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An Evaluation of the Fifty-Caliber Machine Gun
As a High-Resolution Seismic Source
For the Exploration of Shoestring Sandstones

by

Michael D. Seeber

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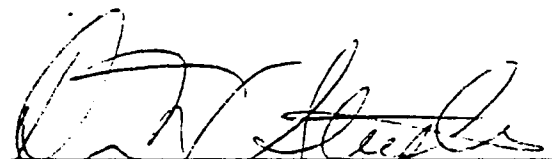
KANSAS GEOLOGICAL SURVEY
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AN EVALUATION OF THE FIFTY-CALIBER MACHINE GUN AS A
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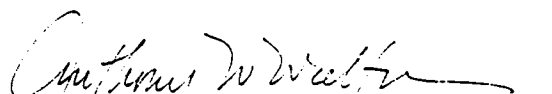
by

Michael D. Seeber
B.S., Kansas State University, 1983

Submitted to the Department of
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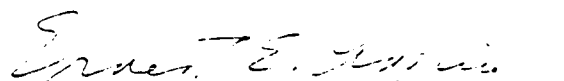


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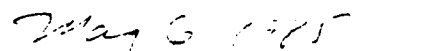




Committee Members



For the Department



Date thesis accepted

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ABSTRACT

Two seismic lines across a shoestring sandstone serve as a test of the fifty-caliber machine gun as a high-resolution seismic source for exploration of shallow sandstones. The lines cross part of the Bronson-Xenia field, which produces from the "Bartlesville" sandstone of the Cherokee Group (Pennsylvanian) in Bourbon County, Kansas, at a depth of 190 meters. The reservoir may represent a superposition of fluvial sandstones. The first seismic line clearly depicts a sandstone 17 m thick. Both the lateral extent of the sandstone body and a slight uplift of underlying layers due to the higher seismic velocity of the sandstone are evident. In addition to the target sandstone, two additional sandstone bodies appear at the east end of line one. A second seismic line of lower data quality reveals a reservoir 10 m thick but the results are not as clear-cut as those for the first line.

The frequency content of the recorded seismic signal is from 30 to 170 hz, with a dominant frequency of about 100 hz. Higher frequencies are retained deep within the section. Analysis of the survey parameters indicates that two shots per shotpoint are the minimum number necessary for the aquisition of high quality

data, and 12-fold is the minimum acceptable coverage. A source with this frequency content should be able to detect (although not resolve) oil-saturated sandstones of thickness greater than four meters and oil-saturated sandstone reservoirs more than 8 m thick where a gas cap exists, provided the frequencies have not attenuated at the depth of interest.

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INTRODUCTION

One of the shortcomings of reflection seismology is limited resolution. Several different types of sources have been tested to improve the ability to detect thin beds. One of the newest, low-cost, high-resolution seismic sources is the fifty-caliber machine gun (Steeple, 1984a). Preliminary testing of the fifty-caliber machine gun by the Kansas Geological Survey has prompted further testing in an area of known geology.

An ideal target for such a study is shoestring sandstone bodies in southeastern Kansas (Steeple, pers. comm.). The nature of these sandstone bodies makes exploration difficult. They occur at different stratigraphic levels and are small and discontinuous (Ebanks, 1979). Even after their initial discovery, development is difficult because the trend of the sandstone is uncertain. What is needed is an exploration tool to locate this type of sandstone reservoir and delineate its outline and trend. The purpose of this study is to evaluate, in an area of known geology, the fifty-caliber machine gun as a such a tool.

LOCATION

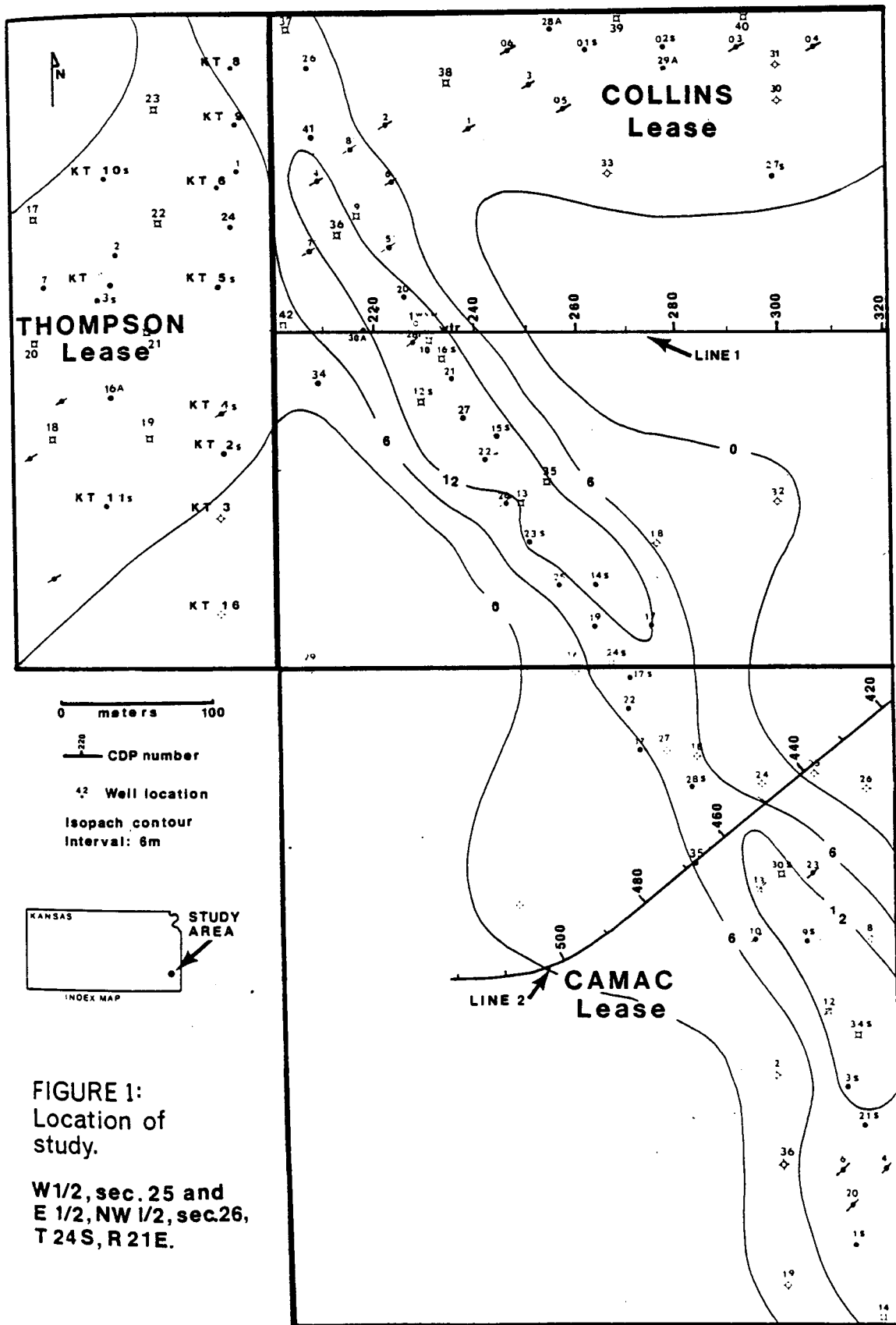
This study concerns the Collins and Camac leases of

the Bronson-Xenia oil field in section 25, T.24 S., R. 21 E., Bourbon County, Kansas (Figure 1). Oil is produced from a sandstone body up to 17 m thick at a depth of 190 m. The upper few meters are gas saturated; the middle section is oil saturated; and the lowest portion is water saturated. The position of the gas-oil contact is identifiable using available neutron logs, but the oil-water contact has not been delineated. Core analyses indicate that the average porosity of rocks in the reservoir is 19 percent, and average permeability is 55 millidarcies. Primary production has depleted the original reservoir pressures, and the reservoir is now being water flooded. About 80 wells have been drilled in the leases. Gamma-ray and neutron-count logs, available for most wells, and sample logs provide geological control. Two separate seismic lines were run. The first line was located where the sandstone is 17 m thick; the second line was located where the sandstone is about 10 m thick.

GEOLOGICAL BACKGROUND

Structural Features

There are several prominent structural features in southeastern Kansas (Figure 2). One such feature is the Nemaha ridge. The Nemaha ridge is a complexly faulted, south-plunging, truncated anticline (Merriam, 1963;



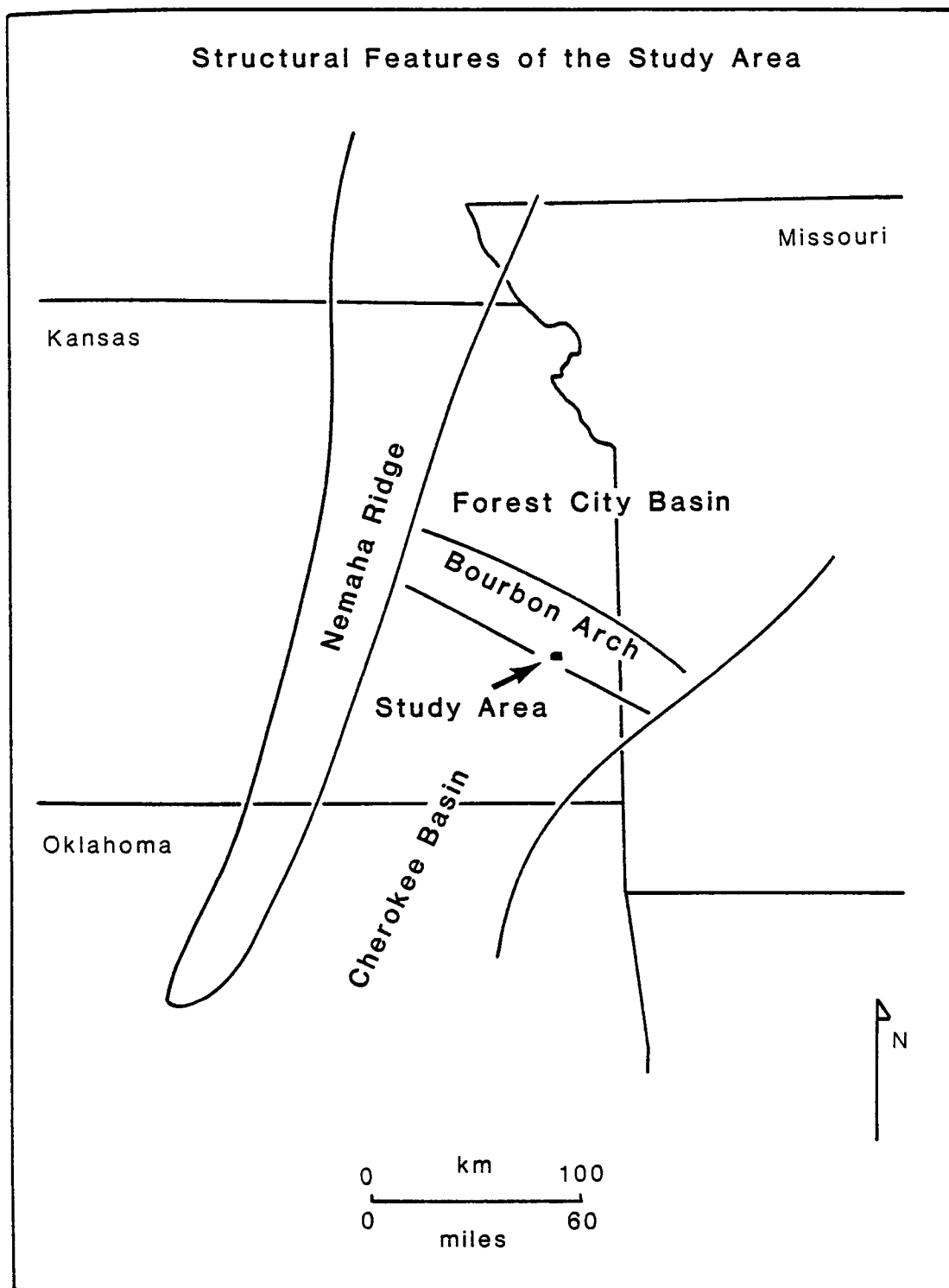


Figure 2. Structural features of southeastern Kansas.

Berendsen and Blair, 1985). The Forest City basin borders the study area on the north and extends into Iowa, Missouri, and Nebraska. The total thickness of sediments in the Forest City basin is approximately 1250 m in northeastern Kansas (Lee, 1943). The Cherokee basin, with a total thickness of 1100 m (Lee, 1943), borders the southern edge of the study area. The most important feature is the Bourbon arch, which underlies the study area. The arch is a subtle structural high that trends ESE-WNW through eastern Kansas and separates the Cherokee basin from the Forest City basin. A pronounced thinning of Pennsylvanian sediments indicates that the arch influenced sedimentation during the Pennsylvanian (Merriam, 1963; Harris, 1985).

Stratigraphy

A formal discussion of stratigraphy was presented by Zeller (1968). This discussion will center upon the dominant rock sequences that are important for seismic interpretation and to petroleum occurrences in the area.

Rocks in the study area range from Precambrian to Pennsylvanian in age (Figure 3). Precambrian rocks consist of granite and rhyolite (Bickford and others, 1981), although the exact lithology is uncertain due to a lack of nearby wells that penetrate basement. The depth to the Precambrian averages about 660 meters.

PALEOZOIC	PENNSYLVANIAN	Kansas City Group	
		Pleasanton Group	
		Marmaton Group	
		Cherokee Group	Cabaniss Formation
			Krebs Formation
	MISSISSIPPIAN	Warsaw Limestone	
		Burlington/Keokuk Limestone	
		Fern Glen Limestone	
		Northview Shale	
		Compton Limestone	
		Chattanooga Shale	
	ORDOVICIAN	Arbuckle Group	Cotter/Jefferson City Dolomite
			Roubidoux Formation
Gasconade Dolomite			
CAMBRIAN	Eminence Dolomite		
	Bonneterre Dolomite		
	Lamotte Sandstone		
PRECAMBRIAN			

Figure 3. Generalized stratigraphy of the study area.

Resting unconformably upon the Precambrian is the Lamotte Sandstone. Overlying the Lamotte Sandstone is the Arbuckle Group, a thick sequence (300 m) of limestones and dolomites. The Arbuckle Group is unconformably overlain by the Chattanooga Shale, the Compton Limestone, the Northview Shale, and another thick (100 m) sequence of Mississippian limestones and dolomites known to area petroleum operators as the Mississippi. Prominent seismic reflectors within this sequence are the Precambrian, the Lamotte Sandstone, the Arbuckle Group, and the Mississippian limestones.

Pennsylvanian rocks are approximately 270 m thick and are the major producers of oil and gas. The major divisions are the Cherokee and Marmaton groups, which are assigned to the Desmoinesian stage, and the Pleasanton and Kansas City groups, which are part of the Missourian stage (Zeller, 1968). The Cherokee Group comprises cyclical sequences of sandstones and shales with interbedded thin limestones and coal deposits (Ebanks, 1979; Figure 4).

The Seville(?) Limestone, the Verdigris (Ardmore) Limestone, and the black shale (known as the V shale), which immediately underlies the Verdigris Limestone and overlies the Croweburg coal, are good stratigraphic markers within the Cherokee Group. The Verdigris

COMPOSITE SECTION OF THE CHEROKEE GROUP, SOUTHEASTERN KANSAS

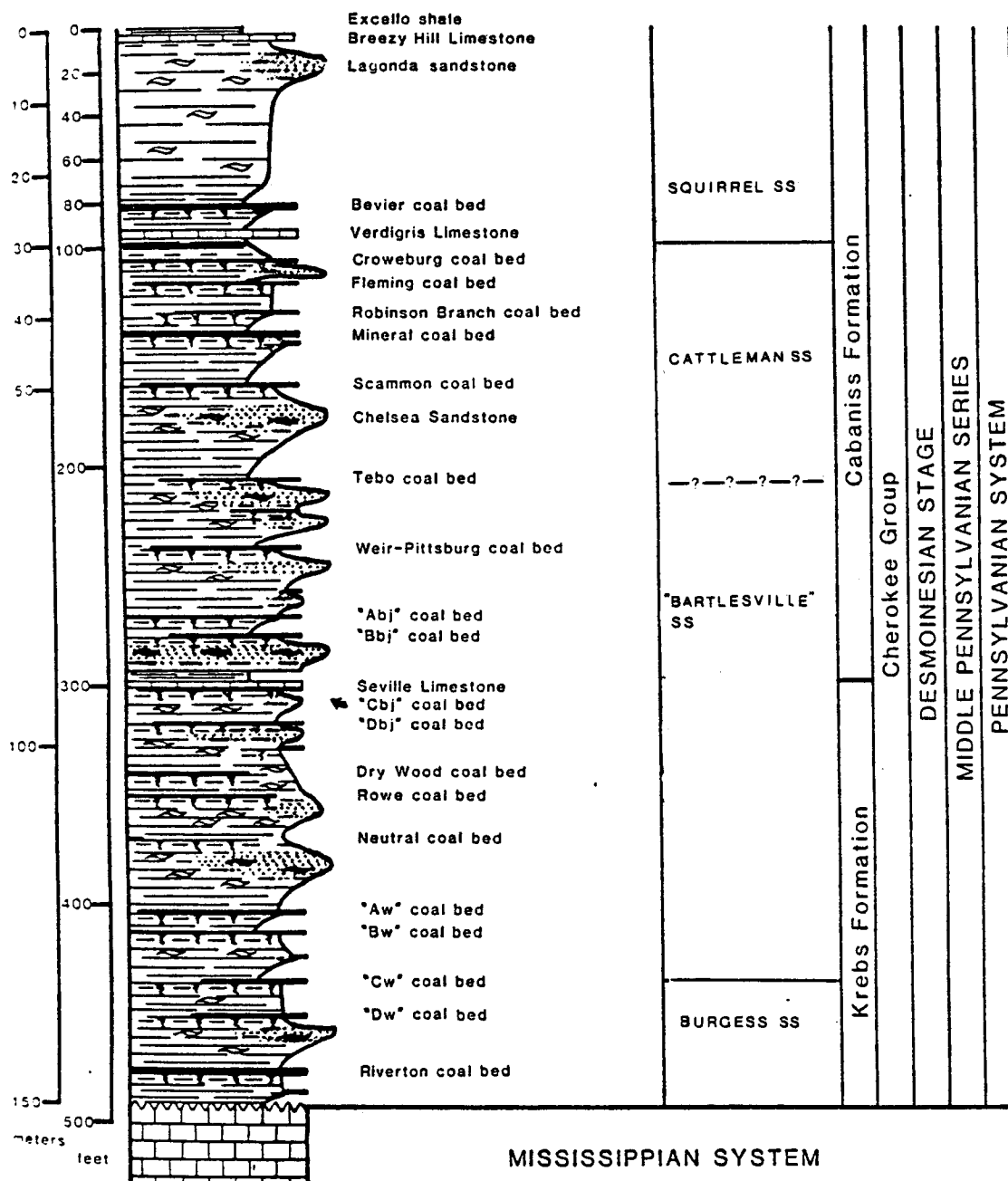


Figure 4. Stratigraphy of the Cherokee Group in southeastern Kansas (after Harris, 1985).

Limestone may be locally absent (Lee, 1943), but the underlying V shale as well as several coal beds, appear to be continuous throughout southeastern Kansas (Harris, pers. comm.).

Sandstones within the Cherokee Group have received much attention, because they are prominent oil and gas reservoirs. These sandstone bodies are informally named depending upon their stratigraphic position within the section. The Squirrel sandstone occurs in the uppermost 30 meters of the Cherokee Group. The name Cattleman sandstone is given to sandstones bodies found in the upper-middle portion of the section. "Bartlesville" sandstones occur in the middle to lower part of the Cherokee Group, and the Burgess sandstone is found at the base of the section (Jewett, 1954). The sandstone chosen for this study is below the Scammon coal bed and above the Bluejacket A coal, using the terminology of Harris (1985). It is stratigraphically equivalent to the Chelsea and Upper Bluejacket sandstones (Zeller, 1968, Harris, 1985). Although the sandstone is not true Bartlesville Sandstone, it is referred to by local petroleum operators and in the literature as the "Bartlesville" sandstone.

The Fort Scott Limestone (Marmaton Group) is a distinctive seismic reflector and serves as good marker horizon in the seismic section above the Cherokee Group.

Geological history of the Cherokee Group

The cyclical nature of Cherokee Group is probably due to eustatic changes in sea level associated with glaciation (Heckel, 1980), as well as variations in sediment supply and the rate of basin subsidence (Ebanks and James, 1974). Interpretations of environments of deposition differ and have included beaches, tidal delta complexes, alluvial and deltaic plains, estuaries, and shallow-marine shelf environments (Ebanks, 1979).

Individual sandstone bodies tend to be elongate in plan view and lenticular in section. They are a significant source of petroleum in southeastern Kansas (Jewett, 1954). These sandstones, colloquially called shoestring sandstones, range from one to several kilometers long, from tens to hundreds of meters wide, and from less than one to several tens of meters thick. Interpretations of individual sandstone bodies have ranged from alluvial-valley fill to offshore bar deposits (Ebanks, 1979). Probably no single

interpretation is correct for all of the sandstone bodies.

