Click to see Poster presentation

Detection of Fluvial Systems Using Spectral Decomposition (Continuous Wavelet Transformation) and Seismic Multi-Attribute Analysis – A New Potential Stratigraphic Trap in the Carbonera Formation, Llanos Foothills, Colombia*

Essam Saeid[1], James Kellogg[1], Christopher Kendall[1], Ibraheem Hafiz[1], and Zyaid Albesher[1]

Search and Discovery Article #42281 (2018)**
Posted October 1, 2018

*Adapted from extended abstract based on poster presentation given at 2018 AAPG Annual Convention & Exhibition, Salt Lake City, Utah, May 20-23, 2018
 DOI:10.1306/42281Saeid2018

[1]School of Earth, Ocean and Environment, University of South Carolina, Columbia, South Carolina (esaeid@geol.sc.edu)

Abstract

Since the discovery of the giant Cusiana Oil Field in Colombia, hydrocarbon exploration in the Llanos Foothills has focused on structural traps in the hanging walls of thrust faults. There has been little exploration success in the footwall blocks, and most of the activity has been based on subtle structural traps. Cusiana Oil Field is considered one of the most important structural traps that produce oil from the Eocene Mirador Formation. In the Llanos foreland basin the main reservoir is the Carbonera Formation (C-1, C-7) which is Oligocene to Lower Miocene in age. Using 3D high-resolution seismic data combined with well logs, we propose a set of prediction methods for complex fluvial reservoirs in the area south of the giant Cusiana Oil Field. The methods (1) use visualization and co-rendering of 3D seismic multi-attribute (including RMS, Coherence, reflection strength) to predict sedimentary sub-facies, (2) use time slices and horizon probes (Sculpture) to predict the configuration of the sandstone using 3D visualization techniques, (3) predict the fluvial structures using spectral decomposition (CWT) with different wavelet (Morlet, Gaussian and, Mexican hat) and (RGB) blending of the frequency cubes, (4) use continuous wavelet transformation for evaluation of hydrocarbon reservoirs, and (5) use multi-attribute analysis on the frequency cubes (frequency domain) to enhance stratigraphic features that are undetectable in time domain seismic data.

Introduction

This article describes how complex fluvial reservoir prediction methods can be used southwest of the Cusiana (giant) Oil Field to interpret seismic data with continuous wavelet transform (CWT) spectral decomposition of high resolution seismic volume and well log data. Seismic interpretation techniques used include (1) 3D seismic attribute technique (RMS, Coherence and reflection strength, etc.) to predict sedimentary sub-facies, (2) time slice and horizon probe (Sculpture) to predict the configuration of the sandstone using the 3D visualization technique, (3) continuous wavelet transformation (CWT) spectral decomposition and (RGB) blending of the frequency cubes to predict the fluvial structures, and (4) CWT for evaluation of hydrocarbon reservoirs. Most of the techniques used here were based on 3D seismic interpretation in Brown (2011), Partyka et al. (2011), Lughlin et al., (2002), Sinha et al. (2005), and Marfurt (2015).

The technique has been applied in the eastern part of the Llanos Foothills 40 km southwest of the giant Cusiana Oil Field in Colombia and east of the Guaicaramo Fault and Medina Basin (Figure 1). The Cusiana Oil Field is considered one of the most important structural traps producing oil from the Eocene Mirador Formation (De'Ath, 1995; Cooper et al., 1995). In the Llanos foreland basin the main reservoir is the Carbonera Formation (C1, C7) that accumulated from the Oligocene to Lower Miocene (e.g. Cooper et al. 1995, Parra et al., 2009b). Since the large Cusiana discovery, hydrocarbon exploration in the foothills along the Cusiana Fault has focused on structural traps in the hanging wall, while most exploration in the footwall targeted subtle structural traps.

Previous Work

The accumulation of the Carbonera Formation of Late Eocene to Late Miocene age Figure 2 was discussed in several regional studies, including Bogota-Ruiz (1988), Cooper et al. (1995), Mora et al. (2006), Bayona et al. (2007), Jaramillo et al. (2009), and Parra et al. (2009b). All the studies have analysed the Carbonera Formation at a basin scale which does not predict the fluvial architecture and distribution of the sand bodies within the Carbonera Formation.

Cooper et al. (1995) described the Carbonera Formation as produced by four major cycles of marine-influenced lower coastal plain deposition that occurred in the Llanos Basin and Foothills and was bounded by widespread maximum flooding surfaces. Each cycle consists of a mud-dominated highstand systems tract followed by a thin, forced retrogradational systems tract, and ended with a sand-prone transgressive systems tract that culminates with the maximum flooding surface.

Bogota-Ruiz (1988), Jaramillo et al. (2009) and Parra et al. (2009b) subdivided the Carbonera Formation into eight informal units (C8 to C1) with odd numbers assigned to sandstones and even numbers assigned to mudstones. Bayona et al. (2008) focused on Member C3, C2 and C1 of the Carbonera Formation in Saltarín-1 well drilled through the Miocene succession of the eastern Llanos Basin. He argued that tectonic subsidence and climate were the controlling factors of the basin filling.

Based on lithology and sedimentary structures, Parra et al. (2009a) subdivided the Lower Carbonera Formation C8-C6 into 15 lithofacies and four facies associations in the Medina Basin just west of the study area. Parra et al. (2010) recognized the same four facies associations for the Upper Carbonera Formation (C5-C1) that represent tidally influenced deltaic, lacustrine, alluvial plain and braided fluvial sedimentary settings. They considered the Lower Carbonera Formation C8-C6 as a syntectonic wedge, while the Upper Carbonera Formation was syntectonic with growth-strata relationships that were rocks equivalent to C5-C2 west of the Medina Basin along the Lengupa Fault. They proposed a new chronostratigraphic framework for the C8-C6 members of Carbonera Formation based on palynological zonation (T-05 to Ca07) which are of Early Eocene-Early Miocene age.

Torrado et al. (2014) integrated 700 km^2 of 3D seismic with well data in the central Llanos Basin to characterize the Carbonera Formation (C1, C3, C5 and C7) from seismic attributes. Their interpretation of fluvial sands focused on identifying geoforms and channel filling material, characterizing them as prospective and non-prospective hydrocarbon plays. Also, they recommended advanced techniques that included spectral decomposition, RGB blending of frequency as well as seismic inversion to detect thinner channels within the wider channel belt complex.

Research Methods

Synthetic Seismogram

A synthetic seismogram was created from well-A logs in the 3D seismic volume (see Figure 1 for location). This synthetic seismic trace was tied to the seismic cross section using well check-shot survey data, and adjusting the T-D function through stretching and squeezing the wavelet accordingly, to match the data Figure 3a. The Carbonera Formation was defined as extending between 2350 and 3025 msec and including the Oligocene to Miocene fluvial sand reservoirs (Figure 3b).

Detection of Fluvial System Using Spectral Analysis, RGB Blending and Horizon Probe (Sculpture) Techniques

Spectral decomposition has been used to determine layer thicknesses (Partyka, 1999, 2011), stratigraphic geometries (Marfurt and Kirlin, 2001), and direct hydrocarbon detection (e.g., Goloshubin et al., 2002; Castagna et al., 2003; Sinha et al., 2005; Welsh et al., 2008; Yu et al., 2011). Additionally, spectral decomposition breaks the seismic signal into narrow frequency sub-bands or horizons (Partyka, 2011). This is achieved by transforming the seismic data from the time domain into frequency domain (Chopra and Marfurt, 2015). We used the recommended workflow by Partyka (2011) for the seismic volume, extracting more than 75 different bands in a frequency range 5-75 Hz. However, we modified this approach. Our spectral decomposition workflow started with data conditioning (Spectral enhancement) and then investigated the dominate frequency for the horizon of interest (Figure 4) constructing a tuning map of the Carbonera Formation to determine the stratigraphic features that could not be resolved in the time domain seismic cube.

