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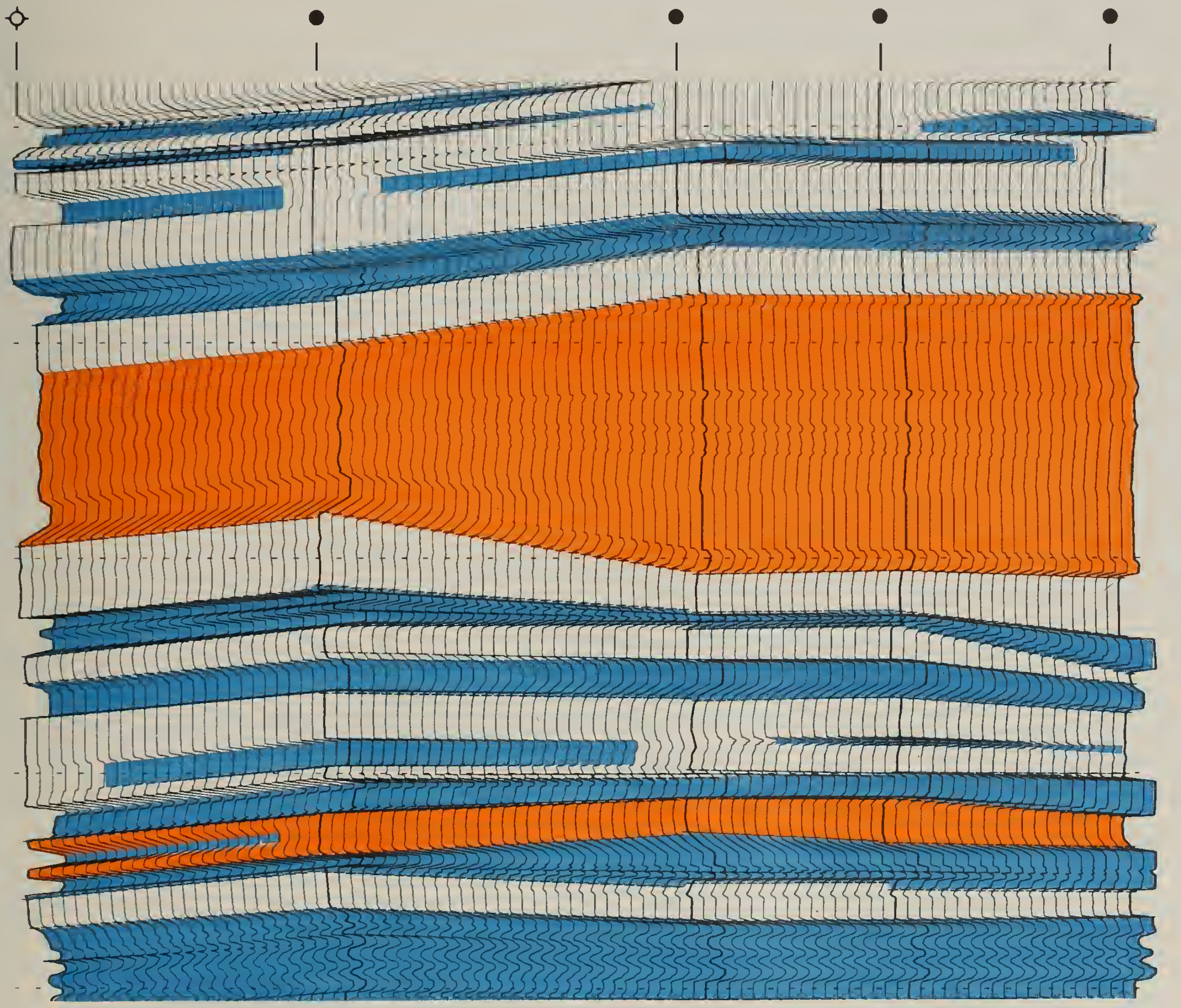
Seismic Stratigraphy, a Technique for Improved Oil Recovery Planning at King Field, Jefferson County, Illinois

Hannes E. Leetaru



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Department of Natural Resources

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ABSTRACT

High-resolution seismic reflection data have been used to delineate reservoir and nonreservoir facies and to provide a means to improve oil recovery in mature fields. Detailed reservoir characterization of the Mississippian-age Aux Vases Formation at King Field, Jefferson County, Illinois, suggests that this reservoir is a compartmentalized, mixed siliciclastic-carbonate system. The Aux Vases reservoir sandstone at King Field occurs at a depth of 2,750 feet, is rarely greater than 20 feet thick, and is considered to be a seismically thin bed because its thickness is below the calculated seismic-tuning thickness of 60 feet.

Old electric wireline logs, the principal data available for King Field, were used to create pseudo-velocity logs, which were subsequently used to create synthetic seismogram models of the facies changes. Comparison of synthetic seismograms with seismic data acquired from King Field indicates that amplitude variations of seismic reflectors can differentiate reservoir sandstone facies from laterally adjacent nonreservoir calcareous lithofacies.

Seismic reflection character analysis was successfully applied to King Field for the high-velocity, nonreservoir, calcareous facies that laterally separates lower velocity reservoir sandstones into compartments. This type of seismic stratigraphic analysis offers a cost-effective technique for optimizing the placement of injector and producing wells in a secondary or tertiary recovery program. In newer fields, seismic reflection data would be useful for planning the development drilling program. Although this study dealt with a mixed siliciclastic-carbonate depositional system, seismic stratigraphy could be used in other formations in the Illinois Basin where there is a distinct contrast in seismic impedance between reservoir and nonreservoir facies.

INTRODUCTION

In the past, most seismic analysis has concentrated on exploration for new fields (Johnston 1992), with a strong emphasis on structural mapping. This paper shows how high-resolution, two-dimensional seismic data can be used to improve oil-field management by delineating reservoir compartments in a heterogeneous discontinuous sandstone. Analysis of high-resolution seismic data provides a method to optimize the location of both injection and producing wells in secondary or tertiary oil recovery programs.

Sheriff (1989) subdivided seismic stratigraphy into three major components: (1) seismic sequence analysis, which is the analysis of seismic sequences associated with depositional systems; (2) seismic facies analysis, which is the analysis and prediction of the depositional environment; and (3) reflection character analysis, which emphasizes the trace-to-trace waveform variation caused by changes in stratigraphy.

Seismic reflection character analysis has been effectively used in many areas of the world for predicting lithofacies (Mathisen and Budny 1990, Halverson 1988). In mature oil fields, such as those commonly found in Illinois, seismic reflection character analysis provides an effective technique for evaluating reservoir heterogeneity and improving oil recovery. This method is becoming more effective because of improvements in acquisition and processing of seismic data (Hardage 1992). Although seismic character analysis has not commonly been used for the study of Illinois reservoirs, it is being used more frequently in conjunction with the availability

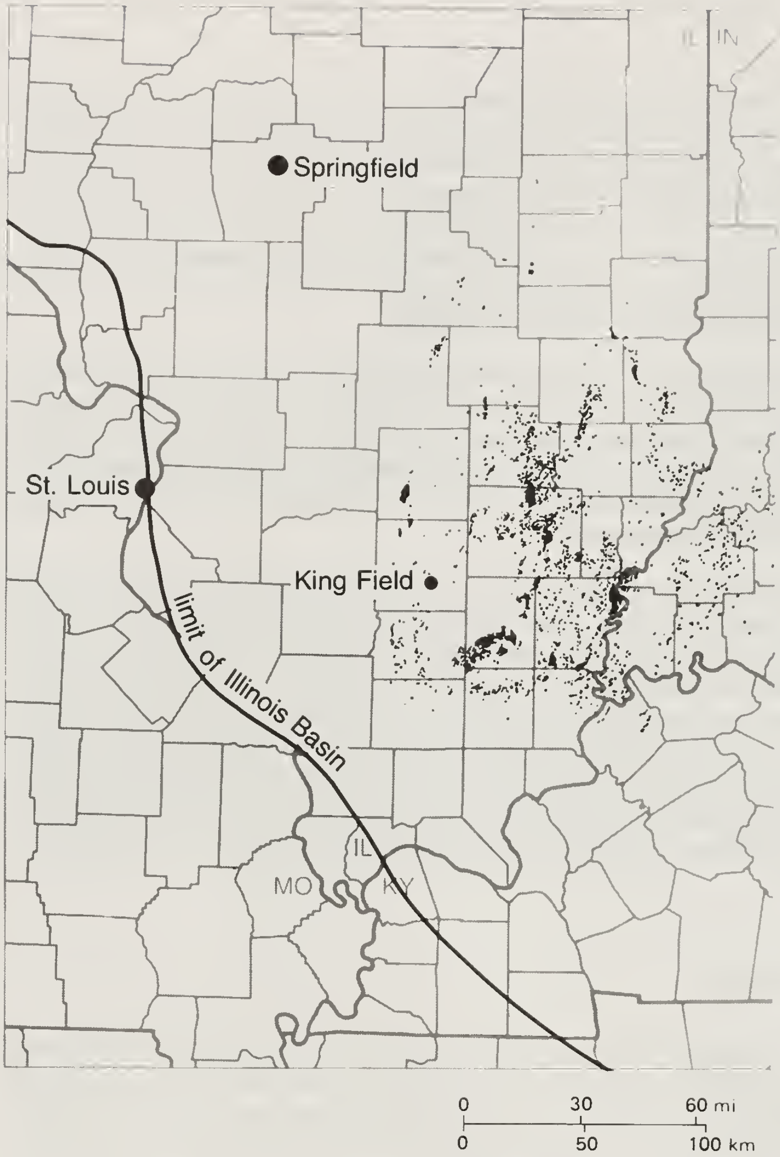

Figure 1 Regional map of Aux Vases producing fields in the Illinois Basin indicating the location of King Field (after Howard 1990).

of higher quality modern two-dimensional and three-dimensional seismic data (Phillip Caserotti, independent consultant, personal communication, 1994). This report uses two-dimensional data. The methods can also be used, however, with three-dimensional data.

For this study, high-resolution seismic reflection data were collected for four lines with a combined length of 10 miles at King Field in southeastern Jefferson County, Illinois. Located 75 miles east-southeast of St. Louis, the field is near the western limit of production from the Aux Vases Formation (Mississippian) (fig. 1). The production in this field is primarily from the Aux Vases Formation (fig. 2) at a depth of about 2,750 feet. Extending for more than 1,700 acres, King Field is 3.5 miles long and 1.5 miles wide, and it has 40 feet of structural closure (fig. 3). The principal axis of this structure trends north–south. The field has produced more than 4.1 million barrels of oil since its discovery in 1942, and it still contains about 1 to 2 million barrels of recoverable oil (Leetaru 1991).

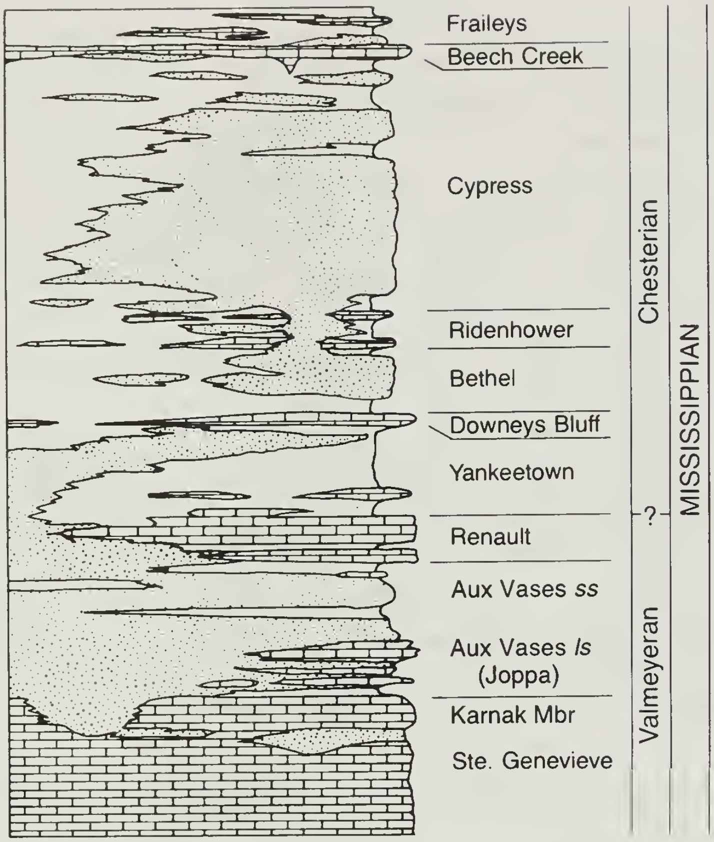

Figure 2 Generalized upper Valmeyeran and Chesterian geologic column of southern Illinois (after Whitaker and Finley 1992).

This report demonstrates the utility of seismic reflection character analysis for improving reservoir management. The application of seismic reflection data to structural mapping is not emphasized here. The King Field structure can be observed at all stratigraphic horizons, including those deeper and shallower than the Aux Vases reservoir. Seismic reflection character analysis helps delineate the reservoir compartments, whereas the structural interpretations help determine if the compartment contains hydrocarbons or water. The goal of this report is to describe a method for using seismic reflection data to predict facies transitions and to delineate productive compartments of the reservoir.

STRATIGRAPHY

The Aux Vases Formation (fig. 2) lies near the top of the Valmeyeran Series (Mississippian) and is 50 feet thick at King Field. The Aux Vases was deposited in a mixed siliciclastic-carbonate, nearshore, shallow marine setting and is composed of interlayered limestone, sandstone, siltstone, and shale. The sandstones may be porous or highly cemented with calcareous cement. At King Field, the Aux Vases is underlain by the Karnak Member of the Ste. Genevieve Limestone. In this report, the Joppa Member of the Ste. Genevieve Limestone, which overlies the Karnak Member (Willman et al. 1975), is referred to as the Aux Vases lime and is included as part of the Aux Vases calcareous lithofacies. Although the upper part of the Aux Vases is primarily composed of sandstone (fig. 2), the unit is intercalated throughout

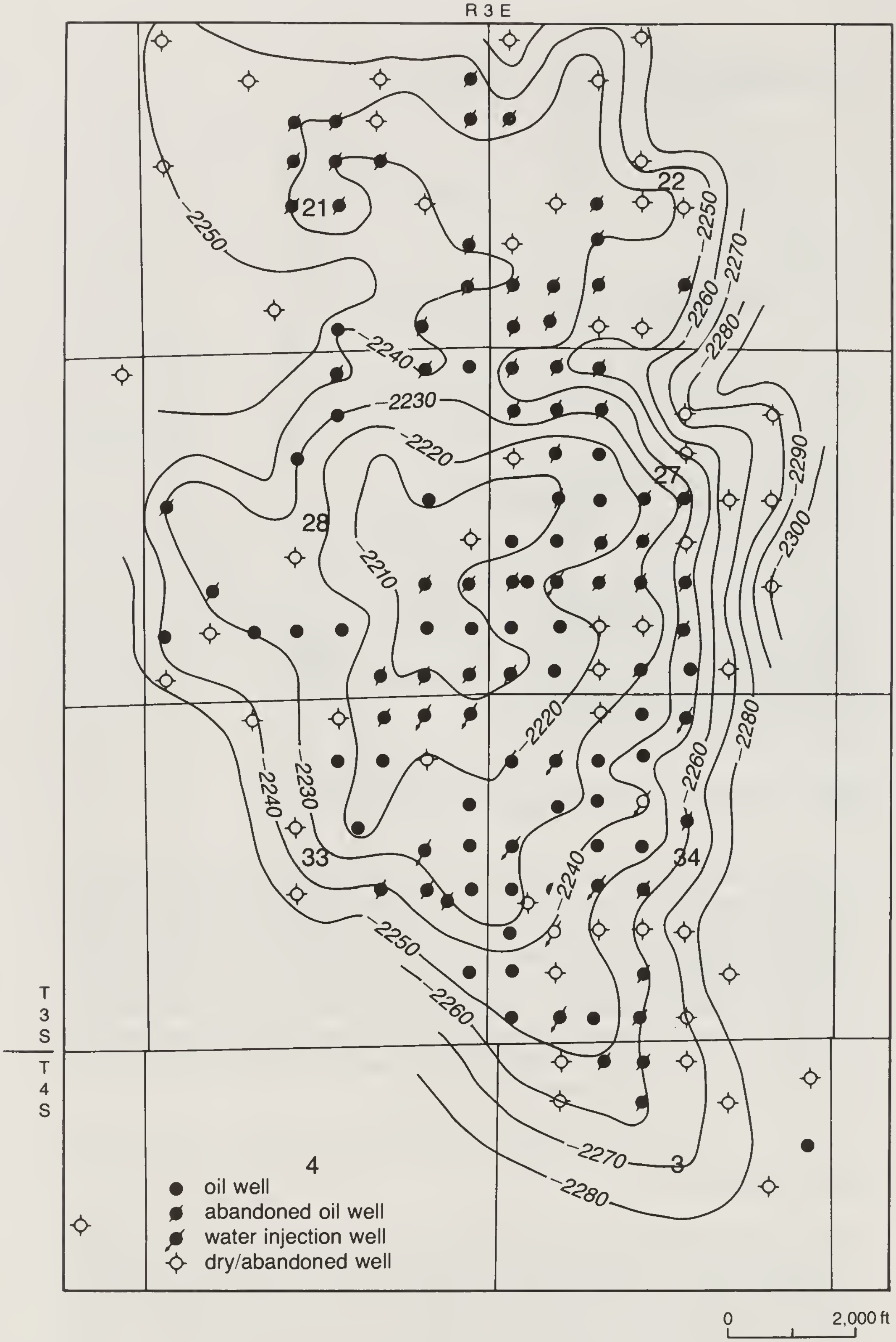

Figure 3 Structure map of King Field contoured on top of the Renault Formation (contour interval 10 feet) (Leetaru 1991).

by limestones, and there is no clear boundary between the rocks classified as the Joppa Member of the Ste. Genevieve and the Aux Vases Formation. The intercalations of the carbonate and siliciclastic lithofacies at King Field are a significant cause of reservoir compartmentalization.

