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Successful application of spectral decomposition technique to map deep gas reservoirs

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Summary

The spectral decomposition of seismic data is the process that transforms seismic amplitudes as a function of space and time to spectral amplitudes as a function of frequency, space and time. Various spectral decomposition methods are commercially available. We apply the high resolution discrete Wigner-Ville transform for finding previously undrilled gas reservoirs but also for investigating the geological setting for possible connections to producing gas wells.

We present a case study in a newly-evaluated tight gas reservoir area with some wells that we can utilize as control points. The largest challenge lies in mapping reservoirs that have not been drilled and are not connected to previously discovered gas wells. We have been successfully applying our high resolution spectral decomposition technique to map the distribution of newly discovered tight gas reservoirs. In addition we can provide important and critical information for updating the field development plan in Daqing.

We successfully applied the high resolution spectral decomposition technique to map the gas distribution along a 7 km arbitrary 2-D seismic line that was extracted from a larger regional 3D data set. The reservoir level has a discontinuous appearance with small hydrocarbon accumulations at various levels within the reservoir zone. The pilot study indicates that the spectral amplitudes are anomalous over gas zones especially at higher frequencies. This indication can be used to predict gas pockets away from known well locations.

We suggest performing the Wigner-Ville spectral decomposition method on the whole 3D data volume. The most obvious advantage for calculating spectral amplitudes on 3D data is the ability to generate horizon maps and time slices at key frequencies for map the reservoir in 3D domain.

Introduction

Daqing Oilfield is the largest continental sandstone oilfield with multi-reservoir zones around 1,200 m depth. During the last few years, deep gas reservoirs at around 3,000 m depth were discovered outside the existing oil production area. These deep tight gas reservoirs are associated with complex fault blocks and volcanic craters. Therefore it is very difficult to map the extent and distribution of the gas reservoir using existing low frequency seismic data and subsequently optimize the gas field development plan.

Through a pilot study project, we successfully applied the high resolution spectral decomposition technique to map the gas distribution along a 7 km arbitrary 2-D seismic line that was extracted over known well locations from a larger regional 3D data set. The spectral decomposition of seismic data is the process that transforms seismic amplitudes as a function of space and time to spectral amplitudes as a function of frequency, space and time. The frequency cubes that result from this process can potentially be used to map variations in bed thickness, geologic discontinuities, attenuation of seismic frequencies resulting from propagation through hydrocarbon reservoirs, and low-frequency shadows resulting from propagation through such reservoirs. The spectral decomposition which was used in this project was performed through an implementation of the Wigner-Ville Transformation. The results of the transform of a 2D line are spectral amplitudes at each frequency, which produces a pseudo-3D. This 3D data set was input into the interpretation workstation for a detailed analysis.

The spectral decomposition yields very high resolution results. Various interpretation methods were tested and we decided to display the spectral amplitudes at various frequencies in color with the seismic amplitude traces as overlay. The results of the spectral amplitudes around the target interval were investigated at each of the 4 gas and 1 dry calibration wells. Some anomalous areas away from the wells are present. These zones should be investigated on the 3D data set as there is a high likelihood they are related to gas reservoirs.

Wigner-Ville spectral decomposition methodology

The spectral decomposition of seismic data is the process that transforms seismic amplitudes as a function of space and time to spectral amplitudes as a function of frequency, space and time. The frequency cubes that result from spectral decomposition can potentially be used to map variations in bed thickness, geologic discontinuities and differentiation of fluids in the reservoir.

Spectral decomposition can be performed with the F-T Time Slice, the F-T Frequency Slice, or the F-T Cube processing steps. The F-T Time Slice step inputs a 2D seismic line and outputs a series of full-spectrum frequency slices over a range of constant times. The F-T Frequency

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Slice step inputs a 2D seismic line and outputs a series of constant-frequency sections spanning the length of the line. The F-T Cube step takes a 2D line as input and outputs an entire 3D volume whose axes are Space, Time, and Frequency. When processing a 3D seismic cube, at each frequency an individual frequency cube will be generated (Rauch-Davies, M., and Ralston, M., 2005).