Environment of Deposition

The dominant environments in which most Desmoinesian sandstones in the Midcontinent were deposited ranged from fluvial in northeastern Kansas to deltaic in Oklahoma (Weirich, 1953; Rascoe and Adler, 1983; Figure 5). Rofheart (in prep.) investigated sandstone bodies in the Bronson-Xenia field 5.5 kilometers southwest of this study area. He concluded that reservoirs consist of multistory point-bar sandstones resulting from deposition in a low-energy meandering stream. The upper 3 m of the sandstone studied by Rofheart is stratigraphically equivalent to the lower 3 m of the sandstone in this study (Figure 6). Although the overall sandstone interval in this study is not exactly stratigraphically equivalent to that of Rofheart, there are many similarities between the them. Both exhibit the apparent fining-upward character of the sandstone as evidenced by gamma-ray-log response (Figures 7). Rofheart (in prep., p. 56) concluded that deflections in gamma-ray responses were erosional surfaces separating rock sequences representing distinct depositional events. Similar deflections were seen in this study (Figure 6). The sandstone(s) in this study

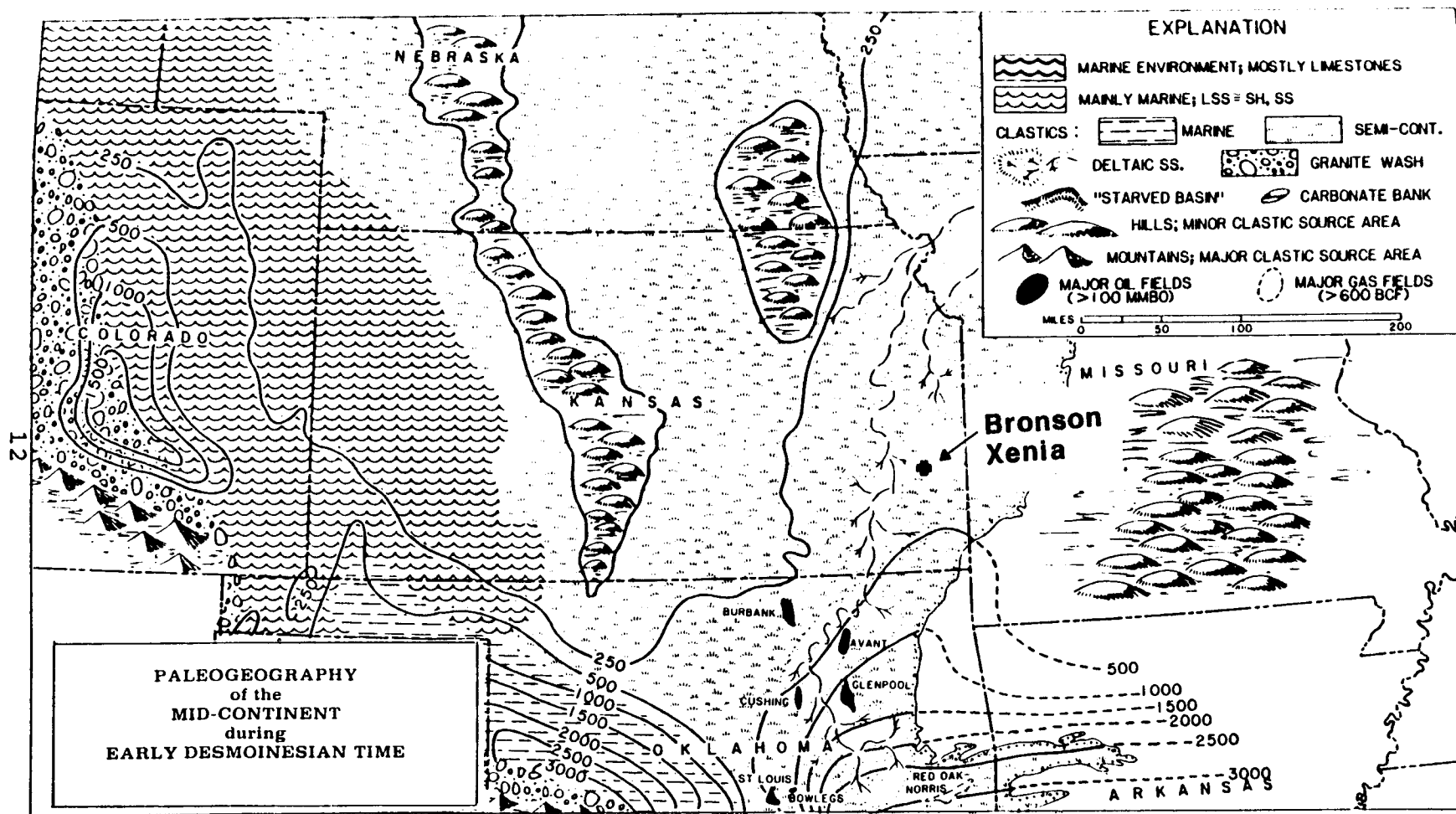


Figure 5. Paleogeography of the Midcontinent during the early Desmoinesian (modified from Rascoe and Adler, 1984).

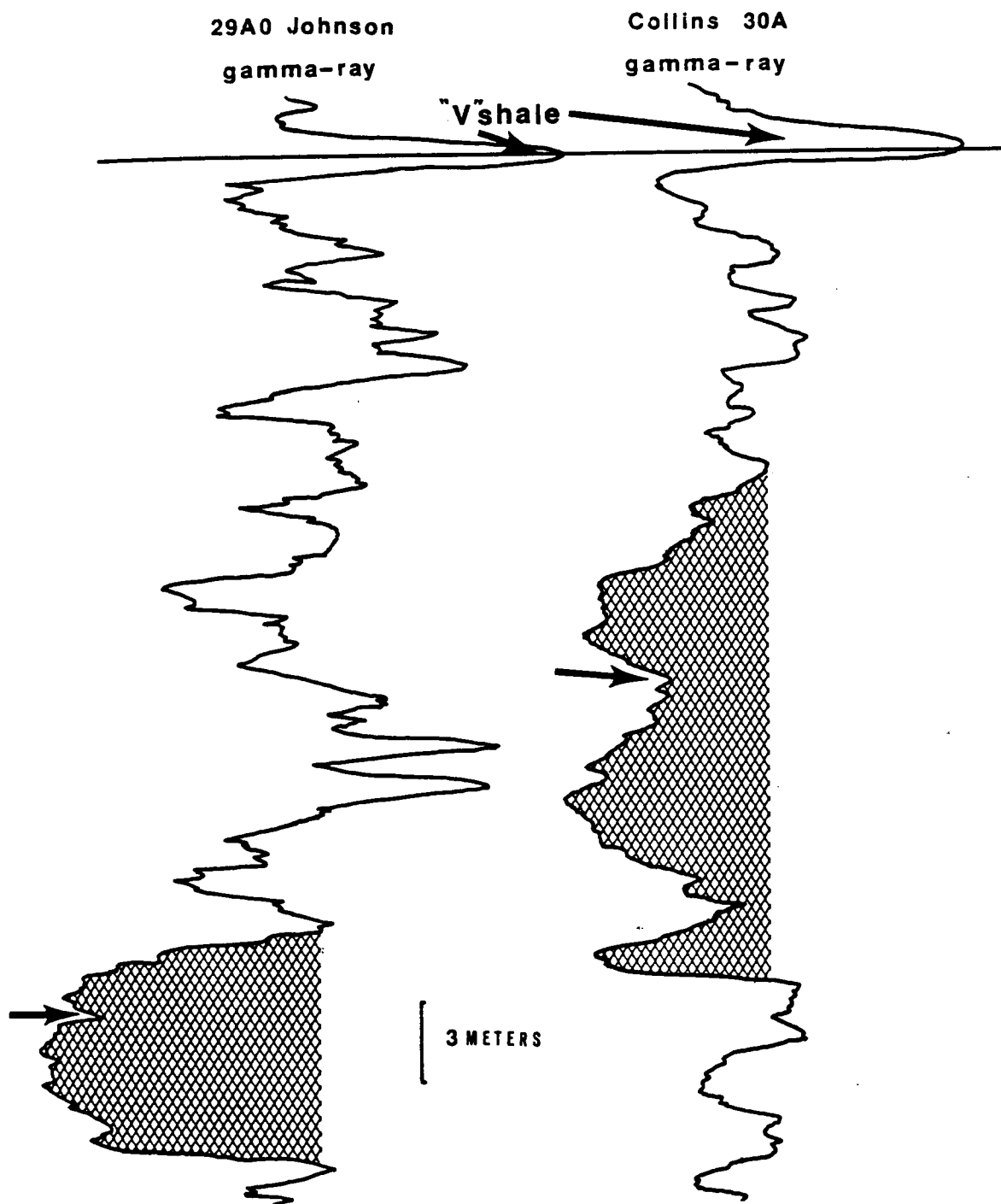


Figure 6. Stratigraphic interval of the sandstone in this study compared to that of Rofheart (1985). Left: arrows indicate inferred depositional contacts in the Colt #29A0 Johnson (Rofheart, 1985). Right: similar deflections as seen in the Collins #30A of this study area.

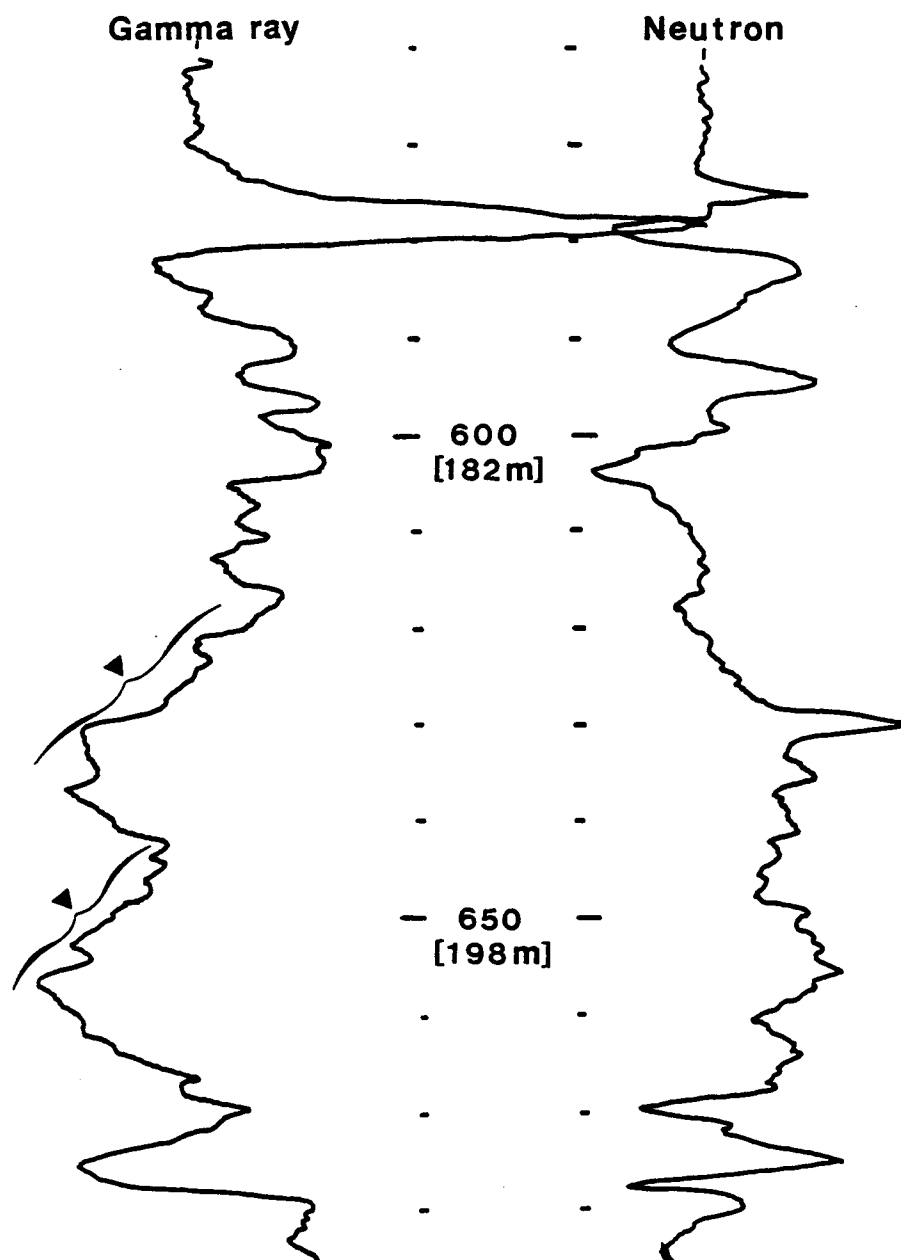


Figure 7. Gamma-ray, neutron logs showing fining upward sequences in the Collins #30A well.

may be fluvial channel deposits, based upon interpretation of log response and the work done by Rofheart.

Reservoir Geometry

To delineate the geometry of the petroleum reservoir, cross-sections were drawn using gamma-ray and neutron-count logs from oil wells located along or near the seismic lines (Plate 1). The reservoir has a continuous flat base. Above this basal sandstone is another sequence, which appears to be a superposition of channel sandstones, giving the reservoir a transitional top, consisting of sandstone grading upward into sandy shale, and irregular lateral terminations. The total thickness of the sandstone is approximately 17 m. Sample logs indicate that the upper 5 m are gas saturated. The sandstone in the south is approximately 9 m thick. It becomes increasingly shaly to the east. Sample logs indicate that the upper 3 meters are gas saturated.

SEISMIC RESOLUTION

Vertical resolution depends upon the frequency and the bandwidth of the seismic wave (Widess, 1973; Anstey, 1978). The thinnest bed for which a distinct reflection can be seen from both the top and the bottom of the bed is one with a thickness of one quarter of the seismic wavelength ($\lambda/4$). The thinnest bed detectable using an interpretation of waveshape is $\lambda/8$ (Weidess, 1973; Anstey, 1978; Figure 9). The wavelength is related to the frequency (f) by the equation:

$$f \lambda = v$$

where v is the velocity of the seismic wave in a medium. For example, a frequency of 125 hz is necessary to resolve a sandstone unit 7 m thick having a seismic velocity of 3,500 m/s.

High frequencies alone are not sufficient for the delineation of thin beds. A sharp seismic pulse is also required (Anstey, 1978). The sharper the pulse the thinner the layer that can be resolved. The sharpness of the pulse is related to the total range of frequencies (bandwidth). The wider the bandwidth, the sharper the pulse. Thus a wide bandwidth must be used to produce a waveform with a sharp pulse.

Horizontal resolution depends on the width of the first Fresnel zone of the seismic wave (Neidell, 1979).

The size of this zone (R) is a function of the velocity (v) of the seismic wave in the medium, the two-way travel time (t), and the dominant frequency (f):

$$R = \frac{v\sqrt{t/f}}{4} .$$

For a frequency of 125 hz, a velocity of 3500 m/s and a time of 100 ms (a depth of 175 m), the radius of the narrowest bed distinctly discernible is 24.7 m.

MODELING

Geologic models of the study area help aid in the understanding of the effect of frequency on resolution. Seismic modeling involves creating a geological model of an area and then calculating the seismic response to that geologic model. The first step is to develop a cross-section of the area of interest using nearby well logs. A velocity is then assigned to each layer by using information from sonic logs from wells near the area. A two dimensional model is created and converted to a series of reflection coefficient profiles. A wavelet is then convolved to the series, and the result is a model of the seismic response of the area.

Two different geologic models are considered here. One involves a sandstone reservoir containing only oil and the other a reservoir partially saturated with oil

but with a gas cap. The same reservoir geometry was used for both models with only the fluid content and thickness of the sandstone varying (Figure 8). The frequency used for these models was 110 hz, and is comparable to the dominant frequency of the seismic data produced by the fifty-caliber machine gun in previous studies (Steeple, 1984b). The seismic response for a section containing no sandstone indicates that prominent seismic markers are at the base of the Fort Scott Limestone, the top of the Verdigris Limestone, and the top of the Mississippian limestones (Figure 9).

The following velocities were used for the model of an oil-saturated sandstone reservoir: 5,000 m/s for the oil-saturated sandstone and 3000 m/s for the shale. The thickness of the sandstone was increased and the resulting seismic response observed (Figure 10).

At a thickness of 1.5 m, the sandstone was not visible. At a thickness of 8 m the sand became visible, but introduction of random noise might render the sandstone seismically invisible at this thickness. The 14-meter-thick sandstone is easily visible and caused a uplift (3 ms) of the underlying layers. A pull-up is defined by R. Sheriff in the Encyclopedic Dictionary of Exploration Geophysics (1985) as "An apparent uplift produced by a local, shallower high velocity region".

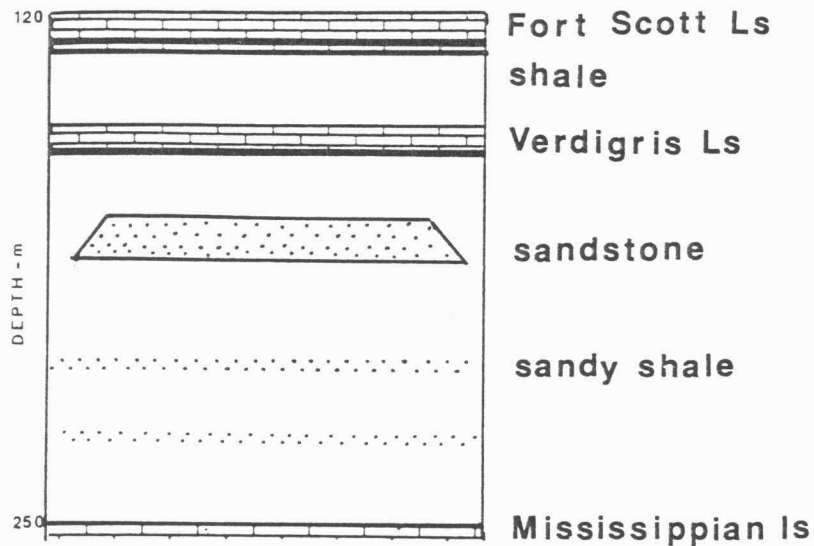


Figure 8. Preliminary model used for modeling sandstone reservoirs in the study area. Thickness and fluid saturation are varied from model to model.

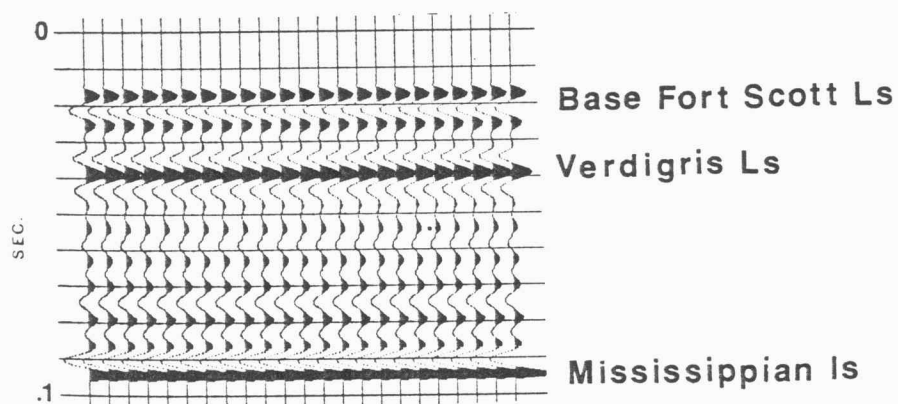
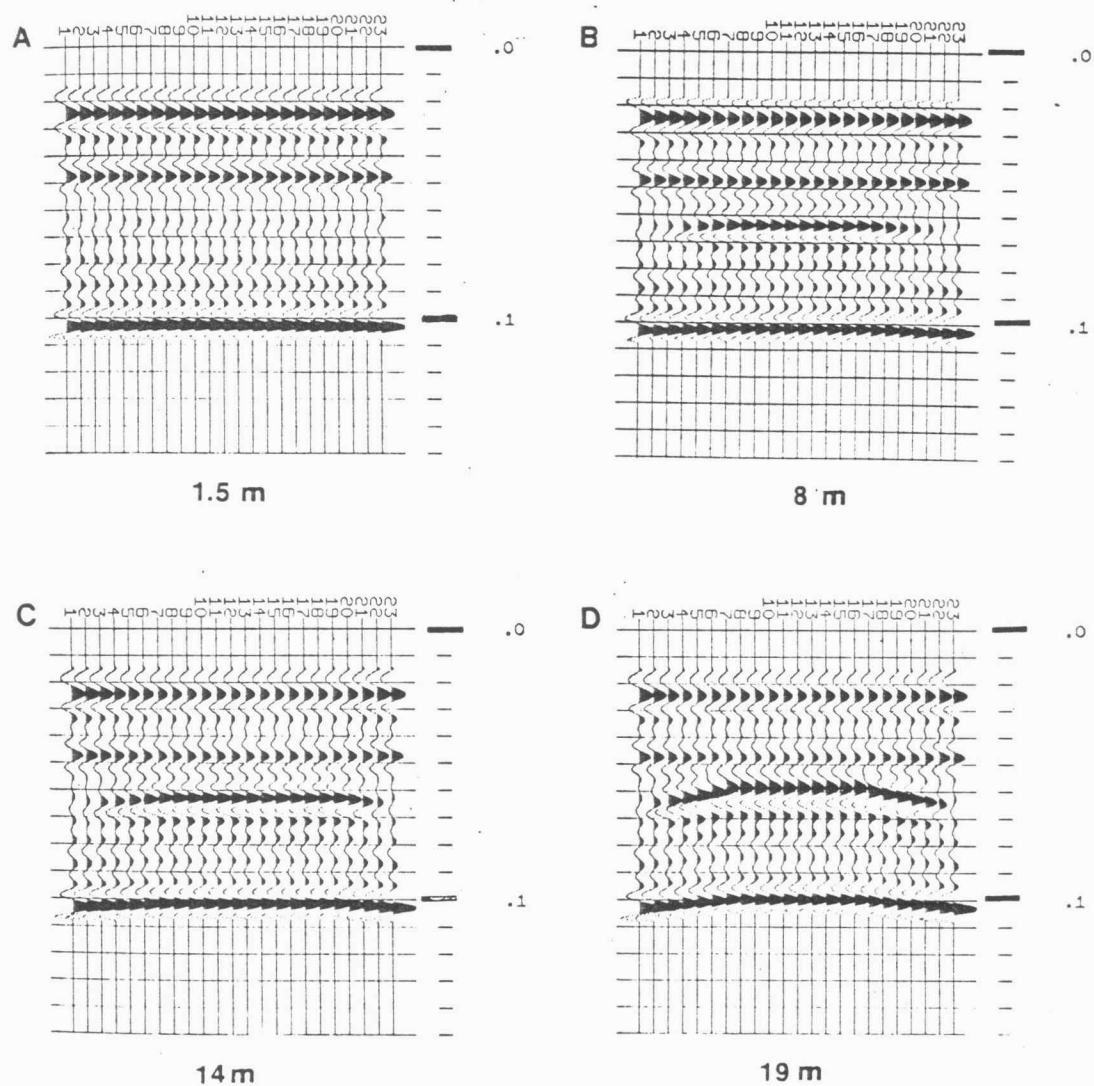


Figure 9. Seismic response of the model with no sandstone present.