The calcareous lithofacies is composed of both fossiliferous limestones and calcareous sandstones. The Aux Vases at King Field is composed of as much as 40% calcareous lithofacies. Although there is some production from this facies, the calcareous lithofacies is usually not of reservoir quality and forms low-permeability barriers between reservoir compartments. Although not as common as the calcareous lithofacies, a siltstone-shale lithofacies can also form low-permeability barriers and increase reservoir heterogeneity.

The Aux Vases reservoir lithofacies is a sandstone that is rarely thicker than 20 feet and is interpreted to have been deposited in tidal channels and marine bars (Leetaru 1991). This reservoir sandstone grades laterally into low-permeability to impermeable siltstone, shale, calcareous sandstone, and limestone. The facies transitions in the field can occur within the spacing of 660 feet between wells.

The Aux Vases Formation is overlain by the carbonate-dominated Renault Formation, a 10-foot-thick unit that is commonly a brown limestone having negligible porosity. Although the Renault Formation is laterally persistent within the outlines of the field, the limestones within the formation are not always present.

SEISMIC ACQUISITION

Sixty-fold dynamite data were acquired in March 1992 using 120 channels, 37.5-foot station spacing, and 37.5-foot shot spacing (SD Consulting 1992). The shots were centered halfway between stations using a split spread 2212.5-18.75-shot-18.75-2212.5 feet. The dynamite sources were located at the bottom of 10-foot-deep drill holes to minimize ground roll. Seven test trials indicated the impulse source should consist of two ¼-pound sticks of dynamite in a single shothole. The data were collected with a low cutoff filter of 12 Hz, a high cutoff filter of 256 Hz, and a 2-millisecond (ms) sample rate. Field data were processed immediately to determine optimal field acquisition parameters. Ten miles of seismic data were acquired using these parameters (fig. 4).

All four seismic lines (fig. 4) are available for purchase at the Illinois State Geological Survey (ISGS). Test records, special plots, and the contractor's report (SD Consulting 1992) are available for review at the Oil and Gas Section of the ISGS.

The 60-Hz power line noise (fig. 5a) and its corresponding harmonics were removed during processing. Figure 5b shows that frequencies greater than 100 Hz should be recoverable from the reservoir interval at 500 ms. High frequencies are attenuated by 30% between 200 and 500 ms (fig. 5b) by upper Mississippian age sandstones and shales. The composite signal at 500 ms contains frequencies as high as 100 Hz. Relative signal amplitude (fig. 6) decreases by about 30% between 0 and 50 Hz. This rapid signal attenuation makes it difficult to pick the "ideal" frequency to use in creating synthetic seismograms. The seismic modeling program used for this study creates a synthetic seismogram by using a single frequency for the entire plot. Because the actual frequency response changes rapidly with depth, it is difficult to get a good match between the entire synthetic seismogram and the acquired data.

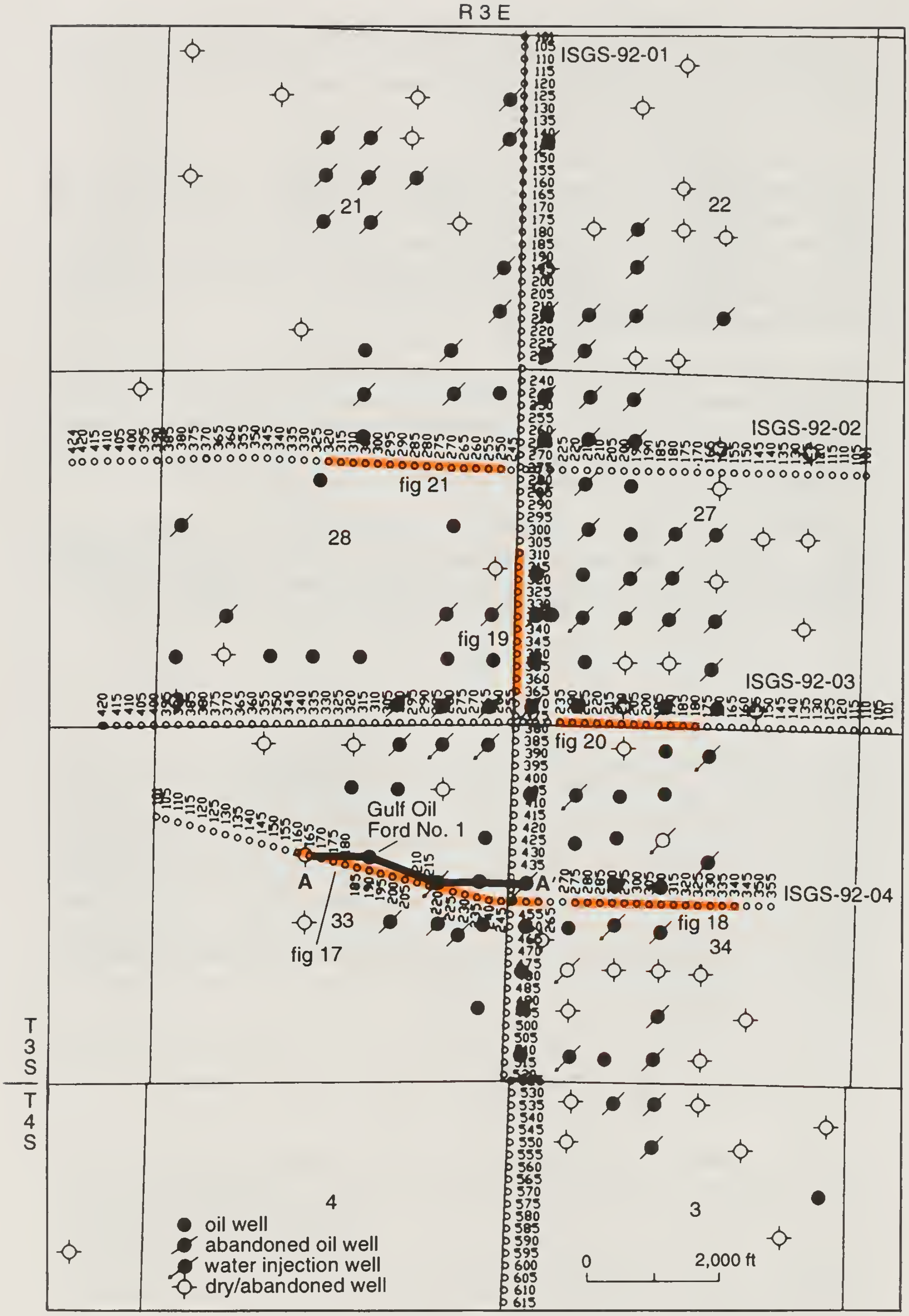

Figure 4 Base map of King Field showing shotpoint locations for the ISGS seismic lines and cross section A–A´. The individual wells and seismic sections discussed are annotated.

PROCESSING

The major steps in processing the data (in order of execution) were as follows: demultiplexing and editing, refraction statics application, velocity analysis, residual statics calculation and application, common depth point sort and normal moveout correction, spiking deconvolution, muting, and stacking.

After a single seismic trace was deconvolved, the plot of frequency versus relative amplitude of this trace showed that there was negligible frequency response above 140 Hz (fig. 6); therefore, a high cutoff filter at 140 Hz was used for the deconvolution and filtering operations.

There were two steps in the post-stack processing. A Karhunen-Loeve analysis was used to remove random noise. The signal was enhanced by transforming the data into F-K space, performing a powering routine, and then transforming the data back into X-T space. These two post-stack processes were used sparingly in order not to mask subtle variations in the data (SD Consulting 1992). Although it did not seem to be a problem in this project, the power routine can sometimes amplify the higher frequencies and increase noise (Levin 1989).

PHASE AND FREQUENCY

Understanding the phase and frequency of the seismic wavelet is of critical importance in seismic reflection character analysis. Without this knowledge, it is difficult to decipher the relationship between changes in lithofacies and reflection character. A seismic wavelet is usually referred to as a minimum-, zero-, or mixed-phase wavelet.

A minimum-phase wavelet has its energy concentrated at the front of the signal, although this does not mean that the first peak or trough has the greatest amplitude (wavelets A and B, fig. 7). Often the lead cycle can be weaker than the first following half cycle (Badley 1985).

A zero-phase wavelet is created during processing and does not occur in nature. This type of wavelet has a central peak and two side lobes of opposite sign and lesser amplitude (wavelet C, fig. 7). The boundary of a seismic reflector would be found at this central peak and not at the wavelet onset, as is the case for a minimum-phase wavelet.

The recorded data should be predominantly minimum-phase because the impulse source was dynamite (which generates a minimum-phase wavelet) and because the earth behaves as a minimum-phase filter (Pritchett 1992). During processing, the data are transformed into F-K space, which is a zero-phase operation (Jim Schroeder, consulting geophysicist, personal communication, 1993). When a minimum-phase wavelet is operated on by a zero-phase process, the resultant wavelet has its amplitude spectrum modified and is a mixture of both minimum- and zero-phase (Hatton et al. 1986). After zero-phase processing, this wavelet is still dominantly minimum-phase for the low frequencies; however, the higher frequencies should contain a zero-phase component (Pritchett 1992). Visual inspection of the seismic data from before and after F-K filtering indicated only subtle differences, suggesting that the filtering did not significantly alter the data.

Zero-phase wavelets should, in theory, have a greater signal-to-noise ratio and therefore be better suited for seismic character analysis. The conversion of the King

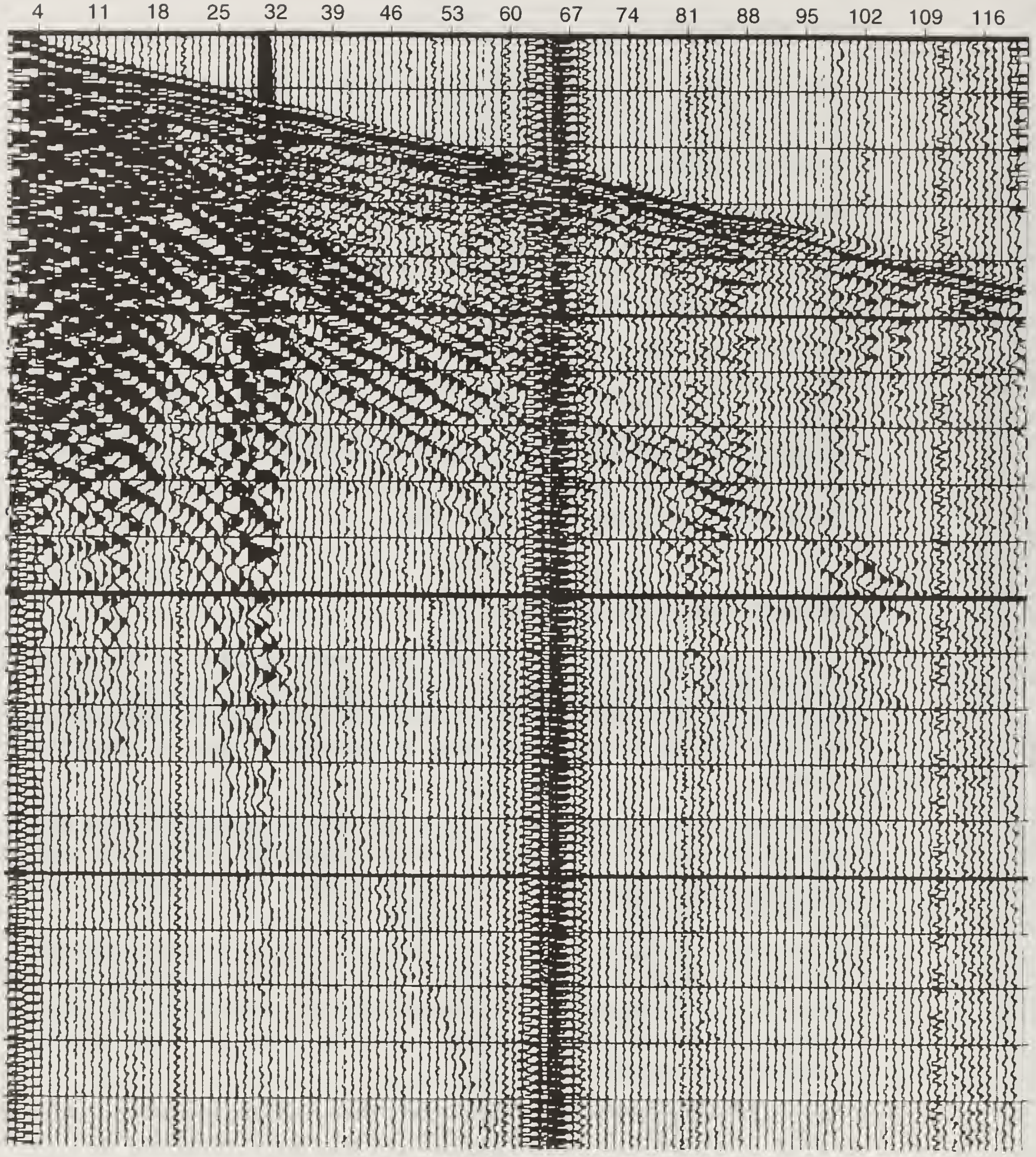

Figure 5a Raw field record showing the acquisition parameters used by the seismic acquisition program. The source was two ¼-pound sticks of dynamite in each 10-foot-deep hole. The interference at geophone locations 56 through 67 is caused by a nearby power line.

Field seismic data from primarily minimum-phase to zero-phase was not successful (Allen Lever, Signature Geophysical, personal communication, 1991). Synthetic seismograms generated from pseudo-velocity logs that were created from wireline resistivity logs showed a good correlation with the seismic data. They were not accurate enough, however, to be used in zero-phase processing (Allen Lever, Signature Geophysical, personal communication, 1994).

