Spectral Detection of Attenuation and Lithology

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Introduction

Traditional seismic interpretation methods rely on imaging where interpreters look for visual structural and stratigraphic features associated with potential reservoirs. This requires the detection, correlation and analysis of seismic features which in turn are better performed on high resolution data. Such techniques rely heavily on amplitude analysis for quantifying reservoir parameters.

Several sophisticated technologies were developed to help improve, support and verify seismic interpretation. The most commonly used are seismic inversion and amplitude versus offset (AVO) analysis [1]. Seismic inversion, in its useful guises as a non-linear deconvolution, attempts to improve amplitude mapping by reducing the effect of interference between close reflectors on their amplitudes. Both inversion and AVO are amplitude-based analysis techniques.

Another important source of information in seismic data is its frequency content. Tools for examining the frequency content of time series data are collectively called spectral analysis. Spectral analysis has established itself as an important tool in seismic data acquisition and processing. In the last two or three decades, applications of spectral analysis to hydrocarbon reservoir detection and characterization emerged [2-5] and have recently intensified [6, 7]

In this paper we explore two complementary ways of employing spectral analysis for hydrocarbon reservoir detection and mapping: attenuation and tuning. We also examine the applications of time-frequency analysis techniques. Finally we present some real data examples.

Spectral Detection of Lithologic/Stratigraphic Changes

Lateral changes in the lithology of a layer can induce corresponding changes in the velocity of the layer. Such changes manifest themselves in the variations in the amplitudes corresponding to the layer and the time thickness of the layer (see Figure 1). However, such changes can be too subtle to detect in the time domain, but easier to detect in the frequency domain. For example, an increase in the time thickness of a channel by 1 ms may not be detectable in the time domain but may induce a noticeable decrease in the frequency content. This, however, requires the ability to estimate the signal spectrum from a short time window, otherwise many other factors may overshadow such effects. Changes in stratigraphy are manifested by changes in the number of layers and/or layer thicknesses. Such changes can also be detected in the frequency domain, and again the ability to estimate signal spectra from short time windows is critical.

To assess the applicability of such an approach to a particular setting, it is recommended that a synthetic model be generated that emulates the problem at hand. The synthetic should use a wavelet estimated from the corresponding seismic data, with SNR compatible with this data. Performing spectral analysis on such synthetics would reveal whether the analyses would work and whether the anomaly is high frequency or low frequency. To accentuate such an anomaly, it is helpful to estimate the background spectrum and subtract it out. Furthermore, several attributes can be extracted from the spectra to summarize their character. Such attributes could reveal the anomaly of interest.

Notice that this approach relies on interactions between the reflection coefficients within the analysis window and the bandwidth of the wavelet. It is feasible that the seismic anomaly of interest could be high frequency for a given wavelet bandwidth and low frequency for another bandwidth as in

