Instantaneous Spectral Analysis Applied to Reservoir Imaging and Producibility Characterization

Feng Shen1* and Gary C. Robinson1, Tao Jiang2
1EP Tech, Centennial, CO, 80112, 2PetroChina Oil Company, China

Summary
Imaging and characterizing fractured shale reservoirs constitute significant challenges. We introduce a workflow and illustrate the application of instantaneous spectral analysis with the aid of a case study on fractured shale reservoirs. With the well log modeling, frequency dependent energy and phase are improved by removing the wavelet overprint. Extracted frequency dependent energy and phase cubes provide an efficient tool to delineate distributions of reservoirs and fault systems. Our results show that the reservoirs distribute along the structure high and are consistent with the paleo-current directions. The attenuation analysis allows observing spectral anomalous variations, representing an alternative tool for hydrocarbon exploration and indirect fracture indicator. Our results also show attenuation anomalies integrated with the production data can guide our predictions of reservoir producibility and indirectly characterize fracture intensity.

Introduction
Spectral decomposition provides a tool for imaging and mapping temporal bed thickness and geological discontinuities over large 3-D seismic surveys (Partyka and Gridley, 1997; Partyka et al., 1999). This technique has been used to delineate facies and depositional environments such as channel sands and incised valley-fill sands (Peyton et al., 1998). Spectral decomposition typically employs the discrete in Fourier transform to generate mono-frequency images from the broadband seismic data. However, this approach is obviously limited because significant properties of the seismic signals must be “traded off” as a function of the type and the length of the selected window. Windowing problems Fourier transform-based methodology bias the amplitude spectra. The wavelet transform allows a seismic signal to be examined in both the time and frequency domains simultaneously. It has become a popular tool for the analysis of non-stationary signals and has replaced the conventional Fourier transform in many practical applications (Van den Berg, 1999).

We introduce a instantaneous spectral imaging technique by using wavelet transform-based spectral analysis. Castagna and Sun (2003) compare the wavelet transform based instantaneous spectral analysis to other spectral decomposition methods including fast Fourier transform, discrete Fourier transform, and the maximum entropy method. Their results prove that instantaneous spectral analysis can achieve excellent time and frequency localization while avoiding windowing problems. Spectral imaging provides energy and phase spectra that can delineate temporal reservoir thickness variability and indicate lateral geological discontinuities. Therefore, the spectral imaging results allow interpreters to quickly and efficiently image and quantify local rock property variability with the 3-D seismic data volume.

Attenuation of seismic waves traveling through oil and gas reservoirs is a function of reservoir rock properties. This attenuation is observed as a pronounced loss of high frequency energy, and these attenuation anomalies can be a useful hydrocarbon indicator. As the instantaneous spectral analysis allows us to obtain a frequency spectrum at each time sample for a seismic trace, seismic attenuation can be described as frequency-dependent spectral variations. These variations enable us to detect high-frequency attenuation associated with oil and gas reservoirs.

The principal aim of this paper is to illustrate the application of the spectral imaging technique to the imaging and producibility characterization of a fractured shale reservoir located in the Songliao Basin of China. To remove the wavelet overprint and better estimate the frequency responses of the reservoir, we model seismic responses by using log data to extract wavelet spectrum. The tuning maximum of the reservoir energy spectrum can be estimated at wells with instantaneous spectral analysis and the optimum frequencies of the reservoirs can be quantified. Then, the wavelet transform based instantaneous spectral analysis is applied to 3-D seismic data to generate the energy and phase cubes and to identify reservoir and fault system. Finally, we estimate the seismic attenuation attributes and apply them to reservoir producibility characterization.

