Spectral Decomposition with Continuous Wavelet Transform for Hydrocarbon Zone Detection of North Bali Waters

Dekomposisi Spektral dengan Transformasi Wavelet Kontinyu untuk Deteksi Zona Hidrokarbon di Perairan Bali Utara

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ABSTRACT: The East Java Basin is developed from an oceanic basin in front of Late Cretaceous Java Trench subduction zone to presently back-arc basin behind the Java-Lombok volcanic arc to the south. Many studies conclude hydrocarbon discovery in deep carbonate Ngimbang Formation. However, as a result of the active tectonic history of the region, there are fractures from Ngimbang Formation upward to the Oligo-Miocene Kujung Formation. It developes enhanced permeability medium for a good hydrocarbon migration. This paper presents shallow gas detection zone in the Mundu Formation by applying the spectral decomposition method with continous wavelet transform. Spectral decomposition can be effectively used to identify hydrocarbon reservoirs by analyzing seismic data in the frequency domain. Spectral decomposition with frequency 20 Hz shows the potential zone at time 779 - 832 ms which is suitable with depth 2237.5 - 2355.6 feet in well TRG-1. This method is supported with quantitative calculation of petrophysical analysis that determines 5 pay flag zones range from 2208.5 feet until 2347.5 feet.

Keywords : East Java Basin, spectral decomposition, continuous wavelet transform, petrophysical analysis

ABSTRAK: *Cekungan Jawa Timur terbentuk dari cekungan samudera di tepi zona subduksi pulau Jawa pada masa Cretaseous/Kapur Akhir hingga cekungan busur belakang sistem vulkanik Jawa-Lombok di selatan. Banyak penelitian menyimpulkan penemuan hidrokarbon pada lapisan karbonat Formasi Ngimbang yang dalam. Namun, sebagai akibat dari sejarah tektonik aktif dari wilayah tersebut, terdapat rekahan dari Formasi Ngimbang sampai ke atas hingga Formasi Kujung pada masa Oligo-Miosen. Kejadian tersebut menyebabkan timbulnya peningkatan permeabilitas medium yang baik untuk migrasi hidrokarbon. Makalah ini menyajikan deteksi zona gas dangkal pada Formasi Mundu dengan menerapkan metode dekomposisi spektral dengan transformasi wavelet kontinyu. Dekomposisi spektral dapat secara efektif digunakan untuk mengidentifikasi reservoir hidrokarbon dengan menganalisa data seismik dalam domain frekuensi. Dekomposisi spektral dengan frekuensi 20 Hz menunjukkan zona potensial pada kedalaman domain waktu 779 - 832 ms yang sesuai dengan 2237.5 - 2355.6 kaki pada sumur TRG-1. Metode ini didukung dengan perhitungan kuantitatif analisa petrofisika yang menentukan 5 zona gas mulai dari 2208.5 kaki hingga 2.347.5 kaki.*

Kata kunci : *Cekungan Jawa Timur, dekomposisi spektral, transformasi wavelet kontinyu, analisa petrofisika*

INTRODUCTION

Since the beginning of digital seismic recording, the measured seismic data has been decomposed into its spectral components using Fourier transform by geophysical scientists to attenuate low-frequency ground roll, 50- or 60-Hz equipment noise, and high-frequency random noise (Xinhui, 2012). Spectral decomposition has the theory by its definition, decomposes the seismic data, including low-frequency ground-roll, cultural and high-frequency random so that noise can be differentiated from the seismic signal. The remaining signal can be used to evaluate changes in layer thickness and lateral heterogeneity with higher resolution than the classic one-quarter wavelength (Chopra and Marfurt, 2007). Also, spectral decomposition can be used to analyze the amplitude of different frequency components of a reflection to detect tuning frequency. Tuning frequency changes as the thickness of a particular bed changes and also changes as a function of velocity. Smaller time thicknesses tune at higher frequencies, while larger time thicknesses tune at lower frequencies. Lateral variation in tuning frequency within the same refection can be interpreted as changes in lithology, fluid, thickness, and/or velocity (Robinson, 2012).

The conventional spectral decomposition method using Fourier transform has many shortcomings in breaking down seismic data into its frequency components (Rojas, 2008). The Fourier transform generates a time frequency spectrum over a chosen time window. Therefore, resolution in seismic data analysis becomes dependent on a user defined window length. The selection for the window length is critical in the Fourier transform (Sinha *et al.*, 2005). Wavelet analysis is the development and extension of Fourier transform method. Wavelet transform is an analysis method in time-frequency seismic data, it has the character of multi-resolution analysis, and can represent seismic data in both time domain and frequency domains. It is a time-frequency localization analysis method in which the area of window is constant, the shape of window is variable and the time window and frequency window can both change. In the low frequency part, it has high frequency resolution and low time resolution, while in the high frequency part it has high time resolution and low frequency resolution (Jahan and Castagna, 2017). Wavelet transforms can do multi-resolution analysis in order to detect shallow gas zone.

Regional Geology

The East Java Basin covers the active southeastern margin of the Sundaland from northern back-arc of the active Java Trench until the Java-Lombok volcano system. The basin is developed from an oceanic basin in front of Late Cretaceous subduction zone to presently back-arc basin behind the volcanic arc to the south (Satyana and Djumlati, 2003). It is bordered to the west by the Karimunjawa Arch, continued eastward into the deep water Lombok Basin, and northward onto the Paternoster High. Three main structural configurations can be established from north to south : the Northern Platform, the Central Deep, and the Southern Uplift (Figure 1).

Madura-Raas/Sapudi-Kangean and Sepanjang island rows are exposed due to rising induction pressure associated with lateral rotation to the left along the main fault line. As time changes from Miocene to the present, a continuously pressure exposes part of the island close to the fault structure. The rear arc ridge is formed at Miocene up to the present between Kangean-Kemirian and Bali island. The upward movement of the Kemirian Mountains and continuous plate pressure resulted in a large normal fault from the south to the Bali-Lombok sub-basin. The great upward movement took place in Eocene-Oligocene, when the Ngimbang and Kujung formations were composed and matured (Aprilana *et al.*, 2016).