The frequency spectra for the Carbonera Formation include the following dominant frequencies: 18-21, 25-33, and 38-41 Hz (Figure 4). The seismic volume within the Carbonera Formation was thus separated into iso-frequency volumes based on these frequencies (Figure 5). These volumes were manipulated and superimposed on generating bodies that matched geological features using the RGB/CMY Mixer application.

Spectral decompositions are short time Fourier transforms (STFT) and continuous wavelet transforms (CWT) and the matching Pursuit algorithm. Each of these has their advantages and disadvantages, and their selection depends on the objectives of the workflow. For instance, the STFT transformation depends on the time gate, a drawback for the transformation method (Sinha et al., 2005). On the other hand, the CWT method is unlike the conventional SFFT method, which limits the time-frequency resolution by a predefined window width (Sinha et al., 2005). Narrow windows give good time resolution but poor frequency resolution, whereas wide windows give good frequency but poor time resolution. However, to a certain extent, CWT solves the dilemma of resolution if one can choose the mother wavelet which works best for the seismic data (Morlet, Gaussian, and Mexican Hat or Ricker). This choice depends on the 3D seismic interpretation package used.

Some seismic interpretation workstations offer general spectral decomposition (GSD) as a hybrid of the STFT and CWT through a design wavelet using three parameters: frequency, number of cycles, and phase. The designed wavelet is eventually used to decompose (Correlation) or filter (Convolution) the input seismic data (Schlumberger, 2017). In this case after extracting the dominant frequencies you have to flatten each frequency volume, and then flatten the horizon of the interest at the flattening frequency, to blend these volumes by RGB mixer in order to detect the channels. Other seismic interpretation workstations offer separate spectral decomposition as STFT and CWT through a design of the window width and wavelet (Morlet, Gaussian, and Mexican) respectively.

We used the CWT algorithms of dGB OpendTect to achieve spectral decomposition and reveal fluvial channels throughout the Carbonera Formation. CWT and the calculated isofrequency seismic sections were based on all three wavelets; Morlet, Gaussian, and Mexican. When examining the frequencies of 18, 25, and 38 Hz using this refined approach, the images seen in Figure 6 and Figure 7 were produced. Since we found that CWT was better than STFT for spectral decomposition of the seismic volume to detect the stratigraphic features in the Carbonera Formation, the remaining analyses were based on the CWT approach.

Using Continuous Wavelet Transformation (CWT) to Detect Fluvial System Channels

The continuous wavelet transform (CWT) is an alternate method for frequency distribution analysis and is achieved by increasing or decreasing time support (transit time defining seismic volume) in the CWT, causing the frequency support (frequency content of seismic volume) of the wavelets to shift towards the high frequencies or low frequencies respectively. Thus, when the frequency resolution increases, the time resolution decreases and vice versa (Mallat, 2009). The CWT is focused on the spectral attributes of horizons rather than the entire stratigraphic interval as in the SFFT method (Sinha et al., 2005). The CWT method depends on the choice of the mother wavelets that include the Morlet, Gaussian, and Mexican hat.

CWT were calculated as single frequency seismic sections based on the Morlet, Gaussian, and Mexican hat wavelets with frequencies of 18, 25, and 38 Hz. The results are shown in Figure 6 for a temporal depth of 2727 ms within the Carbonera Formation. At frequencies of 18 and 21 Hz (Figure 6), the Morlet wavelet provides better resolution when compared to Gaussian or Mexican hat. At 25 Hz a Gaussian wavelet provides better resolution than the frequency slice resolved by the Morlet wavelet. At 38 Hz, both Morlet and Gaussian wavelets provide relatively good resolution, although the Morlet wavelet captures major fluvial channels and the thickness of sediment fill in the channel at high frequencies. The low frequency (18-21 Hz) tunes the thicker part of a fluvial reservoir, whereas the high frequency 38 Hz tunes the thinner sediment fill of the main channel as described by Laughlin et al. (2002).

At frequencies of 18 and 21 Hz (Figure 7), the Morlet wavelet provides poorer vertical resolution than the Gaussian and Mexican hat wavelets. The Mexican hat provides very good vertical resolution at low frequencies. By using different mother wavelets in the wavelet transform process, different results in terms of vertical and horizontal resolution are obtained. Since the Morlet wavelet is considered to be the best mother wavelet horizontally, it was selected for further use in seismic attribute analysis and for comparing the attributes based on time domain to the attributes in the time-frequency domain based on the CWT transform.

Li and Lu (2014) combined spectral decomposition and coherence attributes to provide a qualitative measure of geologic discontinuities such as channels, faults, and caves. Li et al. (2015) used the same workflow as proposed by Li and Lu (2014) and combined RGB images of 20, 35, and 50 Hz spectral decomposition with corresponding coherence images to map the various stages of incised valley fill of the Red Fork Formation in the Anadarko basin, Oklahoma. In this paper we combined spectral decomposition strata slices of C3, C5, and C7 with coherence (Fig. 8) as proposed by Li and Lu (2014) to identify the various stages of the fluvial system with complex superimposed channel geometry.

The horizon probe is another useful technique for visualization of stratigraphic features in the time domain. The horizon probe is an irregular probe that follows one or two interpreted horizon surfaces, also referred to as "Sculpting" in the industry (Schlumberger, 2017). The use of the horizon probe alone may not be sufficient to detect fluvial systems, but when used with opacity, another powerful visualization technique (Roberts, 2011); it allows the interpreter to examine a volume of seismic data using varying transparency revealing the morphology of high-amplitude channel features. Manipulating the transparency of a small cube of seismic data often reveals the morphology of high-amplitude channel features. Figure 8 shows a fluvial system with a complex superimposed channel geometry in C3, C5 and C7 including superimposed channels, point bars and crevasse splays.

Furthermore, we found that the horizon probe was useful for mapping of fluvial systems and identifying their various stages. The spectral decomposition of C7 strata shows high-sinuosity channels oriented NE - SW with widths ranging from 400 ft to 750 ft. The two main channels developed parallel to the present Llanos Foothills (Figure 1 and Figure 8). The paleoflow of C7, inferred from CWT spectral decomposition, is consistent with the paleocurrent pattern and compliments the dipmeter log of Figure 2. The consistent results of these two independent methods support the power of these methods for exploration and production.

The spectral decomposition of C-5 strata shows a low-sinuosity wide channel oriented NW-SE with widths ranging from 1400 to 2500 ft. (Figure 8). The channel cuts through the present foothills and the older fluvial system in C7. The channel lacks sharp edges, but is very clear in almost all the attributes, including Envelop and RMS. The paleoflow of C7 inferred from CWT spectral decomposition is consistent with the paleocurrent patterns in the dipmeter log Figure 2, again showing how powerful these tools are together.

The C3 strata are characterized by high-sinuosity channels incised through the large channel in C5. The channels flow from NW to SE cutting through the edges of the earlier channel with widths ranging from 300 to 650 ft (Figure 8). The paleoflow of C5 and C3 are inferred from CWT spectral decomposition and are again consistent with dipmeter log paleocurrent patterns Figure 2.

3D Seismic Attributes in Frequency Domain and Using Continuous Wavelet Transformation (CWT) for the Evaluation of Hydrocarbon Reservoirs

Many seismic attributes are very useful for detection of fluvial facies. For example, Coherence (or Variance) may help detect sandstones associated with fluvial systems. Root Mean Square (RMS) amplitude helps detect channels with density variations from surrounding units. Combinations of multiple attributes in the same image can provide increased geologic insight (Marfurt, 2015). Envelop attribute or reflection strength as described by Taner et al. (1979) is the amplitude derived from a complex trace by mean Hilbert transforms, that is used to transform a seismic trace to a complex trace. A complex seismic trace can be generated either by a Hilbert transform or a continuous wavelet transform.