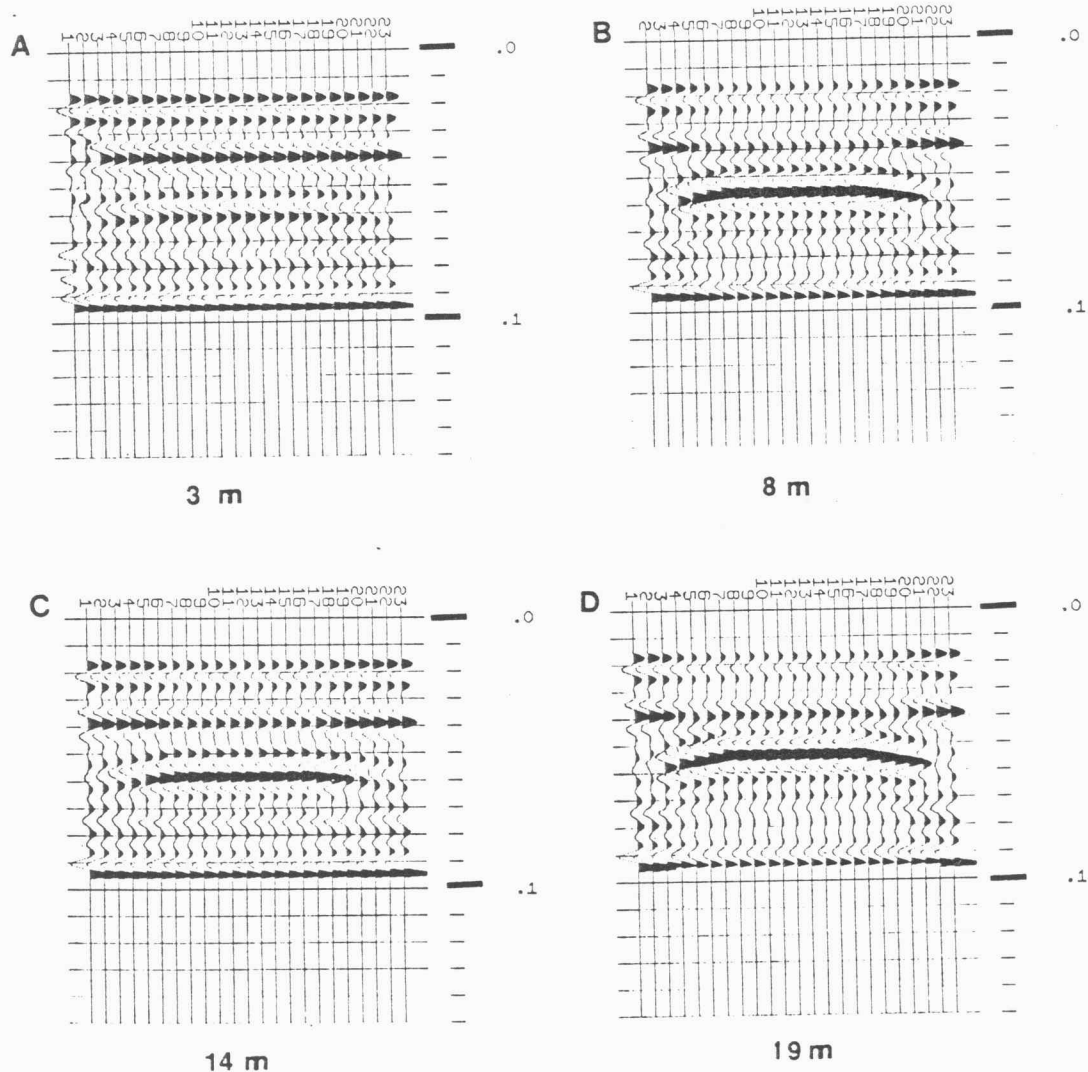


OIL SATURATED SANDSTONE

Figure 10. Model one: seismic response for an oil saturated sandstone. Thickness increases from 1.5 to 19 m.

This pull-up resulted from the higher velocity of the oil sand (5000 m/s) compared to the surrounding shale (3000 m/s). At 19 m the sandstone is thick enough that reflections mark both its top and bottom. At trace four the sand has thinned to a point where the seismic waves constructively interfere with one another. This very high amplitude event is a phenomenon known as tuning. At 19 m the velocity pull-up (5 ms) is easily seen.

The second model is for an oil-saturated sandstone with the upper one-third of the sandstone reservoir gas saturated. The gas saturated-sandstone is modeled at a seismic velocity of 2200 m/s. The sandstone is just seismically visible at a thickness of 3 m (Figure 11). At 8 m the sandstone becomes easily visible. The strength of the reflection increases as thickness increases to 14 m. At 19 m distinct reflections can be seen for the top of the gas-saturated sandstone, the gas-oil contact, and the lower sandstone-shale boundary. At the top of the sandstone there is a negative deflection indicating the abrupt transition from shale to low-velocity, gas-saturated sandstone. A strong positive deflection is seen at the boundary between the low-velocity, gas-saturated sandstone and the high-velocity, oil-saturated sandstone. There is a negative deflection at the interface between the oil saturated



OIL SATURATED SANDSTONE WITH GAS CAP

Figure 11. Model two: seismic response for an oil saturated sandstone with a gas cap. Thickness increases from 3 to 19 m.

sandstone and the shale. A very slight velocity pull-up can be seen. The pull-up is not as great as for a sandstone reservoir saturated with oil only because the low-velocity gas cancels the effect of the high-velocity, oil-saturated sandstone.

Based on the synthetic models, it was predicted that an oil-saturated shoestring sandstone will be detectable when the thickness exceeds four m. The presence of a distinct gas cap increases the thickness necessary for distinct detection of the reservoir to about 8 m. Oil saturation is marked by a distinct pull-up of the layers underlying the sandstone. Gas saturation is marked by a sharp negative deflection at the top of the gas-saturated sandstone and a lessening of the velocity pull-up, as compared to a hydrocarbon reservoir containing oil only.

Another form of modeling is the generation of synthetic seismograms (or forward modeling) from geophysical well logs. Synthetic seismograms aid in geological interpretation by producing a simulation of the seismic response of an area, based on data taken from geophysical well logs from wells at or near the seismic line. The seimogram can be overlain on an actual seismic section, and stratigraphic markers can then be identified. In the Midcontinent it is generally

assumed that all major acoustic contrasts result from a change in velocity between two layers (Galloway and Dutton, 1979). Synthetic seismograms can be created from sonic logs and where sonic logs are not available, from pseudosonic logs. The sonic logs are converted from depth, sonic-transit-time pairs to depth-velocity pairs. From these depth-velocity pairs, a series of reflection coefficients is generated. The resultant reflection coefficient profile is convolved with a wavelet, and the results are plotted with respect to time.

Synthetic seismograms are commonly derived from sonic logs. Many times, however, sonic logs are not available in the area being studied. Therefore some other type of log must be converted to a pseudosonic log. Rudman and others (1975) developed a method to convert resistivity logs to pseudosonic logs. Both seismic velocity and resistivity are related to porosity, thus an empirical relationship between sonic travel time and resistivity can be developed. Resistivity logs may then be converted to pseudosonic logs. Similarly, neutron-porosity and neutron-count logs may be converted to pseudosonic logs (Ready, in prep.). Because neutron-porosity and sonic logs are both related to porosity, they can be correlated to

determine a set of coefficients for converting neutron-porosity logs to pseudosonic logs. This is done by applying a polynomial fit to a crossplot of the two logs. The resulting coefficients are used as conversion factors. These coefficients can then be used to convert any neutron-porosity log in the same geological setting or region, to a pseudosonic log. Neutron count logs can also be converted to neutron porosity logs, using the 40-to-1 method (Doveton, 1982), and the results can then be converted to pseudosonic logs.

This technique must be applied with caution in areas with gas-saturated rocks. The neutron-count log effectively measures the density of hydrogen ions within the rock. The presence of gas-saturated sandstone causes a neutron-count response that can be interpreted as low-porosity sandstone or limestone rather than a gas-saturated sandstone. When converted to a synthetic seismogram, the resultant reflection coefficient corresponds to a high-velocity bed, not a low-velocity, gas-saturated sandstone.

A sonic log and sidewall neutron-porosity log from a well 30 km to the east of the study area were used to calculate conversion factors for this study. The polynomial used for conversion and the standard deviation are given in Table 1. The standard deviation

Table 1. Results of Log Conversion

COEFFICIENTS

Third order polynomial

A= 51.008026
B= 0.31067943
C= 0.11722130
D= -0.00209815

CONVERSION RESULTS

Neutron porosity to pseudosonic-- 30-270 meters
travel time-- sonic log: 71.7023 ms
travel time-- pseudosonic log: 71.5041
percent change-- .0025%
standard deviation-- +/- 10.57 microseconds
percent standard deviation-- 10.6%

Neutron count to pseudosonic-- 30-270 meters
travel time-- sonic log: 71.7023 ms
travel time-- pseudosonic: 69.5318 ms
percentage change-- 4.15%
standard deviation-- +/- 11.89 microseconds
percent standard deviation-- 11.9%

for conversion from neutron-count to neutron-porosity, as well as the subsequent conversion to a pseudosonic log are also given in Table 1.

The conversions appear to be valid. A direct overlay of the pseudosonic logs with the original sonic log shows a good match (Figure 12).

Several synthetic seismograms were created from wells near seismic line one. The Collins #30A is located immediately adjacent to the seismic line, at CDP 218. The Collins #42 is 13 m north of CDP 204, and the Collins #10 is 13 m south of CDP 234. Wells #42 and #30A were logged to the depth of the sandstone (190 m). Well #10 was logged to the top of the Mississippian limestones. The Collins #32 is located 180 m south of the seismic line and was logged to the Mississippian limestones. Finally, the Rhoton well #15 (located 800 meters north of the seismic line) was used because it was logged to the top of Arbuckle group (345 m).

SEISMIC METHOD

The Common-Depth-Point Seismic Technique

The common-depth-point (CDP) seismic technique involves introducing an acoustic signal into the ground. This signal is reflected from acoustic boundaries in the subsurface and returns to the surface. The amplitude of

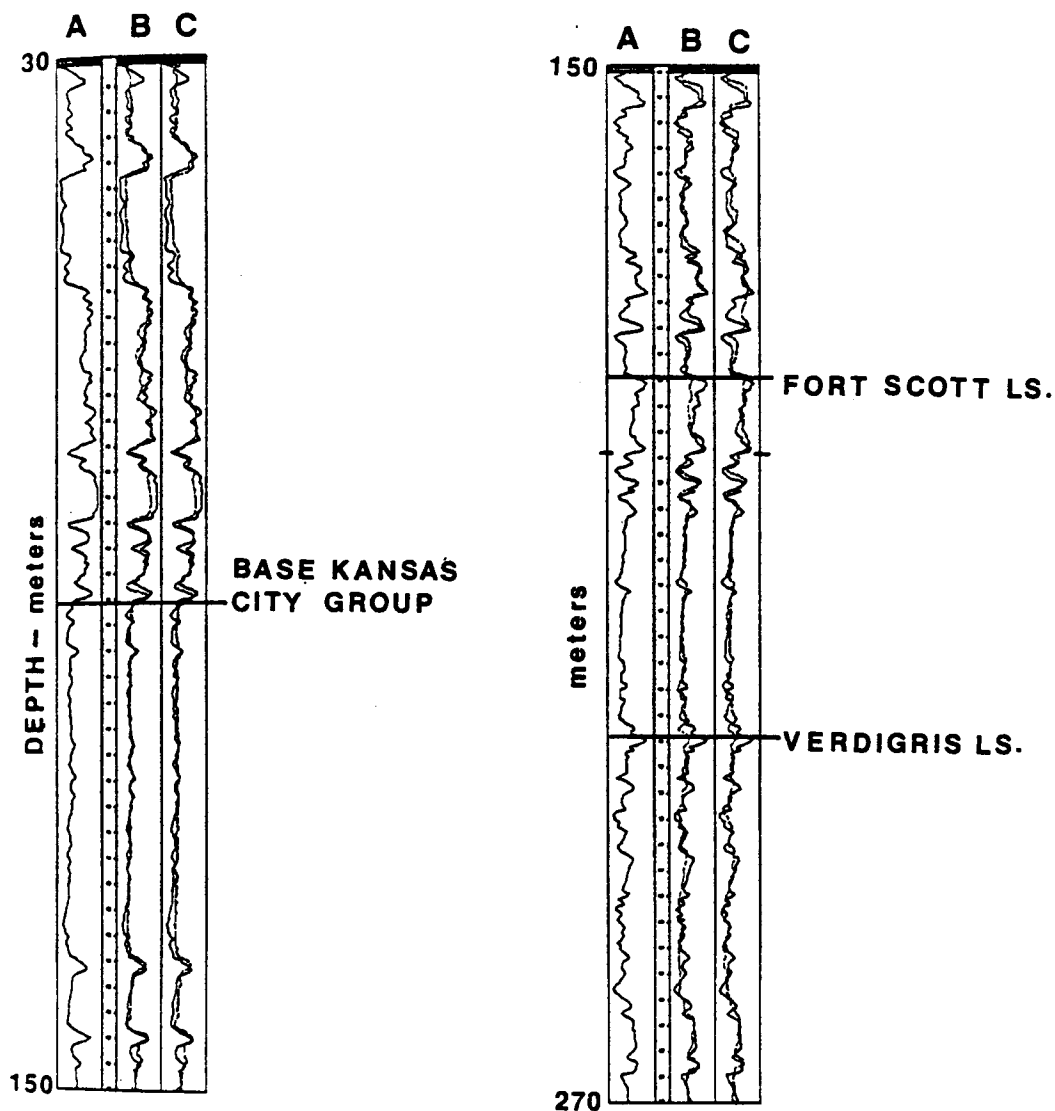


Figure 12. An overlay of sonic and pseudosonic logs
 A-- sonic log alone
 B-- sonic log (solid line) and pseudosonic log from neutron porosity log.
 C-- sonic log (solid line) and pseudosonic log from neutron count log.

the reflection is determined by the acoustic contrast of the two layers. For two rock layers (1 and 2), the acoustic contrast is a function of the velocities (V_1 and V_2) of the seismic wave within the layers, and densities (p_1 and p_2) of the layers by the equation:

$$\frac{V_2 p_2 - V_1 p_1}{V_2 p_2 + V_1 p_1}.$$

Thus the reflections may result from an interface between two different rock types that have different acoustic properties (e.g. a limestone and a shale) or from a vertical change in lithology or porosity within a single rock unit.

As the signal reaches the surface, it is detected by geophones, which are sensitive to the velocity of ground motion. The magnitude of the ground motion, and the elapsed time since source initiation are measured by the geophones. A seismogram is a plot of the signal received by the geophones and is displayed in units of lateral distance versus two-way travel-time, not depth. A conversion to depth can be obtained by multiplying the one-way time to the reflector by the average velocity of the intervening rocks.

The CDP seismic method was used in this study. A CDP survey obtains several reflections from a single point in the subsurface (a common depth point (CDP); Figure 13). These reflections are geometrically

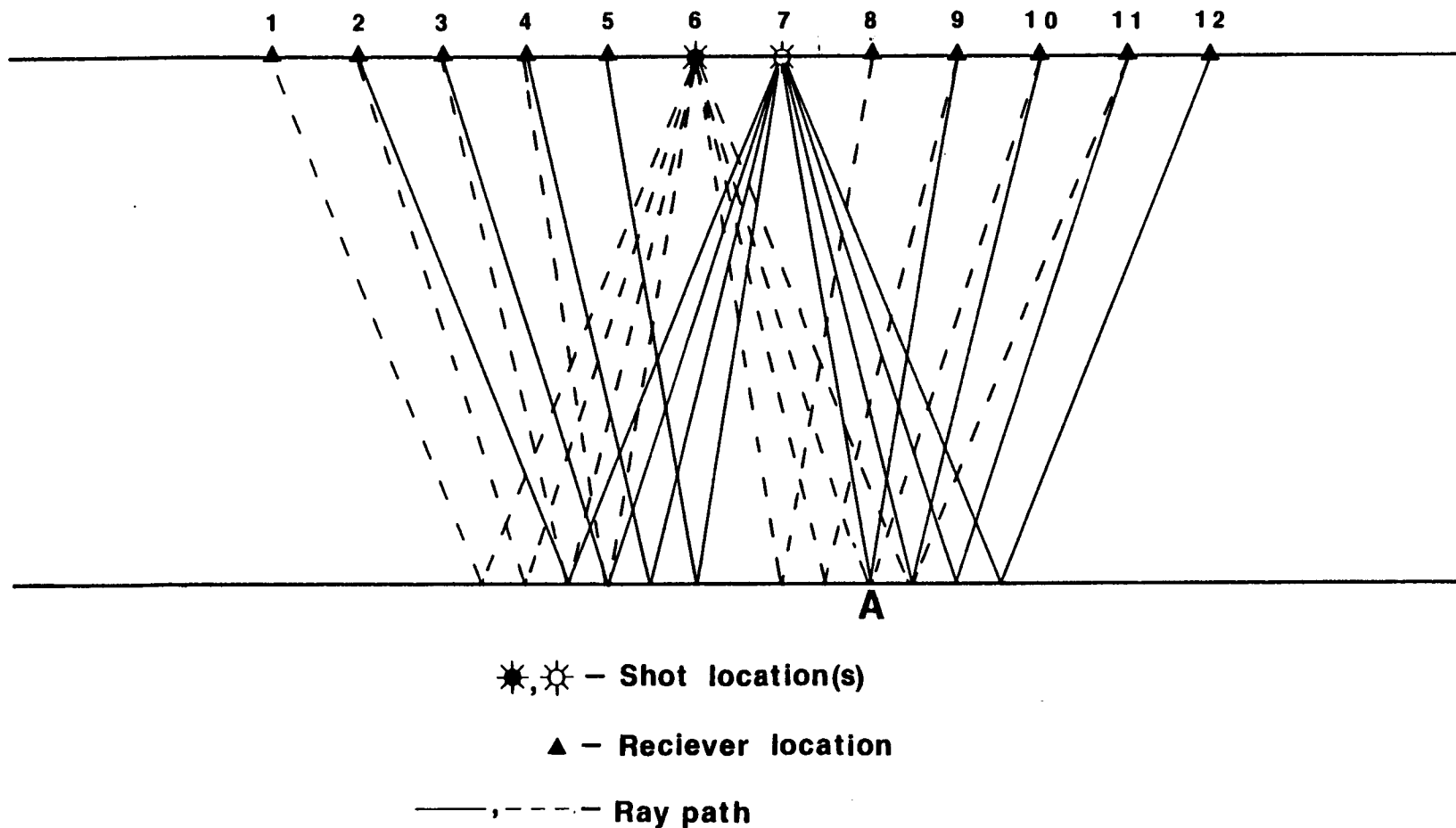


Figure 13. Common Depth Point Seismic Technique: shots are indicated as is the common reflecting point, A. Ray paths 6-A-10 and 7-A-9 are reflected from the same point on the acoustic interface. They are summed during CDP processing.

corrected by a computer and then summed to form a single record for that point. This summation (or stacking) raises the ratio of signal to noise, improving quality of the data. Noise is used here in the sense of anything on the seismogram that is not a reflection. Receivers are placed at equal distances on both sides of the source (a split spread). The source is then moved along the line, recording different CDP's for each shot.