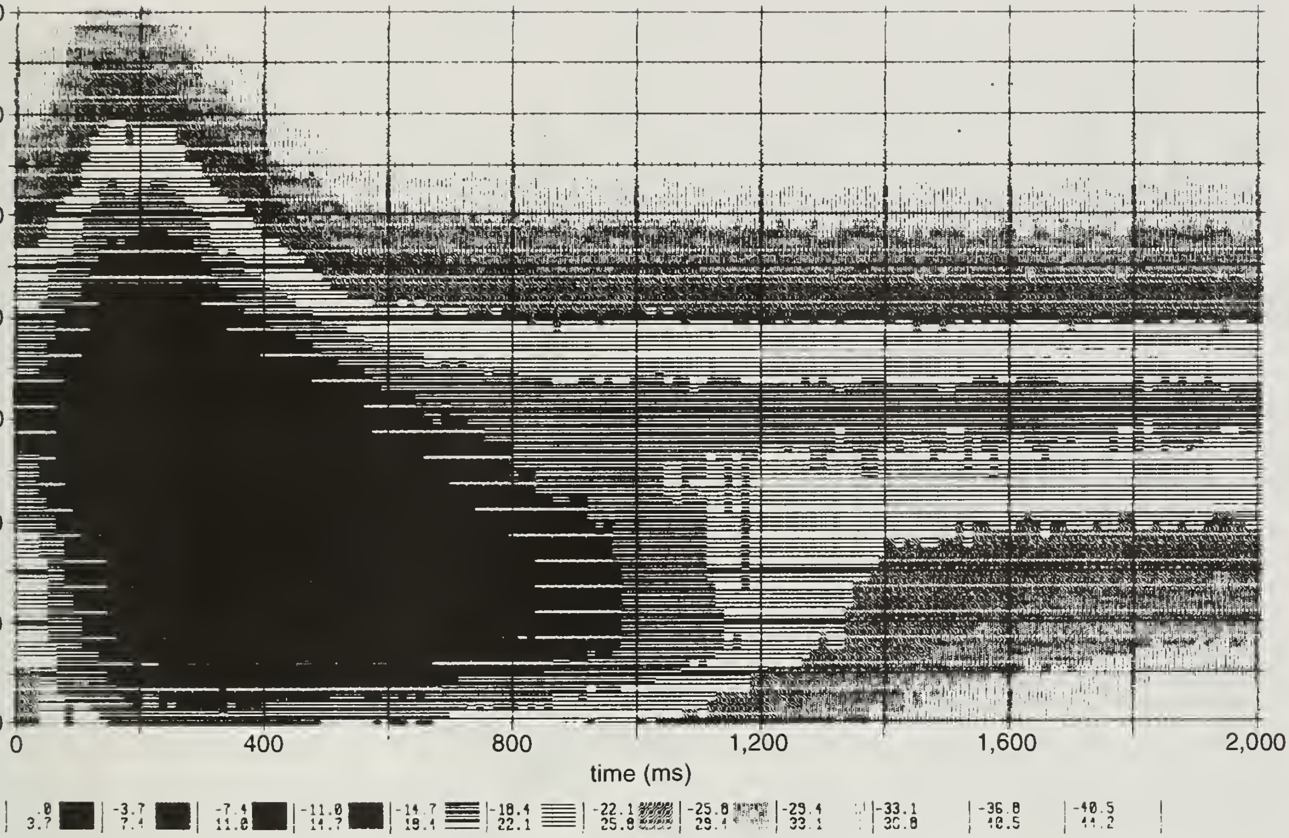

Figure 5b Frequency-time plot of the raw field record. There is a 30% attenuation of the high frequencies from 200 to 500 ms.

The practical limit of seismic resolution is proportional to the dominant frequency of the data (Kallweit and Wood 1982). The dominant frequency of the seismic wavelet was estimated from several King Field seismic sections using the methods described by Badley (1985). In this method, the distance between isolated high-amplitude continuous reflectors, consisting of a lead and follow half cycle, is measured. This method only approximates the dominant frequency because of seismic interference between reflectors. Using Badley's method, the shallower portion (<300 ms) of the King Field seismic sections has a dominant frequency of more than 80 Hz. The dominant frequency at the Aux Vases reservoir interval at 500 ms is approximately 50 Hz and, by the time the signal is reflected back from the Devonian reflector at 800 ms, the dominant frequency is 30 Hz. Comparison of the synthetic seismograms with the acquired seismic data also suggests that the dominant frequency is approximately 50 Hz. Field records (fig. 5b) and relative amplitude plots (fig. 6) suggest that the dominant frequency may be greater than 50 Hz and that the high-frequency component is higher than 100 Hz.

To produce a seismic reflection, a layer must have a thickness of at least one-thirtieth of the wavelength (Badley 1985). The resolution of seismic data is defined as the capability of defining a top and a base of a seismic reflector. The top and base will not be resolvable if the reflecting layer has a thickness of less than one-thirtieth of the wavelength. Numerous studies have shown that individual beds that are thinner than one-fourth of the dominant wavelength are below seismic resolution (Widess 1973, Sheriff 1977, Kallweit and Wood 1982); therefore, the individual bed may

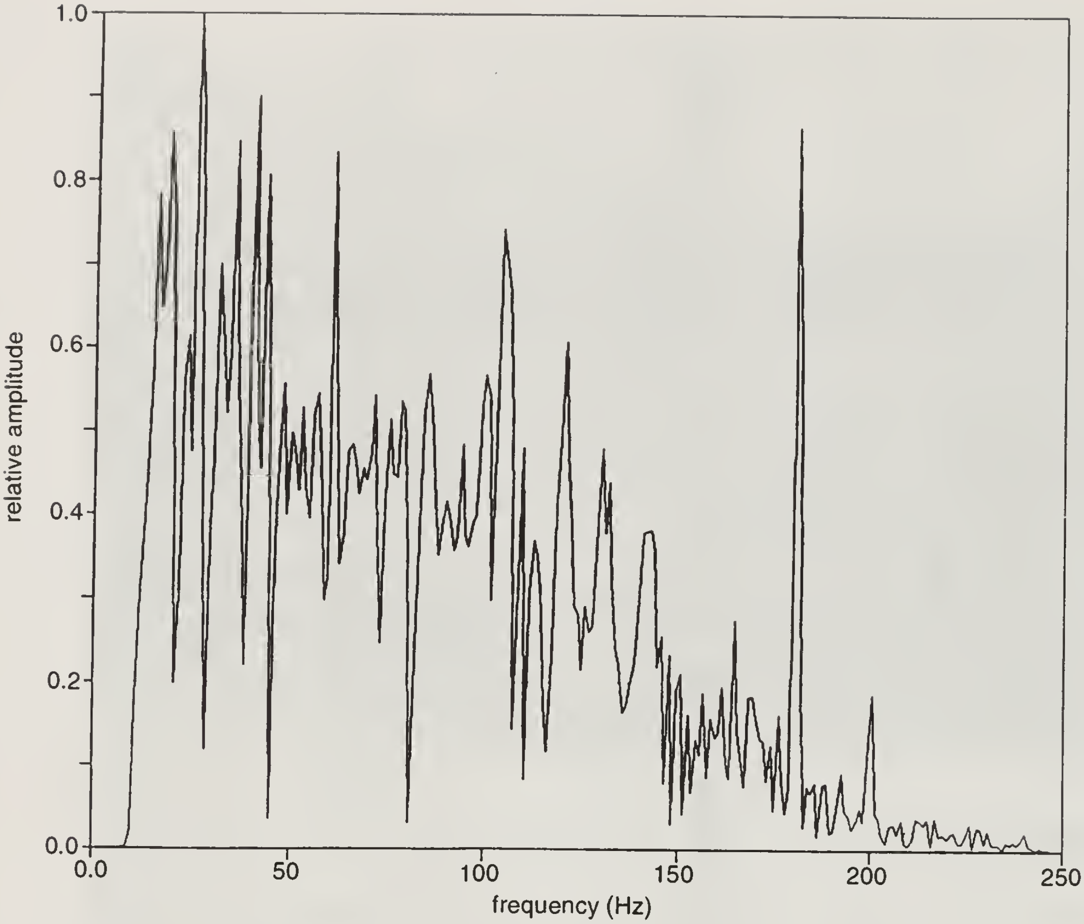

Figure 6 Amplitude spectrum versus frequency for a single trace deconvolution. The spectrum shows a rapid attenuation of the signal above 140 Hz.

cause or influence a seismic reflection, but its top and base cannot be resolved. At spacings near one-fourth of the wavelength, the signals from the top and bottom of the bed constructively interfere with each other. This constructive interference is known as tuning and results in an increase in amplitude of the reflection signal.

The maximum thickness of the Aux Vases reservoir at King Field is rarely greater than 20 feet, which is below the tuning thickness of 60 feet. The interval velocity of the Aux Vases as measured from velocity logs from Markham City Field is 12,000 feet per second (ft/s). At a time of 500 ms, the dominant frequency is 50 Hz and the seismic wavelet is 240 feet long. Variations in lithofacies, however, can produce changes in seismic amplitude that may not resolve the top and bottom of a 20-foot-thick sandstone bed but may indicate its presence or absence.

The display polarity for the acquired seismic data at King Field is the reverse of the normal polarity display as defined by the Society of Exploration Geophysicists (SEG) (S. Daut, SD Consultants, personal communication, 1993). The oil industry in the United States typically displays and works with the reverse of the SEG normal (Anstey 1980). Therefore, all of the synthetic or acquired seismic plots have positive reflections during a transition from a low-velocity zone to a high-velocity zone. For example, the reflection for a transition from a low-velocity shale above to a high-velocity carbonate below is displayed as a black peak or area of positive amplitude.

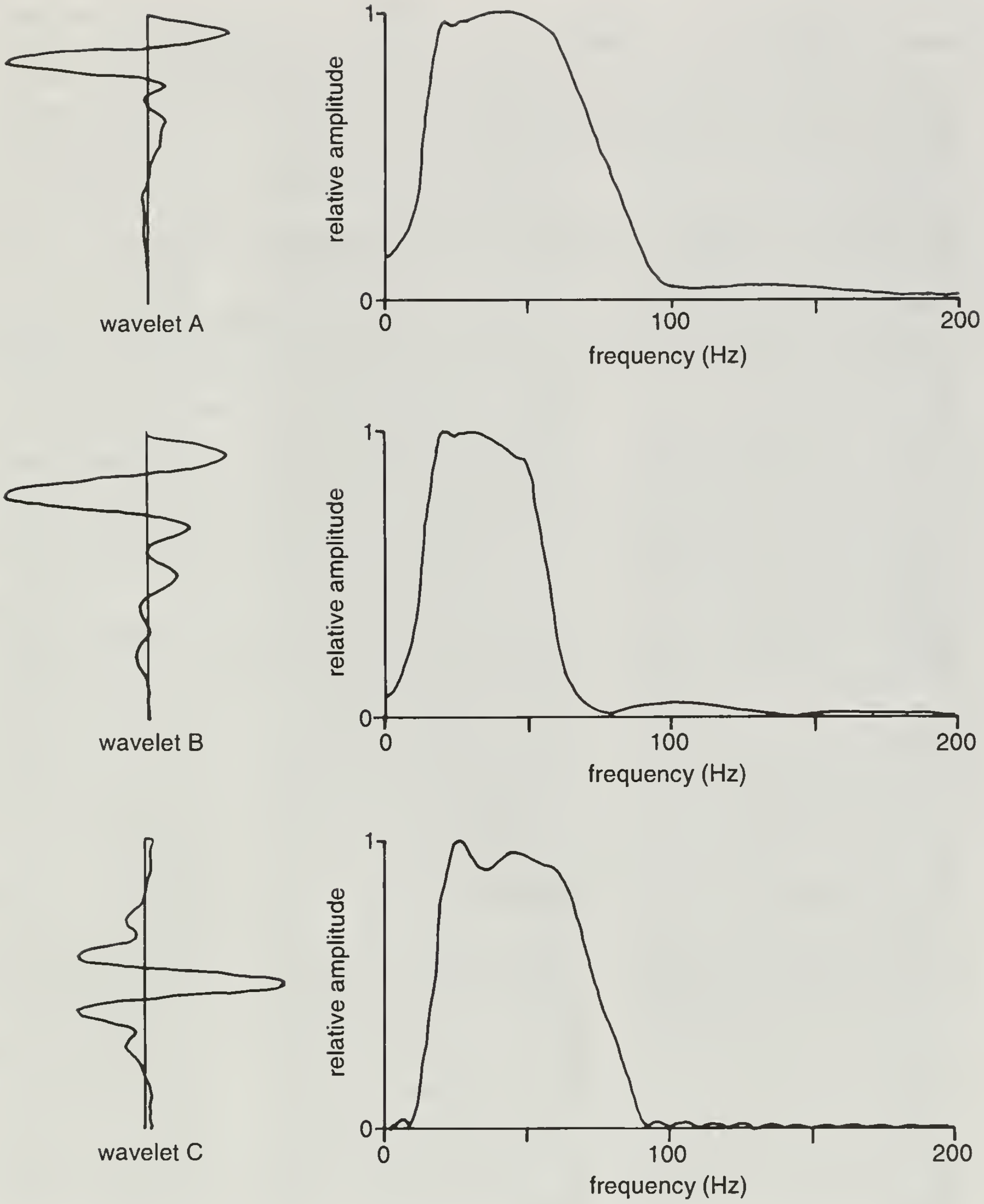

Figure 7 Three different wavelets used to create the synthetic seismograms and seismic models used in this report. Wavelet C is zero-phase, whereas wavelets A and B are minimum-phase.

COMPARISON OF 15-, 30-, AND 60-FOLD DATA

To provide the greatest possible flexibility for processing and modeling, we acquired 60-fold seismic data for this study. The current (as of this report) cost of acquiring and processing two-dimensional 60-fold seismic data is approximately $7,000 to $8,000 per mile, whereas 30- and 15-fold data cost $5,500 to $6,500 and $4,500 to $5,500 per mile, respectively (Allen Lever, Signature Geophysical, personal communication, 1994). (These negotiable costs are subject to the size of the program and shooting conditions.) Comparison of the three sets of data indicates that, although 60-fold data are of better quality, the 30-fold data could be used to do additional seismic stratigraphy in King Field (fig. 8). The 15-fold data, which usually are no longer acquired, had too much noise and are not recommend for stratigraphic seismic acquisition programs in Illinois.

SEISMIC MODELING AND LITHOFACIES PREDICTION

Geologic modeling of seismic response at King Field is constrained because of the vintage of the wireline logs. Most of the wells at King Field were drilled in the 1940s and 1950s (Leetaru 1991). Because velocity logs were not developed until the late 1950s, no velocity logs are available at or above the reservoir interval in this field.

In most of the wells in the field, the old electric log is the only wireline tool that was run. However, there is generally a good relationship between resistivity measurements and seismic velocity within the Illinois Basin. Rudman et al. (1975, 1976) showed that, in the Mississippian section, relative changes in velocities indicated by resistivity changes were correct, but absolute velocity values were not. A velocity log from the Markham City Field, which is located 5 miles to the northeast of King Field, was manually stretched or thinned using resistivity wireline logs from King Field as a template to create pseudo-velocity logs for King Field. Each pseudo-velocity log of a well from King Field uses the velocities for corresponding lithologies from the velocity log for the Markham City Field. Velocities of limestones, shales, and sandstones from the Markham City Field are tied to the lithologies predicted by the old electric wireline logs for wells in King Field. These artificial or pseudo-velocity logs should be more accurate than those produced by direct resistivity to velocity conversions because the velocities are derived from an actual velocity log. There should be no significant difference in the velocities of the formations between Markham City and King Fields because they were originally deposited in similar environments and presently occur at similar depths (Whitaker and Leetaru 1992).

Numerous synthetic seismic models were used to assess the effect of stratigraphic changes on seismic reflection character. Although a large number of different wavelets were used for the synthetic seismic modeling, only three of the different bandpass filters used to generate the seismic wavelet are considered in this discussion. Wavelet A has a higher and wider range of frequencies than wavelet B (fig. 7). Wavelets A and B are both minimum-phase; however, wavelet A frequencies range up to 100 Hz, whereas wavelet B is completely attenuated to 70 Hz.

The Gulf Oil Company Ford No. 1 well, located near shotpoint 189 on seismic line ISGS 92-04 (fig. 4), was one of the best Aux Vases producers at King Field (fig. 9a) and was used as the type well for all of the synthetic models in this report. The synthetic seismogram for the Gulf Ford No. 1 (generated from the pseudo-velocity log using wavelet A) shows a good overall comparison between the synthetic seismogram and acquired seismic data (fig. 9b).

