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[PS]Study of Seismic Anomalies in the Frequency Spectrum as a Hydrocarbon Reservoir Characterizer

Argenis Pelayo[1] and Ivan Omaña[1]

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[1]Simon Bolivar University

Abstract

In the present research, the variation in seismic response as a function of frequency, influenced by changes in fluid saturation and the gas-oil ratio (GOR), is analyzed through the development of two synthetic models and the examination of field data. Fluid substitution is performed using Gassmann's Equation (1951), enabling the estimation of Vs, Vp, and density for reservoirs with varying properties. The instantaneous frequency attributes and the Continuous Wavelet Transform (CWT) method were applied in this study. The findings reveal a complex relationship between frequency-dependent reflections, porosity, saturation, and fluid type. Observations from mathematical models and field data suggest that the presence of gas, both within oil reservoirs and in its gaseous state, leads to an increase in reflection energy, the generation of low-frequency anomalies, and the attenuation of high frequencies immediately below the reservoir. This effect is attributed to areas with a low Vp/Vs ratio and a decrease in density. Furthermore, an increase in porosity significantly enhances the energy of these anomalies, making these effects strong indicators of reservoir quality.

Introduction

Low-frequency seismic anomalies are relatively enriched events of low-frequency content, commonly observed within and below hydrocarbon reservoirs (Taner et al., 1979; Goloshubin et al., 2002; Goloshubin & VanShuyver, 2006; Castagna & Sun, 2003, among others). Although several studies have been conducted in this area, the mechanisms behind these anomalies are not yet fully understood.

Taner et al. (1979) were among the first to study these phenomena. They proposed that (1) gas sands filter high frequencies due to (a) frequency-dependent absorption or (b) natural resonance, or (2) that the travel time through gaseous sand is increased by low velocities, preventing proper summation of reflections from the underlying layers.

Castagna and Sun (2003) suggested that low-frequency shadows are not merely a result of attenuation, as attenuation alone should reduce high frequencies rather than enhance low frequencies. Tai et al. (2009) concluded that low-frequency seismic anomalies arise from low-velocity zones, as there is insufficient travel time for them to be attributed to absorption or attenuation. Hwang and Lellis (1988) reported that bright spots in seismic sections in Louisiana are associated with oil fields with a high gas-oil ratio (GOR). Their laboratory tests demonstrated that Vp decreases as GOR increases.

Understanding the frequency-dependent seismic response of fluid content is essential for estimating reservoir quality, characterizing its properties, and determining its lateral extent. Therefore, this research focuses on studying the relationship between frequency and fluid content and estimating the mechanisms responsible for this phenomenon.

Methodology

The Powder River Basin was selected as one of the fields for the study. The Powder River Basin is located northeast of the state of Wyoming, southeast of the state of Montana, and southwest of the state of Dakota, in the United States of America. Four wells were distributed along the basin whose gas-and crude-producing intervals were known. Later, through an analysis petrophysical and bibliographic review, the petrophysical and geochemical parameters of each reservoir to be used in the fluid substitution were determined (see table 1).

Parameters	13-MX-11	32-A-34	23-A-34	14-AX-11
Gravity API	35	34	34	34
Gas-Oil Ratio [Vol/Vol]	27.4	19.6	313.8	17.5
Specific Gravity of Gas [API]	0.8	0.8	0.8	0.8
Temperature [°C]	68	48	47	53
Pressure Psi	4014	3115	2966	3258
Salinity Water [PPM]	28000	28000	28000	28000
Porosity [In Fraction]	0.2	0.2	0.17	0.25
The volume of Clay [in fraction]	0.4	0.14	0.13	0.14
Initial Water Saturation [in fraction]	0.57	0.34	0.49	0.34
Vp [ft/sec]	14490	12050	12050	12050
Vs [ft/sec]	9056	6530	6530	6530
RHOB [g/CC]	2.32	2.37	2.37	2.33

Table 1. Petrophysical and Geochemical Parameters for each well.

Fluid Substitution

For fluid substitution, Gassmann's Equation (1951) was used to predict velocity changes in a medium resulting from different fluid saturations. Matlab was used for this analysis, with a code extracted from Kumar (2006) that incorporates a series of petrophysical and geochemical input parameters (see Table 1) to estimate P-wave and S-wave velocities, as well as reservoir density under specified conditions. To analyze variations in seismic response and predict the underlying phenomena, four models were developed: (1) initial conditions, (2) 100% oil saturation, (3) 100% gas saturation, and (4) 100% water saturation. The results are presented in Table 2.

100% Gas				**100% Oil**		**Initial Conditions**				**100% Water**		
Wells	Vp [ft/s]	Vs [ft/s]	RHO [g/CC]	Vp [ft/s]	Vs [ft/s]	RHO [g/CC]	Vp [ft/s]	Vs [ft/s]	RHO [g/CC]	Vp [ft/s]	Vs [ft/s]	RHO [g/CC]
14-AX-11	12574	6976.4	2,044	12408	6749.4	2.1838	12404	6722.1	2.2016	12472	6670	2.2361
32-A-34	12258	6838.5	2.1638	12249	6666.9	2.2767	12265	6646.5	2,297	12265	6646.5	2.2907
23-A-34	12405	6728.7	2,235	12306	6399.9	2.2952	12241	6633.4	2.2997	12537	6538.3	2.3671
13-MX-11	14890	9399.4	2.1564	14646	9183.2	2.2592	14607	9129	2.2861	14619	9088.7	2.3064

Table 2. Results of fluid substitution for (1) initial conditions, (2) saturated with oil at 100%, (3), gas saturation at 100% and (4) water saturation at 100%.

Synthetic Models

The program used for the development of the synthetic model was SeismicUnix. The model has a length of 24000 m and a depth of 2000 m (Figure 1).

