Application of dip and spectral maps to the Pikes Peak data

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ABSTRACT

The frequency content of the seismic data may reveal some additional information to the interpreter. The unique form of the frequency analysis (S-transform) described in this paper allows us to display 2D seismic data in the form of dip and spectral maps. The S-transform has been successfully applied to the Pikes Peak seismic data to validate the position of the anomaly earlier discovered on the inverted section. The dip maps were used to trace the geological structure of the surveyed area, the spectral maps revealed a low-frequency anomaly just below the productive zone. The frequency analysis combined with conventional interpretation methods can lead to a greater understanding of data and more accuracy in reservoir prediction.

INTRODUCTION

The Pikes Peak oil field is located 40 km east of Lloydminister, Saskatchewan (Figure 1) and produces heavy oil from the Waseca sands of the Lower Cretaceous Mannville Group. The oil bearing formation is discontinues under the surface, so we employ the frequency analysis to delineate the productive zone. Two parameters: the length of the frequency vector and its angle, were extracted from the seismic data, and the maps of interest were generated. The Resolution Software Package (a product of Calgary Scientific Inc.) was used to calculate the S-transform and to create all images.

Some progress in the S-transform application has also been made at the seismic data processing stage. The Resolution software is able to filter different parts of the seismic image with different filtering parameters, allowing the suppression of unwanted signals in an efficient and unique way. One-dimensional signals can also be treated with the S-transform, where the first break can be detected with more accuracy than by using conventional frequency analysis.

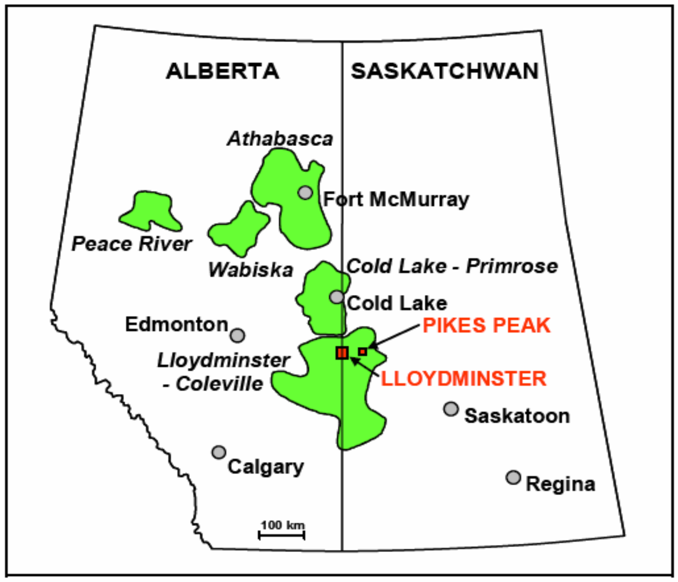

FIG. 1. Map of major heavy-oil deposits of Alberta and Saskatchewan, and location of the study area. (Watson, 2004)

THEORY

The P-wave seismic data from the Pikes Peak heavy oil field were analyzed using the Resolution software from Calgary Scientific Inc. (Figure 3). This software allows displays of both standard Fourier transforms and Stockwell (S) - transforms for creating seismic image, angle and frequency maps. The software can also be used to filter the area of interest on the seismic image. The basic theory behind the Resolution software was developed by Pinnegar (2003).

The S-transform is a time-frequency spectral localization method, similar to the short-time Fourier transform, but with a Gaussian window whose width scales inversely, and whose height scales linearly with frequency. The time-domain expression of the S-transform of a continuous function *h* is given by the formula:

$$S(\tau, f, p) = \int_{-\infty}^{\infty} h(t) w(\tau - t, f, p) \exp(-2\pi i f t) dt, \qquad (1)$$

where t - time, f – frequency, w – modulating window which translates along the time axis, τ - position of the modulating window, p - any parameters that define w. The S-transform has an advantage over other wavelet transforms because it retains the absolute phase of each localized frequency component. This led to its application for detection and interpretation of events in time series in a variety of disciplines including seismology.

Any seismic image analysed in the Resolution package can be treated as a number of white and black stripes (peaks and troughs) at different directions. For simple geology cases, these stripes are almost parallel, for complex subsurface structures, like salt domes or thrust faults, the directions of seismic events vary considerably throughout the area.

The idea of the Resolution software is to find the number of wave cycles, later referred to as wave number *k*, in both horizontal, k_x, and vertical, k_y, directions for any image.