Seismic models based on interpreted geologic variations within King Field were generated using Daniel Geophysical™ software to evaluate the effect of geologic variations in the Aux Vases Formation. In the cross sections and seismic displays within this report, blue indicates the calcareous lithofacies predominates and orange indicates that the sandstone lithofacies predominates. Because the seismic wavelet is an average of a large interval, the color on the seismic display indicates only average lithology within the Aux Vases and does not imply that the entire interval is one lithology. The top and base of the Aux Vases Formation, as interpreted by the

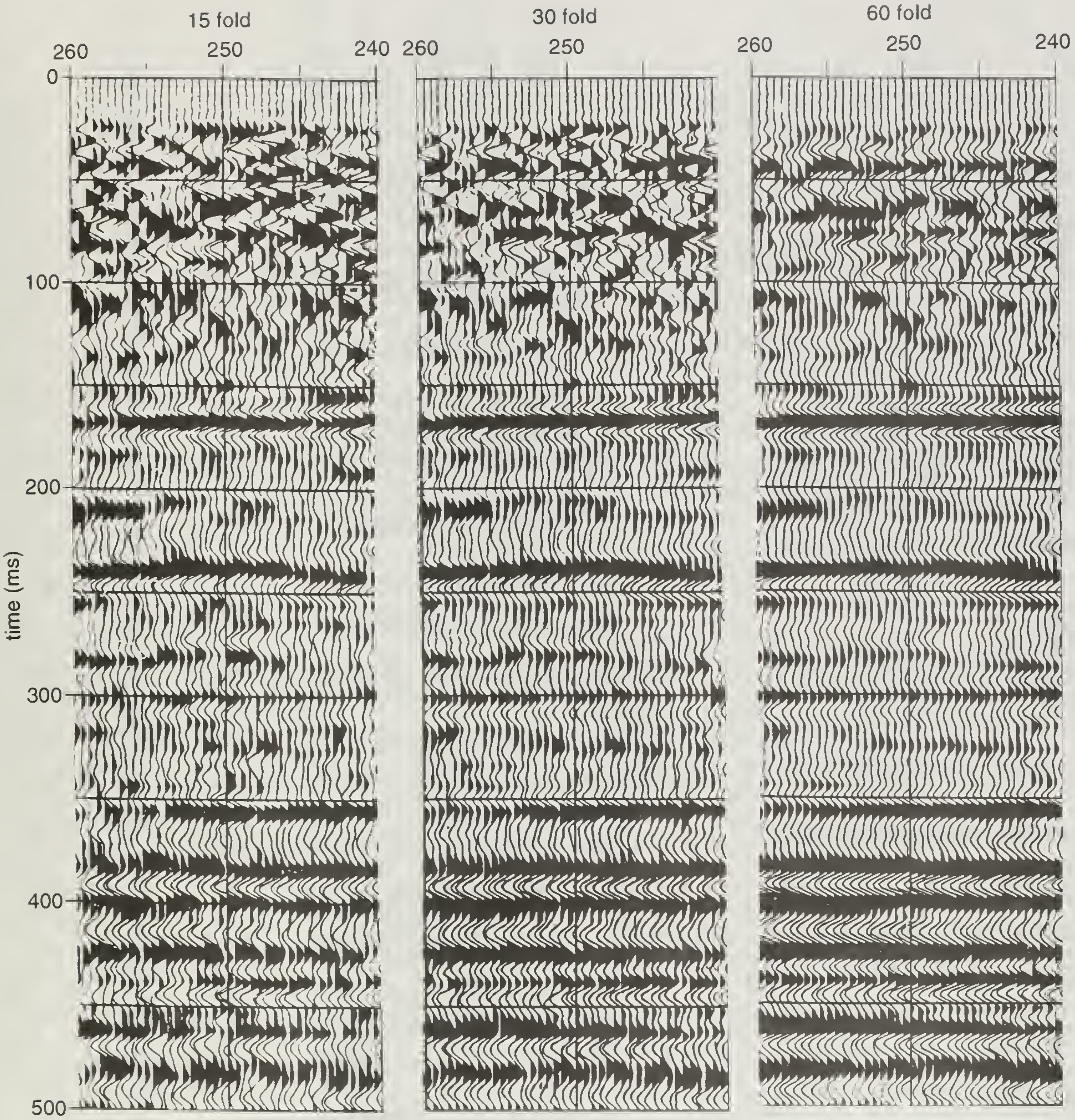

Figure 8 Comparison of 15-, 30-, and 60-fold seismic data from line ISGS-92-03. The 15- and 30-fold data were artificially generated by removal of seismic traces from the original seismic line.

seismic response, are not necessarily the same as the actual formation top and base identified on wireline logs. The formation boundaries on all of the synthetic seismic models and acquired seismic lines refer to the seismic reflectors, not the wireline log correlations.

The reflection character of the Aux Vases interval is affected by lithofacies and interval thickness changes both within the formation and above and below the reflector. The first three seismic models (figs. 10, 11, 12) show the effects of simple changes in stratigraphy, lithology, and/or thickness on the seismic data for part of line ISGS-92-04. In each of these three models, one end-member well was a

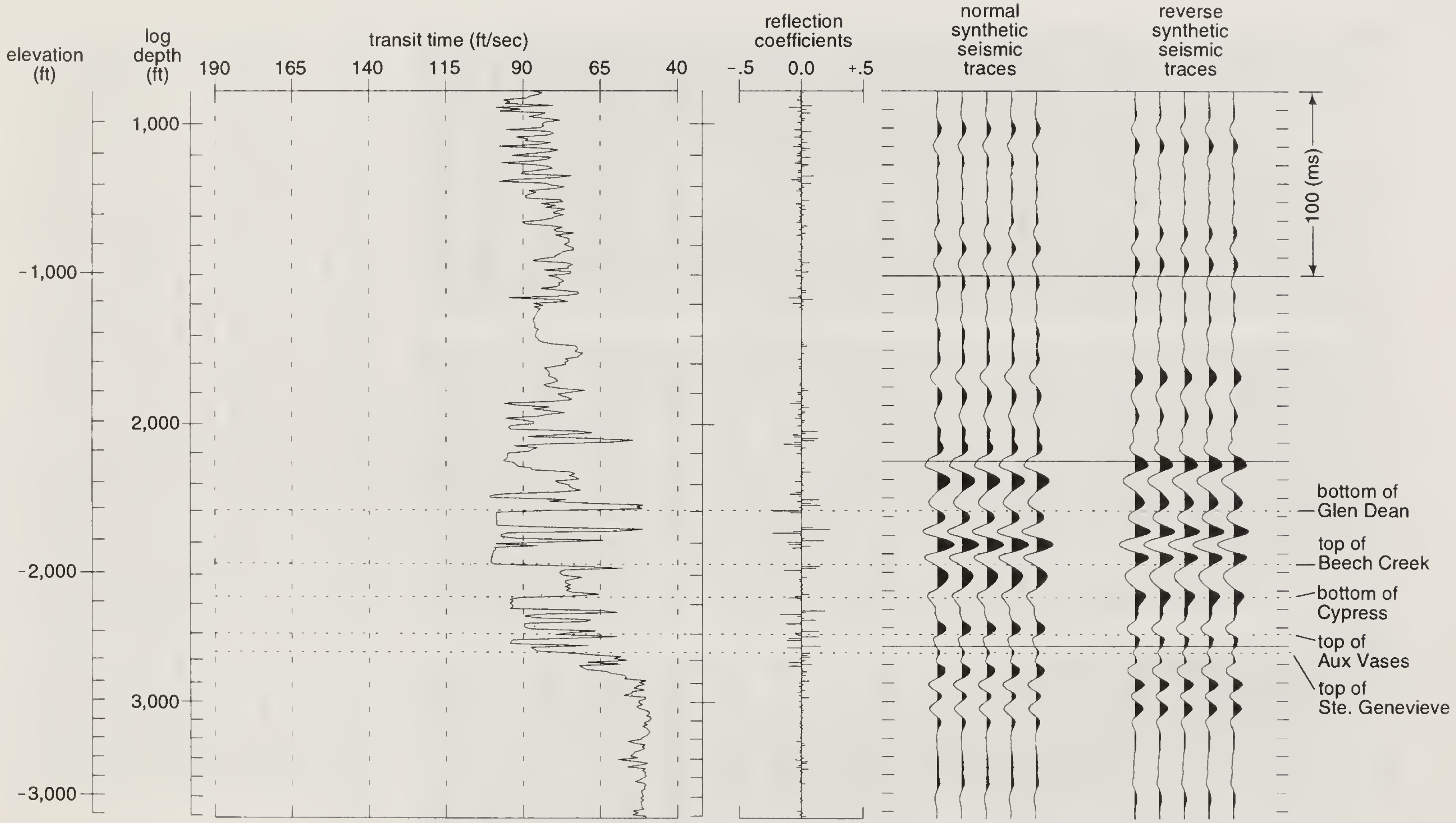

Figure 9a Synthetic seismic model of Gulf Ford No. 1 well. The left curve is a pseudo-velocity log based on the resistivity log values. The synthetic traces are displayed in both normal and reverse polarity.

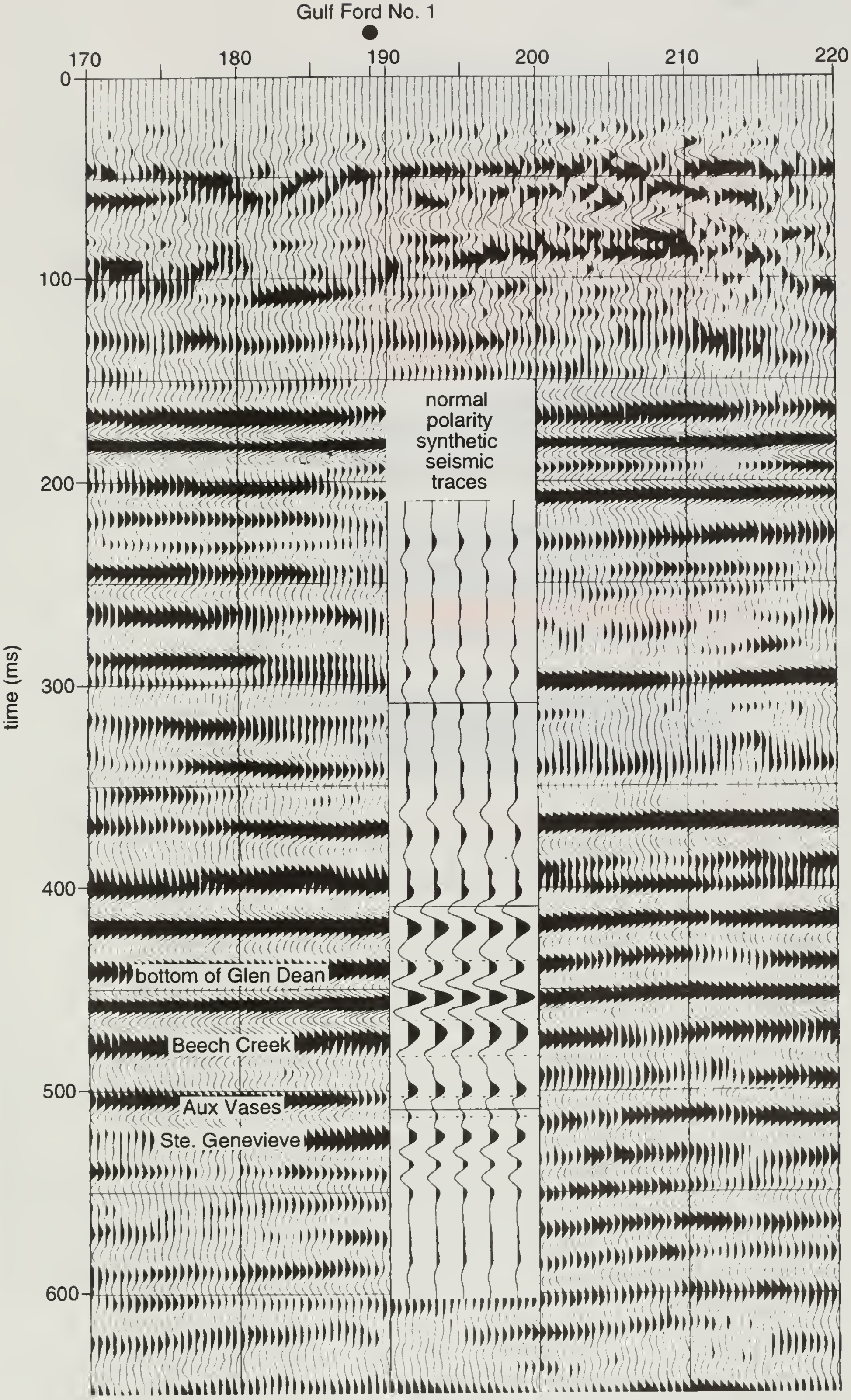

Figure 9b Seismic line ISGS-92-04 compared to the normal polarity synthetic seismic traces of Gulf Ford No. 1.

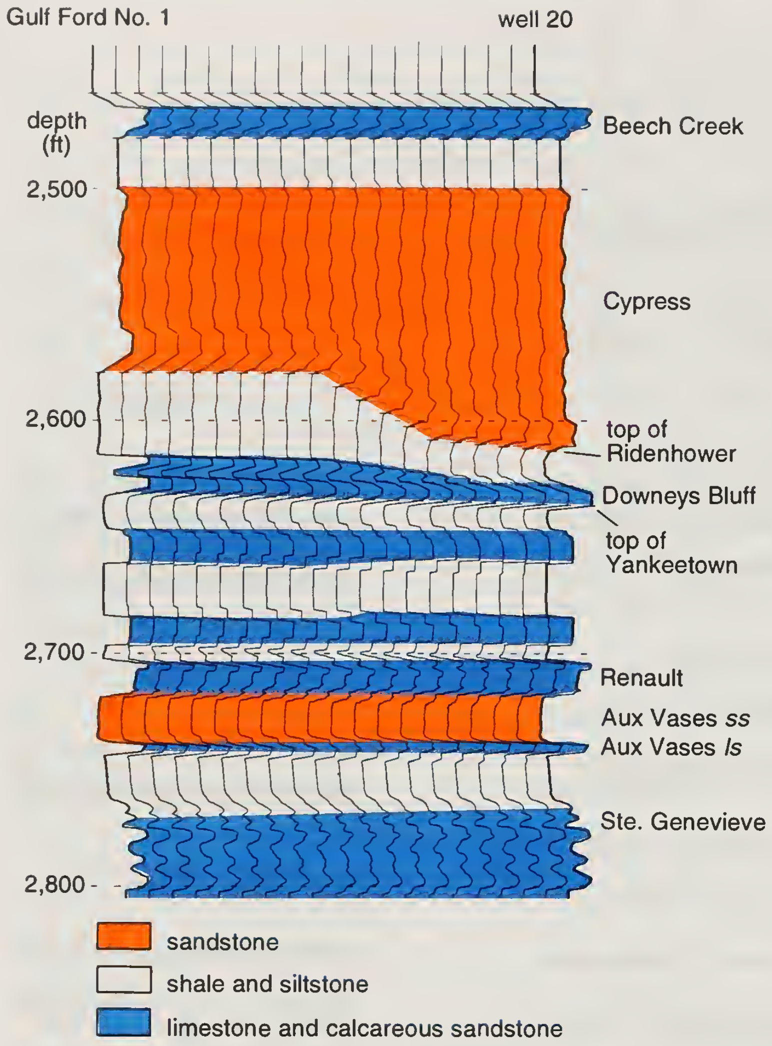

Figure 10a Model of pseudo-velocity logs shows thickening of the Cypress Sandstone from left to right. Well 20 is the same as the Gulf Ford No. 1 except for an artificial thickening of the Cypress interval.

pseudo-velocity log from the Gulf Ford No. 1 well, and the other end-member well was a modified Gulf Ford No. 1 log in which the velocities were altered to model a change in stratigraphy. For each of the seismic models, part (a) of the figure shows the interpolated pseudo-velocities between two wells; parts (b) and (c) are the synthetic seismic models generated from the interpolated pseudo-velocity well logs using wavelets A and B, respectively. All of the synthetic models with wavelet B have broader reflectors than wavelet A models because wavelet B has a lower dominant frequency. The faint horizontal lines on each illustration are correlation lines used by the modeling program to control the linear interpolation between individual wells.

