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ORIGINAL PAPER

# MULTI-ATTRIBUTE ANALYSIS IN DELINEATING LATERAL CONTINUITY OF HYDROCARBON TRAPS IN THE MAARI FIELD, NEW ZEALAND

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ABSTRACT

Reservoir classification depends on several parameters tied to different aspects of a Petroleum system. The fundamental approach for any classification begins with identifying types of petroleum structures or traps. As most structures are complex, an innovative approach combining two or more approaches to improve subsurface mapping is being suggested in this work. This paper highlights two prime attributes for analysing the vertical and horizontal parameters of seismic data. The criteria employ mapping of the thickness and the continuity of a reservoir which can be mapped simultaneously using a single technique to classify a reservoir. The Maari field consists of a complex depositional system which varies from fluvial, deltaic to shallow marine and this heterogeneity and lateral continuity poses challenges in mapping the reservoir. Therefore, the use of multi-attribute analysis poses an innovative approach to overcome these mapping challenges. The spectral decomposition study of the Maari field leads to the estimation of the optimal frequency that belongs to the targeted reservoir and is indicative of the thickness of the layer. For an instantaneous phase, it highlights the stratigraphic boundaries, as the phase of events is consistent within the reservoir section but changes at the top and bottom of the reservoir. The instantaneous phase characteristic is a valuable tool for delineating formation and understanding depositional patters. Geological features such as channel thickness, fault boundaries, and continuity of reservoir sands can also be conveniently mapped using this technique.

## INTRODUCTION

Seismic attribute plays a vital role in the identification of structural and stratigraphic traps and simultaneously it is widely used to study the characteristics of a play and a prospect of a reservoir and to determine the depositional environment and the structural deformations (Chopra et al., 2007). Seismic attribute analysis is essential when studying an area with lack of well data and each attribute contributes to a specific property of a reservoir (Gnapragasan et al., 2016).

The spectral decomposition analysis in this study was introduced by Partyka in the middle of 1990s with the successful implication of short window discrete Fourier transform (SWDFT) and eventually named as (NAMED -) Spectral decomposition (Partyka et.al., 1999). The Fourier analysis enables us to view THE seismic in A? frequency domain and reveals that the higher frequency spectrum represents thinner geological features, while the lower frequency spectrum represents thicker features (Chopra et al., 2007). Features such as channels and lateral continuity of lithology can be best predicted by such techniques. The computational method in this research is based on the Gaber-Morlet complex wavelet transformation (Chopra et. al., 2013). Another technique that IS widely used to enhance the visual quality of the seismic interpretation is RGB (red, green, blue) blending. As the human eyes ARE restricted only to a certain frequency band, 400 (violet) to 700 (red) nanometers, it is vital to understand the representation of colours in the seismic interpretation, especially in the spectral decomposition analysis. This technique would be best applied during the preliminary work and would be useful for every geoscientist before diving into a deeper understanding of a reservoir and the detailed interpretation (Taner et al., 1977). The spectral decomposition and the RGB colour blending techniques are used to detect localized geomorphological features and it was proven by recent studies by Harishidayat et al. (2024), Li et al. (2024) and Nurul et al. (2023).

The instantaneous phase attribute records the beginning of the wavelets, and it suggest a trending pattern of an event; therefore, this attribute is independent of reflection strength, and it often makes weak coherent events clearer (Chopra et. al., 2007). The phase attributes are effective in showing discontinuities, faults, pinchouts, angularities, and events with different dip attributes which interfere with each other (Taner et al., 1977).

Zhang et al. (2021) managed to track horizons by integrating multiple seismic attributes and deployed instantaneous phase to map the subsurface precisely.

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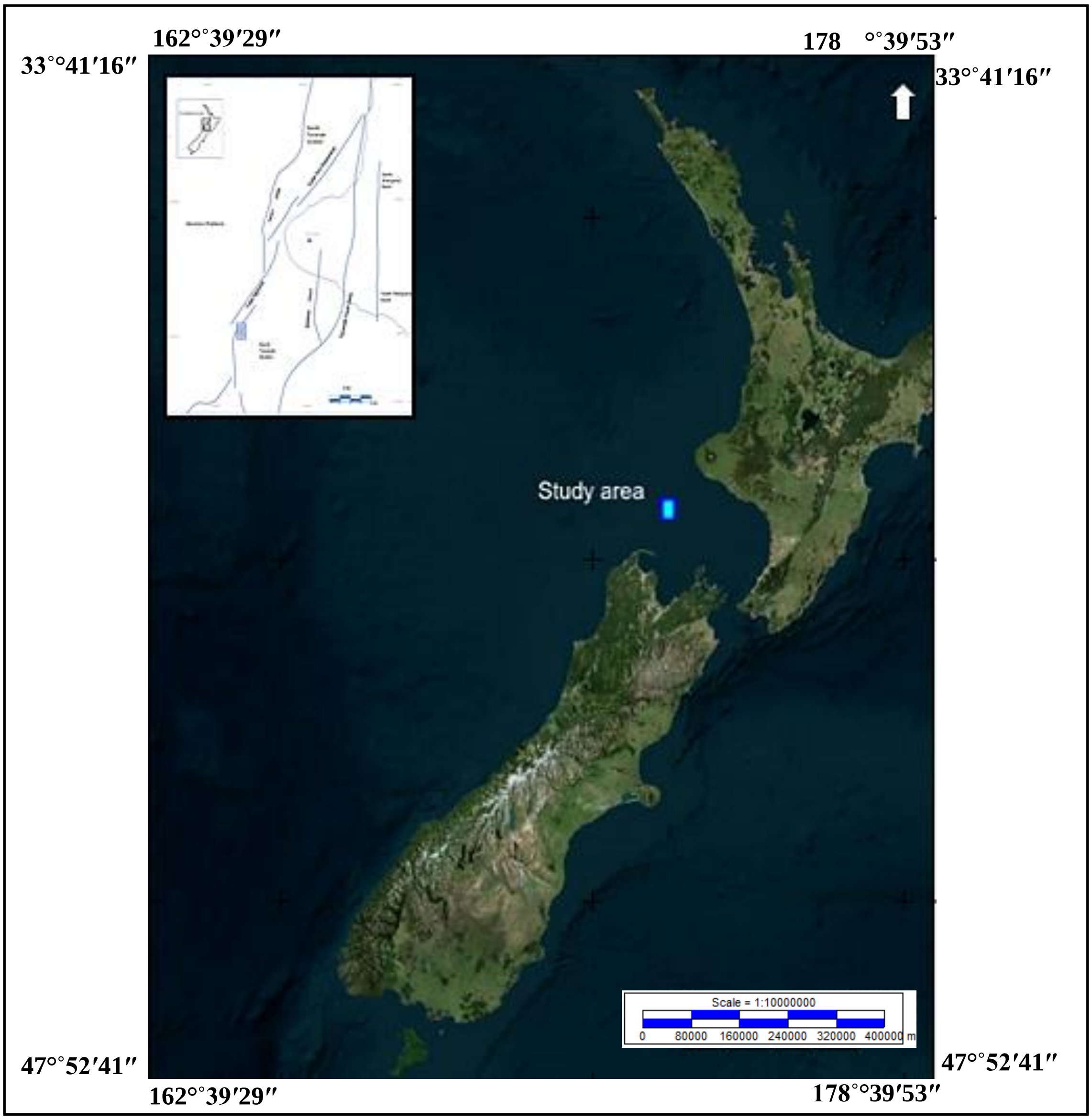


**Fig. 1** Study location of the Maari field (coloured in blue) which is, located southwest of the Taranaki Basin.

The outcome from this attribute analysis was used to merge horizon patches to create a relative geological (RGT) model. As the reflectors in this study area (do) are not continuous, computing horizons using patching techniques with instantaneous phase attribute resolves the issue. Yuan et al. (2019) used instantaneous phase to refine the horizon patches to better mark the subsurface features. In his research, the instantaneous phase proved to better delineate the subsurface and improve the accuracy of the horizon patches, hence generate generates a robust relative geological time model.