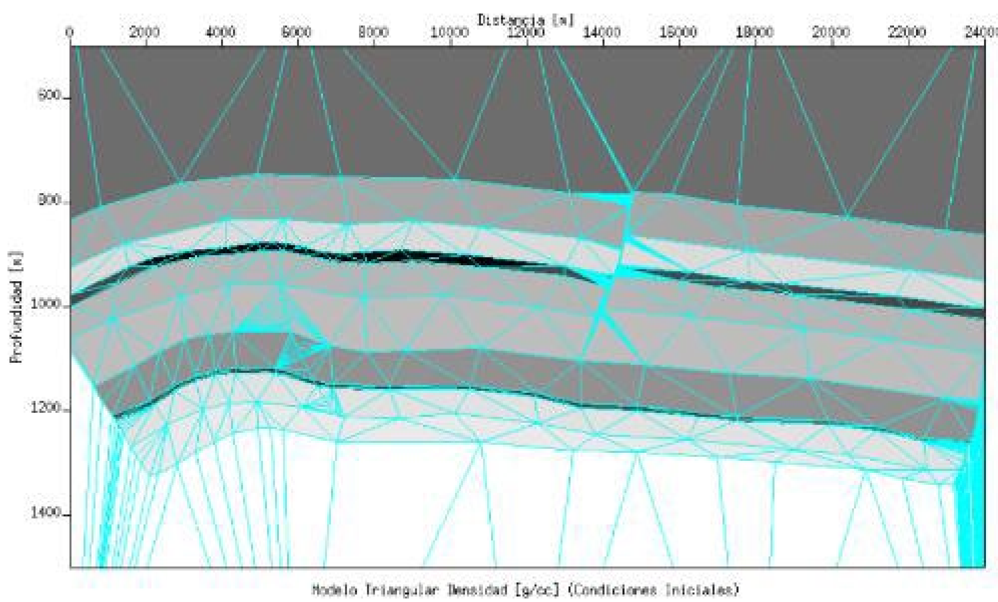


Figure 1. Triangular Model.

This model was executed following the following methodology:

- Define the subsurface layers.
- Assign velocity (S and P) and density values to each layer based on formation and fluid type.
- Design the seismic acquisition process.
- Conduct velocity analysis.
- Apply NMO correction and perform stacking.
- Execute post-stack migration.
- Analyze seismic responses based on fluid type.

For the acquisition process, the following parameters were used (see table 3).

Distance Between Shooting	200m
Sampling interval in time	0, 0005seg
Time of recording	2seg
Dominant frequency	30Hz
Type of wavelet	Gaussian
Source type	Waves Q

Table 3. Input Parameters for the seismic acquisition process.

The dominant frequency was extracted from actual seismic data to ensure consistent input parameters across both cases. A three-layer model was then created, representing the formations in the Teapot Dome. The layer thicknesses were adjusted for representational purposes. Given the model's vertical resolution of approximately 40 meters, the Second Wall Creek member (a producer) was assigned a thickness of 80 meters to clearly observe its top and bottom in the seismic data. The modeling was performed using Seismic Unix, with the final model spanning 2000 meters in length and 700 meters in depth.

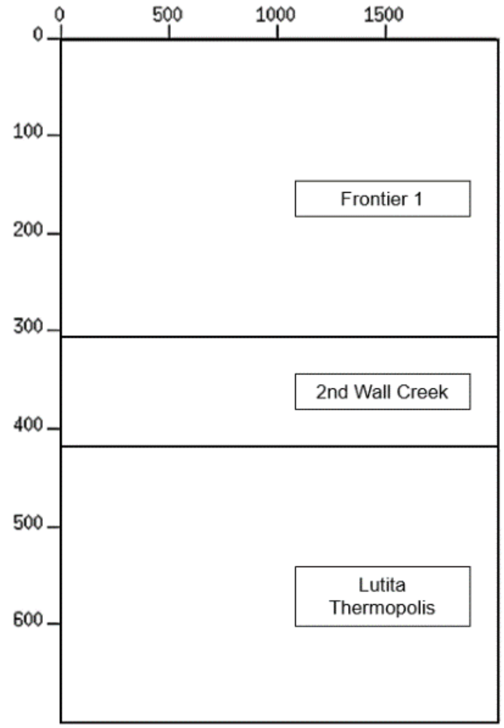


Figure 2. Sketch of the Synthetic Model.

For the acquisition process, the following parameters were used (see table 4).

Distance Between Shooting	50m
Sampling Interval in time	0.0005 sec
Time Of Recording	0.35 sec
Frequency Dominant	30Hz
Type of Ondícula	Gaussian
Source Type	Waves Q

Table 4. Acquisition Parameters for Saturation model

The second field is the Stratton Field in the state of Texas. It goes from the Kleberg County and the Condado County. This field has an enormous rate of production and plenty of successful wells have been done. This field was used to study the effects of gas-saturated reservoirs when applying frequency-dependent attributes. For this study eight gas-producing wells distributed all along the field were analyzed.

Results

Synthetic Models

A synthetic model was created to study the variations in the seismic response due to fluid changes. Four producing wells were known, and, through analysis of well records and bibliographic reviews, the petrophysical and chemical properties of each producer reservoir were determined.