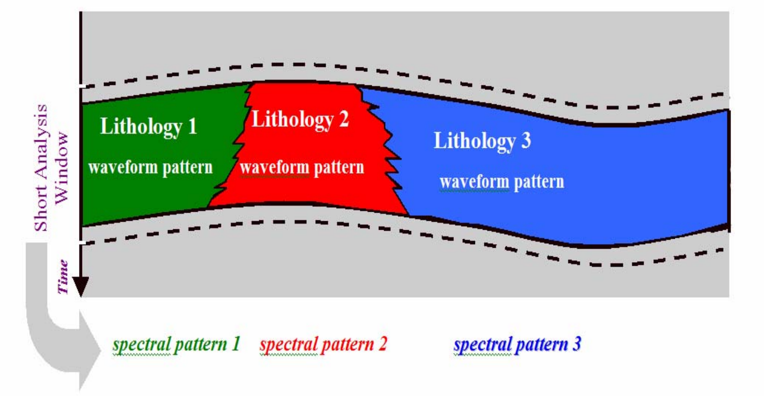


Figure 1. Spectral Detection of Lithology

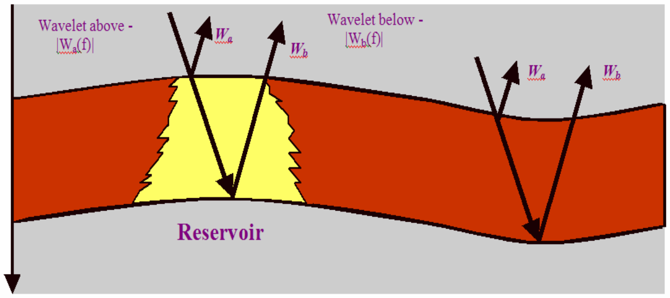


Figure 2. Attenuation

Attenuation

It has been experimentally established that fluid-bearing porous rock formations attenuate seismic waves preferentially, i.e., higher frequencies within the seismic band used in exploration, are more severely attenuated than lower frequencies [8]. Theories to explain the mechanisms of this phenomenon have been slowly developed over the last 50 years or so. The current consensus is that the mechanism involves fluid flow [9].

Over the past 20 years or so, we have been using attenuation as a direct hydrocarbon indicator [2-5]. Attenuation could be caused by scattering effects and the seismic spectrum is contaminated by the presence of additive noise and the effect of the reflectivity. Therefore, our approach is to first estimate the signal spectrum and use it to estimate the wavelet spectrum. We employ the spectral ratio of the wavelet below the target and above the target as an estimate of the attenuation spectrum (see Figure 2). In order to localize the attenuation estimate, the spectra should be estimated from as short a time window as possible.

Figure 3 shows attenuation spectra at 16 known wells in a gas field. In this example the attenuation of higher seismic frequencies predicted the well condition with more than 90% accuracy.

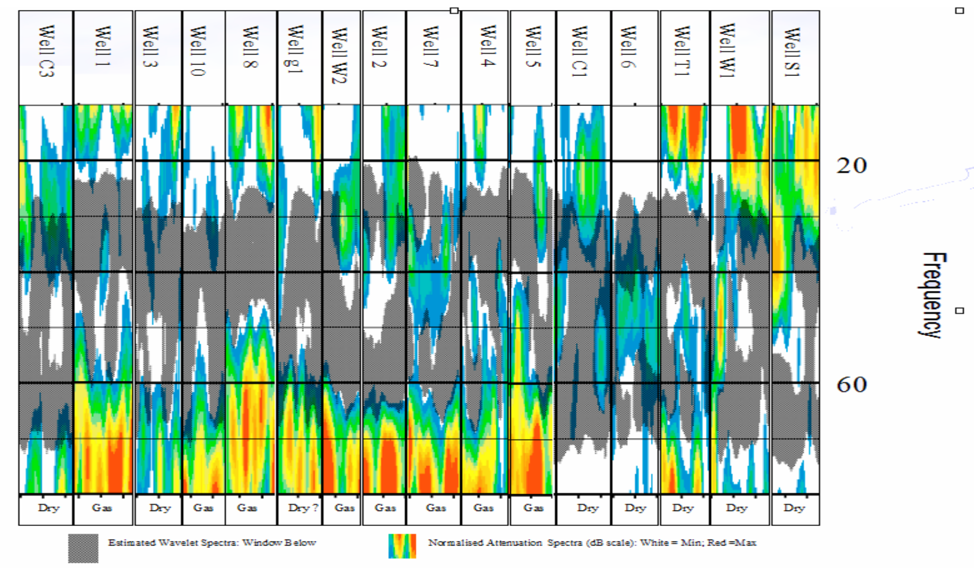


Figure 3. Normalized Attenuation (16 well ties)

