Practical Vertical Resolution Limits of CDP Data Targeting Reflectors Less Than 125 m Deep near Independence, Kansas

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SUMMARY

Shallow high-resolution reflection surveys can be used to study hydrocarbon reservoir analogs on a scale of 1 m vertically and 5 m horizontally. This scale is two orders of magnitude up from laboratory specimens and two orders of magnitude down from typical production reservoirs. A 12-fold CDP survey designed to determine practical resolution limits imaged geometric changes in an oolitic limestone near Independence, Kansas, at a depth of approximately 75 m. The dominant frequency of the stacked data is in excess of 180 Hz. The predicted resolution limits at this site, according the the 1/4-wavelength criterion, is on the order of 2 to 3 m. Practical resolution limits at this site could be as small as 1 to 1 1/2 m. Seismic reflection can be utilized at this site to accurately place stratigraphic core drilling holes for determining depositional environments and geologic processes responsible for the present geologic setting.

INTRODUCTION

A high-resolution seismic-reflection feasibility study was conducted in southeastern Kansas to delineate the orientation and geometry of a shallow oolitic limestone. Knowledge of orientation and geometry serves as an aid in determining the depositional setting. The 12-fold CDP profile was designed to image geometric changes of the oolitic limestone at a depth of about 75 m in a depositional shelf-to-basin environment. An initial seismic survey revealed truncations and pinch-outs in strata that sandwich the oolitic limestone. These features are significant from both a geologic and geophysical perspective. Geologically, the nature of a truncation or pinch-out, either from erosion or a facies change, is important for determining the depositional history. Geophys-ically, the pinch-out or truncation represents an opportunity to quantify the practical thin-bed resolution of shallow high-resolution seismic reflection at this site.

This study highlights the geophysical aspects of quantifying practical thin-bed resolution. The data were acquired and processed to focus on a distinct shallow high-resolution seismic reflection at approximately 65 ms (stratigraphically underlying the oolitic limestone unit) that either pinches out or is truncated by an overlying reflector. The results of this study will aid ongoing interpretations of the pinch-out or truncation of the oolitic limestone unit and will allow accurate placement of core holes intended to determine whether the pinch-out or truncation is due to erosion or to a depositional facies change.

The thin-bed resolving power of the CDP seismic-reflection technique is dependent upon the dominant frequency of the recorded reflection wavelet (Widess, 1973). Increasing the dominant frequency of recorded reflection signal involves: (1) generating a high-frequency source pulse, (2) sensing the signal with receivers with high voltage output, low noise, and flat frequency response, (3) recording the signal digitally on a seismograph with a large instantaneous dynamic range and electronically quiet analog filter and gain capabilities, and (4) optimizing the spread interval and receiver spacing for the target of interest (Knapp and Steeples, 1986). Criteria for resolving converging thin-bed sequences rely on observations of interference as evidenced by distortion of reflection waveforms (Ricker, 1953).

Practical resolution limits are dependent not only on recorded reflection frequencies but also on wavelet characteristics and noise. Zero phase wavelets possess the highest resolving potential (Knapp, 1990). A known theoretical wavelet can be phase-filtered to zero phase. Successful application of deconvolution requires a statistically large number of unique reflection wavelets and data with a large signal-to-noise ratio (Yilmaz, 1987). Shallow high-resolution reflection data sets rarely have more than four to six reflections and are notoriously noisy (Steeples and Miller, 1990). Practical optimization of shallow high-resolution data sets by phase filtering to zero phase is generally not possible.

GEOLOGIC SETTING

The study area is located near Independence, in Montgomery County, Kansas (Figure 1). The strata of interest in this area are Pennsylvanian in age and consist of interbedded limestones, shales and sandstones. The Drum Limestone was selected

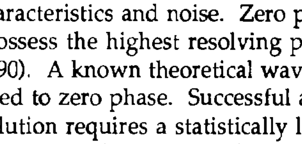

FIG. 1 Location map of study area near Independence, Kansas.

as the stratigraphic interval of interest because it contains an isolated oolite body that is potentially analogous to oolitic petroleum reservoirs in central and western Kansas. The area around Independence was selected for study because it is located at or near the depositional slope break where thickness and facies changes in the Drum Limestone, as well as overlying and underlying units, occur over short distances.

The goals of the overall project are to determine the geometry of the oolite body, determine the relationship between the facies and geometry of the Drum Limestone and the facies and geometry of underlying and overlying units, and to determine the role of other controlling factors such as tectonic effects and sea level changes (e.g., Feldman and Franseen, 1991).

FIELD PROCEDURES

Data for this study were acquired on an EG&G Geometrics 2401 seismograph. The seismograph amplifies, filters (analog), digitizes the analog signal into a 15-bit word, and stores the digital information on magnetic media. The selected low-cut filters have a 18 dB/octave rolloff from their indicated -3 dB point. Production lines were acquired with 100 Hz analog low-cut and 500 Hz analog high-cut filters. The 1024 samples recorded per trace were at a 1/2 ms sampling interval. The dynamic range of the seismograph was more than adequate to record high-quality reflection information in the presence of source-generated and cultural noise at this site.