Data Acquisition

The source used in this study was a fifty-caliber machine gun. A previous study (Steeple, 1984b) had compared the fifty-caliber machine gun to the Betsy Seisgun (trademark, Betsy Seisgun, Inc.), a commercially available seismic source using a 8 gauge shotgun with a three ounce lead slug. The Betsy Seisgun has produced dominant frequencies of 80 to 90 hz to a depth of 500 m in tests run in Oklahoma, and has an optimum depth of penetration of 1500 m (Biggs, 1981). Steeples (1984b) found that the fifty-caliber machine gun produced a seismic signal of higher energy and richer in high frequencies than the Betsy Seisgun.

The fifty-caliber machine gun is fired vertically into the ground while the gun is mounted on the back of a truck. At the shot point the gun assembly is lowered

to the ground and the weight of the truck is used to keep the gun and mount firmly coupled to the ground. A single shot is fired into the ground. For this study three shots were taken per shotpoint, because a preliminary study indicated that data quality increases with the second and third shots (Steeple, 1984b). This increase in quality of data is attributed to the greater depth of penetration and increased coupling of the bullet to the ground with each successive shot.

This survey used the split spread, CDP seismic method. Each geophone group comprised ten 28-Hz geophones in a linear array. Group interval was 13 m. Recording was done with a 24 channel Input/Output DHR 2400 digital seismograph.

LINE ONE

Line one is crosses the northern portion of the study area where maximum sandstone thickness is 17 m and several wells are available near the line to provide geological control.

Inspection of the seismic section for line one reveals an overall decrease in quality of data and thus a decrease in reflection strength from CDP 200 and continuing to 230 (Figure 14, Plate 2, Table 2). This is due to a change in coupling between the source and the ground. From CDP 200 to CDP 234 the surface was hard-packed gravel. At the location of CDP 234 the ground surface changed from hard-packed gravel to pasture. The geophone coupling appeared to be better in the pasture than on the gravel.

A significant, and detrimental, component of the raw data was ground roll. To enhance the signal-to-noise ratio in the lower section, the ground roll was muted out. This effectively removes all reflections above 90 milliseconds (ms). As a result synthetic seismograms offered no aid to interpretation above 90 ms.

The match between the synthetic seismograms from wells #42, #30A, and #10 and the seismic section is fair to good (Figure 15). Although the overall character

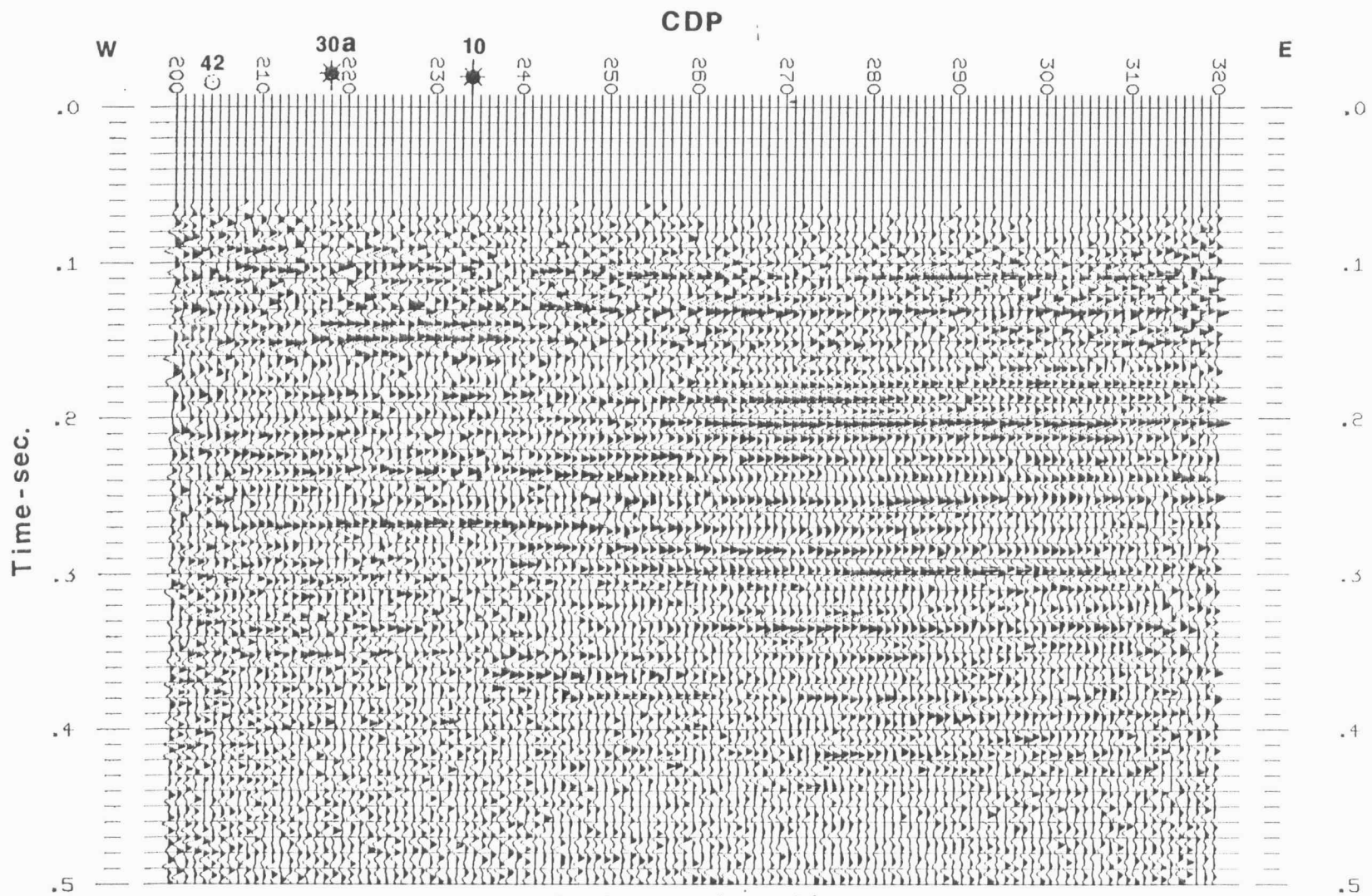


Figure 14. Seismic section: line one.

Table 2. Processing sequence for line one

SHOTS: two and three
MUTE: first arrivals and ground roll
EDIT
SORT
STATICS: elevation and weathering
DECONVOLUTION: spiking
 40 ms operator
 3% prewhitening
 Hamming smoothing
SCALE: 150 ms rms
RESIDUAL STATICS: 230 ms center
 400 ms window
FILTER: 50-120 hz bandpass
STACK
PLOT
POLARITY: normal

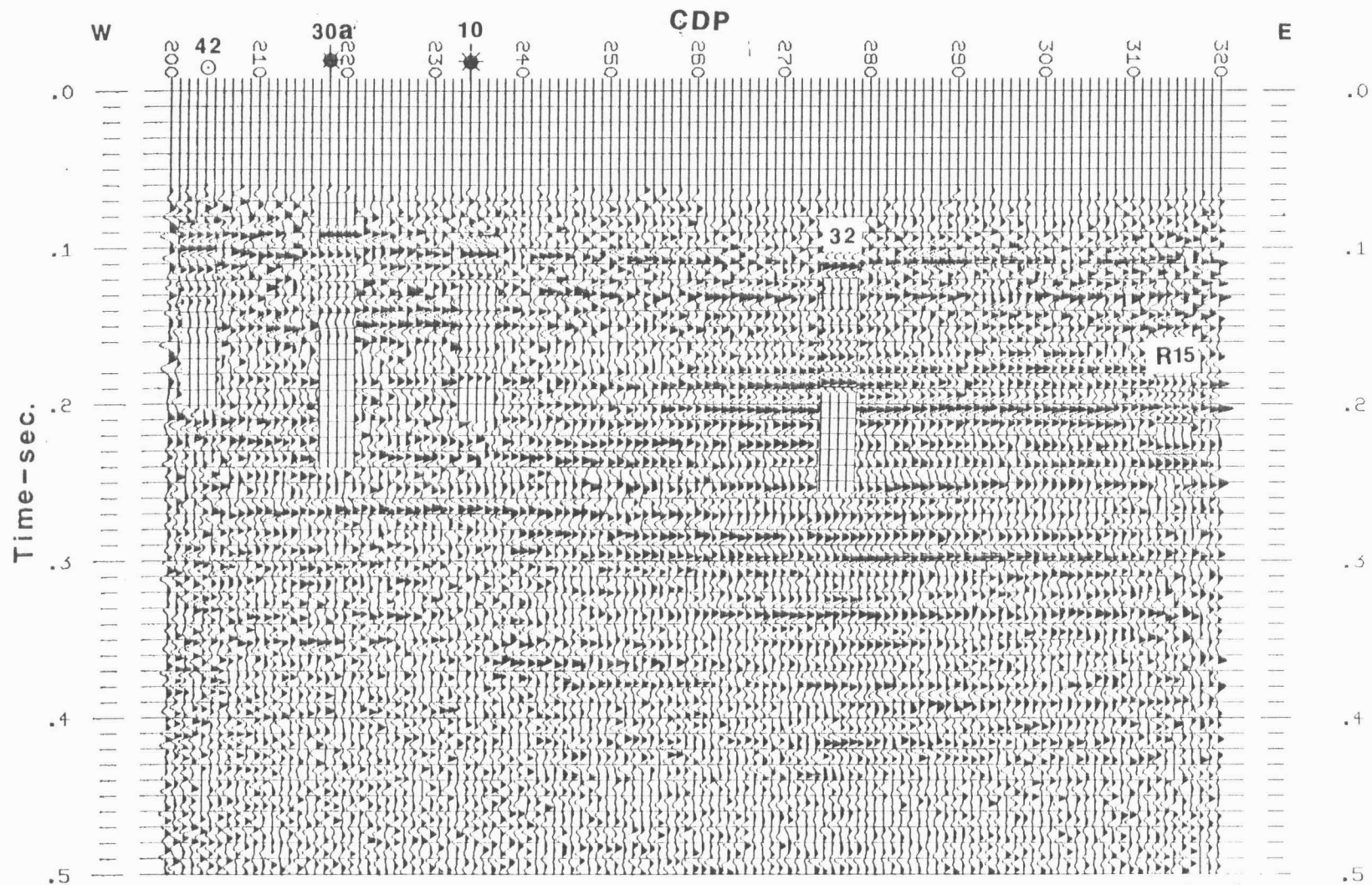


Figure 15. Comparison between the synthetic seismograms and seismic line 1. Synthetic seismograms are overlain on the seismic section.

of these three seismograms matches the overall response of the observed seismic section, they do not show the large negative deflection (the unshaded trough on the seismic section) at 140 ms seen on the seismic section. This is because conversion from the geophysical well log to a pseudosonic log does not produce velocities appropriate for a gas-saturated sandstone, which is located in this time interval. The match for the Collins #32 well is good, and the synthetic seismogram from the Rhoton #15 well shows an exceptional match from the top of the Mississippian (187 ms) to the top of the Arbuckle Group (240 ms).

Interpretation

The Fort Scott Limestone is the prominent reflector at 110 ms on the section (Figures 16, 17). At 130 ms is the Verdigris Limestone. This event (an event is defined by Sheriff (1985) as "a lineup on a number of traces which indicates the arrival of new seismic energy, denoted by a systematic phase or amplitude arrival on a seismic record") loses coherence on the west end of the line, possibly due to the overall lower quality of the data, or perhaps due to a change in porosity of the limestone. Well logs from the surrounding areas indicate that the porosity of the Verdigris Limestone is variable with porosity high on the west end of the line. The

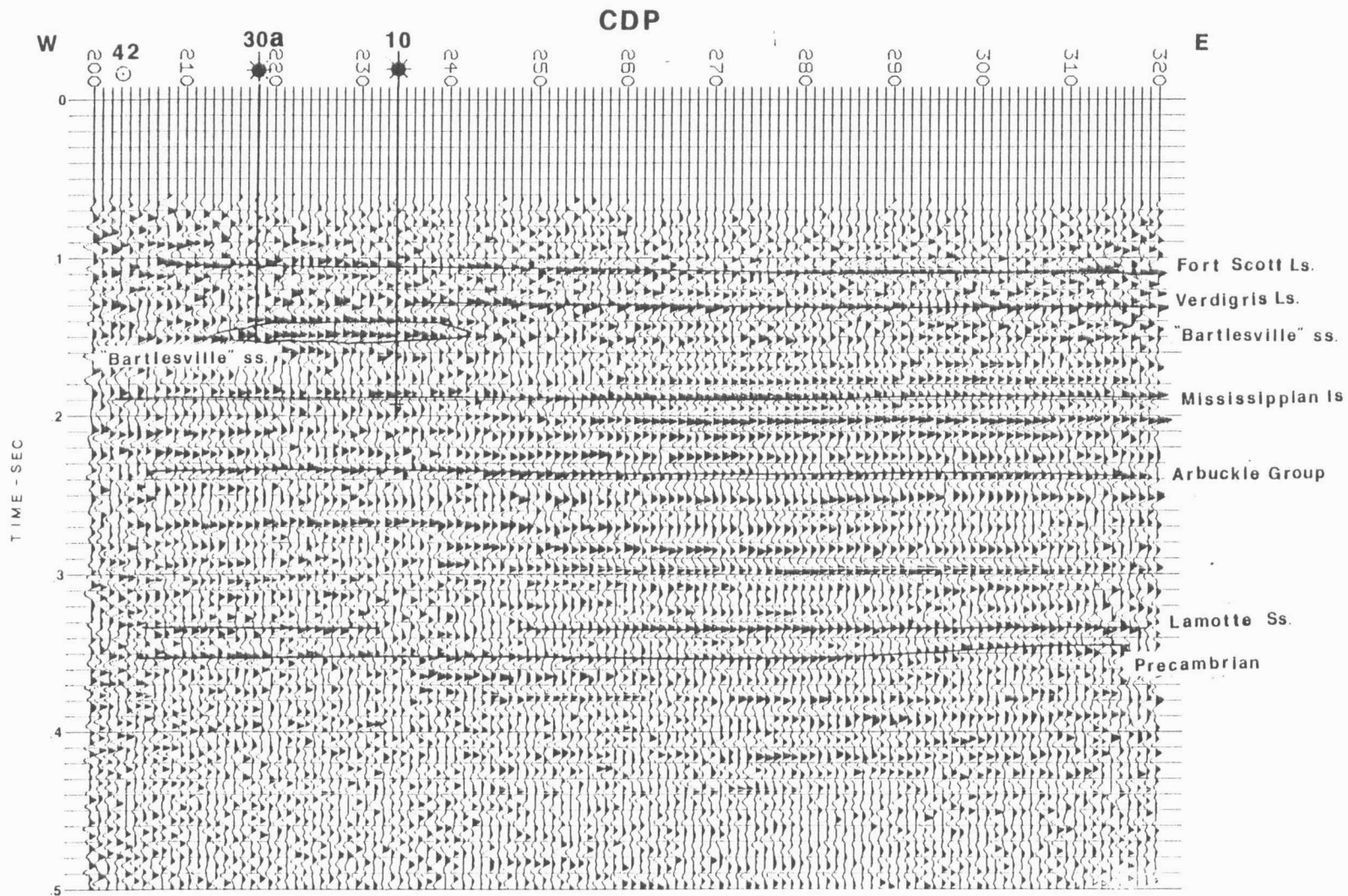


Figure 16. Interpretation of line 1.

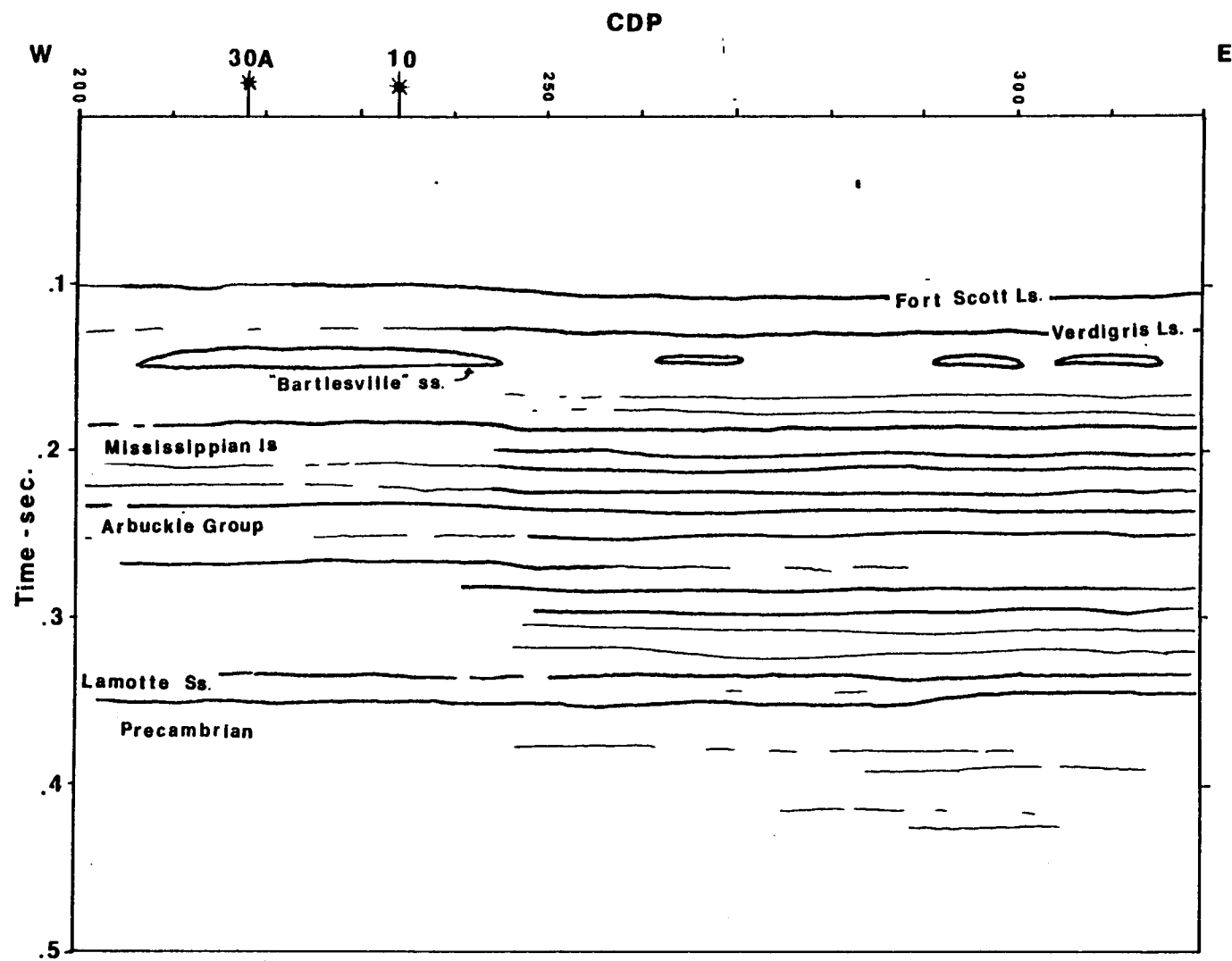


Figure 17. Line drawing interpretation of line 1.

reflections at 145 ms between CDP's 204 and 240 are interpreted as reflections from the target sandstone. Two other reflections are visible within this time interval are believed to be sandstone bodies, based on the character of the events and their position within the stratigraphic interval. One lies between CDP's 255 and 270 and the other between CDP's 290 and 315.

The Mississippian limestones occur at 180 ms. The strength of this reflection decreases between CDP's 280 and 290. Gamma-ray, neutron logs from the area show the top of the Mississippian to vary in both lithology and porosity (Figure 18). The weakening of this reflection may be due to such geologic variation. Reflectors within the Mississippian may be due to facies changes within the rocks of this interval. The top of the Arbuckle group is visible at 230 ms. Precambrian basement is believed to be the reflection occurring at 340 ms. Above the Precambrian, a possible thinning of the Lamotte Sandstone is seen between CDP's 290 and 299 and may indicate Cambrian deposition of the Lamotte Sandstone across a paleotopographic high on the Precambrian basement. Events below 340 ms may represent actual lithologic variations within the Precambrian basement terrane, but are most likely long-path and peg-leg multiples.

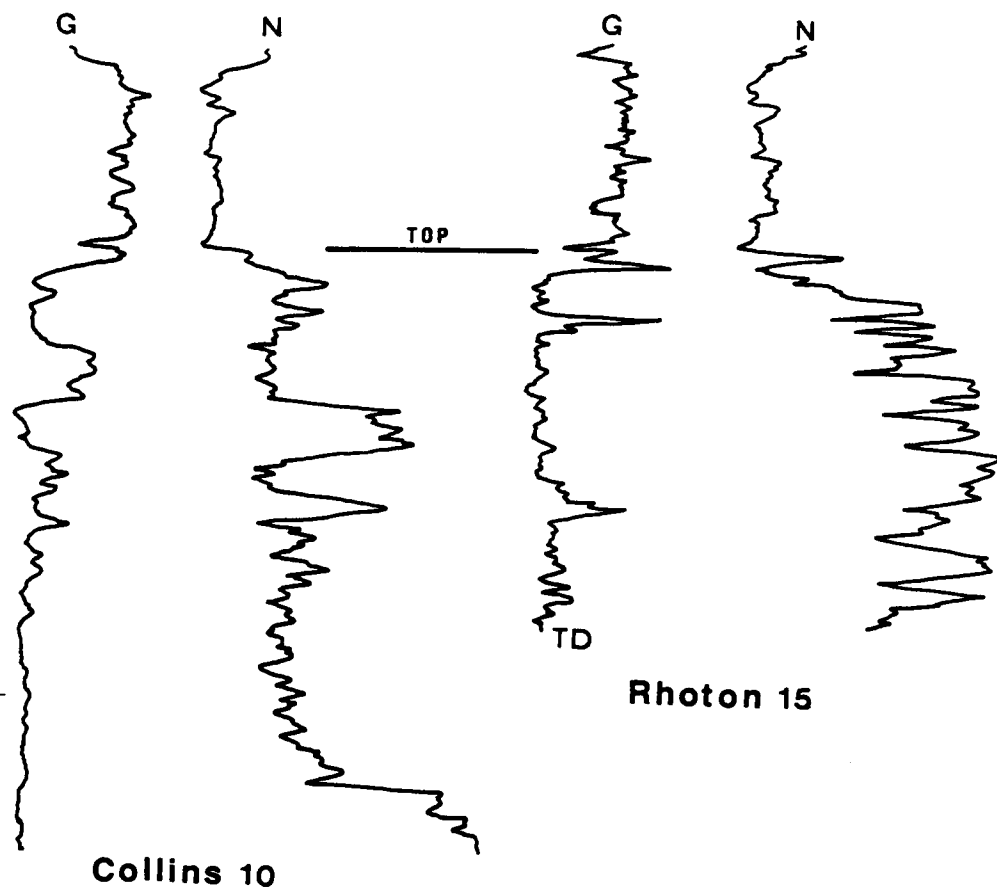


Figure 18. Gamma-ray, neutron log responses showing variations of lithology and porosity of the top Mississippian strata in the study area.

Seismic signature of the sand body.

A seismic model of the interpreted geology was made and compared with the observed seismic section (Figure 19). The model used the reservoir geometry as determined from the cross section prepared earlier, and the velocities were obtained from the psuedosonic logs. The match between the model and the actual seismic section supports the interpretation of the seismic line. The sandstone reservior is prominent in the section. The clear lateral terminations help to identify the extent of the reservoir. As predicted by the model, a strong negative deflection marks the top of the sandstone and is an indicator of the potential for gas saturation. Immediately below this deflection is a strong positive deflection marking the oil-gas contact. Another strong positive deflection marks the transition from sandstone to shale at the base.

There is also indirect seismic evidence for the presence of this sandstone. The Fort Scott Limestone appears structurally higher in the section where the sandstone is present. This draping of the Fort Scott Limestone over the sandstone, as well as a draping of the Verdigris Limestone over the sandstone, is confirmed by structure maps of the study area (Figure 20). The draping is probably due to greater compaction of the

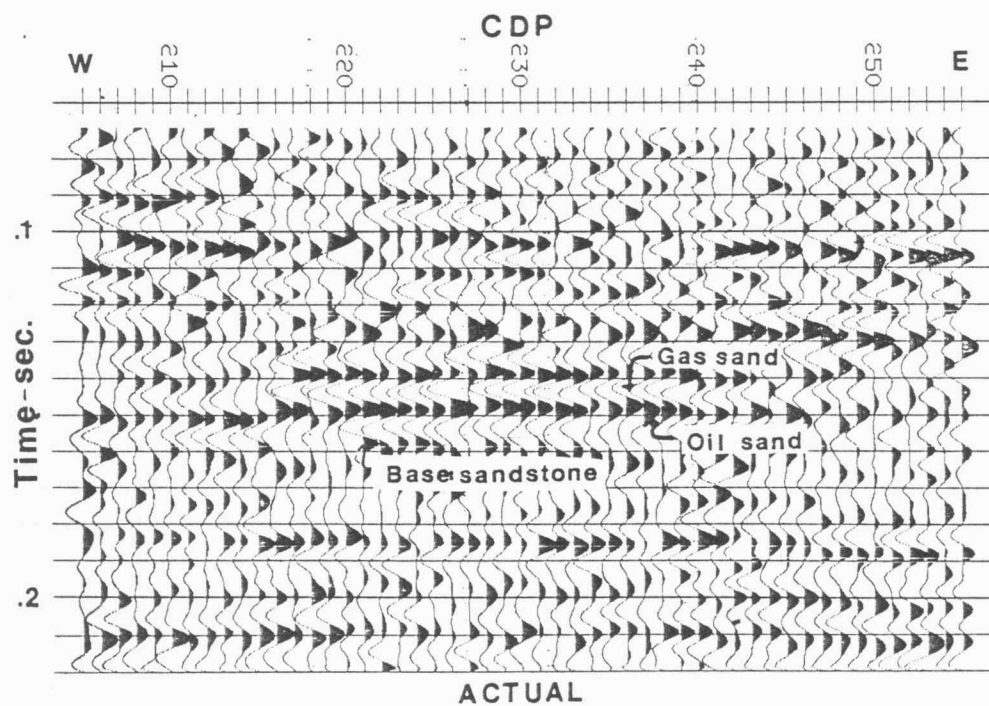
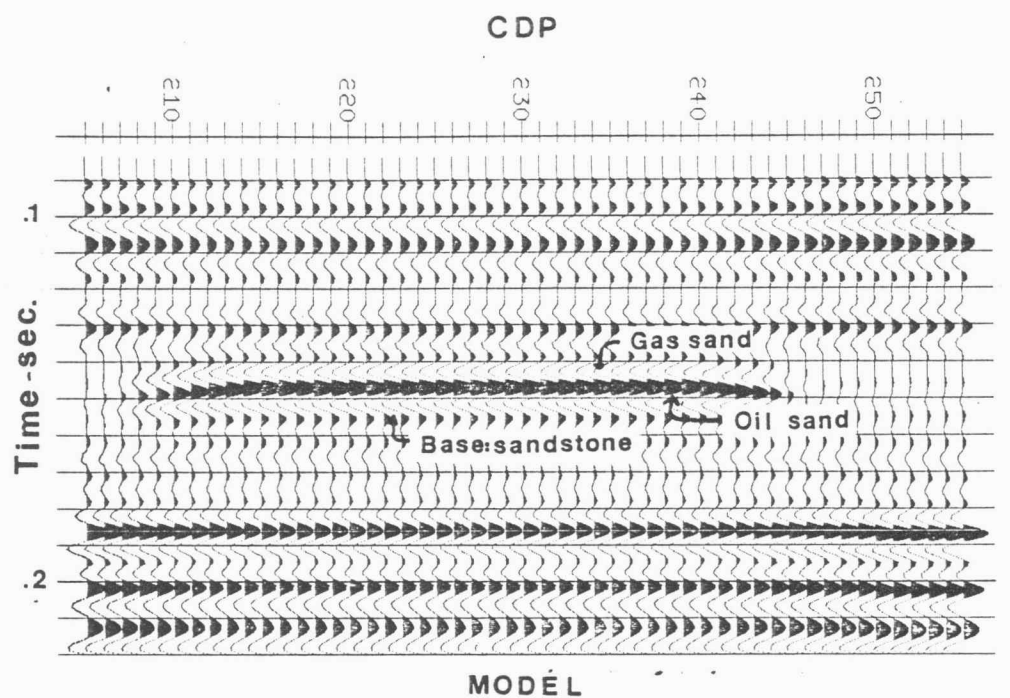


Figure 19. Comparison of the modeled sandstone and the actual seismic line.

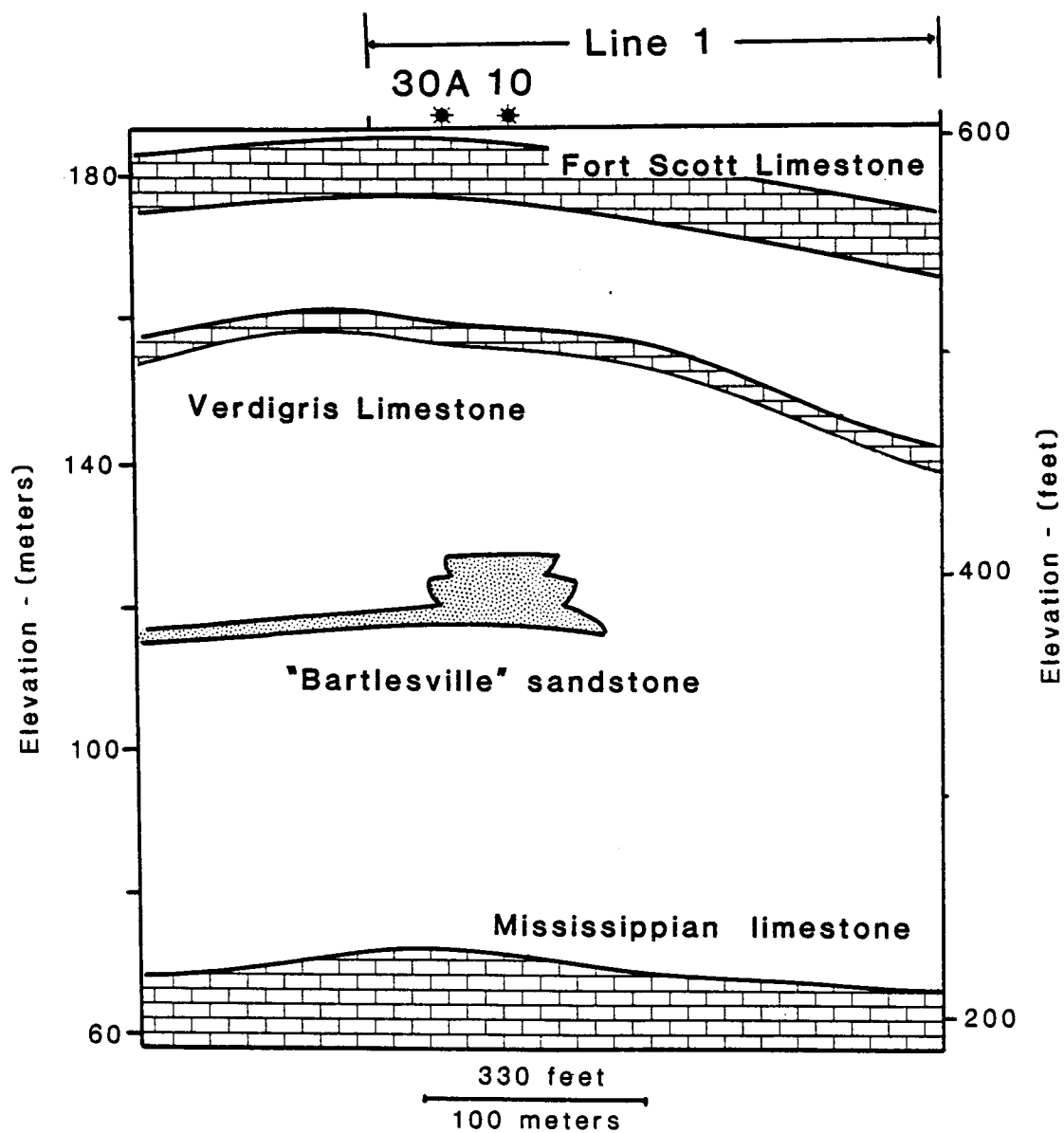


Figure 20. Structural cross section of the study area.

shale surrounding the sandstone. The reflections stratigraphically below the sandstone appear higher in the section beneath the sandstone than do the events to the side of the sandstone. This is due in part to a small velocity pull-up of these layers and in part to the actual structural position of these layers.

Two other events occur within the same stratigraphic interval as the target sandstone. They are located in an area where no wells have been drilled and may indicate the presence of additional sandstones (Figure 21). The character of these reflections is similar to those seen in the preliminary modeling. They are marked by the presence of low amplitude, high frequency, continuous reflections. These sandstones, however, may not be very porous. Economically significant porosity would be marked by an indication of fluid saturation. The absence of significant liquid content is indicated by the lack of pull-up of lower events. Furthermore, the sandstones are probably not saturated with gas, as indicated by the lack of a sharp negative deflection that marks the top of a gas-saturated sandstone. The maximum thickness of these inferred sandstones is about 7 m.

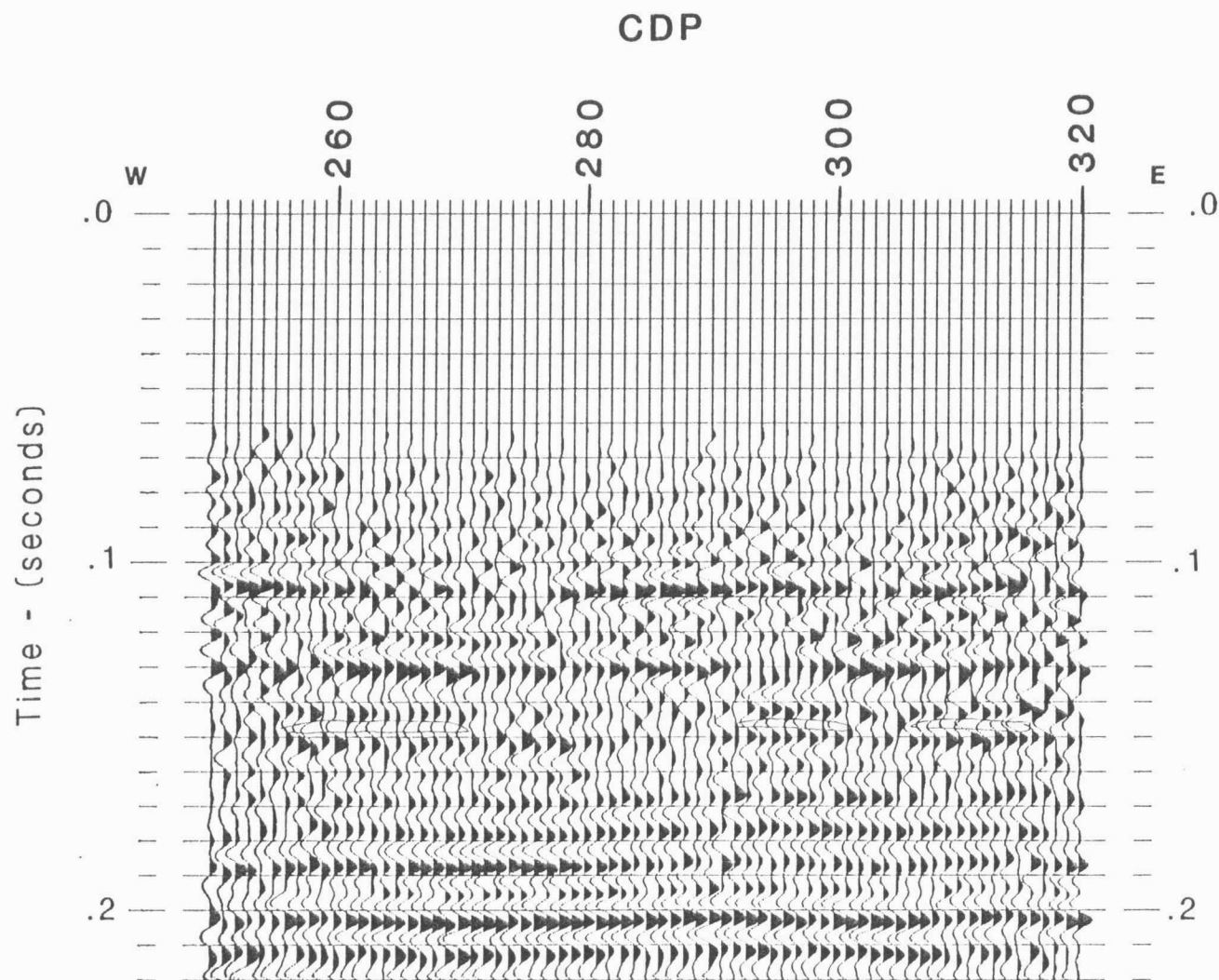


Figure 21. Inferred sandstone bodies.

LINE TWO

Quality of line two is lower than that of line one (Figure 22; Plate 3; Table 3). A slower velocity of ground roll than on line one required deeper muting, effectively muting all coherent reflections from the surface to the Verdigris Limestone. Quality of data is also lowered by an increased amount of air blast associated with problems with the operation of the gun.

Interpretation

Two aids to interpretation of line two are synthetic seismograms (Figure 23) and correlation from line one (Figures 24 and 25). The Mississippian limestones and the top of the Arbuckle Group are the two dominant reflectors in the lower portion of this section. The Lamotte Sandstone occurs at 330 ms, and the top of the Precambrian is at 340 ms. The "Bartlesville" sandstone lies between CDP's 440 and 480 at 140 ms. The Verdigris Limestone (130 ms) appears to be draped over the top of the sandstone, possibly due to differential compaction. A velocity pull-up of the Mississippian limestones is visible below the sandstone. The reservoir is only 9 m thick at this location. It is well defined to the west but becomes increasingly shaly to the east. Because of the thickness, change in lithology of the sandstone, and the low quality of data,

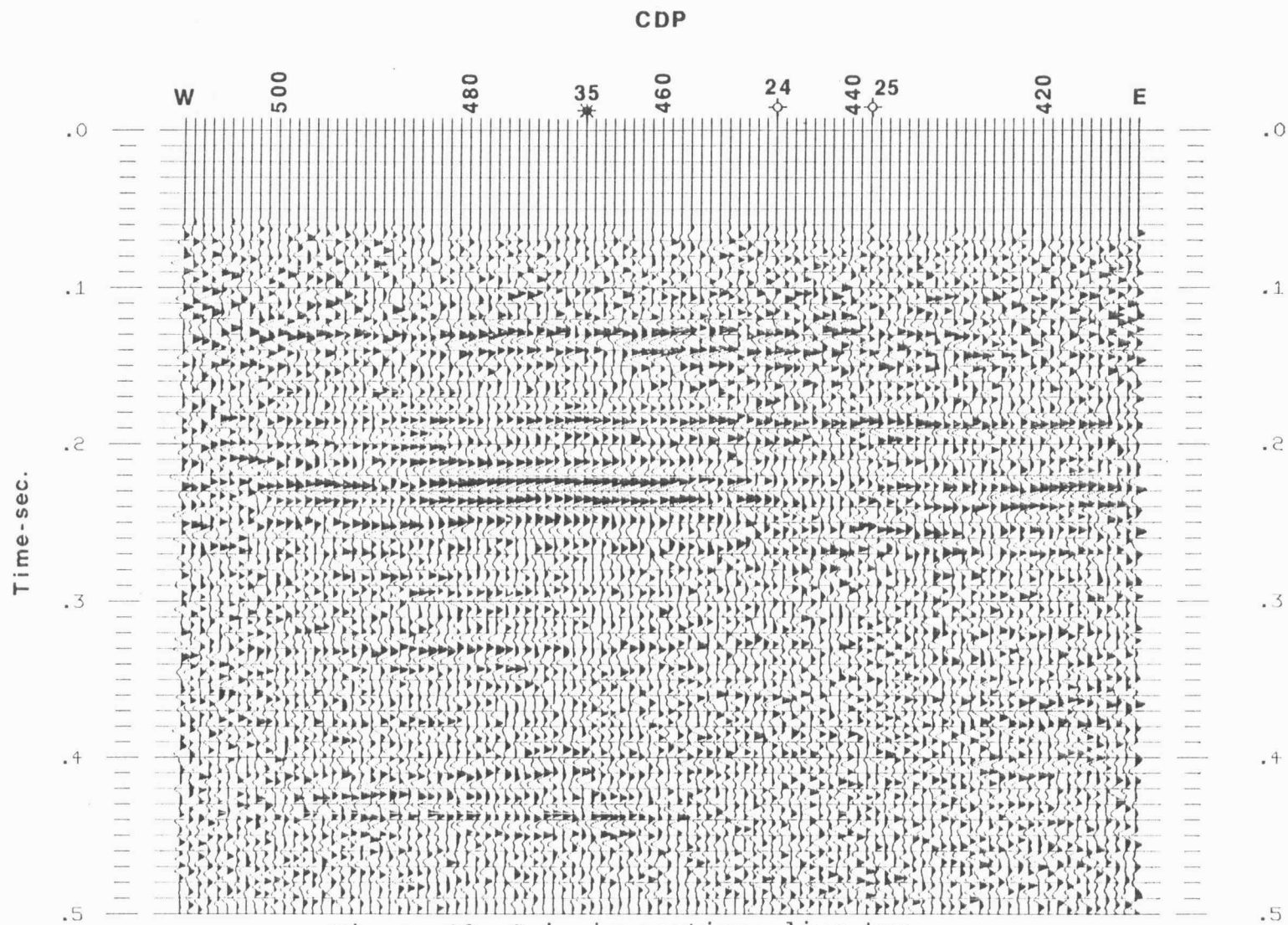


Figure 22. Seismic section: line two.

Table 3. Processing Sequence for line two.

SHOTS: two and three

MUTE: first arrivals and ground roll

EDIT

SORT

STATICS: elevation and weathering

DECONVOLUTION: spiking
40 ms operator
3% prewhitening
Hamming smoothing

AUTOMATIC STATICS: 200 ms center
60 ms window

SCALE: 150 ms rms

RESIDUAL STATICS: 230 ms center
400 ms window

FILTER: 50-120 hz bandpass

STACK

PLOT

POLARITY: normal

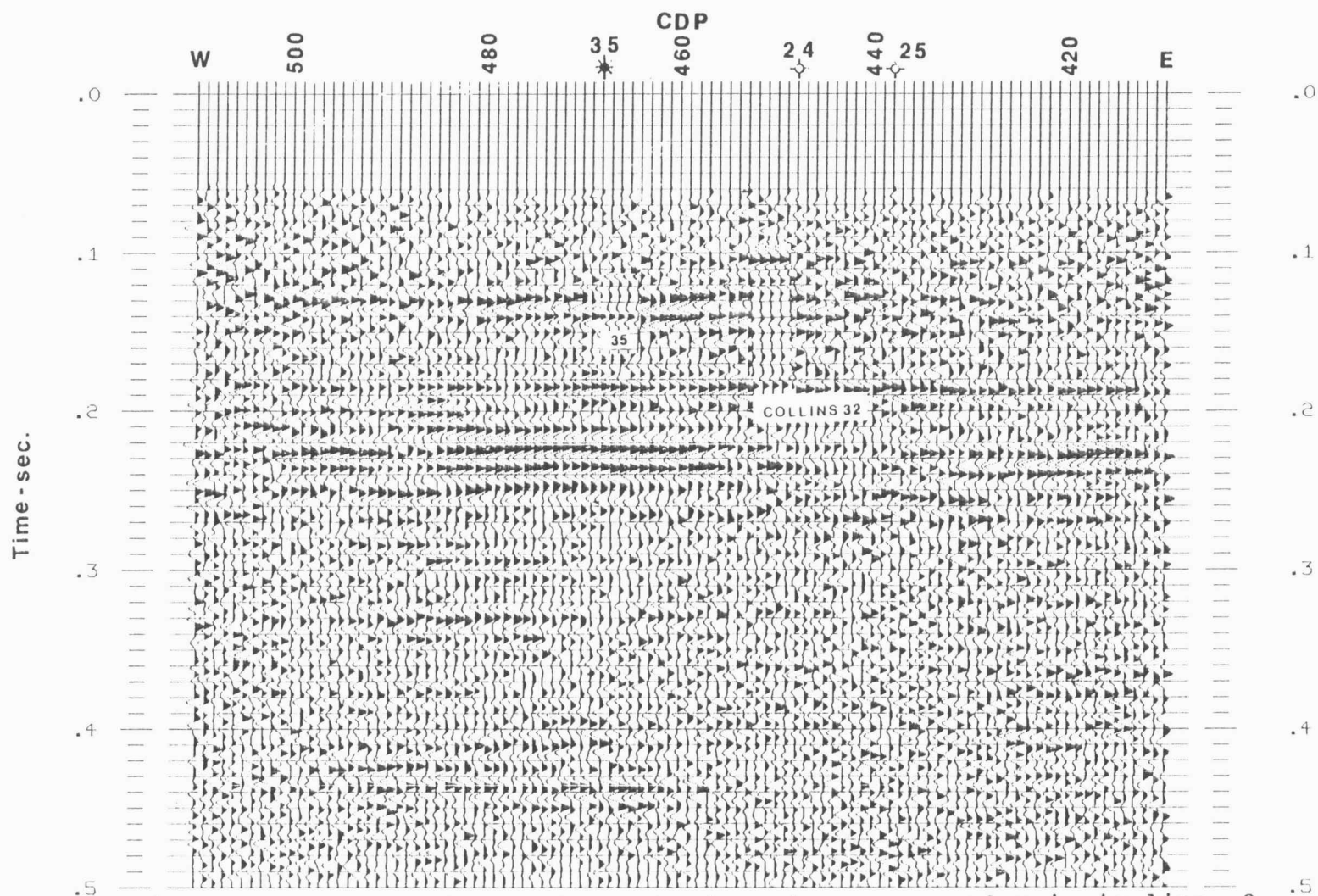


Figure 23. Comparison of synthetic seismograms and seismic line 2. Synthetic seismograms are overlain on the seismic section.

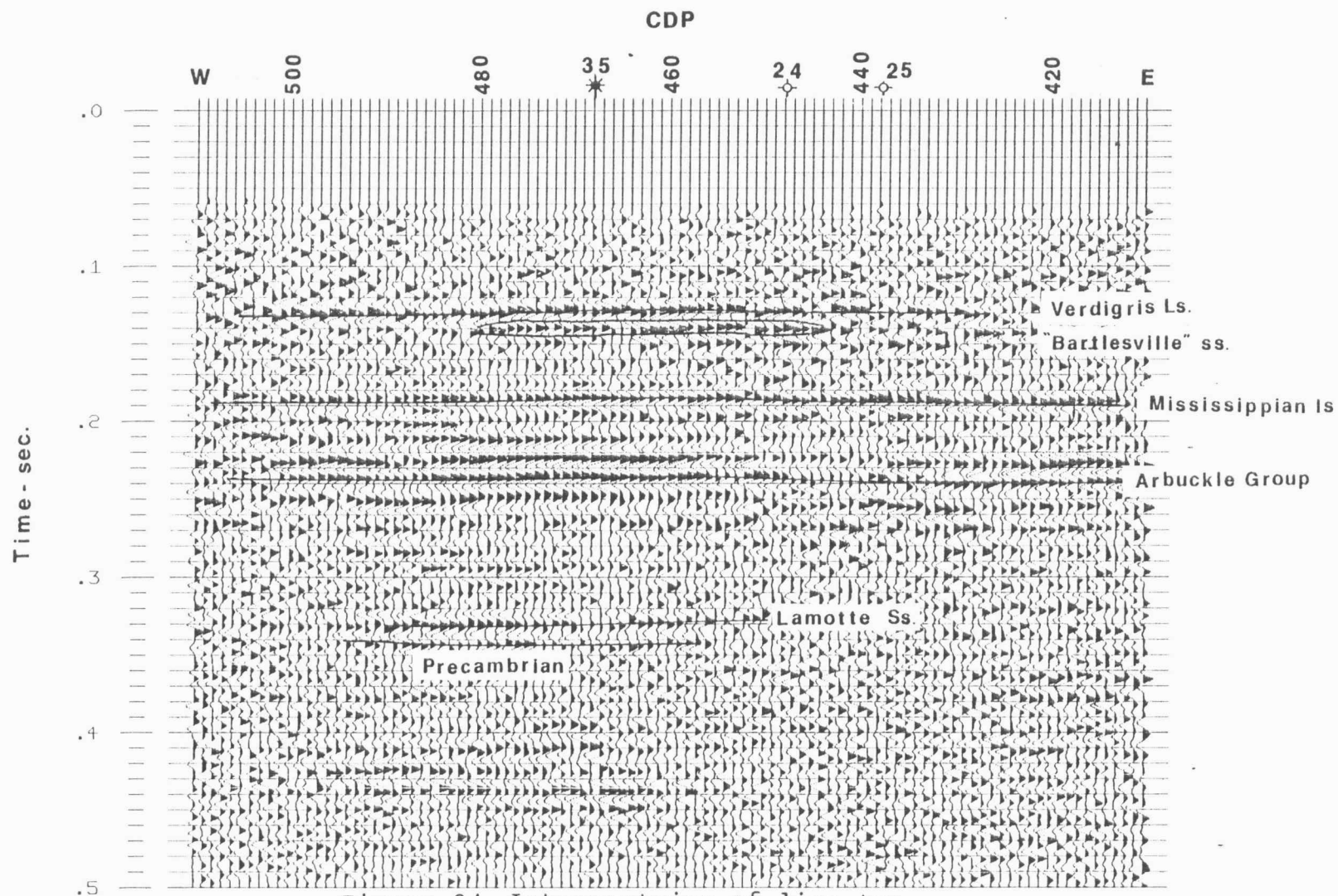


Figure 24. Interpretation of line two.

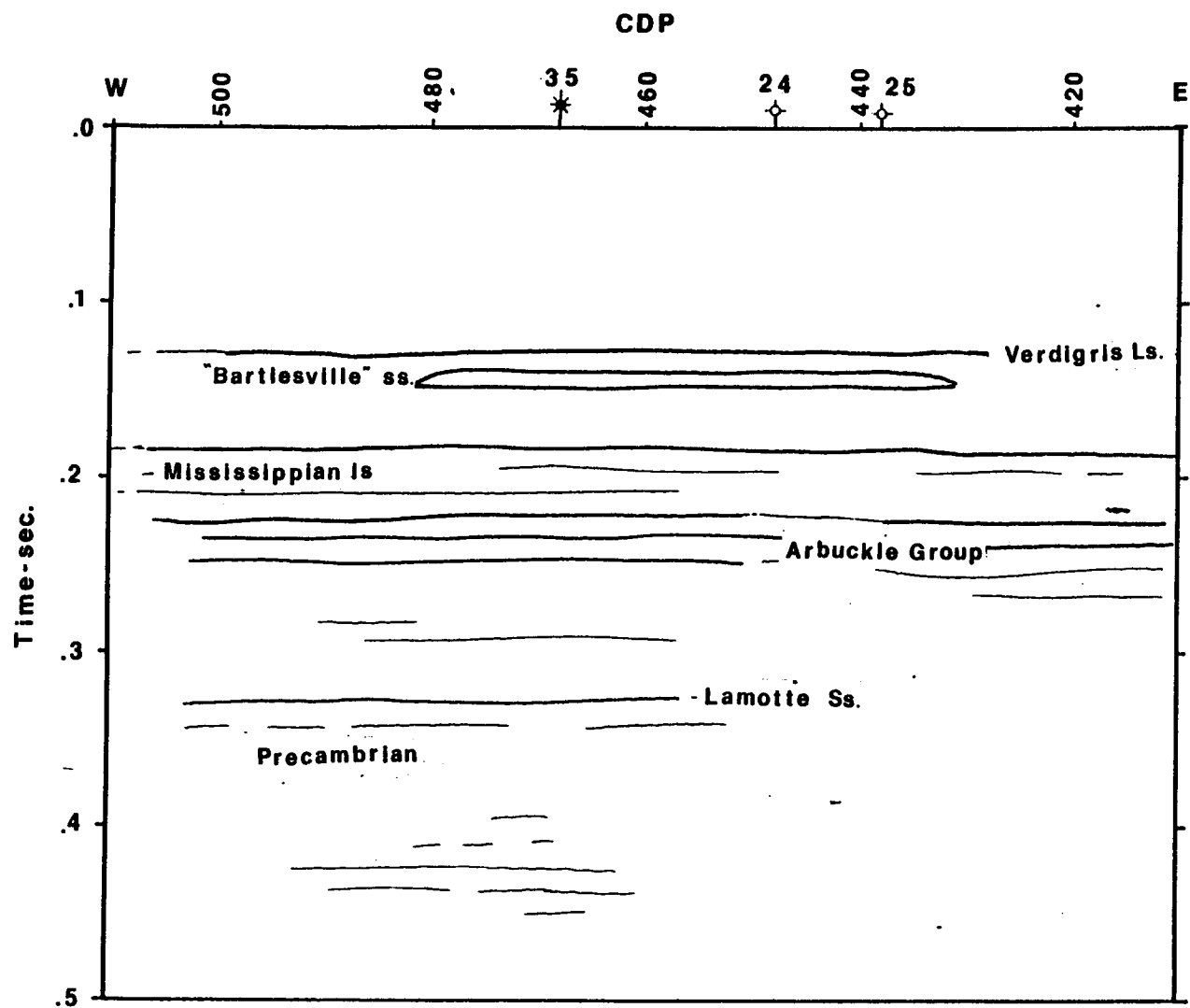


Figure 25. Line drawing interpretation of line 2.

the sandstone is at the limit of resolution.

A comparison of the modeled sandstone to that observed in the seismic section reveals some difference (Figure 26). The seismic section shows a very strong reflection at the top of the sandstone, which is absent in the model. This lack of a strong reflection may be because the upper portion of the reservoir is less porous and of higher velocity than that modeled. The lack of a significant reflection from the sandstone is due to a decrease in quality of data and the inability of the seismic method to resolve clearly the individual components of the reservoir. This inability stems from the thickness of the sandstone and the change in lithology from a sandstone to a sandy shale.

COLOR SEISMIC SECTIONS

Color seismic sections aid geological interpretation. Sections can be displayed with different colors representing a range of amplitudes or phase characteristics. Amplitude displays are useful for identifying deflections of large magnitude (Taner and Sheriff, 1976). The phase display emphasizes continuity of events. Weak reflectors, if continuous, are enhanced in a phase display.

The target sandstone in line one is easily visible on the amplitude display (Figure 27), as are the other

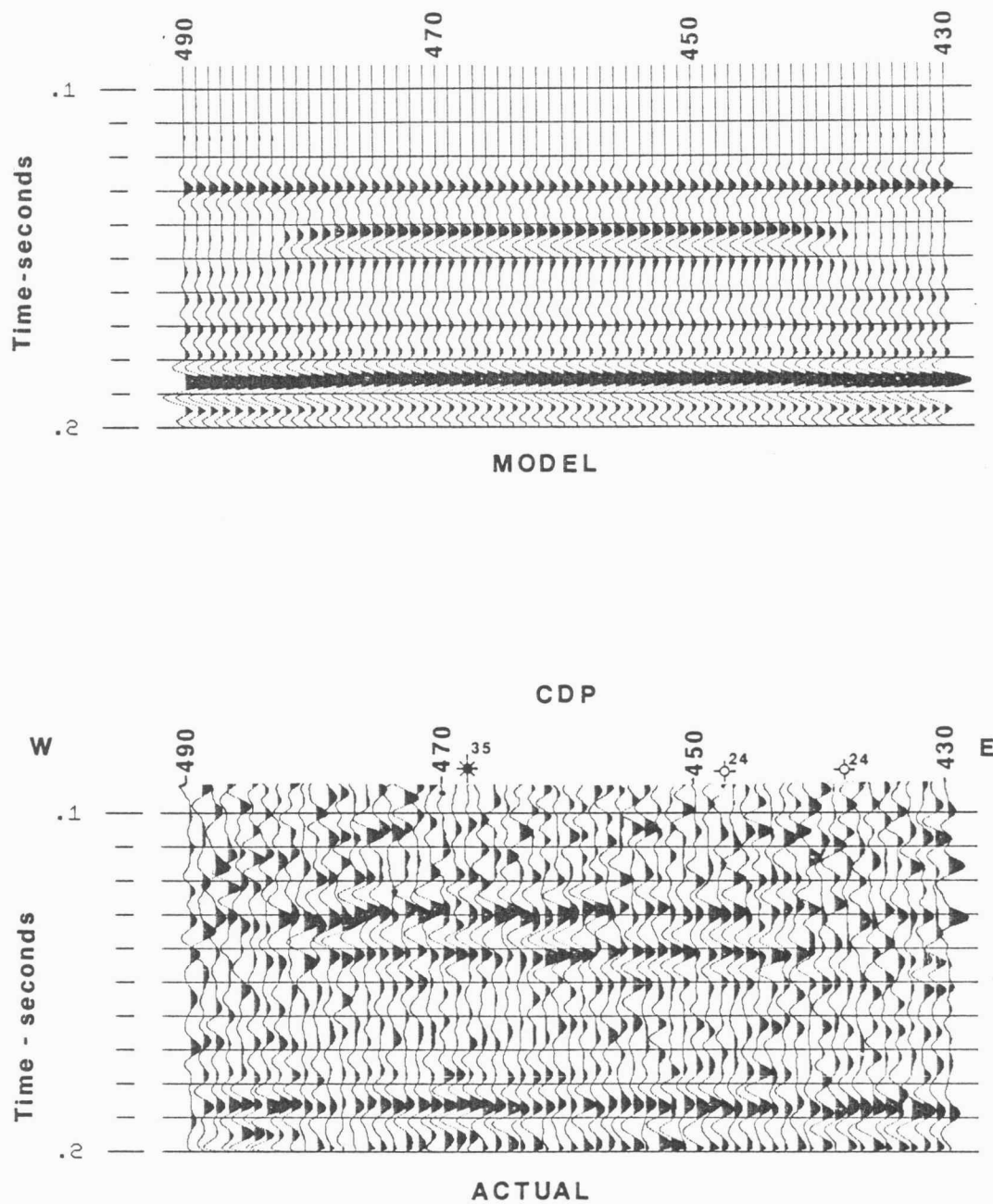


Figure 26. Comparison of the modeled sandstone to the actual seismic section.

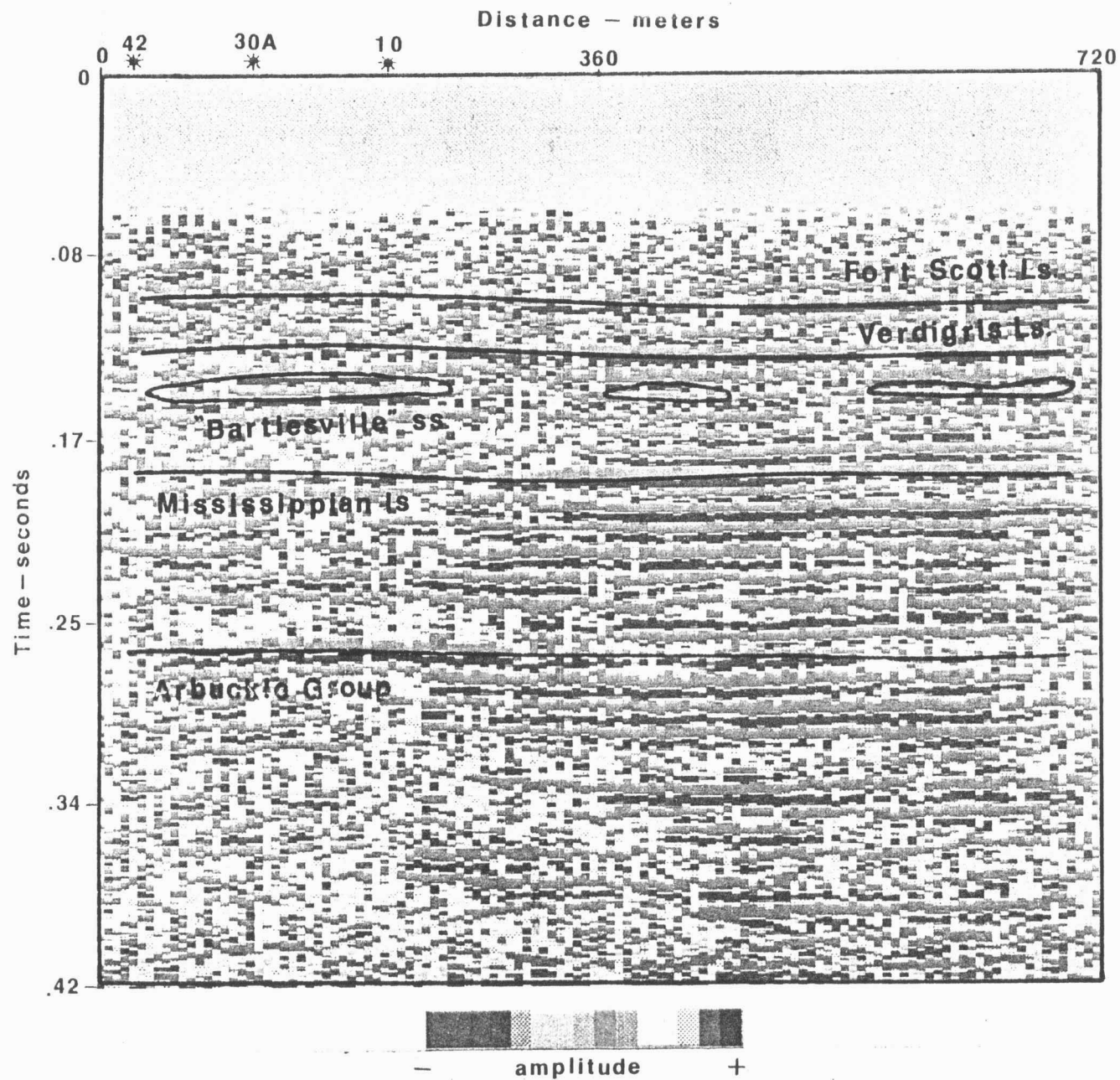


Figure 27. Amplitude display of line 1.

inferred sandstone bodies. The phase display yields little new information for this line, although it does reveal that the Verdigris Limestone is continuous over the sandstone, whereas this is not apparent on the black-and-white display (Figure 28). The continuity of the events corresponding with the Mississippian Limestones is also enhanced.

