EXPLORING FOR SUBTLE MISSION CANYON STRATIGRAPHIC TRAPS WITH ELASTIC WAVEFIELD SEISMIC TECHNOLOGY

SEMI-ANNUAL PROGRESS REPORT

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Disclaimer

Abstract

The 9C3D seismic data that will form the principal data base needed for this research program have been successfully acquired. The seismic field data exhibit a good signal-to-noise (S/N) ratio for all elastic-wave modes. Thus the major hurdle of acquiring optimal-quality 9-C seismic data has been cleared. The stratigraphic oil-reservoir target that will be the imaging objective of the seismic data-processing effort is described in this report to indicate the challenge that now confronts the data-processing phase of the project.

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Introduction

Dawson Geophysical acquired 9C3D seismic data across our selected study area in Mountrail County, North Dakota, during this report period. The acquisition geometry was described in our previous-period report (February 6 – August 5, 2003). We still conclude, as we stated in that report, that we assembled the largest number of vector-based sensors and vector-based sources for this acquisition program that has ever been used onshore-U.S. for a multicomponent seismic survey. Excellent data quality was achieved using this equipment-rich field program and the design parameters described in our previous report.

The stratigraphy of our oil-reservoir objective is described in this report to emphasize the imaging challenges that now have to be dealt with as each elastic mode of the 9C3D wavefield is processed to produce an independent image of the subsurface stratigraphy and lithofacies geometries.

Executive Summary

We confirm in this report that the 9C3D seismic design parameters developed during the early phase of this project did result in high-quality, full-elastic seismic wavefields being acquired across our Williston Basin study area. The critical seismic data-acquisition phase of the project has thus been completed. We describe here the imaging target that was illuminated by the 9C3D seismic wave modes that need to be processed. Our 9C3D seismic data-processing effort was initiated late in this report period. Key findings from this data-processing research will be described in our next progress report.

Experimental

A claim was made in our previous-period report that the 9C3D seismic survey implemented in this project would involve the largest number of vector (3-C) sensors and vector (3-C) sources ever used for an onshore-U.S. multicomponent seismic survey. We still believe that statement is correct. For example, the vector-source effort used in the data acquisition is illustrated in Figure 1, which is a photograph of the vector sources that were deployed. Twelve vibrators were involved in the seismic data-acquisition program. Four vibrators were deployed in an array at each source station to create a vertical-displacement vector wavefield; a second array of four vibrators created an inline horizontal-displacement vector wavefield; and a third array of four vibrators generated a crossline horizontal-displacement vector wavefield. Approximately half of the horizontal vibrators currently available in the U.S. were used in this seismic field program.

Results and Discussion

Geology Overview

A major portion of the geology data base needed for the project was amassed and documented during the period. We present here a brief overview of that data base to illustrate the stratigraphic, structural, and lithofacies character of the oil-reservoir target that has to be imaged.

Structural Configuration of Imaging Target

The primary reservoir targets are shoals of porous oolitic limestone occurring within the Mission Canyon interval of Mississippian rocks in the Williston Basin. The regional structural configuration of the Mission Canyon within the North Dakota portion of the Williston Basin is shown in Figure 2, and the location of the project study area is indicated on this structure map. The basin is a simple, symmetrical, bowl-like depression with only a few isolated, minor structural ridges and noses. The Mission Canyon formation has no distinctive structural features near our study area. Thus structural configuration of the Mission Canyon cannot be used to recognize where oolitic shoal facies should be encountered. Specifically, the structure of the Mission Canyon across a distance similar to that of our study area consists of flat, near-horizontal bedding.

Stratigraphic Character of Imaging Target

The stratigraphic correlation chart and stratigraphic nomenclature for the North Dakota portion of the Williston Basin are illustrated in Figure 3. The Mission Canyon formation is the central portion of the Madison Group, with the older Lodgepole and younger Charles formations completing the Madison Group interval. The rock series, in sequential order from oldest to youngest, across the Madison Group are Kinderhook (Lodgepole Formation), Osage (Mission Canyon Formation), and Meramec (Charles Formation).

Lithofacies types and thicknesses for each of the Madison Group series are shown in Figure 4. The Osage series, the targeted interval spanning the Mission Canyon, exhibits an east-to-west thickening into the basin center, with the series being about 1000 feet thick in the project area. The lithofacies across the Osage series is limestone. The principal variation in lithofacies is that Osage-series limestones have variable shale content. The lithofacies map in Figure 4 segregates the Osage series into only two rock types: “clean” limestone and shaly limestone. The location of the boundary between these two lithofacies is difficult to define from well control and even more difficult to map with conventional seismic data. All of the maps in Figure 4 should be viewed as generalized lithofacies models, not as detailed description of lithofacies distributions. It is correct to state that our project area is in the shaly limestone portion of the Osage series.

A more detailed stratigraphic correlation and nomenclature for the Mission Canyon formation is illustrated in Figure 5. Locally to the project area, our targeted oolitic reservoirs are in the Sherwood interval, in the central portion of the Mission Canyon rock column. Included at the top of this stratigraphic model is a generalized description of the depositional environments that created each carbonate unit within the interval. From east (shallower basin) to west (deeper basin), the depositional environment progressively changes from sabkha, to lagoon, to shoreline, to shallow shelf, with these environments prograding basinward as carbonate deposition continues into the overlying Charles formation. Local to the study area, a vertical well bore will penetrate all of these depositional environments as it progresses from younger to older Mission Canyon rocks.