The first model (fig. 10) examines the effects of thickness changes in the overlying Cypress Sandstone, which lies 100 feet above the Aux Vases reservoir (fig. 2) at King Field. Synthetic seismic modeling suggests that this change in thickness is resolved by the seismic reflection data. In the model (fig. 10a), the Cypress Sandstone simulated in well 20 is 30 feet thicker and the Ridenhower and Downeys Bluff Formations 12 feet thinner than in the Ford No. 1 well. This thickening and

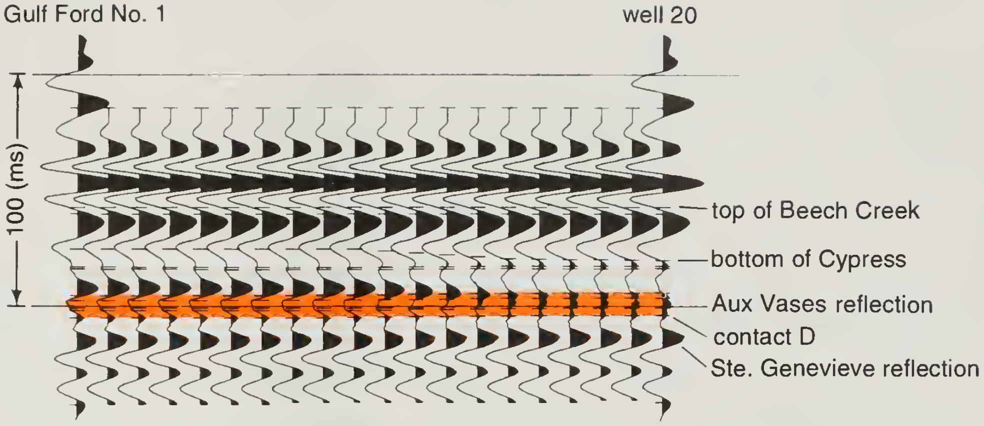

Figure 10b Synthetic seismic model of (a) convolved with wavelet A. The base of the thicker Cypress Sandstone is defined by an increase in amplitude toward well 20 on the right. Contact D is the top of the Ste. Genevieve Limestone as correlated from wireline velocity logs. The Ste. Genevieve reflector and the formation top from velocity logs are not always the same because of the length of the seismic wavelet.

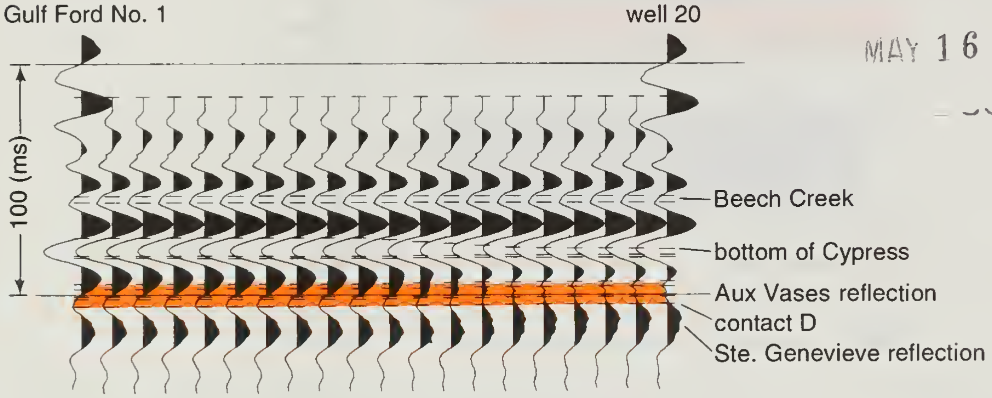

Figure 10c Synthetic seismic model of (a) using wavelet B. The amplitude increase at the base of the thicker Cypress Sandstone model (from b) is not present in this lower frequency model; however, the top of the Aux Vases interval shows a decrease in amplitude. Contact D, the top of the Ste. Genevieve as determined from wireline logs, is structurally flat across the model, but there is an apparent structure at the Ste. Genevieve reflector caused by constructive and destructive interferences of the seismic wavelet.

thinning is similar to the actual thickening and thinning observed on geologic cross sections of the field. Modeled with wavelet A, the reflector that corresponds to the base of the Cypress Sandstone increases in amplitude from well 1 to well 20 (fig. 10b). This increase in amplitude at the base of the thicker Cypress interval is not present in the wavelet B model (fig. 10c) because the change in sandstone thickness cannot be resolved with this lower frequency seismic wavelet. Also, for the Aux Vases reflector, there is a pronounced change from a negative to a positive amplitude for the wavelet A model in the areas where the Cypress Sandstone is thicker. For wavelet B models, this amplitude shift is less prominent.

It is important to note that the reflector and the formation boundary are not necessarily equivalent. For example, as noted in figure 10c, the Ste. Genevieve formation boundary is flat, as determined by wireline log correlations (contact D),

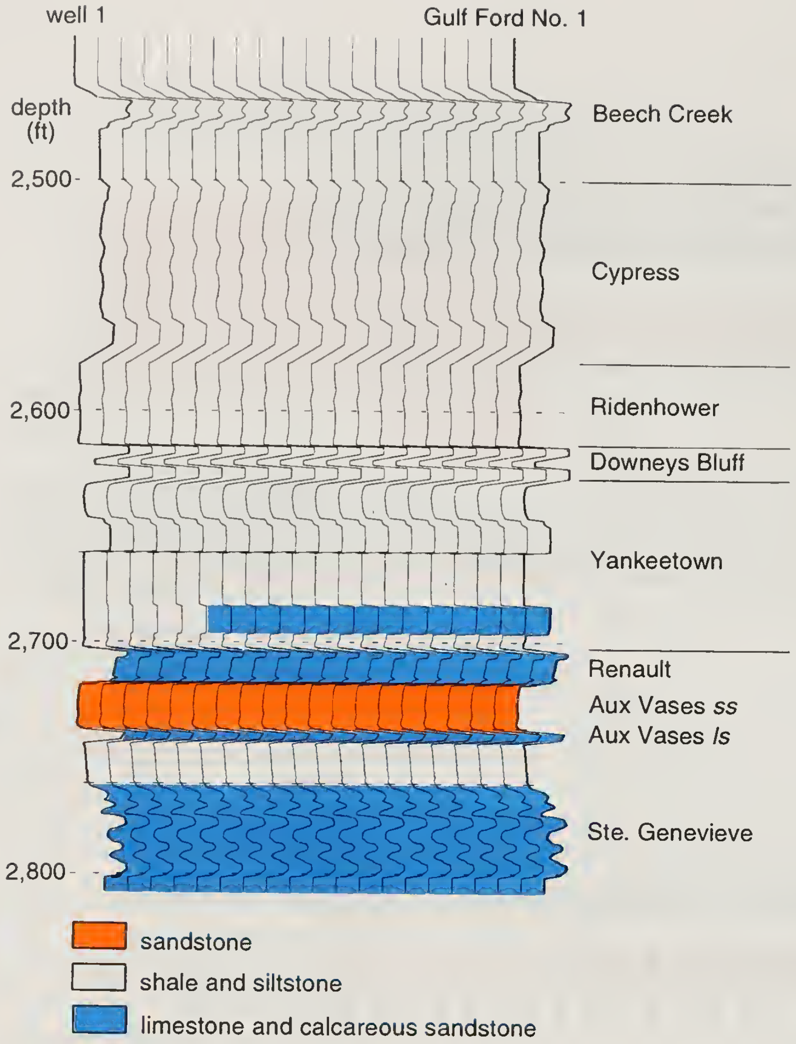

Figure 11a In this model, the calcareous Yankeetown interval in the Gulf Ford No. 1 well has been removed in well 1. The curves in between these two wells are pseudo-velocity logs created by a linear interpolation between the two end wells.

but the top of the Ste. Genevieve reflector is higher near well 20. The reason for this effect is the length of the seismic wavelet. The seismic wavelet in this formation is approximately 240 feet in length. Therefore, this wavelet is a compilation of various lithologic changes in formations other than the Ste. Genevieve. The interpreter cannot assume that any change in seismic amplitude marks the exact formation boundary.

The second model (fig. 11) shows the effects of changes in the lower Yankeetown, a unit composed of discontinuous sandstone layers that overlie the Renault limestone (fig. 2). When present, these sandstones are tightly cemented with calcite, and the amount of calcite cementation, as determined by the wireline resistivity logs, varies across King Field. The sandstone layers with pervasive cementation have higher velocities than the surrounding shales. The Ford No. 1 well in figure 11a has 10 feet of calcareous Yankeetown that is gradually removed as the traces progress to well 1. The signal from the Ste. Genevieve reflector forms a doublet in the synthetic model using wavelet A (fig. 11b), and the top portion of the doublet decreases in

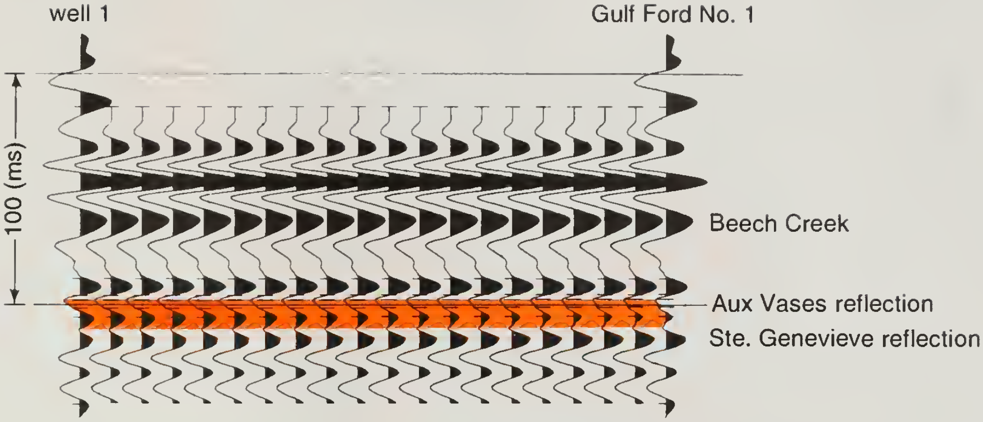

Figure 11b Synthetic seismic model of (a) convolved with wavelet A. The Ste. Genevieve reflector is a doublet. The top part of the Ste. Genevieve doublet decreases in amplitude where there is an overlying calcareous Yankeetown sandstone.

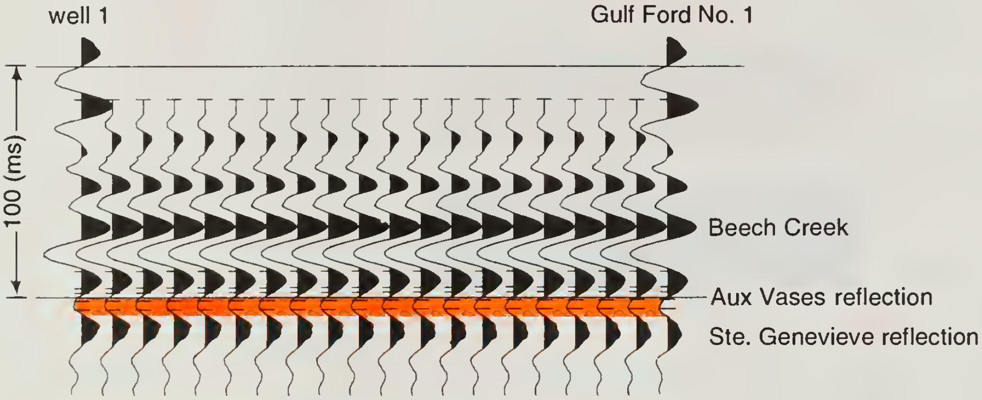

Figure 11c Synthetic seismic model of (a) convolved with wavelet B. The Ste. Genevieve reflector is a single peak. There is a slight change in the seismic amplitude of the Ste. Genevieve reflector, but this change is negligible and would probably not be discernible on acquired seismic lines.

amplitude toward the Ford No. 1 well where the highly calcareous Yankeetown Sandstone is present. At the lower frequencies of the wavelet B model (wavelet B, fig. 11c), this doublet is not present. Instead, the Ste. Genevieve reflector is represented by a single broad peak, and, instead of a distinct amplitude change at the Ste. Genevieve reflector, there is a slight flattening of the signal amplitude toward the Ford No. 1 well where the highly cemented Yankeetown is present. In addition, the top of the Ste. Genevieve appears lower in the section in wells where this calcareous interval is present.

In the third model (fig. 12), the Aux Vases reservoir interval changes from 20 feet of clean porous sandstone in the Ford No. 1 well to a well cemented, calcareous sandstone in well 1. This variation in lithofacies is common in King Field and is a significant cause of reservoir compartmentalization. Both the wavelet A (fig. 12b) and wavelet B (fig. 12c) synthetic models show variations in the amplitude of the seismic signal with this change. As one would expect, the amplitude of the wave trough that represents the Aux Vases is greatest for the higher porosity sandstones. It is more subdued where the calcareous lithofacies is present. Additionally, the

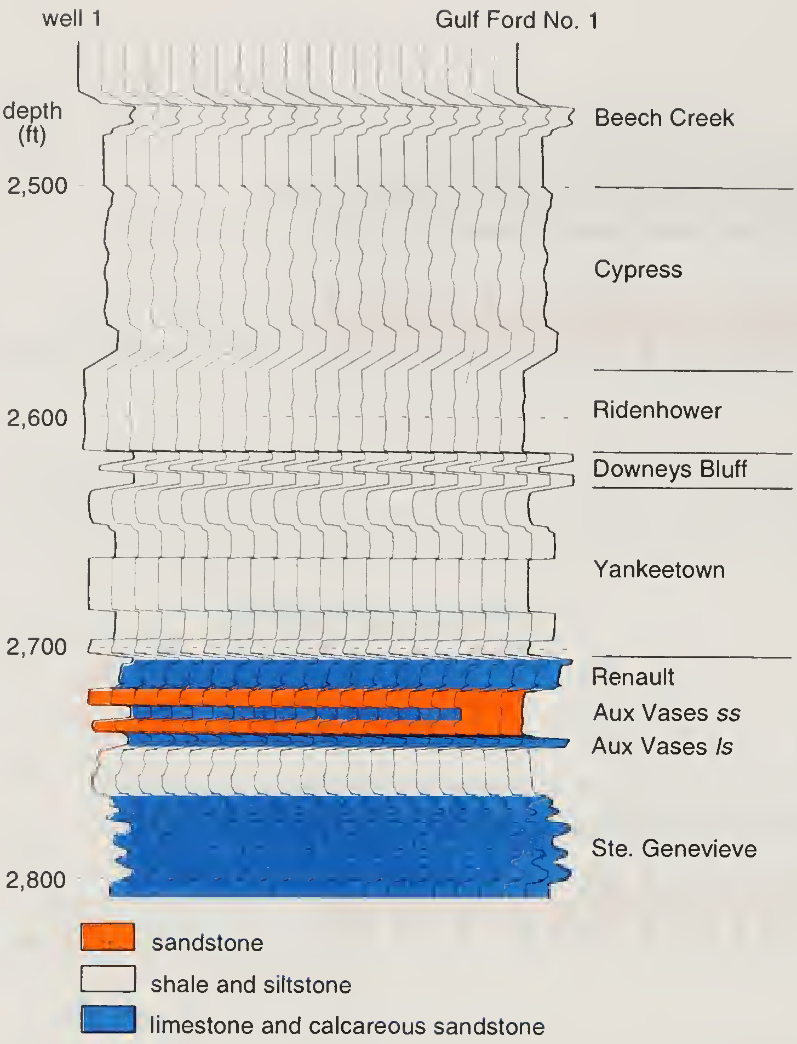

Figure 12a In this model, the Gulf Ford No. 1 has a clean Aux Vases reservoir sandstone. In well 1, this sandstone has been replaced in part by a calcareous interval. The curves are pseudo-velocity logs created by a linear interpolation between the two wells. Only the Aux Vases interval is changed in this model.

signal from the Ste. Genevieve reflector has a higher amplitude where the more porous Aux Vases reservoir sandstone is present. Because the seismic velocity of the Ste. Genevieve formation is constant in this synthetic seismic model, the observed change in signal amplitude is the result of destructive and constructive interference of the seismic wavelets resulting from the lithologies of the formations above the Ste. Genevieve. The signal from the Ste. Genevieve reflector is formed by a composite seismic wavelet that is 240 feet in length and includes reflections from the Aux Vases and Renault Formations. Thus, the presence of a high-amplitude reflection from the Ste. Genevieve can help in distinguishing between reservoir and nonreservoir lithofacies in the Aux Vases Formation. However, velocity variations resulting from lithologic variations in overlying units would change the Ste. Genevieve amplitude and complicate the interpretation.

