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Seismic Attributes Method for Prediction of Unconsolidated Sand Reservoirs of Heavy Oil

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Abstract: Heavy crude oil is known as oil that is highly viscous and of a higher density than that of conventional oil. Sand reservoirs containing heavy oil generally consist of unconsolidated sediments deposited at a shallow burial depth, with high porosity and permeability. In seismic exploration, acoustic impedance inversion is a commonly used tool in reservoir prediction. However, due to the unconsolidated characteristic of heavy oil reservoirs, the wave impedance difference between heavy oil sandstones and mudstones becomes less apparent, thus limiting the ability of impedance inversion to accurately characterize the reservoir. Therefore we must expand our characterization of the target heavy oil reservoirs to include correlation analysis of different seismic attributes to the unconsolidated reservoir thickness. The results show that there has a strong correlation between the seismic attribute value of instantaneous frequency and unconsolidated reservoir thickness, more than other seismic attributes in the target strata. Thus the instantaneous frequency attribute can be used to predict qualitatively the lateral distribution of unconsolidated reservoirs, which in turn, indicates the vertical variation of thickness for the unconsolidated reservoirs. By using frequency attributes which are sensitive to unconsolidated sediments, coupling with additional geologic information, we can predict the distribution of sedimentary facies accurately in the study area, which results in a more reliable prediction for the lateral and vertical distributions of heavy oil reservoirs.

Keywords: Heavy crude oil, reservoir prediction, seismic attributes, unconsolidated sandstone.

1. INTRODUCTION

Heavy oil, which was the conventional oil in oil reservoirs before, usually formed by the influence of secondary actions such as oxidation, water washing, biodegradation, and other physical and chemical processes. It has been defined as any liquid petroleum with an API gravity less than 20° [1]. One of the main geological factors resulting in the formation of secondary heavy oil reservoirs is that oil reservoirs kept staying at shallow burial depths throughout or have even experienced a long period of buried at shallow depths. Thus, heavy oil reservoirs are notable for the characteristics of loose cementation, high permeability, and poor diagenesis, meanwhile being found at shallow depths. With burial depth, the differences in compaction effects on mudstones and sandstones are noted. In the earlier stages, the effects of compaction are more noticeable in mudstones than in sandstones. Wave impedance in shallow sandstone is low and similar to the wave impedance of mudstone. Therefore, it is difficult to use wave impedance inversion attributes to identify mudstones from sandstones in the areas where heavy oil produced.

Seismic attributes data contain extensive geological information, and the laws reflected by seismic attributes data are usually controlled by multiple geological factors [2-6]. In recent years, with advancements in reservoir characterization methods, this combination of geological interpretation and seismic data study results in more extensive application of seismic attribute analysis in hydrocarbon and reservoir prediction [7-11].

2. MATERIALS AND METHODOLOGY

The study area is relatively large, for a total area of about 5500 km^2, and covered with 2-D seismic lines. The 2-D seismic data are obtained in batches with field productions through about 50 years, with the spacing between lines is 1 km and line spacing near the boundaries of the study area is 2 km. Additionally, there is about 37 km^2 of 3-D seismic survey acquired inside the study area. Because the 2-D line spacing is large, there is substantial distance between the well locations and seismic lines. Therefore, for the correlation analysis of seismic attributes to reservoir properties, we use the 37 km^2 3-D data and well data within it to obtain the correlation, identify the seismic attributes which are sensitive to heavy oil reservoirs, and then extend these results to the widely qualitative reservoir prediction in the whole area.

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Table 1. Correlation coefficient between seismic attributes and reservoir thickness.

Average Instantaneous Frequency	Average Instantaneous Phase	Average Amplitude	Maximum Trough Amplitude	Gradient Amplitude
-0.698	-0.590	0.457	0.147	-0.207
Reflective Energy	**Absolute Amplitude**	**RMS Amplitude**	**Total Energy**	**Reflection Energy Slope**
-0.130	0.104	-0.14	-0.080	0.147

We choose the seismic attributes that are not relevant to each other and then analyze the 3-D seismic attributes for correlation to reservoir thickness at the well location (Table **1**). The results show that there has a strong negative correlation between the instantaneous frequency attribute and the sandstone thickness, with a correlation coefficient of -0.698 (Fig. **1**).