Based on the wave number, some approximations about the frequency at a particular point of the seismic image are made, and this, in turn, can help to localize any frequency anomaly on the seismic section.

Let us consider a signal with the wave vector (6, 4), as shown in Figure 2a. According to Fermat's principle, the vector of the dominant frequency is perpendicular to the wave front.

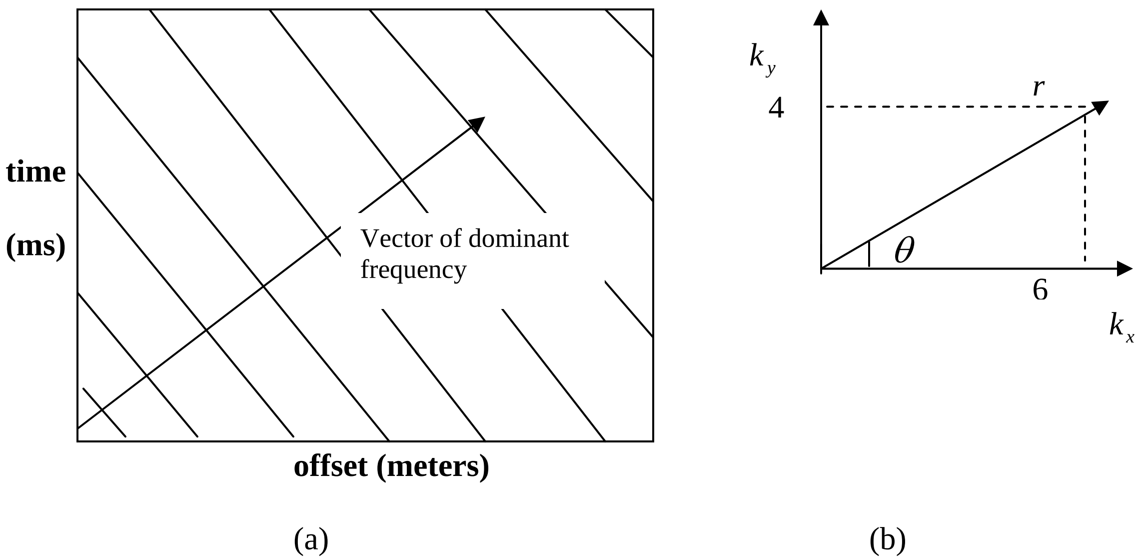

FIG. 2. (a) The schematic diagram of the signal with a wave vector (6, 4), and (b) its decomposition in the frequency domain.

The frequency vector can be characterized by its length *r* and the angle from the horizontal direction, θ, (Figure 2b). Thus, the wavelength and the angle of the dominant frequency can be defined as follows:

$$r = \sqrt{k_x^{\,2} + k_y^{\,2}} \quad (2)$$

$$\theta = \arctan\left(\frac{k_y}{k_x}\right) \quad (3)$$

The above mentioned parameters (equations 2 and 3) play a key role in the generation of the spectral and dip maps produced by the Resolution software.

FFT AND LOCAL SPECTRUM FOR THE PIKES PEAK DATA

P-wave data from the Pikes Peak multicomponent seismic line were loaded into Resolution. (Figure 3). The software interface is divided into four panes: two windows on the left have the units of space, and on the right – units of frequency. The standard Fourier transform is shown here for the whole seismic image. The FFT window (Figure 3b) shows that all useful frequencies are concentrated in a narrow frequency range (two symmetrical light blue zones), where k_x is close to zero and k_y varies from 0 to 0.15 scaled units of frequency. Since the Pikes Peak geology is quite flat, the main direction of the dominant frequency is almost vertical; no cycles can be detected in the horizontal direction. The fast Fourier transform representation is shown here with the direct current in the middle, so the image looks symmetrical.