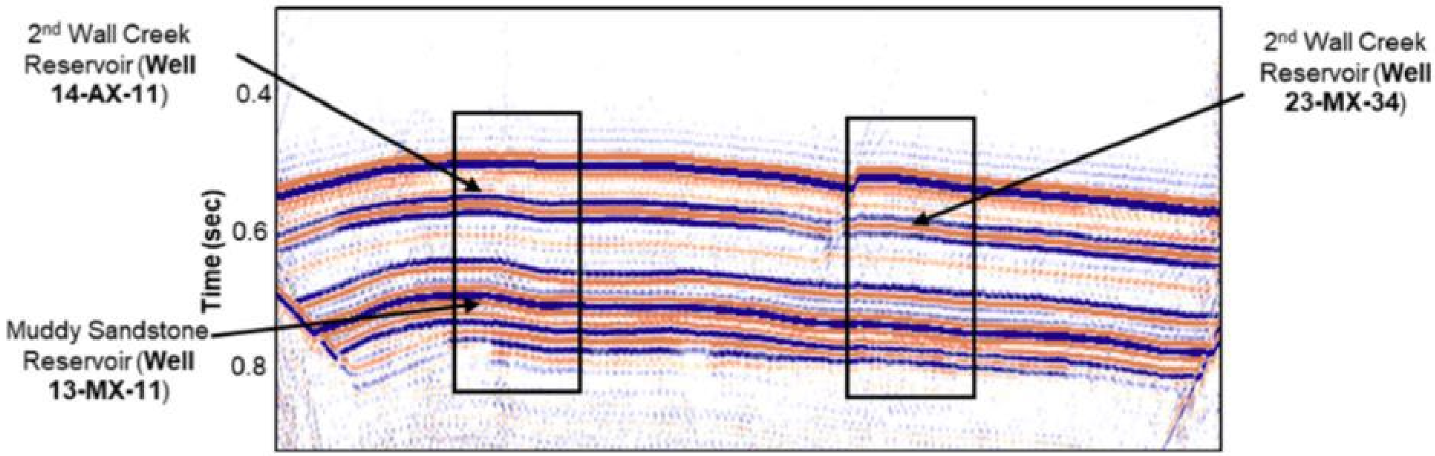


Figure 3. Identification of the zones for the study of the seismic response to the change of fluids.

Instantaneous frequency, instantaneous amplitude, and spectral decomposition attributes were applied. The CWT method was used for spectral decomposition. The results are shown in the following figures.

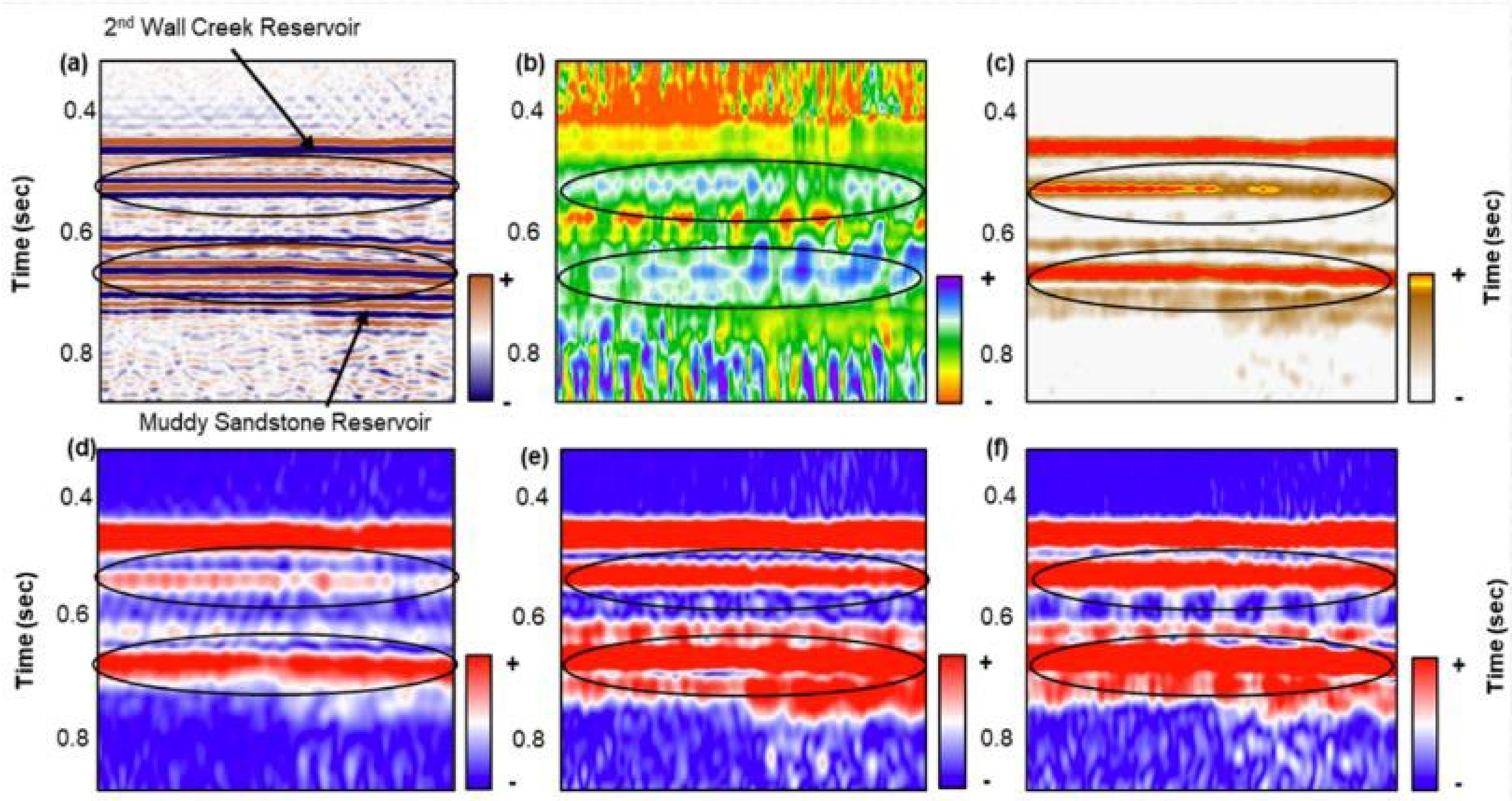


Figure 4. Seismic Attributes for 100% oil-saturated synthetic model. Wells 14-AX-11 and 13-MX-11. (a) Amplitude, (b) Instantaneous Frequency, (c) Instantaneous Amplitude and Spectral decomposition at (d) 15 Hz, (e) 30 Hz and (f) 45 Hz.