The decomposition of the seismic trace data is achieved through an implementation of the Wigner-Ville Distribution (WVD) that was developed by the Institut Francais du Petrole (IFP). The WVD describes the evolution of a signal's energy distribution as a function of both time and frequency. A Wigner-Ville Distribution is the Fourier transform of the autocorrelation function of the signal x(t) with respect to the delay variable:

$$W_x(t,f) = \int_\tau x(t+\frac{\tau}{2})x^*(t-\frac{\tau}{2})e^{-i2\pi f\tau}d\tau$$

To reduce the effects of aliasing, the WVD is calculated from the analytic signal of the trace data. Although often compared qualitatively with the results of the Short-Time Fourier Transform and the Wavelet Transform, the WVD has superior resolution than other spectral decomposition methods (Cohen L., 1995).

For this study, the discrete WVD transform was used. It takes a time-scaled window function in which the window length is the analytic trace length = 2*data trace length and the samples are scaled down to either side of the analyzed sample (Figure 1). The method represents the Fourier transform of a time series that is produced by forming the product of samples of the seismic trace at past times with samples of the trace at future times, with time into the past being equal to time into the future.

Interpretation methodology

The output of the spectral decomposition of a 2D seismic line consists of a pseudo 3D spectral amplitude cube with the CDP direction representing the inline and the frequencies the cross-line direction. This 3D attribute data set is loaded into workstation for the detailed interpretation. Also used are target horizons for generating spectral amplitude maps around these horizons. These maps do not show structure but the evolution of the spectral amplitude along the frequencies. If available, log data and litholgocial properties of wells are used for calibration purposes.

Various ways of extracting the spectral amplitudes around the horizons and between horizons are tested. Horizon spectral amplitude maps at all frequencies are produced and the evolving spectral amplitude behavior along the frequency bandwidth is analyzed.

Data examples

For this study one arbitrary 2D seismic line that was extracted from a larger 3D data volume was used. When performing spectral decomposition on a seismic 2D line, the results will be a spectral amplitude line at each frequency. These lines are combined to a pseudo 3D cube and interpreted as such. The target horizons were duplicated as many times as frequencies are available in order to simulate 3D horizons.

The final migrated stack input data for the project are of reasonable quality and the spectral decomposition was performed from 5 to 60 Hz. There are 5 target horizons in this gas reservoir. These time picks were used for the spectral amplitude calibration at the well locations.

Figure 2 displays the seismic profile of the arbitrary 2D line that was used for the spectral decomposition pilot study. The calibration wells #1, #2, #3, #4 and #5 are annotated together with the key horizons. The target interval lies between the top and base horizon and we can clearly see a very inconsistent reservoir level. This leads to one well intersecting gas and another nearby well intersecting no sands or a wet reservoir.

The seismic data quality is reasonable good and spectral amplitudes between 5 and 60 Hz were calculated. However, the detailed interpretation demonstrates that only frequencies between 15 and 30 Hz can be used for the final interpretation and fluid prediction.

The resulting pseudo 3D cube from the Wigner-Ville transform was loaded into the interpretation workstation. The horizons were duplicated 56 times in order to simulate a 3D horizon pick with 56 crosslines which represents frequencies from 5 to 60 Hz. Numerous interpretation methodologies are available and we decided the most accurate one for this study is to investigate the change of the spectral amplitudes with frequencies on the pseudo crosslines and display spectral amplitude profiles in color at various key frequencies. The overlay represents the seismic amplitude trace. These displays clearly show the extent of the gas at the individual wells and are easy to interpret.

Spectral amplitude profiles from 15 Hz (Figure 3), 20 Hz (Figure 4), 25 Hz (Figure 5) and 30 Hz (Figure 6) were displayed in color with the seismic amplitude trace as overlay. All figures show the well paths and the known gas accumulations. These composite plots show anomalies at the known gas accumulation at the low and high frequencies. We can see similar anomalies at other areas along the 2D line that could also be associated with gas.

Figure 3 displays the spectral amplitudes at 15 Hz in color with the seismic amplitudes as wiggle overlay. The well locations together with the target horizons are annotated. Also, indicated are the known gas reservoirs at all wells. A spectral amplitude anomaly is present at the gas sand on wells #1, #4 and #5. The gas reservoir at well #2 does not show any anomaly at this frequency. The well #3 has no known gas at the target interval.

Figure 4 represents the spectral amplitudes at 20 Hz in color with the seismic amplitudes as wiggle overlay. Spectral amplitude anomalies are present at wells #1, #2, #4 and #5. No anomalies can be seen at well #3. The spectral amplitudes at 25 Hz in color is shown in Figure 5 without the seismic trace overlay. The calibration well locations are annotated together with the target horizons.