These depositional environments can be combined to produce the depositional model for the Mission Canyon depicted in Figure 6. As defined in Figure 5, the environment varies successively from sabkha in the east to lagoon, shoreline, and shallow shelf as the profile extends west into the deeper part of the basin. The shoreline environment in Figure 5 is labeled *strandline-shoal* in Figure 6. The shoal mounds developed in this shoreline environment are our reservoir targets and seismic-imaging targets. Under proper depositional conditions, these shoals are porous, oolitic bodies bounded by sealing lagoonal and shaly shallow-shelf facies. These oolitic mounds rarely create reflector terminations in conventional P-wave seismic data and seldom result in significant changes in P-wave reflection waveshape. The subtle, complex lateral and vertical changes in carbonate lithofacies associated with these oolitic-mound drilling targets cause them not to be significant features in P-wave seismic data, which is the principal reason why we are using a full-elastic seismic wavefield imaging approach in this study.

Lithofacies Character of Imaging Target

The location of the 9C3D seismic survey acquired during this report period is defined by the rectangular outline in Figure 7. Ten wells have been drilled inside the seismic image space. A southwest-to-northeast profile is shown connecting four of these wells. Subsurface control from these wells will be used to describe the complex interfingering stratigraphy within the targeted reservoir interval. As stated in the figure caption, the locations of the oolitic shoals indicated on this map are suggestions, not reality. The objective of the seismic imaging effort is to define such oolitic-shoal geobodies with an imaging accuracy and reliability that will result in a high success rate for new exploration wells.

Log curves for the four wells along the profile are displayed in Figure 8. Three wells are dry holes; one is a producer. The logs are depth shifted to create a flat horizontal surface for the State A unit, a thin anhydrite that is a popular stratigraphic datum in the area. Neutron-porosity and density-porosity logs are used to segregate the various rock types. The separation character between these two porosity response curves leads to the lithofacies definitions labeled in this cross-section plot. The facies that needs to be drilled is the porous Sherwood limestone occurring in the productive Nordquist 43-23 well. Laterally and vertically, this targeted reservoir facies is bounded by sealing mudstones, tight dolomites, tight limestones, and anhydrites. All of these lithofacies interfinger in complex, unpredictable patterns, and each rock unit is thin in terms of seismic resolution, with individual unit thicknesses ranging from 10 to 50 feet. The end result is that Sherwood oolitic shoal geobodies are difficult, subtle targets to image with seismic technology.

An important petrophysical property of these oolitic shoal targets that indicates that seismic programs that exploit these reservoirs should be based on multicomponent data, not on conventional P-wave data, is documented by local dipole sonic log data. It is not common to acquire full-waveform sonic log data in the project area. Dipole sonic log data could be found in only one well near the seismic survey area, the Van Eeckhout 21-16 well about 10 miles to the northeast. These log data are shown in Figure 9. The Sherwood facies penetrated by this well was a clean limestone, a desirable reservoir facies. Although the P-wave slowness curve exhibits some variation at the top and base of this limestone, P-wave seismic data rarely show significant changes in Sherwood reflection character. These logs indicate that S-wave slowness exhibits a different behavior at the top of the Sherwood, that being a slow ramp-like increase (Vs decrease), which should cause S waves to produce a different Sherwood reflection behavior than P waves. Our belief is that this difference in P-wave and S-wave impedances is significant and supports the logic for doing the multicomponent research investigation that we have initiated. Additionally, the logs indicate that the Vp/Vs velocity ratio undergoes a significant increase across the clean-limestone Sherwood interval. This Vp/Vs ratio can be estimated from the P and S images that will be produced in this study and may be an important new seismic attribute for mapping lithofacies units within the Sherwood interval.

Seismic Facies Character of Imaging Target

Multicomponent seismic data were acquired along a 2-D test profile across Wabek field, about 10 miles northeast of the study area, shortly before the start of the research project. These data offer an additional encouragement that seismic modes other than the P-wave mode are preferred options for imaging Sherwood oolitic shoal targets. Only two elastic wave modes were used for imaging along this 2-D test line: a P-P mode and an SH-SH mode. The seismic line was positioned so that it crossed three wells that were poor, medium, and good Sherwood producers. Comparisons of the P-P and SH-SH images are provided in Figure 10.

The SH-SH data were processed by two contractors, and each contractor version is shown. The P-P image exhibits no significant character change between good and poor reservoir conditions, which is the customary P-P response. In contrast, each SH-SH image displays a seismic character at the good producer that differs considerably from the waveshape character at the two less productive wells. Our objective is to determine if similar seismic facies changes can be retrieved from P-P, SH-SH, SV-SV, and P-SV images that will be constructed from the 9C3D seismic data just acquired across the study area.

Conclusions

The seismic data-acquisition phase of this project has been successfully completed. A rather comprehensive geologic data base has been compiled that provides good descriptions of the subsurface structure, stratigraphy, and lithofacies properties of the oolitic-shoal limestone targets that need to be imaged in the Sherwood interval of the Mission Canyon formation. The 9C3D seismic data are now being processed to determine which elastic mode(s) best images these subtle oil reservoirs.

References

Craig, L. C. 1972, Mississippian system: Geologic Atlas of the Rocky Mountain Region, Rocky Mountain Assoc. of Geol., p. 100 – 110.

Hansen, A. R., 1972, The Williston Basin: Geologic Atlas of the Rocky Mountain Region: Rocky Mountain Assoc. of Geol., p. 265 – 269.

Sperr, J. T., Stancel, S. G., McClellan, W. A., and Hendricks, M. L., 1993, Wabek and Plaza fields: carbonate shoreline traps in the Williston Basin of North Dakota: Field Study 1, North Dakota Geological Survey.