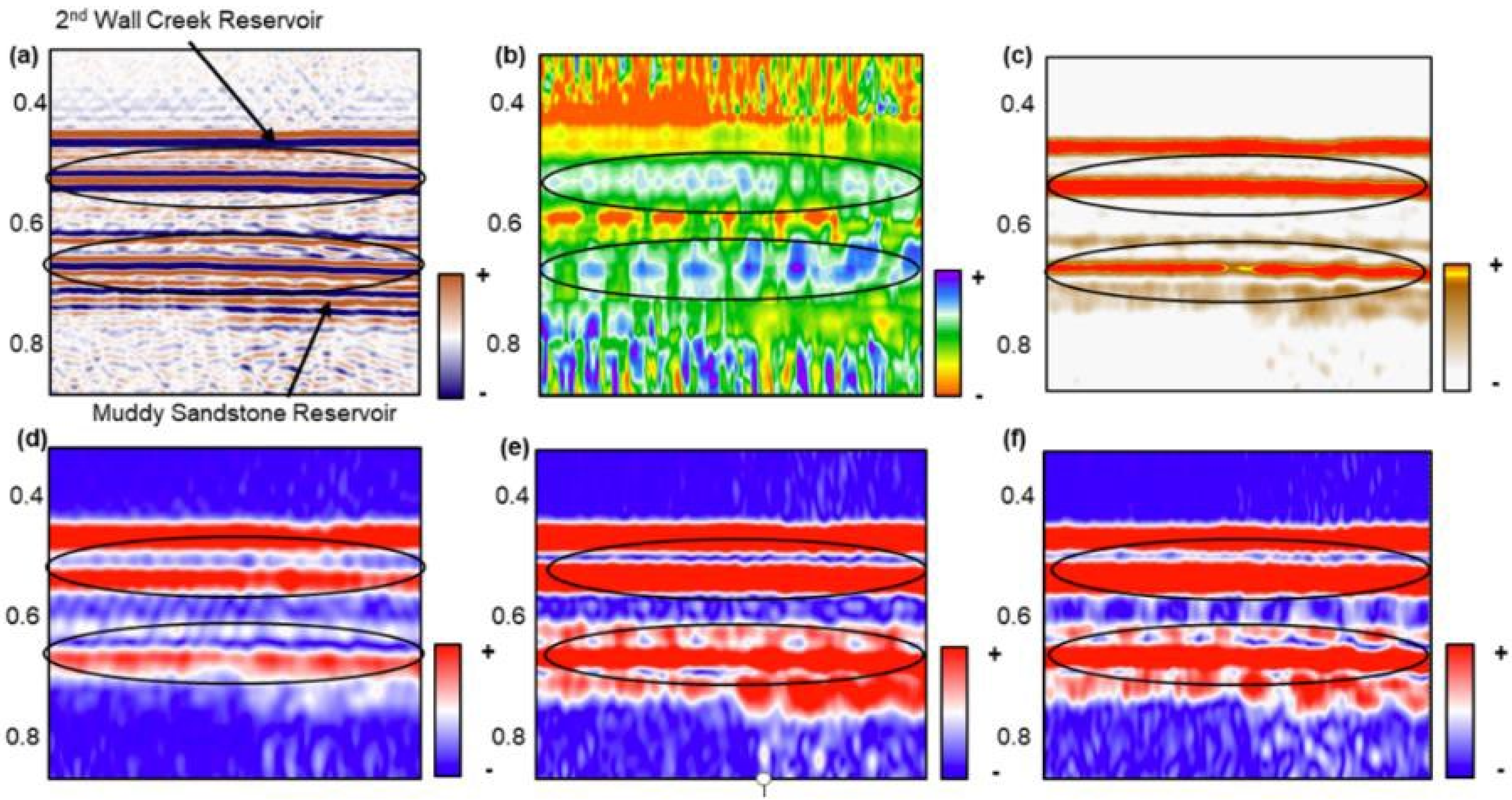


Figure 5. Seismic Attributes for 100% gas-saturated synthetic model. Wells 14-AX-11 and 13-MX-11. (a) Amplitude, (b) Instantaneous Frequency, (c) Instantaneous Amplitude and Spectral decomposition at (d) 15 Hz, (e) 30 Hz and (f) 45 Hz.