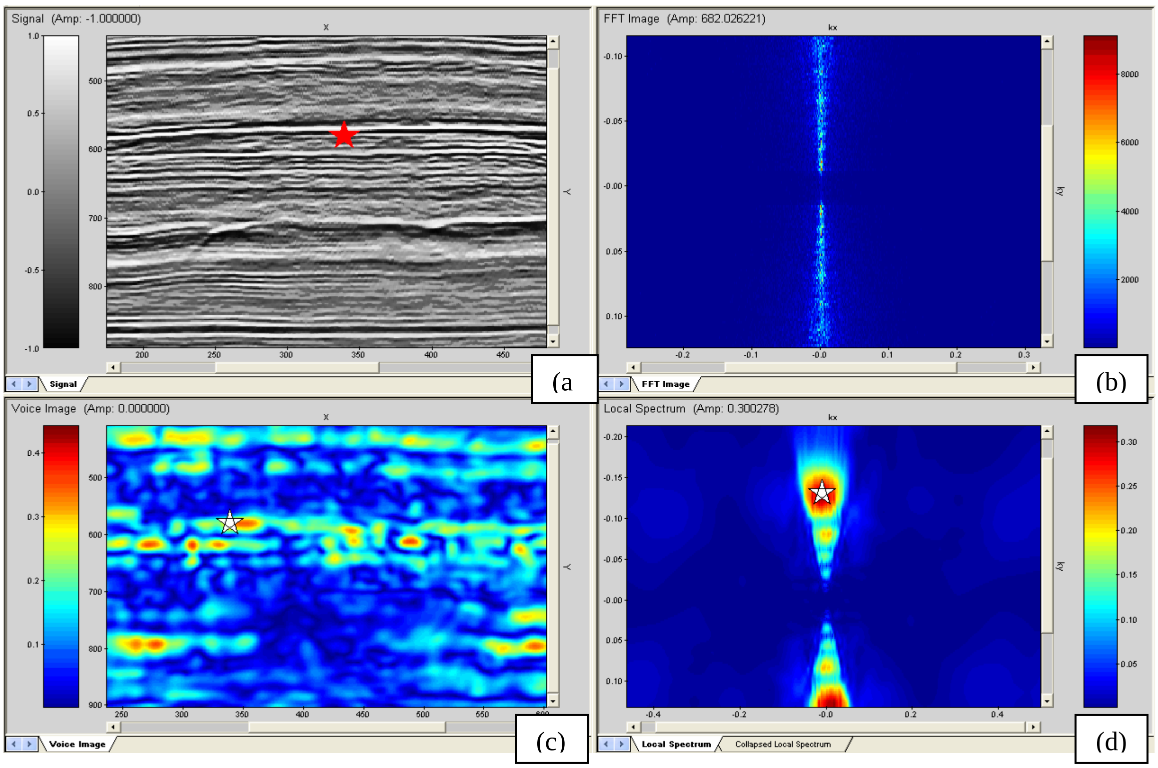

FIG. 3. Resolution window with loaded seismic data, where (a) seismic image in time, (b) Fourier transform for the whole image, (d) local spectrum for a particular point, (c) voice image.

Both top images (Figure 3a and 3b) correspond to standard ways to represent seismic signals and their spectra. The S-transform (Figure 3c and 3d) is a unique method implemented in Resolution, which allows us to conduct a highly effective frequency analysis of a seismic image.

Figure 3d is generated for a single point selected in the Image pane (at the red star). Here the signal is transformed from the time to frequency domain using formula (1). The resulting local spectrum is used to identify all frequencies that are present at a selected point in the image. If we draw a line between two dominant frequencies (Figure 3d, dark red points) we can get an impression about the direction of the frequency vector. In our case, the dominant frequency comes from the vertical direction, which indicates almost horizontal layering in the survey area. Figure 3c shows the corresponding Voice Image for a single frequency selected from the Local Spectrum. We define the Voice Image as a spatial distribution of one conjugate pair of frequency. It is generated to show all points within the signal image where the chosen frequency occurs. Typically, the Voice Image can be useful to identify unwanted signals.

The local spectrum (Figure 3d) is the input from which to create dip, spectral and peak amplitude maps in MatLab using the scripts developed by CSI. The dip map is intended to show the angle of layering for a geological structure, and the spectral map – its frequency component. The peak amplitude map indicates the points where the seismic amplitude reaches its maximum.

DIP, SPECTRAL, AND PEAK AMPLITUDE MAPS

A portion of seismic data (400-900 ms) was loaded into Resolution (Figure 3), and the S-transform was calculated for the seismic image. Then the maps of interest were generated.

