SPECTRAL DECOMPOSITION AND RESERVOIR ENGINEERING DATA IN MAPPING THIN BED RESERVOIR, STRATTON FIELD, SOUTH TEXAS

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ABSTRACT

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Spectral decomposition is an innovative seismic attribute that showed excellent results particularly in tertiary basins such as the Gulf of Mexico and West Africa on which the technique was first implemented. Therefore many interpreters worried that it would not work well in other environments. We conducted a spectral decomposition study at Stratton Field, in South Texas. We focus on Middle Frio fluvial F-39 reservoir, a gas producing reservoir in the Stratton field. The main purposes of this study are: First, to test spectral decomposition ability to infer information documented in previous work about this thin and deep reservoir. Second, to reveal more stratigraphic features that might not be revealed previously. Due to the complexity of the reservoir, well data calibration and correlation played a key role to locate the reservoir interval. Interestingly, spectral decomposition could successfully image reservoir and its compartments and provide information that correlate very well with production history and reservoir's pressures data. Moreover, it enabled us to map the reservoir compartments' boundaries and a meandering channel reservoir that was unseen in seismic broadband. Indeed, the study shows that spectral decomposition can work very well even in very complex and extremely thin reservoirs. Furthermore, it shows how geophysics, geology, and reservoir engineering technologies when best integrated can address very complex formations and reveal much reliable information.

KEY WORDS: broadband, spectral decomposition, compartments, channel, stratigraphy.

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INTRODUCTION

The 3D seismic and well data used in this study are public-domain Stratton data set from South Texas provided by The Bureau of Economic Geology (BEG) at The University of Texas at Austin. The BEG has completed several research studies to better understand the internal architecture of complex, heterogeneous oil and gas reservoir systems (Finley et al., 1992; Levey et al., 1992). One of these research efforts was the Secondary Gas Recovery (SGR) project, which meant to determine if reservoir compartmentalization in older producing properties creates gas accumulations that have either not been contacted, or not been effectively produced, by the perforated intervals in production wells (Sippel and Levey, 1991). The field studies are done in producing intervals that have minimal faulting because faulting introduces a reservoir compartmentalization that overprints and complicates any compartmentalization effects inherited from the depositional system. The studies are also done in older producing properties because such fields usually have enough well-by-well production history and pressure documentation to confirm whether or not reservoir compartment boundaries are present (Hardage et al., 1994). The efforts of Hardage et al. (1994) resulted in detecting a narrow, meandering channel fill reservoirs as thin as 10 ft and as narrow as 200 ft. Additionally, they proposed a geologic model that accounts for all the interpretations inferred from different available data (seismic, well data, static pressure). In this investigation we focus on one of these thin channel reservoirs (F39); we try to go further beyond seismic resolution by decomposing the seismic broadband into individual frequencies using wavelet transform.

We run Continuous Wavelet Transform (CWT) spectral analysis to the data. This allows us to compare which frequency component is dominant within our area of interest and use these frequency components to map our reservoir stratigraphic features. The decomposition reveals that the amplitude contrast between the gas sand and shale is much higher at individual frequencies than it was in seismic broad band imaging. Furthermore, it could image a narrow meandering channel reservoir that did not appear in seismic. It also did support the reservoir compartmentalization's interpretation by Hardage et al. (1994) and even indicate their boundaries.

SPECTRAL DECOMPOSITION IN RESERVOIR STUDIES

Spectral decomposition is an innovative seismic attribute used for reservoir imaging and interpretation technology originally developed and commercialized by BP, Apache Corp. and Landmark (Partyka et al., 1999). The technology utilizes a sequence of seismic frequency slices through an area of interest to create a suite of amplitude maps which can be selectively combined to yield much higher resolution images of reservoir boundaries, lithologic heterogeneities and interval thicknesses than the traditional broad-band seismic displays (Burns and Street, 2005). The technique showed excellent results particularly in tertiary basins such as the Gulf of Mexico and West Africa. Therefore many interpreters worried that it would not work well in other environments (Chopra and Marfurt, 2008).

Over the last decade numerous published work discussed how this new attribute can be used to differentiate both lateral and vertical lithologic and pore-fluid changes (Burnett et al., 2003; Sinha et al., 2005; Goloshubin et al., 2006; Chen et al., 2008); as well as delineating stratigraphic traps and identifying subtle frequency variations caused by hydrocarbons (Burnet et al., 2003; Castagna et al., 2003; Goloshubin et al., 2006; Loizou and Chen, 2012; Farfour et al., 2012; Yoon and Farfour, 2012). All these work among others proved that spectral decomposition is an applicable technology in different areas around the globe, and in variety of environments.