Pre-Tertiary Metasediments are formed in complex fore-arc which are considered to be peneplaned during Late Cretaceous to Early Eocene (Figure 2). Some of the formations are formed with fluvial or deltaic origin deposited from quartz sand, coal, and carbonate fragments during Middle Eocene to

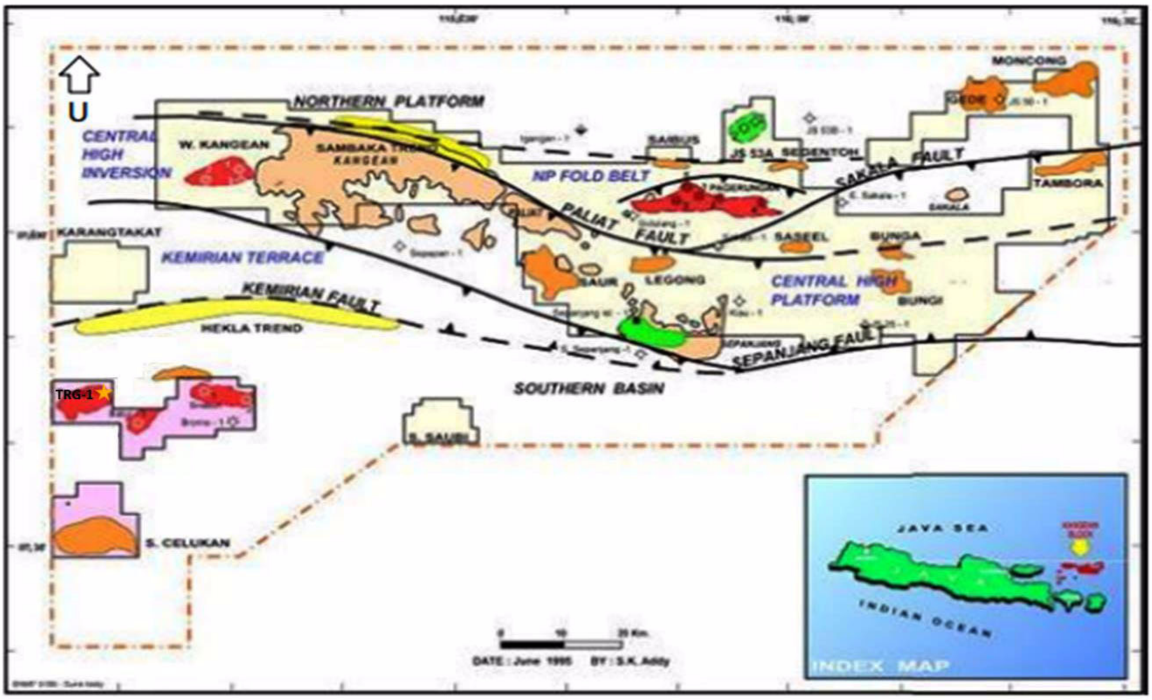

Figure 1. Tectonic setting of North Bali waters - Kangean island (Kangean Energy Indonesia, 2012)

Late Eocene, composing the clastic Ngimbang which is part of the Ngimbang Formation (Granath *et al.*, 2011). Sedimentation rate of the carbonate Ngimbang caused a reduction in the East Java Sea and its accumulation of broad and thin shale fragments settled during Late Eocene. The shale layer comprises the Lower Ngimbang which is part of the Ngimbang Formation at Late Eocene and the Kujung Formation at Oligocene. Ngimbang Formation is known as one major source of hydrocarbon supply in the Northern East Java Basin. The Oligo-Miocene Kujung Formation of East Java Basin is a carbonate reservoir that enhanced by fracturing (Magee *et al.*, 2011). However, as a result of the active tectonic history of the region, it developes enhanced permeability medium for a good hydrocarbon migration.

Tectonic regional events (N7-N14) during the Middle Miocene formed a sedimentary basin on the Kangean block. Kangean island and Kemirian Mountains were then pushed upward and the sediments are lifted up and surrounded the basin. Late Miocene sedimentation in the Bali-Lombok sub-basin takes place in the deep ocean for the deposition of carbonates, clays, and quartz sand. The structure process at Middle Miocene has stopped, then filled with Cepu Formation (Soeparyono and Lennox, 1990). The Cepu Formation consists of the napal limestone of planktonic and nanoplankton precipitation. Above the Cepu Limestone in Late Miocene and Early Pliocene are the Paciran sandstones, which are part of the Mundu Formation. The sand is deposited in the delta complex and it is very broad in the well TRG-1 area (Figure 2).

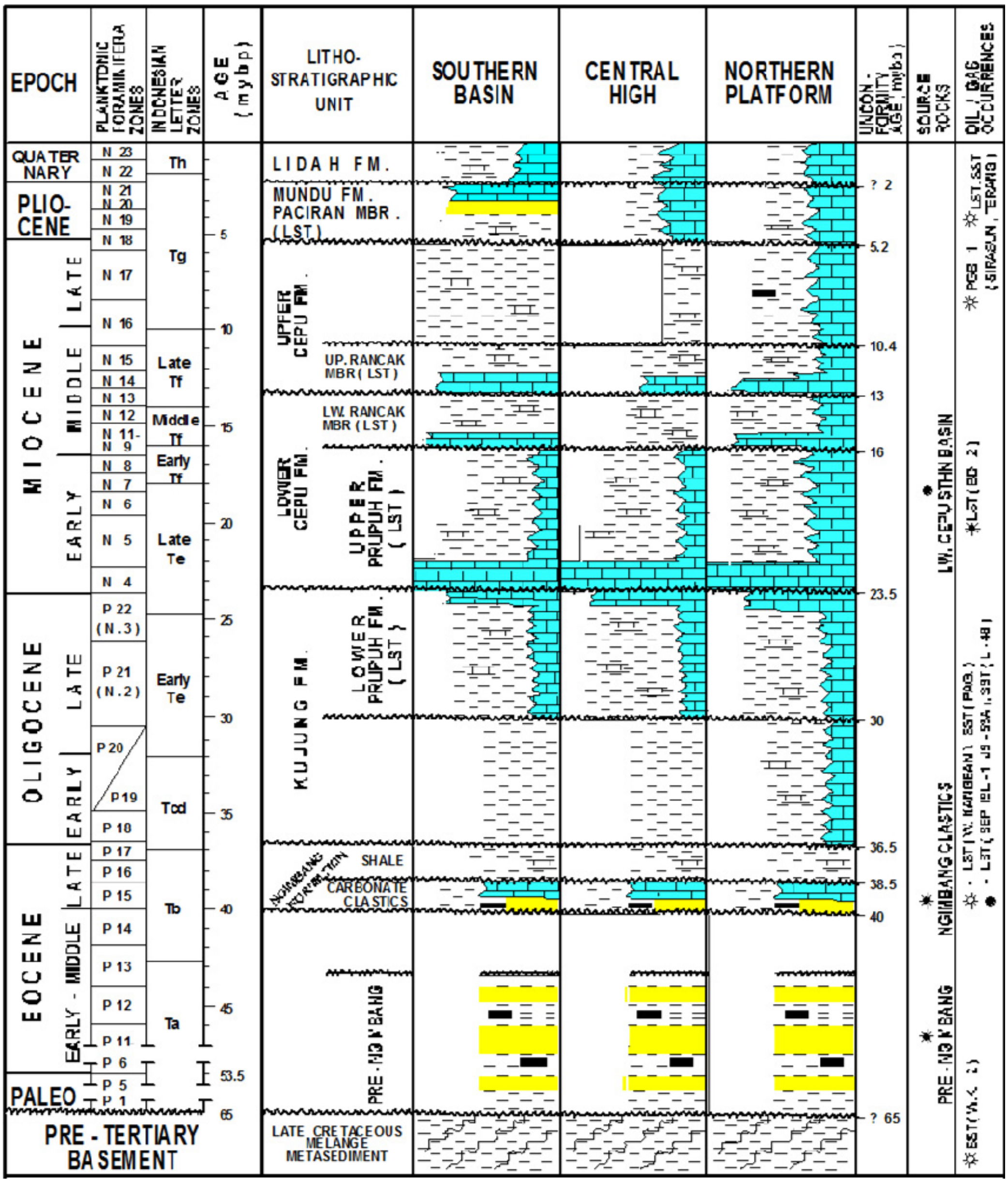

Figure 2. Stratigraphy column of Kangean block (Davies, 1989)