The Hilbert transform works in the time domain, whereas the continuous wavelet transform works in time-frequency domain to generate a complex trace. High-reflection strength is often associated with major lithologic changes between adjacent rock layers and with gas accumulations (Taner and Sheriff, 1977).

The application of reflection strength in CWT Morlet 18-21 Hz enhances the stratigraphic information (Figure 9) where sand bodies represent high reflection strength enclosed by shales with low strength. On the other hand, these significant details of stratigraphic features such as river channel levees and point bars are undetectable in time domain seismic data even with close scrutiny.

One of the objectives of this study is to use the continuous wavelet spectral decomposition method for direct hydrocarbon detection through the frequency anomalies in a geologically and seismically challenging area such as the Llanos Foothills. Most of the traditional methods to detect hydrocarbons are based on the amplitudes of seismic reflections (bright spots) which are subject to variations of many parameters such as thickness, lithology, porosity, and fluid content (Avseth et al., 2005). The high resolution of the CWT method provides a good reservoir image (Figure 9) and detects low frequency shadows under the reservoir which have been linked to HC content in multiple cases study (e.g., Castagna et al., 2003; Goloshubin et al., 2006; Welsh et al., 2008; Tai et al., 2010).

Conclusion and Future Applications

We conclude that CWT spectral decomposition techniques provide powerful tools to help resolve fluvial sediment distribution in the subsurface for exploration and production models. In particular they can be applied to other subsurface data sets to study the fluvial systems.

In this study CWT spectral decomposition was used to detect and map fluvial systems in the frequency domain. CWT mapping of the fluvial system in Carbonera Formation captured the complicated paleocurrent orientations of the sandier horizons of C7, C5 and C3. The results of CWT spectral decomposition were found to dependent upon the choice of wavelets, namely the Morlet, Gaussian and Mexican hat. Our results show that the CWT Morlet wavelet has good horizontal resolution, especially at low frequencies compared with the other wavelets. The Gaussian wavelet had relatively good resolution at low and medium frequencies but not as good as with a Morlet wavelet. On the other hand, the Morlet wavelet has poor vertical resolution compared with Gaussian and Mexican hat. The Mexican hat provides very good vertical resolution, especially at low frequencies, and the Gaussian wavelet has relatively good vertical resolution at medium to high frequencies.

The horizon probe is a powerful visualization technique useful for mapping of fluvial systems and identifying their various stages in time domain if used with opacity. Furthermore, by mapping the fluvial system using CWT spectral decomposition we were able to tie the variations in fluvial systems to the regional tectonics of the Eastern Cordillera. The C7 horizon fluvial facies were mainly high sinuosity channels consistent with the well log paleo-currents flowing with the regional drainage of the Oligocene Proto-Orinoco river system as described by Villamil (1999). Within the thick fluvial system of the C5-C3 horizons the drainage switched from low sinuosity to high sinuosity channels with the channel directions consistent with the paleo-currents obtained from well logs. A key observation related to the C5 horizon is a change in spectral strata suggesting an evolution from braided fluvial accumulation to the overlying C3 horizon that captured a meandering fluvial system.

These changes in geometric character document a change in slope gradient, sediment sources and tectonic activity of the present-day Eastern Cordillera. The application of continuous wavelet transforms provides a better understanding of how regional scale structures and tectonic movement affected the local sedimentary history and helps explain the processes and mechanisms involved in producing the regional stratigraphic section. It is the contention of this paper that use of these techniques can help explorationists to better resolve, identify and interpret the style of channel fill from braided to meandering systems, point bar fill, stranded ox-bows and abandoned channel fill, crevasse splays and other over bank phenomena.

In conclusion, the application of the attribute analysis in frequency volumes enhances the stratigraphic features that are undetectable in time domain seismic volumes. It is hoped that this study will be expanded to a more detailed multi-attribute analysis in frequency domain for reservoir characterization and sand connectivity of the Carbonera Formation and other formations in the region and beyond. By using CWT spectral decomposition new potential reservoirs plays were recognized southwest of the giant Cusiana Oil Field in the footwall of the Cusiana Fault and this could open a new exploration era along the eastern flank of the Eastern Cordillera.

Acknowledgements

We would like to thank Pacific E&P Colombia for generously providing 3D seismic and well data for the Llanos Foothills. We would like to thank Fangyu Li, Obi Egbue, Camelia Knapp, and Andrew Lier for helpful discussions. General spectral decomposition volumes were produced using Petrel 2016, which was donated by Schlumberger. CWT Spectral decomposition volumes were prepared with OpendTect 6 provided by dGB Earth Sciences. This study was supported by a Doctoral Fellowship awarded to the first author from the Libyan Ministry of Higher Education and Scientific Research.

Selected References

Avseth, P., T. Mukerji, and G. Mavko, 2005, Quantitative Seismic Interpretation: Applying Rock Physics to Reduce Interpretation Risk: Cambridge University Press, Cambridge.

Bayona, G., C. Jaramillo, M. Rueda, A. Reyes-Harker, and V. Torres, 2007, Paleocene-Middle Miocene flexural-margin migration of the nonmarine Llanos foreland basin of Colombia: CT&F Ciencia, Tecnología y Futuro, v. 3/3, p. 141-160.

Bayona, G., M. Cortés, C. Jaramillo, G. Ojeda, J.J. Aristizabal, and A. Reyes-Harker, 2008, An integrated analysis of an orogen-sedimentary basin pair: Latest Cretaceous-Cenozoic evolution of the linked Eastern Cordillera orogen and the Llanos foreland basin of Colombia: GSA Bulletin, v. 120, p. 1171-1197. doi: 10.1130/B26187.1.

Bogota-Ruiz, J., 1988, Contribucion al Conocimiento Estratigrafico deal Cuenca de los Llanos, Colombia: III Simposio Exploracion Petrolera en las Cuencas Sun-Andinas, p. 308-346.

Brown, A.R., 2011. Interpretation of three-dimensional seismic data, 7th ed.: AAPG Memoir 42 and SEG Investigations in Geophysics No. 9. Website accessed September 13, 2018.
http://library.seg.org/doi/book/10.1190/1.9781560802884

Castagna, J.P., S. Sun, and R.W. Siegfried, 2003, Instantaneous spectral analysis: Detection of low-frequency shadows associated with hydrocarbons: The Leading Edge, v. 22, p. 120-127.

Chopra, S., and K.J. Marfurt, 2015, Choice of mother wavelets in CWT spectral decomposition: 83rd Annual International Meeting, SEG, Expanded Abstracts, p. 2957-2961.

Cooper, M.A., F.T. Addison, R.M. Coral, R.H. Graham, A.B. Hayward, S. Howe, J. Martinez, J. Naar, R. Peñas, A.J. Pulham, and A. Taborda, 1995, Basin development and tectonic history of the Llanos basin, Eastern Cordillera, and Middle Magdalena Valley, Colombia: AAPG Bulletin, v. 79/10, p. 1421-1443.

De'Ath, N., 1997, Discovery history of the giant Cusiana and Cupiagua oil fields, Colombia: Geol. Soc. Malaysia Bulletin, v. 41, p. 31-39.

Goloshubin, G., V. Korneev, and V. Vindaloo, 2002, Seismic low-frequency effects from oil-saturated reservoir zones: 72nd Annual International Meeting of the Society of Exploration Geophysicists, p. 1813-1816.