Acronyms and Abbreviations

P: Compressional seismic wave (P-wave)

P-P: An elastic wave mode involving a downgoing P wave and a reflected upgoing P wave

P-SV: An elastic wave mode involving a downgoing P wave and a reflected upgoing SV shear mode

S: Shear seismic wave (S wave)

SH: Horizontal-shear seismic wave

SH-SH: An elastic mode involving a downgoing SH wave and a reflected upgoing SH wave

S/N: Signal-to-noise ratio

SV: Vertical-shear seismic wave

SV-SV: An elastic wave mode involving a downgoing SV wave and a reflected upgoing SV wave

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Figure 1. Vector sources used to acquire 9C3D seismic data. This assembly of 12 vibrators consists of 4 vertical-displacement vibrators, 4 inline horizontal-displacement vibrators, and 4 crossline horizontal-displacement vibrators.

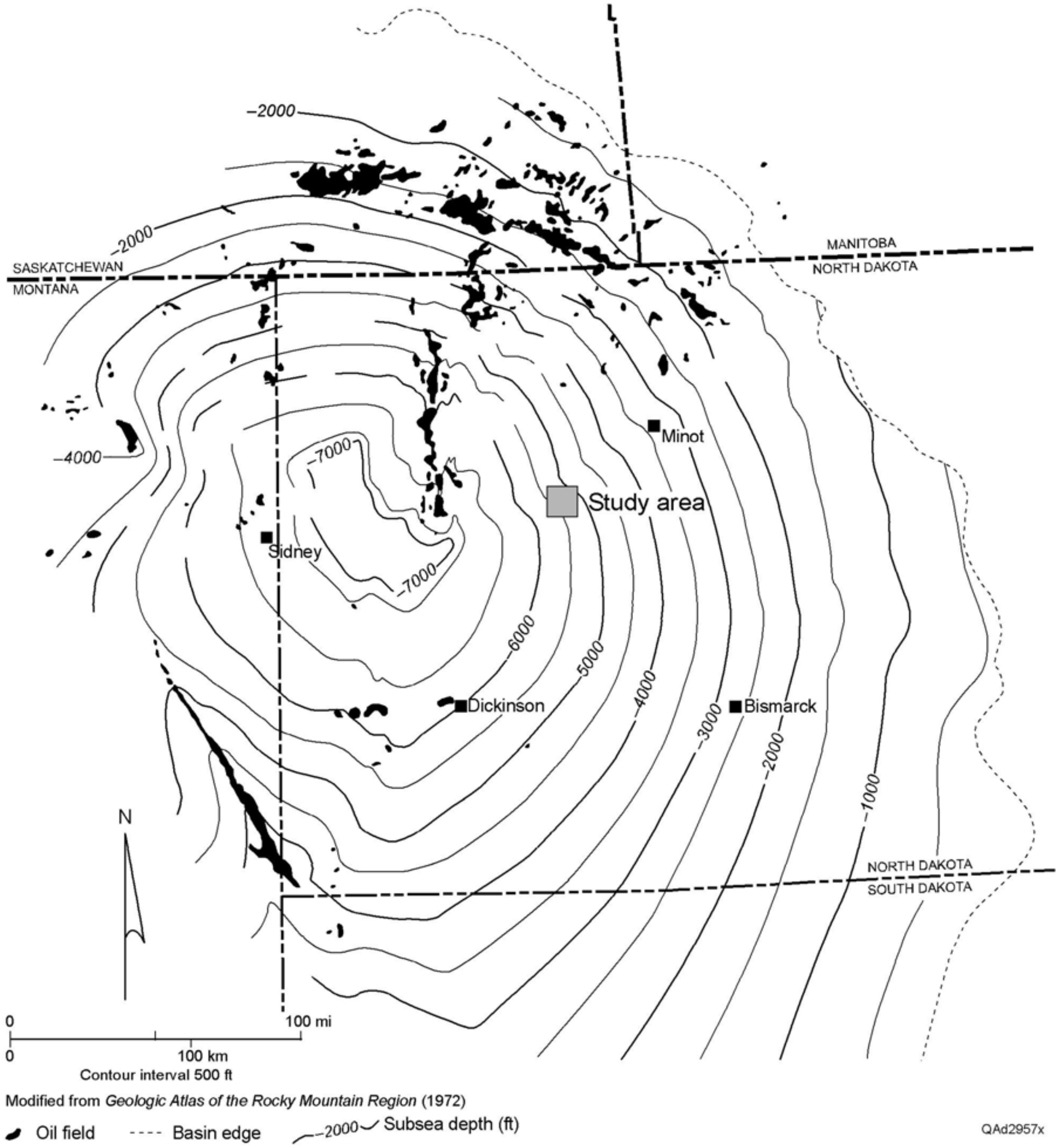

Figure 2. Mission Canyon structure map showing the location of the study area (modified from Hansen, 1972).