DATA AND METHODS

Seismic Data

The seismic acquisition survey is situated on the North Bali Waters in between 114^{0}30’ – 116^{0} E and 7^{0}15’ – 8^{0}15’ S (Figure 3). The 2D seismic acquisition surveys shot using MV Geomarin 3 that was fully operated by Marine Geological Institute. Seismic field data were acquired using Sercel Inc. 60 channels single-streamer and 630 cu. in. power pressure Bolt airgun at average 4.5 knot vessel speed. Seismic acquisition parameter obtained from observer report is used as input parameter in seismic processing software (Table 1). The time migrated section of line LBU-6 (Figure 4) was studied because it was the nearest seismic line to the well TRG-1. Noise and multiple attenuation were applied to the seismic data in order to gain more accurate well-seismic interpretation.

Gamma ray logs measure gamma-ray radiation generated by radioactive elements such as uranium, thorium, potassium which are present in shale and clay, and small amount of natural gamma radiation in sandstones, limestones, and dolomites (Nazeer *et al.*, 2016). High gamma ray response signifies that the formation contains shale or clay, while the low gamma ray response indicates the formation is sandstone or limestone that can be indicated as a hydrocarbon reservoir.

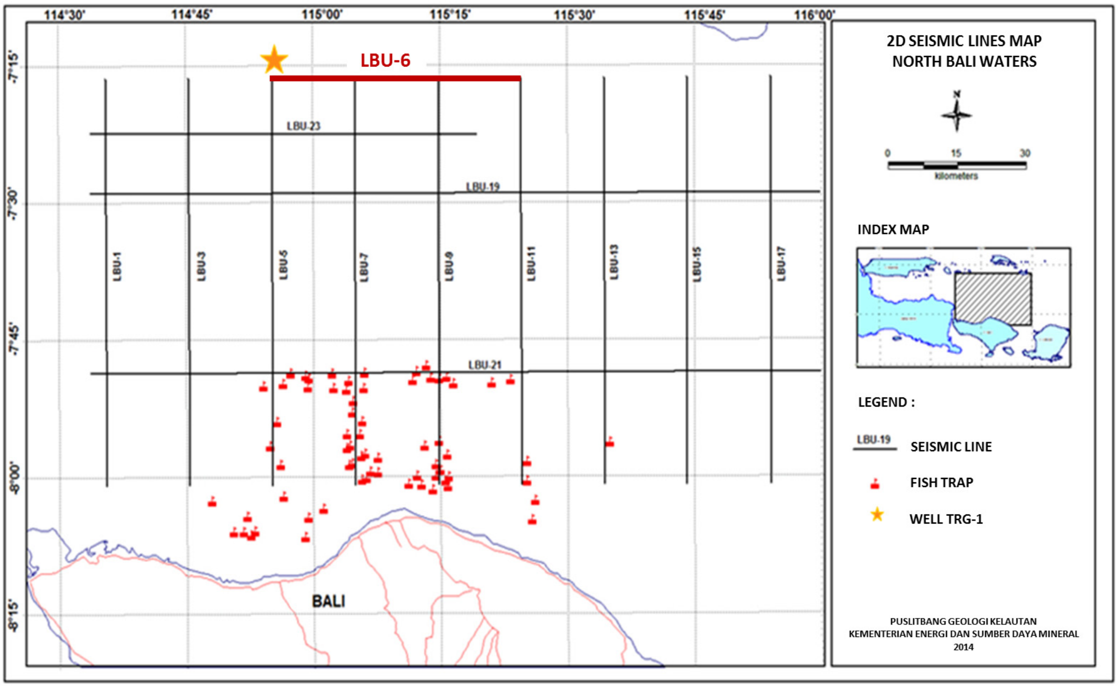

Figure 3. Seismic acquisition map

Table 1. Seismic Acquisition Parameter

CONFIGURATION	OFF-END
Active Channel	1-60
Line Azimuth	90^{0}
Shot Interval	37.5 m
Group Interval	12.5 m
Shot Number	2011
Offset	150 – 887.5 m
Maximum Fold	15
Total Seismic Line	75.375 km
Sampling Rate	2 ms

Well Data

The well TRG-1 has actual location on 114^{0}55’37.56” E and 7^{0}16’11.94” S plotted in Figure 3. It is drilled 308 feet below sea level, total depth is 7455.5 feet, and situated in between the North Bali and Southwest Kangean island. It has main data logs such as gamma ray, neutron-density, and resistivity logs. The well data report also has sonic log and check-shot information for the well-seismic tie.