Geological and Regional Setting
There are three sets of reservoirs to be investigated in our working area. They are distributed in the Upper Qingshankou Formation and Yaojia Formation, deposited in the middle Cretaceous in the Songliao Basin of China. The reservoir intervals consist of silt and sandy shale and belong to lacustrine deposits. The Yaojia Formation overlays Qingshankou Formation and is characterized by transgressive sedimentary sequence. The Upper
Qingshankou Formation is composed of sediments deposited in the water regressive sequence, while the Lower Qingshankou Formation is characterized by water transgressive sedimentary sequence. Several organic-rich intervals within the Qingshankou Formation constitute the source rocks for the overlying reservoirs. Both Qingshankou and Yaojia formations exhibit highly abnormal pressure conditions. The structure is a NW dipping mono-clinal folding and the sedimentary layers thicken westward. Faulting within the Qingshankou and Yaojia Formations is complex. 3-D seismic surveys are acquired over the area. Drilling results reveal the fractured reservoirs developed in these two formations that exhibit high producibility. Imaging and characterizing these reservoirs in the Qingshankou and Yaojia Formations are the key issues for the project.

Application of Spectral Imaging to Reservoir Imaging and Producibility Characterization

Well log constrained spectral analysis and interpretation are necessary for us to relate quantitatively energy and phase spectra to reservoir properties and make the interpretation geological meaningful and physically effective. Our spectral imaging workflow includes well log modeling, reservoir imaging by using spectral analysis on 3-D seismic data, and reservoir producibility characterization using attenuation attributes.

Well log modeling

In general, the seismic energy spectrum comprises three components: thin bed interference, the source wavelet overprint, and noise. Thin bed interference depends on the acoustic properties and thickness of the geological layer. As the thin bed interference is the most interesting component to us, we need to remove the source wavelet overprint without degrading the embedded geological information.

Well log modeling is carried out in five wells, where the production data and lithological interpretation are available to understand lithology and spectrum characteristics. We first model seismic responses in each well by using the log data and extracted wavelet to generate the synthetic seismogram. To determine the optimum phase value of the seismic source wavelet at each well, the phase of the seismic trace at each well location is varied systematically, and the resulting traces are correlated with the synthetic. The source overprint could then be removed from the synthetic and 3-D seismic data by using the extracted source spectrum. Figure 1 shows the comparison of synthetic seismogram spectra before and after the removing source wavelet overprint. Our results show that, after removing the wavelet spectrum overprint, the tuning cube is reduced to thin bed interference and noise and geological tuning varies along a flattened horizon. The geological tuning is easily detected.

The wavelet-based instantaneous spectral analysis is applied to synthetic seismogram and seismic traces around the wells. Figure 2 shows the well log synthetic seismogram tie, interpreted reservoir lithology, log data, and energy spectra for the synthetic trace. Based on well data and reservoir production data, the reservoirs within the Qingshankou and Yaojia Formations can be quantified in the time and frequency domains. The reservoir in the Upper Yaojia Formation is obvious on both synthetic and seismic spectra, and is characterized by high energy around 0.78s. It is observable when the frequency is greater than 20Hz. The reservoir in the Lower Yaojia Formation can also be observed both on synthetic and seismic spectra around 0.91s. However, its tuning frequency becomes higher than the reservoir above

Figure 1: Comparison of synthetic seismogram spectra before and after the removing source wavelet overprint.

Figure 2: Well log synthetic seismogram tie, interpreted reservoir lithology, log data, and energy spectra for the synthetic trace.
Instantaneous Spectral Analysis Applied to Reservoir Imaging

it. The reservoir within the Upper Qingshankou Formation is located around 0.93s and its tuning frequency is greater than 50Hz on both the synthetic and seismic spectra. The same analysis is applied to the other wells. The obtained results can be used to determine frequency ranges worthy of further investigation in the reservoirs and guide us in the analysis and interpretation of the spectrum characters.

Instantaneous spectral analysis applied to reservoir imaging

Spectral analysis can generate mono-frequency amplitude and phase cubes that can be used to image the reservoir, including lateral geological discontinuities such as reservoir boundaries and fault systems. In a discrete frequency energy cube, thin bed interference appears as coherent amplitude variations. This property is used to delineate clastic channel systems as described by Partyka et al (1999). In addition, the discrete frequency energy cube can efficiently capture the subtle features and variations within these sedimentary facies.