In line two, color sections show clearly the overlying Verdigris Limestone and to some extent aid the identification of the primary reservoir (Figure 29). The drop of seismic coverage at the end of the seismic line is obvious. The phase display seems to indicate that the reservoir may be continuous to the west end of the line (Figure 30). This may be an extension of the basal sandstone to the west.

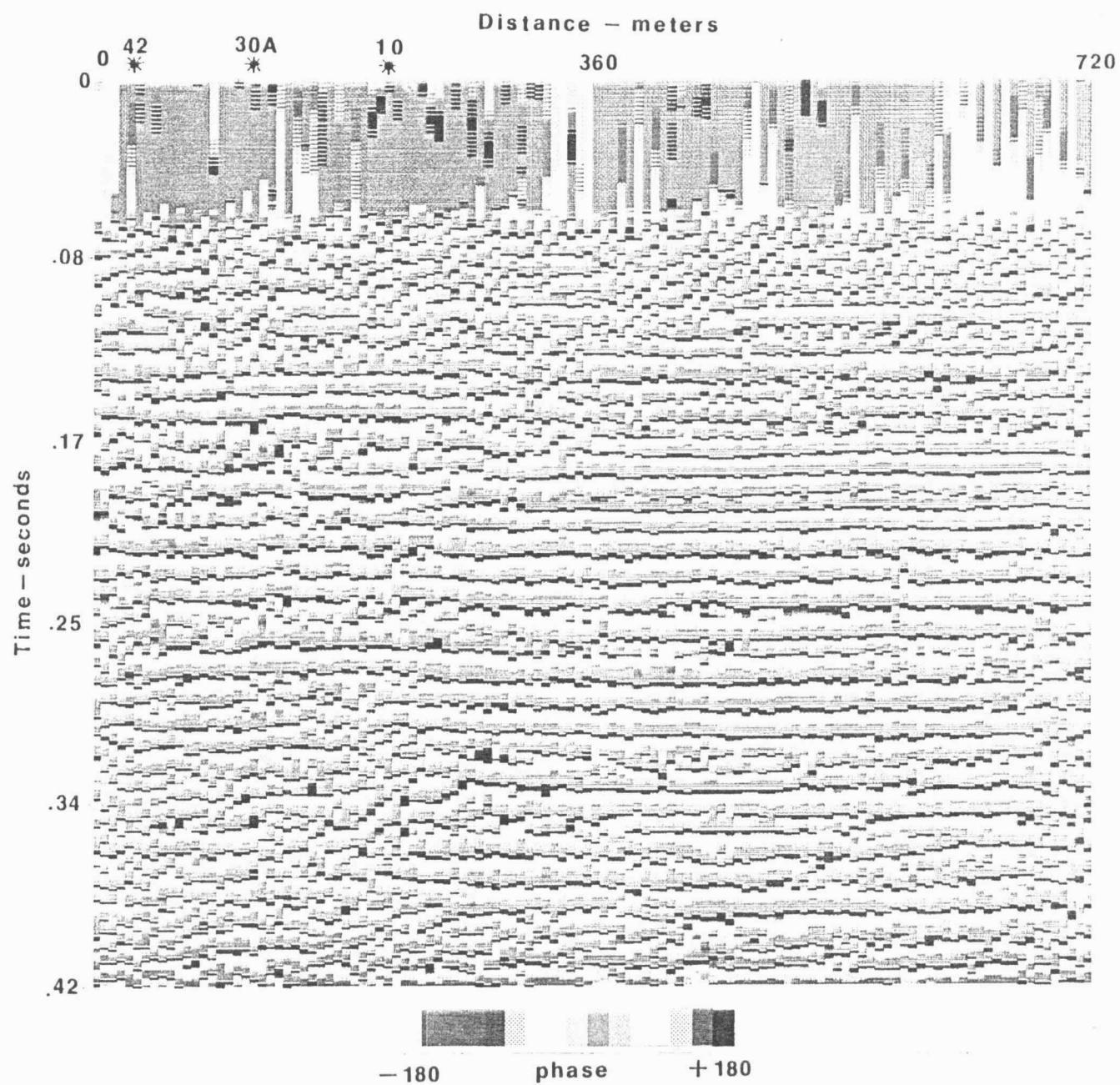


Figure 28. Phase display of line 1.

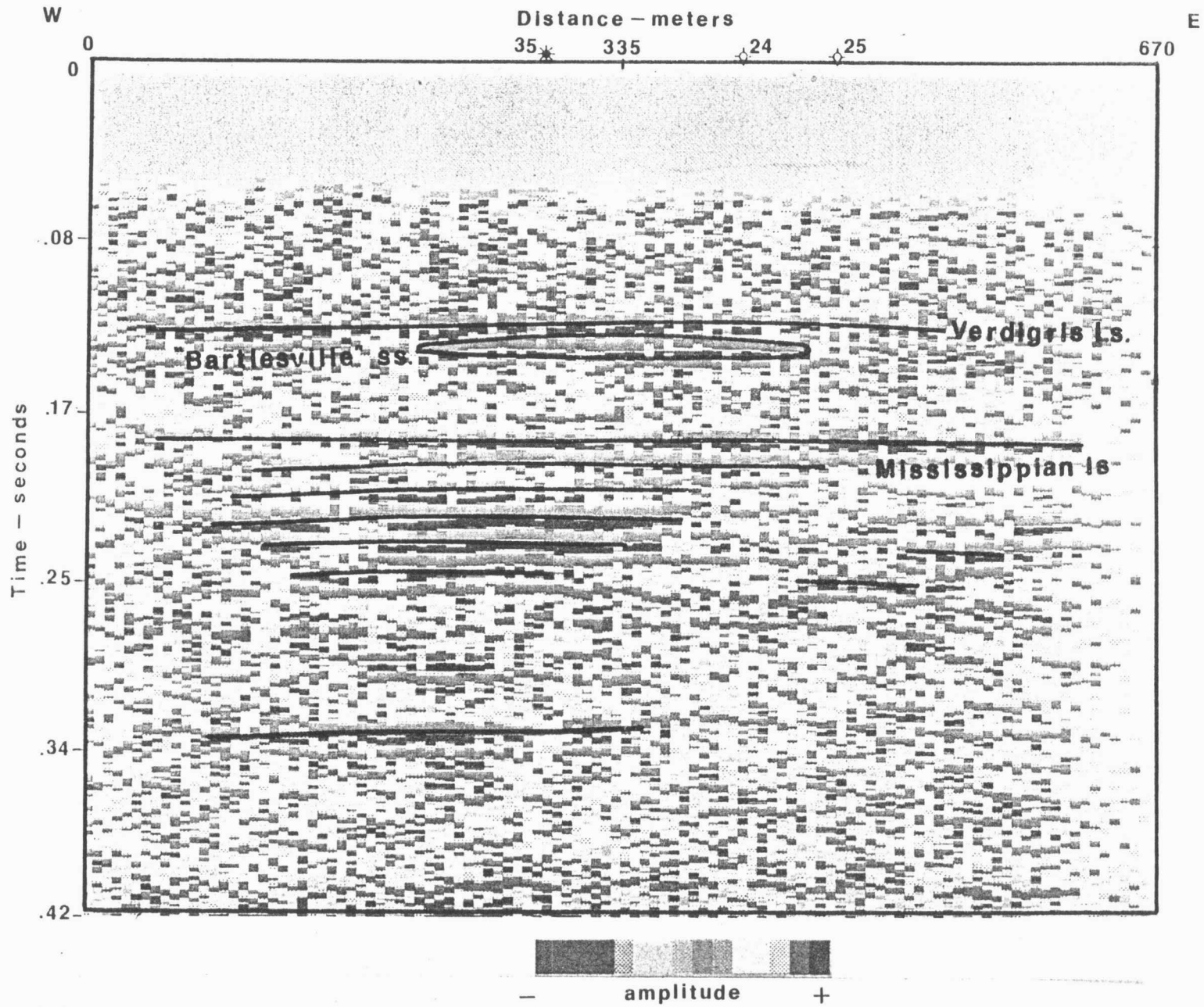


Figure 29. Amplitude display of line 2.

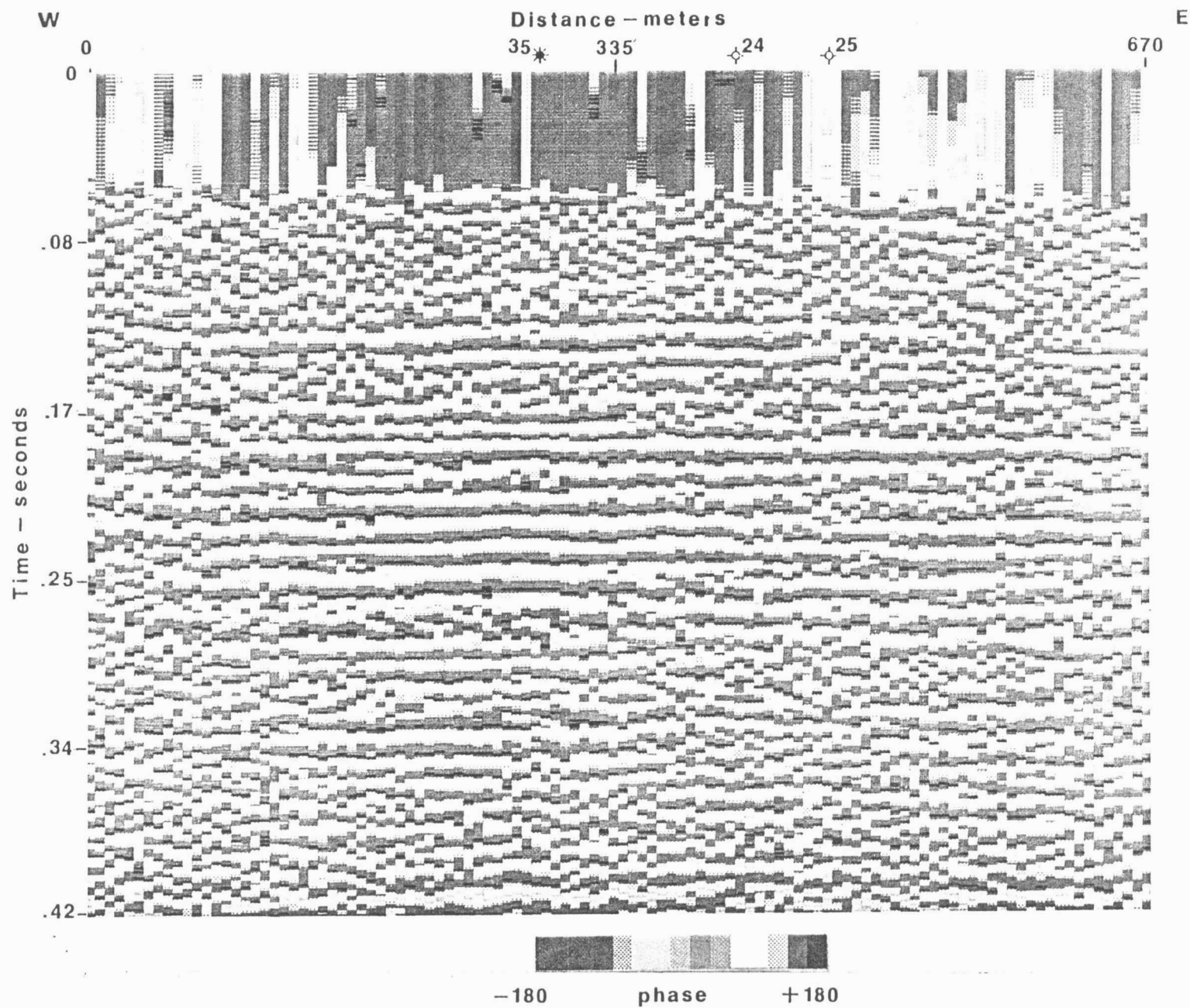


Figure 30. Phase display of line 2.

FREQUENCY CONTENT

As stated previously, high frequencies are essential for both vertical and horizontal resolution. High frequencies attenuate with depth; thus a source must be powerful enough to produce high-amplitude, high-frequency energy that resists deterioration with depth. One method to measure the success of a source is to measure the frequency content of the signal versus time within the earth.

The frequency content of the data ranges from 40 to 170 hz (Figure 31A). Maximum amplitudes occur from 50 to 130 hz with a dominant frequency of about 100 hz. The frequencies are retained with depth with a significant frequency component of 75 to 170 hz at a time of 500 ms (Figures 31B, 32, 33). The presence of high frequencies at this time indicates that the fifty-caliber machine gun is powerful enough to produce high-frequency, high-resolution seismic data even at depth.

An estimation of the minimum resolvable thickness of bed at a certain time on a seismic section can be made by estimating rock velocities at that time and analyzing the frequency content. From 400 to 500 ms (a depth of approximately 550 to 650 m) the dominant frequency is approximately 85 hz. For a gas-saturated sandstone with a seismic velocity of 2200 ms, the

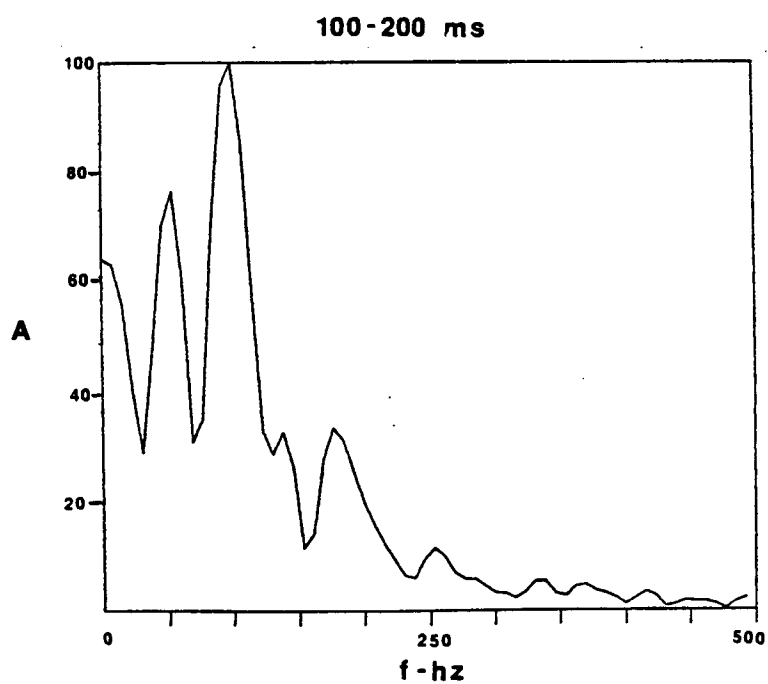
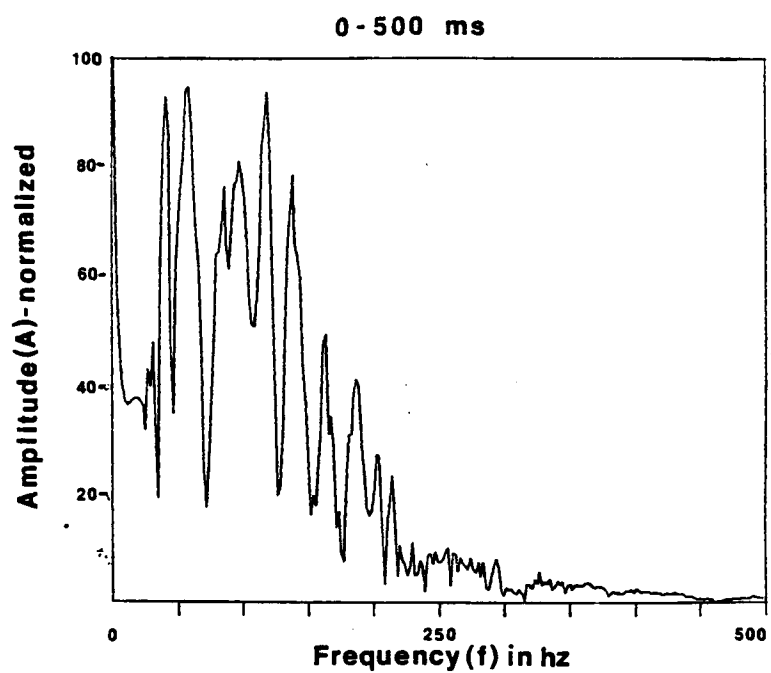


Figure 31. Amplitude spectrum of a single trace from:
A: 0 to 500 ms.
B: 0 to 100 ms.

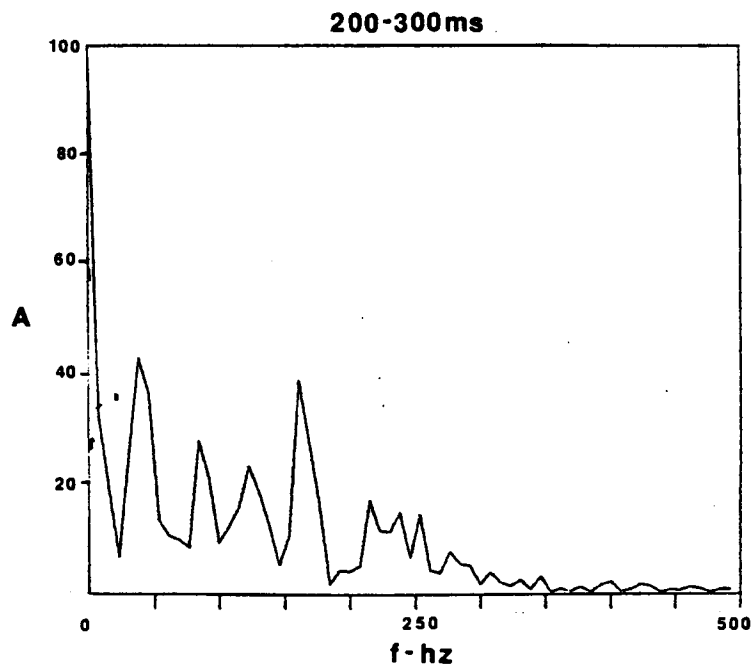
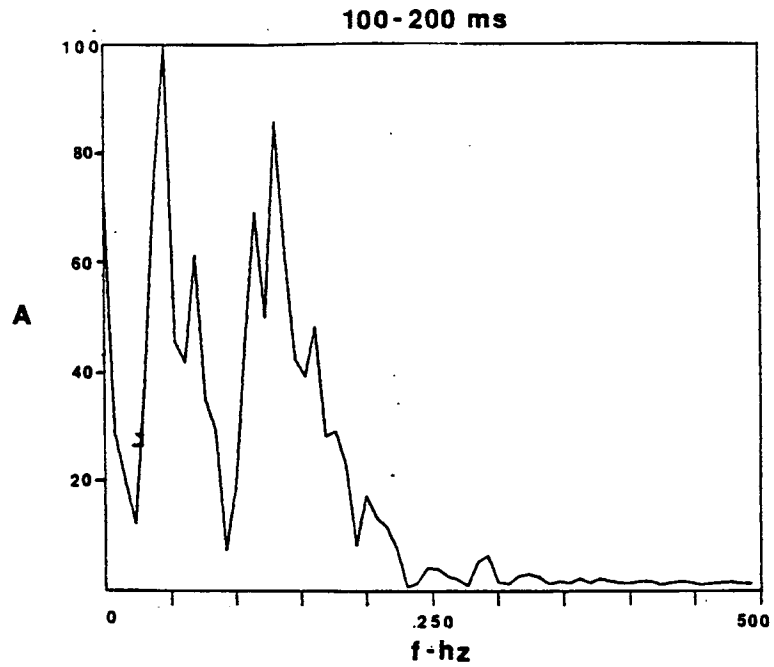


Figure 32. Amplitude spectrum from:
Top: 100 to 200 ms.
Bottom: 200 to 300 ms.