A series of walkaway-noise tests was conducted prior to acquisition of the production seismic lines. The spectral and total energy characteristics of the downhole .50-cal. seismic source made it the source of choice at this site for this geologic target. The receiver array consists of three 40-Hz geophones equally spaced over approximately 1 m and centered on each station. The receiver array is designed in an attempt to attenuate some of the source-generated noise. Analysis of the noise tests allows acquisition parameters and equipment to be optimized for the site conditions.

The nominal 12-fold CDP production lines were acquired using an end-on source/receiver geometry. Analysis of the walkaway data allowed determination of an optimum source-to-nearest-receiver offset of 17 m and source-to-farthest-receiver offset of 75 m. A large component of direct and refracted wave energy inhibited closer source-to-receiver offsets. Near vertically incident recording minimizes normal move-out corrections and the associated stretch allowing a higher frequency, less distorted reflection wavelet to be recorded (Miller, 1992). The target reflector is approximately 75 m deep which is within the optimum recording offset as evidenced by the walkaway-noise tests and general rules of thumb (Knapp and Steeples, 1986).

DATA PROCESSING

The CDP data were processed at the Kansas Geological Survey (KGS) using a proprietary set of algorithms developed by the KGS *(Eavesdropper)*. Extreme care was used during the editing process to ensure removal of all non-seismic energy that could either be misinterpreted as reflections on stacked data or that hampered interpretations of real reflection events. Velocity analysis incorporated iterative constant velocity stacking with detailed 1/5 wavelength surface-consistent statics to improve both accuracy of velocity corrections and time/depth conversion on interpreted cross sections. The main distinctions between the shallow high-resolution processing flow used on this data and most routine petroleum explanation sequences relate to conservative use and application of correlation statics, precision required during velocity and spectral analysis, extra care during muting operations, and lack of deconvolution.

RESULTS

Unequivocal identification of reflection energy on field files is essential for accurate interpretation of CDP stacked sections. All raw field files have at least one confidently identifiable reflection event. Digital filtering and trace balancing greatly enhanced the signal-to-noise ratio of the raw field files. The Dennis Limestone reflection is interpreted at approximately 60 ms (Figure 2). A shallower reflection event at 35 ms is also evident on the filtered field file. The

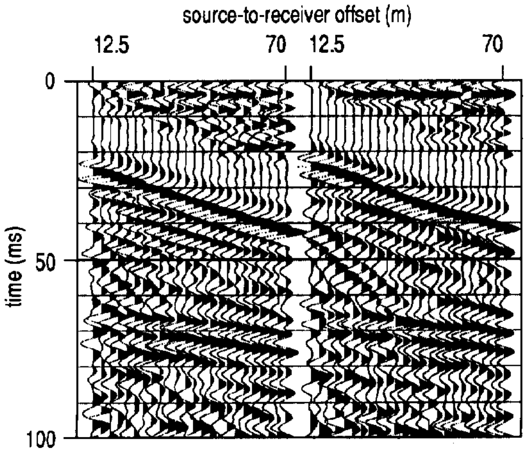

FIG. 2 Two different digitally filtered and scaled field files.

dominant frequency of reflection energy ranges from 150 to over 250 Hz. Reflection events interpreted on field files strongly support coherent events on the CDP stacked data.

Differentiation of reflection energy from seismic noise on field files is essential for confident and consistent interpretations on stacked seismic sections. Refraction arrivals, present as the first breaks (first source-generated energy recorded) on seismograms, were meticulously removed with individual relatively severe first-arrival mutes. Low velocity, low frequency linear arrivals, identified on field files as ground roll, were easily attenuated with the digital filter. Air-coupled wave arrivals were outside the optimum recording window and presented no problems. The effects of 60 Hz and higher mode noise from electrical sources (pipelines and power lines) are obvious on files from the north end of the seismic profile. The dominant 180-Hz component of the noise hampered the optimization of the digital filter. The overall quality and the resolving power of the seismic-reflection method can be maximized when all forms of non-reflection energy are not recorded or can be suppressed during digital processing.

The 12-fold CDP stacked section has several high-quality, high-frequency reflecting events (Figure 3). An uphole velocity survey at this site combined with the core from the borehole allows confident identification of reflecting events. The reflection at approximately 40 ms is a sandstone unit at approximately 50 m of depth. The high amplitude event at 60 ms is the Dennis Limestone unit. Between the Dennis and the reflection at 70 ms, which is the Mound Valley Limestone, is an interbedded shale and sandstone. Beneath the Mound Valley Limestone are Pennsylvanian cyclic sequences of predominantly limestones and shales.

