fig. 2.3. A map of the MWX field site showing the source and receiver geometry for the 3-D seismic survey.

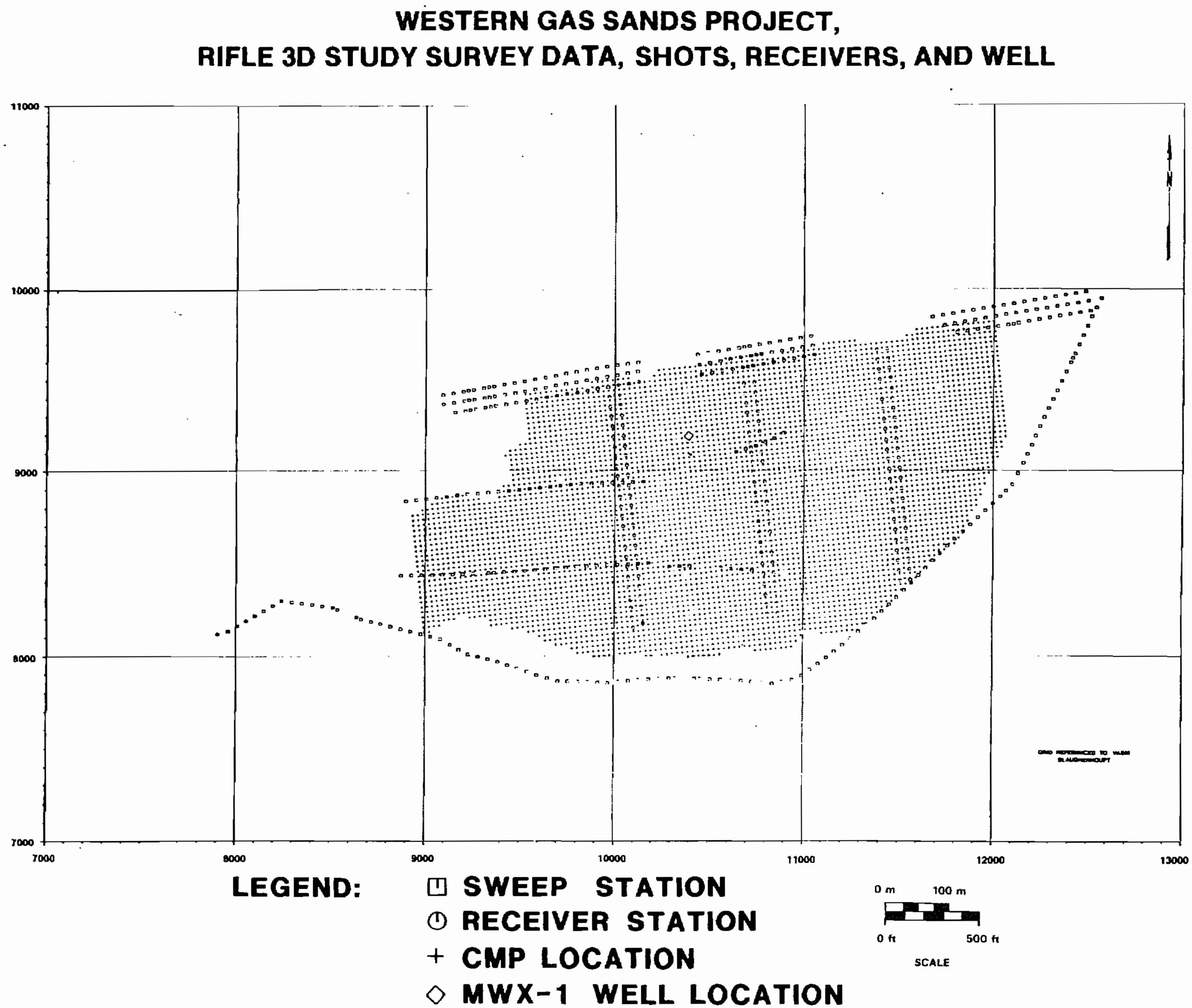


Fig. 2.4. Common midpoint map for the 3-D seismic survey showing:
a) the source, receiver, and CMP bin locations.

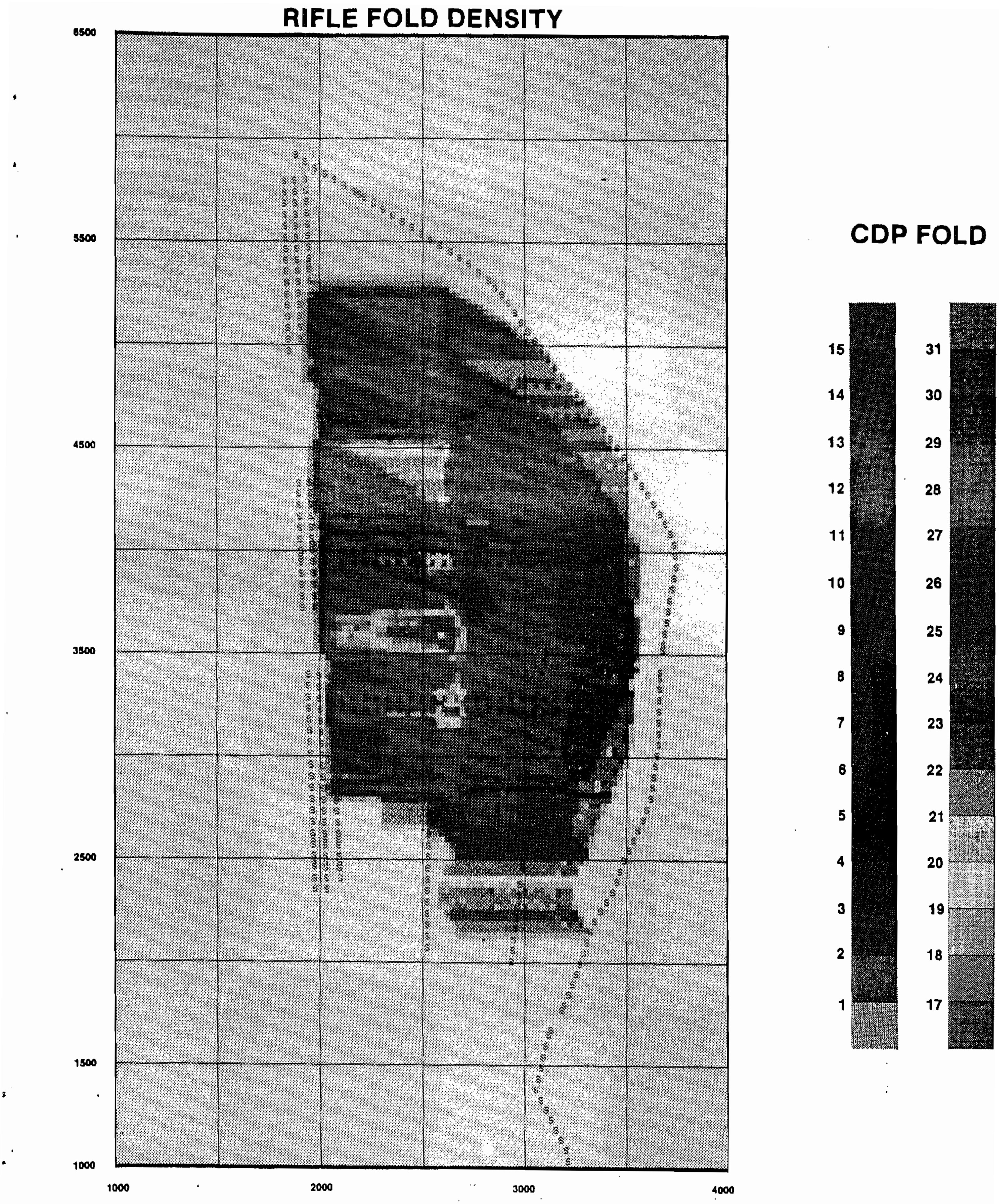
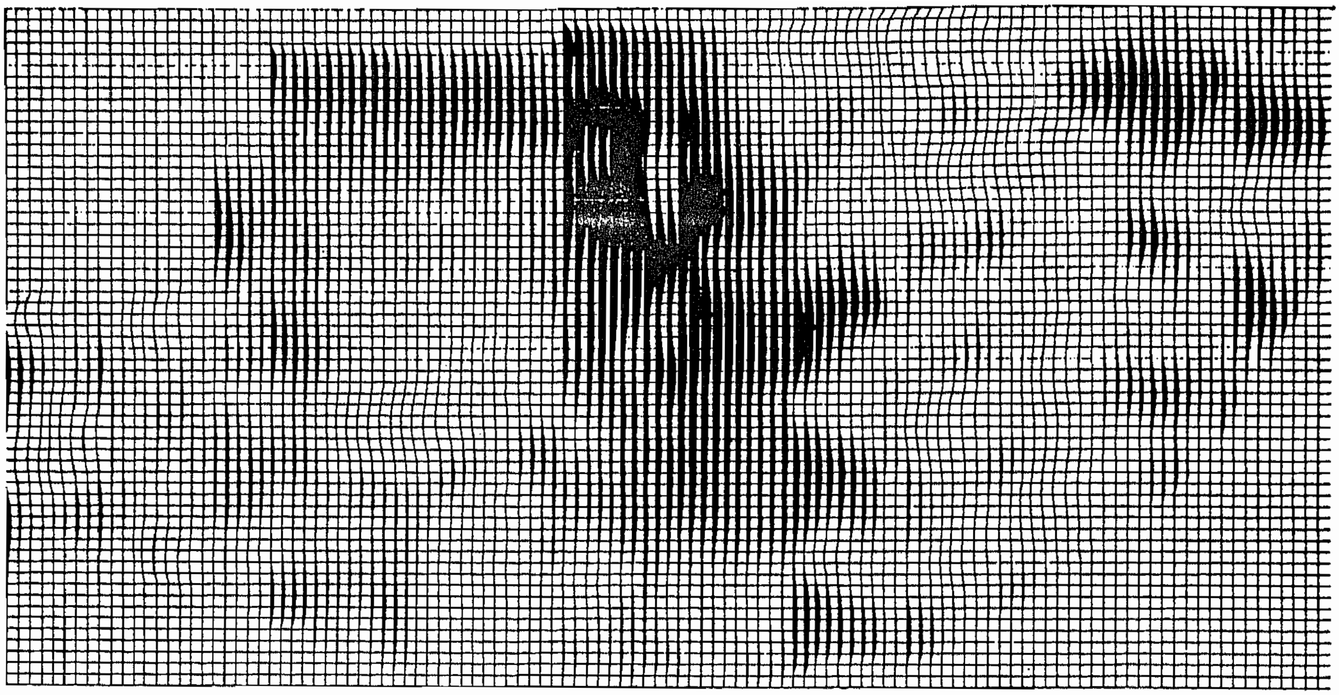
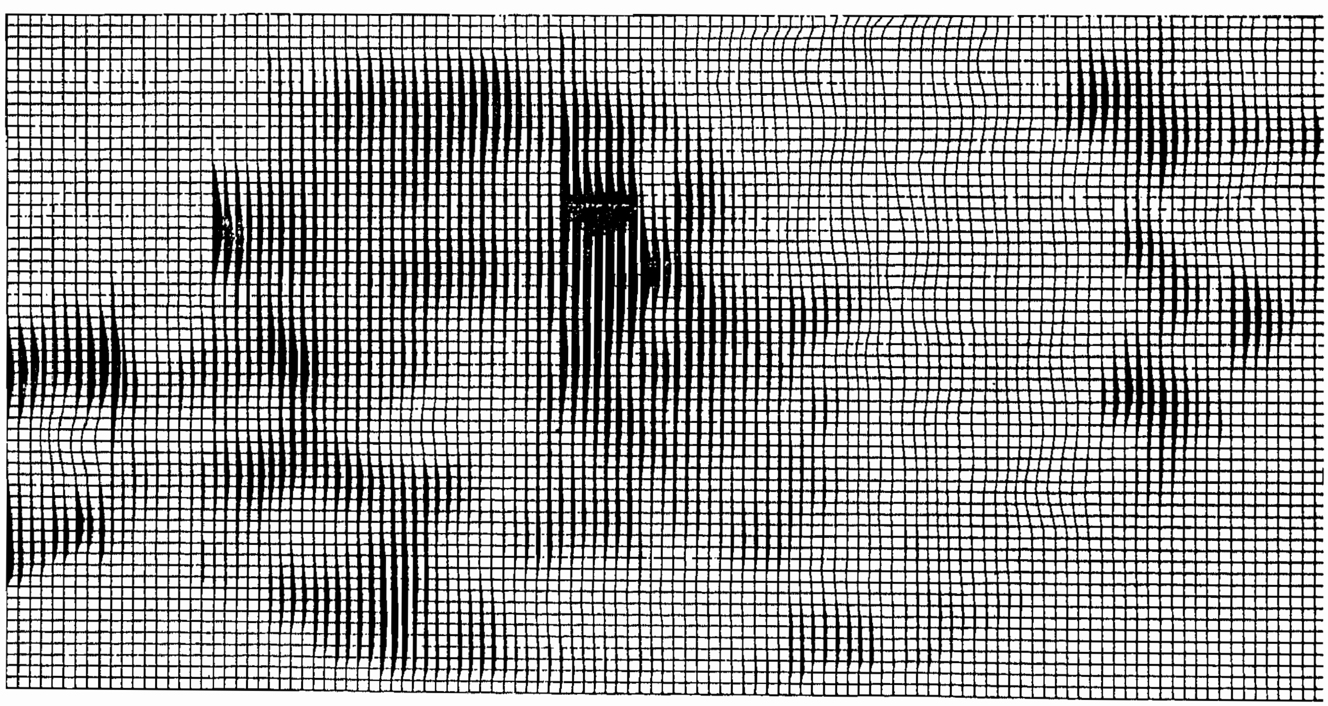


Fig. 2.4. Common midpoint map for the 3-D seismic survey showing:
b) the fold density for each of the CMP lines.