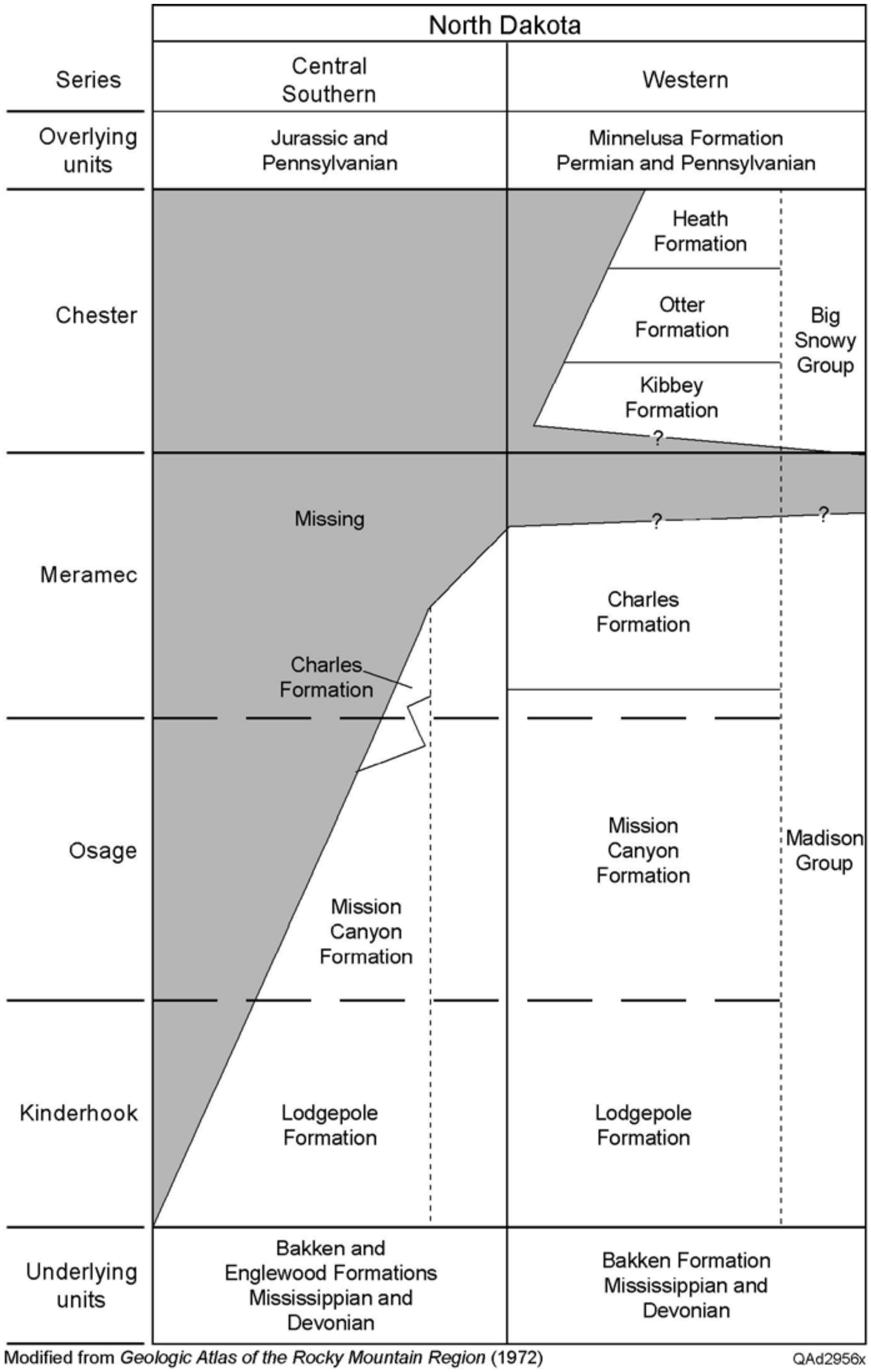

Figure 3. Correlation chart of Mississippian formations across the Williston Basin (modified from Craig, 1972).

