Phase Decomposition Analysis for Hydrocarbon Exploration: A Case Study

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Keywords

Phase decomposition, Matching Pursuit, Seismic, CWT, Thin layers, Phase, Spectral decomposition

Abstract

Seismic data analysis plays a crucial role in understanding subsurface structures and predicting the behaviour, heterogeneity of geological formations. However, interpreting seismic data can be challenging due to the complex nature of the recorded waveforms. Phase decomposition has emerged as a powerful technique for enhancing seismic data analysis by extracting valuable information embedded within seismic signals.

Any seismic trace can be decomposed into a 2D function representing the amplitude-time and phase relationships. This process is known as phase decomposition, which separates the seismic data into phase components that describe the amplitude variations over time for specific seismic phases. Phase components simplify the analysis when interpreting seismically thin layers. Subtle lateral changes in impedance within these thin layers can be amplified in their seismic expression when isolated phase components are examined.

When assuming a zero-phase wavelet, features such as flat spots and unresolved water contacts may be directly visible on the zero-phase component. Similarly, thin beds and impedance ramps are observable on components that are 90° out of phase with the wavelet. Bright spots caused by hydrocarbons in thin reservoirs, occurring when the reservoir has a remarkably low impedance, can be assumed to appear on the component that is -90° out of phase with the wavelet. However, other phase components associated with bright reflection events, resulting from different impedances above and below the reservoir, may obscure the hydrocarbon signal. Therefore, interpreting bright spots is greatly simplified on the -90° phase component, assuming a zero-phase wavelet.

This paper provides an overview of phase decomposition and its application in seismic data analysis of the Tapti Daman, a hydrocarbon-prone area. The challenge in this area is to map thin hydrocarbon-bearing sands having very low impedance contrast.

Introduction

The study area is situated in the Western Offshore Basin (Fig 1) and is covered by 3D seismic data. The primary goal of phase decomposition analysis is to identify gas-bearing sands within the multi-stack channels found in the Daman formation. In this area, the clastic rocks consist of fine sands and siltstone, displaying favourable porosity, permeability, and production behaviour. These clastics are considered highly promising reservoir facies. They were deposited in a deltaic environment with a high deposition rate, resulting in a minimal impedance contrast between the reservoir and the overlying rock. So sometimes it is very difficult to identify the reservoir through reservoir characterization in this area.

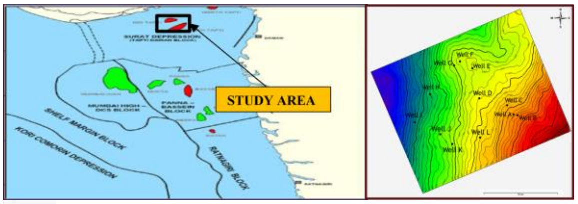

Fig 1 Location & Base Map of the study area

Phase decomposition is an innovative technique that can be utilized to break down composite seismic signals into separate phase components. This method has no relationship with instantaneous phase attributes and phase rotation. Phase decomposition technology is very much similar to spectral decomposition. As we know various techniques have been developed for spectral decomposition, including the Continuous Wavelet Transform (CWT), Matching Pursuit (MP), Hilbert transform, and Stockwell transform. Each technique offers unique

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advantages and limitations, and their selection depends on the specific goals of the seismic analysis.

Phase decomposition technology was first introduced by Castagna et al (2016). This methodology is mainly based on the idea that a very thin layer has unique characteristics to the effects of hydrocarbon. This has been explained in Fig 2 that a reflectivity generated through brine sand is compared with a reflectivity generated after fluid replacement of hydrocarbon showing a -90^0 phase change. This effect is known as the hydrocarbon effect.

In cases where the data contains a zero-phase wavelet and thin low-impedance layers below the tuning thickness, the resulting phase waveform response after applying phase decomposition often exhibits an unusual value of -90 degrees. This distinctive phase response is noteworthy due to its abnormal nature. Conversely, a corresponding thin layer with high impedance exhibits a similar waveform response but with a phase angle of +90 degrees.