CONTINUOUS WAVELET TRANSFORM

For a nonstationary signal such as a seismogram, the frequency content changes with time. The amplitude spectrum of the Fourier transform indicates the presence of different frequencies but does not show temporal distribution of these frequencies. If we assume that the signal through a small window of time is stationary, then its Fourier transform or Short Time window Fourier Transform (STFT) provides us with the frequency content of the signal in that time period. By shifting this time window appropriately, the frequency content of the signal is extracted and a 2D representation of frequencies versus time is produced (Chakraborty and Okaya, 1995).

A wavelet transform (WT) is also a technique to decompose a signal to identify its frequency distribution through time. This technique differs from the Short Time window Fourier Transform (STFT) in that while an STFT uses a fixed size time window, a wavelet transform uses a variable window size.

The continuous wavelet transform (CWT) is an example of WT technique. It was first introduced by Morlet et al. (1982) and Goupillaud et al. (1985), but received full attention of the signal processing community when Daubechies (1988) and Mallat (1989) established connections of the WT to discrete signal processing.

The main advantage of using a CWT over an STFT in addition to that mentioned previously is that the CWT has good frequency resolution for low frequencies and good time resolution for higher frequencies (Chakraborty and Okaya, 1995; Castagna et al., 2003). In the CWT, wavelets dilate in such a way that the time support changes for different frequencies. Smaller time support increases the frequency support, which shifts toward higher frequencies. Similarly, larger time support decreases the frequency support, which shifts toward lower frequencies. Thus, when the time resolution increases, the frequency resolution decreases, and vice versa (Mallat, 1999).

A wavelet is defined as a two-dimensional function $\psi(t)$ with a zero mean, localized in both time and frequency. By dilating and translating this wavelet $\psi(t)$, we produce a family of wavelets:

$$\psi_{\sigma,\tau}(t) = 1/\sqrt{\sigma}\;\psi(t - \tau/\sigma) \quad , \tag{1}$$

where σ, τ are real. σ is not zero and σ is the dilation parameter or scale. Note that the wavelet is normalized such that the L_2-norm $\|\psi\|$ is equal to unity.

The CWT is defined mathematically as the inner product of the family of wavelets $\psi_{\sigma,\tau}(t)$ with the signal s(t),

$$S_\omega(\sigma,\tau) = \int_{-\infty}^{\infty} s(t)(1/\sqrt{\sigma})\bar{\psi}(t - \tau/\sigma)dt \quad , \tag{2}$$

where $\bar{\psi}$ is the complex conjugate of ψ and S_ω is the time scale map (scalogram) (Sinha et al., 2005).

In this study we use the Morlet wavelet, one of the most commonly used wavelets in seismic spectral decomposition. The Morlet mother wavelet is defined as:

$$\psi_0(t) = \pi^{-1/4}e^{i2\pi t}e^{-t^2} \quad . \tag{3}$$

In practice the CWT approach involves the following steps:

- Decompose the seismogram into wavelet components, as a function of the scale σ and the translation shift τ.
- Multiply the complex spectrum of each wavelet used in the basis function by its CWT coefficient and sum the result to generate instantaneous frequency gathers.
- These gathers then sorted to produce constant frequency cubes, time slices, horizon slices, or vertical sections (Chopra and Marfurt, 2007).

In our case we first select the wavelet type (Morlet) and set the initial frequency and the increment. The CWT attributes over any frequency range will be calculated, starting from the initial frequency at any frequency interval. As a result the output displays the spectral decomposition component at the frequencies that the user wants to evaluate.

GEOLOGIC SETTING

We performed this study in a portion of Stratton Field in Kleberg and Nueces Counties of South Texas. The stratigraphic interval we studied was the Oligocene Frio Formation, a thick, fluvially deposited sand shale sequence that has been a prolific gas producer in Stratton Field and in several other fields along the FR-4 depositional trend (Fig. 1).