(a) TIME SLICE 1180 ms



(b) TIME SLICE 1184 ms

Fig. 2.5. Time slice displays from the paludal zone showing a banding that aligns with the processing grid.

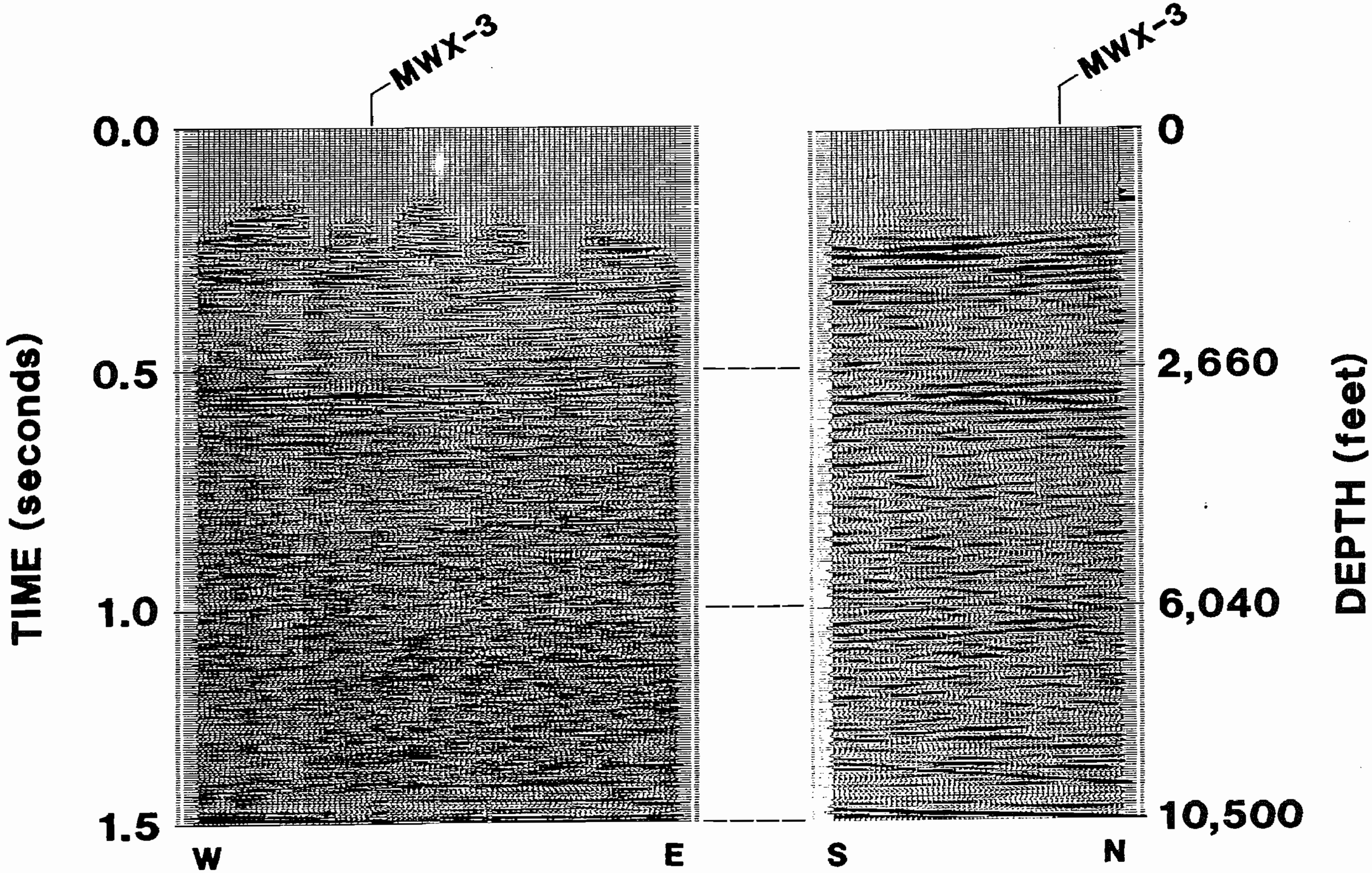


Fig. 2.6. Vertical seismic sections through MWX - 3 as computed by the Colorado School of Mines.

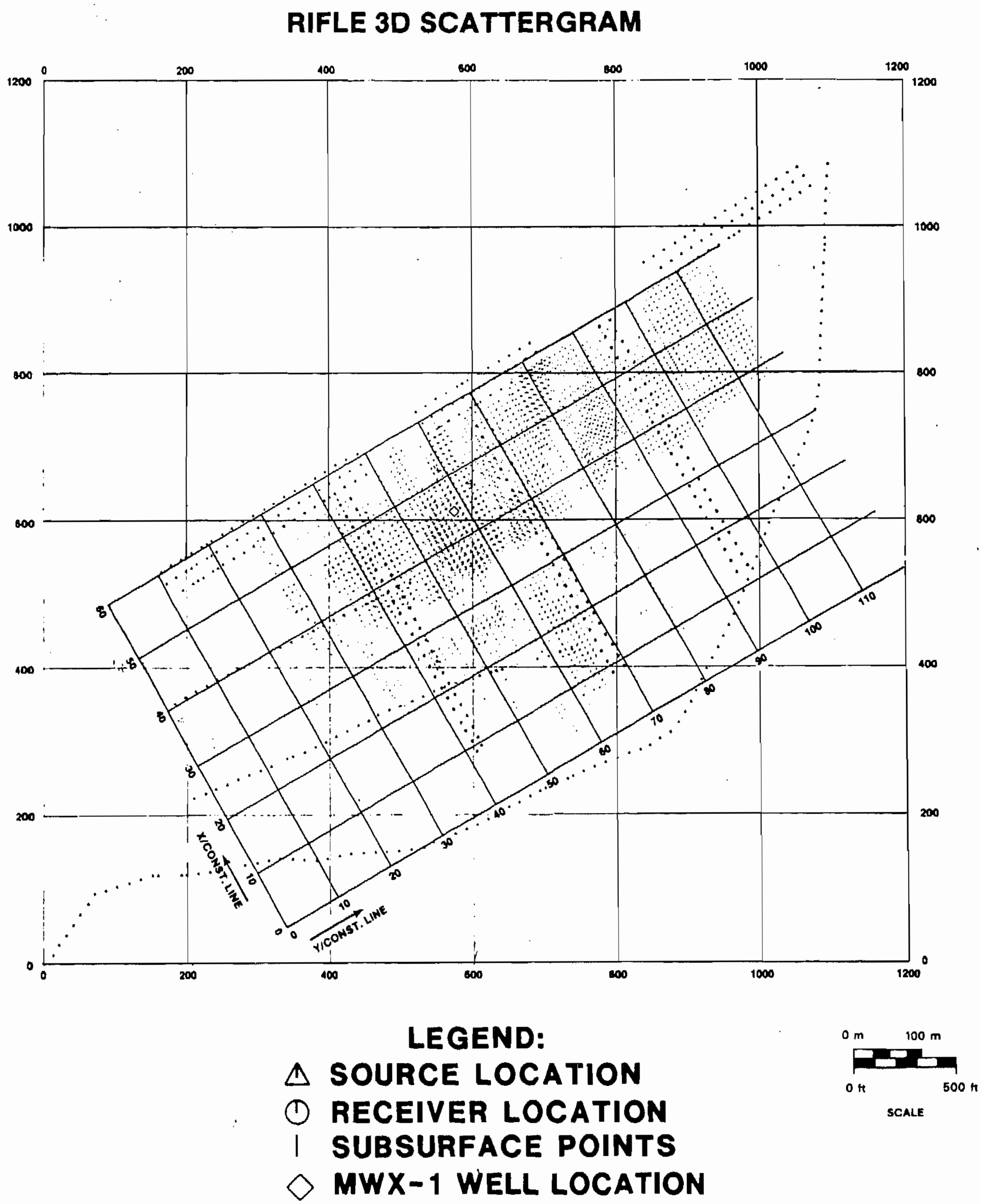


Fig. 2.7a. Scattergram for the 3-D seismic survey showing the sorting grid, source and receiver positions, and true CMP positions with orientations.

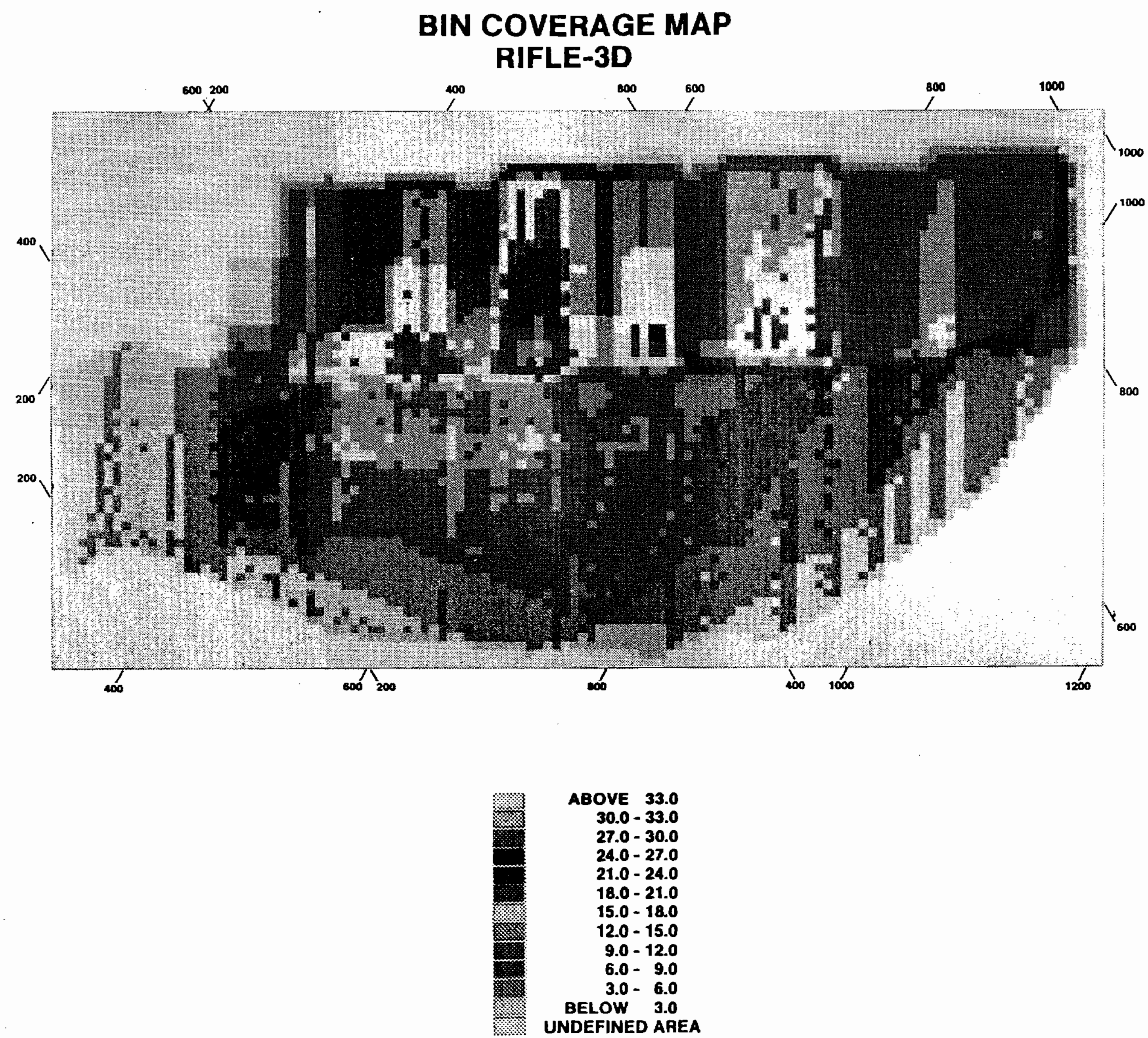
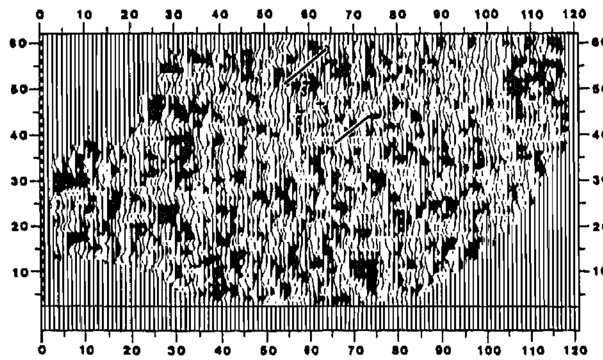
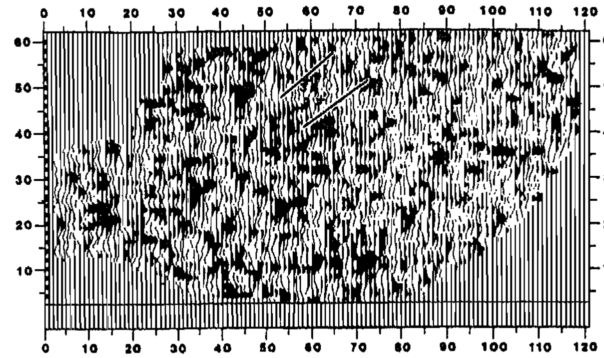


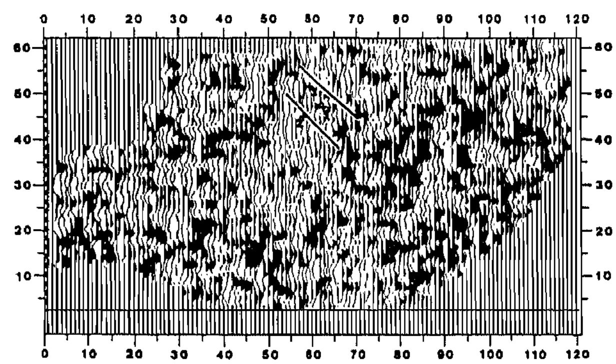
Fig. 2.7.b. Fold density map as determined for data reprocessing.