Safari et. al. (2023) used instantaneous phase to detect the displacement in the seismic that was caused by the faults. The technique involves manual faults curve extraction and blending the results with the instantaneous phase to create a model to show the displacement in a vector field. This method was eventually coded to map sedimentary layers with fault displacement automatically.

Duff and Mason (1989) mentioned that instantaneous phase is a crucial attribute to be considered when it comes to 3D interpretation. According to him the attribute is best to be used in a horizontal time slice for rapid and accurate 3D structural mapping as it enhances the continuity of the reflectivity event. It also provides the interpreter with the most precise display for directly interpreting spatial relationships with seismic sequences. Khawaja and Thabit (2022) proved that using the instantaneous phase, he manged to detect reef buildups and confirmed the existence of a stratigraphic hydrocarbon trap which was not obvious in the conventional seismic amplitude display.

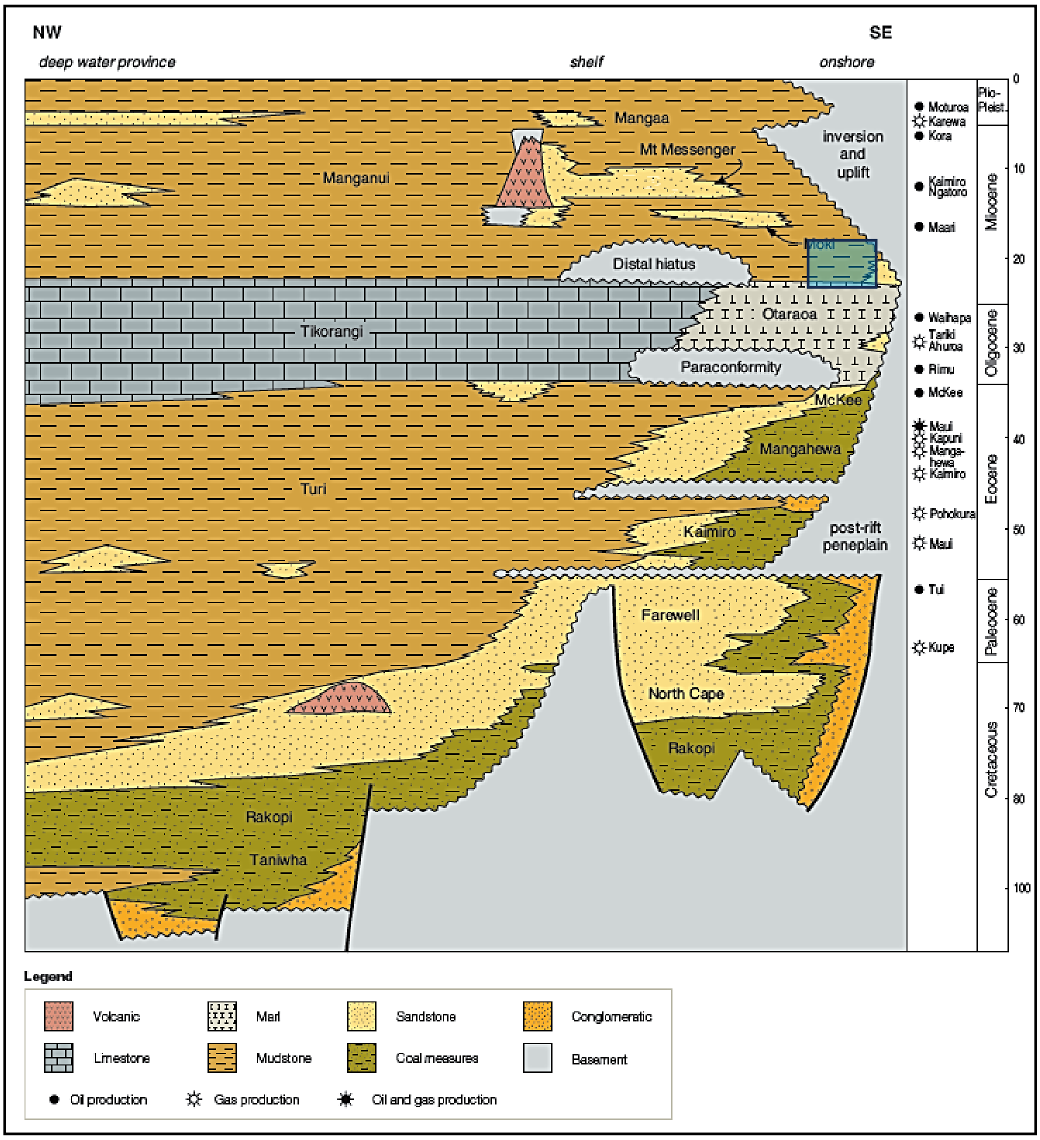


**Fig. 2** Generalized stratigraphy section of Taranaki basin with Maari well highlighted in blue, penetrates the Moki formation (Mid-Miocene). Source: Grahame (2015).

## STUDY AREA

Maari Oil field is one of the producing fields which is located 80 kilometres off the coast of South Taranaki, New Zealand (Fig. 1). The production of this field comes from a reservoir located at the Moki (Miocene) and Mangahewa (Eocene) formations (Palmer and Bulte, 1991). The structural trap of the reservoir was identified as a 4-way dip closure at the depth of 1300 meters. The field is located at the axis of the basin and currently it is in the oil production stage (McBeath, 1977).

The basin started to evolve during Cretaceous time when the sea floor started to spread around 75 Ma ago and created the Tasman Sea which separates the continents Australia and New Zealand (King, 2000). The stratigraphy records show the basin was deposited with thicker sediment ranges from Upper Cretaceous to Recent, sited on top of Palaeozoic and Mesozoic basement rocks (Palmer and Bulte, 1991).

Taranaki basin underwent an extensional phase during Late Cretaceous – Early Tertiary time and it created normal faults with half grabens which is an essential factor in creating a basin depocenter (Palmer and Bulte, 1991). The oldest sedimentary rock of Pakawau group is dated as Late Cretaceous – Paleocene. On top of this group sits the Kapuni group sediment which was deposited during Early Paleocene to Early Oligocene (Fig. 2). Studies show that the Kapuni group was distributed widely in the Taranaki basin, and it reached a thickness of 2000 m in this basin. The depositional environment indicates terrestrial and paralic characteristics with some transgressive marine siltstone, coal and some back-beach lagoon.