Goloshubin, G., C.V. Schuyver, V. Korneev, D. Silin, and V. Vindaloo, 2006, Reservoir imaging using low frequencies of seismic reflections: The Leading Edge, v. 25/5, p. 527-531.

Haq, B.U., J. Hardenbol, and P.R., Vail, 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156-1166.

Jaramillo, C., M. Rueda, G. Bayona, C. Santos, P. Florez, and F. Parra, 2009, Biostratigraphy Breaking Paradigms: Dating the Mirador Formation in the Llanos Basin of Colombia: SEPM Special Publication No. 93, p. 29-40.

Laughlin, K., P. Garossino, and G. Partyka, 2002, Spectral decomposition applied to 3D: AAPG Explorer, p. 28-31.

Li, F., J. Qi, and K. Marfurt, 2015, Attribute mapping of variable-thickness incised valley-fill systems: The Leading Edge, v. 34, p. 48-52.

Li, F., and W. Lu, 2014, Coherence attribute at different spectral scales: Interpretation, v. 2, SA99-SA10.

Mallat, S., 2009, A wavelet tour of signal processing: Academic Press, 3rd edition.

Marfurt, K.J., and R.L. Kirlin, 2001, Narrow-band spectral analysis and thin-bed tuning: Geophysics, v. 66, p. 1274-1283.

Marfurt, K.J., 2015, Techniques and best practices in multiattribute display: Interpretation, v. 3/1 p. B1-B23.

Mora, A., M. Parra, M.R. Strecker, A. Kammer, C. Dimate, and F. Rodriguez, 2006, Cenozoic contractional reactivation of Mesozoic extensional structures in the Eastern Cordillera of Colombia: Tectonics, v, 25, TC2010. doi:10.1029/2005TC001854

Parra, M., A. Mora, C. Jaramillo, M.R. Strecker, E.R. Sobel, and R. Gonzalez, 2009a, Episodic orogenic front migration in the northern Andes: Constraints from low-temperature thermochronology in the Eastern Cordillera, Colombia: Tectonics, v. 28, TC4004, p. 1-27.

Parra, M., A. Mora, C. Jaramillo, M.R. Strecker, E.R. Sobel, L. Quiroz, M. Rueda, and V. Torres, 2009b, Orogenic wedge advance in the northern Andes: evidence from the Oligocene-Miocene sedimentary record of the Medina Basin, Eastern Cordillera, Colombia: Geological Society of America Bulletin, v. 121, p. 780-800.

Parra, M., A. Mora, C. Jaramillo, V. Torres, G. Zeilinger, and M.R. Strecker, 2010, Tectonic controls on Cenozoic foreland basin development in the north-eastern Andes, Colombia: Basin Research, v. 22, p. 874-903.

Partyka, G.A., M.D. Bush, P.G.A. Garossino, and P.R. Gutowski, 2011, Spectral Decomposition, *in* A.R. Brown, ed., Interpretation of three-dimensional seismic data, 7th ed.: AAPG Memoir 42 and SEG Investigations in Geophysics No. 9.

Partyka, G., J. Gridley, and J. Lopez, 1999, Interpretational applications of spectral decomposition in reservoir characterization: The Leading Edge, v. 18, p. 353-360.

Roberts, D.M., 2011, Visualization and Visual Integration, *in* A.R. Brown, ed., Interpretation of three-dimensional seismic data, 7th ed.: AAPG Memoir 42 and SEG Investigations in Geophysics No. 9.

Sinha, S., P.S. Routh, P.D. Anno, and J.P. Castagna, 2005, Spectral decomposition of seismic data with continuous-wavelet transform: Geophysics, v. 70/6, p. 19-25. doi: 10.1190/1.2127113

Tai, S., C. Puryear, and J.P. Castagna, 2010, Local frequency as a direct hydrocarbon indicator: SEG Houston 2009 International Exposition and Annual Meeting.

Taner, M.T., F. Koehler, and R.E. Sheriff, 1979, Complex seismic traces analysis: Geophysics, v. 44, p. 1041-1063. doi: 10.1190/1.1440994

Taner, M.T., and R.E. Sheriff, 1977, Application of amplitude, frequency and other attribute to stratigraphic and hydrocarbon determination, *in* C.E. Payton, ed., Application to hydrocarbon exploration, AAPG Memoir 26, p. 301-327.

Torrado, L., P. Mann, and J. Bhattacharya 2014, Application of seismic attributes and spectral decomposition for reservoir characterization of a complex fluvial system: Case study of the Carbonera Formation, Llanos foreland basin, Colombia.

Villamil, T., 1999, Campanian–Miocene tectonostratigraphy, depocenter evolution and basin development of Colombia and western Venezuela: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 153, p. 239-275.

Welsh, A., F. Brouwer, A. Wever, and W. Flierman, 2008, Spectral decomposition of seismic reflection data to detect gas related frequency anomalies: EAGE Conference and Exhibition, June.

Yu, B., L. Zhou, and X. Wang, 2011, Application of the oil-bearing prediction methods based on spectral decomposition: SPG/SEG International Geophysical Conference, Expanded Abstracts, 16631668.