We have applied the Matching pursuit spectral decomposition method to extract phase information for our study. In our study area, 12 Wells were drilled and out of 12 Wells, 3 Wells were hydrocarbon bearing from the Mahuva formation. After phase decomposition +/- 90 deg phase stacks were generated to identify the low-impedance hydrocarbon reservoirs.

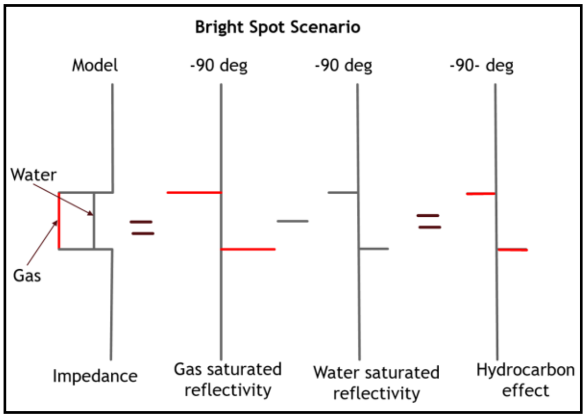


Fig 2 Shows the Gas saturated model and Water saturated Model having a -90^0 phase and the difference is also a -90^0 phase.

Theory and Method

As mentioned earlier the phase decomposition technique is very similar to spectral decomposition methods. Let's see some theoretical aspects of spectral decomposition used for this study:

1. Continuous Wavelet transform (CWT)

The continuous wavelet transform (CWT) (Jean Morlet, 1980) is a mathematical technique used for analyzing signals or time series data. It provides a way to analyze the frequency content of a signal over time with variable resolution.

The CWT uses a set of wavelet functions to decompose a signal into different frequency components. These wavelets are generated by dilating and translating a mother wavelet function. The formula for the continuous wavelet transform is as follows:

$$CWT\ (a, b) = \int [f\ (t) * \psi^*[(t - b) / a]]\ dt$$

In this formula:

CWT (a, b) represents the result of the continuous wavelet transform at a specific scale (a) and translation (b).
f(t) is the input signal or time series data.
$\psi(t)$ is the mother wavelet function.

“a” is the scale parameter, which controls the width of the wavelet function. Smaller values of ‘a’ provide better time resolution but lower frequency resolution, while larger values of ‘a’ give better frequency resolution but lower time resolution.
“b” is the translation parameter, which shifts the wavelet function along the time axis.

2. Matching Pursuit methods

Matching Pursuit (MP) is a signal decomposition method that represents a signal as a linear combination of elementary waveforms or atoms from a predefined dictionary. The MP algorithm iteratively selects atoms from the dictionary that best matches the signal, estimates coefficients to quantify their contribution, updates the residual signal, and repeats the process until a stopping criterion is met. MP aims to achieve a sparse representation where only a few coefficients are significantly nonzero.

We conducted spectral decomposition using both the Matching Pursuit method and Continuous Wavelet Transform (CWT), and our findings indicate that Matching Pursuit (MP) offers advantages in terms of sparse signal representation and adaptability. On the other hand, CWT demonstrates superior performance in terms of time-frequency localization and analyzing non-stationary signals, as depicted in Fig 3.

The frequency gathers shown in Fig 3 has been used to identify the dominant frequency or useful frequency to determine the reservoir. As we know different seismic response tune-ups differently in different phase components. By seeing frequency gather +/- 90 deg phase components have been identified.

We have also studied an instantaneous phase attribute on the spectral decomposed data set as shown in Fig 4. The information embedded in this attribute is very difficult to interpret.