Figure 6 displays the spectral amplitudes at 25 Hz in color with the seismic amplitudes as wiggle overlay. Spectral amplitude anomalies are visible at wells #1, #2, #4 and #5 at the gas reservoir level. The anomaly caused by the gas at well #1 is becoming weak. A strong anomaly starts to form between wells #2 and #3 at a two way time of 1,810 ms. At the dry well #3, a spectral amplitude anomaly is starting to form at a two way time of 2,000 ms. However, both spectral amplitudes are not anomalous at the low frequencies, which generally indicates good gas reservoirs. Therefore, they are most likely caused by lithology.

Figure 7 shows the spectral amplitudes at 30 Hz in color with the seismic amplitudes as wiggle overlay. No spectral amplitude anomalies are present at the known gas intervals.

Conclusions

An arbitrary 2D line was extracted from a regional 3D dataset and used for the spectral decomposition with the high resolution Wigner Ville transform method. This line intersects 4 gas producing wells and one dry well. These wells were utilized as calibration points.

The gas wells #1, #2, #4 and #5 have strong spectral amplitude anomalies approximately between frequencies 15 and 26 Hz. The dry well #3 only exhibits a spectral amplitude anomaly at the target interval between 25 and 30 Hz. This study indicates that the spectral amplitudes are anomalous at the low and high frequencies in the presence of gas. If one of the frequency ranges is missing, the remaining anomalies are not related to the presence of gas but more likely to lithology.

Between the wells #2 and #3 a strong spectral amplitude anomaly is present between frequencies 22 and 30 Hz at a two way time of 1,810 ms. No anomalies are visible at the low frequencies and it is assumed that this interval has either very thin gas sands or no gas at all. Between the wells #3 and #4 a spectral amplitude anomaly is visible between frequencies 20 and 30 Hz at a two way time of 1,950 ms. None of the displayed wells intersects this interval and it is likely that it contains gas sands. To the right of the Figure 5, below the top horizon a strong spectral amplitude anomaly is visible between frequencies 17 and 30 Hz at a two way time of 2,005 ms. The appearance of this anomaly indicates the possible presence of gas at this interval.

The results of the pilot study are very encouraging and we successfully mapped the gas distribution a long a 7 km long 2-D seismic line by using a high resolution spectral decomposition technique. Daqing has decided to perform a spectral decomposition study over a larger 3D data set that covers additional wells and prospect areas. The advantage of using 3D data is that spectral amplitude horizon maps can be generated and the spectral amplitude behavior over a large area can be mapped. In addition to investigating horizon maps, time slices at various frequencies can be produced and calibrated to existing wells but also used to predict new drilling locations.

References

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Acknowledgments

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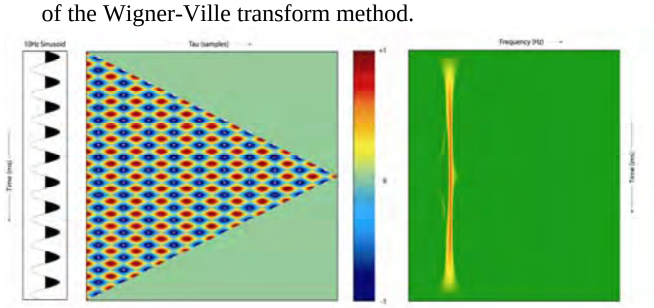

Figure 1: Spectral decomposition of a synthetic trace (far left) uses the discrete Wigner-Ville transform. Middle is the corresponding signals in the τ domain, and right side shows the spectral amplitudes.

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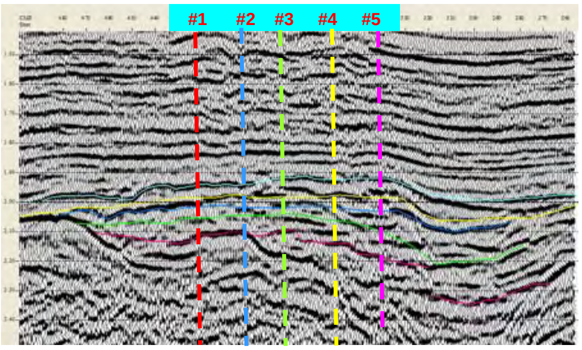

Figure 2: Seismic profile of arbitrary 2D line. The well paths of the calibration wells are annotated together with the target horizons.