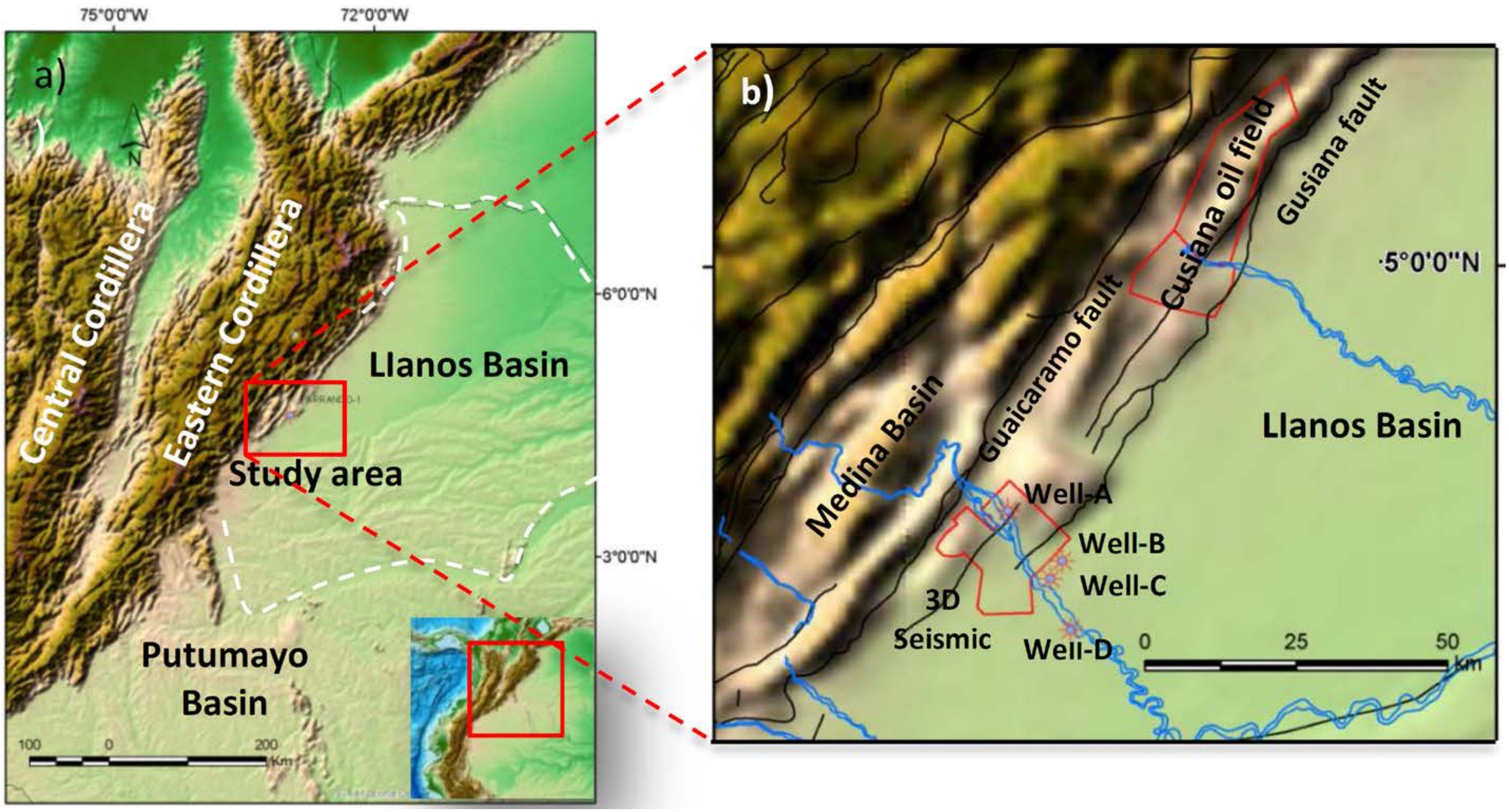

Figure 1. (a) Location map of study area: Llanos Foothills, Llanos Basin, Eastern Cordillera of Colombia. (b) Location of Cusiana oil Fields and the 3D seismic surveys.

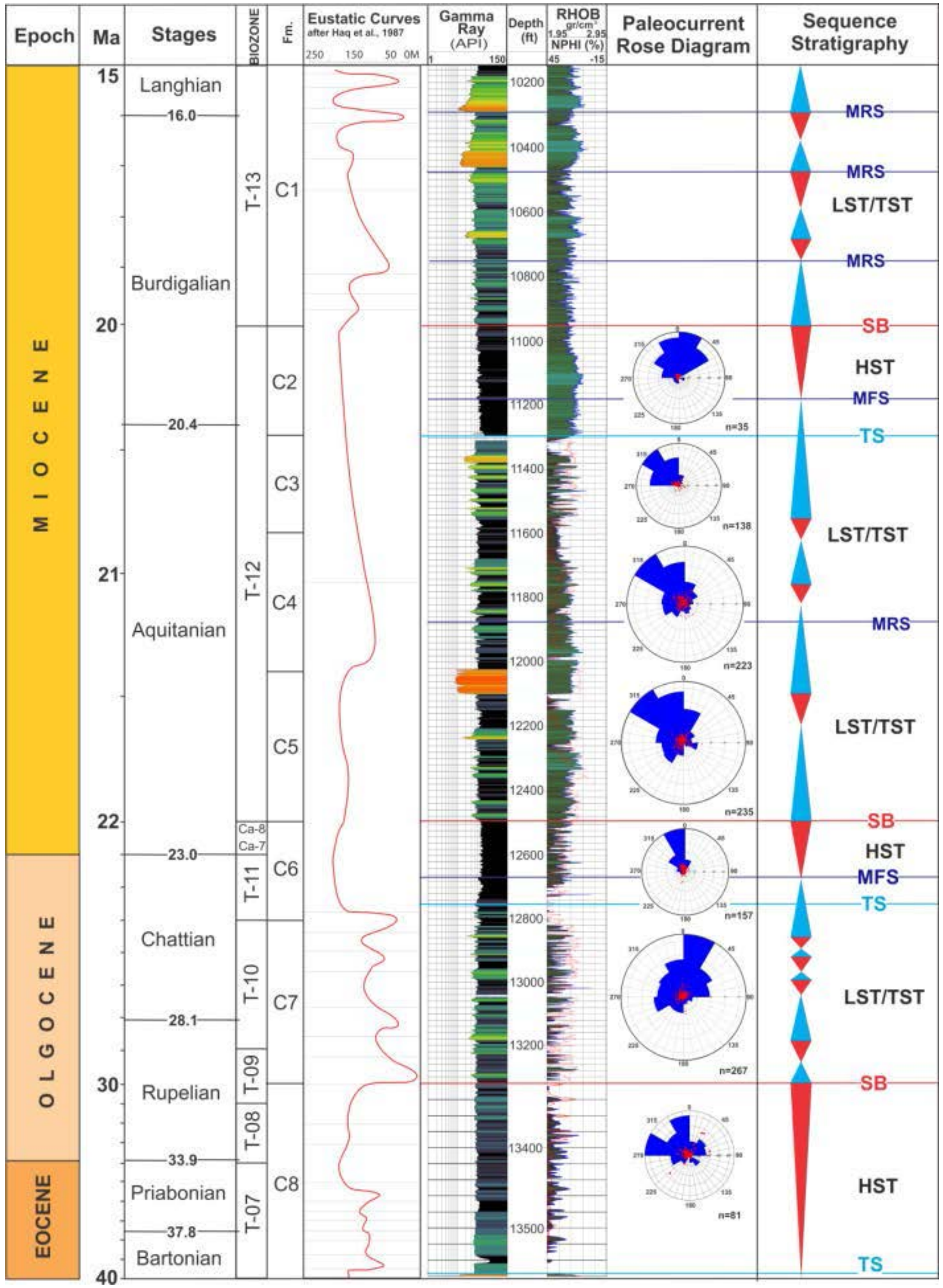

Figure 2. Stratigraphic column for the Carbonera Fm. showing biozones after Parra et al. (2009 & 2010), Eustatic curves after Haq et al. (1987), Gamma ray, density and neutron logs, palaeocurrent rose diagrams and sequence stratigraphy in Well (A).

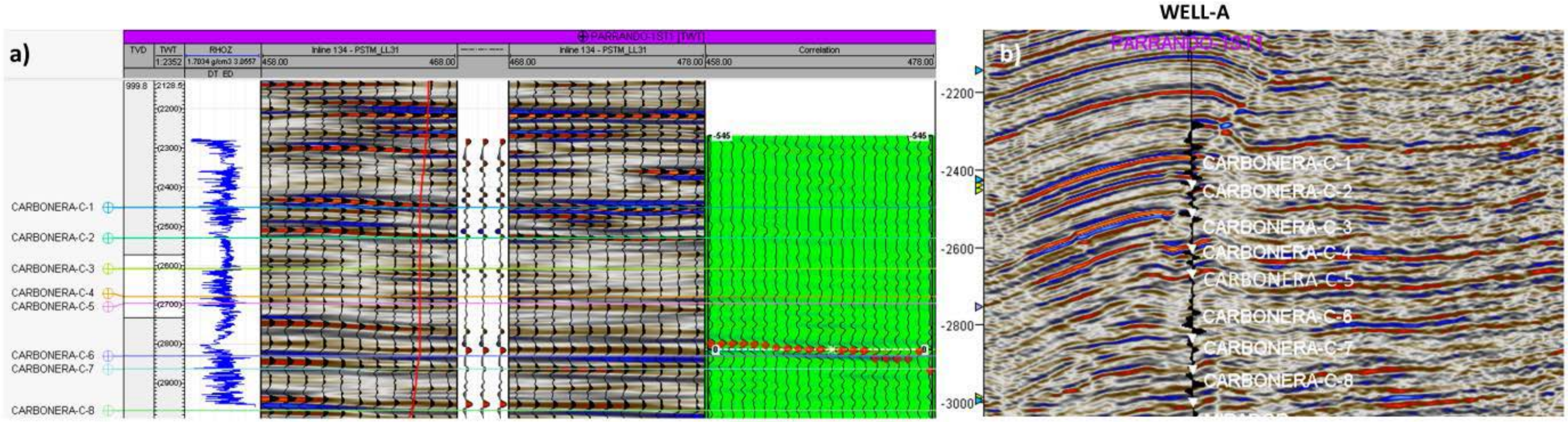

Figure 3. (a) Synthetic seismogram along with sonic and density logs. (b) Seismogram displayed on the seismic section showing the horizon of interest.