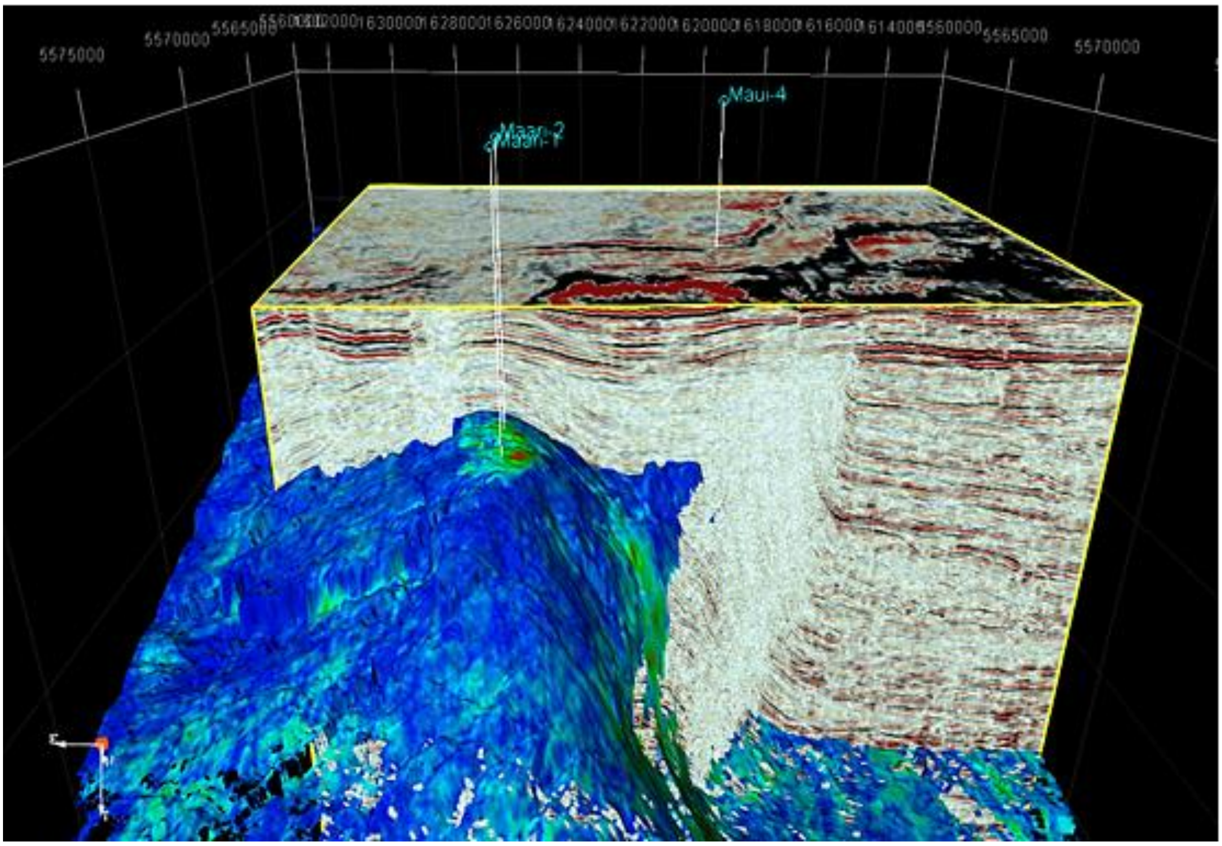


**Fig. 3** A 3-Dimentional view of the dome structure near Maari field with the Maari fault which is trending NE-SW.

Western platform and Southern Taranaki Basin are two zones within Taranaki basin that have been through relatively different tectonic events. Both zones are divided by two major faults, Maari and Cape Egmont faults with a maximum throw along the fault zone that can reach up to 2100 meters (Pilaar and Wakefield, 1984). The western platform is located west of Maari fault (Fig. 3) and extends westward up to the continental shelf edge (Reilly et al., 2014). This zone was affected by Late Cretaceous to Eocene margin block faulting. The accumulation of sediment in this area ranges from 2000 to 5000 meters. Western platform is also known for its simple and broad structures (Palmer and Bulte, 1991), and on the other hand the southern Taranaki Basin structures are composed of steep, subparallel, normal and reverse faults (McBeath, 1977). The Southern Taranaki basin has been involved in several tectonic events from Cretaceous to Palaeocene (~ 80-55Ma) normal faulting, Oligocene to younger Oligocene contraction (<~34 Ma) and Plio-Pleistocene (3.7 -0 Ma) extension (Reilly et at., 2014).

The methods comprise into two parts, which is are creating spectral decomposition attributes and choosing the right spectral range to create RGB blending. The second part of the step is to co-blend the RGB blend with the instantaneous phase to achieve precise and accurate results in the spectral analysis studies (Fig. 4). The project is based on a 3D survey approximately around 590 km$^2$ with 3 wells on the at a structurally high location. The 3D seismic data was received from New Zealand Petroleum and Minerals (2017) for research purpose. This is 2 ms sample interval data, and the record lengths are around 5.998 seconds. The seismic data went through a conditioning process before the spectral analysis and horizon interpretation. Once the Spectral decomposition attribute is created, the chosen spectral frequencies are assigned to the respective colours (red, green, blue) and the RGB blending was eventually used to enhance the features of the subsurface events. RGB is one of the false-colour image techniques that resembles the multicolour optical images which is were acquired by the remote sensing or satellite imagery method (Chopra et. al., 2007). Normally, the selected time slices will be flattened according to the targeted zone, however, for this workflow, after the amplitude horizon has been interpreted, 3 different attributes are extracted using the horizon extraction method using the Kingdom Software.

The extractions are based on 3 Spectral horizons, namely 13.3 Hz, 28.8 Hz and 61.9 Hz. These 3-frequency range ranges were chosen based on the optimal frequencies of the subsurface. Apart from enhancing the subsurface features, the RGB image provide provides detail detailed information of the

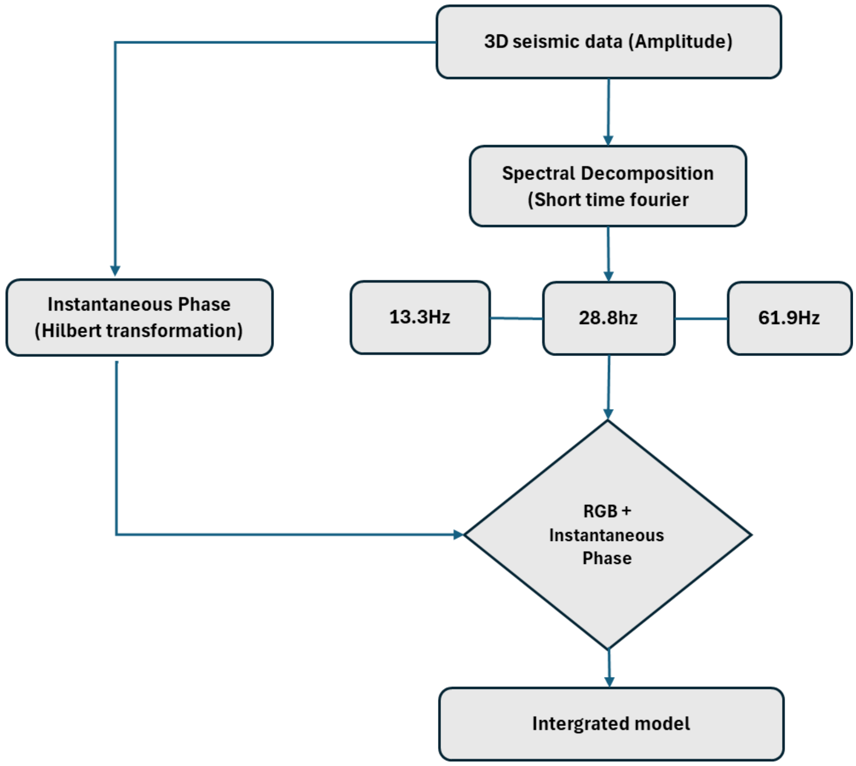


**Fig. 4** The flowchart outlines the workflow for the data processing and attribute creation. First, the 3D amplitude seismic is decomposed and 3 main frequencies are identified. Then, these frequencies were co-blended using the RGB method. Simultaneously, an instantaneous phase attribute is created from the 3D amplitude seismic and is co-blended with the RGB model to create an integrated display.