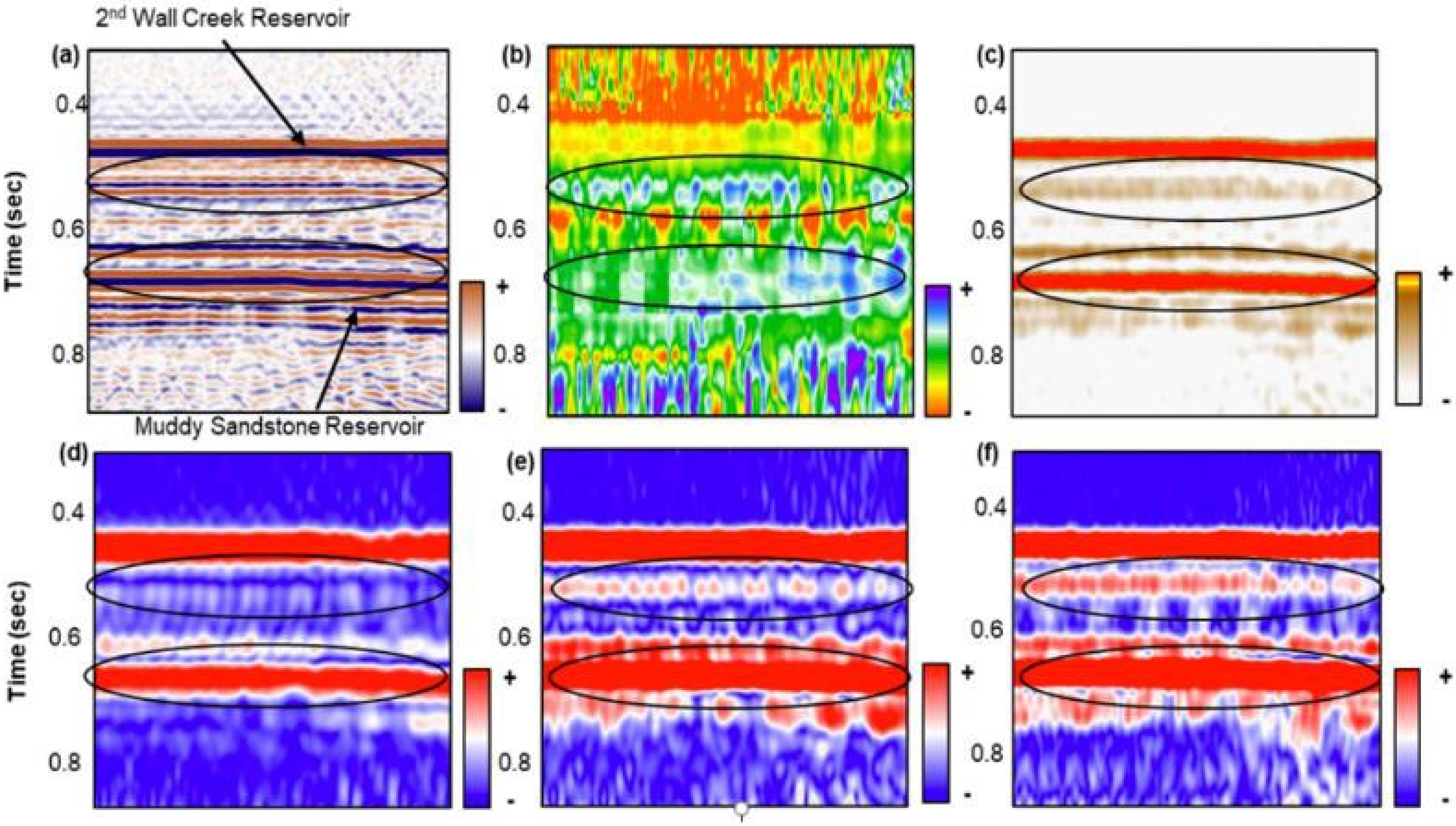


Figure 6. Seismic Attributes for a synthetic model of 100% saturated with water. Wells 14-AX-11 and 13-MX-11. (a) Amplitude, (b) Instantaneous Frequency, (c) Instantaneous Amplitude and Spectral decomposition at (d) 15 Hz, (e) 30 Hz and (f) 45 Hz.

In this section, a three-layer synthetic seismic model was created to analyze how frequency varies with changes in saturation and gas-oil ratio (GOR). The petrophysical and chemical properties used were based on well 14-AX-11. The Second Wall Creek member was assigned a thickness of 80 meters to ensure clear observation of its top and bottom in the seismic data. This setup allowed for studying the attenuation effect on energy across different frequencies.

To estimate energy, the CWT method was applied. The amplitude at the top and bottom of the formation was determined within the frequency spectrum using the following equation:

$$Energy = \frac{A_b - A_t}{A_m}$$

Where *Ab* is the amplitude in the bottom, *At* is the amplitude at the top and *Am* is the maximum amplitude of the spectrum studied.

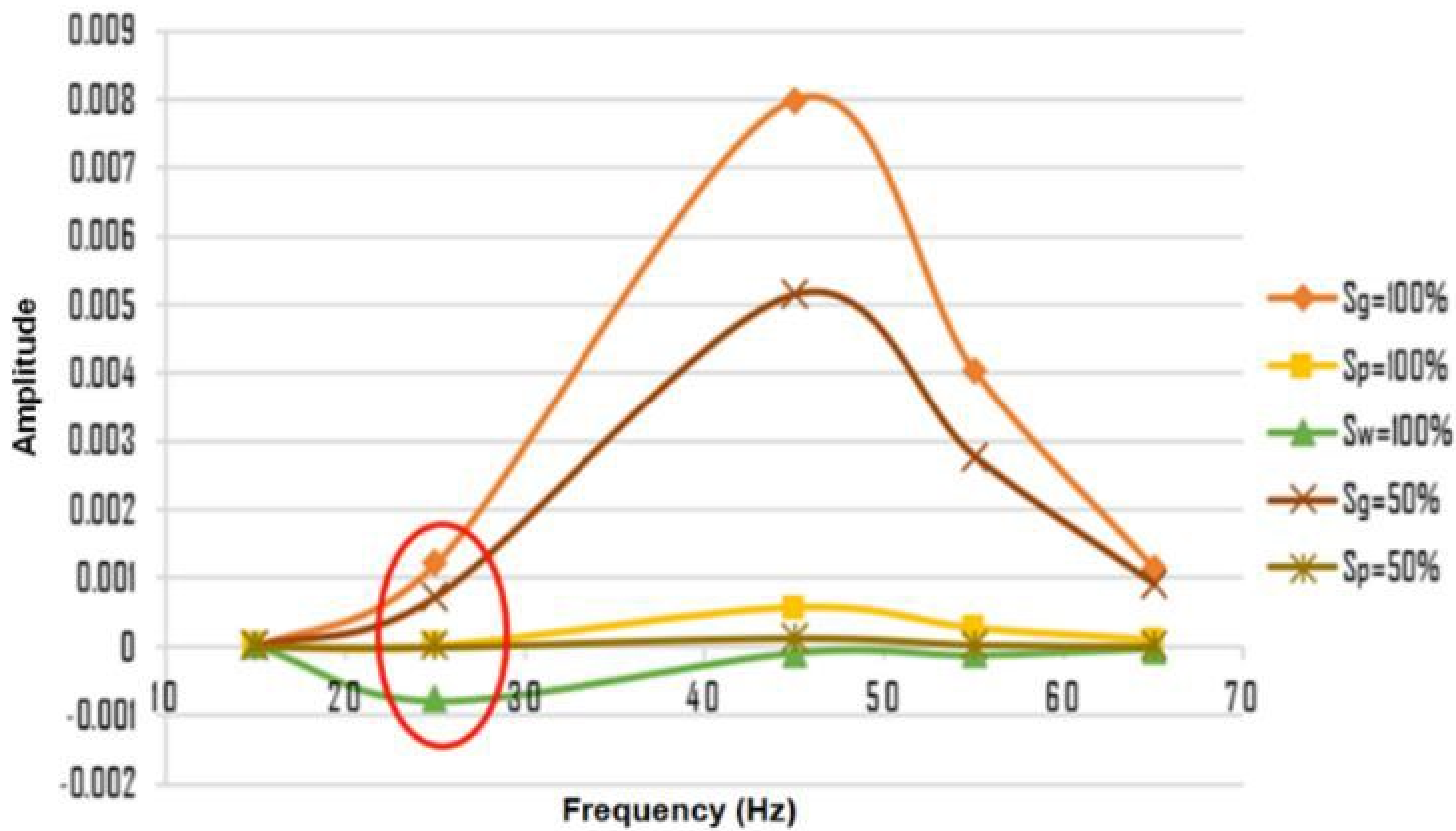


Figure 7. Variation of the frequency energy of the bottom with respect to the top for different fluids with varying saturation. Sg corresponds to the gas saturation, Sp to the saturation of oil and Sw to water saturation.