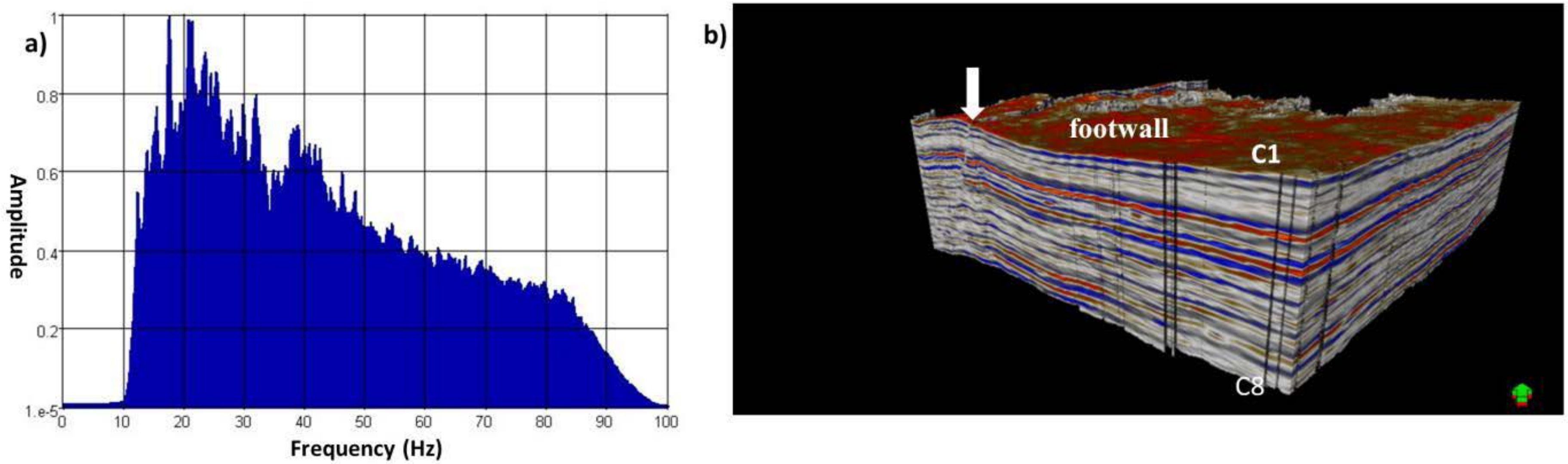

Figure 4. (a) Frequency spectrum for the zone of interest. (b) 3-D horizon probe of Carbonera Fm (C-1 to C-8) showing a reverse fault (white arrow) and the footwall study area.

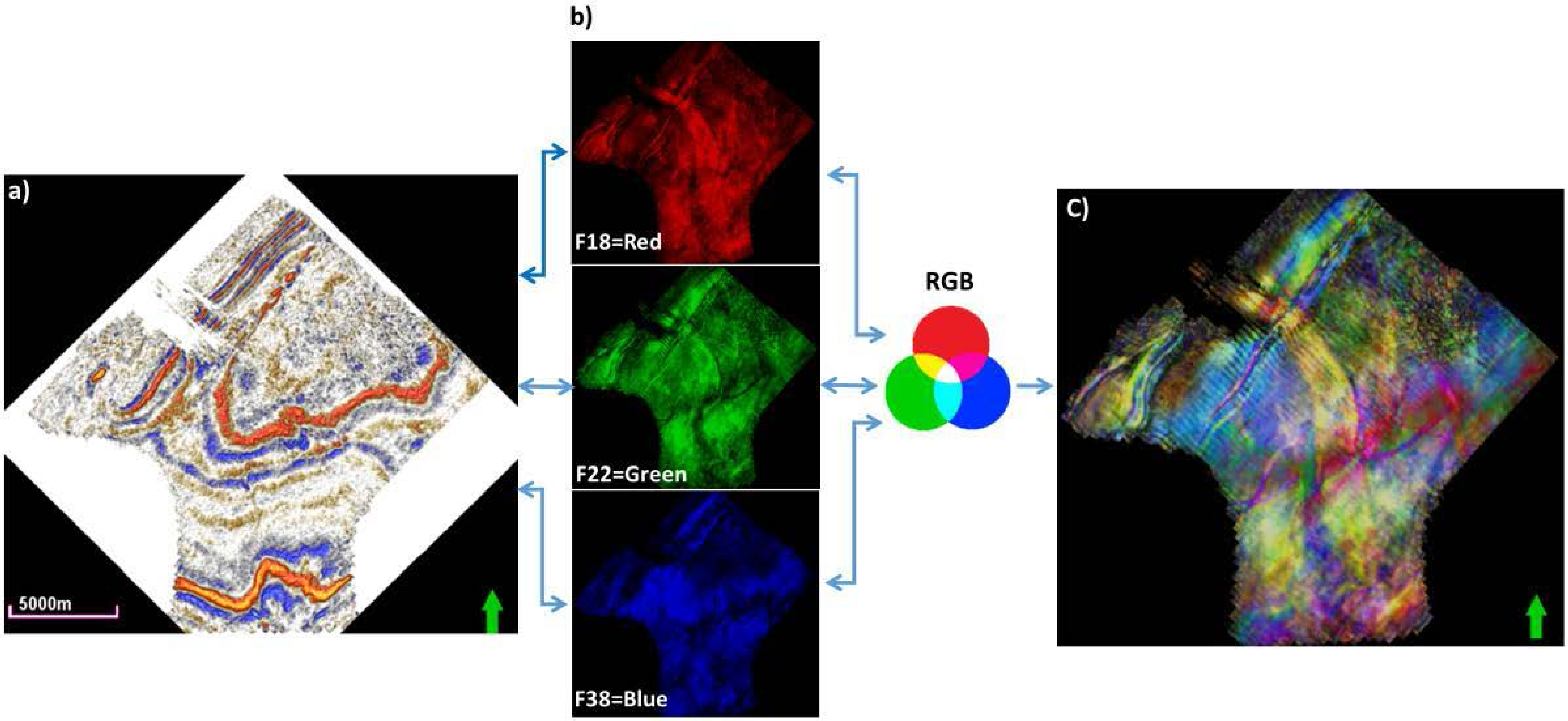

Figure 5. (a) Amplitude time slice at 2424 ms. (b) Frequency slice showing amplitude in narrow frequency bands around 38 Hz as blue, 22 Hz as green and 18 Hz as red. (c) RGB blends of iso-frequencies F18, F22, and F38.