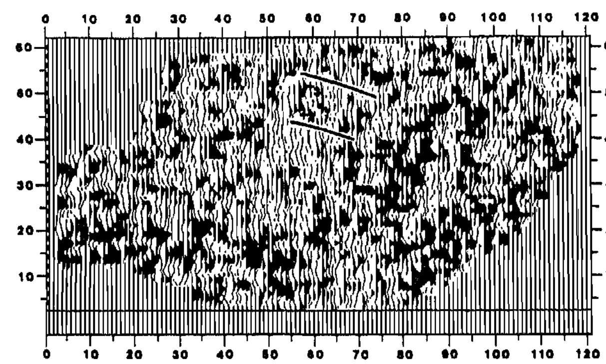
RED A



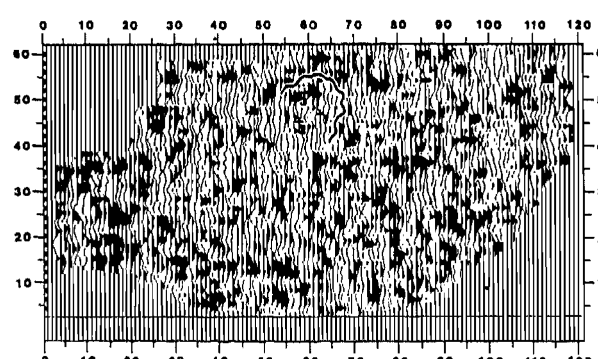
RED B



YELLOW A



YELLOW B



YELLOW C

Fig. 2.8. Time slices from the red and yellow sands in the coastal zone with channel boundaries as determined by Lorenz (1984).

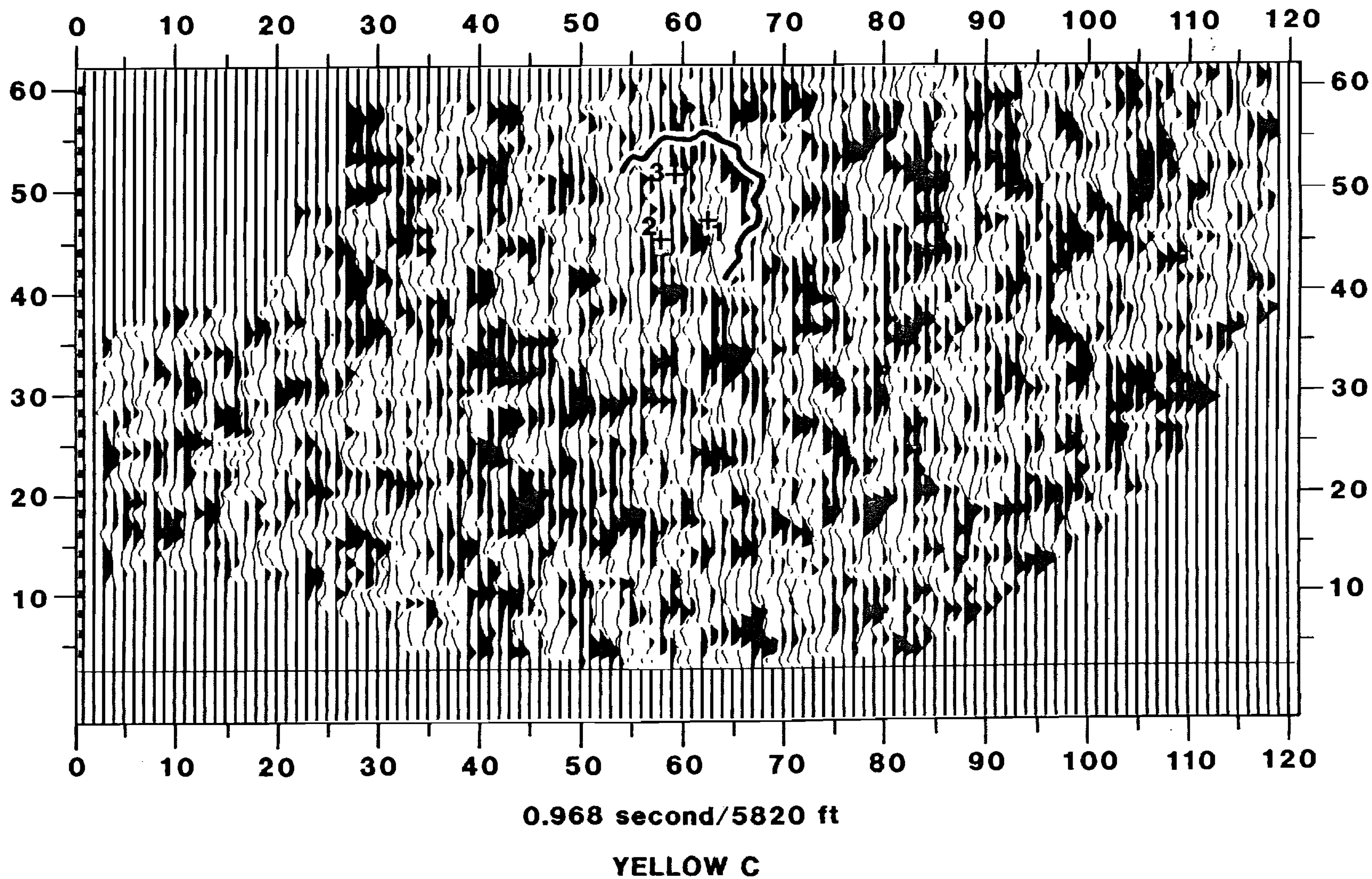


Fig. 2.9. 3-D time slice from 5820 ft compared with the channel interpretation from the yellow C. The match here is entirely artificial indicating the high noise level in the data.

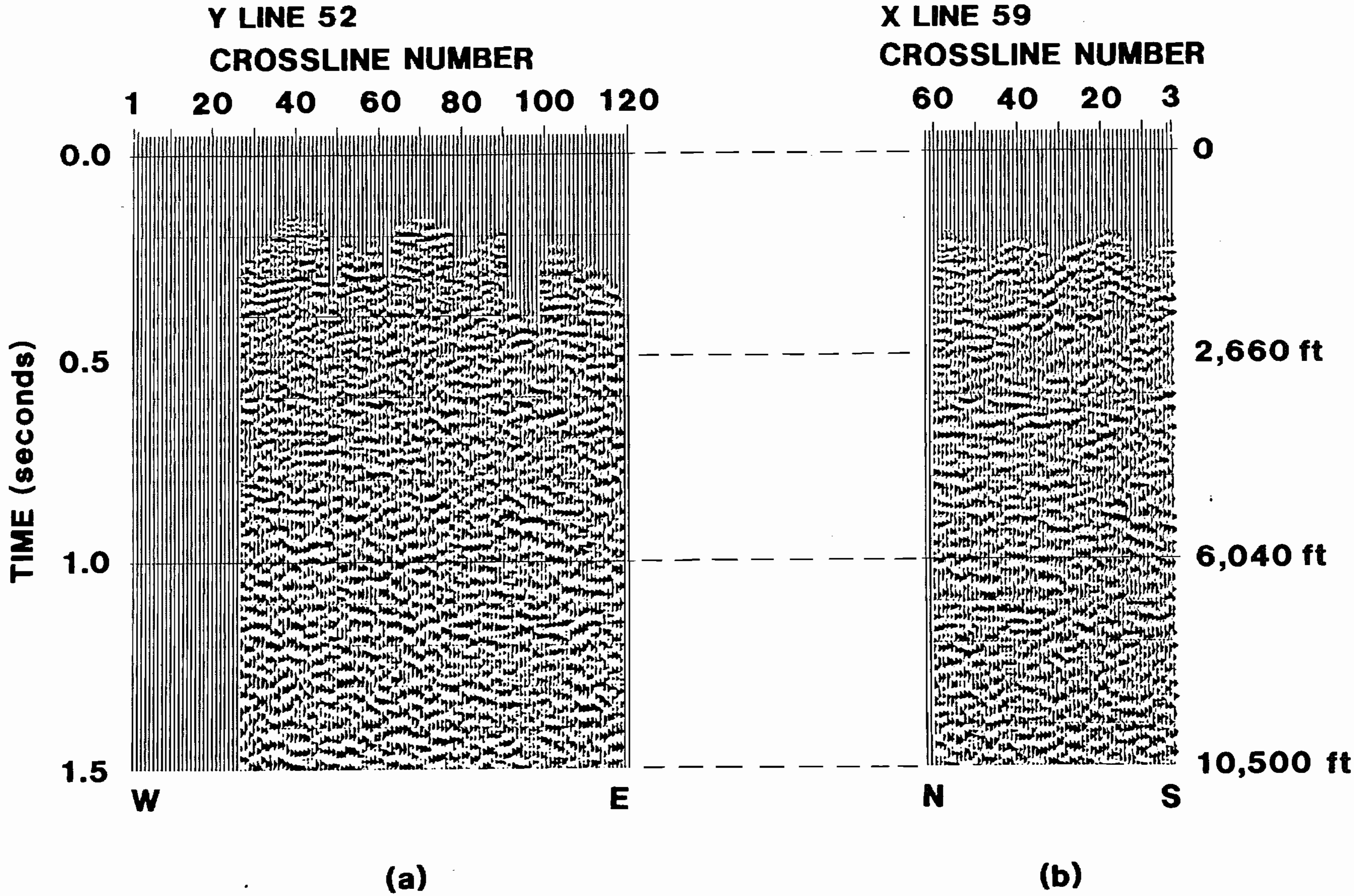


Fig. 2.10. Vertical seismic sections through MWX-3 as computed by Prakla-Seismos:
a) East-West section and
b) North-South section.

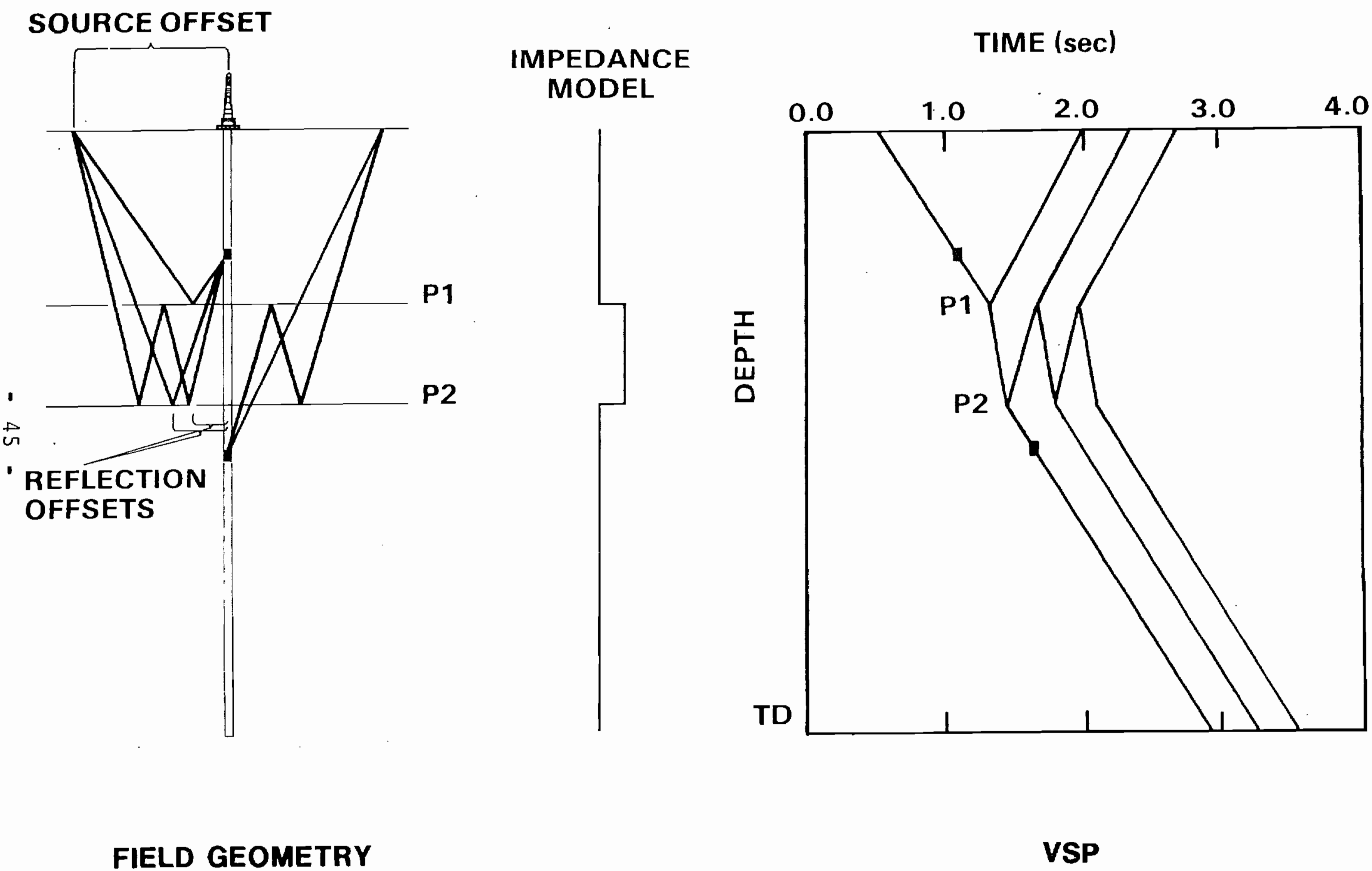


Fig. 3.1. Schematic diagram of the vertical seismic profiling method.