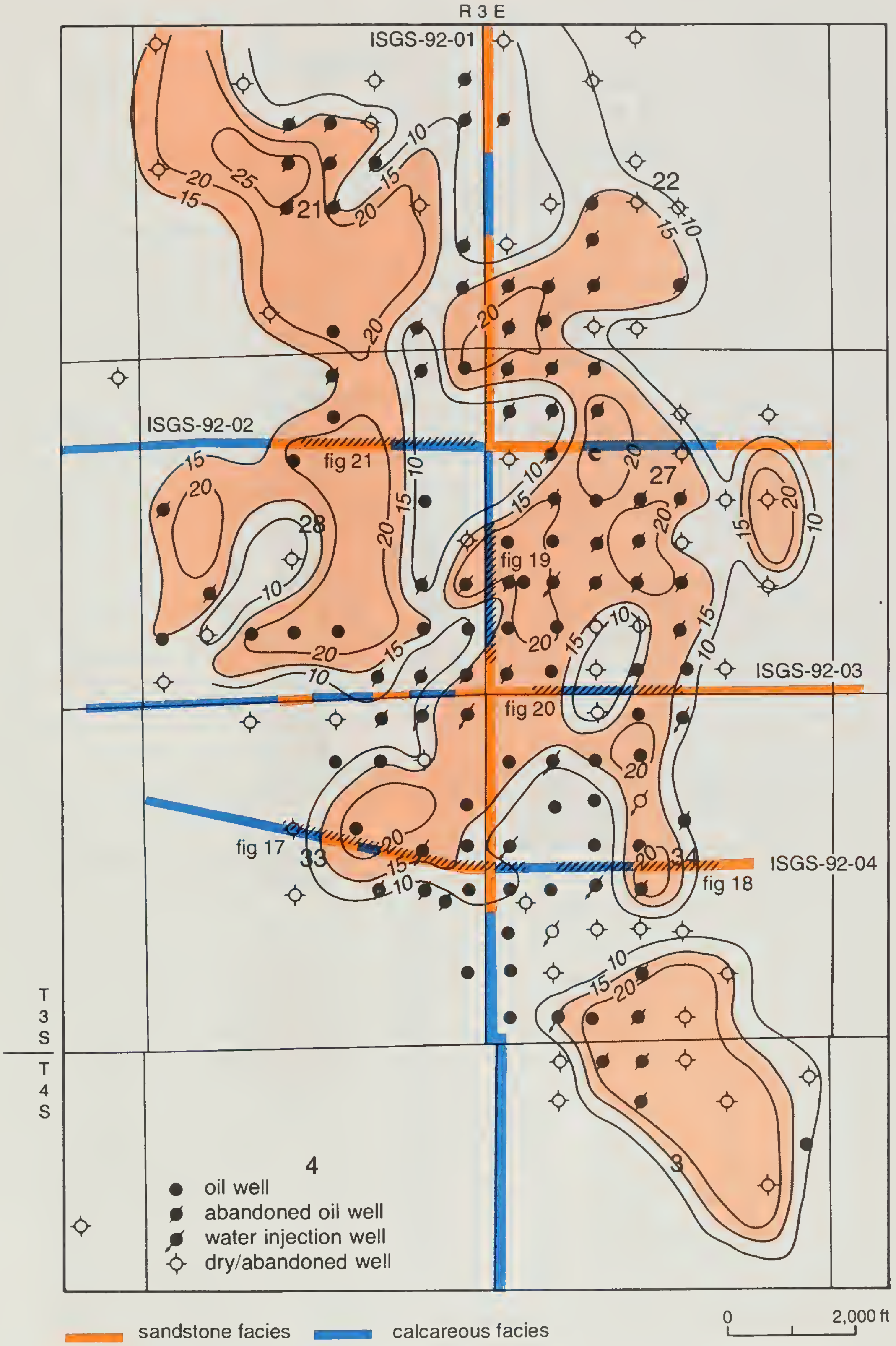

Figure 14 Map of the net thickness of clean Aux Vases sandstone (contour interval 5 feet). A clean sandstone is defined as having an SP response that is at least 50% of the SP response of a clean, thick Cypress Sandstone. Areas in orange have more than 20 feet of sand. The two colors on the seismic lines indicate sandstone or calcareous Aux Vases lithofacies as interpreted by seismic character analysis.

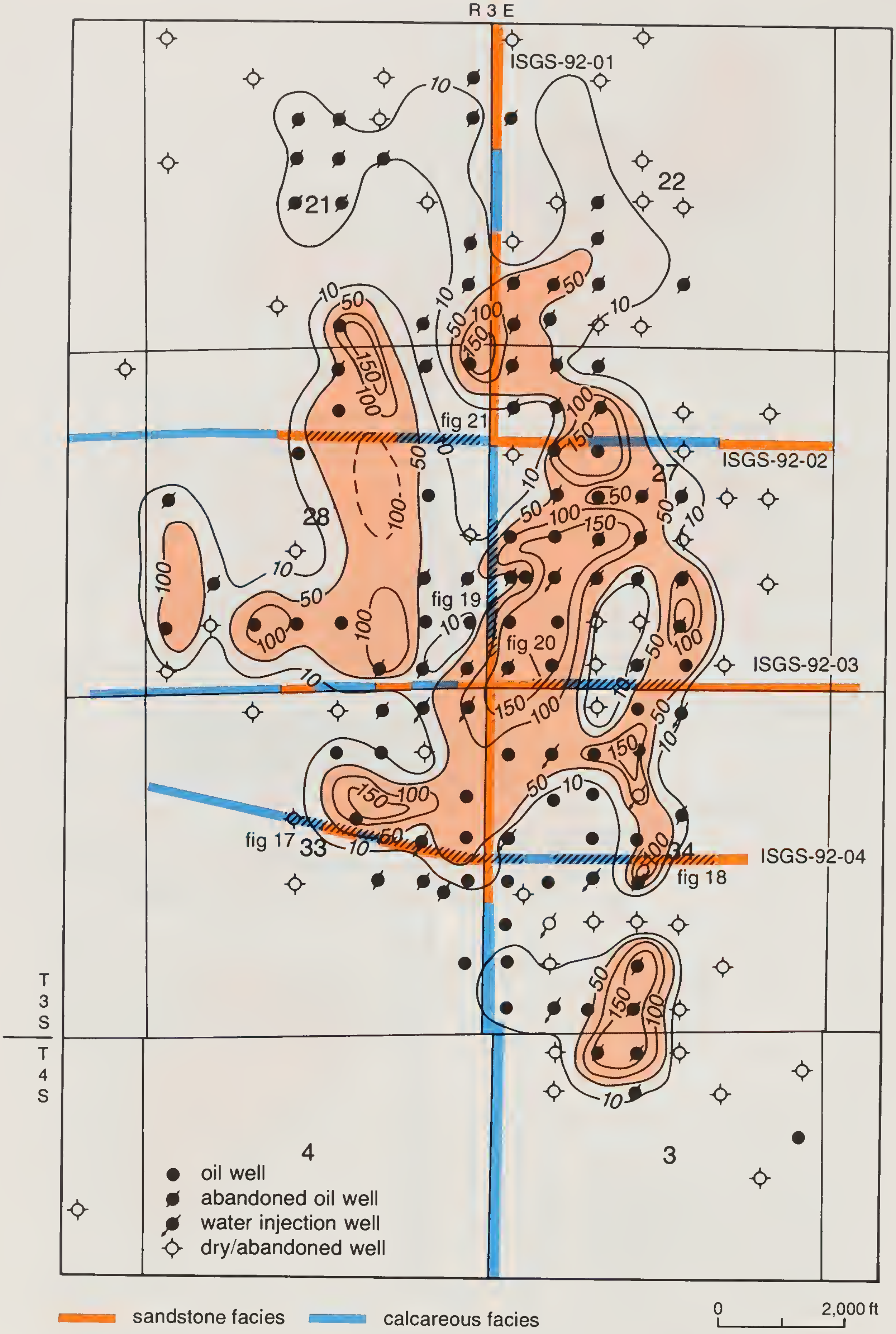

Figure 15 Map of the results from initial production tests of wells completed in the Aux Vases at King Field (contour interval, 50 BOPD [barrels of oil per day] with a minimum contour interval of 10 BOPD). Areas that tested greater than 100 BOPD are shown in orange (Leetaru 1991). The orange and blue on the seismic lines indicate sandstone or calcareous Aux Vases lithofacies, respectively, as interpreted by seismic character analysis.

(Leetaru 1993) and production data (Leetaru 1991) indicate a multicompartment reservoir.

Changes between the calcareous lithofacies and the sandstone lithofacies of the Aux Vases should be recognizable in high-resolution seismic data because the velocities of the two facies are markedly different. Velocity logs show that permeable Aux Vases sandstones have an average velocity of 12,000 ft/s, whereas the average velocity of the calcareous lithofacies is 16,000 ft/s. The sandstone lithofacies cannot be differentiated from the siltstone-shale lithofacies because these two lithofacies have similar seismic velocities and, therefore, similar reflection coefficients. The following discussion identifies the problems associated with attempts to differentiate between the calcareous and sandstone facies within King Field.

Line ISGS-92-04 was selected to demonstrate the correlation between geology, synthetic seismic modeling, and acquired seismic data for three reasons: (1) lateral carbonate-sandstone facies changes occur within one well spacing along this line, (2) well data near the line are abundant, and, most important, (3) all of the wells along shotpoints 164 to 255 penetrated the entire Aux Vases reservoir. Many of the wells on the other seismic lines only partially penetrated the Aux Vases Formation.

Cross section A–A′ (fig. 16a) was used to create a multiwell geological model that matches shotpoints 164 through 255 on line ISGS-92-04. The pseudo-velocity wireline logs in this cross section were made by the previously discussed method of modifying a nearby velocity log using old wireline logs as a template. This cross section shows not only the stratigraphic changes in the interval from the Cypress through the Ste. Genevieve but also the structural high at the center of the field.

The Aux Vases sandstone reservoir interval is structurally 17 feet higher near the center of cross section A–A′ (near well 550, fig. 16a) than it is at the west end (at well 1337). All of the formations between the Beech Creek Limestone and the Ste. Genevieve Limestone show variations in either lithofacies and/or thickness. The most significant change is the 30-foot increase in the thickness of the Cypress toward the east. The top and base of the Cypress Sandstone have slightly higher velocities, probably as a result of calcite cementation. The Ridenhower shale decreases in thickness in relative proportion to the increase in Cypress thickness. The Downeys Bluff thins in the center of the cross section at wells 550 and 2377. The calcareous facies in the Yankeetown is 10 feet thick in well 488, but it is thin or absent in the other wells in this cross section. The Renault Formation is thinnest at well 550 and thickens gradually on either side of this well. The calcareous lithofacies of the Aux Vases is represented by two types of units in this cross section. The westernmost well (well 1337) has an areally limited upper calcareous facies that bisects the lower velocity sandstone lithofacies. A more widespread calcareous facies lies directly below the sandstone lithofacies and thickens to the east. Both of these intervals will affect the seismic reflection characteristics of the Aux Vases.

Two different seismic models were created on the basis of the geology using wavelets A and B (fig. 16b, c). The model generated using the higher frequency wavelet A (fig. 16b) gave the best overall match with the acquired seismic data (line ISGS-92-04). Wavelet B, however, produced the closest match of the seismic data with the synthetic model of the Aux Vases interval (fig. 16c).

The amount of structural relief shown in the cross section (fig. 16a), the synthetic seismic models (fig. 16b, c), and the acquired seismic (fig. 17) is similar. All models show that the eastern part of the line is up dip and flat as compared with the western end.

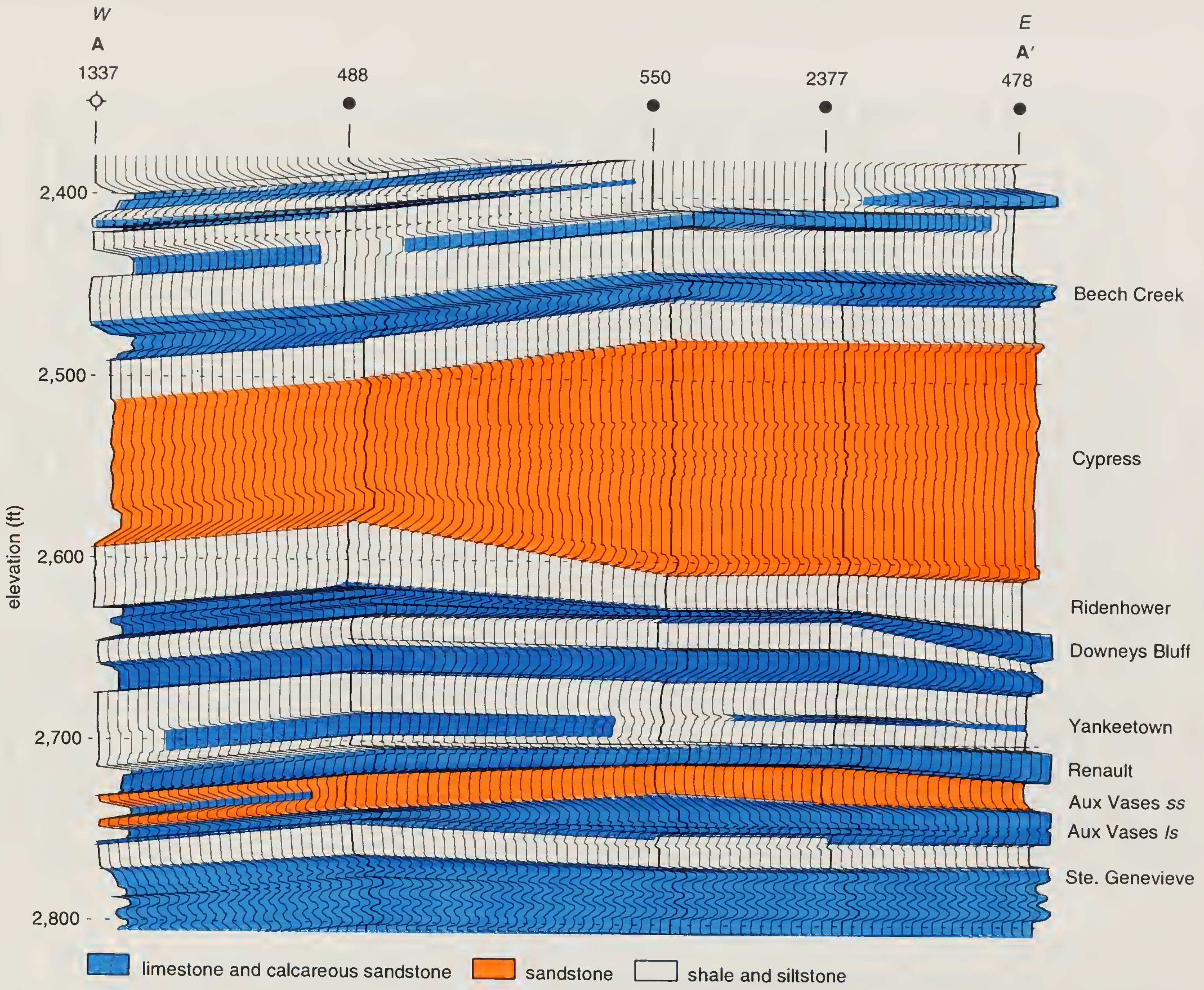

Figure 16a Interpolated velocity cross section A–A′ constructed from pseudo-velocity logs of five wells adjacent to shotpoints 164 through 255 of seismic line ISGS-92-04. The two colors indicate the sandstone and calcareous lithofacies as determined from electric log responses. Location of cross section is shown on figure 4.