reservoir characteristics, such as thickness, stratigraphic features relating to onlap, downlap, toplap, sequence boundaries, and other seismic stratigraphic features (Gnapragasan et al., 2016). The Spectral decomposition is also used to study the resolution of the seismic and to analyse the resolved or unresolved phenomena (Sherrif, 1997).

## DATA CONDITIONING

The 3D seismic data needs to be conditioned before creating a 3D spectral volume. For spectral analysis, the data should be at least zero phase, and it is strongly recommended not to use any spiking deconvolution as it might reshape the original wavelets (Gnapragasan et al., 2016). The seismic data for this project is nearly zero phased and it was sampled using Nyquist Frequency (Fig. 5).

The conditioning enhances the signal quality, reducing reduces noise and reveals the most reasonable representation of the geology. This is the most crucial part for interpreters to determine reservoir characteristics and identify subsurface features. Apart from this, 3D post-stack seismic data conditioning and several other data conditionings have been applied to get a better result. Bandpass filter (8-12-80-24) Hz has been applied to the amplitude volume to condition the data. The main use of the bandpass filter is to eliminate waterborne noises which occur at the lower frequencies, including sounds from ships, offshore instruments and other noises which travel through the water. Some frequencies which are released from the seismic recording instruments have higher frequency seismic waves. Another common higher frequency would be the signal attenuation while travelling from water to sediments (Yilmaz, 2001).

## SPECTRAL DECOMPOSITION ANALYSIS

Upon completion of horizon picking on a 3D amplitude, spectral decomposition volumes are generated using a computational method within the Kingdom software. There are several algorithms which can be used to create the spectral decomposition volumes, the simplest would be the discrete Fourier Transform, followed by the continuous wavelet transform, the S-transform and the matching pursuit decomposition. The SD technique in this paper creates an output envelope of amplitudes based on the frequency bands that were assigned. The output focuses on monitoring amplitude variation throughout the different bands. The 3D seismic SD volumes were decomposed using Octave scale to have a similar wave pattern (Fig. 6). After creating an amplitude attribute map, three main spectral decomposition attribute maps are generated using horizon extraction method within the software as follows, 13.3 Hz (red), 28.8 Hz (green) and 61.9 Hz (blue).

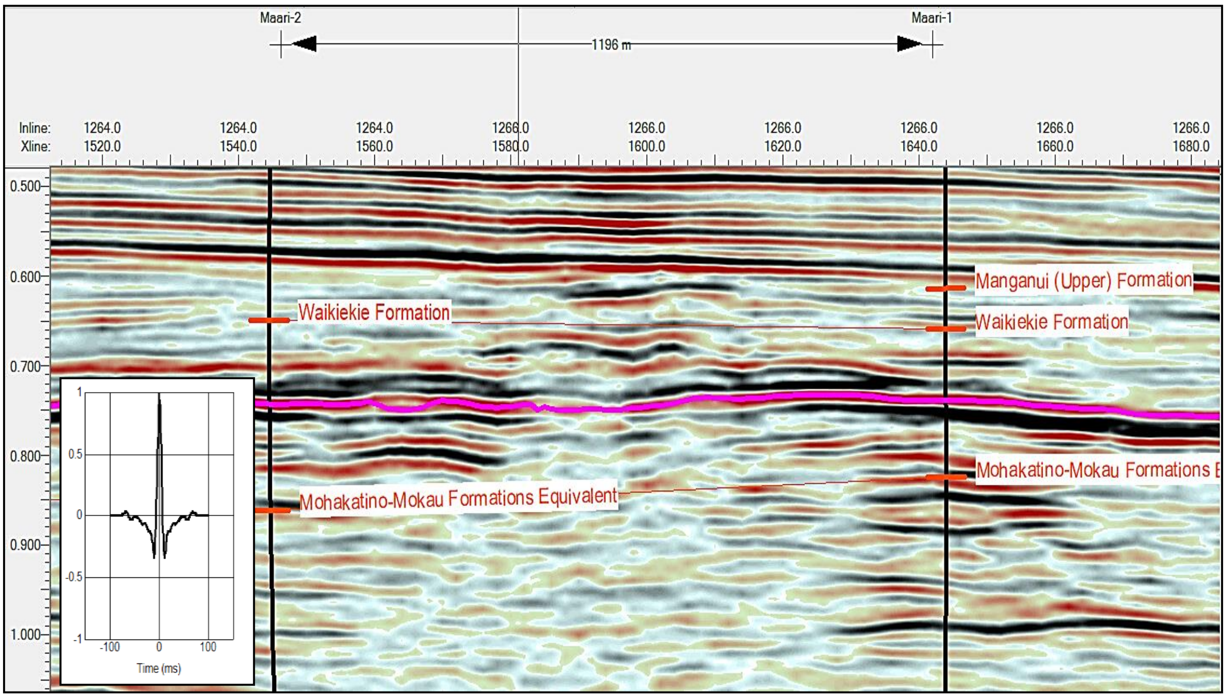


**Fig. 5** The zero phase wavelet extracted surrounding Maari-1 well. The zero phase wavelet shows higher energy at time zero.