Time-Frequency Analysis

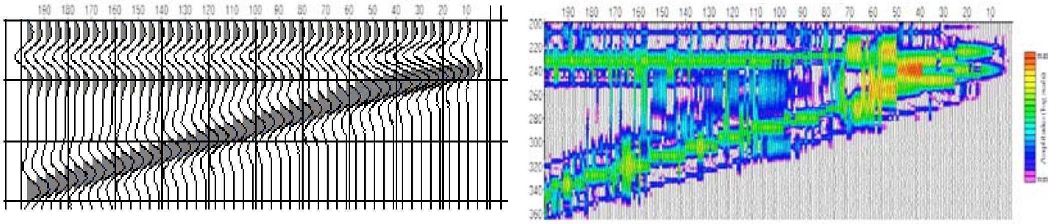
While Fourier analysis describes a signal in terms of everlasting oscillations, time-frequency analysis describes the frequency content of a signal as a function of time. Thus, in Fourier analysis, one would not know when an oscillation with a particular frequency starts and when it ends. This knowledge is important for localizing spectral anomalies associated with lithologic/stratigraphic changes, thereby highlighting the need for time-frequency analysis tools.

Time-frequency analysis maps a one dimensional signal into a two-dimensional signal where the energy is simultaneously distributed along the time and frequency axis. Obviously localization is restricted. After all, a signal with a given frequency exists in some time space and a signal with a given time span has an associated frequency band as well. Unlike the unique Fourier transform, there are many time-frequency transforms, each may lead to a different spectrum. The simplest way to do time-frequency analysis is to window the data, apply Fourier transform to the windowed data and assign the resulting spectrum to the center of the window. By sliding the window every T samples, new spectra are obtained and assigned to time points T samples apart corresponding to the centers of the windows. This is the short-time Fourier Transform (STFT). The frequency resolution is inversely proportional to the window length and thus low and high frequencies would have the same resolution when analyzed using STFT. Another technique which has high resolution is the Wigner-Ville distribution which is a quadratic transform and consequently has cross terms which hinder the interpretation of the resulting small window spectra. The wavelet transform was developed to address these problems by analyzing low frequency components using longer windows and higher frequency components using shorter windows such that the resolution bandwidth for all frequencies is proportional to the corresponding frequency. However, such a transform is overly redundant and does not provide good time-frequency localization. This prompted the idea that the representation of the signal in terms of a few wavelets with different time-frequency characteristics would help improve the time-frequency localization. This is the approach we employ for time-frequency analysis.

One of the problems with time frequency distributions is that geology and wavelet effects are not separated. Therefore, time-frequency analysis should not be used as a measure of attenuation. However, time-frequency analysis has many potential applications including: detection of lithology, detection of coherent noise such as multiples and converted waves, and detection of anisotropy.

Figure 4 shows time frequency analysis using sparse decomposition on two synthetic wedge models. The second model contains a shale plug inside. Note the changes in reflectivity are identified very well by the time-frequency analysis, however, these changes are clearly a result of changing reflectivity and not an indication of attenuation.

Wedge without a plug



Wedge with a plug

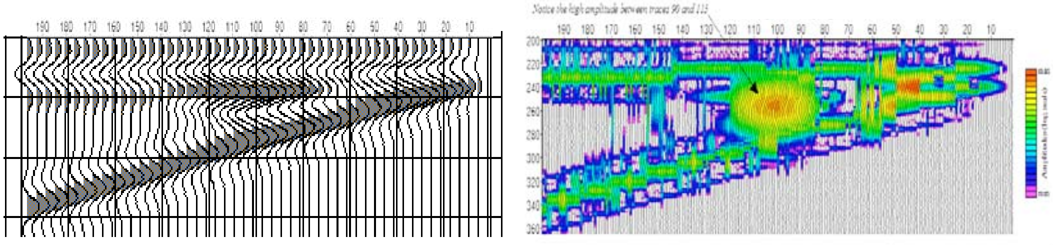


Figure 4. 16 Hz frequency slice of two wedge models

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