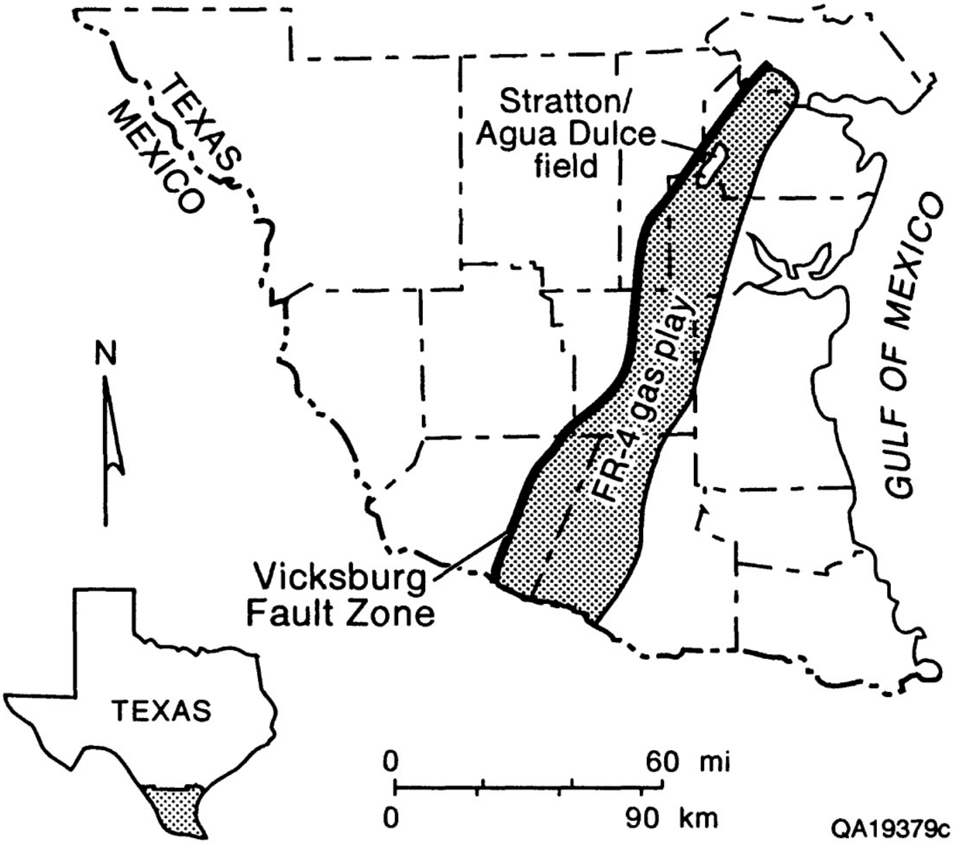

Fig. 1. Map of the prolific Frio FR-4 gas trend in south Texas showing the location of Stratton Field (From Hardage et al., 1994).

The middle Oligocene section was deposited during the Catahoula-Frio depositional episode described by Galloway (1977). The entire Frio Formation is divided into 10 gas plays on the basis of regional variations in structure and depositional setting. The Frio Fluvial/Deltaic Sandstone play along the Vicksburg Fault Zone (gas play FR-4 from Kosters et al., 1989) is ranked as the third largest of all 73 gas plays in Texas and the largest of all nonassociated gas plays in the Gulf Coast; cumulative production had exceeded 12 Tcf as of January 1, 1991. Hydrocarbon trapping in reservoirs of the FR-4 gas play is controlled by a combination of structural and stratigraphic factors, including faulted anticlinal closure, facies change, and reservoir pinch-out. Most of the gas production in the FR-4 play is from middle Frio reservoirs (Levey et al., 1994).

WORKFLOW

It was somewhat difficult to relate the BEG cube to previous work in the literature. The BEG cube is only a 1 × 2 miles subset of a much larger 3D survey. Also the few wells supplied along with the BEG data set use generic numbering 1 through 20; whereas the wells in the original paper are referenced by the well name (e.g., BEG well 9 is Wardner 175 in literature). Note that the two remaining wells locations are used just as approximations to show the locations of the real wells and the compartments they are positioned in. Well 16 is used instead of well W197, while well 02 is representing W75. The polarity of the data set was also different, thus, we have reversed the data polarity so that we facilitate the comparison and calibration with the published data.

Since most reservoirs in this field are considerably thin and they are closely stacked, in some areas separated only 10-15 ft (3-5 m), a precise calibration of stratigraphic depth versus seismic travel time to locate and track our reservoir was highly required. In addition, to reduce all risks that might be generated from tracking such complex thin reservoirs' horizons we use HorizonCube (De Grout et al., 2010; Brouwer et al., 2012). The approach currently being adopted for generating the horizon cube involves two main steps. First, a dip steering cube is generated which calculates local dip azimuth at every sample position within the seismic cube. The smoothed steering cube is subsequently used to generate a dense set of autotracked horizons that are typically separated by one sample apart on average which is very useful in our case. This densely tracked horizons mapping technique enables us to generate a set of continuous, chronologically consistent horizons. We then extract our attributes and perform our analysis at the horizon and slice that the reservoir interval occurred. After that we study carefully the spectral-decomposition response to the reservoir area. Each frequency component was expected to help understand and interpret subtle details of the stratigraphic framework of the compartmented reservoir.

As the formations in the area of interest are characterized by horizontal to slightly dipping reflections, in some cases we would use time slices instead of horizon slices.

RESULTS AND DISCUSSION

Most of the Frio reservoirs including F39 are thin and closely stacked vertically. Furthermore, the dominant period of reflected events according to Hardage et al.(1994) is about 20-25 ms. In such situations, seismic signals are composite and resulting from constructive and/or destructive interferences of the waves reflected from the neighboring reflectors; therefore, it was not easy to image this thin reservoir with seismic alone. Then, we have been searching for some seismic response similar to that of Hardage et al. (1994) study in which seismic data was carefully calibrated using vertical seismic profile (VSP) control (Fig. 2). This fact facilitates somewhat the task for us to find the reservoir.