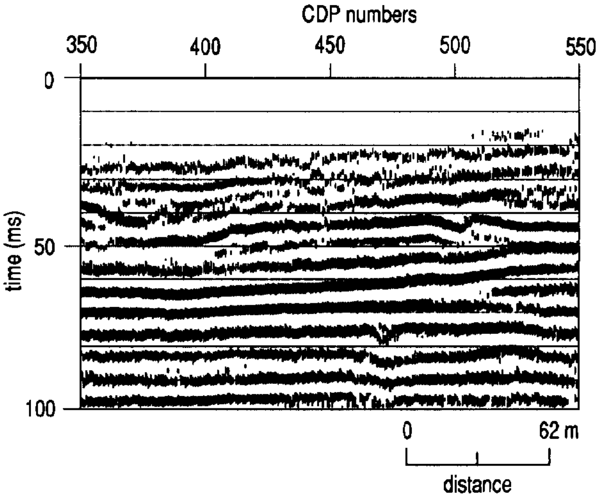

FIG. 3 Variable area plot of the 12-fold CDP stacked section. The pinch-out can be observed at approximately CDP 510. This section plotted with fewer traces/inch, and wiggles allow bed resolution as thin as 1.5 m.

The concave bottom defined by the Dennis Limestone reflection converges and becomes asymptotic on the north end of the seismic line to the Mound Valley Limestone. The sandstone reflection at 40 to 45 ms was deposited after the formation of the Dennis Limestone concavity. The variability in apparent depth of the sandstone reflector is likely related to post-depositional erosion. The apparent thinning of the interval between the Dennis Limestone and the Mound Valley Limestone is associated with a decrease in the thickness of the interbedded shale separating the two limestones (mostly Galesburg Shale). The Galesburg Shale is in excess of 14 m thick at the south end tapering to less than 6 m at the north end of the seismic line. Apparent structural features beneath the Mound Valley Limestone are related to depositional irregularities and/or erosion.

The mixed-phase source wavelet of the downhole .50-cal. rifle could not be removed with standard deconvolution operators; therefore, consideration must be given for the non-zero phase reflection wavelets when making stratigraphic determinations. Tuning of the Dennis and Mound Valley Limestone reflection wavelets can be observed between CDPs 420 and 480. The frequency and sharpness of the reflection tuning increases from CDP 480 to maximum correlation between CDPs 446 and 420.

Dominant reflection frequencies on the stacked section are generally in excess of 180 Hz. With average velocities on the order of 2000 m/s between 50 and 80 ms at CDP 490, the maximum theoretical bed resolution of this survey (in accordance with the 1/4 wavelength criteria of Widess, 1973) should be approximately 2 to 3 m. A reflection time separation of 2.8 ms represents 1/4 wavelength for data collected on this survey. Evidence exists to confidently suggest the presence of the pinching interbedded unit at CDP 492 with a time separation of 1.25 ms (1.25 m) and possibly as far as CDP 487 with a time separation of approximately 0.75 ms (0.75 m).

CONCLUSIONS

The CDP seismic-reflection technique has the potential vertical resolution necessary to image stratigraphic features as thin as 1 m at a depth of around 70 m at a site near Independence, Kansas. The predicted theoretical resolution at this site, according to the 1/4 wavelength criteria, is on the order of 2 to 3 m. Practical resolution limits at this site could be as small as 1/8 wavelength on high quality broad-band data using a qualitative analysis of wavelet interference. Vertical thinning in excess of 8 m can be observed on the CDP stacked section across a horizontal distance of less than 70 m. Seismic reflection can be utilized at this site to accurately place stratigraphic core drilling holes for determining depositional environments and geologic processes responsible for the present geologic setting.

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REFERENCES

Feldman, H. R., and Franseen, E. K., 1991, Stratigraphy and depositional history of the Drum Limestone and associated strata (Pennsylvanian) in the Independence, Kansas, area: A Field Trip Guidebook and Road Log: Kansas Geological Survey Open-file report 91-45, 29 p.

Knapp, R. W., and Steeples, D. W., 1986, High-resolution common depth point seismic-reflection profiling: field acquisition parameter design: Geophysics, 51, 283-294.

Knapp, R. W., 1990, Vertical resolution of thick beds, thin beds, and thin-bed cyclothems: Geophysics, 55, 1183-1190.

Miller, R. D., Steeples, D. W., and Myers, P. B., 1990, Shallow seismic-reflection survey across the Meers fault, Oklahoma: Geol. Soc. Am. Bull., v. 102, 18-25.

Ricker, N.,1953, Wavelet contraction, wavelet expansion, and the control of seismic resolution: Geophysics, 18, 769-792.

Steeples, D. W., and Miller, R. D., 1990, Seismic-reflection methods applied to engineering, environmental, and ground-water problems: Soc. Explor. Geophys. volumes on Geotechnical and Environmental Geophysics, Stan Ward, ed., Vol. 1: Review and Tutorial, 1-30.

Widess, M. B., 1973, How thin is a thin bed? Geophysics, 38, 1176-1180.

Yilmaz, O., 1987, Seismic data processing; S. M. Doherty, ed; *in* Series: Investigations in Geophysics, no. 2, Edwin B. Neitzel, series ed.: Soc. Explor. Geophys., Tulsa, OK, 526 p.