VSP SOURCE LOCATIONS

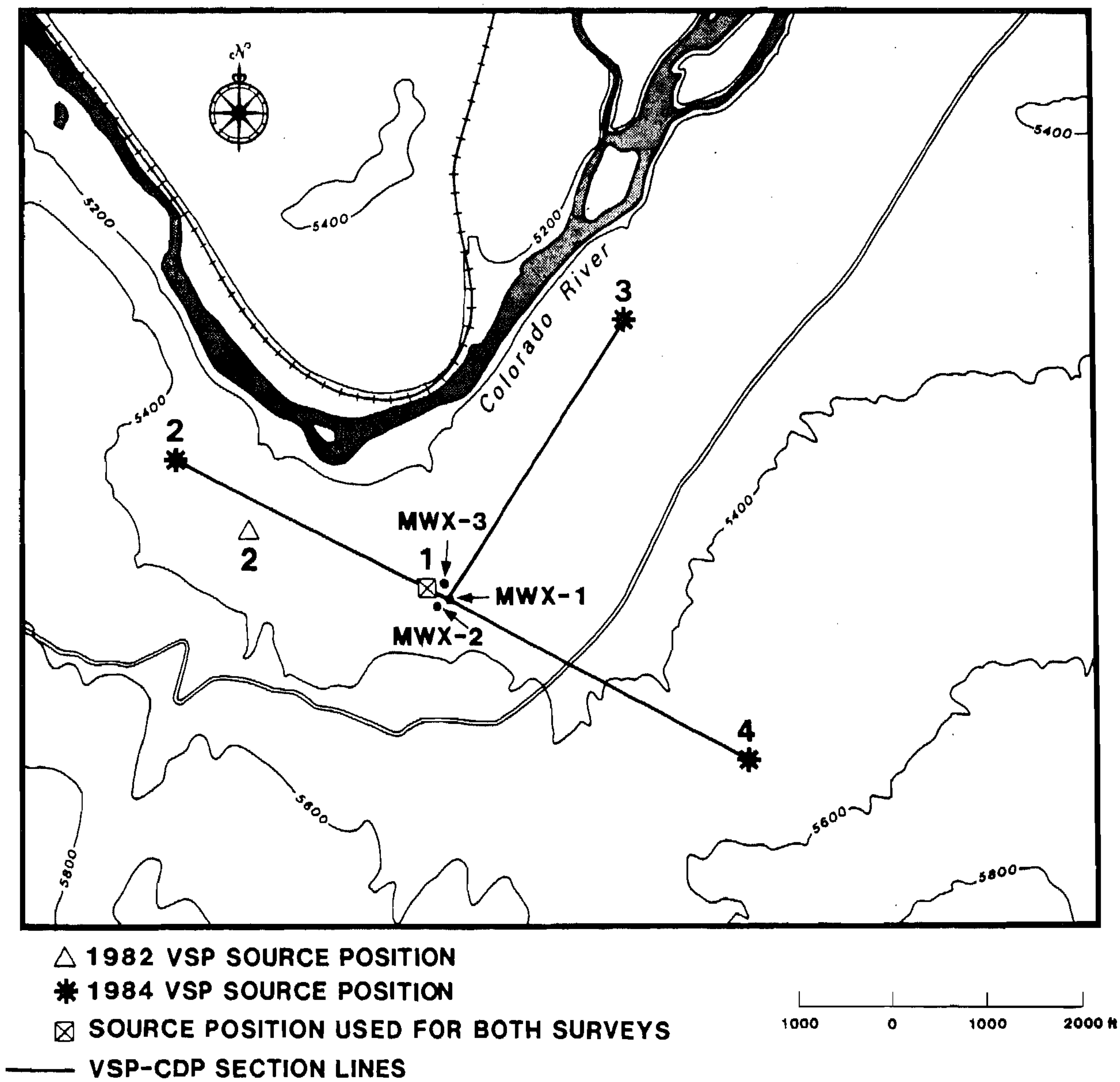


Fig. 3.2. Surface configuration for the VSP surveys at the MWX field site.

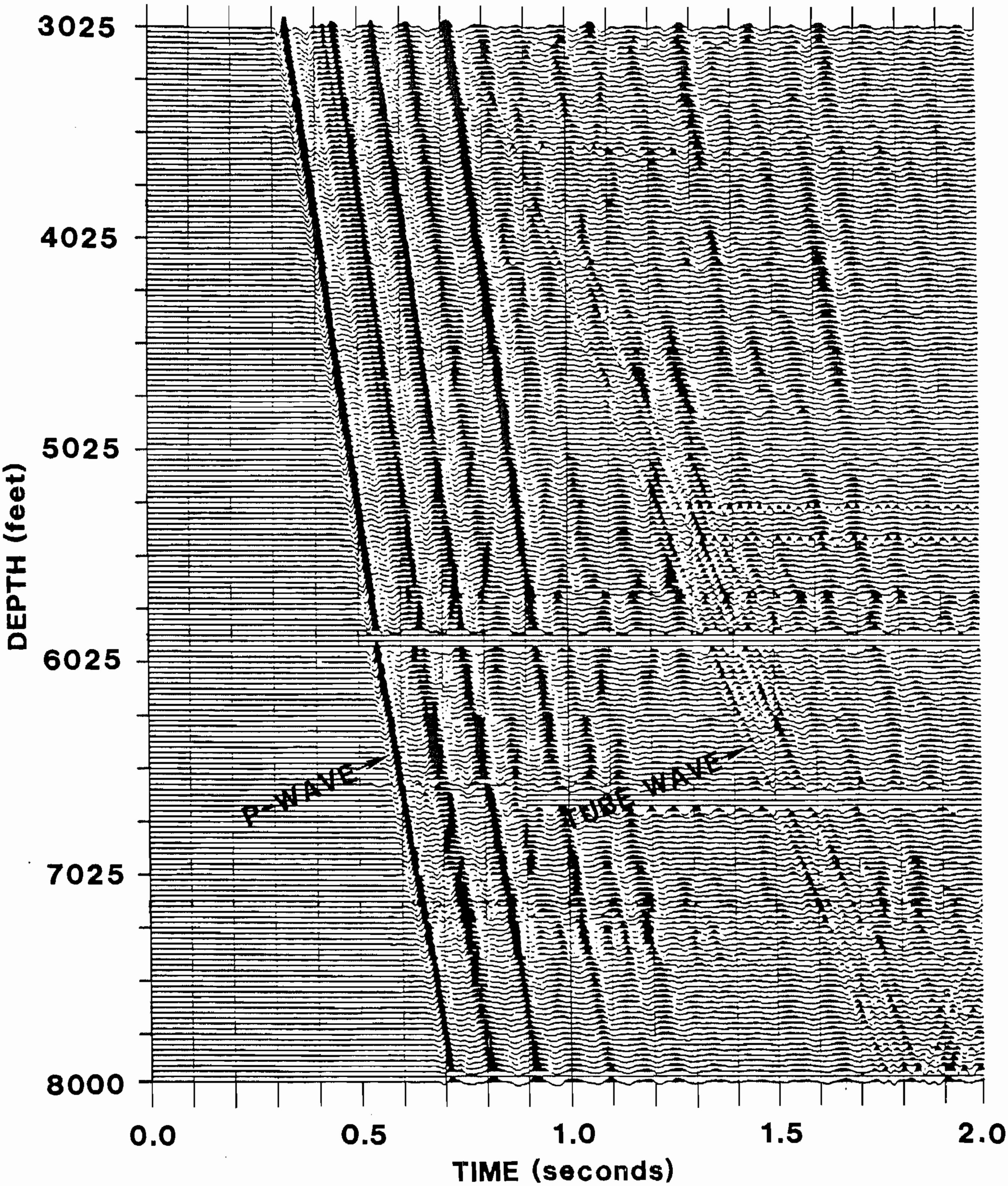


Fig. 3.3. Unprocessed vertical seismic profile data stack for the 1982 survey of MWX-2 showing both the P wave direct arrival and the tube wave. Note the long ringing of the first arrival.

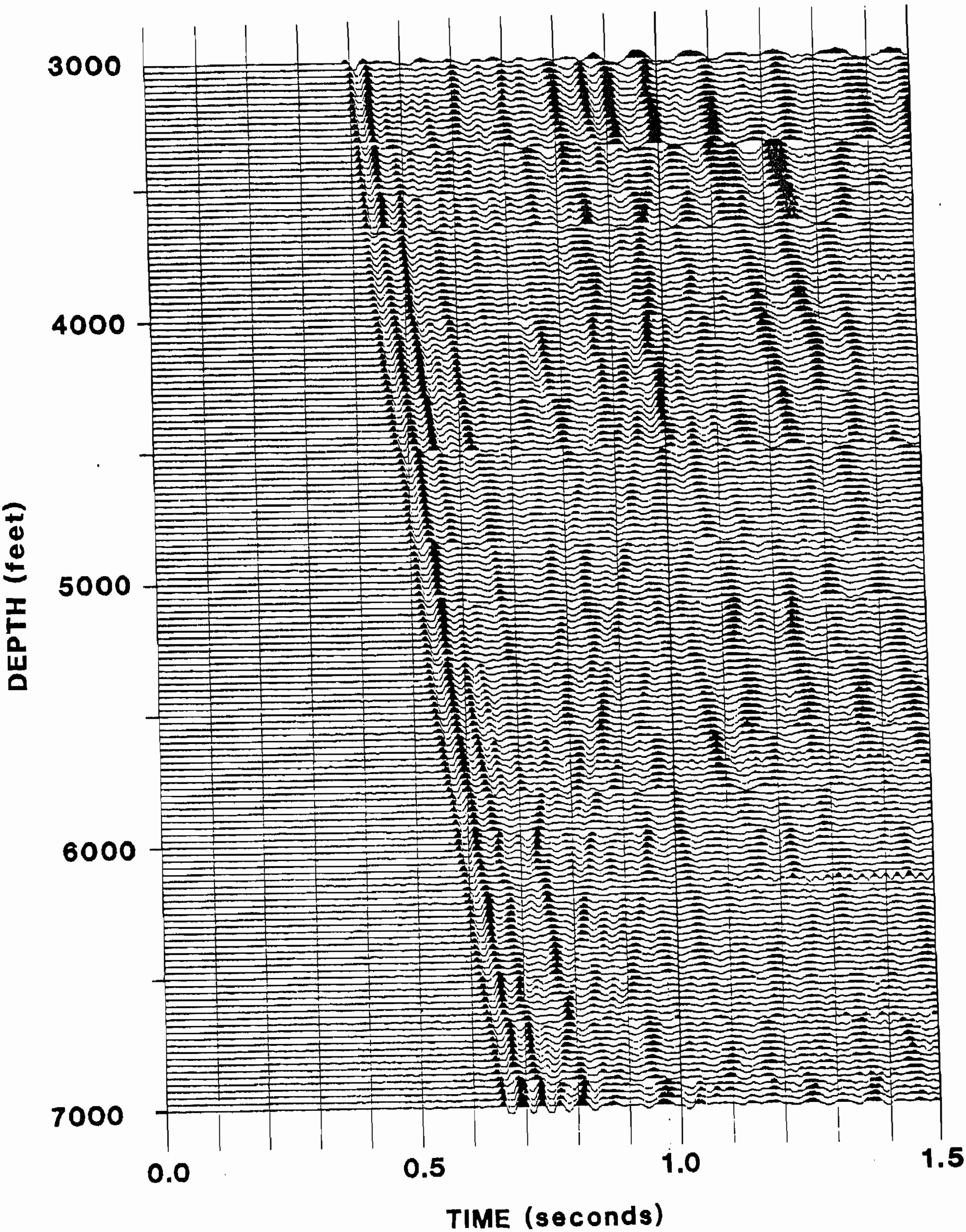


Fig. 3.4. Unprocessed vertical seismic profile data stack for the 1982 survey of MWX-3 from source location 3. Note the abrupt changes in waveform resulting from moving the source.

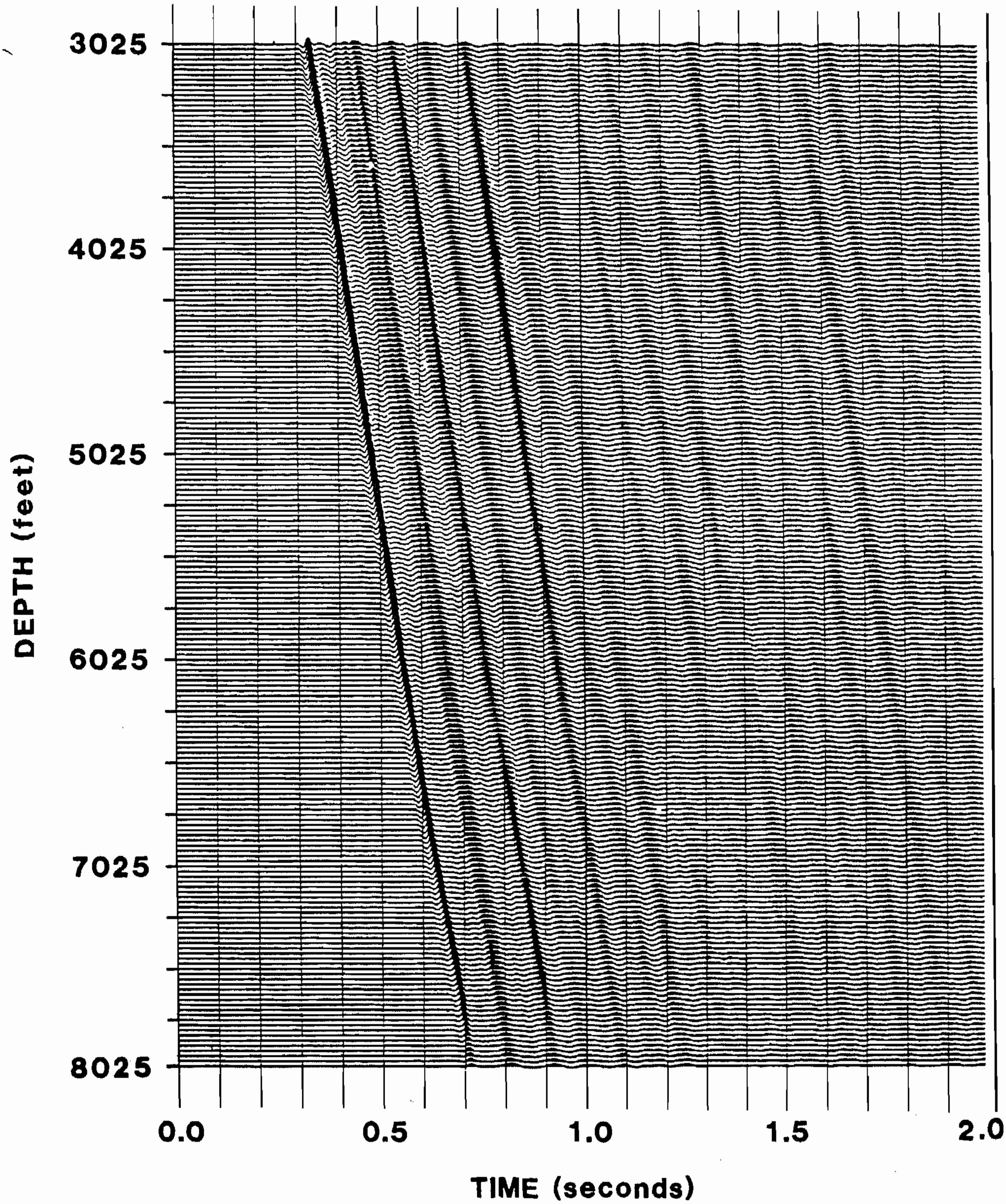


Fig. 3.5. Downward propagating wave separation for the 1982 survey of MWX-2 from source location 1.