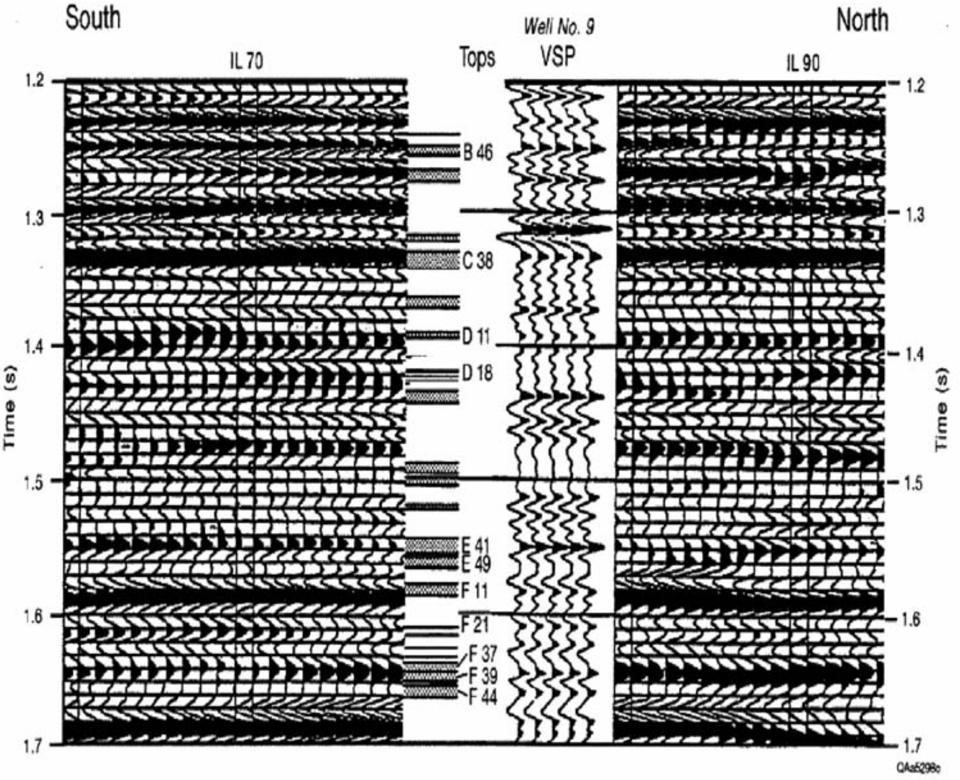

Fig. 2. Calibration of the F39 reservoir using the vertical seismic profile VSP in well no.175 (09). Note how reservoirs are thin and close. As a result reflection amplitude is composite and shows lateral changes that cannot be related to a single reservoir (From Levey et al., 1994).

Time slices could show a very close response to Hardage et al. (1994), however, horizons did not appear very similar. This is due to difficulty in duplicating horizons, especially when horizons are not easy to handle and mapping techniques are different. We thus begin our analysis on time slices first, and then we run the analysis on the horizons. Fig. 3 shows measured static pressures of 3 key producing wells. The wells provide very significant key information; because differences in their static pressures suggested that each well might be belonging to a different compartment. The seismic images according to Hardage et al. (1994) did indicate some possible compartment boundaries explaining the static pressure change. For example, in Fig. 4 which shows a seismic response quite similar to that was interpreted by Hardage et al. (1994), according to the authors, the most likely cause of the compartment boundary that separates well 197(16) from the other wells, is the depositional variation that created the (positive/negative) amplitude changes that trend north-south between crossline coordinates 72 and 83. Similarly, the figure displays a probable seismic indication of the compartment boundary that segregates well 20 from the other wells which is the positive-to-negative amplitude change trending north-south between crossline coordinates 87 and 97.