The energy at the bottom of the reservoir is highest when the rock is fully gas-saturated and decreases as gas saturation declines. In oil-saturated conditions, the energy curve is minimal and further diminishes as water saturation increases. In a fully water-saturated rock, high-frequency energy is nearly undetectable, while low-frequency energy decreases at the reservoir's bottom. Since this study focuses on relative changes, only the variations in energy for different reservoir types were evaluated.

Field Data

1. Powder River Basin

In figure 8 the tops and bottoms of the formations are shown. For the characterization of hydrocarbons, the attributes of instantaneous amplitude, instantaneous frequency, and spectral decomposition were used using the CWT method. The dominant frequency is approximately 30Hz, so three windows were studied in the frequency spectrum: 15Hz, 30Hz and 45Hz. The results are shown in figure 9.

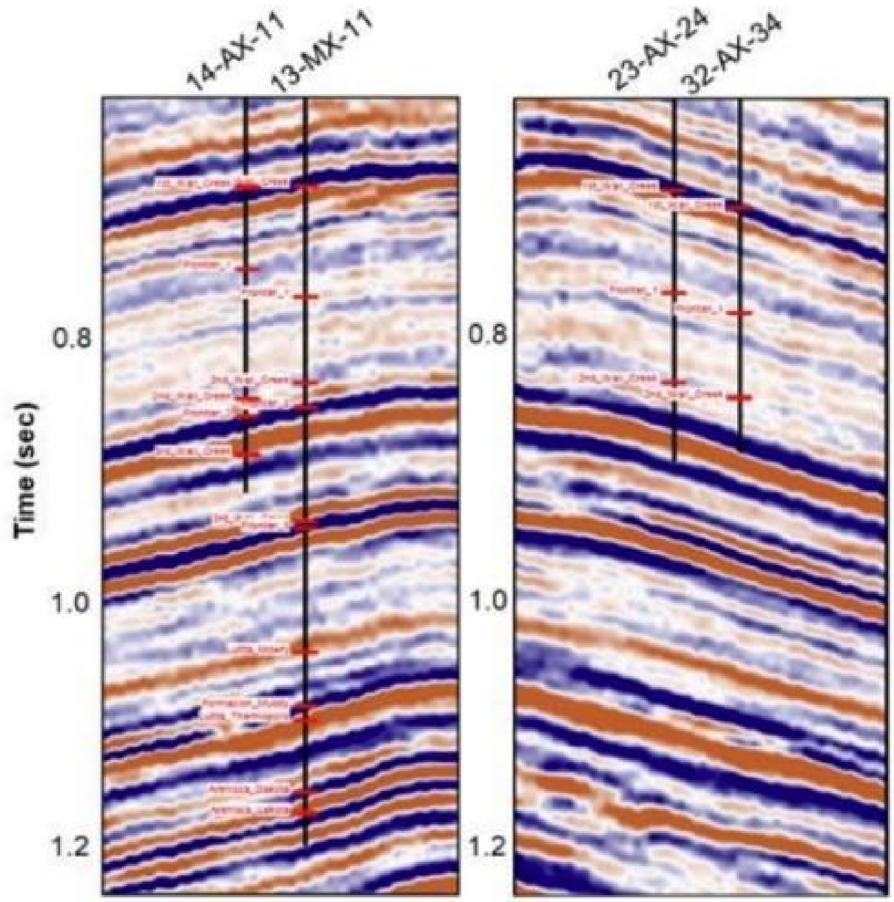


Figure 8. Domo Teapot. Top of the formations.