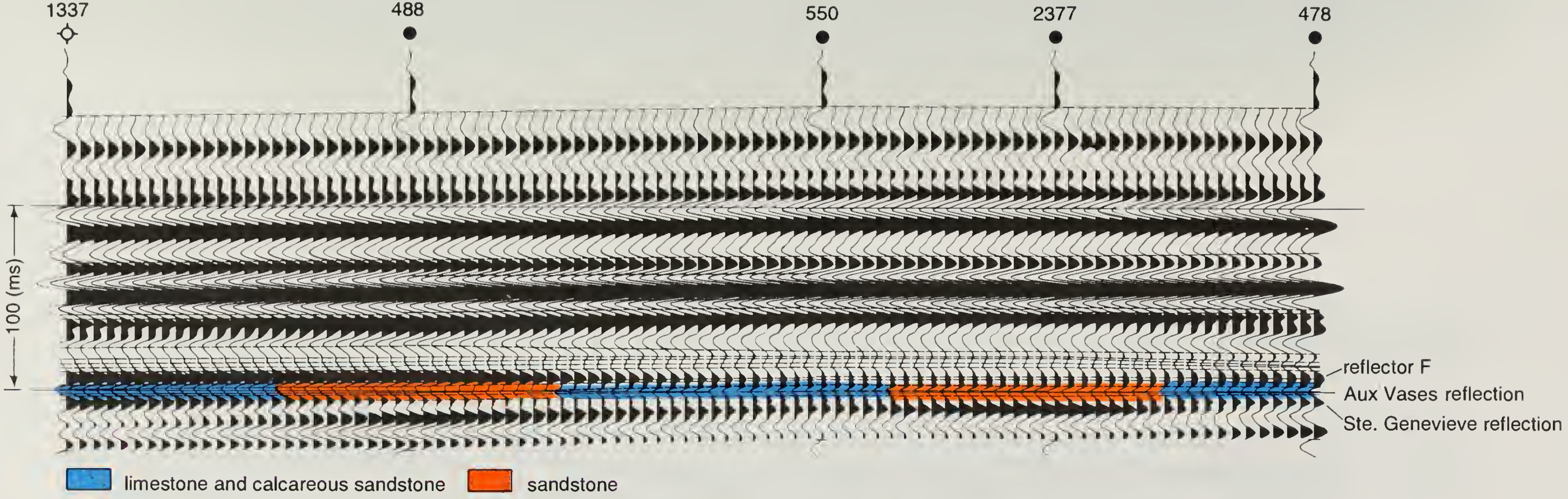

Figure 16b Synthetic seismic model of segment A–A´ of seismic line ISGS-92-04 created by convolving wavelet A with the pseudo-velocity model shown in (a). Reflector F would be equivalent to the Renault-Downeys Bluff interval.

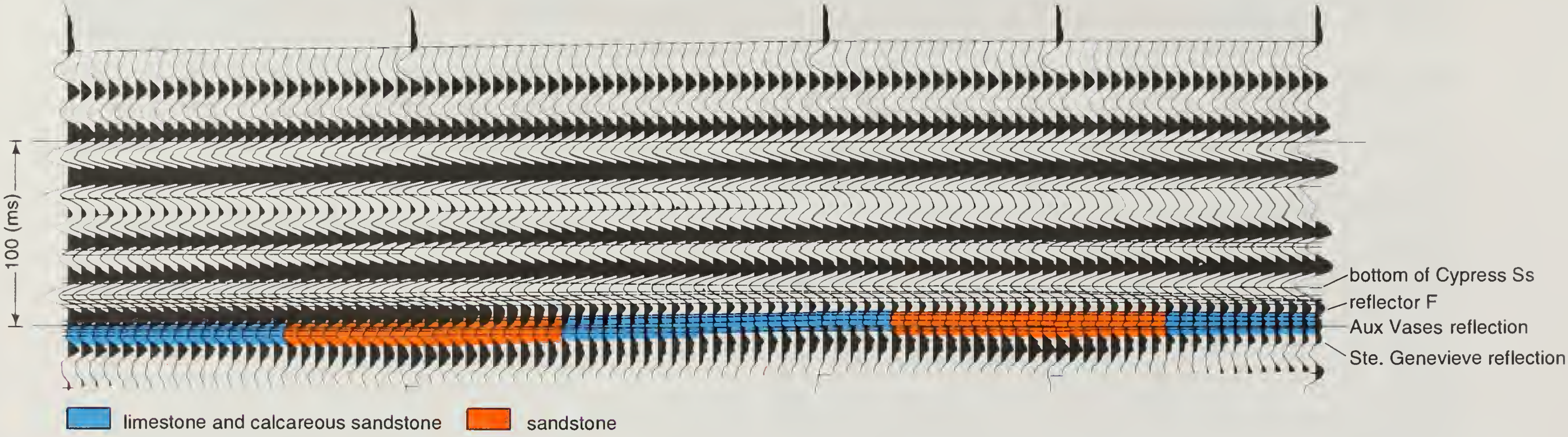

Figure 16c Synthetic seismic model of segment A–A´ of seismic line ISGS-92-04 created by convolving wavelet B with the pseudo-velocity model shown in (a). Reflector F would be equivalent to the Renault-Downeys Bluff interval.

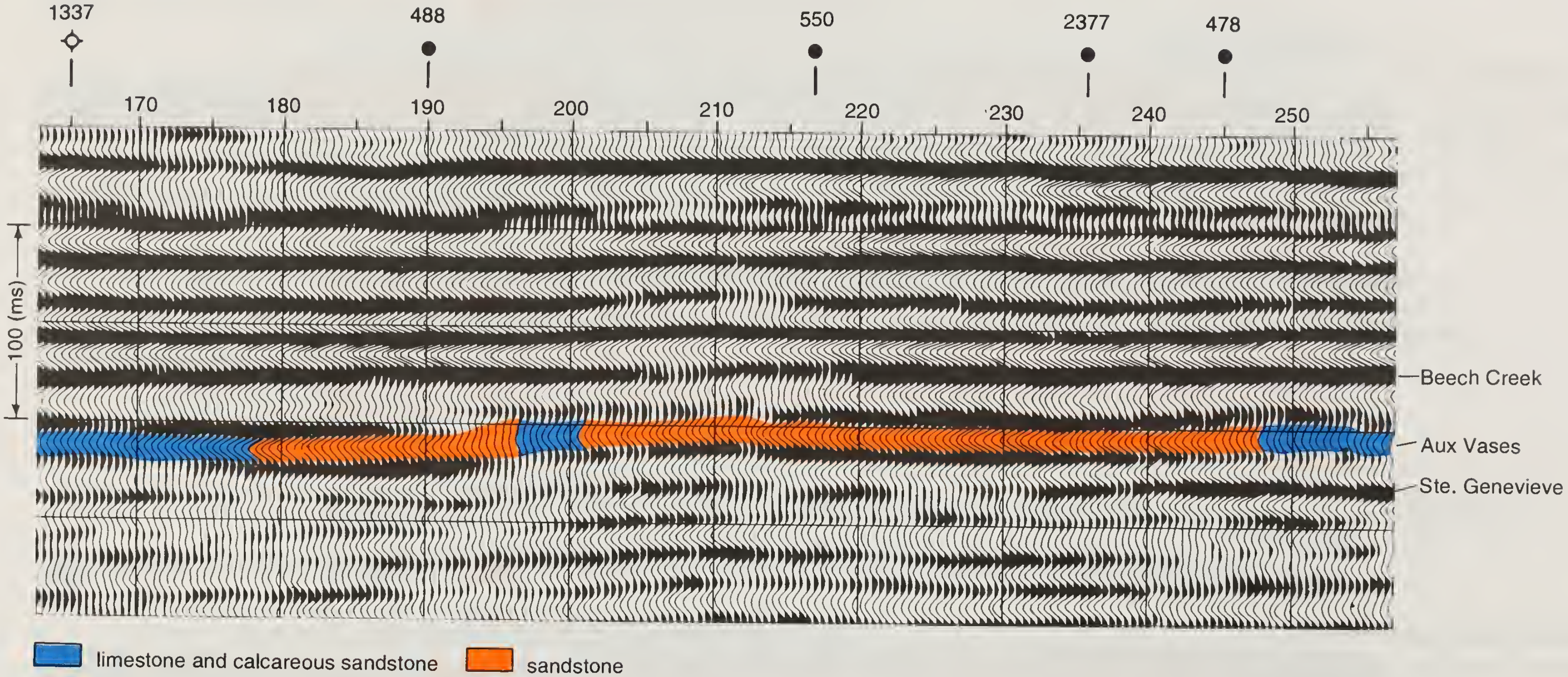

Figure 17 Seismic line ISGS-92-04, shotpoints 165 through 255. The intervals of high seismic amplitude at the Ste. Genevieve reflector are indicative of clean, thick Aux Vases reservoir sandstones. There is a good match between this seismic data and the synthetic seismic models except for the change in the shape of the Aux Vases trough between wells 488 and 550. The change in the trough shape may be related to the thickness of the Cypress.

The Cypress Sandstone thickens by more than 30 feet between wells 488 and 550 (fig. 16a). In the easternmost three wells, the low-velocity Ridenhower shale has been scoured and replaced by Cypress Sandstone. This thickening of the Cypress Sandstone is seen on the synthetic models (fig. 16b, c) as a decrease in seismic amplitude in the reflector above the Aux Vases trough (reflector F). The increase in amplitude of reflector F in well 478 may be a result of the increase in the Downeys Bluff thickness. The variation in the amplitude of the reflector F between wells 488 and 550 on the acquired seismic data for line ISGS-92-04 (fig. 17) may have been caused by this thickening of the Cypress Sandstone. The lower amplitude reflector F in the two models is not present on well locations 550 and 2377 on line ISGS-92-04 (fig. 17). This difference in reflector F character may have been caused by geologic changes that occurred away from the line of section, such as increases in the thickness of the Downeys Bluff thickness. The thickening of the Cypress Sandstone between wells 488 and 550 caused the shape of the Aux Vases reflection in the seismic models (fig. 16b, c) to be changed in a manner similar to the simple Cypress-thickening model (fig. 10). For unknown reasons, this change in the Aux Vases reflector was not observed in the acquired seismic data.

According to wireline log interpretations, a 10-foot section of the Yankeetown calcareous sandstone is present at well 488 (fig 16a). The synthetic seismic model of line ISGS-92-04 using wavelet A (fig. 16b) showed the Ste. Genevieve reflector forming a doublet similar to the one that formed in the wavelet A simple seismic model (fig. 11b). However, the Aux Vases and Ste. Genevieve reflectors on the acquired seismic data are closer in character and shape to the models generated by wavelet B; no Ste. Genevieve reflection doublet is seen on the acquired seismic data. This absence of a doublet indicates that the recovered frequencies in the acquired seismic data are similar to wavelet B and that the wavelet A frequency may be too high.

The thickness of the Renault limestone varies by only a few feet along line ISGS-92-04, and this difference is not seismically resolvable. In other areas of King Field, however, the thickness of the Renault limestone varies by more than 10 feet, an amount that would affect seismic response. This limestone unit will have a seismic response similar to that of the Yankeetown calcareous sandstone (fig. 11).

As was the case with the simpler model (fig. 12), seismic modeling using the actual wells near line ISGS-92-04 also shows a correlation between the amplitude of the signal from the Ste. Genevieve and Aux Vases reflectors and the lithofacies type. The best match between the seismic model and the acquired seismic data was with wavelet B. On line ISGS-92-04, wells 488 and 2377 have the greatest thickness of clean Aux Vases sandstone reservoir (fig 16a). Well 1337 was a dry hole because the Aux Vases reservoir interval there is calcareous. The Ste. Genevieve reflector decreases in amplitude between wells 488 and 1337. As predicted by the seismic modeling, however, the character of the Aux Vases reflection in the acquired seismic data is similar in these two wells. In wells 550 and 478, the Aux Vases sandstone facies is thin, having been replaced at its base by the Aux Vases limestone. In the wavelet B seismic model, the trough shape of the signal from the Aux Vases reflector is more distinct, and the signal from the Ste. Genevieve reflector has a greater amplitude near wells 488 and 2377. The Ste. Genevieve reflector signal has a decreased amplitude and the Aux Vases trough is poorly developed near wells 1337 and 478. The wavelet B seismic model also shows an apparent structural low for the two wells with thin Aux Vases limestone and well developed Aux Vases reservoir sandstone. The acquired seismic data over the same interval show a similar response. The amplitudes of the signals from the Ste. Genevieve reflector and the Aux Vases trough and the apparent structural relief in the Ste. Genevieve in the acquired seismic data are in most cases coincident with the wavelet B model. The reason for the discrepancies between the seismic models and the acquired seismic data are unknown, but they may be the results of some combination of the following: (1) incorrect geologic interpretations, (2) lithologic changes near the line but not seen in the individual wells, or (3) selection of an incorrect seismic wavelet during modeling.

The synthetic seismic modeling of line ISGS-92-04 illustrates why seismic response is not always effective in delineating the reservoir facies. Wells with lower initial production potentials have thicker sections of the calcareous lithofacies within the Aux Vases Formation (figs. 14, 16), but the calcareous lithofacies occurs at two different stratigraphic intervals within the Aux Vases Formation. Where the lithofacies is present within the reservoir interval, the calcareous lithofacies compartmentalizes the reservoir (well 1337; fig. 16a). Wells with a thicker section of the calcareous lithofacies below the reservoir interval usually have lower initial production rates (e.g., well 550, fig. 16a) because the reservoir interval is thinner and, in many cases, is of poorer quality.

Another problem in using seismic character analysis to delineate the reservoir facies is that the seismic "sandstone lithofacies" of the Aux Vases may include shale, a nonreservoir lithofacies. The seismic velocities of sandstone and shale are too similar to be differentiated by seismic reflection data.

The demonstrated relationships between the character of seismic reflections and changes in lithofacies along line ISGS 92-04 were also identified along the other acquired seismic lines. Correlations between seismic reflection characteristics in the acquired data and actual lithofacies changes at King Field ranged from very good to poor. The following examples illustrate how lithofacies changes may be interpreted from changes in signal amplitudes along the seismic line. The predicted lithofacies in these examples should be compared with those on maps of the percent calcareous facies, clean sandstone isopach, and the initial production (figs. 13, 14, 15). These geologic maps were made before the seismic data were acquired. In general, there is a positive correlation between the facies predicted from seismic character analysis and the geology extrapolated from well control.

On line ISGS-92-04 (fig. 18), the change from the calcareous to the sandstone lithofacies is interpreted to occur to the right of shotpoint 310, (fig. 18). The Aux Vases reflector becomes less distinct to the left of shotpoint 310, and the Ste. Genevieve reflector decreases in amplitude. The Ste. Genevieve reflection to the right of shotpoint 310 has a higher amplitude.

On line ISGS-92-01, near shotpoint 348 (fig. 19), the facies transition from the porous sandstone facies on the left to the calcareous facies to the right is marked by the change in the shape of the trough that characterizes the Aux Vases reflector. This trough becomes less well defined in the calcareous facies. The lithofacies, as drawn on the map, was determined on the basis of interpretation of wireline logs and does not match the seismic signature. Wireline log correlations indicate that the area between shotpoints 316 and 340 is part of the sandstone lithofacies, but the seismic signature suggests that this lithofacies should be carbonate rich. This lithofacies map was completed before the seismic data were collected and may be incorrect.