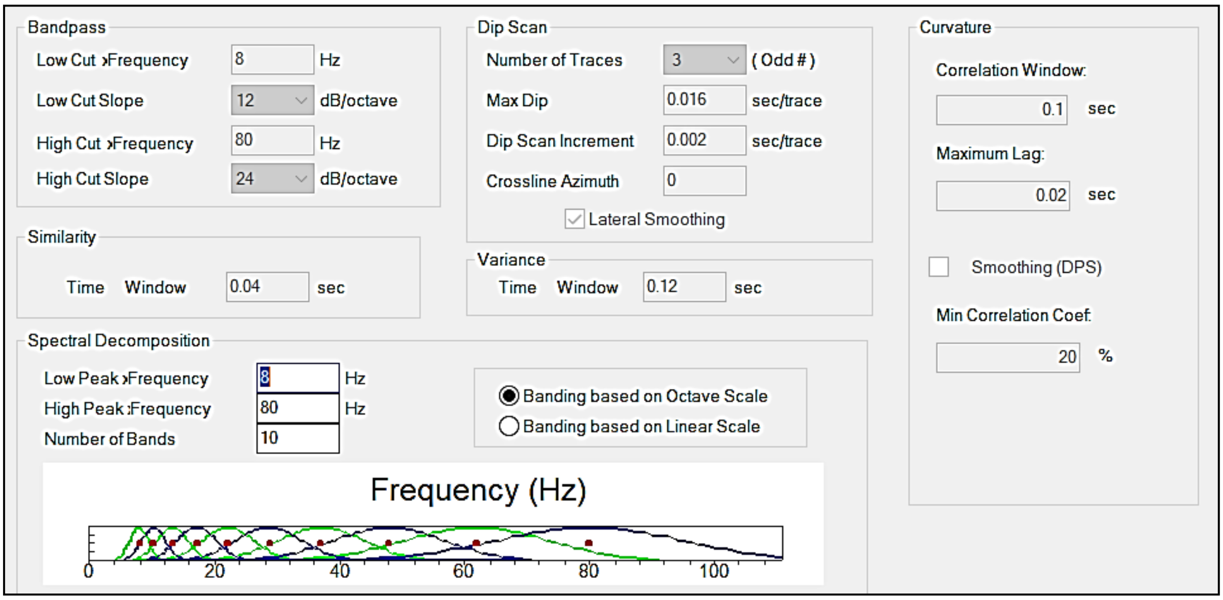


**Fig. 6** Spectral decomposition analysis on the 3D seismic amplitude data type. A bandpass filter was applied to the data. The 3D seismic was decomposed using Octave scale to create 10 different volumes.

## RGB BLENDING

Now, with the extracted Spectral decomposition, the three frequency layers represent the RGB colours co-blended with one another to achieve the hue, lightness, and saturation levels. Based on the cubic colour model (Fig. 7), the three corners which represent red, green and blue are the basic colours which can be easily detected by our naked eyes. From these 3 colours there are A? few other colour combinations that create the hues. Taking the model as a reference, the saturation of the colours tells the presence of the frequency range at a specific location on the survey area. Foran example, when all three colours are present, the specific point will be highlighted in a brighter colour compared to the darker ones.

When these 3 spectrums merge with an equal opacity range, it will create a lighter colour hence it represents the subsurface features much more clearly. With a specific frequency that represents each colour

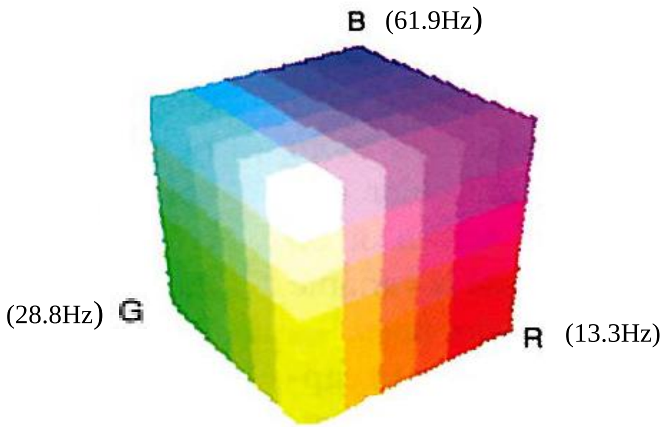


**Fig. 7** The RGB (red, green, blue) colour model which is widely used in the electronic industry such as TV screens and computer monitors. Modified after Chopra and Marfurt (2007).

code, it is much easier to see the spectrum variations and interpret changes in the bed thickness and frequency variations.

**INSTANTANEOUS PHASE ANALYSIS**

Instantaneous phase attribute is independent of amplitude and makes it possible to identify geological features that may not HAVE been seen or identified by the amplitude data. The ability of the AN? instantaneous phase can be used to map complex structures and angularities more clearly than then standard reflectivity data (Bacon et al., 2003).

The instantaneous phase $\theta(t)$ in seismic interpretation is derived from the analytic signal, which is a complex signal (1) formed by combining the real (original) seismic trace $f(t)$ and the Fourier series $f^*(t)$ (Taner et al., 1979).

The complex trace $F(t)$ is described as below.

$$(t) = f(t) + jf^*(t) \tag{1}$$

$f(t)$ = Real part
$f^*(t)$ = Imaginary part

The real seismic trace $f(t)$ can be expressed in the form of time dependent amplitude A(t) and time dependent phase θ(t) as per below equation (2),

$$f(t) = A(t)\, cos\, \theta(t) \tag{2}$$

Whereas the quadrature trace (imaginary part) $f^*(t)$ can be written as (3),

$$f^*(t) = A(t) \sin \theta(t), \tag{3}$$

Now, the complex trace $F(t)$ is written as (4),

$$F(t) = f(t) + jf^*(t) = A(t)e^j\theta(t) \tag{4}$$

If the $f(t)$ and $f^*(t)$ are known, we can solve the reflection strength $A(t)$ and instantaneous phase $\theta(t)$, (5) and (6) respectively.

$$A(t) = [f^2(t)^{+f^{*2}}(t)]^{\frac{1}{2}} = |F(t)| \tag{5}$$

and the instantaneous phase is derived as below expression,

$$\theta(t) = \tan^{-1}[f^*(t) \,/\, f(t)] \tag{6}$$

As the amplitude information is suppressed, the peak and through information can be followed across a section with the constant phase of 0° and 180° and the zero-crossing phase as ±180° (Bacon et al., 2003).

**RESULTS AND DISCUSSIONS**

Three dominant frequencies, 13.3 Hz, 28.8 Hz and 61.9 Hz were identified to further investigate the subsurface features of the Maari field. The spectral at 13.3 Hz (Fig. 8) shows a thicker stratigraphic layer in the vertical seismic section with a corresponding time slice showing a significant structure interpreted as an anticline. A bright amplitude is noted on the crest of the anticlinal structure, and it starts to fade away toward the flanks. The zone of interest marked in red represents the thick and continuous layer.

Time slice of the 13.3 Hz spectrum showing shows a low amplitude reading at the southern part and a brighter amplitude towards northern area. Low amplitude reading is connected to low acoustic impedance from the sand layer, which could be caused cause by the presence of gas, and in this case, it is proven that the area we are looking at shows presence of gas and it was verified by (Singh et al. 2016).

Besides the spectral 13.3 Hz, the decomposed spectral at 28.8 Hz (Fig. 9) shows similar patterns with amplitude variation. The time slice shows a presence of gas chimney at the southern part of the survey trending NE-SW.

The highest frequency 61.9 Hz (Fig. 10), shows better separation between the gas sand with and the non-gas bearing sand. The spectral image also gives us an indication that the layers at the southern part of the basin are most likely a gas prominent reservoir, marked by the dotted line.