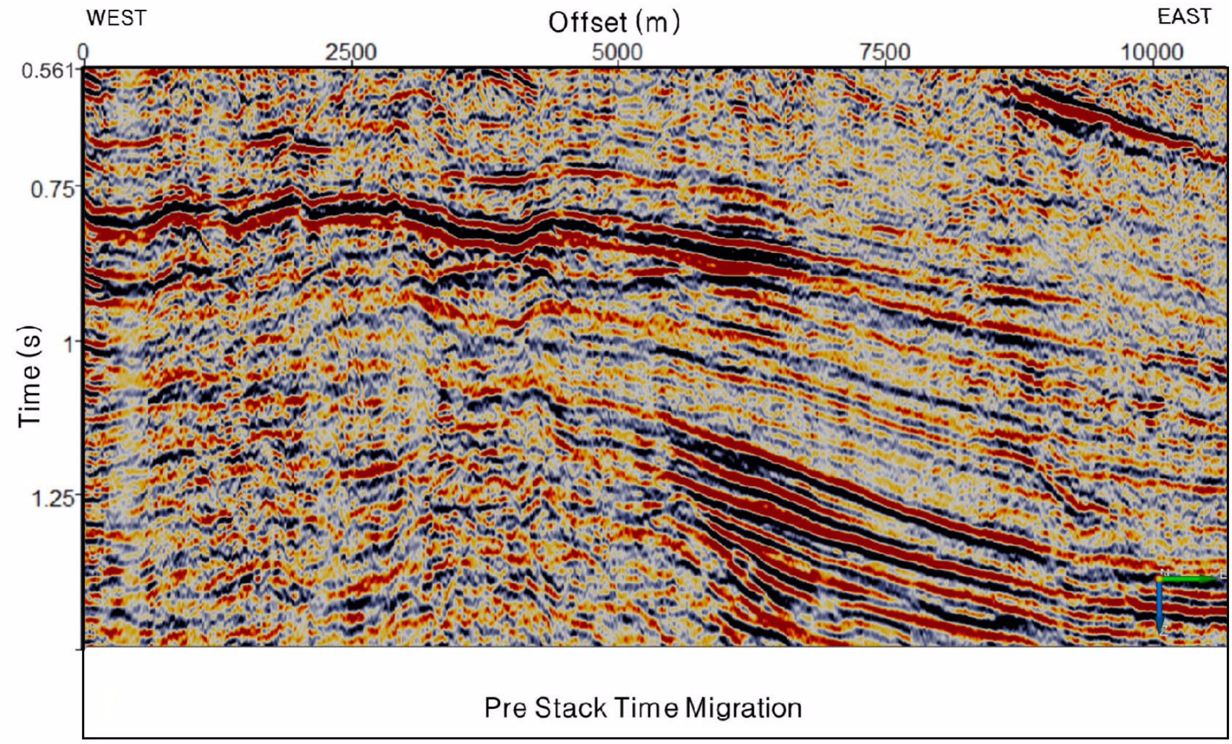

Figure 4. Post-processing seismic section line LBU-6

In determining the availability of hydrocarbons and their hydrocarbon types through qualitative analysis can be seen from the positive separation between density log RHOB with neutron log NPHI and resistivity log pattern (Kumar *et al.*, 2018). The value of density log RHOB graph increases from left to right while the neutron log NPHI graph increases from right to left. A large positive separation occurs if value of the density and the neutron log are low. In homogeneous rocks containing gas, the log graph will have a much lower density log reading than those containing oil and water because oil and water have a higher density compared to gas. The gas content in rock pores will also respond to lower neutron log values than those containing oil and water because the gas has a lower hydrogen index than oil and water. Therefore, if density and neutron logs are overlaid then on rocks filled with gas, it will create a wider positive separation than those containing oil or water. The wide positivity between density and neutron logs in the well TRG-1 (Figure 5) are found at depths of 2208-2273 feet, 2281-2297 feet, and 2300-2350 feet, respectively.

Determination of hydrocarbon reservoir using neutron-density logs can be supported by information of formation resistivity logs which are not affected by mud filtrate obtained from ILD (Deep Induction Log) and resistivity value affected by mud obtained from MSFL (Micro Spherically Focused Log). The type of mud used is saltwater mud which has a low resistivity so that if the rock is filled with oil, the resistivity value of the ILD log will be higher than the resistivity reading in the MSFL log and if the rock is filled by the gas then the ILD log read will be higher since the gas resistivity value which is higher than oil (Zhang *et al.*, 2015).

Continuous Wavelet Transform

The CWT (Continuous Wavelet Transform) is one of the wavelet transform methods and also it is an alternative method to analyze the frequency distribution of a nonstationary time series. It is based on wavelet analysis to decompose a time-scale spectrum into a time frequency spectrum. Wavelet analysis examines the frequency distribution of a nonstationary time series using a set of windows that have compact support in time (i.e. decays to zero quickly) and are band-limited in the frequency domain (Rojas, 2008). These window functions resemble tiny waves that grow and decay in short periods of time and hence have the name wavelets. Similar to Fourier transform method, wavelet analysis includes transforms such as the wavelet series expansion, the continuous wavelet transform, the discrete wavelet transform, and the wavelet packet transform (Chakraborty and Okaya, 1995).

Commonly used wavelets in CWT are Ricker, Morlet, and Mexican Hat wavelet depending on the desired resultant vertical resolution (Chopra and Marfurt, 2015). The Ricker wavelet is a compact wavelet with high temporal resolution, but poor