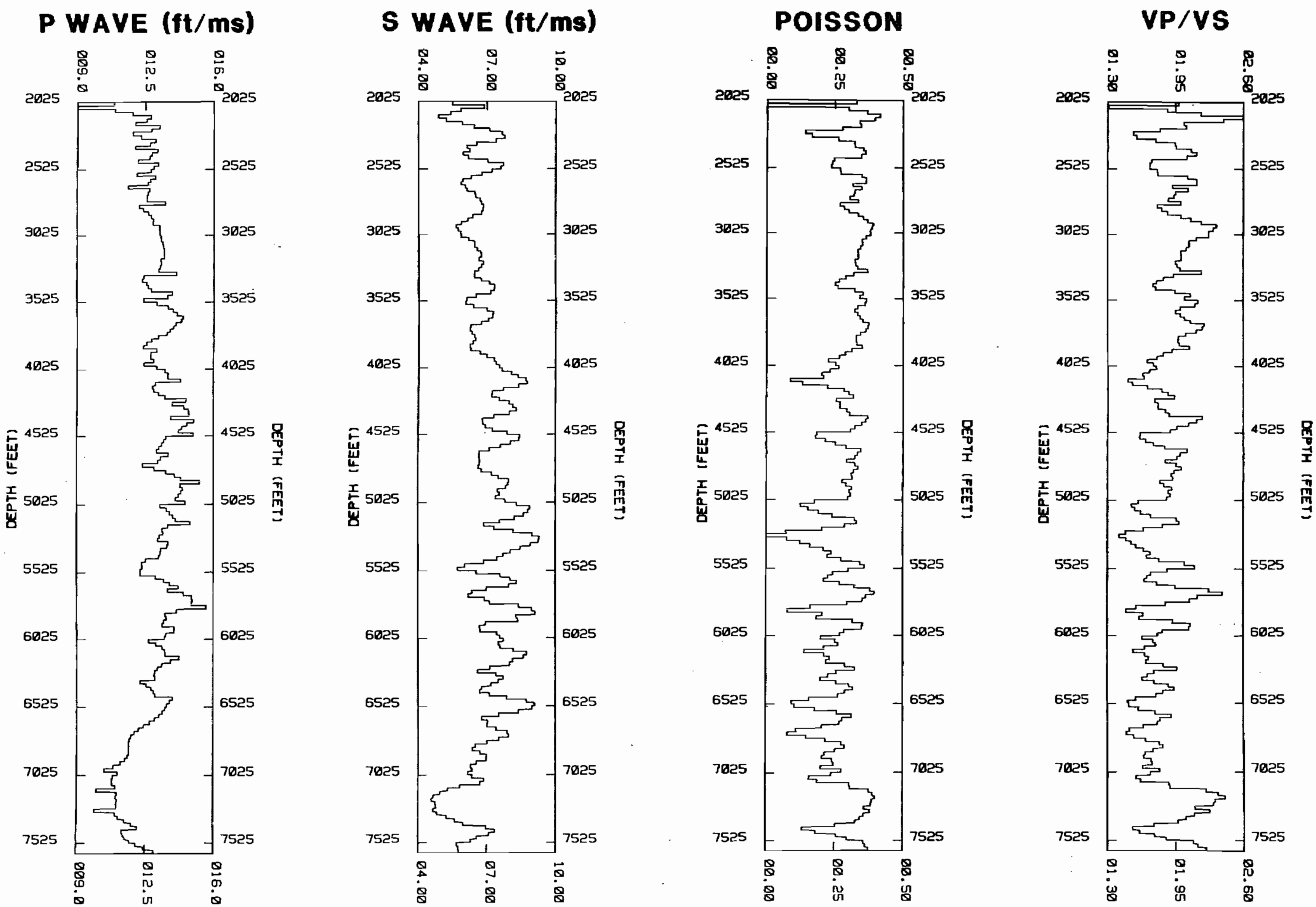


Fig. 3.6. Interval values for seismic velocities, velocity ratios, and Poisson's ratio as determined from the 1982 survey of MWX-2.

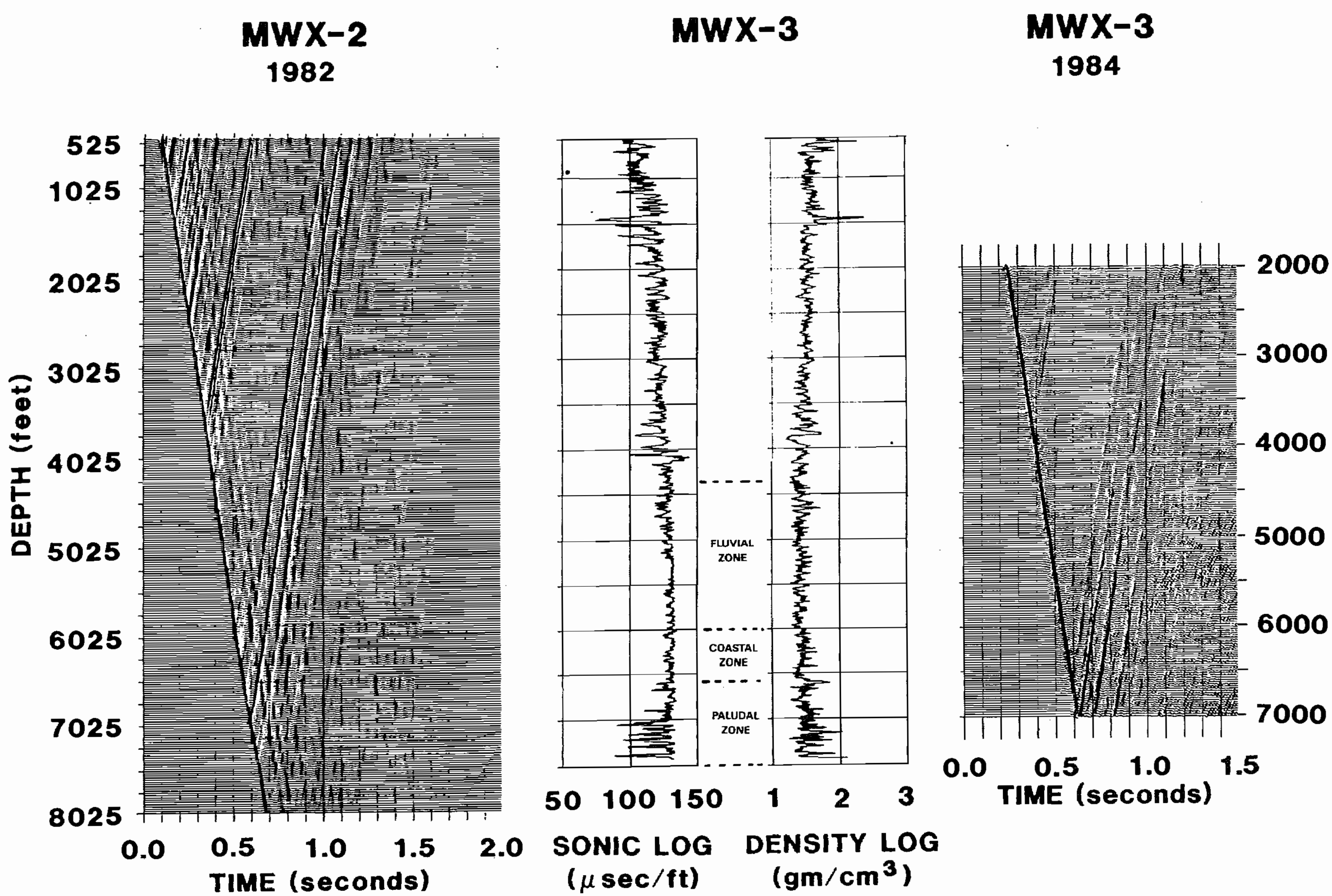


Fig. 3.7. Processed VSP surveys from both the 1982 and the 1984 surveys of MWX-2 and MWX-3 respectively with the sonic and density well logs for reference.

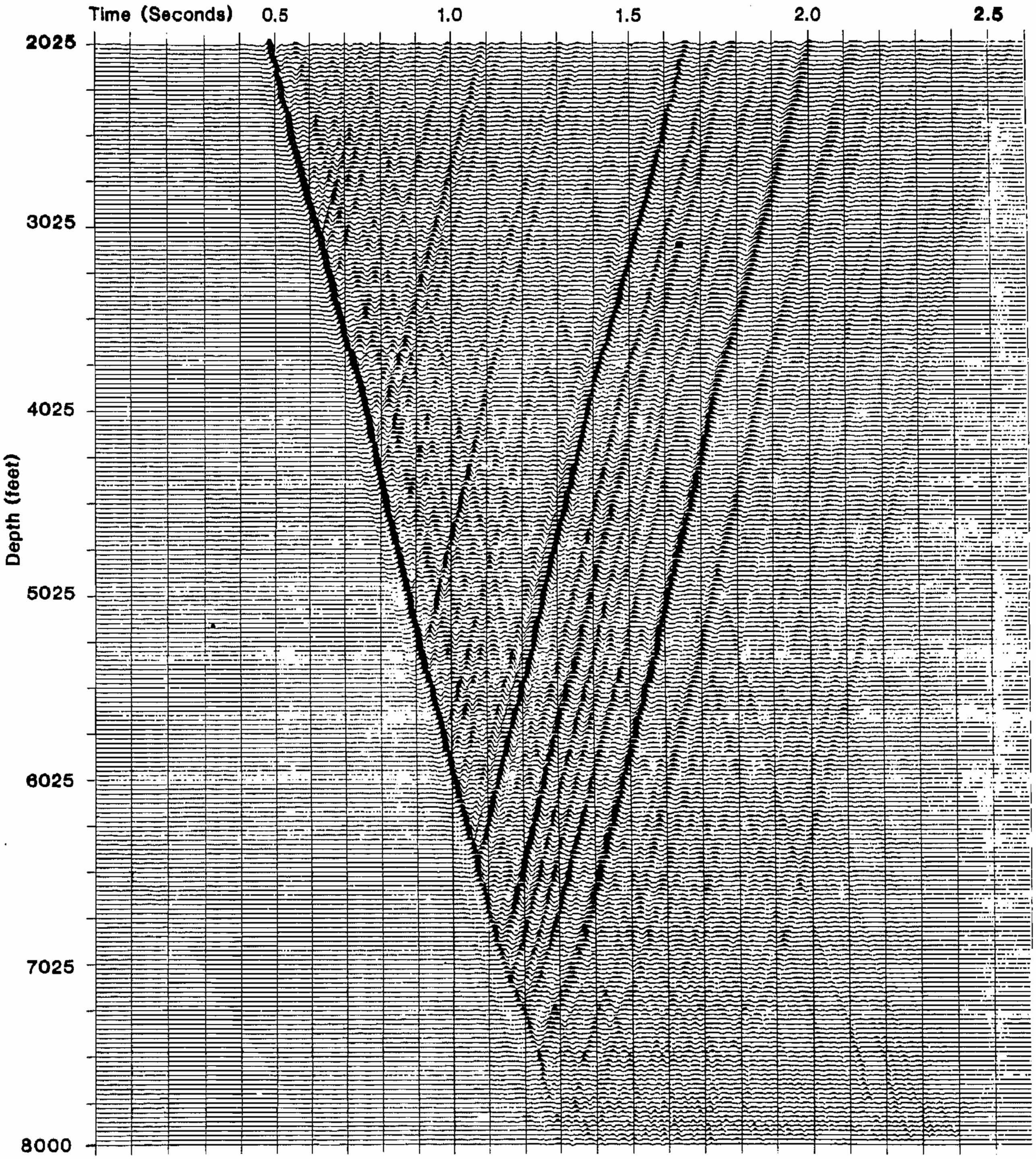


Fig. 3.8. Shear wave VSP for the 1982 survey of MWX-2 from source location 2.