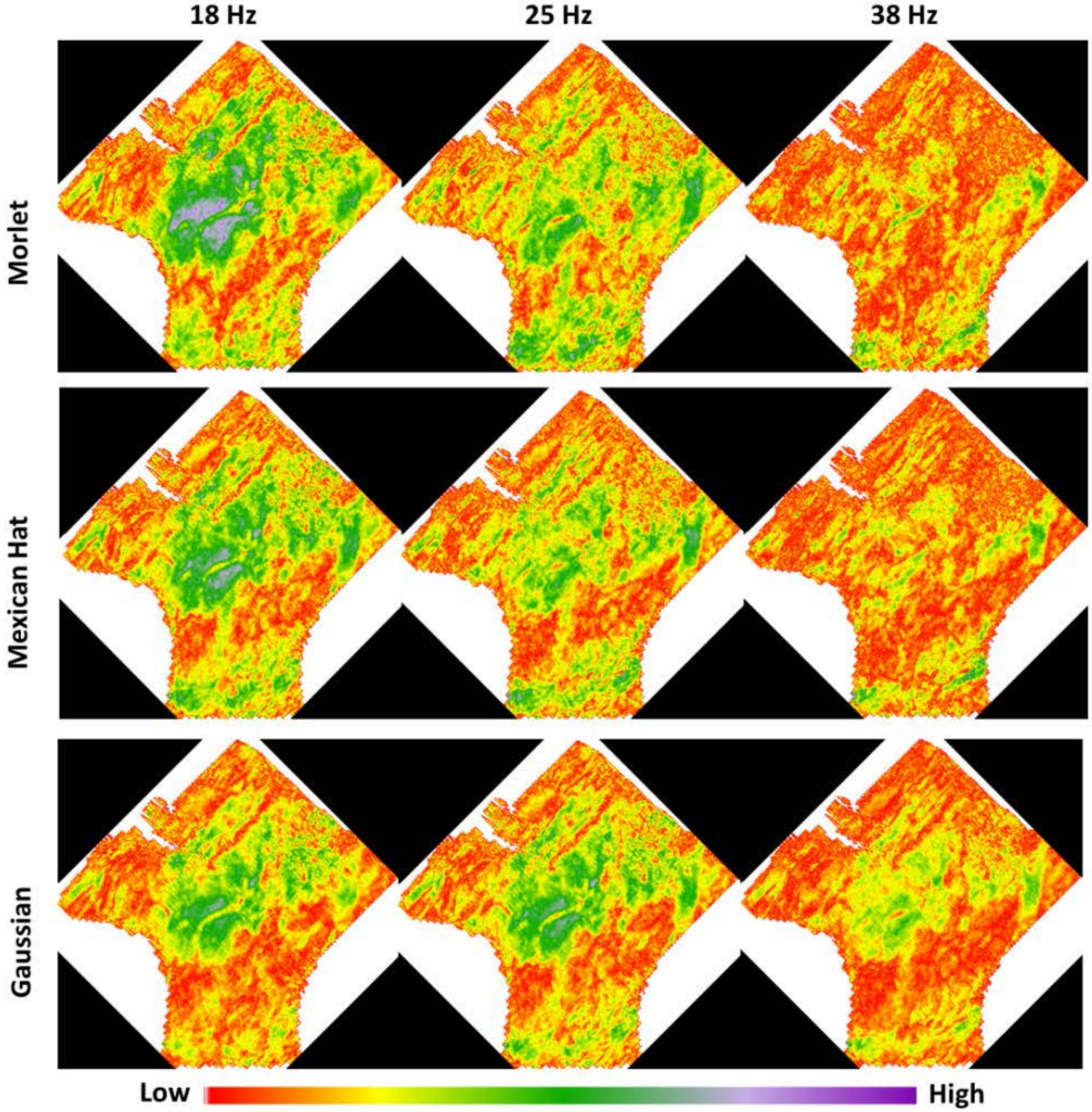

Figure 6. Time slices (2727 ms) from 18 Hz (left), 25 Hz (middle), and 38 Hz (right) volumes showing CWT spectral decomposition carried out using Morlet (upper), Gaussian (middle), and Mexican (lower) wavelets.

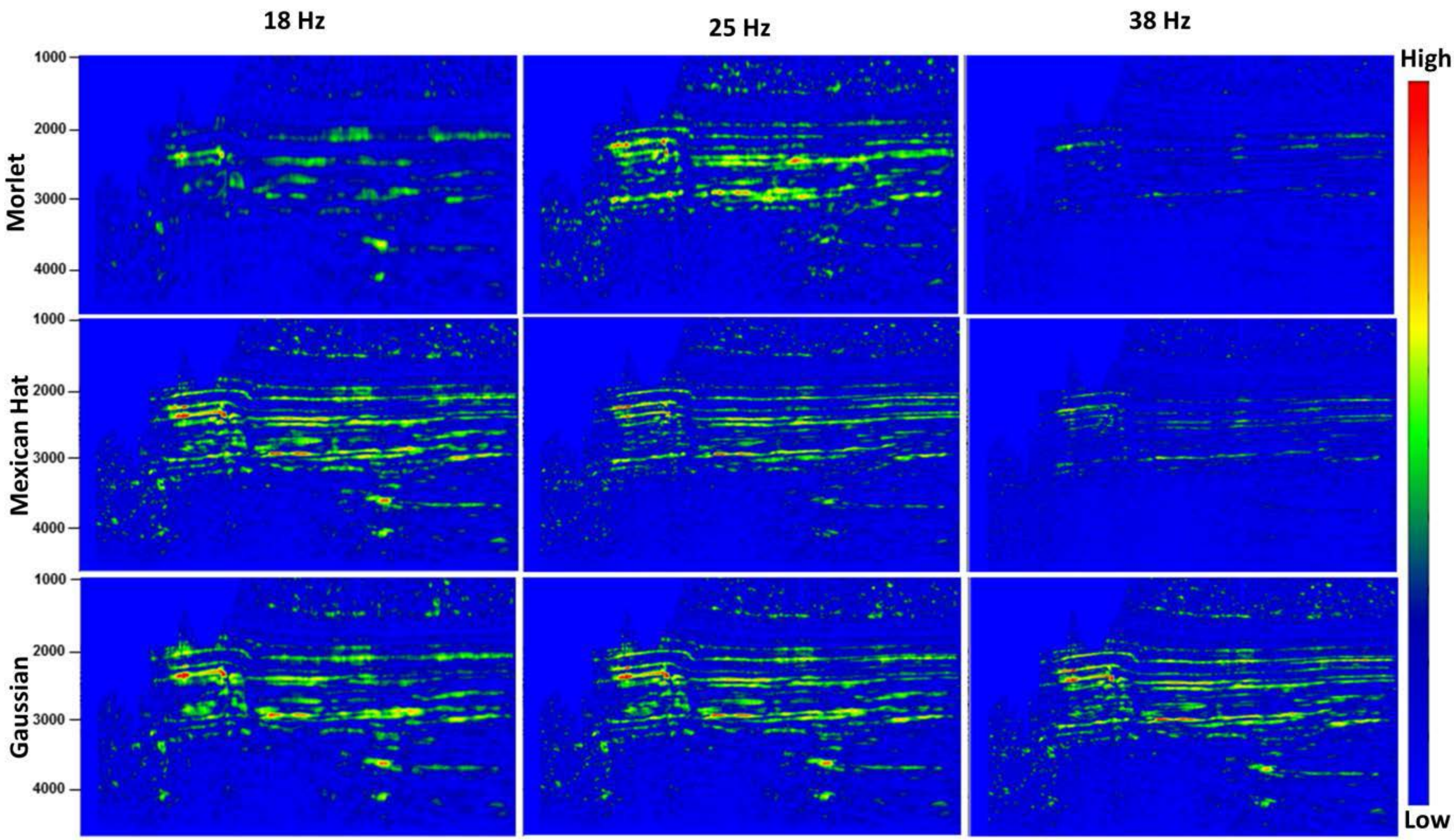

Figure 7. Seismic sections (inline 243) from 18 Hz (left), 25 Hz (middle), and 38 Hz (right) volumes showing CWT spectral decomposition carried out using Morlet (upper), Mexican Hat (middle), and Gaussian (lower) wavelets.