The average instantaneous frequency is defined as the derivative of the instantaneous phase.

$$W(t)=\frac{d\theta(t)}{dt} \tag{1}$$

where w(t) is the average instantaneous frequency, θ represents instantaneous phase, t represents time. In general, the instantaneous frequency attribute mainly reflects the degree of seismic wave energy attenuation. It has been used to identify gas accumulation zones and the low instantaneous frequency attribute zones; to determine the thickness of sediments; and to identify sudden changes such as pinch-outs and oil-water contacts. In fluids-bearing rocks, the attenuation of seismic wave energy are primarily caused by the presence of fluid viscosity and internal friction between viscous fluid and the sediments. As a result, energy is absorbed in the propagation of the seismic waves, and high frequency wave energy attenuation is strong while low frequency wave energy attenuation is weak. With higher porosity, the stronger high frequency wave attenuation occurs. Meanwhile, the viscous properties of fluid in the pores also have a strong influence on high frequency seismic wave, resulting in greater attenuation. Thus the frequency attributes of seismic waves can provide insight to the reservoir and fluid characteristics. Due to higher porosity and strong fluid viscosity, seismic waves are usually subject to more high frequency attenuation in unconsolidated reservoirs [12-15]. Therefore the frequency attributes of the seismic wave are very sensitive to reservoir detection in unconsolidated sediments [16-19].

Due to the 2-D nature of the data, the seismic attribute data obtained from frequency analysis must be interpolated for use in the whole field. We compared these interpolated frequency attribute values to the reservoir thickness at the well location, and plotted the average instantaneous frequency attribute values against the sandstone thickness values interpreted from well log data for the three formations of interest in the field, denoted Formation A, Formation B, and Formation C. This crossplot is shown in Fig. (**2**).

From Fig. (**2**) we can infer that:

(1) The instantaneous frequency attribute and reservoir thickness show a strong negative correlation. As the seismic instantaneous frequency attribute values decrease, reservoir thickness increases. This correlation persists until the instantaneous frequency attribute value reaches a minimum threshold, whereupon the reservoir thickness becomes zero;

(2) The distribution of the seismic instantaneous frequency attribute values correlate to the characteristic thickness of the reservoirs in different formations. Formation A contains instantaneous frequency values in a wide range of distribution (30 Hz-90 Hz), which corresponds to a reservoir thickness variation of a wide range (0.5 m-11 m); Formation B shows a narrower instantaneous frequency distribution of 48 Hz-62 Hz and subsequently narrower reservoir thickness range of 0.8 m-7.5 m; Formation C contains a narrow distribution of instantaneous frequency values, in the high frequency band of 60 Hz-80 Hz, which mainly corresponds to thin reservoirs. The above results are in agreement with the changes in geological characteristics of the sedimentary environment in the study area. This attribute analysis demonstrates that

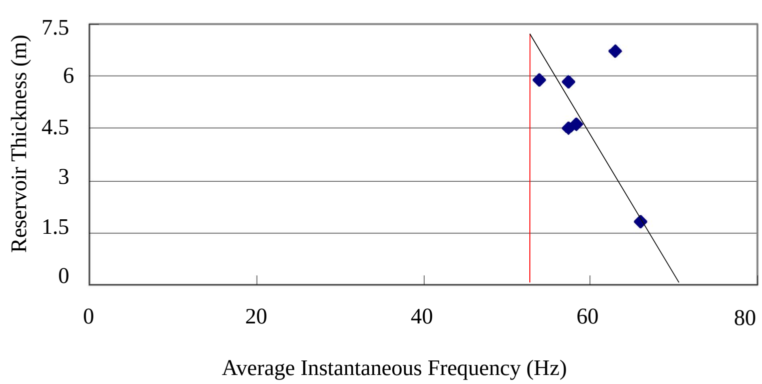


Fig. (1). Relationship between average instantaneous frequency values and reservoir thickness.