Line ISGS-92-03 (fig. 20) has a poorly developed trough for the Aux Vases reflector between shotpoints 188 and 202. It may be caused by the presence of the calcareous facies. The Ste. Genevieve reflector shows an apparent structural low in the area overlain by the Aux Vases calcareous facies. The Aux Vases seismic model (fig. 12) shows a similar response to the presence of the calcareous

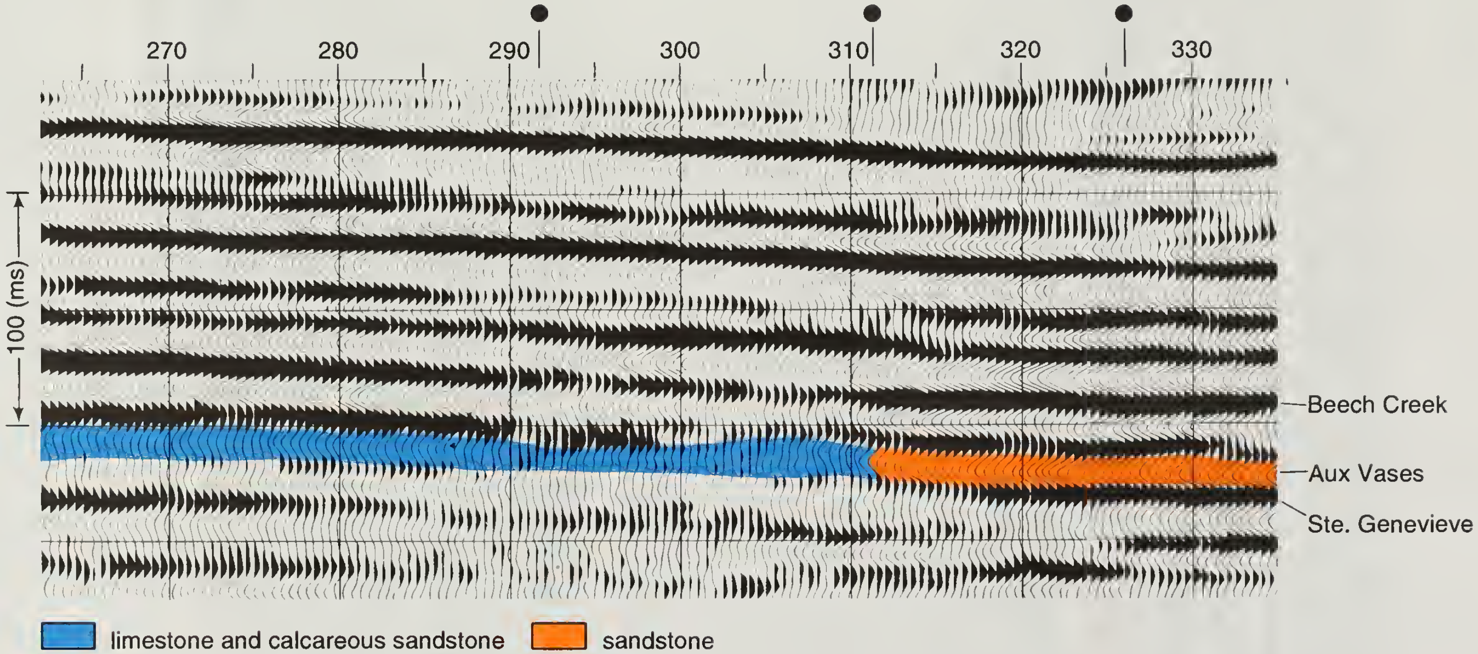

Figure 18 Seismic line ISGS-92-04, shotpoints 265 through 330. The interval of high seismic amplitude and a good Aux Vases trough indicates porous Aux Vases reservoir sandstone from shotpoints 312–334.

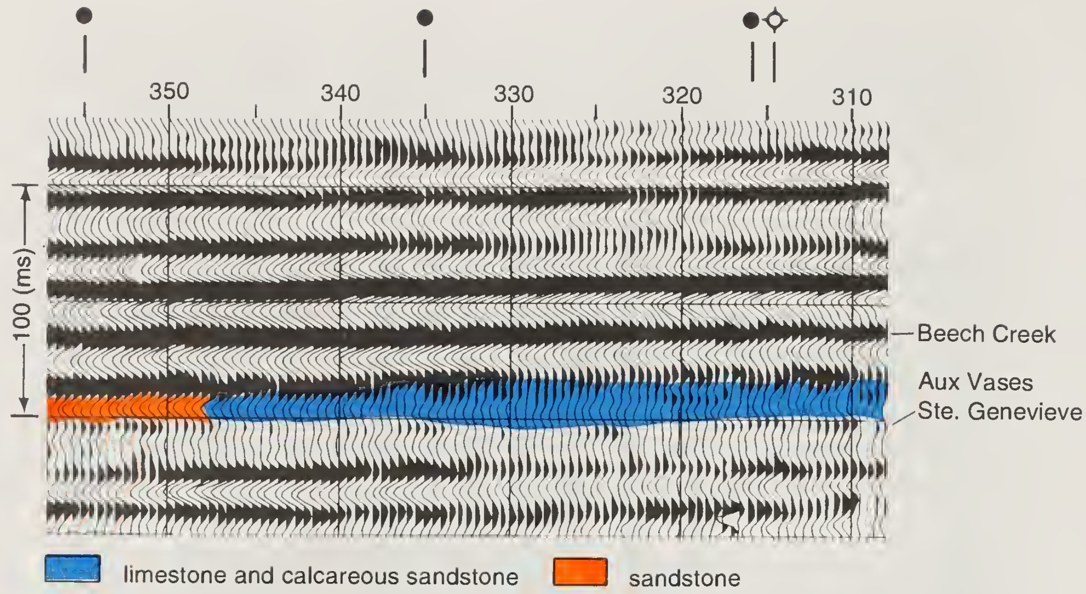

Figure 19 Seismic line ISGS-92-01, shotpoints 310 through 355. The change in facies is characterized by a change in the shape of the Aux Vases trough. The trough becomes less distinct in the areas of calcareous deposition. The Ste. Genevieve reflector peak is not identifiable until it is below the Aux Vases sandstone lithofacies near shotpoint 348.

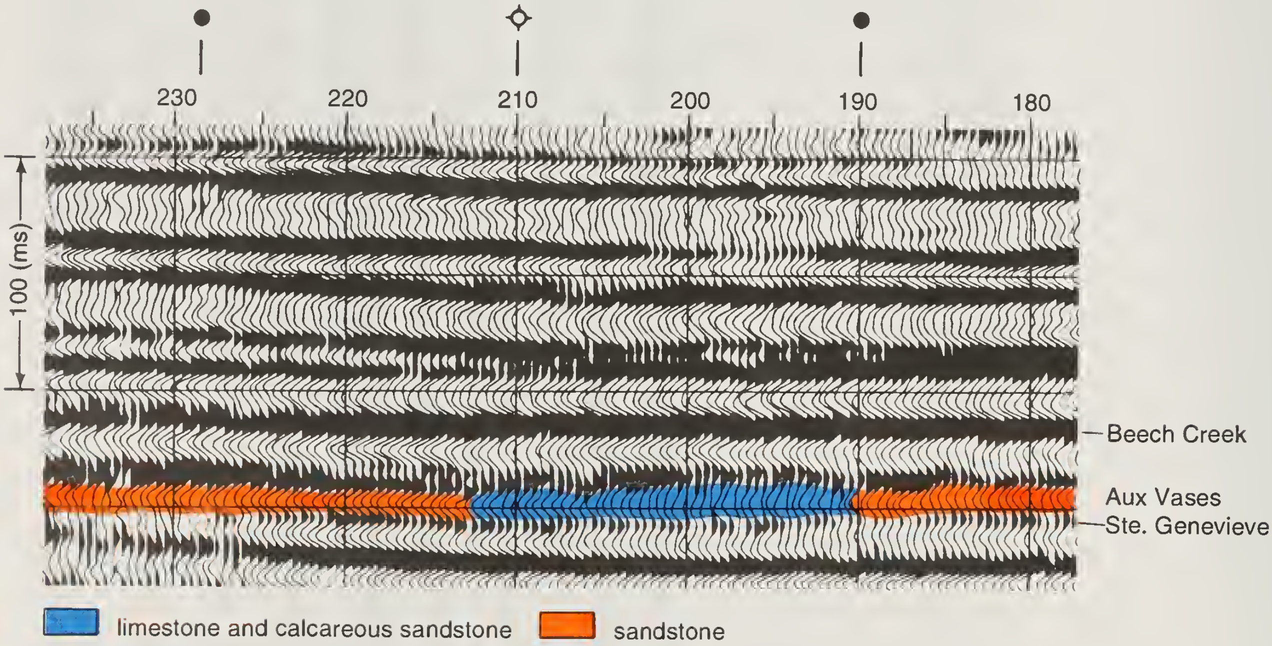

Figure 20 Seismic line ISGS-92-03, shotpoints 180 through 235. The Aux Vases trough becomes less distinct within the calcareous facies (shotpoints 190–214). There is an apparent structural low at the Ste. Genevieve reflector in the area overlain by the Aux Vases calcareous facies.

lithofacies. This seismic lithofacies interpretation is almost identical to the wireline log lithofacies interpretation.

On line ISGS-92-02, between shotpoints 260 and 290 (fig. 21), there is another sandstone-calcareous-sandstone facies transition. The seismic reflections on either side of this shotpoint interval are clearly those of a porous sandstone. There is not only a flattening in the character of the Aux Vases trough, but the Ste. Genevieve reflector also decreases in amplitude in the zone interpreted as the calcareous-rich lithofacies. The well control near this line is not adequate to confirm the seismic interpretation.

SEISMIC STRATIGRAPHY AND ITS APPLICATION TO IMPROVED OIL RECOVERY

Problems in predicting reservoir compartmentalization have been documented in many different reservoirs including those in Illinois (Barber et al. 1983). Reservoir continuity cannot be accurately mapped using wireline log data alone. Barber et al. (1983) showed how, in general, the interpreted continuity of the reservoir decreased as well spacing was decreased.

This inability to predict reservoir compartmentalization is recognized as a problem in the Aux Vases Formation. Waterfloods in the Aux Vases commonly do not match the geologic model's predictions (Bernard Podolsky, personal communication, Podolsky Oil, 1990). Seismic stratigraphy may be a useful tool for delineating the size and areal extent of reservoir compartments. Accurate evaluation of reservoir compartment boundaries would enable an operator to avoid drilling some dry holes, better place injector and producer wells in a waterflood or secondary recovery program, and thereby improve oil recovery.

The Aux Vases reservoir at King Field can serve as an analog for other reservoirs where significant changes in seismic velocity are associated with changes in lithofacies. This study suggests that high-resolution seismic data could be an effective tool for reservoir studies in mature oil fields. The two-dimensional seismic program for King Field was constrained by available funding and was further limited because lithofacies changes occur within one well spacing of 660 feet. It is difficult to project accurately between the widely spaced individual lines. An effective seismic program for reservoir characterization should include both careful mapping of lithofacies by interpretation of existing wireline logs and acquisition of seismic data along closely spaced lines or implementation of a three-dimensional seismic program.

CONCLUSIONS

This study has shown that seismic stratigraphy analysis can be used to help define reservoir compartments in a thin-layered, mixed siliciclastic-carbonate depositional system. Although this study was limited to the Aux Vases Formation at King Field, the results indicate that seismic reflection analysis is applicable to other fields or basins where the reservoir and nonreservoir facies have significantly different seismic velocities.

The Aux Vases reservoir at King Field is usually less than 20 feet thick, occurs at a depth equal to a 500-ms two-way travel time for seismic waves, and is principally composed of sandstone. A significant cause of reservoir compartmentalization is the presence of a low-permeability calcareous lithofacies. The sandstones have

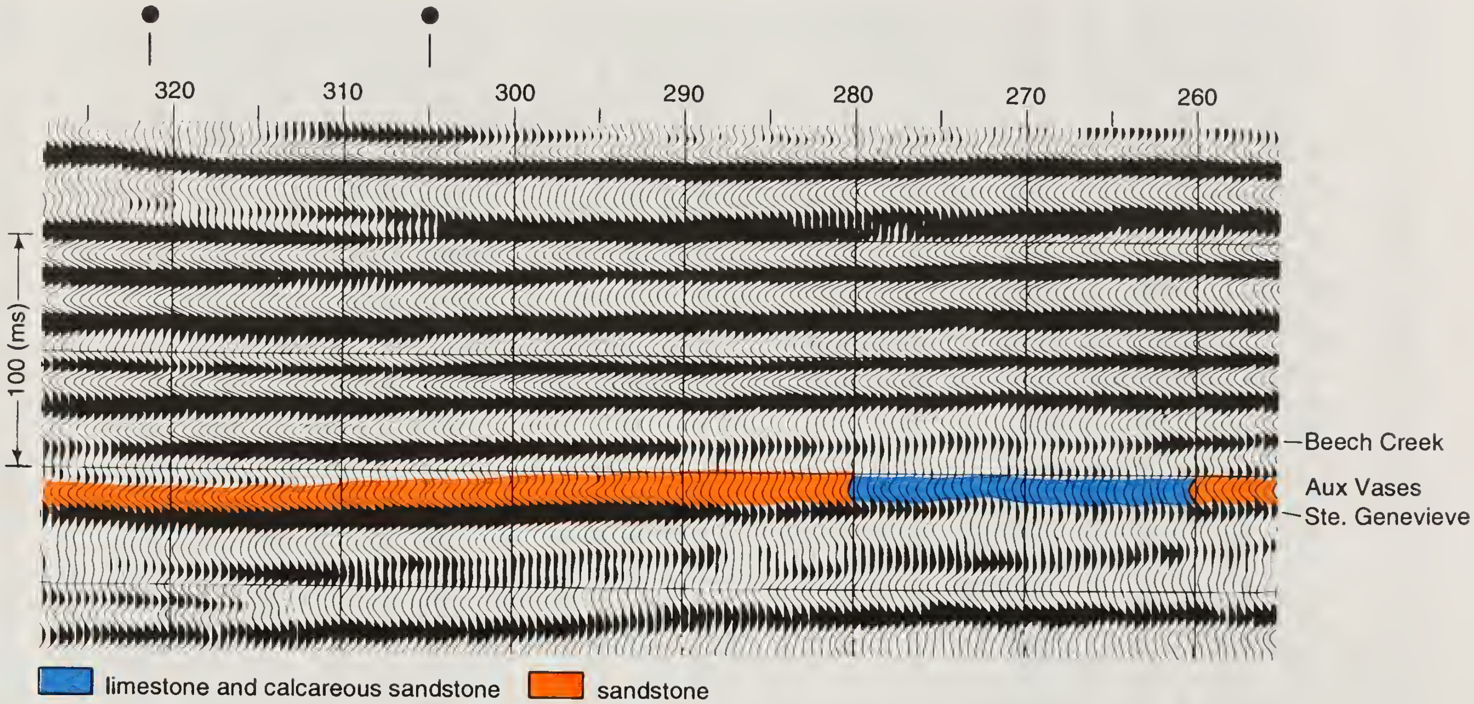

Figure 21 Seismic line ISGS-92-02, shotpoints 260 through 325. The calcareous facies occurs between shotpoints 260 and 289. As with most of the other examples, the calcareous facies is characterized by a decrease in the character of the Aux Vases trough and the Ste. Genevieve reflector.

seismic velocities of 12,000 ft/s, whereas the calcareous zones have velocities of 16,000 ft/s. Such large lateral changes in velocities commonly produce significant variations in the amplitude of seismic signals.

Because old, mature fields such as King Field have few or no velocity logs, old electric logs were used to make a lithology and depth template that was used to modify sonic logs from nearby areas and to create pseudo-velocity logs. There is an acceptable match between the acquired seismic and the synthetic seismograms created using pseudo-velocity logs.

Destructive and constructive interference of seismic signals from overlying formations modify the character of the seismic reflections from the Aux Vases. Variations in lithofacies within the Aux Vases Formation will, because of seismic interference, also modify the relative amplitude of the signal from the Ste. Genevieve reflector directly below. In areas of high-quality reservoir sandstone, the Aux Vases reflector has increased negative (trough) amplitude, and the top of the Ste. Genevieve reflector has an increased positive (peak) amplitude. In nonreservoir intervals dominated by calcareous lithofacies, the amplitudes of both the Aux Vases trough reflector and the Ste. Genevieve peak reflector decrease.

Destructive and constructive interference between seismic waves will create apparent structures in horizons that are really structurally flat. Areas with thick reservoir (low velocity) facies in the Aux Vases Formation will have Ste. Genevieve reflectors that appear to be structurally lower than the same Ste. Genevieve reflectors under Aux Vases with calcareous (high velocity) facies. Apparent structural relief of Ste. Genevieve and Aux Vases reflectors may not be real and can be artifacts of this constructive and destructive interference. Subtle thickness effects, tuning, and bed interference all affect the character of the seismic reflection and change the seismic interpretation of the lithofacies. The character of the seismic reflection is also strongly influenced by the frequency of the acquired data. In lower frequency data, the wavelets are broad and amplitude changes may be more significant. At higher frequencies, the shape of the wavelet, whether it forms a doublet or not, may also be important.

Seismic stratigraphy at King Field has helped differentiate reservoir and nonreservoir facies in the Aux Vases Formation. Subtle changes in the character of seismic wavelets that pass through the Aux Vases Formation appear to be related to changes in the average lithology of the formation. Zones with thick intervals of the calcareous lithofacies are poor producers and may separate the reservoir compartments. Seismic character analysis can be used to help locate the calcareous intervals at King and other Aux Vases fields, and this can be used to create a cost effective program to improve the siting of development wells and the design of more effective secondary recovery programs.

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