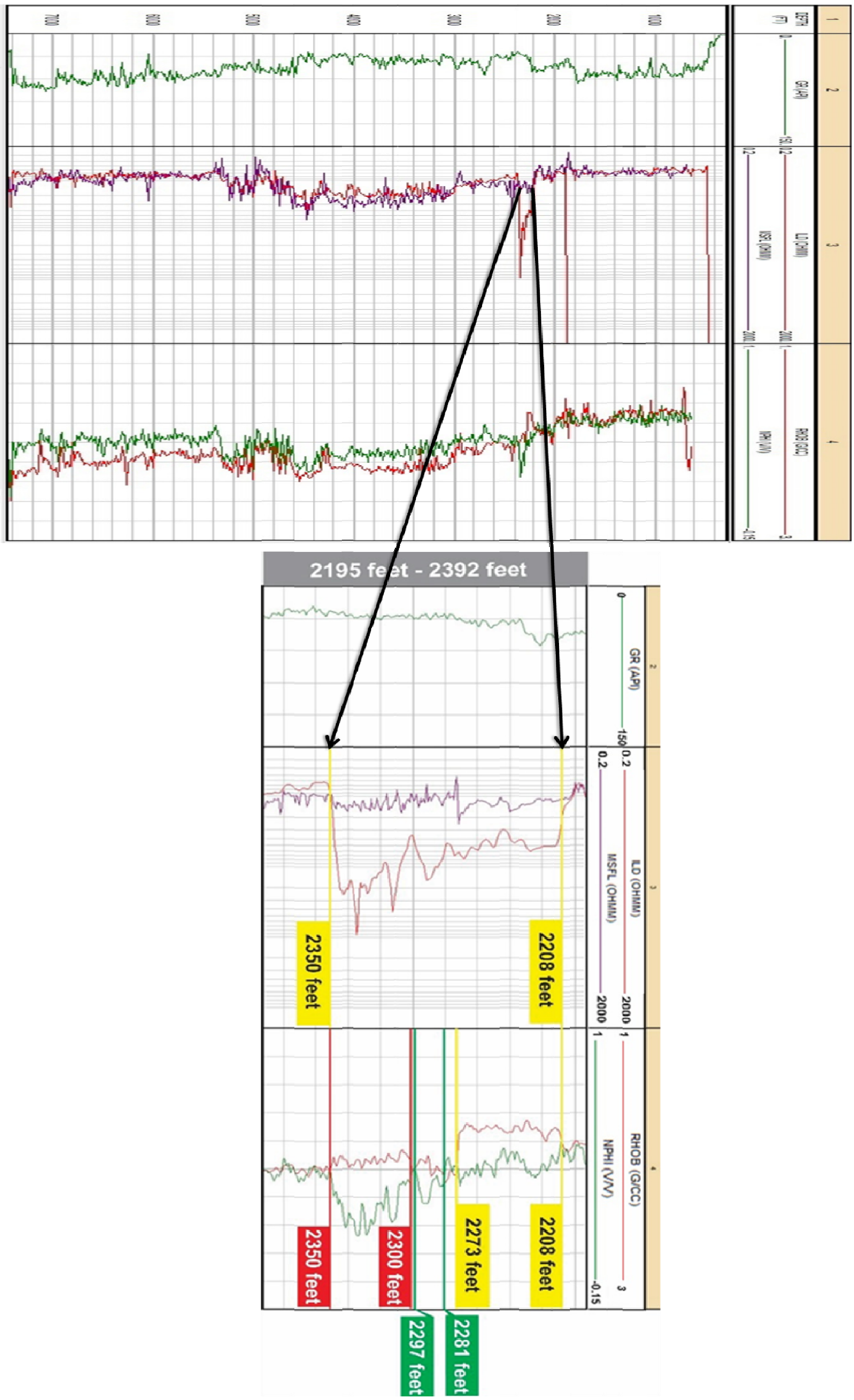

Figure 5. Well TRG-1 data log

frequency resolution (Robinson, 2012). A Ricker wavelet is commonly used for modeling because it is similar to typical Earth responses. It is defined by its dominant frequency and its zero-phase nature and is characterized by a large peak and minimal sidelobes. Morlet wavelet was introduced in Morlet *et al.* (1982). A Morlet wavelet is composed of sine and cosine functions that are modulated by a Gaussian Tapper (Chopra and Marfurt, 2007). Morlet wavelets are commonly used in CWT because of the simplicity between scale and frequency interpretation, since the center frequency is inversely proportional to the scale (Sinha *et al.*, 2005). Morlet wavelets consist of high frequencies, with a broader frequency spectrum, but shorter temporal extent when compared to SWDFT wavelets (Chopra and Marfurt, 2007). One disadvantage to the Morlet wavelet is that it is a less compact wavelet with multiple sidelobes, resulting in poor vertical resolution (Castagna and Sun, 2006). The Mexican Hat wavelet is a complex function. As a result, the spectral components obtained from CWT are also complex. Thus, when spectral decomposition is carried out on seismic data, it yields the spectral magnitude and phase at each time-frequency sample. The spectral magnitude represents the energy that correlates with the trace, and the phase represents the phase rotation between the seismic trace and the Mexican Hat wavelet at each instant of time. The CWT (Continuous Wavelet Transform) with the Mexican Hat wavelet is applied in this paper to obtain the best high frequency resolution in lower frequency spectrum.

RESULTS

The series of decomposed spectral frequencies 10 Hz, 20 Hz, and 30 Hz are chosen from extracted spectral magnitude and phase of seismic data. Those three spectral frequencies are representation of dominan frequencies in the migrated seismic section. Although those three spectral frequencies have similar pattern of hydrocarbon detection zones, but those values give different hydrocarbon detection depths in time domain. Using Well TRG-1 as tied well-seismic data and the series of decomposed spectral frequencies, the hydrocarbon detection zone at spectrum frequency 10 Hz lies at time 1022-1108 ms (Figure 6). The spectrum frequency 20 Hz of the hydrocarbon detection zone lies at time 779-832 ms (Figure 7). There are two hydrocarbon detection zones at time 781-828 ms and 895-918 ms from the decomposed spectral frequency 30 Hz (Figure 8). All three spectrum frequencies describe different hydrocarbon detection zones. Therefore, the next step to determine the frequency value that is able to accurately describe the hydrocarbon detection zone, it is necessary to validate the suitability of well log analysis with spectral decomposition results for spectrum frequencies 10 Hz, 20 Hz, and 30 Hz.

In determining the suitability of the results of petrophysical analysis and spectral decomposition, it is necessary to bind the well data with seismic data. This is commonly applied because of domain differences between seismic data and well data where the results of petrophysical analysis of well data are in the depth domain while the spectral decomposition of seismic data is in time domain (Bian *et al.*, 2017). The result of binding of well data with seismic data shows correlation with strong category with correlation value of 0.55 between synthetic seismogram and field data seismic (Figure 9).

Quantitative analysis of well TRG-1 data log is applied to determine porosity, water saturation, and clay volume. Porosity evaluation uses effective porosity (PHIE) model to determine portion capacity of porous material to store fluids porosity. Water saturation (S_W) is calculated by using Dual Water model to match effective porosity model by bounding subtracted water component from the porosity value before being input to the equation. Clay volume computes a minimum clay volume from single curve shale indicators (arithmetic and geometric shale indicators crossplot). Larionov Tertiary rock shale indicator equation is used to estimate the rock's clay volume for the tertiary rock formation. Using cutoff 25% effective porosity as gas reservoir flag cutoff, we determine 5 (five) pay flag zones range from 2208.5 feet until 2347.5 feet (Figure 10).

After binding of well data and seismic data, it will get an equivalent relationship between time and depth domain. The potential hydrocarbon zone of petrophysical analysis resides in the time-depth domain, Top gas A-B-C and D depth is equivalent to time 775 ms, 780 ms, 782 ms, and 788 ms, respectively. Bottom gas E depth is equivalent to time 831 ms. From the result of binding of well data with this seismic data hence can be made marker which become marker position of potential hydrocarbon zone result of petrophysical analysis on seismic data (Figure 11).

DISCUSSION

The detection zone of 10 Hz spectral decomposition at 1022 - 1108 ms or 2828 - 3152 feet depth does not correspond to marker zone reservoir of petrophysical analysis (Figure 12a). Although around its zone there is a low frequency anomaly indicated in association with the hydrocarbons, but both results have not shown good suitability. So that the 10 Hz frequency cannot be used to identify the hydrocarbon reservoir in the study area.

Spectral decomposition with frequency 20 Hz shows the potential zone at time 779 - 832 ms which is

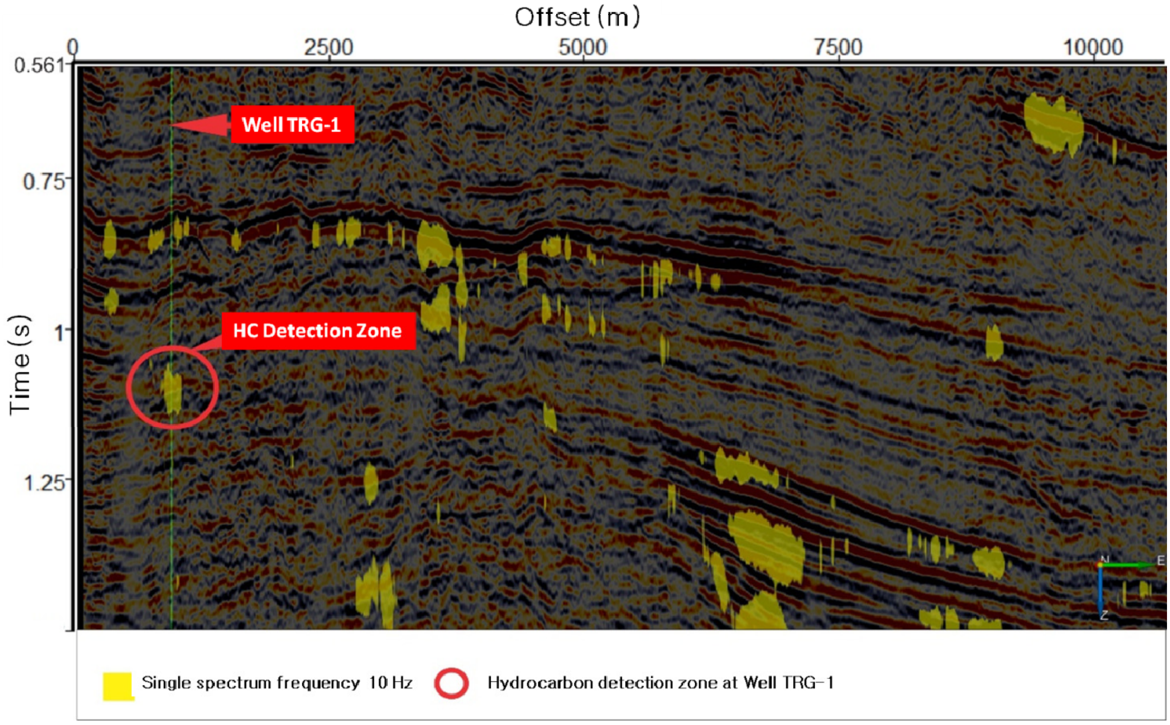

Figure 6. Hydrocarbon detection zone at single spectrum frequency 10 Hz at Well TRG-1