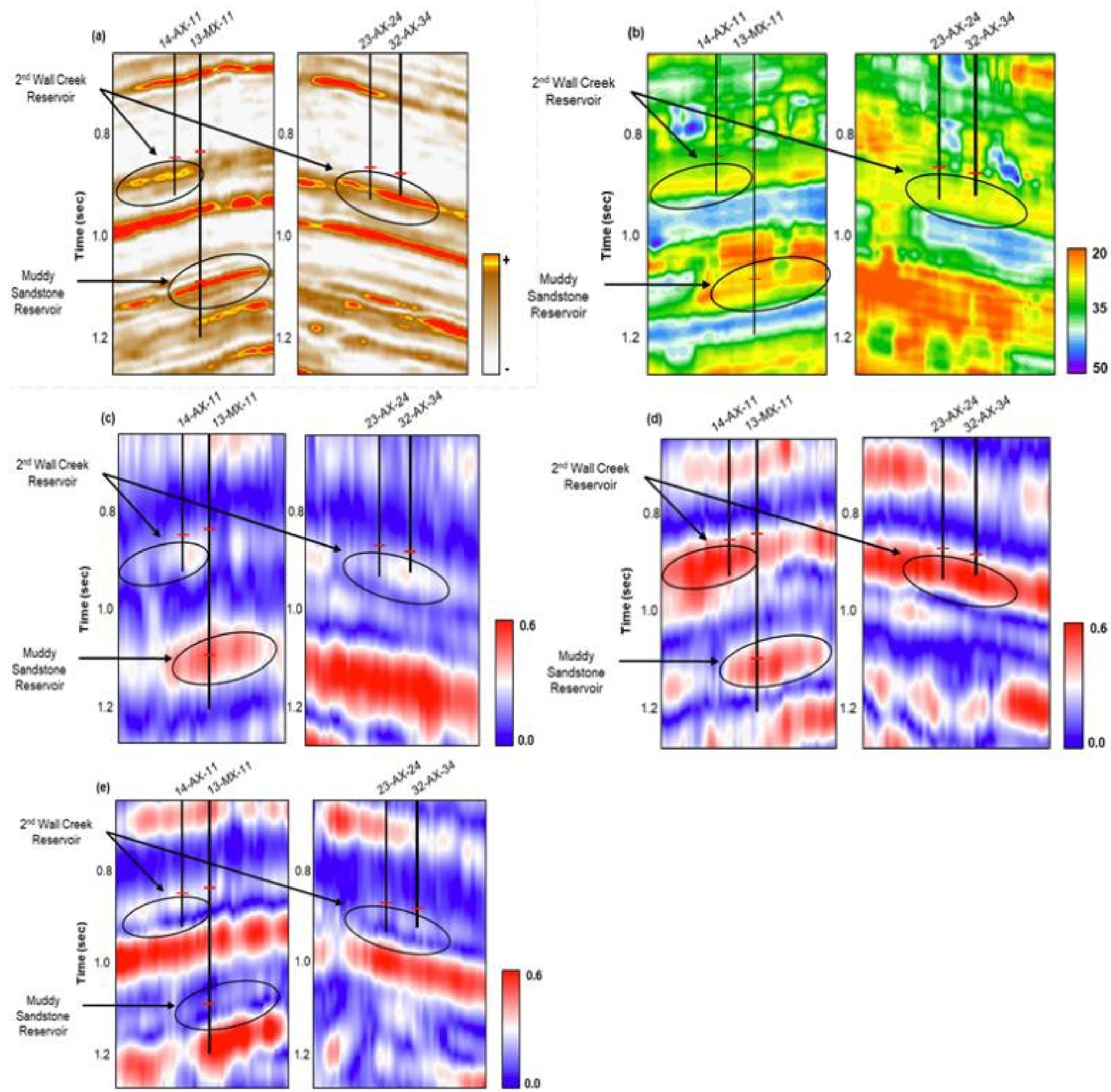
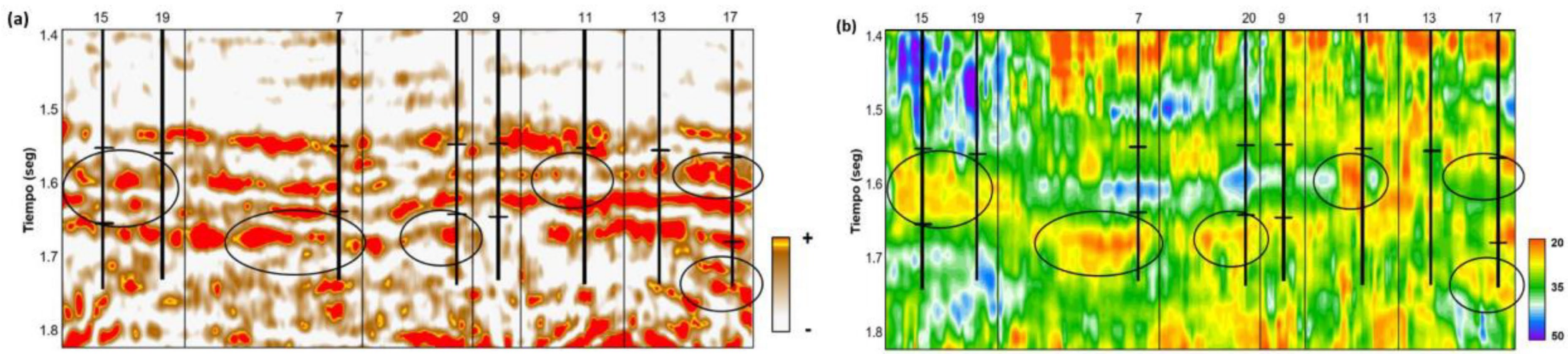


Figure 9. Seismic Attributes applied to the Teapot Dome. (a) Instantaneous Amplitude, (b) average Instantaneous Frequency and Spectral decomposition at (c) 15 Hz, (d) 30 Hz and (e) 45 Hz.

2. Stratton Field

This field was analyzed to study the seismic response to gas reservoirs using frequency attributes. Instantaneous frequency, instantaneous amplitude, and the CWT method were applied. Given that the dominant frequency of the Frio formation is 35 Hz, anomalies were examined at 20 Hz, 35 Hz, and 50 Hz.

A strong correlation was observed between gas reservoirs and high reflection intensity in the instantaneous amplitude data. However, applying the instantaneous frequency attribute revealed low-frequency values in areas with high instantaneous amplitude. Spectral decomposition further showed that regions with both high amplitude and low-frequency anomalies exhibited strong energy at 20 Hz, which intensified at 35 Hz but largely dissipated at 50 Hz.