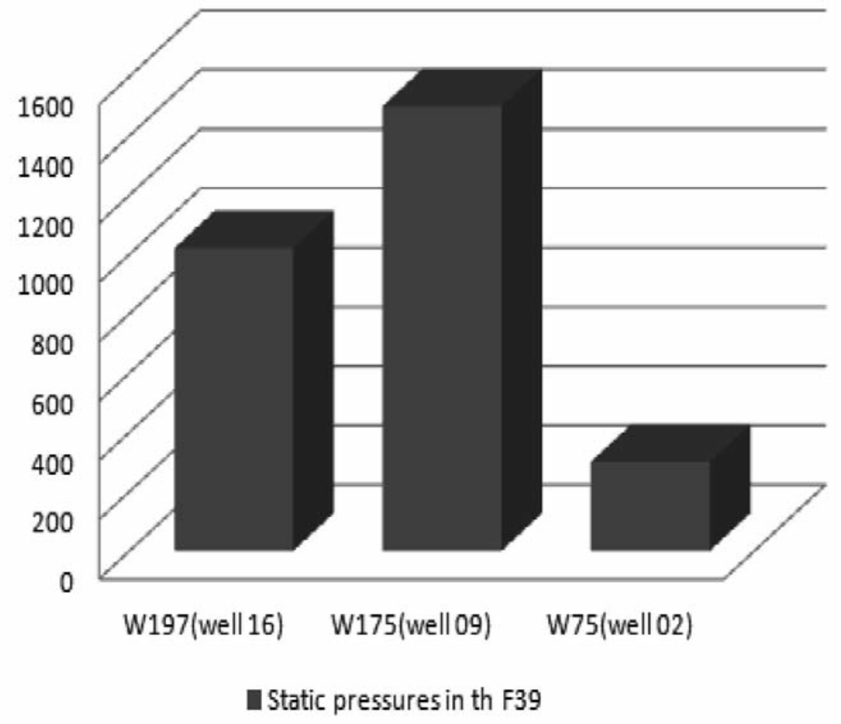

Fig. 3. Static pressure in the F39 reservoir measured during January 1992 in the three wells in Fig. 4 (modified after Hardage et al., 1994).

Several frequencies were computed for this latter time slice. In Figs. 5, 6 and 7 we display its corresponding frequency components at 15, 20 and 25 Hz. At 15 Hz no noticeable response was seen. At 20 Hz, the compartments boundaries that the seismic images suggested between 72 and 83 as well as between 87 and 97 in Fig. 4 are clearly visible. A meandering channel reservoir is also apparent at this frequency, ensuring that 20 Hz is closer to the reservoir compartments' tuning frequency than 10 Hz is. At 25 Hz the channel change slightly and becomes unclear, whereas the boundaries are still present. However, the frequency behaviors of the wells surrounding areas are still noticeably different and telling us that a compartmentalization had occurred and the wells belong to different compartments.

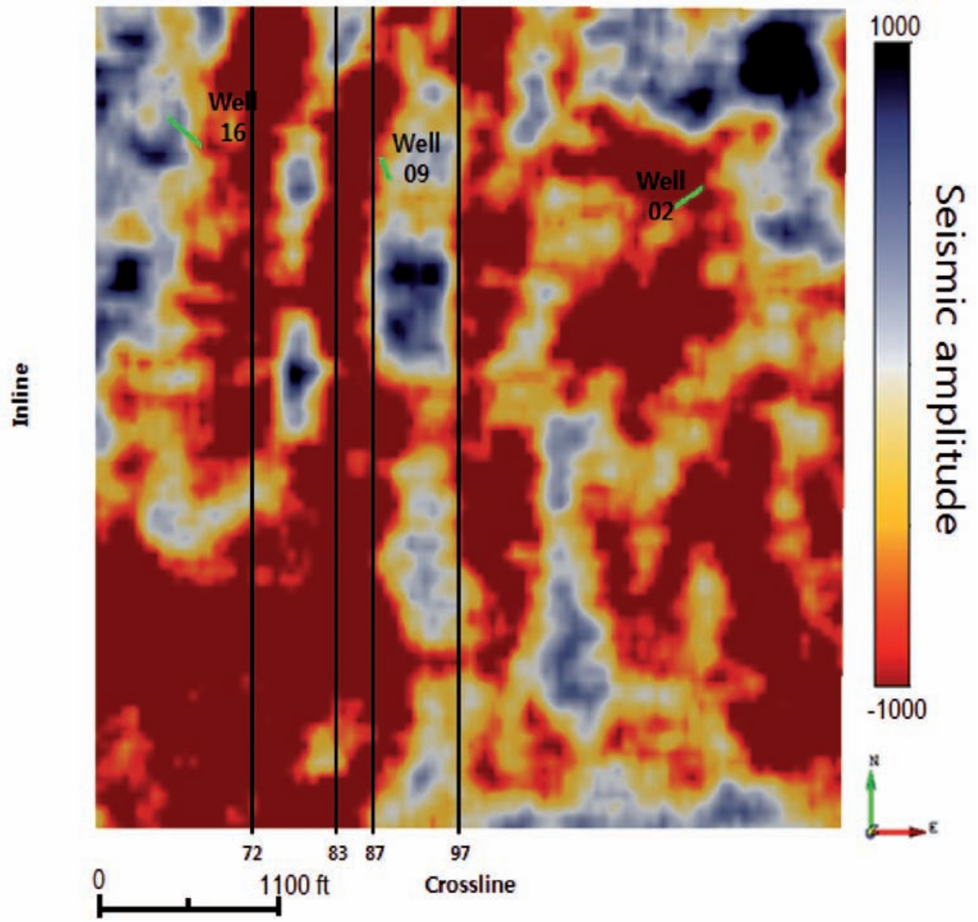

Fig. 4. Time slice shows seismic response of the F39 reservoir in the vicinity of the 3 critical wells. Note that the general trend of the slice is similar to the response observed by Hardage et al. (1994).