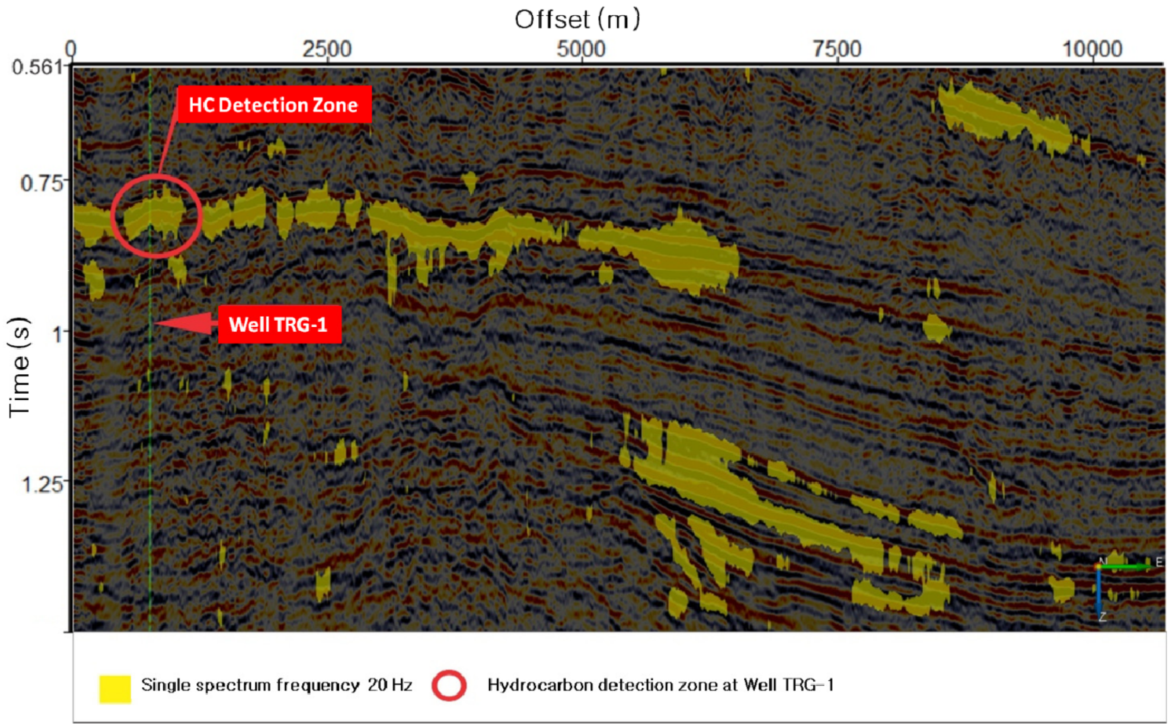

Figure 7. Hydrocarbon detection zone at single spectrum frequency 20 Hz at Well TRG-1

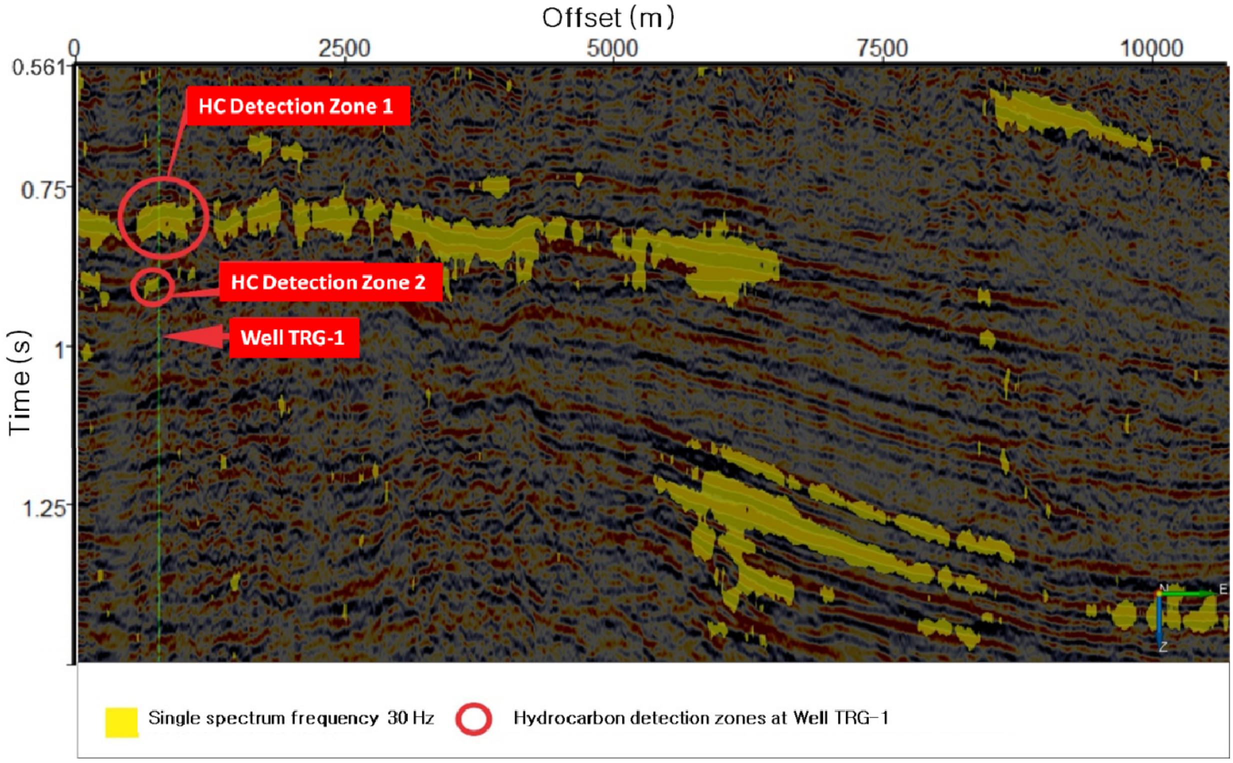

Figure 8. Hydrocarbon detection zones at single spectrum frequency 30 Hz at Well TRG-1