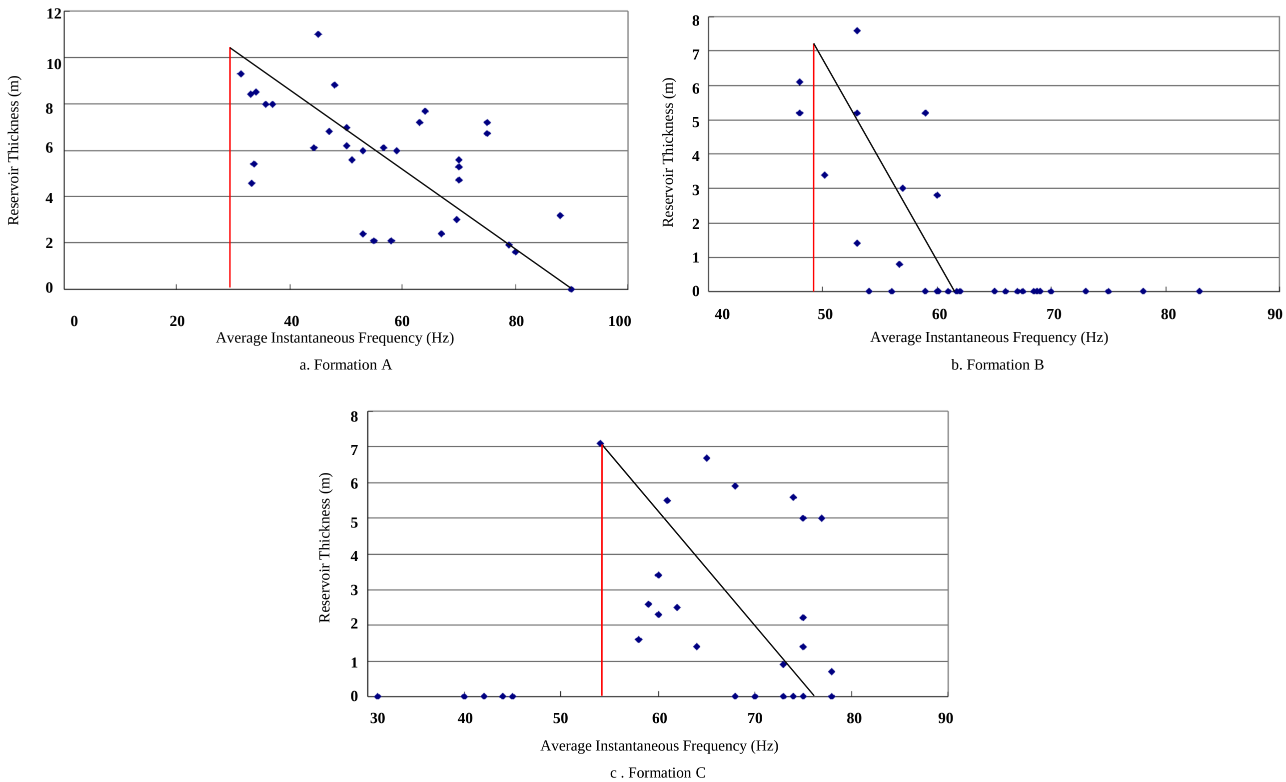


Fig. (2). Cross-plot of average instantaneous frequency attributes versus reservoir thickness.

instantaneous frequency is sensitive to the detection of unconsolidated, heavy oil reservoir, and can be used to quantify a thickness distribution for the reservoir sands.