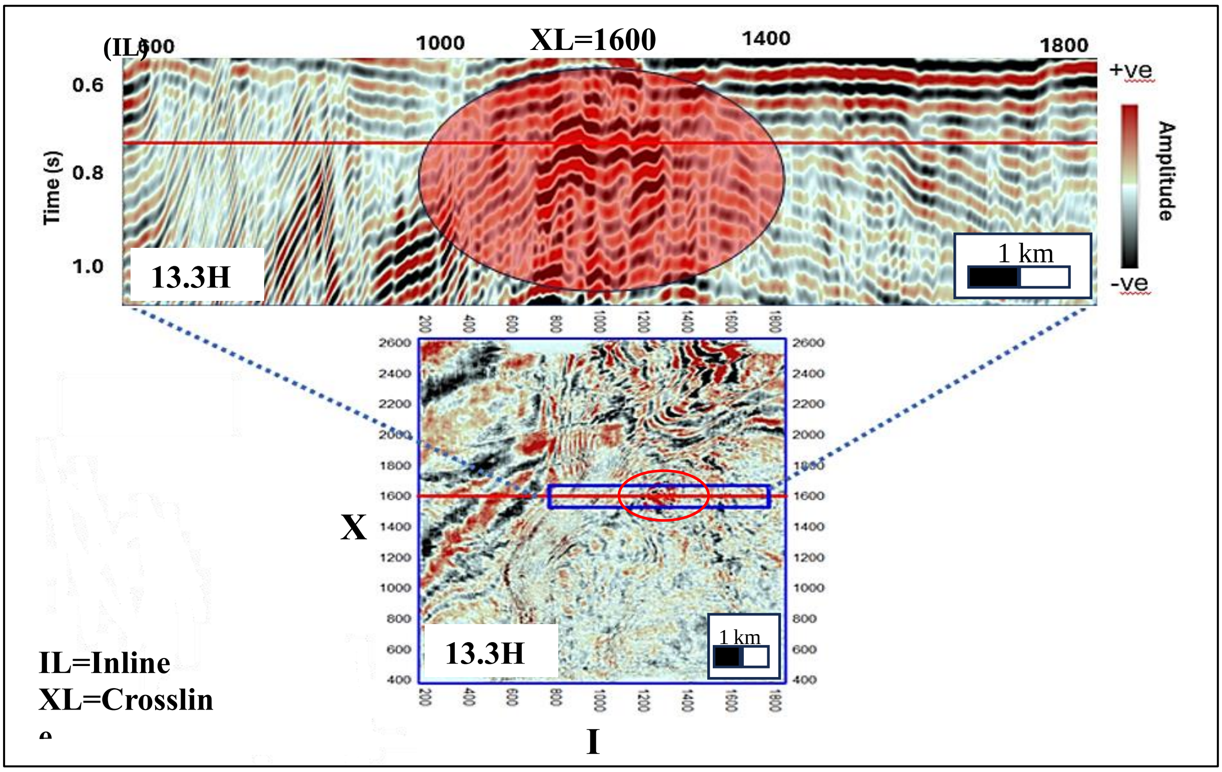


**Fig. 8** The frequency spectrum at 13.3 Hz highlighted an area of interest on the vertical section as well as the time slice at 0.75 s below the vertical section. The time slice points at (red circle) the bright anomaly which is represented on the vertical section with thick continuous layers.

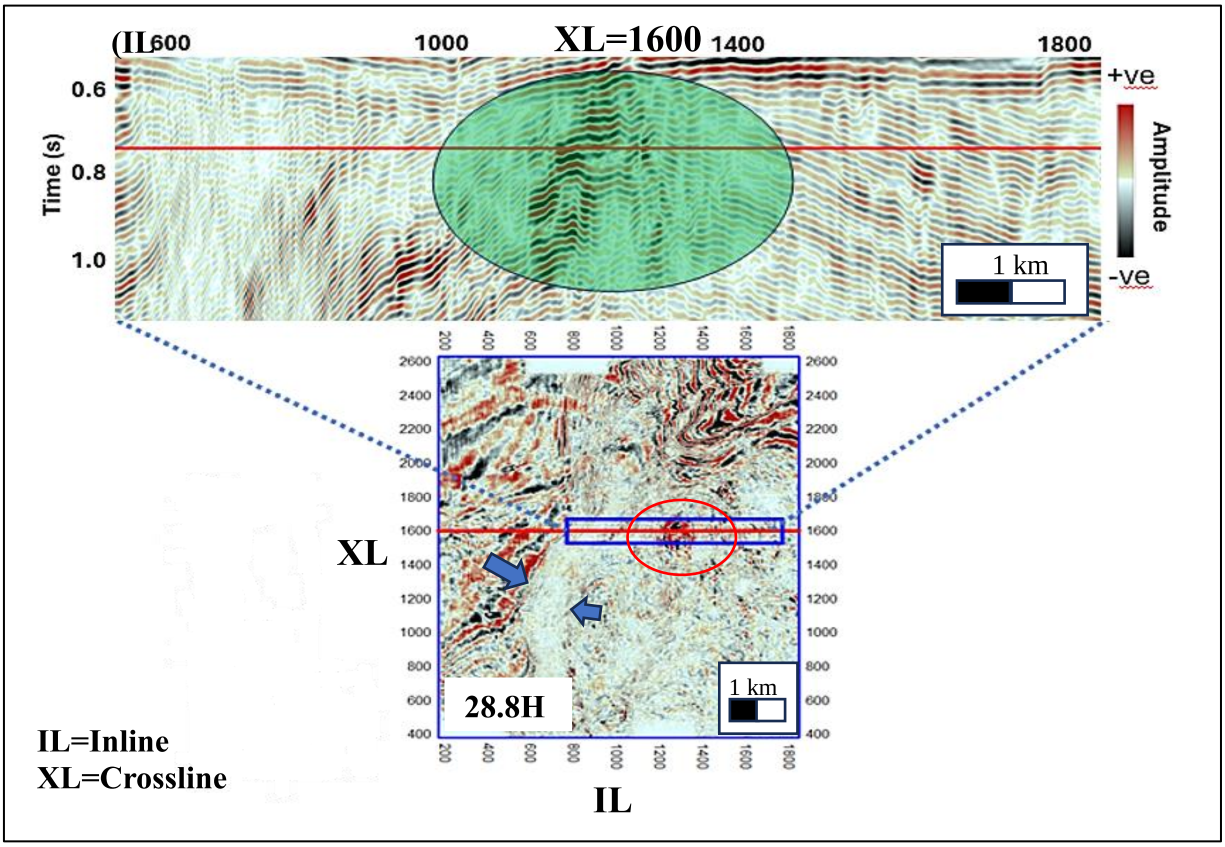


**Fig. 9** Frequency spectrum at 28.8 Hz highlighted an area of interest on the vertical section as well as the time slice below the vertical section. Blue arrows indicate a gas chimney at the southern part of the survey.