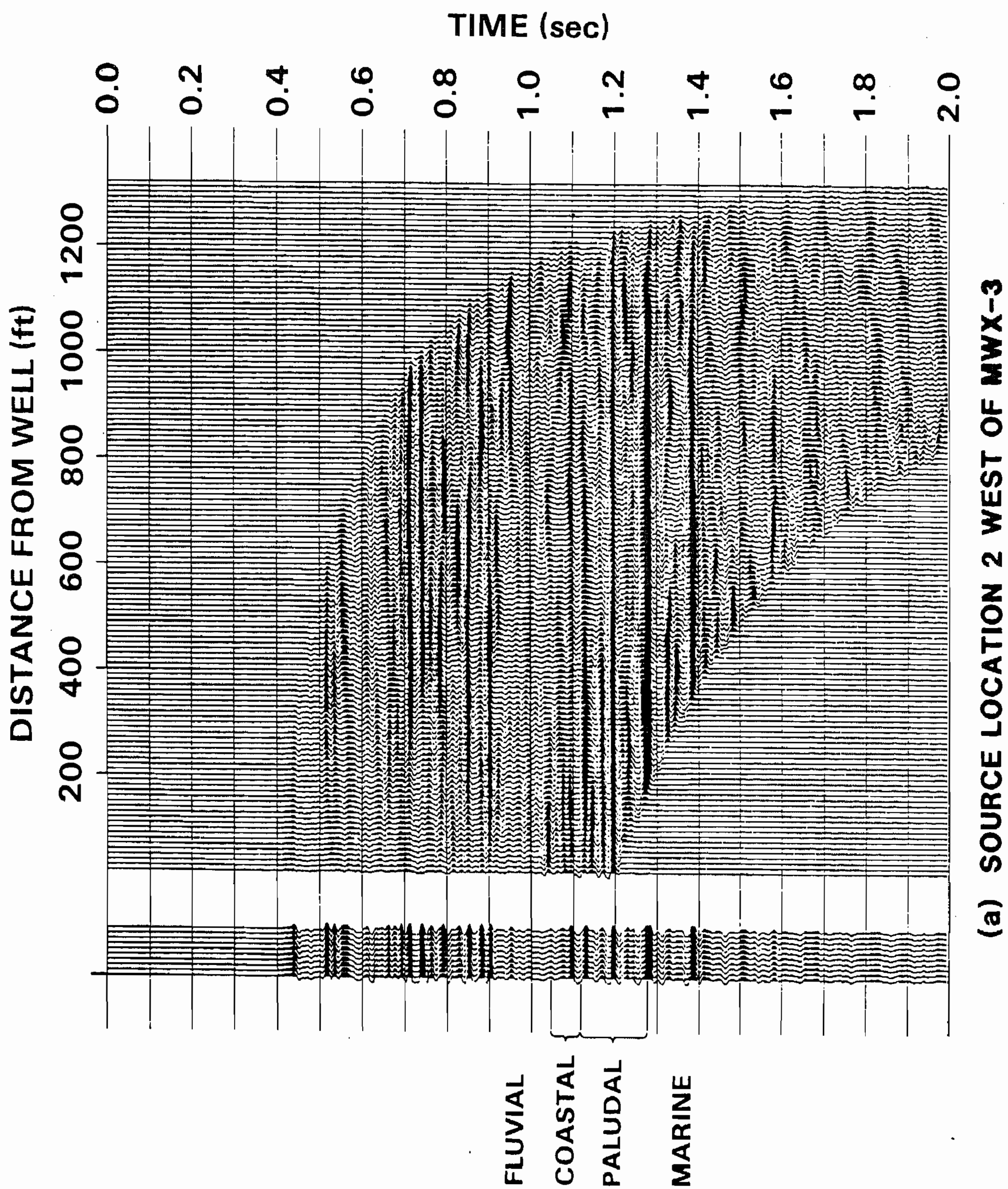


Fig. 3.9. Vertical seismic profile - common depth point display for the 1984 survey of MWX-3 from source locations
a) 2 (west of the site).

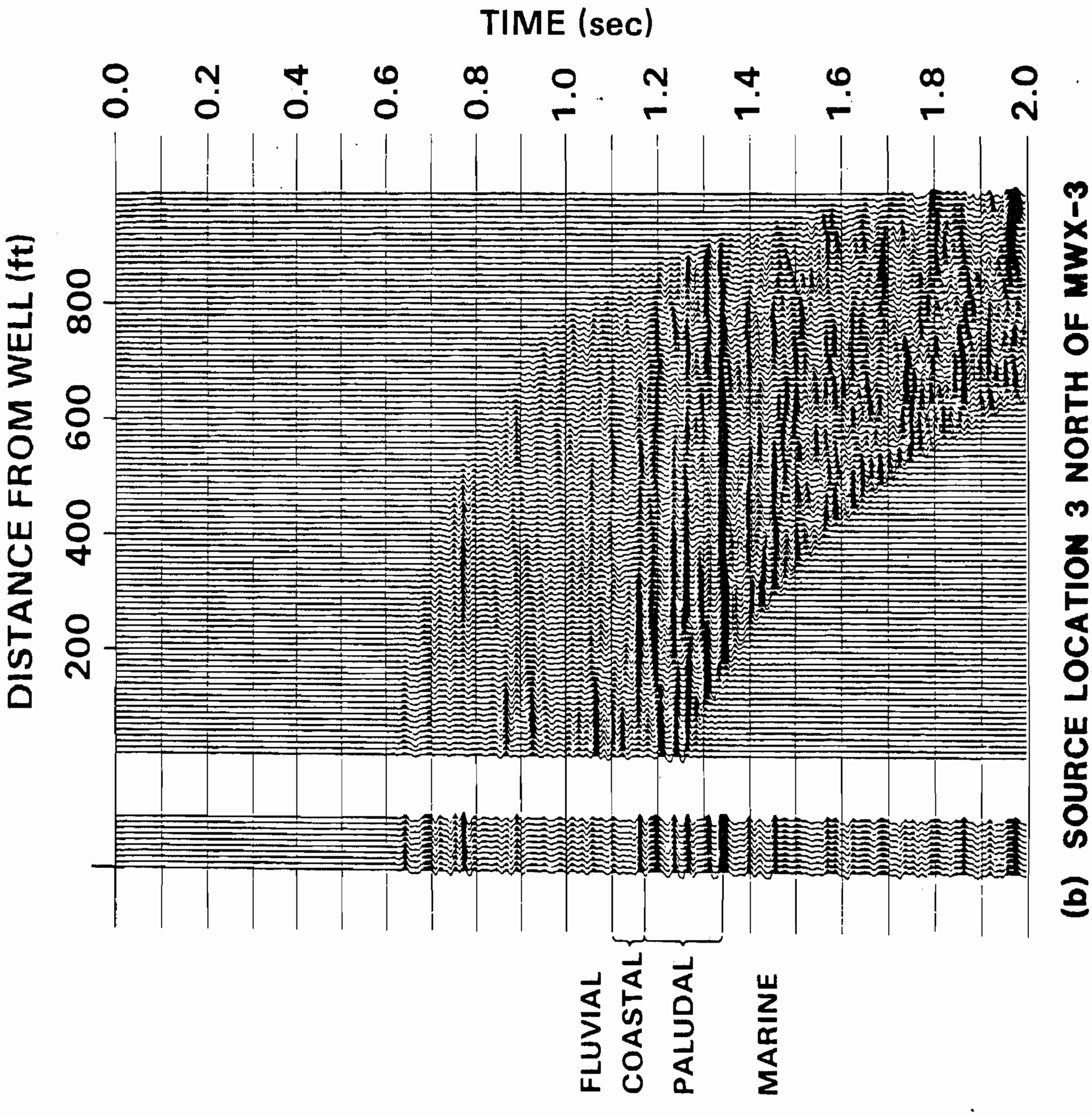


Fig. 3.9. Vertical seismic profile - common depth point display for the 1984 survey of MWX-3 from source locations
b) 3 (north of the site).

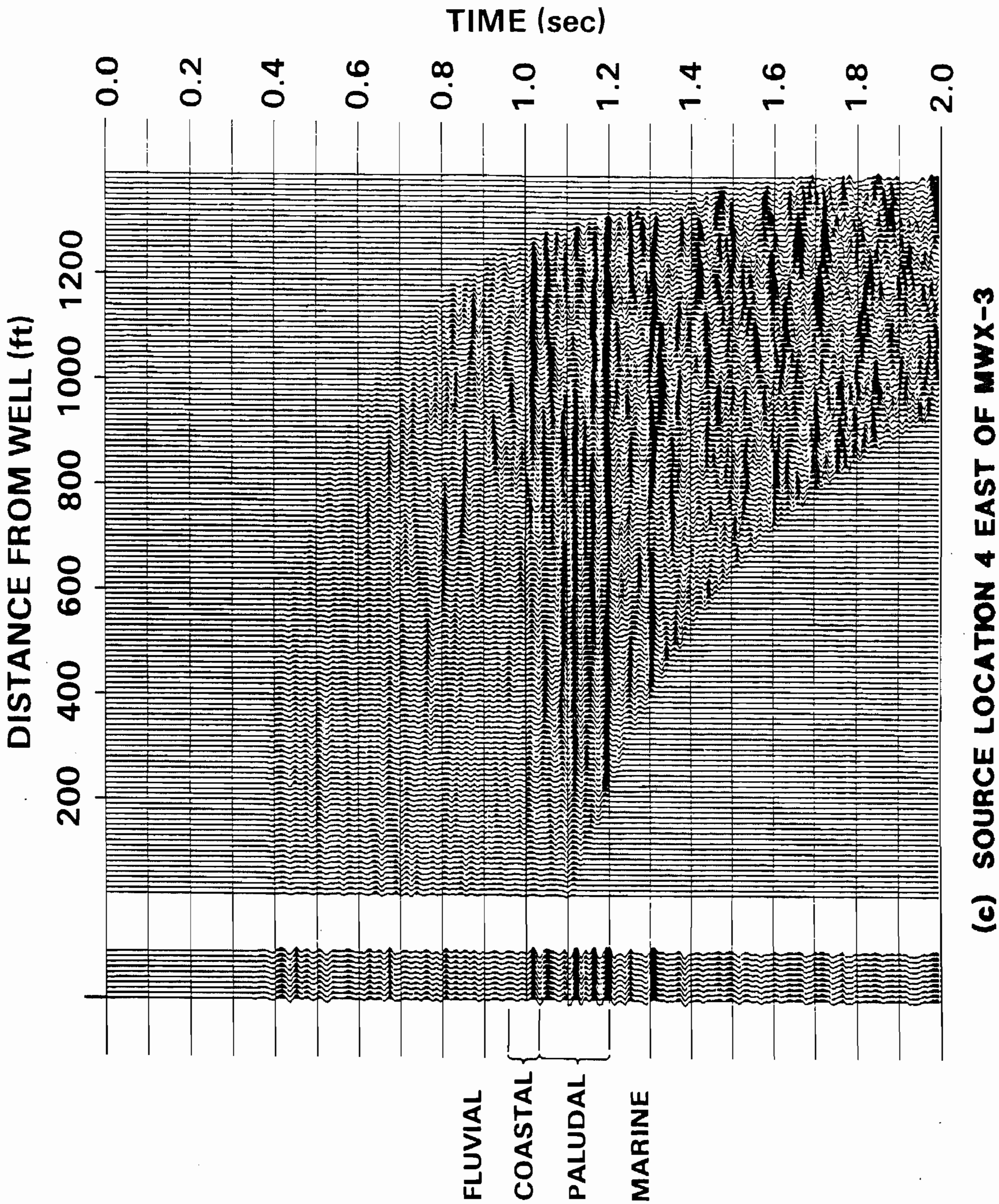


Fig. 3.9. Vertical seismic profile - common depth point display for the 1984 survey of MWX-3 from source locations c) 4 (east of the site).

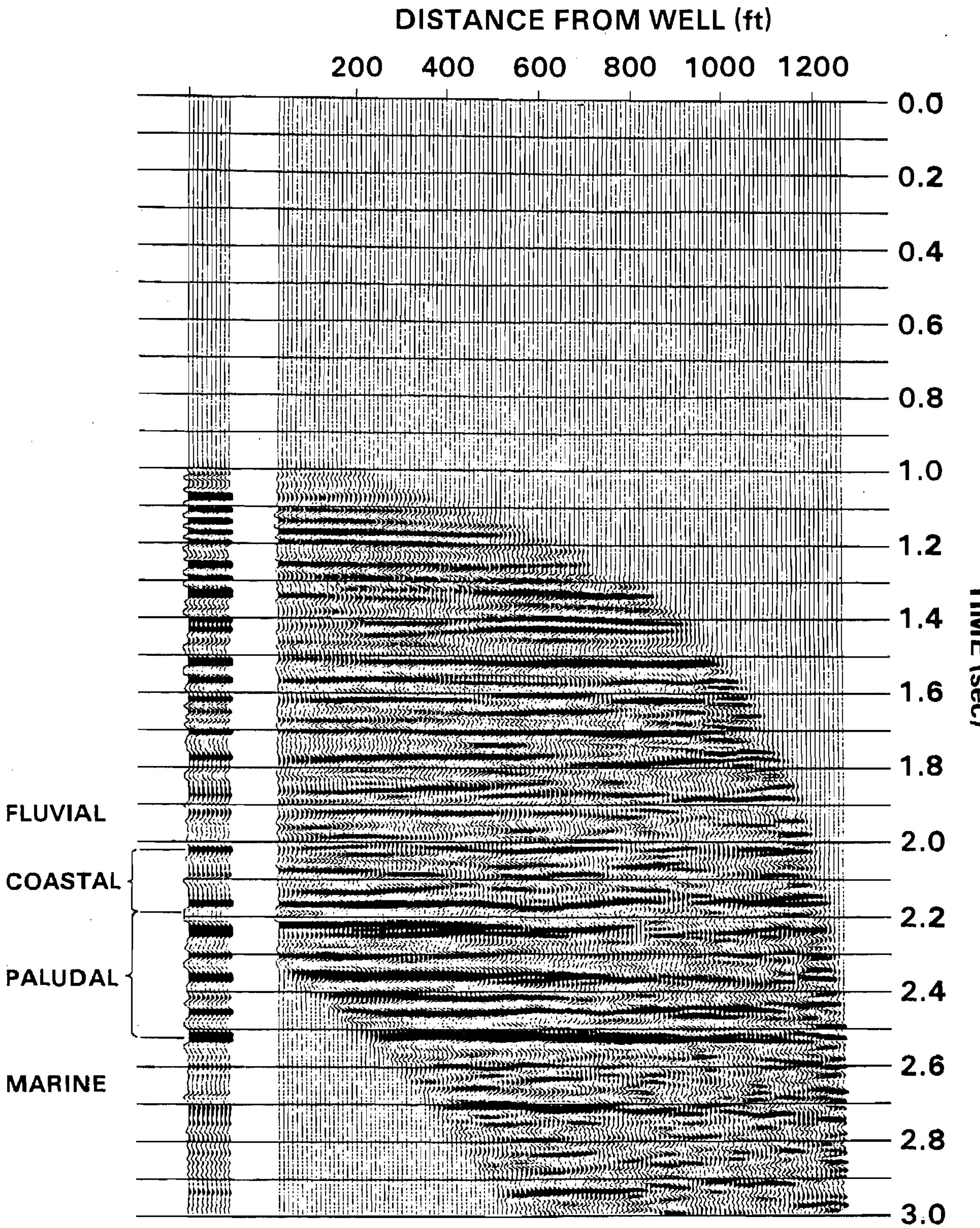


Fig. 3.10. Shear wave VSP-CDP display from the 1984 survey from source location 2.