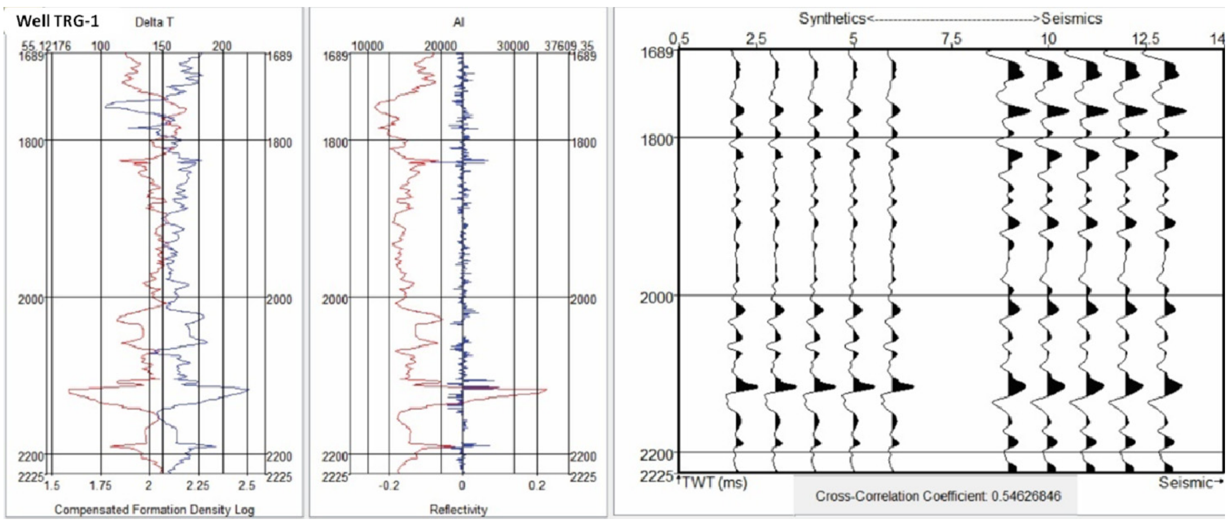

Figure 9. Well-seismic tie

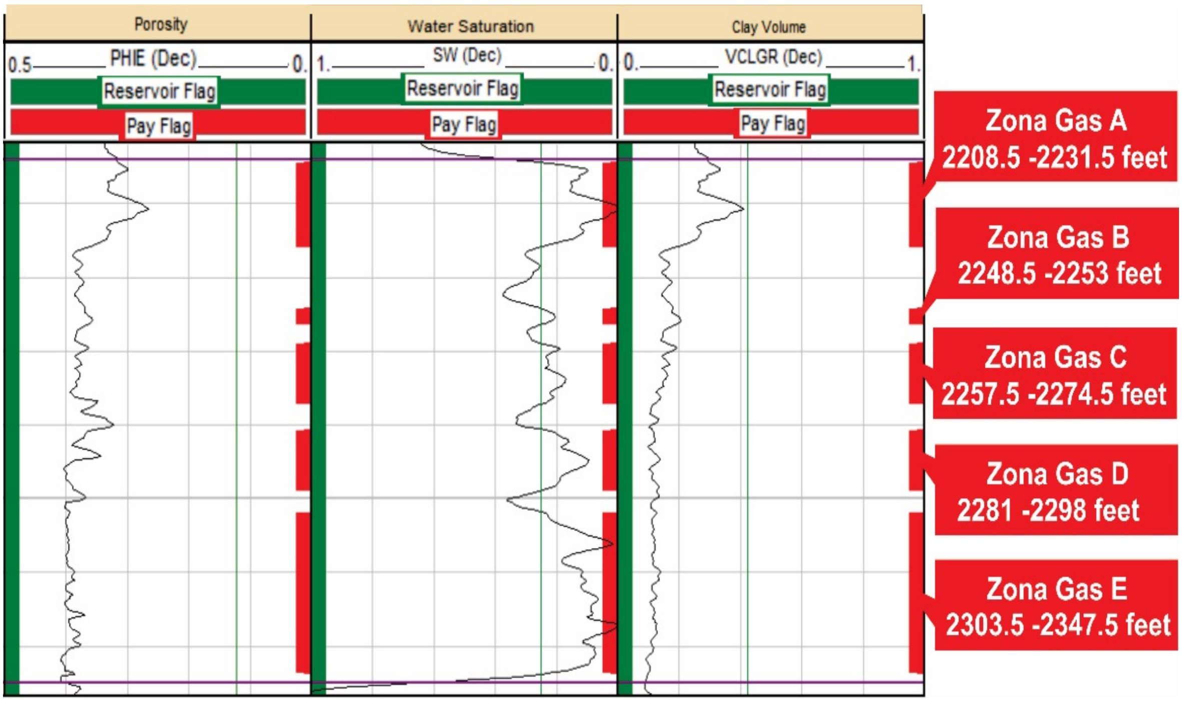

Figure 10. Reservoir flag and pay flag zones

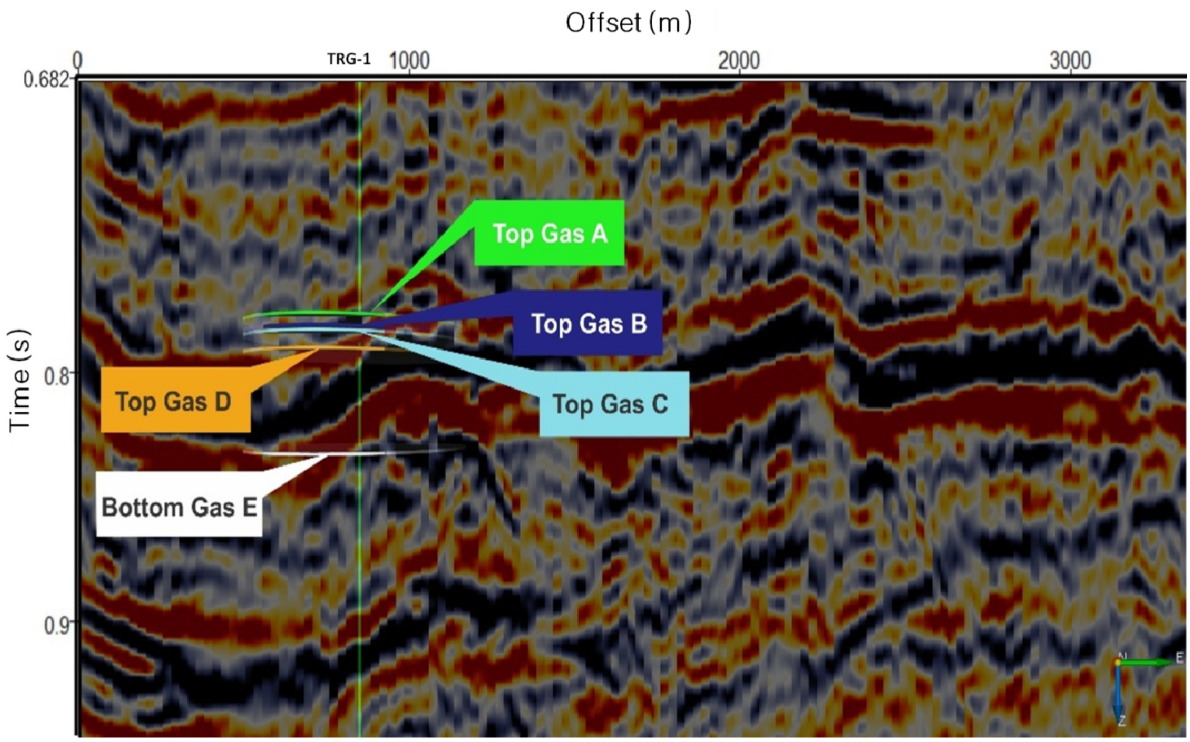

Figure 11. Gas detection zone markers

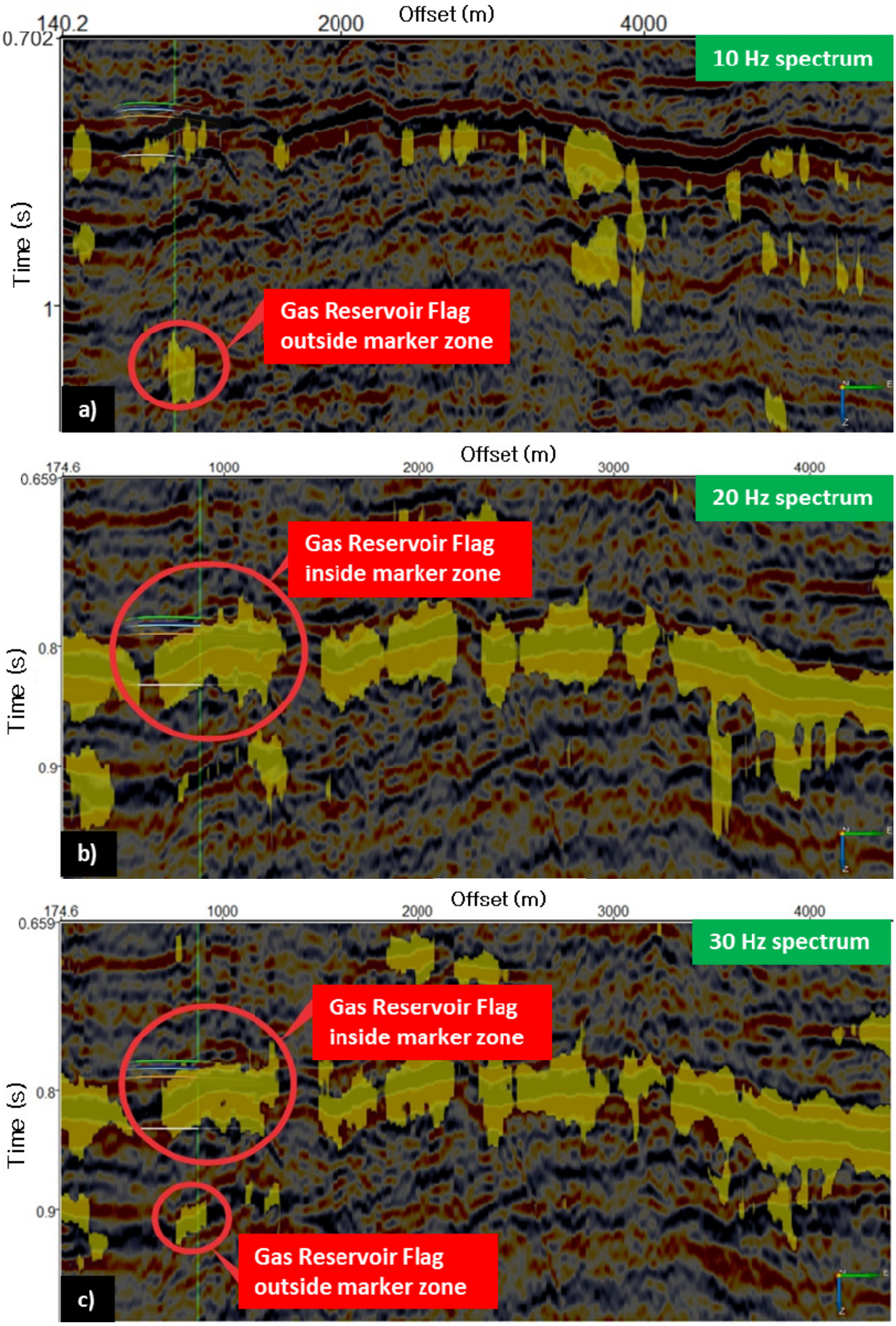

Figure 12. Gas reservoir zones with decomposed spectral frequencies. a) 10 Hz spectrum, b) 20 Hz spectrum, c) 30 Hz spectrum.

in TRG-1 well area with depth 2237.5 - 2355.6 feet (Figure 12b). The potential zone at a frequency of 20 Hz has good compatibility with the potential zone marker from petrophysical analysis within a thin depth difference between top gas zone A and top zone potential spectral frequency of 20 Hz by 29 feet or 8.8 meters. The depth difference between the gas bottom E and bottom zone by 8.1 feet or 2.4 meters with the same spectral frequency. Although the five potential zones of hydrocarbon analysis petrophysical results can not be separately displayed by the method of spectral decomposition at 20 Hz frequency, its limitations of seismic resolution and the results of anomalies are clearly shown at low frequencies.

The result of spectral decomposition with a frequency of 30 Hz shows two potential zones in the well TRG-1 area, namely the potential zone 1 at 781 - 828 ms which is at a depth of 2250.6 - 2339.2 feet and potential zone 2 at 895 - 918 ms with a depth of 2500 - 2532 feet (Figure 12c). The potential zone 1 shows a fairly good match between the results of the 30 Hz spectral frequency decomposition and the hydrocarbon potential zone marker from petrophysical analysis with a depth difference between top gas A and top potential zone 1 at 42.1 feet or 12 meters. But at a frequency of 30 Hz there is a potential zone 2 that is not in accordance with the results of petrophysical analysis therefore the frequency 30 Hz can not be used to identify the hydrocarbon potential in the study area.