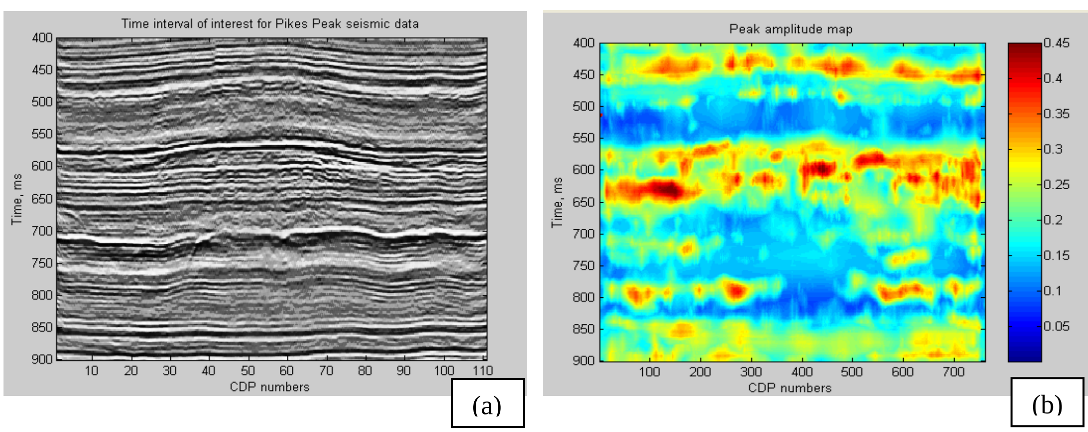

FIG. 4. Seismic image (a) and peak amplitude map (b).

The PP seismic data and corresponding peak amplitude map are shown on Figure 4. Note that the visible amplitude peaks correspond to the brightest reflections on the seismic section. In other words, the maximum amplitudes are located where a considerable contrast in densities and seismic velocities between two neighbouring layers exists. For this case, the main reflections can be easily seen by the naked eye. However, for some cases, when the seismic image is not so clear, the peak amplitude map provides additional information about the main horizons and position of the anomaly on the section.

Originally, the dip map returned the angle of the frequency vector for every pixel in the seismic image. Since we know that the vector of dominant frequency is perpendicular to the bedding, we rotate the dip values by 90 degrees obtain the dipping angle for the structure.

Figure 5 demonstrates the dip and spectral maps for the same line. As we can see, the majority of points have zero degree dip (Figure 5a). According to the color bar, we can assume that the left part of the image (yellow and light blue) is tilted to the left; and the right part of the image (dark blue, blue) is tilted to the right, which confirms the presence of a mild anticline centered at around CDP 400.

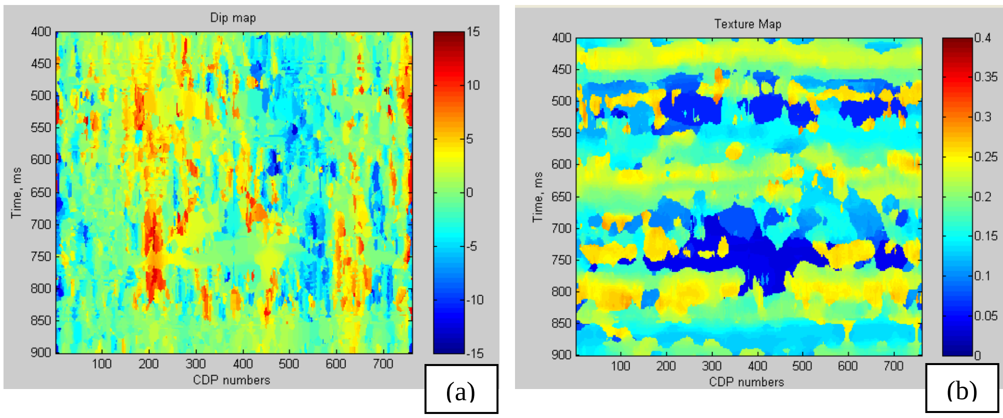

FIG. 5. (a) Dip and (b) spectral maps.

The spectral map (Figure 5b) shows the wavelength of the frequency vector (equation 2) at different spatial points. It is given in units of sampling frequency from 0 to 0.4. The interesting detail that we found is the low-frequency anomaly (dark blue) just below the productive zone. The first anomalous zone (dark blue, CDP 150-500) coincides with the well known productive zone (however it is shifted down by about 100 ms), and the second zone matches the area that I picked as a proposed channel location using Hampson-Russell Software (CDP 680-710).

According to Hilterman (2001), these are some indicators of a hydrocarbon reservoir:

Amplitude changes on a stacked section

Velocity changes

Wavelet changes

Frequency changes

Flat spots

Changes in amplitude with offset

In terms of frequency changes, there can be a decrease in frequency immediately beneath the reservoir because of deconvolution and attenuation. (Hilterman, 2001). We were encouraged by this fact, since the same situation was also observed in other data briefly mentioned in this report. In particular, 10 datasets out of 15, processed in Resolution, revealed the low-frequency anomaly below the productive interval, (Figures 6, 7).