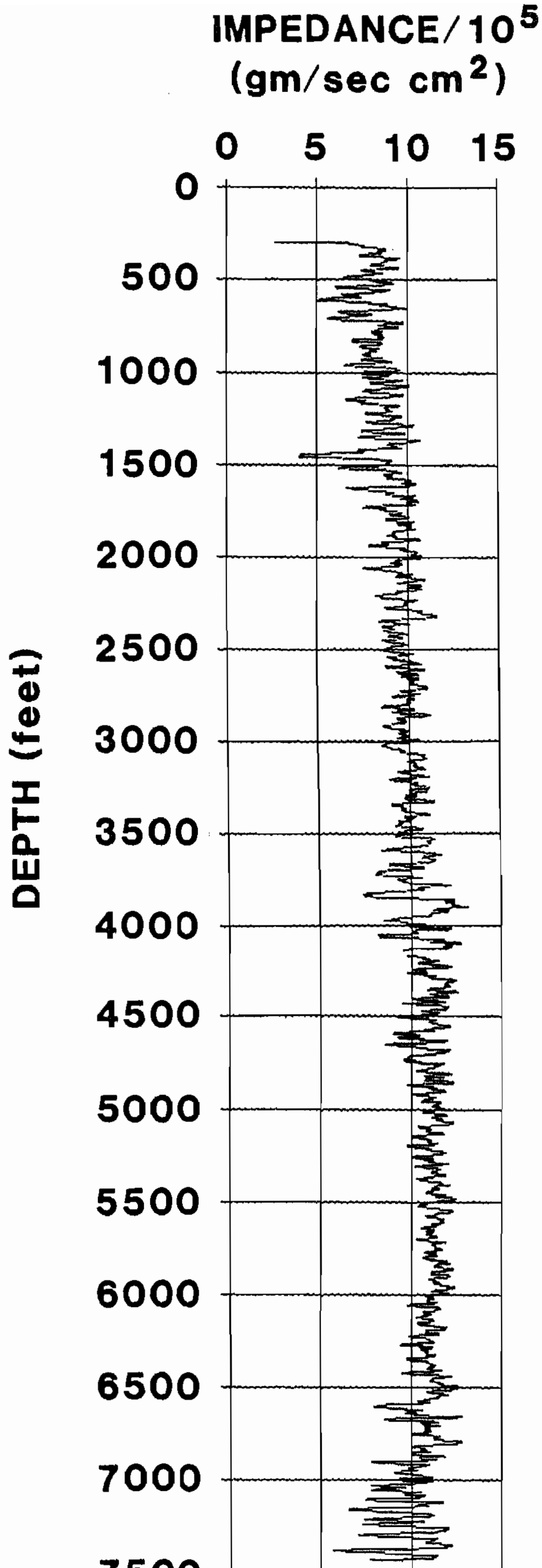


Fig. 4.1. The seismic impedance log for MWX-3.

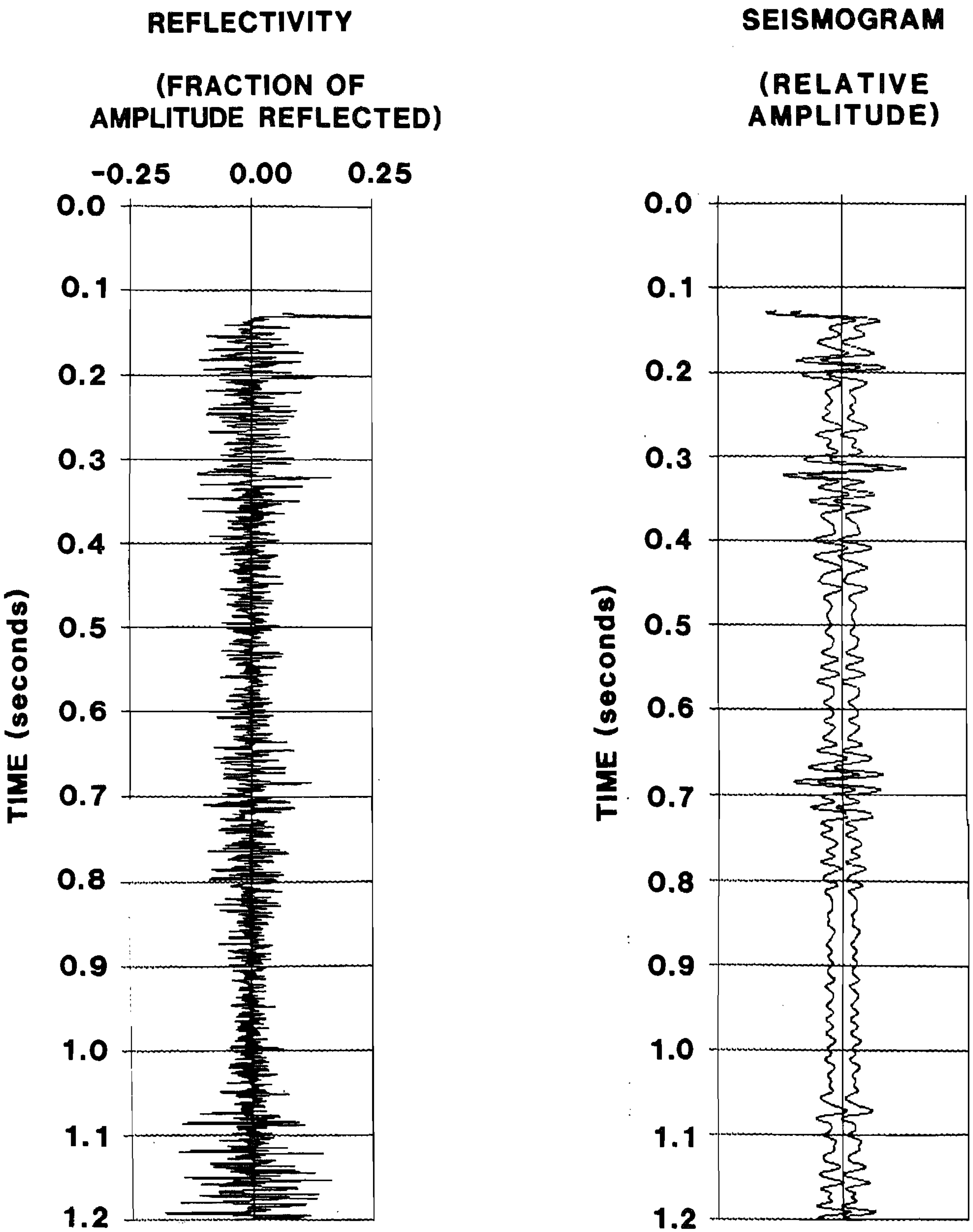


Fig. 4.2. Reflection coefficient versus time as computed from the sonic impedance [sonic velocity x material density] log and the synthetic seismogram that is the result of a 40 Hz Ricker wavelet passing through this reflectivity series.

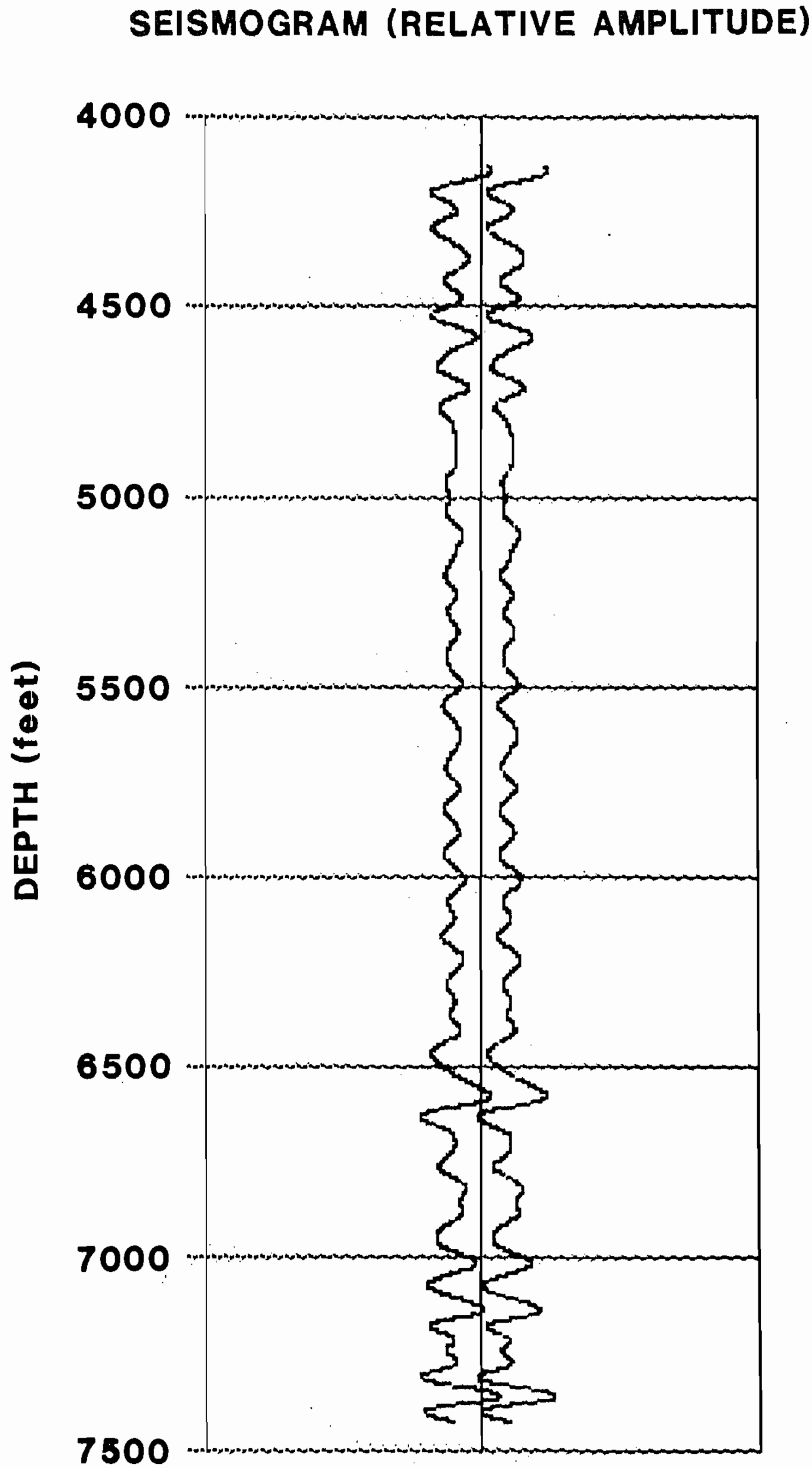


Fig. 4.3. The 40 Hz synthetic seismogram for the lower portion of MWX-3 as a function of depth.