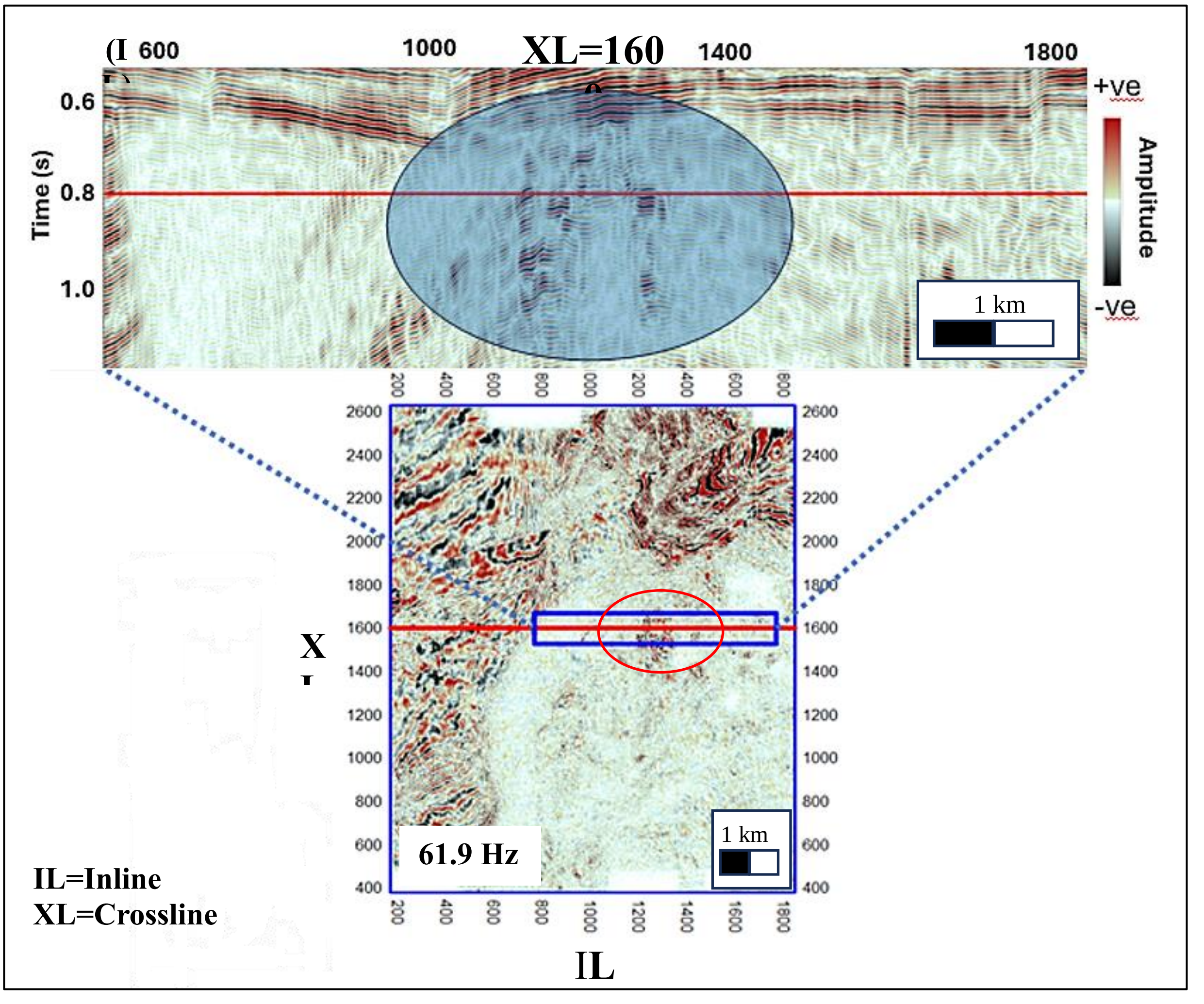


**Fig. 10** Spectral decomposition at 0.75 seconds with frequency at 61.9 Hz. The changes of the amplitude at Southeast indicate the thin layers with probable hydrocarbon presence.

**Table 1** Showing the thickness of the targeted reservoir at each frequency stage. Average velocity has been used to calculate the thickness of the reservoir.

| Frequency (Hz) | Thickness (m) | Velocity (m/s) |
|---|---|---|
| 13.3 | 65.58 | 3489 |
| 28.8 | 30.29 | 3489 |
| 61.9 | 14.09 | 3489 |

After comparing the three frequency spectrums, the lower frequency spectrum shows brighter features on the seismic vertical profile, however on the time slice the features are stand out less compared to other frequency ranges. This could be due to the thickness of the reservoir sand as the frequency at this depth is well resolved. There are some possibilities that the bright amplitude represents the presence of hydrocarbon, and this is due to the association of the low frequency readings with hydrocarbon (Castagna et al., 2003). Given that the seismic displays a pull-up feature, the highlighted feature on the vertical section also denotes a chimney.

Based on the thickness calculation, all 3-frequency data have been converted to thickness using the formula below, and the depth details have been recorded in Table 1.

Thickness,

$$h = V/4f \tag{7}$$

V = Average velocity of a seismic data
f = Frequency of the seismic data

The frequency 28.8 Hz indicates a flat spot (DHI) on the seismic section; however, we may need to confirm the presence of hydrocarbon with well log data. The continuity of the amplitude remains the same in this spectral data, however it started to show some discontinuity below 0.75 s. At this point one the assumption was made that the reservoirs are not heterogeneous.