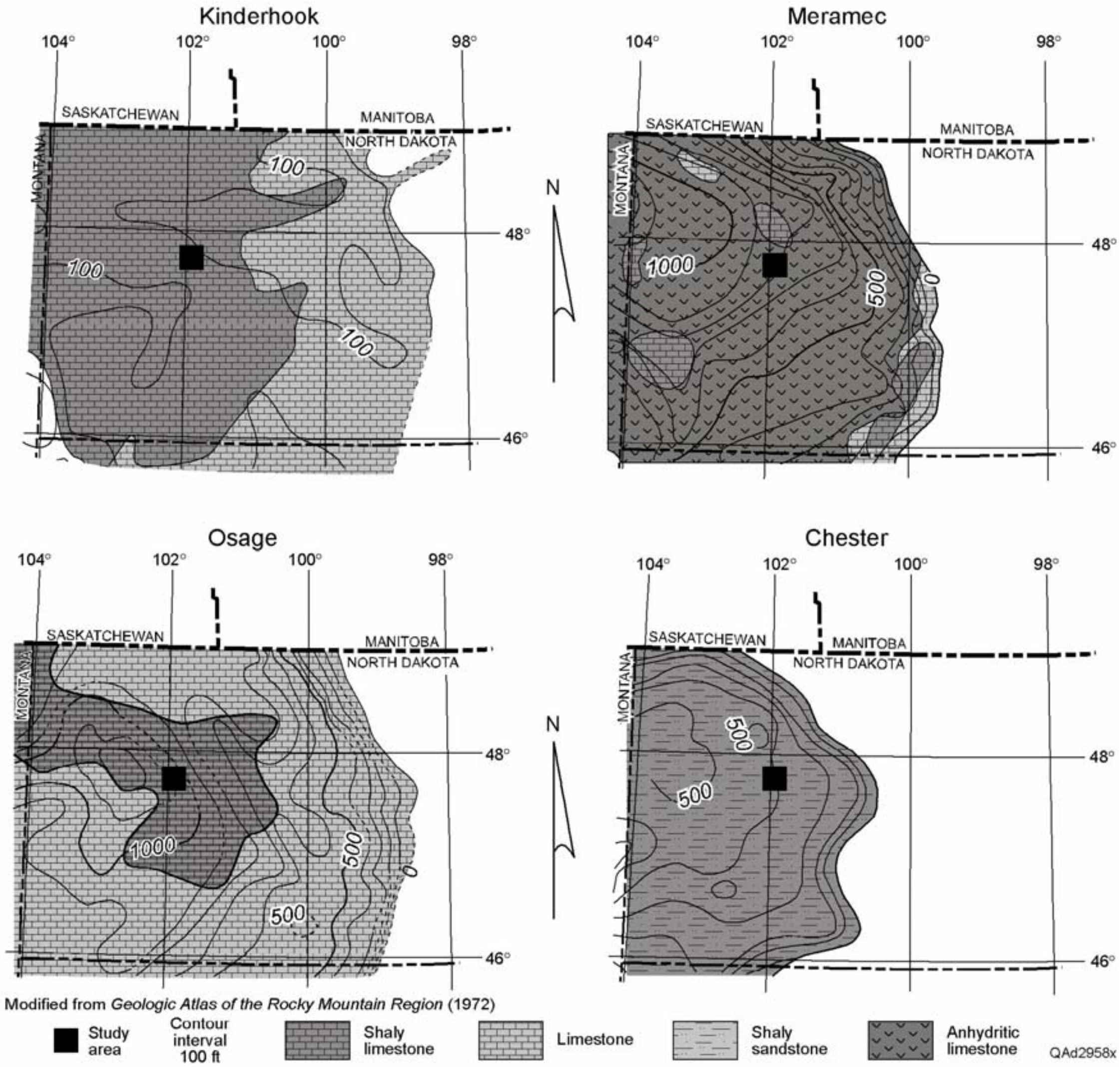

Figure 4. Thicknesses and lithofacies of Mississippian series in the North Dakota portion of the Williston Basin (modified from Craig, 1972).

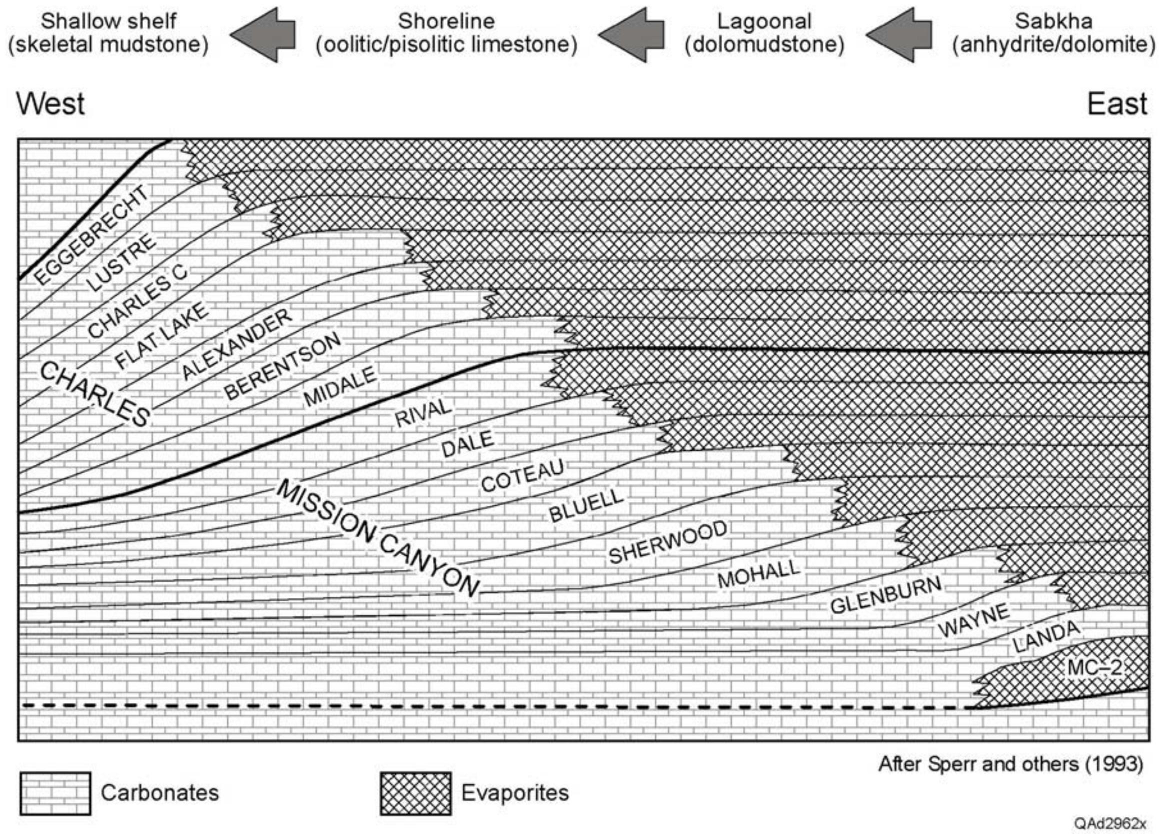

Figure 5. Lithofacies, environments, and stratigraphic nomenclature for the target interval across the study area (modified from Sperr, 1993).