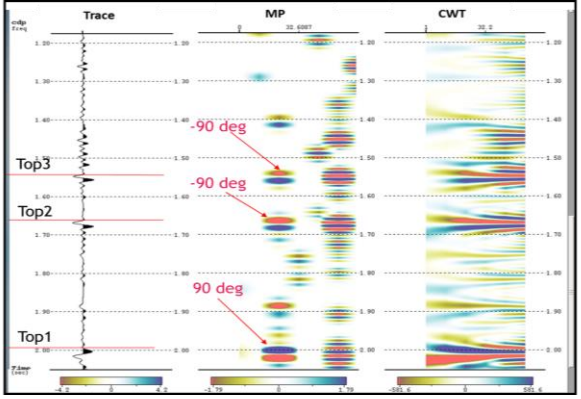


Fig 3 Frequency gather a) Matching Pursuit (MP) and b) CWT method

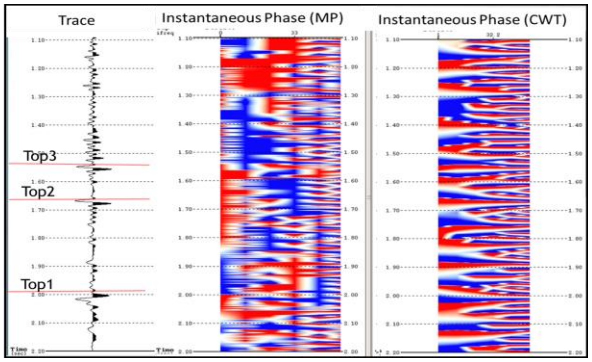


Fig 4 Instantaneous Phase a) Matching Pursuit (MP) and b) CWT method

After generating frequency gather phase filtering has been applied to generate Phase gather as shown in Fig 5. The phase gather helps us to get the desired phase amplitude stack for better interpretation. The workflow to generate phase components has been described in Fig 5a.

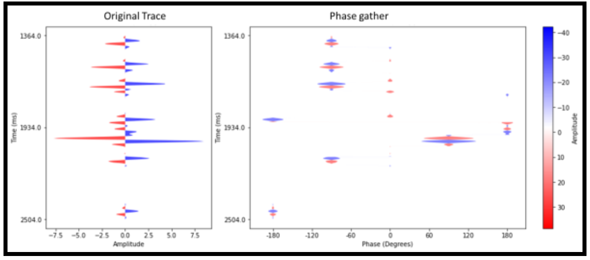
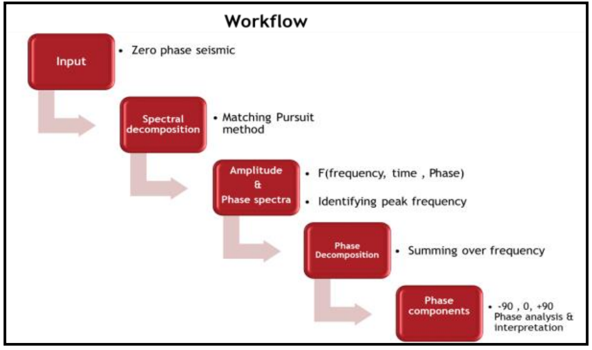


Fig 5 Phase decomposition. (a) Seismic trace (b) Phase gather



Workflow

- Input
  - Zero phase seismic
- Spectral decomposition
  - Matching Pursuit method
- Amplitude & Phase spectra
  - F(frequency, time , Phase)
  - Identifying peak frequency
- Phase Decomposition
  - Summing over frequency
- Phase components
  - -90 , 0, +90 Phase analysis & interpretation

Fig 5a Workflow applied to calculate the various phase components

Discussion and Results

In this study zero phase seismic data with SEG normal polarity convention have been used and three hydrocarbon-bearing wells were analyzed to calibrate the results. The Status of drilled Wells falling in the study area is given in Table 1.

SL No.	Well Name	Status (Mahuva formation)
1	Well A	Hydrocarbon bearing
2	Well B	Hydrocarbon indication
3	Well C	Water Bearing
4	Well D	Hydrocarbon Bearing
5	Well E	Water Bearing
6	Well F	Water Bearing
7	Well G	Water Bearing
8	Well H	Water Bearing
9	Well I	Water Bearing
10	Well J	Hydrocarbon Bearing
11	Well K	Water Bearing
12	Well L	Water Bearing

Table 1 Status of Wells in the study area

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Using the Matching Pursuit method, a seismic trace at Well A has been decomposed into different frequencies, as depicted in Fig 6. At a peak frequency of 22 Hz, dominant waveforms with a phase of -90° can be seen on Top 3 and Top 2. These waveforms are hydrocarbon-bearing. Similarly, near Top1, a waveform with a phase of +90° is visible which is water-bearing.