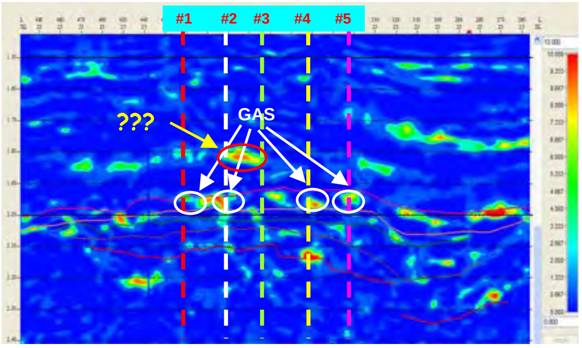

Figure 5: Spectral amplitudes map at 25 Hz. The calibration well locations are annotated together with the target horizon.

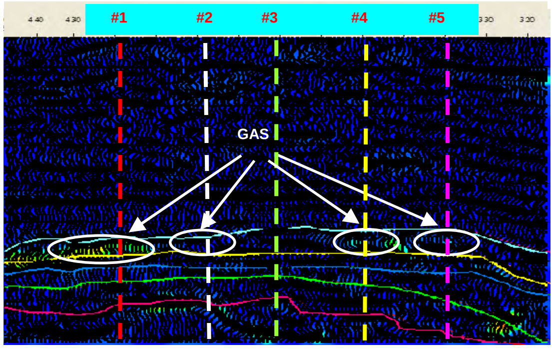

Figure 3: Spectral amplitudes at 15 Hz in color with the seismic amplitude traces as wiggle overlay. The calibration well locations are annotated together with the target horizons.

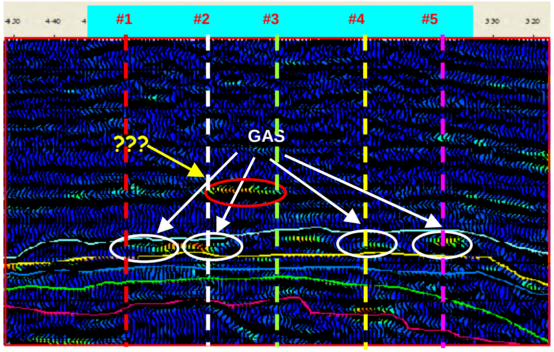

Figure 6: Spectral amplitudes at 25 Hz in color with the seismic amplitude traces as wiggle overlay. The calibration well locations are annotated together with the target horizons.

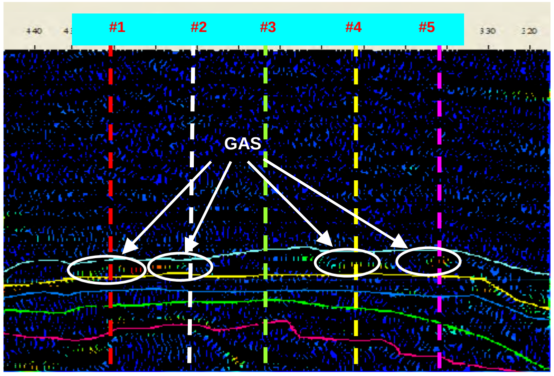

Figure 4: Spectral amplitudes at 20 Hz in color with the seismic amplitude traces as wiggle overlay. The calibration well locations are annotated together with the target horizon.

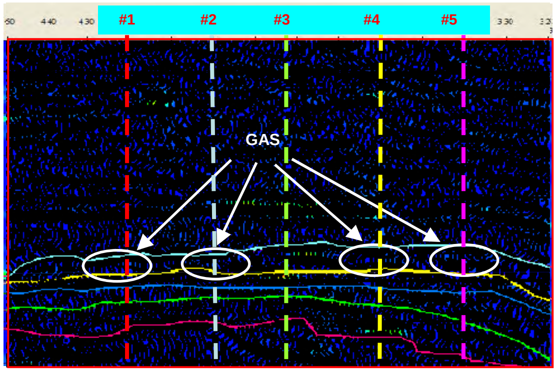

Figure 7: Spectral amplitudes at 30 Hz in color with the seismic amplitude traces as wiggle overlay. The calibration well locations are annotated together with the target horizons.

EDITED REFERENCES

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