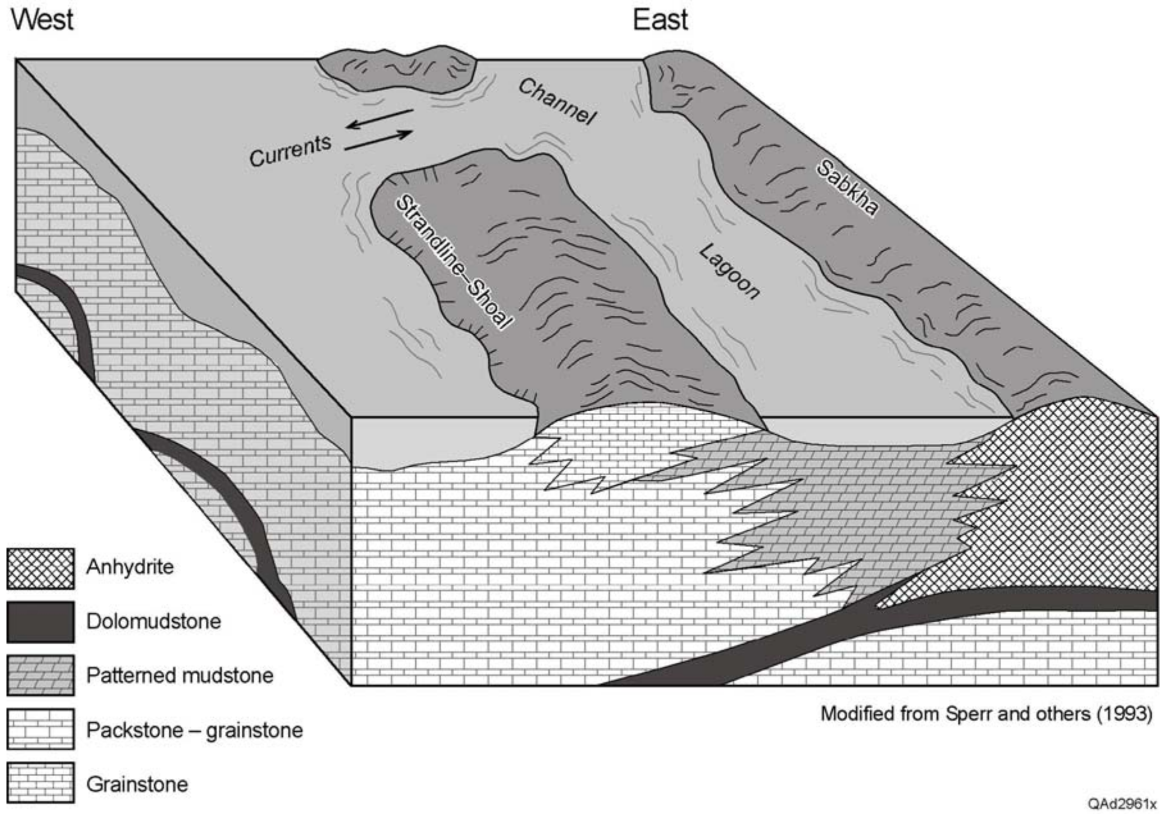

Figure 6. Mission Canyon depositional model (modified from Sperr, 1993).

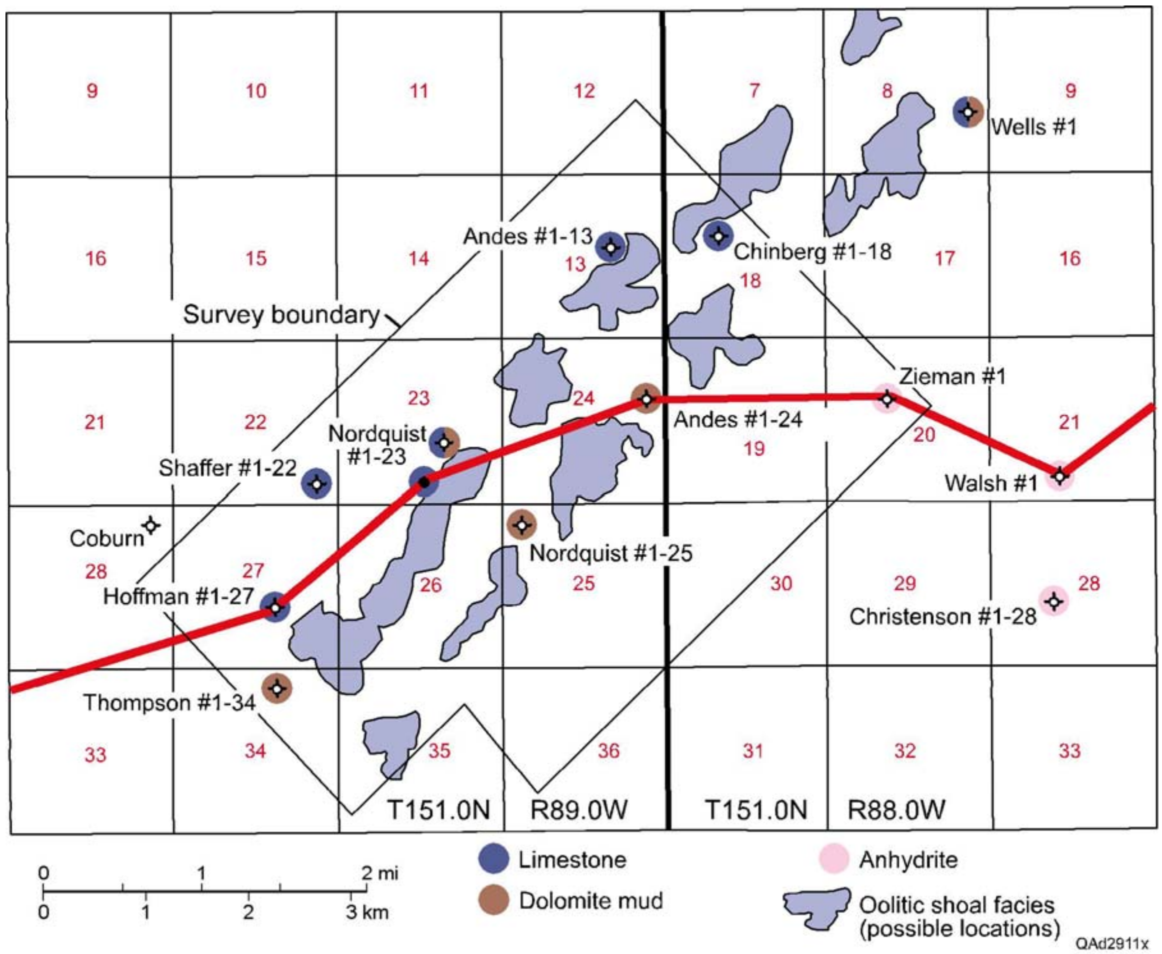

Figure 7. Wells used to construct detailed stratigraphy across the seismic image space (rectangular area). The oolitic shoal areas that are indicated are hypothetical, not actual, target locations.