3. CASE ANALYSIS

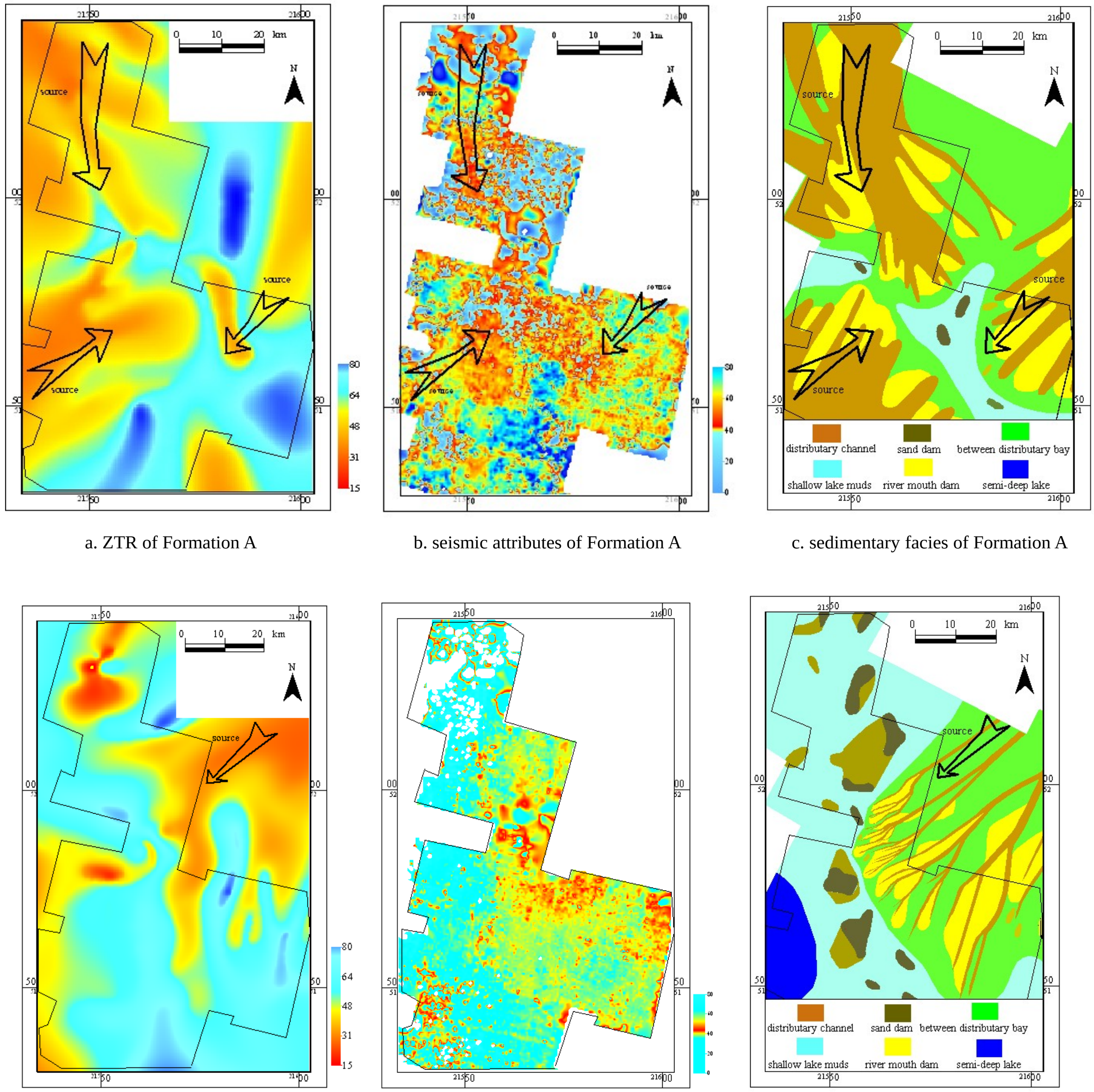
The research area of interest in this study is in the early development stages of petroleum exploration. For this reason, information from the area is relatively limited; wells are highly dispersed and the spacing among wells is large. It is difficult to accurately predict the distribution of sedimentary facies through the field according to wells data only. The ZTR index refers to the percent content of three extremely stable minerals include zircon, tourmaline and rutile in total heavy minerals. It represents the mincralogical maturity of rocks in the sample. The greater the ZTR index, the higher the degree of mincralogical maturity of the rocks. Systematic findings demonstrate that the ZTR index value and its change trends from small to large can be used to roughly determine sediment transport distance and direction, so as to judge the direction of provenance, which plays an important role in the formation of the sedimentary system [20, 21]. By ZTR (zircon, tourmaline and rutile) analysis, we find that sediment influx direction is consistent with the directional distribution of seismic frequency values (Fig. **3**). This indicates that the seismic instantaneous frequency attribute and its subsequent correlations to reservoir thickness distribution are geologically consistent and can be used to assist in the identification of sedimentary facies. Thus, the reservoir prediction method which integrated information from well log data and instantaneous frequency seismic attributes and instructing by geological theories, can be used to improve the reliability of sedimentary facies identification through accurately determining sedimentary provenance directions and predicting reservoir sands thickness, especially in areas where well data is scarce.

From ZTR analysis, Formation A shows a ZTR index distribution of higher values in the middle regions, and lower values in the surrounding areas (Fig. **3a**). There are three distinct ZTR index value change trends from small to large, which indicate that sediments in study area are primarily controlled by three sedimentary systems respectively in southwest, northwest, and northeast direction (Fig. **3c**). These results are also consistent with the instantaneous frequency directional distribution for Formation A (Fig. **3b**).

Formation B is shown to have a depositional trend from the northeast to southwest, along which ZRT index is increasing gradually (Fig. **3d**). This indicates that, during the depositional period of Formation B, the study area was mainly affected by provenance in the northeast direction, which corresponds to the northern sedimentary system (Fig. **3f**). These results are also in agreement with the directional distribution of the instantaneous frequency attributes for formation B (Fig. **3e**).

CONCLUSION

Due to the characteristics of loose cementation, high porosity and permeability, poor diagenesis and relative high fluid viscosity in unconsolidated heavy oil reservoirs, the effects of seismic frequency attenuation are particularly significant in unconsolidated, heavy oil reservoirs. Our work



a. ZTR of Formation A b. seismic attributes of Formation A c. sedimentary facies of Formation A

d. ZTR of Formation B e. seismic attributes of Formation B f. sedimentary facies of Formation B

Fig. (3). Distribution for the ZTR index, instantaneous frequency attributes and sedimentary facies of the Formation A and B.

demonstrates that the instantaneous frequency attribute of seismic waves can describe the reservoir distribution qualitatively in unconsolidated heavy oil sands, instead of wave impedance inversion attribute. The reservoir prediction method that integrated information from well log data and instantaneous frequency seismic attributes and instructing by geological theories, can be used to improve the reliability of sedimentary facies identification in unconsolidated heavy oil reservoirs through accurately determining sedimentary provenance directions and predicting reservoir sands thickness, especially in areas where well data is scarce.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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