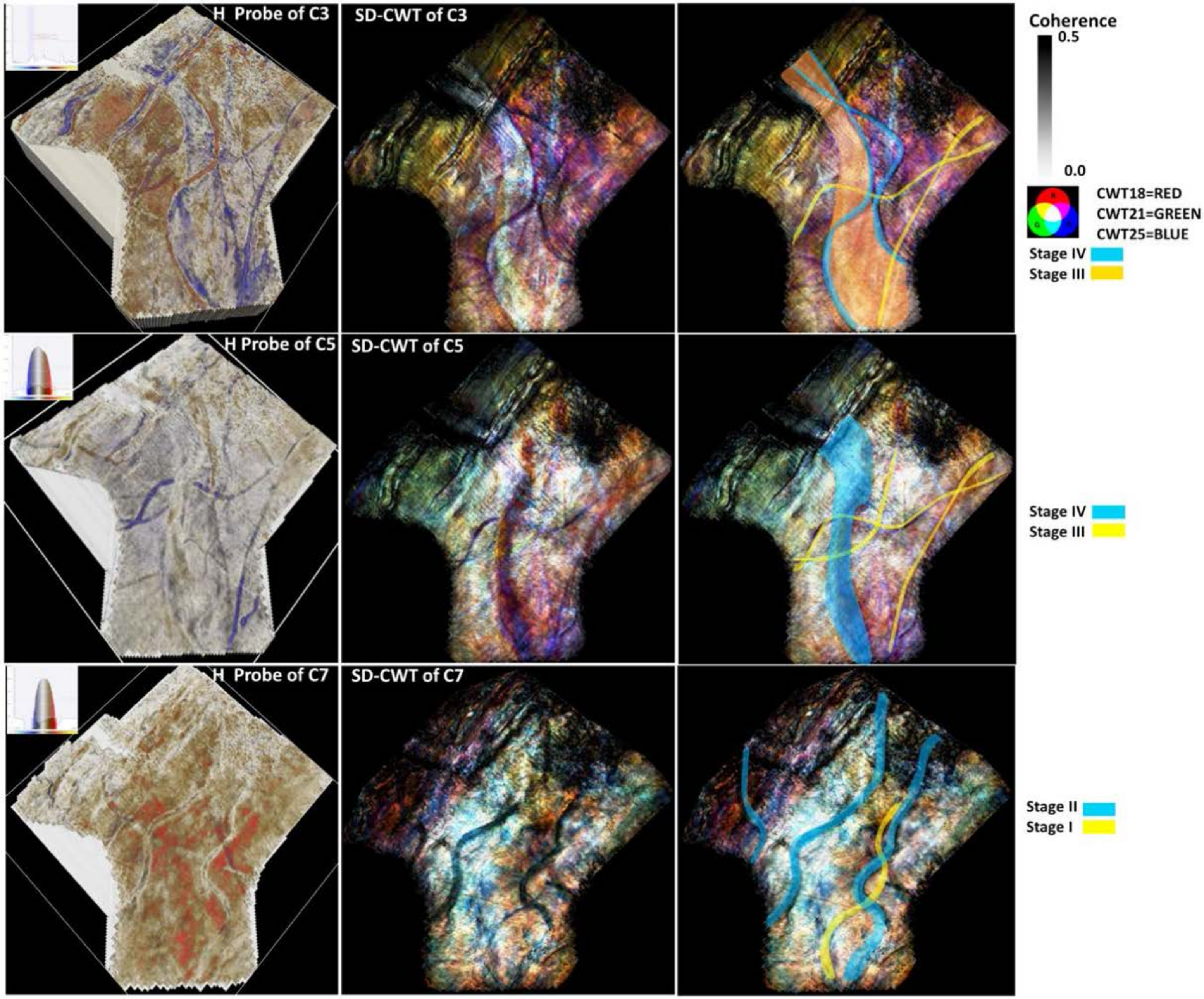

Figure 8. Horizon probe used manipulated transparency (left) versus CWT Spectral decomposition (middle) strata slices for C3 (upper), C5 (middle), and C7 (lower). The CWT spectral decomposition used a Morlet wavelet in narrow frequency bands around 38 Hz as blue, 22 Hz as green, and 18 Hz as red co-rendered with coherence attribute, with our fluvial interpretation stages (right).

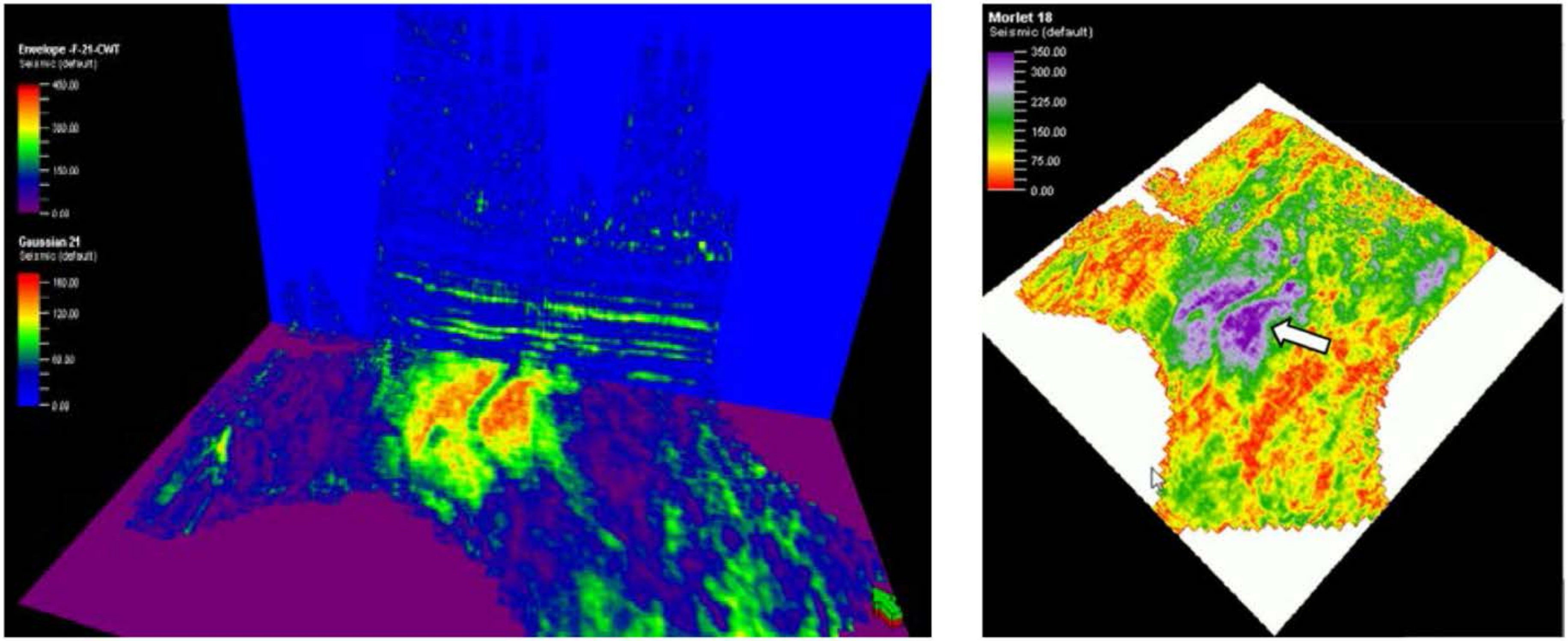

Figure 9. Application of attributes to CWT volumes and hydrocarbon indication, (a) reflection strength (envelop) time slice (2727 ms) from 21 Hz volume showing CWT Morlet with CWT-Morlet (inline-243) vertical cross section. (b) Low frequency shadow within the C7 seismic frequency volume below a potential reservoir. Note the meandering channel fill (green) and the overbank sediments beside it (blue, white arrow).

[Click to view poster presentation.]