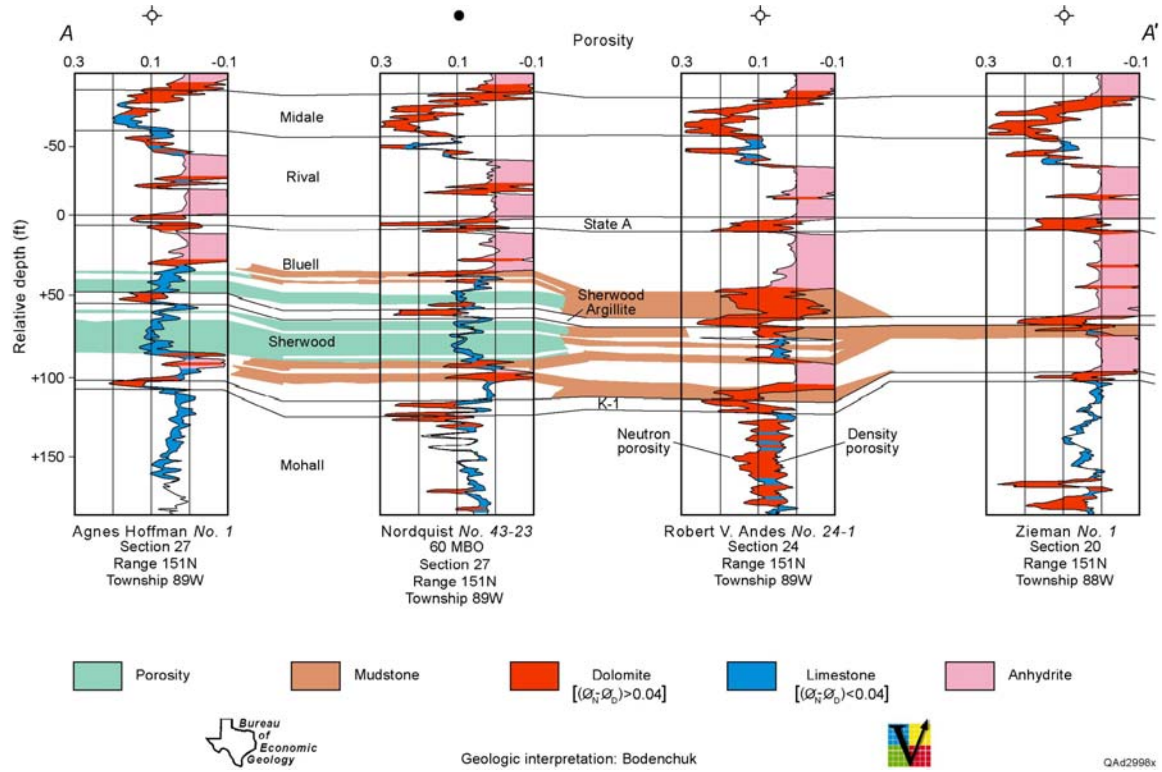

Figure 8. Lithofacies and stratigraphic interpretation of the target interval for the study area. The high-porosity Sherwood facies found in the Nordquist 43-23 well is the seismic (and drilling) target.