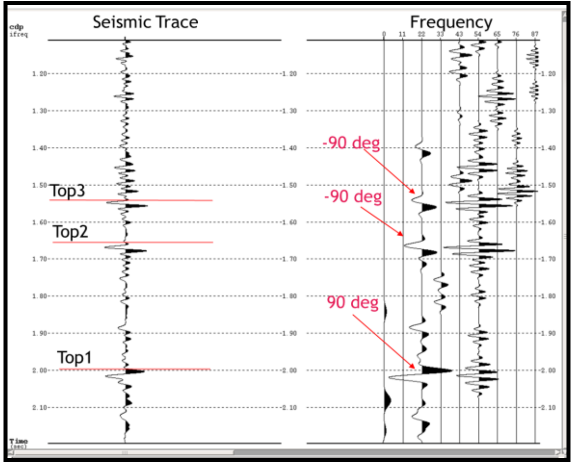

Fig 6 Spectral decompose frequency gather with +/- 90^0 Phase Components

Based on analysis at Well-A stack volumes with +/- 90° components have been generated through phase filtering. These volumes have been analyzed to segregate hydrocarbon bearing Wells from Water bearing Wells.

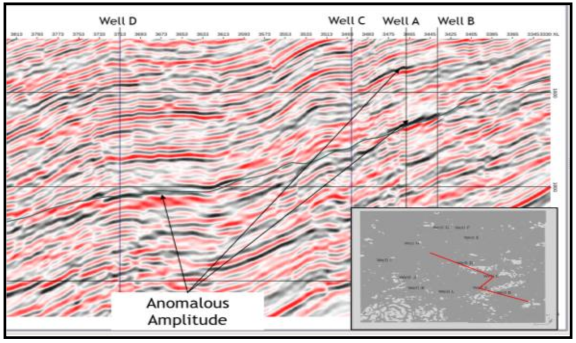

Fig 7 Zero phase Seismic section along Well D, Well C, Well A & Well B.

Fig 7 shows a seismic profile of the area showing obvious amplitude anomalies. However, not all bright events exhibit characteristic trough/peak responses, and the magnitude of anomalies varies with layer thickness. Interference with other reflections can obscure the interpretation of bright spots. By viewing only the -90° component (Fig. 8), most spurious reflections are reduced and more uniformly anomalous in amplitude, producing only events with the desired trough/peak response. The result is a very simplified and very different amplitude interpretation for detecting thin layers under tuning. Phase decomposition values are most evident in the map view as shown in Fig 10.

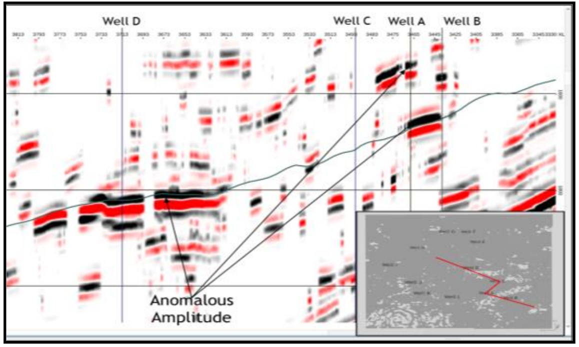

Fig 8 Spectral decomposed seismic section with -90^0 Phase components along Well D, Well C, Well A & Well B.

Fig 9 & Fig 10 are the amplitude maps extracted along Mahuva pay from zero phase full stack dataset and -90^0 component respectively. The marked zone A & B shows some bright amplitude in the map of the full stack dataset. The same anomalies traced in the -90° component (fig 10) get diluted and become very weak. The bright amplitude seen in the full stack map may be due to the wrong phase in full stack data.