We can attribute the clear anomalous amplitude that the reservoir compartments and channel show at 20 Hz to the result of both thin bed tuning and hydrocarbon charge which is observed along the channel and around wells locations as well. The gas charge presence makes the reservoir compartments reflectivity coefficients larger than those in the adjacent non hydrocarbon filled areas. The thin bed tuning effect of those large reflection coefficients preferentially reflects 20 Hz frequency, thus making the gas sand compartments brighter and clearer than at other frequencies lower or higher than 20 Hz. It was noticed also that the frequency maps show a different distribution of frequency amplitude within each particular compartment. A possible reason for this might be due to change in thickness of the reservoir and hydrocarbon saturation.

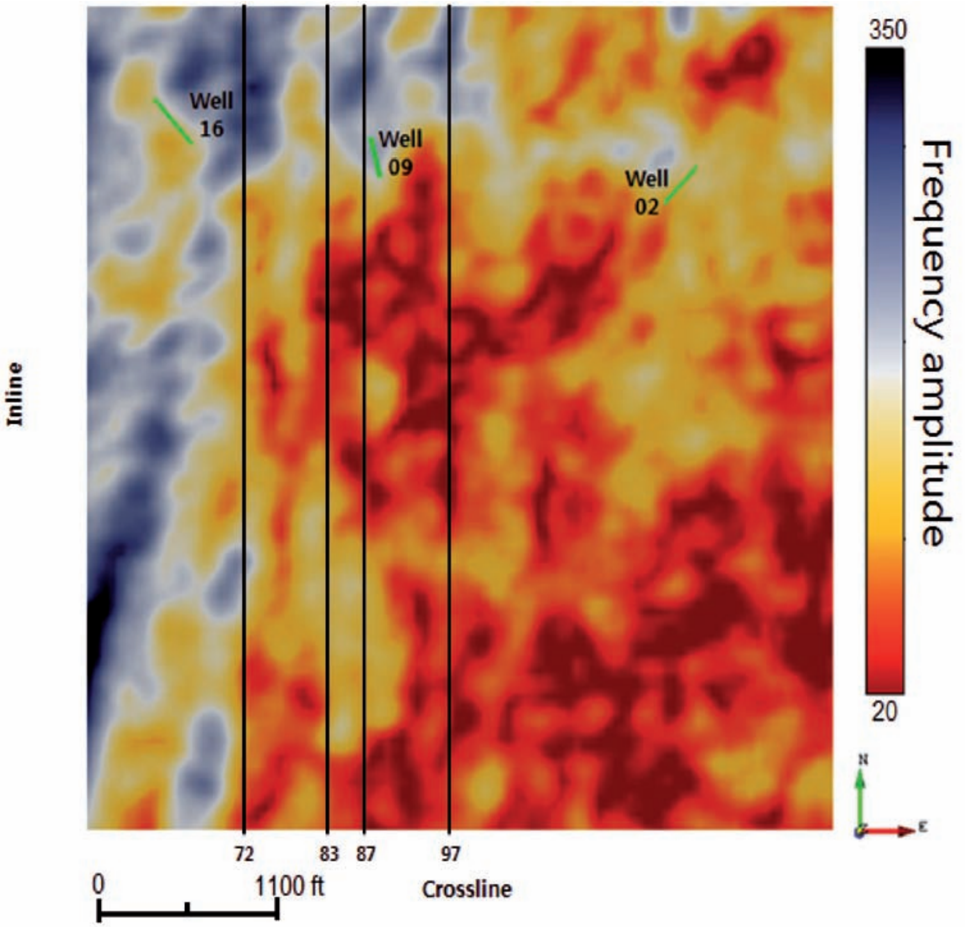

Fig. 5. 15 Hz spectral decomposition. No information about the reservoir is apparent.

Additionally, we found that, in seismic broadband, horizons are somewhat much sensitive to tracking errors than in spectral decomposition frequencies. Thus, we conclude that it is much safer to interpret spectral decomposition images than seismic images. Furthermore, the spectral decomposition time slice in Fig. 6 and horizon in Fig. 8 exhibit almost the same frequency expressions. The reason might be due to the fact that geological features, or at least most of them, can be seen on more than one closely-spaced horizon slice (Roksandic, 1995).