Through the suitability method between the petrophysical analysis and the potential zones resulting from spectral decomposition, the results of spectral decomposition with a frequency of 20 Hz can illustrate the potential hydrocarbon distribution of the study area.

CONCLUSION

The Continuous Wavelet Transfrom based on wavelet analysis of line LBU-6 seismic migrated section is enable to locate potential reservoir zone containing hydrocarbons. Three spectral frequencies have similar pattern of hydrocarbon detection zones, 10 Hz frequency is at time 1022 - 1108 ms, 20 Hz at time of 779 - 832 ms, and frequency of 30 Hz at 781 - 828 ms and time 895 - 918 ms. Those spectral frequencies have similar pattern of hydrocarbon detection zones, but they give different hydrocarbon detection depths in time domain.

Quantitative calculation of petrophysical analysis of the well TRG-1 determines 5 (five) pay flag zones range from 2208.5 feet until 2347.5 feet. The petrophysical analysis with well-seismic tie also defines marker position of potential hydrocarbon zone top gas A-B-C-D and bottom E depth, those markers are equivalent to time 775 ms, 780 ms, 782 ms, 788 ms, and 831 ms, respectively.

Spectral frequency 20 Hz is able to identify zone of hydrocarbon potential better than both 10 Hz and 30 Hz. Further research on higher seismic resolution and more spectral frequencies can be used to enhance the spectral decomposition method with Continuous Wavelet Transform.

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