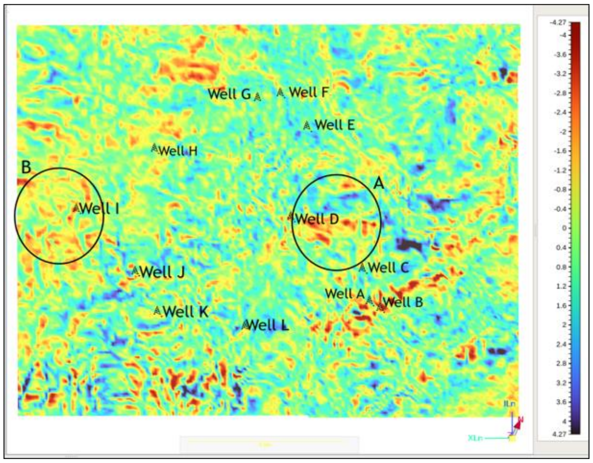

Fig 9 Amplitude map of Zero phase full stack

Some of the maximum amplitude anomalies have been appearing in the -90° component (Fig10) as compared to the full stack map (Fig 9). These anomalies may consider new prospects. The map of -90^0 components helps us in distinguishing water-bearing sand bodies from hydrocarbon-bearing sand.

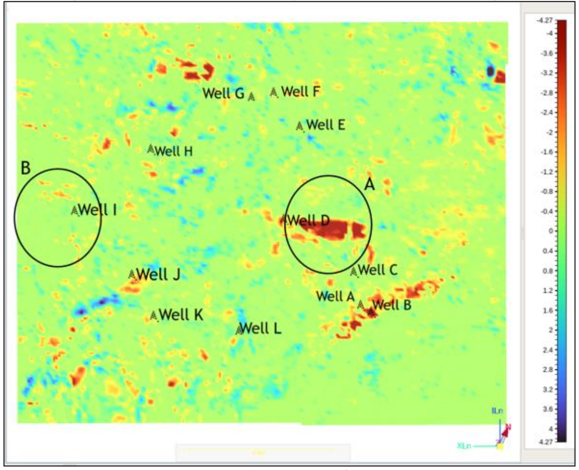

Fig 10 Amplitude map of -90^0 phase component

Conclusion

Phase decomposition analysis has proven to be a valuable technique in seismic data analysis for hydrocarbon exploration, as demonstrated in this case study of the Tapti Daman area. By separating seismic data into phase components, phase decomposition allows for the identification and characterization of subtle features such as thin hydrocarbon-bearing sands with low impedance contrast. The application of phase decomposition, particularly the use of Matching Pursuit (MP) methods, has provided insights into the presence of hydrocarbon reservoirs in the study area.

The results obtained through phase decomposition analysis have highlighted the significance of specific phase components, such as the -90° phase component, in simplifying the interpretation of seismic data. The identification of hydrocarbon indicators, such as bright spots, has been greatly enhanced by isolating the -90° phase component and assuming a zero-phase wavelet. This approach has allowed for a clearer distinction between hydrocarbon-bearing sands and water-bearing sands.

Furthermore, the comparison between the full stack dataset and the phase components has revealed the limitations of relying solely on the full stack data. The presence of wrong phase information in the full stack data can lead to misleading interpretations, whereas the phase components provide a more accurate representation of the subsurface features.

Overall, phase decomposition analysis, in conjunction with techniques like MP and CWT, offers a powerful tool for improving seismic data analysis in hydrocarbon exploration. By extracting valuable information embedded within seismic signals, phase decomposition enhances our understanding of subsurface structures and aids in the identification of potential hydrocarbon reservoirs. The insights gained from this study can contribute to more accurate reservoir characterization and ultimately improve the success rate of hydrocarbon exploration efforts in similar geological settings.

In conclusion, phase decomposition analysis has proven to be a valuable tool for hydrocarbon exploration, providing insights into thin hydrocarbon-bearing sands and improving the interpretation of seismic data. Its application has the potential to enhance our understanding of subsurface structures and optimize hydrocarbon exploration strategies in complex geological environments.

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