Finally, we believe that we might be able to image also the F37 reservoir which is located just 4 ms above our target reservoir (F39), in the same way,

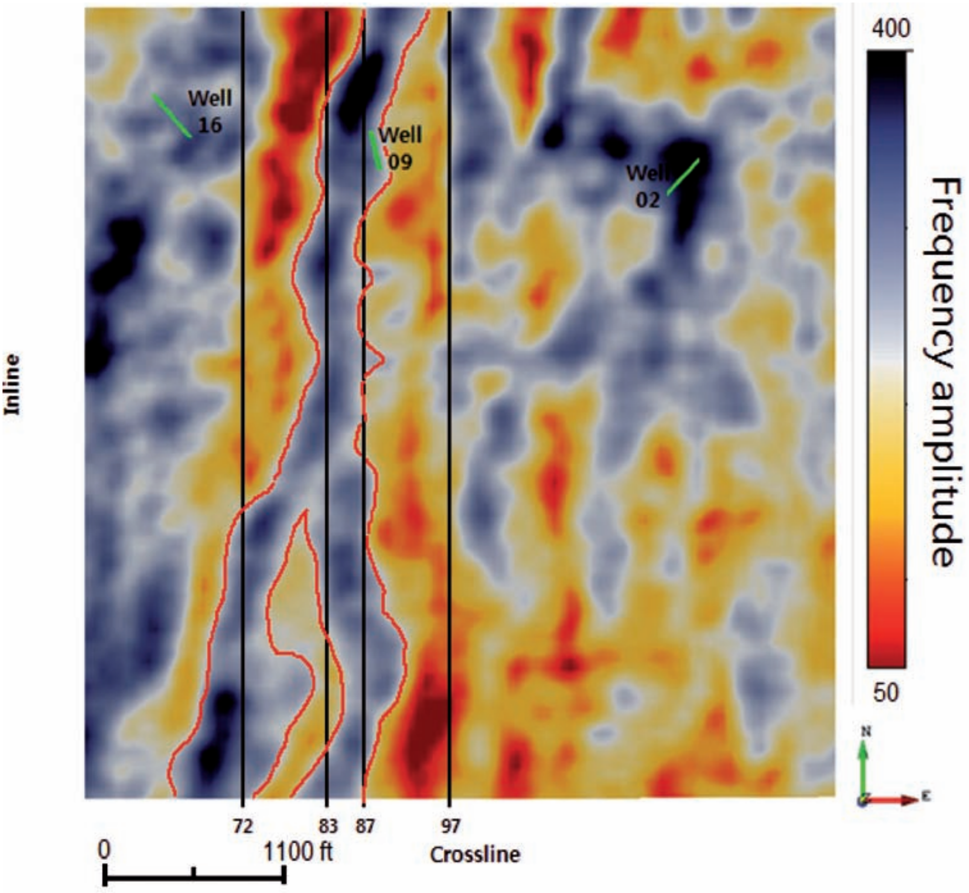

Fig. 6. 20 Hz time slice frequency component shows amplitude barriers and a clear meandering channel reservoir (outlined channel). Note that the F39 reservoir is composed of different compartments and each well belongs to a different reservoir compartment. Boundaries can be seen between crosslines 72 and 83, 87 and 97 (lines in black).

since there would be not too much change in the frequency behaviour from that of the F39 reservoir interval. However, based on the BEG study, the F37 reservoir area is located between 0 to 120 inline, whereas our small subset covers only the area from 140 to 220 inline.

It is important to notice that all these interpretations, derived from spectral decomposition, were found consistent with interpreted seismic and engineering data in Hardage et al. (1994) work. Thus, spectral decomposition not only confirmed information from seismic but could go beyond the seismic capability and provide clearer interpretation that was confirmed by reservoir engineering data.