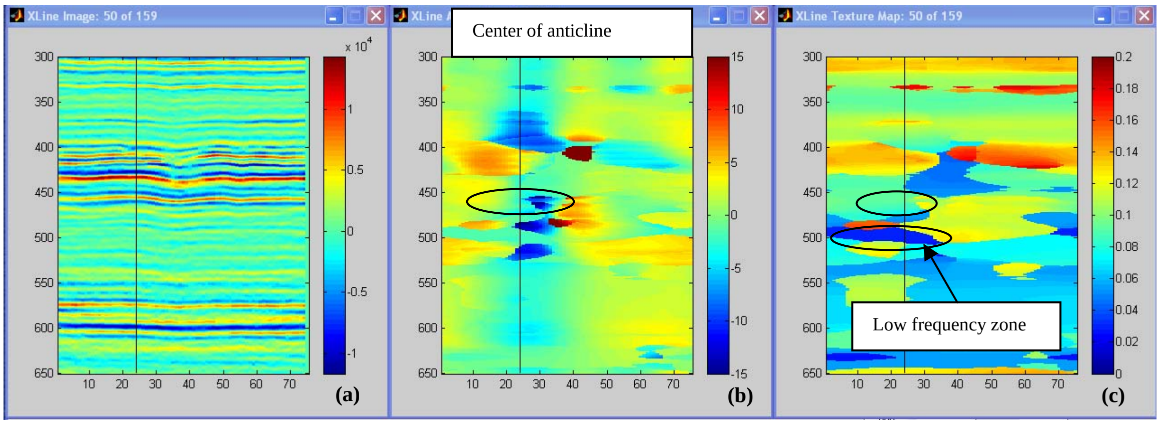

FIG. 6. Seismic image (a), Dip map (b) and Spectral map (c) for the X Line 50 from the 3D survey in the Driver area, Saskatchewan; the black line indicates the well location.

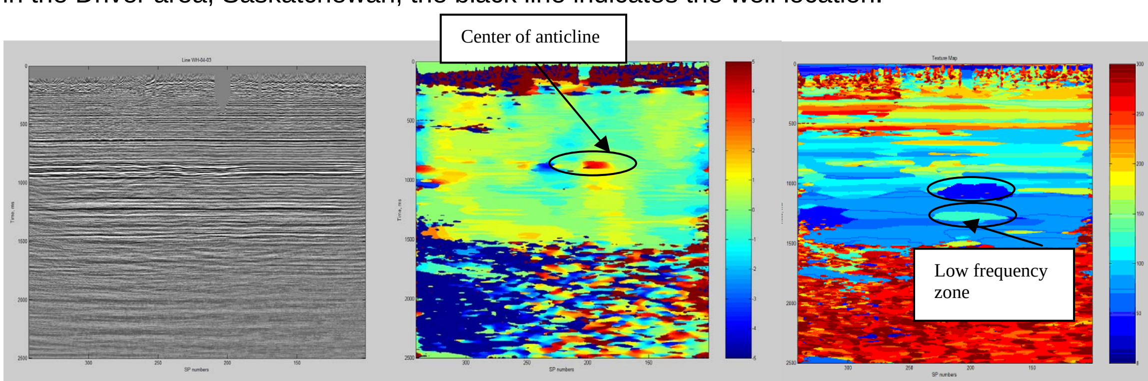

FIG. 7. Seismic image (a), Dip map (b) and Spectral map (c) for the line WH-04-03 from 2D survey in the Whiteside area, Saskatchewan.

On the dip maps (Figures 6b and 7b) the transition from yellow to blue indicates the centre of the anticlinal structure. Both spectral maps (Figures 6c and 7c) reveal the low frequency anomaly (dark blue) below the proposed reservoir location.

CONCLUSIONS

1. Dip maps are a seismic transform that allow us to: determine the dipping angle of the layers and the position of an anomaly (anticline or syncline) on a seismic section. However, they give us no idea about the lithological content of an anomaly: whether it is gas sand, oil sand, a shale channel, or sand saturated with water.

2. Spectral maps indicate the frequency content of the data. Thus they provide some information about the lithology. Harder rocks have a higher quality factor, thus waves within such rocks attenuate more slowly. Similarly, attenuation is high in softer rocks. Rocks have a range of quality factors. Some qualitative information about the nature of a rock may be obtained by inspecting spectral maps.

3. A low-frequency anomaly on the spectral map might be considered as an additional indicator of a hydrocarbon reservoir.

4. All maps should be used in conjunction with the seismic section. Combining all the types of available data (seismic section, CSI Maps, well log data) may well lead to a more accurate prediction of the productive zone.

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