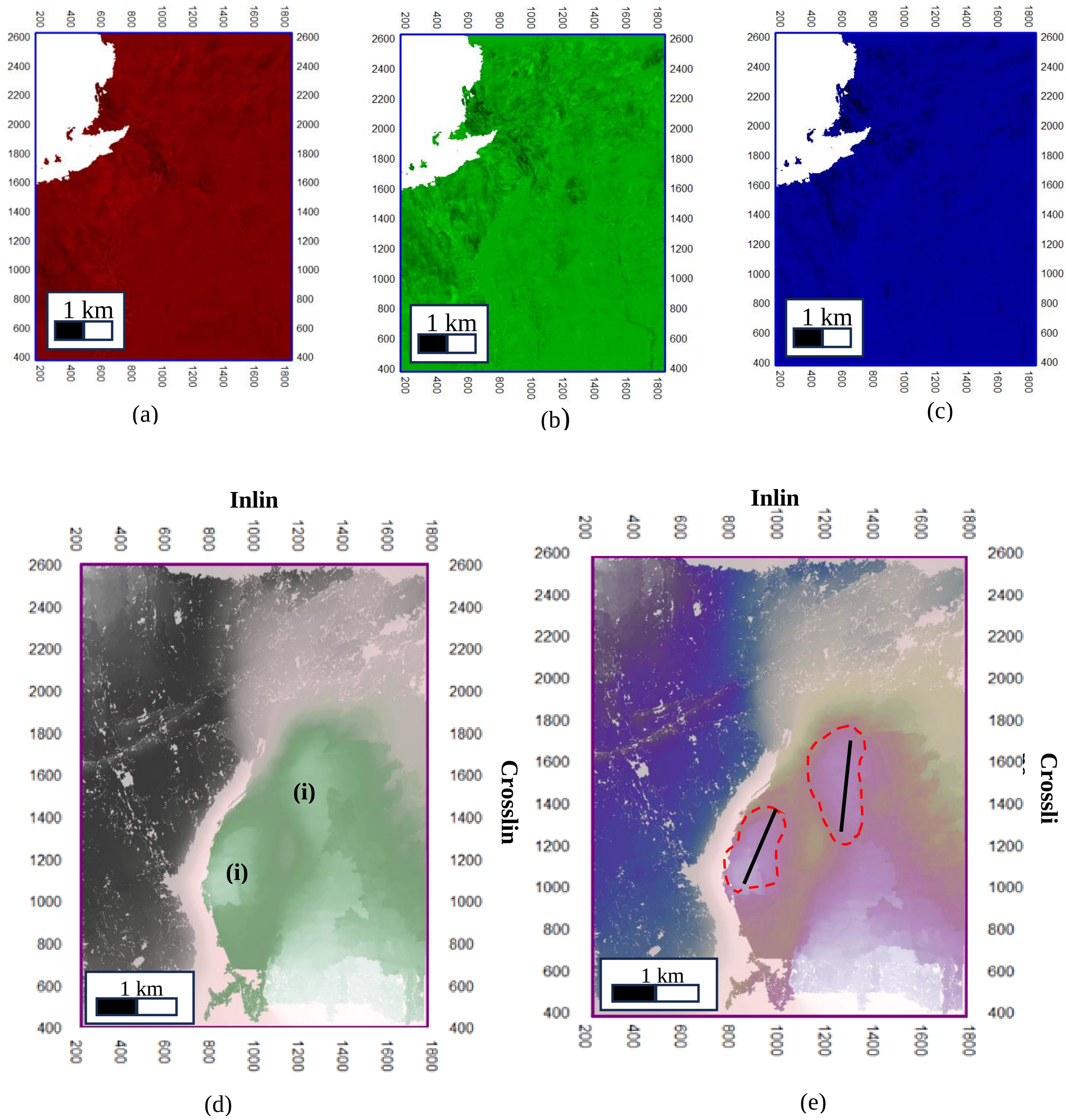


**Fig. 11** RGB blending of the 3 spectra 13.3 Hz (a), 28.8 Hz (b) and 61.9 Hz (c). Combination of these 3 spectra (d) shows more prominent subsurface features such as anticlines (i), channels (ii), and the reservoir thickness. The Combination of an Instantaneous phase and the RGB blending is shown in Figure (e), which indicates the lateral changes in the reservoir characteristics.

At the higher frequency of 61.9 Hz, the vertical section tends to show some thin bed tuning (Fig. 10). The spectral variation tends to show very strong amplitude change from a bright to a dim spot mainly affected by the lithology and the possible presence of hydrocarbon (Oumarou et al., 2021). The red dotted line marks the presence of a brighter amplitude at NW and a dimmer amplitude at SE.

The vertical seismic profile shows a poor continuity of the reservoir sand at the frequency 61.9 Hz. This phenomenon can be verified against the frequency 28.8 Hz, where the reservoir is considered heterogeneous. However, based on the time slice, the lateral extent of the reservoir could not be calculated properly therefore, it would be best to overlay an instantaneous phase attribute to verify the extend.

The completed RGB blending was colour coded which 3 optimal frequencies 13.3 Hz, 28.8 Hz and 61.9 Hz reveal most of the characteristics of the Maari field (Fig. 11). Most of the channels are trending towards NE-SW and two main anticline features were identified using the spectral decomposition method.

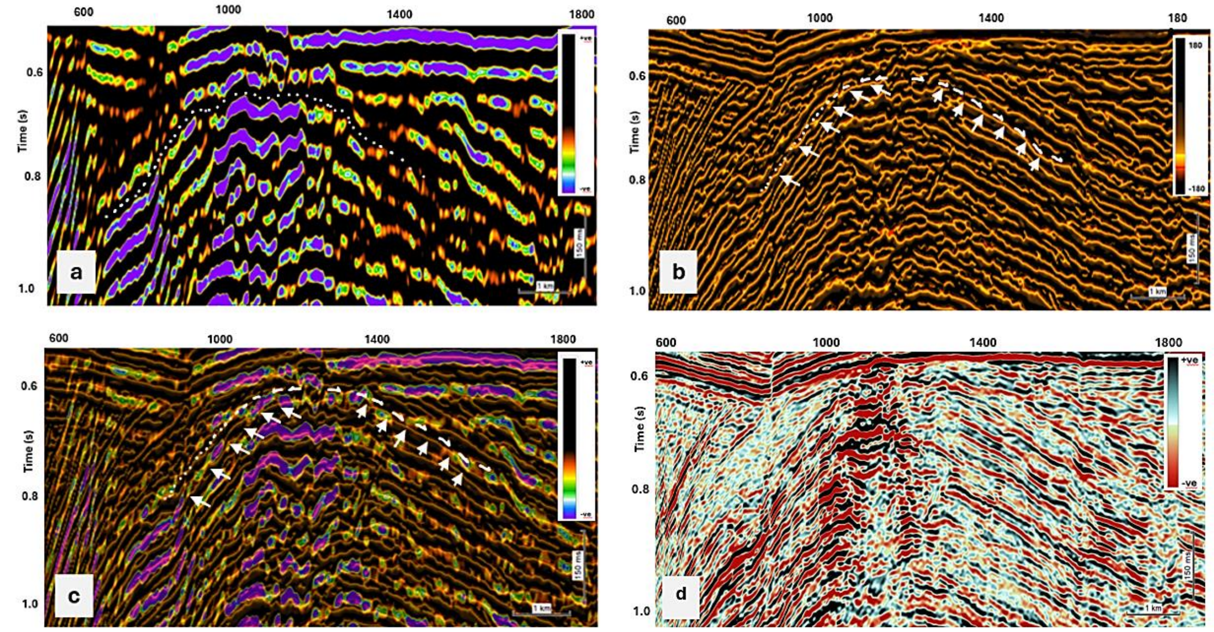


**Fig. 12** The progression pattern of a layer using co-blending technique. (a) Spectral decomposition attribute, (b) Instantaneous phase attribute, (c) Co-blending of spectral and instantaneous attribute, (d) Original amplitude data.

The prominent structures are located at the NE part of the survey. When combing the three spectra in RGB, we can find A similar structure at the SW part of the survey. Instantaneous phase attribute was incorporated into to the study to enhance the lateral extend of the reservoir.

The attribute analysis result of the instantaneous phase shows a bright event (orange colour) indicating the location of zero-crossing with the phase of ± 90°. The image 12 (b) shows events which is follow the zero-crossing marked by the upward arrows and the layers trending with downward arrows. Such event is not easily marked in the original amplitude data 12 (d).

## CONCLUSIONS

Spectral decomposition enhances seismic interpretation by providing geoscientists with a deeper understanding of subsurface features. This technique is particularly useful for delineating the lateral continuity of reservoir bodies. Given that true isotropic reservoirs are exceedingly rare, it is essential that seismic interpretation methods emphasize reservoir heterogeneity and leverage the latest technology to quantify these variations. Spectral decomposition is one of the many advanced techniques employed by geoscientists today. Alongside it, instantaneous phase analysis plays a crucial role in the reservoir characterization workflow. Integrating spectral analysis with rock physics, which utilizes well log data to assess reservoir characteristics, further refines our ability to predict hydrocarbon presence.

Instantaneous phase attribute is deployed in the seismic interpretation to identify the structural traps; however, it can be a useful tool to detect seismic stratigraphic events such as onlaps, down laps, unconformities and truncation reflections. As the wave front of the instantaneous phase represents constant reading along the boundary of the reflection, it can be used in the seismic interpretation to discriminate geological features and trace the lateral continuity of a reservoir. Co-blending spectral decomposition and instantaneous phase is managed to classify two possible reservoirs, A and B with the thickness of around 65 meters with the lateral extending from 5000-6000 meters. The future work of this research is to work on geometrical and wavelet attribute sand create a best match to identify the complex structures.

The structures in the Maari field are considered as structural traps, however the challenge is in identifying the boundary of the structures. Based on the interpretation, the seismic at this location shows poor horizontal quality and this might be due to processing effects and gas leakage at the crest on the anticline, however using instantaneous phase we managed to identify the precise reflection boundaries and the reflection terminations of the layer.

## AUTHOR CONTRIBUTIONS

Joseph Gnapragasan: Conceptualisation, writing-original draft preparation, investigation, and methodology.

Andy Anderson Bery: Supervision and Resources.

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