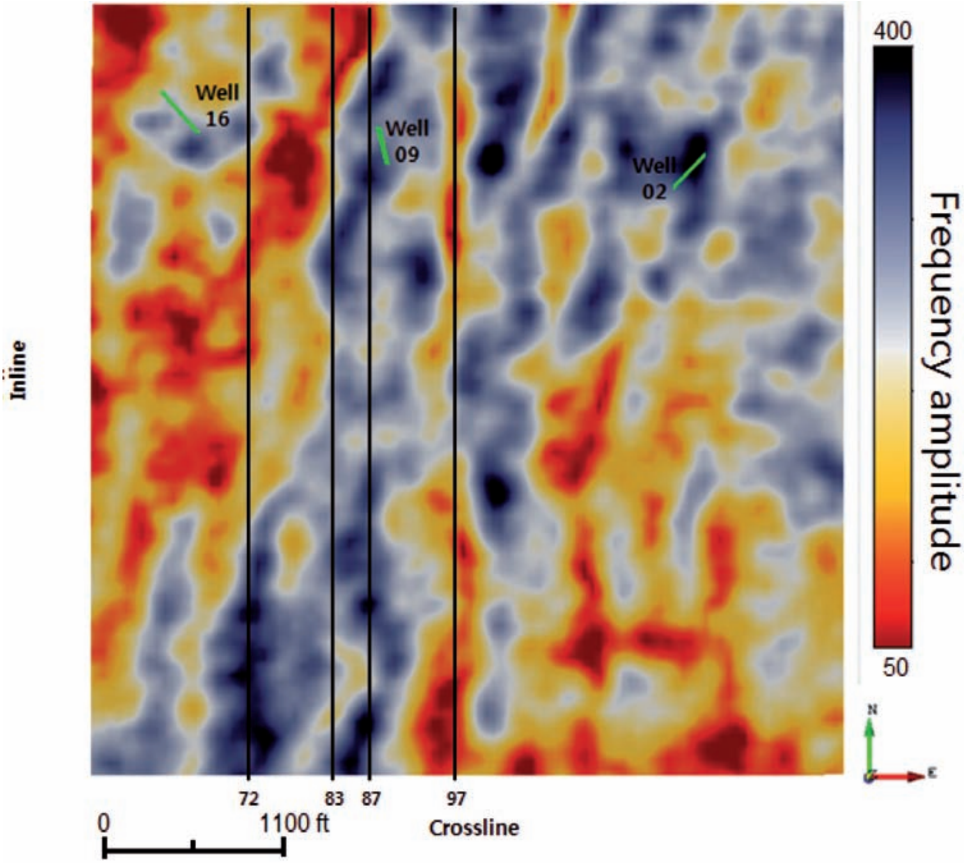

Fig. 7. 25 Hz spectral decomposition slice of the F39 reservoir. Note that the meandering channel that was clear in 20 Hz disappears in 25 Hz however the barriers still exist.

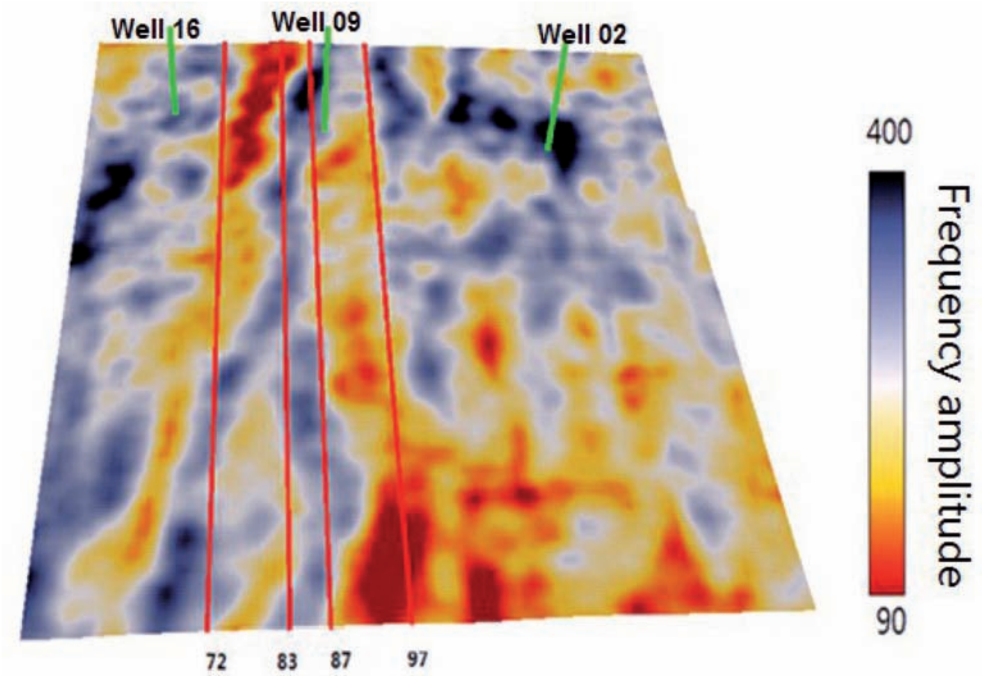

Fig. 8. 20 Hz spectral decomposition horizon of the F39 reservoir shows also the meandering channel and the compartment boundaries between wells.

CONCLUSION

This study presents an example among many other successful applications of spectral decomposition for delineating and characterizing hydrocarbon reservoirs.

Very thin reservoirs could be clearly imaged by decomposing the seismic broad band into its frequency components using continuous wavelet transform.

The decomposition did confirm the seismic images interpretation regarding the thin reservoir compartmentalization and reveals clearly the compartment boundaries and a channel-like structure reservoir that was unseen in seismic images. Moreover, it could explain the change in static pressures of wells and confirms that they are positioned in different compartments.

The study proves that spectral decomposition can work well and reveal vital information about reservoirs in more complex environments than those of the Gulf of Mexico and West Africa, in which the technique was first implemented. It shows also how seismic attributes, geology and engineering data, once best integrated, together can overcome problems that are difficult if it is not possible to solve using seismic alone.

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