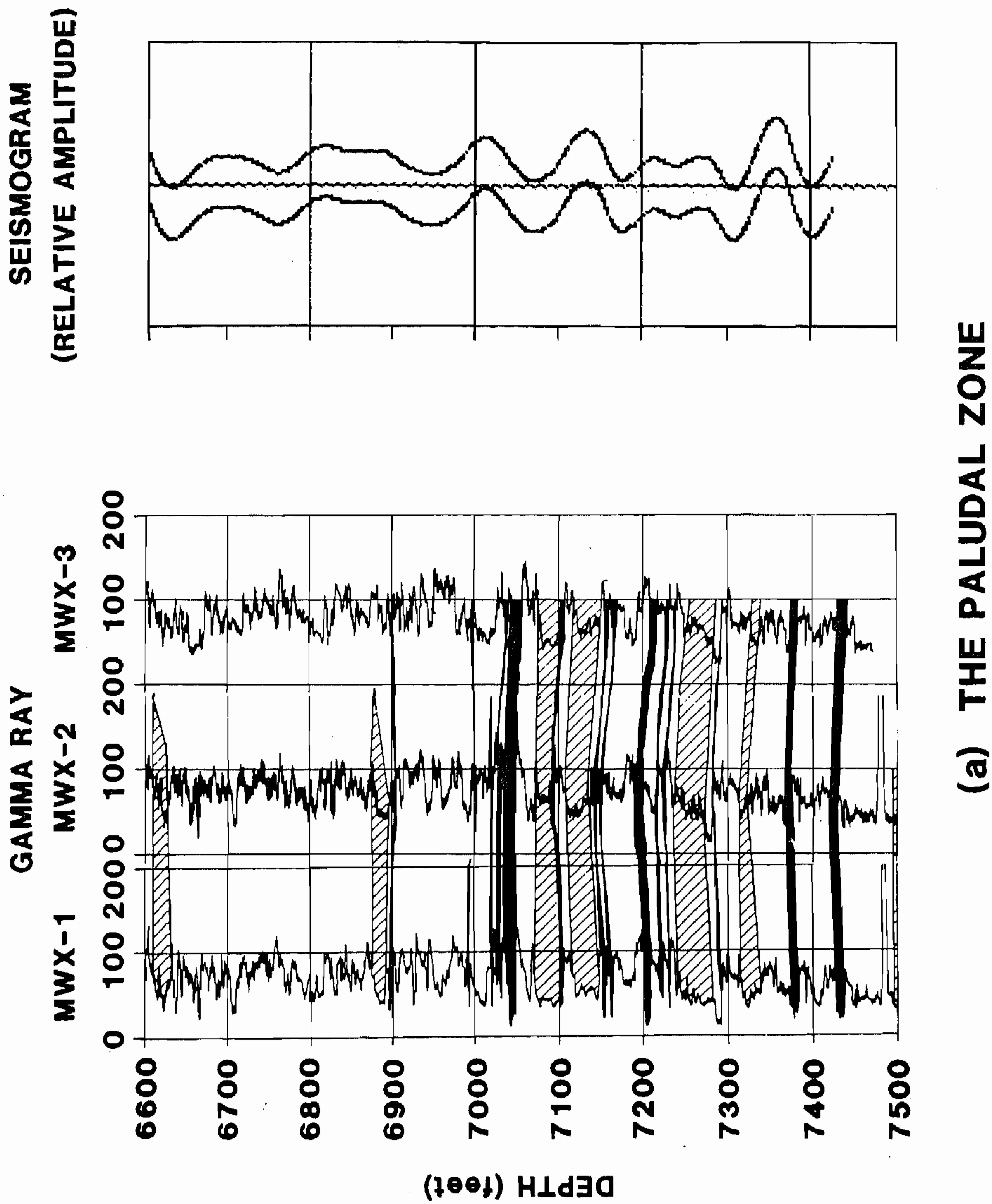


Fig. 4.4. Geological interpretation and gamma ray logs with the corresponding synthetic seismogram for
a) the Paludal zone,

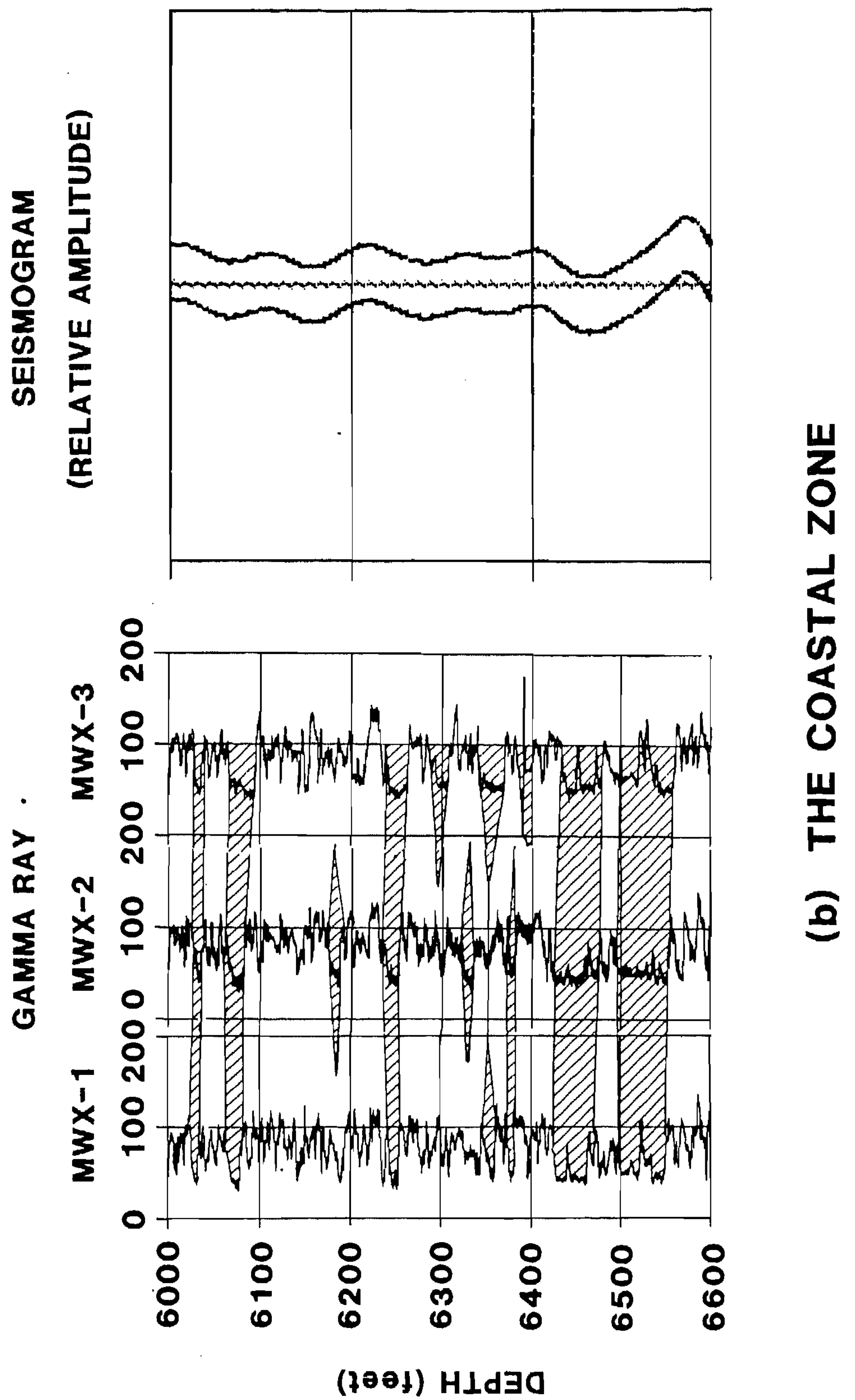
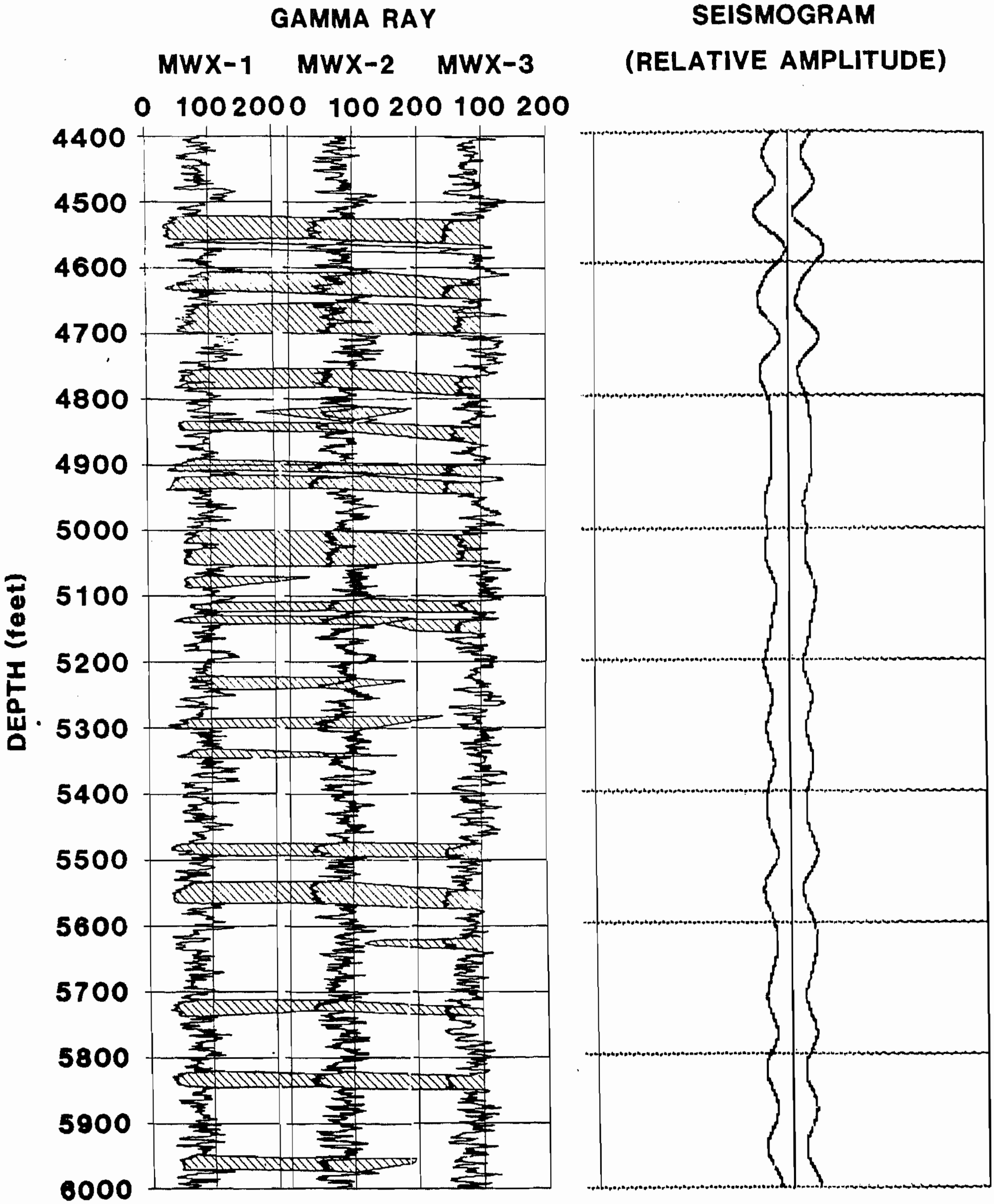


Fig. 4.4. Geological interpretation and gamma ray logs with the corresponding synthetic seismogram for
b) the Coastal zone,



(c) THE FLUVIAL ZONE

Fig. 4.4. Geological interpretation and gamma ray logs with the corresponding synthetic seismogram for
c) the Fluvial zone.

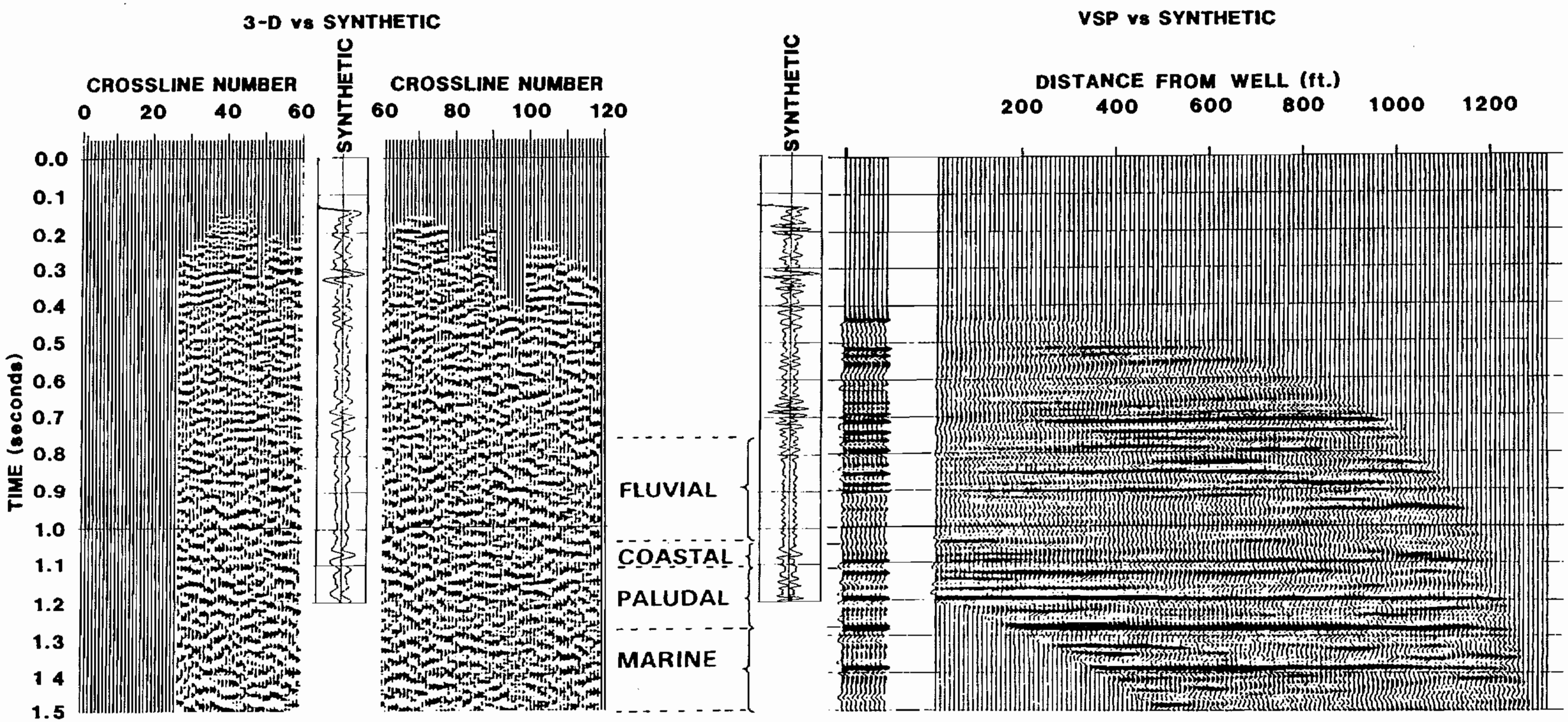


Fig. 5.1. A comparison of the 3-D, VSP, and the synthetic seismic data for MWX-3.

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