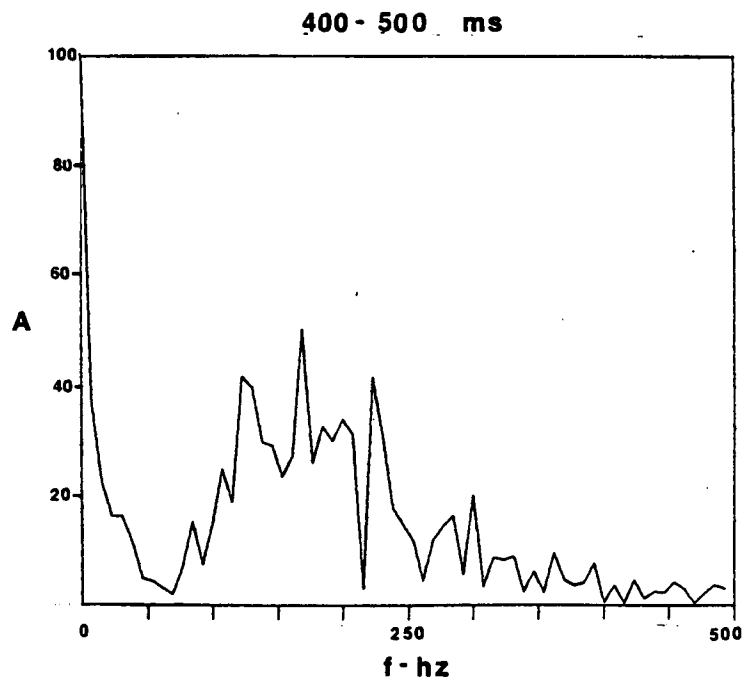
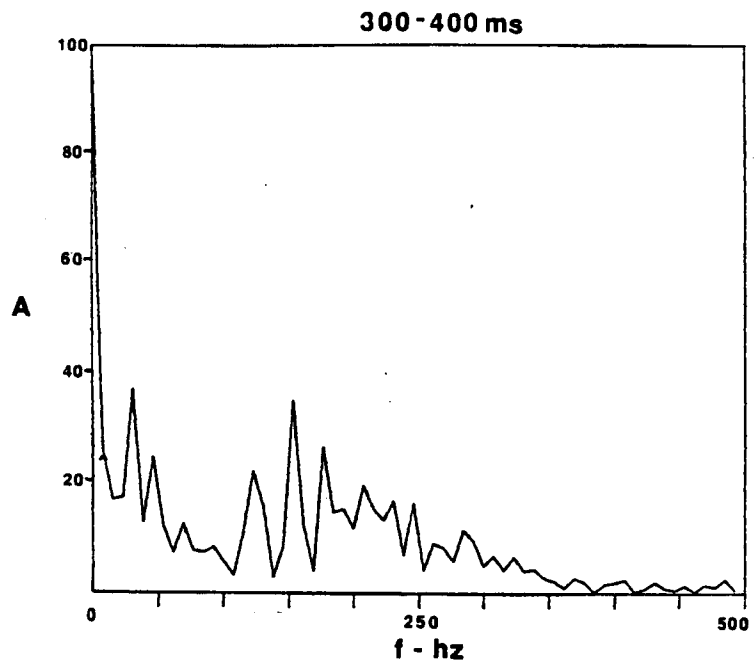


Figure 33. Amplitude spectrum from:
Top: 300 to 400 ms.
Bottom: 400 to 500 ms.

minimum detectable thickness is 5.2 m. For an oil saturated reservoir of seismic velocity of 4800 m/s, the thinnest detectable sandstone body is 14 m. The weaker signal, and lower signal to noise ratio with depth, may detrimentally affect these estimates. Overall, the data and analysis presented here suggest that shoestring-type sandstones might be successfully mapped in eastern Kansas to depths of 550 meters or more.

EVALUATION OF SURVEY PARAMETERS

After evaluation of the effectiveness of the source and frequency content, the next step is to evaluate the survey parameters. Preliminary experiments suggested that a second shot provided data of higher quality than a single shot. Stacked sections indicate that the data from the second and the third shots are of higher quality (Figure 34). The reflection from the sandstone (140 ms) is much clearer on the stacked sections from shots two and three, respectively, as is the event at 270 ms. Furthermore, data from the individual shots can be summed (Figures 35-37), changing the fold from 12 to pseudo-36. This increase in coverage results in a minor increase in the quality of data.

Minimum coverage has an important effect upon the quality. It appears empirically that 12-fold data is

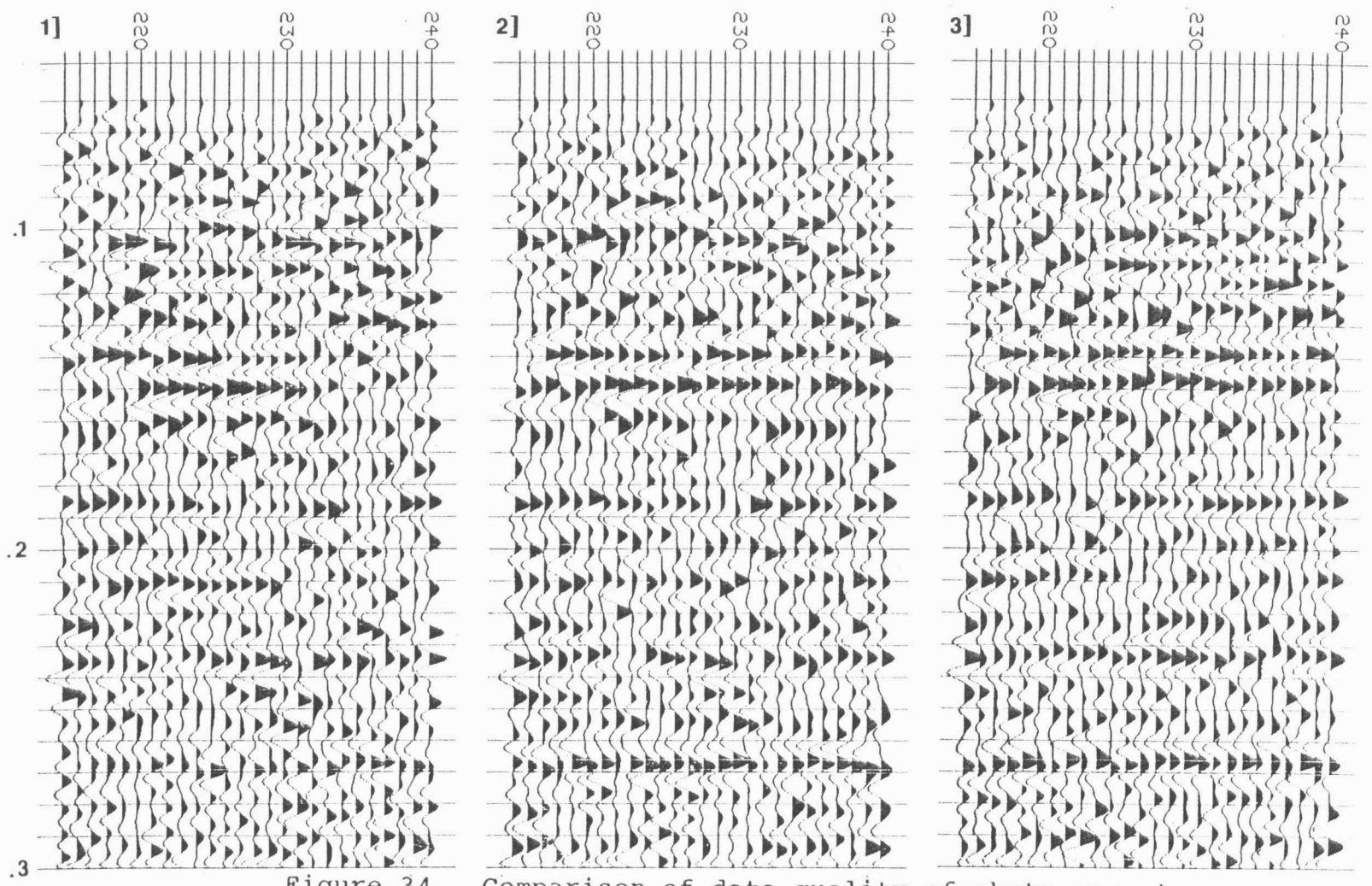


Figure 34.
and three.

Comparison of data quality of shots one, two

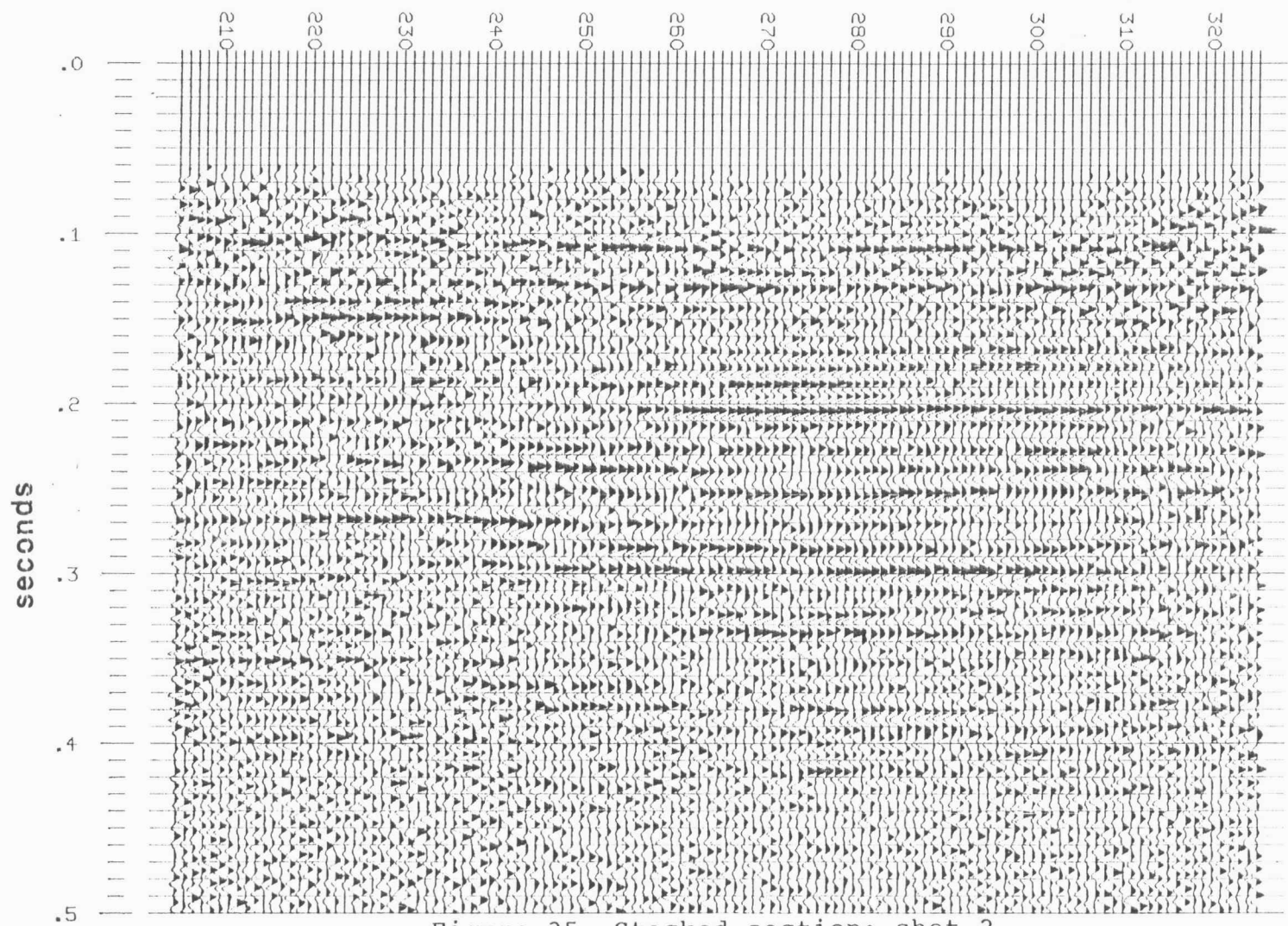


Figure 35. Stacked section: shot 2.

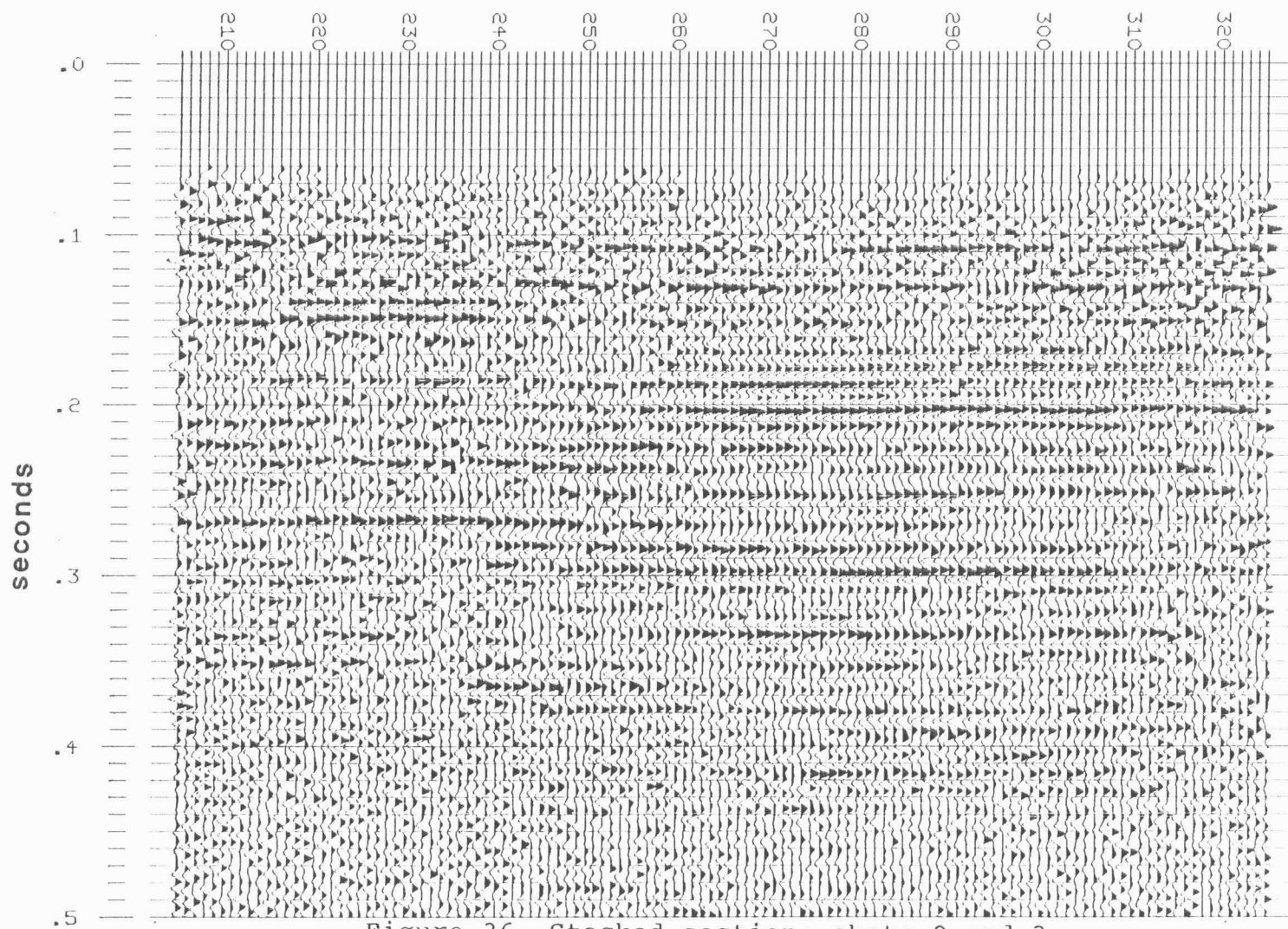


Figure 36. Stacked section: shots 2 and 3.

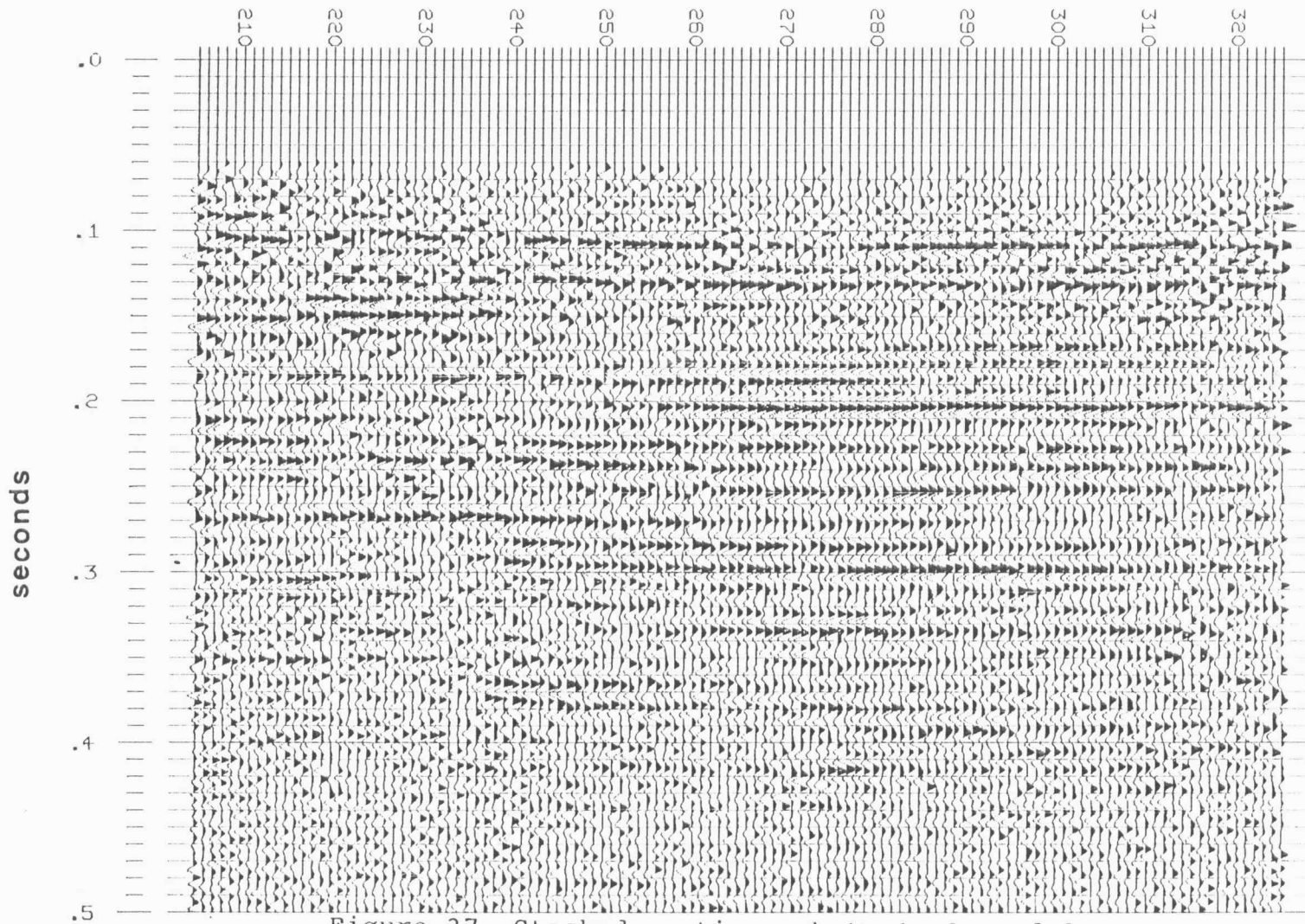


Figure 37. Stacked section: shots 1, 2, and 3.

the minimum for acceptable quality of data. This was demonstrated by an obvious drop in data quality associated with the decrease in seismic coverage at the edges of lines one and two. Thus this study indicates that the source requires at least two shots per shot point and should be at least 12 fold.

As Precambrian basement occurs at a depth of only 600 m, effective depth of penetration by the fifty caliber machine gun cannot be determined by this study. The strength of basement reflections in line one and the continued high frequency content of the data at 500 ms. implies that this source will be effective as a high frequency source to depths greater than those of interest in the study area.

CONCLUSIONS

The fifty-caliber machine gun appears to be good seismic source for the exploration of shallow sandstone reservoirs in southeastern Kansas. Identification and mapping of the sandstone reservoir under line one is easily accomplished. Indirect evidence of the presence of a sandstone, in the form of draping of overlying units and velocity pull-up of the underlying layers is easily seen. Not only was the target sandstone resolved, but two additional sandstones were inferred where well control was lacking. Although the lower quality of data due to problems with the seismic survey yielded diminished results for line two, there is still evidence of the sandstone. Modeling indicates that with optimum survey conditions the minimum detectable thickness for an oil-saturated sandstone is about four m, while the minimum detectable thickness for an oil-saturated sandstone with a gas cap is approximately eight m.

The frequency content of the seismic data using of the fifty-caliber machine gun ranges from 30 hz to 170 hz with a dominant frequency of about 100 hz. The higher frequencies are preserved to the end of the seismic record.

The fifty-caliber machine gun appears to be an economical seismic source. Cost per round of ammunition is about \$1.00 (Steeple, pers. comm.). High-quality data can be acquired with a minimum coverage of 12 fold. Two shots per shot point appear to be the minimum number for data collection, while three or more do not appear to improve significantly the data. Environmentally, the source is acceptable, producing little or no damage to the surrounding landscape when used in a rural setting.

Thus it appears that the fifty-caliber machine gun provides a solution to some of the exploration problems associated with small sandstone bodies. The study also indicates that the fifty-caliber machine gun may also be the answer to many other problems of reflection seismology requiring high-resolution seismic data.

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