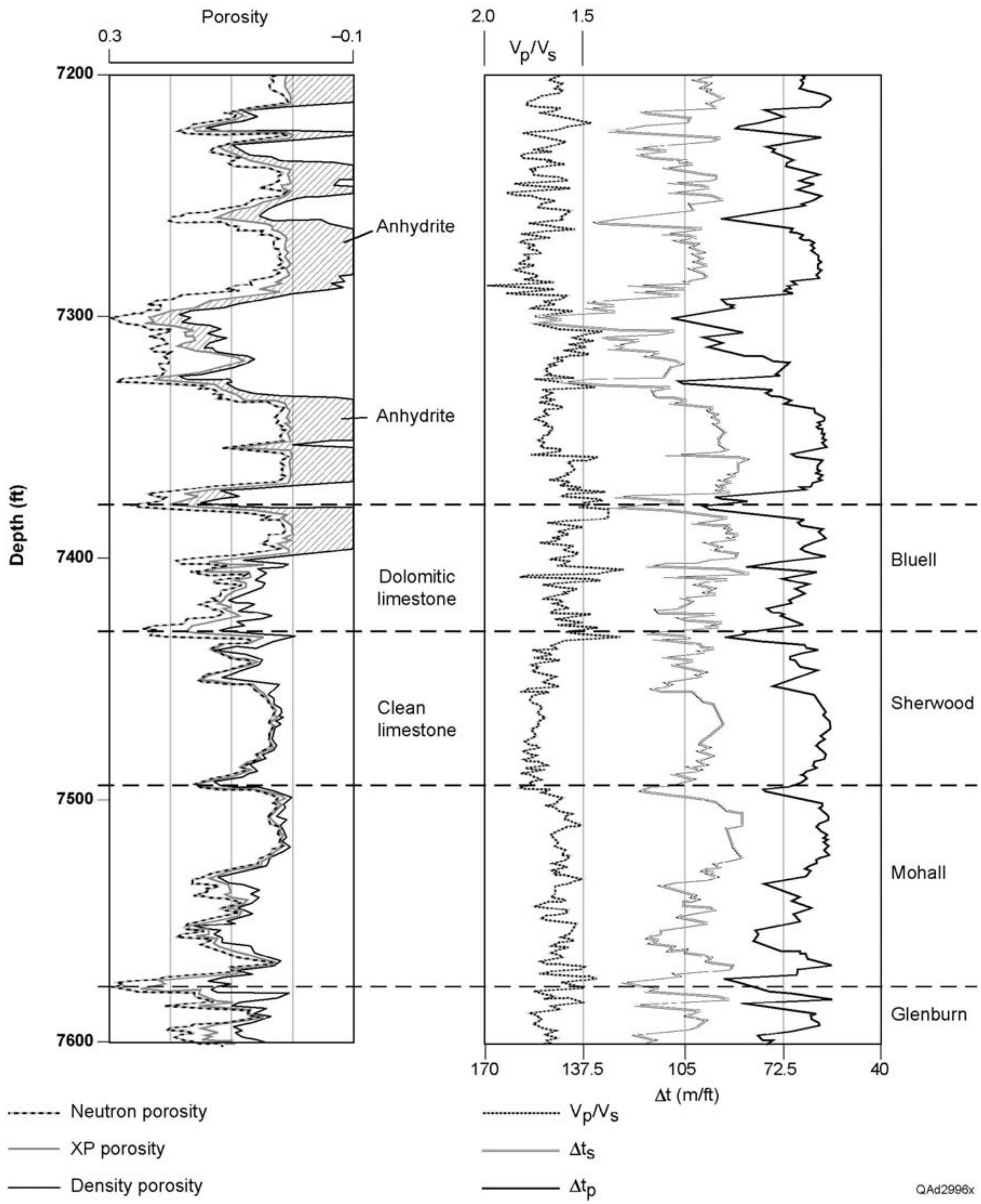

Figure 9. P-wave and S-wave velocity information acquired in a well near the study site.

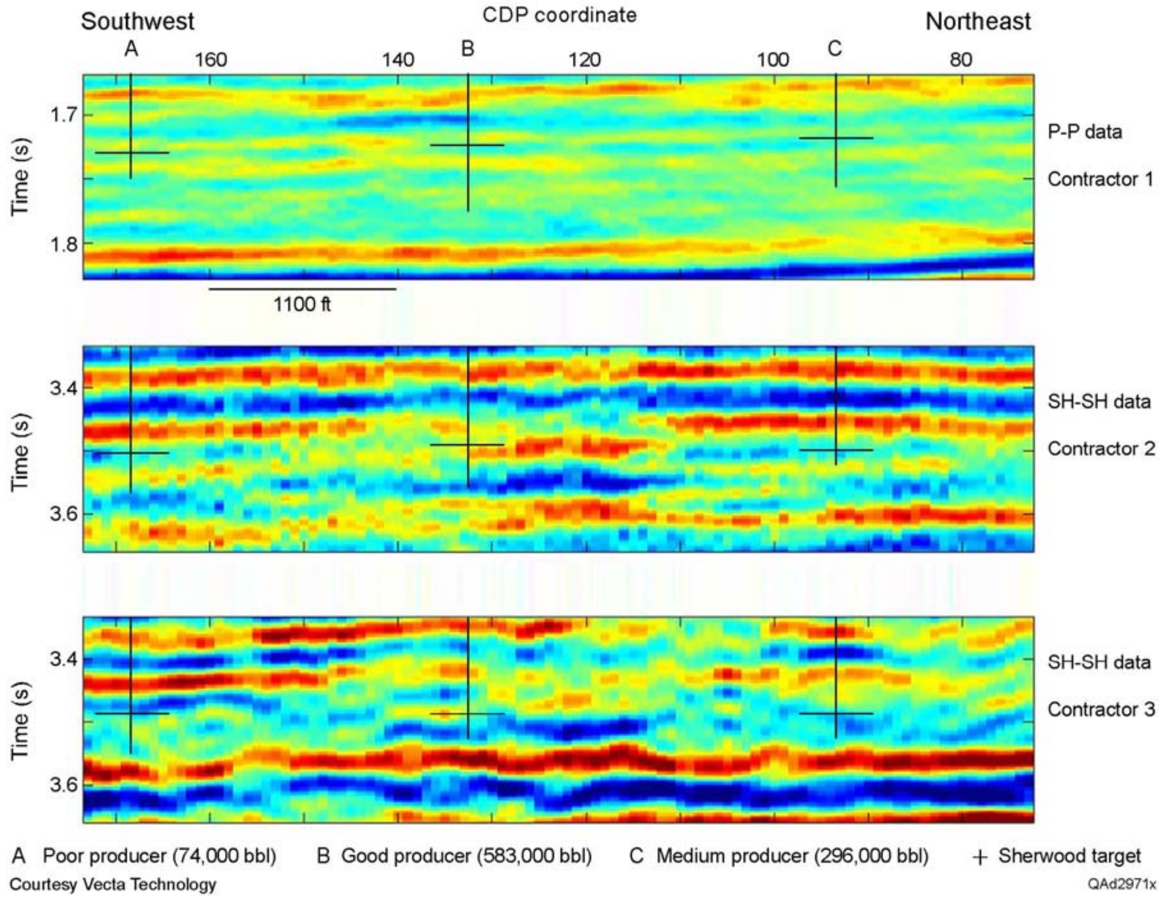

Figure 10. Imaging results from two elastic wave modes (P-P and SH-SH) along a 2-D seismic test line about 6 miles north of the study area.