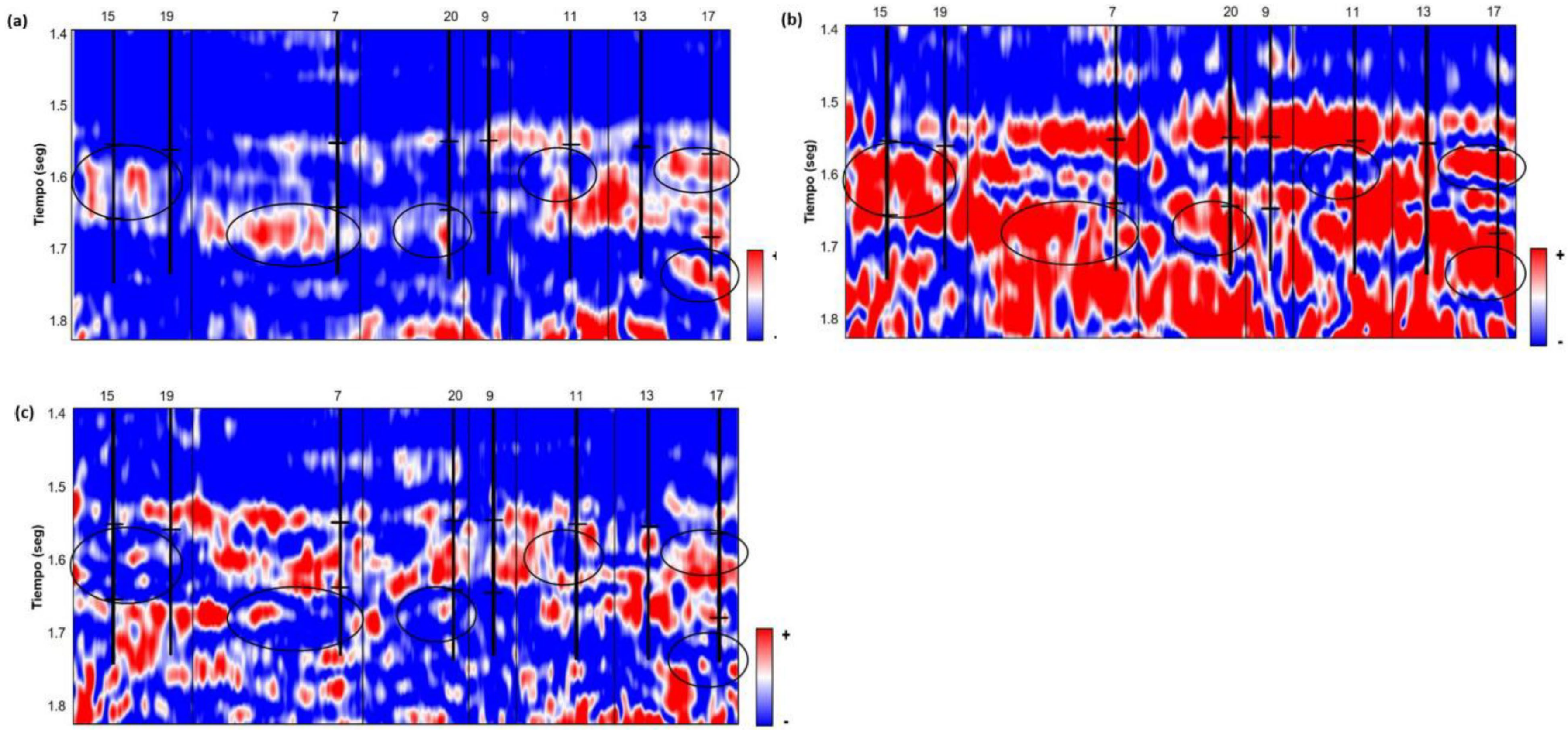


Figure 10. (a) instantaneous amplitude, (b) instantaneous frequency. Spectral decomposition at (a) 20 Hz, (b) 35 Hz and (c) 50 Hz.

Discussion

Interpretation of Synthetic Models

The seismic response in synthetic models is primarily driven by variations in layer velocity and density. Consequently, the observed anomalies result solely from changes in the density and velocity of the acoustic wave as it propagates through the reservoir.

Reservoirs containing gas or oil exhibit higher energy levels across the entire frequency spectrum at the reservoir's base. However, the substitution of oil with water causes only minor changes in physical properties, making seismic attributes less effective for monitoring oil/water saturation shifts. Additionally, in a fully water-saturated layer, low-frequency energy decreases at the bottom compared to the top of the reservoir.

In summary, a low Vp/Vs ratio combined with a decrease in bulk density relative to oil/water conditions is the primary factor behind increased low-frequency energy.

Interpretation of Field Data

Observations from the Powder River Basin suggest no direct correlation between GOR and an increase in low-frequency reflections. However, wells with higher porosity and/or hydrocarbon saturation exhibit stronger low-frequency reflections. This indicates that, beyond fluid characterization, frequency analysis can serve as a valuable tool for assessing reservoir quality. Porous reservoirs with high hydrocarbon saturation are more likely to display pronounced low-frequency anomalies, making frequency spectrum analysis an effective method for monitoring changes in gas and water saturation.

Similarly, observations from the Stratton Field indicate that free-gas-saturated reservoirs exhibit strong low-frequency anomalies along with high seismic reflection intensity, known as "bright spots." Given this relationship, the combined use of instantaneous amplitude and instantaneous frequency attributes can be highly effective in analyzing gas reservoirs.

Conclusions

An increase in low-frequency energy at the base of the reservoir is observed when oil is replaced with gas, accompanied by a rise in seismic reflection intensity. Gas-saturated reservoirs exhibit higher energy levels at both high and low frequencies, but this energy diminishes exponentially when gas is replaced with oil and becomes imperceptible when substituted with water.

A key observation is the significantly lower energy in the low-frequency range for water-saturated reservoirs. Unlike hydrocarbon-filled reservoirs, which show an increase in low-frequency energy at the base relative to the top, water-saturated layers display the opposite trend—a decrease in low-frequency energy at the bottom. This effect serves as an important fluid discriminator: hydrocarbon reservoirs tend to enhance low-frequency energy at their base, whereas water-saturated layers show a decline. While gas- and oil-filled reservoirs generate higher energy at both high and low frequencies compared to water, the substitution of oil with water results in only minor changes in physical properties. As a result, physical seismic attributes alone may not be effective for tracking oil-to-water saturation changes.

The reservoirs studied in the Powder River Basin and Stratton Field are no thicker than 30 meters ($\leq 1/4\ \lambda$), meaning there is insufficient travel time for attenuation effects caused by fluid mobility or macroscopic phenomena. Based on mathematical models and seismic data from hydrocarbon-producing fields, low-frequency anomalies are attributed to areas with a low Vp/Vs ratio.

Applying frequency-based attributes can effectively assess reservoir quality, as porous layers with high hydrocarbon saturation are more likely to exhibit pronounced low-frequency anomalies at the reservoir's base. Consequently, frequency spectrum analysis is a valuable tool for monitoring gas/water saturation changes.

Instantaneous amplitude analysis highlights reflections caused by high impedance contrasts between strata, typically associated with liquid hydrocarbon reservoirs containing free gas. Additionally, instantaneous frequency is a strong fluid discriminator, identifying regions where increased low-frequency energy at the base of a reservoir is often linked to the presence of free gas.

Field data analysis indicates no increase in high-frequency energy, only a rise in low-frequency energy. This effect is attributed to assumptions in Gassmann's Equation (1958), which considers a homogeneous, permeable reservoir and does not account for chemical interactions between rock and fluids.

For future studies, it is recommended to expand the analysis to a larger dataset with more wells to further investigate the effects of saturation and gas-oil ratio. Additionally, examining fluid behavior in large reservoirs exceeding 100 meters in thickness will provide deeper insights into the relationship between frequency content, fluid saturation, and reservoir thickness.

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