We apply the instantaneous spectral analysis to 3-D seismic data in which the wavelet overprint has been moved. We followed the optimum frequency band of each set of reservoirs based on our well log modeling and quantify them in the time and frequency domains. Figure 3 shows the energy spectrum of the reservoir in the Upper Yaojia Formation. The reservoir is distributed on the structural high and its spatial distribution is oriented in the southwest direction, which is consistent with the data of paleo-current directions in this field. Our results show that the reservoir is cut by the faults along the NNW direction. The reservoirs in the Lower Yaojia Formation and Upper Qingshankou Formation have a similar distribution, but their spatial extent shows differences, which can be explained by different the depositional environment, or water regressive and transgressive cycles of sedimentation.

Phase cubes are very useful in mapping local rock properties and lateral discontinuities. As phase is sensitive to subtle perturbations in the seismic character, it is ideal for detecting lateral acoustic discontinuities. Figure 4 shows the corresponding phase spectrum of the reservoir in the Upper Yaojia Formation. Faults are clearly distributed along the NNE direction and the lateral acoustic discontinuities are well developed along the slope of the structural high. Our results show that phase data can also provide sharper definition of faults than coherence data.

Figure 3: The 25 Hz energy spectrum of the reservoir in the Upper Yaojia Formation.

Figure 4: The 25 Hz phase spectrum of the reservoir in the Upper Yaojia Formation.

Instantaneous spectral analysis applied to reservoir producibility characterization

Fractures are a crucial factor controlling the performance of producing wells due to the low permeability in the shale. The vertically or obliquely distributed fractures and their networks are the key geological elements that impact the reservoir producibility. We understand that the generation of fractures is controlled by many possible geologic drivers such as structure, thickness, lithology, and faults (Ouens and Hartley, 2000). Quantifying the spatial reservoir distribution can help us further to identify its producibility. For the fractured shale reservoirs in our working area, the reservoirs with well developed fractures will have good producibility.

The presence of fractures and hydrocarbon can cause high frequency attenuation within or below the reservoir. Using instantaneous spectral analysis, we can estimate the
Instantaneous Spectral Analysis Applied to Reservoir Imaging

attenuation attributes for each sample along the seismic trace, and detect local attenuation anomalies as a function of time. As these attenuation attributes can be obtained throughout the entire time range of the signal, this preserves the original features of the data and gives an idea of how the spectra vary in the time and space. This analysis also allows monitoring attenuation variations spatially and characterizing a relative attenuation zone. As mentioned above, the occurrence of high fracture intensity and hydrocarbons in the shale reservoirs can cause strong scattering of seismic waves. Therefore, the observed significant attenuation around the producing wells is correlated with their producibility. These attenuation anomalies can be integrated with the well producibility to guide our predictions and simulations of reservoir performance.

Discussion Conclusions

Our results suggest that instantaneous spectral analysis can be applied to reservoir imaging and producibility characterization. Frequency dependent energy and phase cubes qualitatively and quantitatively provide more details and resolution in the reservoir than conventional energy and phase responses. To the Cretaceous fractured shale reservoirs, the well log modeling provides different optimum frequencies for each reservoir layer. The differences in optimal frequencies are a function of reservoir thickness and acoustic properties. From the Qingshan Kou to Yaojia Formation, the paleo-current was in the southeast direction and sediments are dominated by silt or sandy shale. Structures are more complex in the Qingshan Kou Formation than those in the Yaojia Formation, which indicates that the paleo-tectonic stress loading decreases. The attenuation attributes allow us to monitor attenuation variations spatially and defining a relative attenuation zone. Our results show that fractures within the reservoirs are greatly controlled by fault system. This case study demonstrates that the detailed reservoir information can be extracted with the instantaneous spectral analysis using a rigorous process flow that integrates well log, geological, seismic, and production data.

References:


