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Article

Non-Repetitive Time-Shifted Seismic Monitoring Study Based on Ocean Bottom Cable and Towed Streamer Data

Fengying Chen [1,2], Xiangchun Wang [1,*], Wei Liu [3], Yibin Li [3] and Zhendong Liu [1]

1 School of Geophysics and Information Technology, China University of Geosciences (Beijing), Beijing 100083, China; chenfy0717@163.com (F.C.); pengyufei0707@163.com (Z.L.)
2 School of Electronics and Information Engineering, Guangdong Ocean University, Zhanjiang 524088, China
3 Zhanjiang Branch of CNOOC Ltd., Zhanjiang 524057, China
* Correspondence: wangxc@cugb.edu.cn

Abstract: Time-shifted seismic research plays an important role in monitoring changes in the gas-water interface uplift, the weakening of amplitude attributes, and gas distribution due to mining. When time-shifted seismic research involves non-repeatable data with significant differences between data sets due to variations in seismic data acquisition parameters and seismic geometries, it necessitates consistent processing before time-shifted monitoring comparisons. In this paper, a study of time-shifted seismic monitoring using two non-repetitive data sets based on the ocean bottom cable (OBC) and towed streamer data is presented. First, amplitude, frequency, wavelet, and time difference are processed to achieve consistency for time-shifted comparisons. Secondly, three modes of seismic geometry normalization are compared to optimize the appropriate offset, azimuth, and signal-to-noise ratio (SNR). Finally, after eliminating the fault surface wave, the maximum trough amplitude attribute is extracted for the same position in the two data sets to analyze time-shifted differences under the three modes using the ratio method and difference method. The conclusions show the following: the OBC and towed streamer data can achieve consistency in terms of amplitude, frequency, wavelet, azimuth, SNR, and time difference; the data reconstruction method outperforms other methods in normalizing offset, azimuth, and SNR; and the time-shifted comparison method of the amplitude attribute ratio method proves more effective than the difference method. This study offers a reliable foundation for future time-shifted seismic research with non-repetitive data to monitor changes in subsurface oil and gas. It also provides a methodological basis for carbon capture and storage (CCS) monitoring technology.

Keywords: non-repetitive time-shifted seismic research; time-shifted monitoring; data reconstruction; amplitude attributes

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1. Introduction

Time-shifted seismic techniques for solving reservoir dynamic description challenges date back to the 1950s and 1960s [1,2]. These techniques serve as an oil and gas dynamic monitoring method, integrating aspects of geophysics, petrophysics, geology, and reservoir engineering [3–5]. The foundation of time-shifted seismic comparisons lies in the changes in reservoir fluids during oil and gas field development, which subsequently alter seismic amplitude and travel time [6]. Consequently, after a certain period of oil and gas field development, repeated seismic data acquisition at the same location was conducted to capture dynamic changes in fluid properties—such as saturation, formation pressure, and temperature—using the same acquisition method and parameters. These changes in seismic attributes correspond to a change in the fluid field conditions [7]. Monitoring these changes in oil and gas fields through time-shifted seismic technology significantly enhances the dynamic understanding of geological reservoirs, improves the accuracy of model characterization for subsequent reservoir modeling, and guides the practical production of oil and gas fields. Furthermore, this technology is pivotal in optimization reservoir management, exploration, and identifying the potential for residual oil [8,9].

Domestic research on time-shifted seismic methods and applications began in the 1980s [10,11]. In 2007, the China National Offshore Oil Corporation (CNOOC) conducted a significant time-shifted seismic monitoring study, systematically analyzing petrophysics data, undertaking offshore repeatable seismic data acquisition, consistency processing, and targeted seismic data interpretation. This study proved successful in its application and provides valuable experience for future time-shifted seismic research [7]. In 2015, CNOOC advanced its research and application of key time-shifted seismic technologies, presenting a noteworthy example of offshore time-shifted seismic technology in practice [10]. Furthermore, the four-component ocean bottom cable (4C-OBC) technology has been shown to enable the real-time and long-term dynamic monitoring of gas hydrate reservoirs through time-shifted seismic methods [12].

Due to the high cost associated with acquiring data using repeated methods and parameters for time-shifted seismic studies, two non-repetitive data used for time-shifted seismic monitoring have emerged as cost-effective alternatives [13]. In 2015, Sinopec successfully implemented consistency processing on two 3D seismic data sets acquired with different geometries and acquisition parameters in onshore oilfields, achieving favorable results in oilfield time-shifted seismic monitoring [14]. Since 2007, a series of non-repetitive time-shifted seismic techniques have been developed, encompassing data processing to comprehensive interpretation following generalized secondary acquisition [15]. In 2020, CNOOC advanced this approach by integrating 3D seismic data with 2D broad-line seismic data for non-repetitive time-shifted seismic monitoring [16]. The consistent processing of non-repetitive time-shifted seismic data can be effectively guided by the merge processing method [17–19]. By ensuring the consistent processing of amplitude, frequency, and phase of two non-repetitive acquired seismic data, it becomes possible to predict residual oil distribution through time-shifted seismic comparisons [20–23].

Although the advantages of multi-component seismic data are increasingly recognized, there has been no research on non-repetitive time-shifted seismic studies using multi-component data combined with towed streamer data. This paper addresses this gap by conducting a time-shifted seismic study using OBC data acquired in 2021 and 3D-towed streamer data acquired in 2004, each obtained under different acquisition parameters and seismic geometries. After applying consistency processing techniques—such as amplitude, frequency, and phase matching—as well as seismic geometry normalization, a time-shifted comparison can be conducted through various methods. This approach provides a more reliable foundation for non-repeatable time-shifted seismic studies.

2. Seismogeological Characteristics

2.1. Tectonic Characteristics

The research area is located in the South China Sea (as the black square shows in Figure 1). The tectonic features of the area can be divided into three major blocks—north, central, and south—separated by major faults. The entire region is characterized by normal faults, predominantly consisting of fault blocks and a fault nose structure. The interior of the fault blocks is further complicated by secondary-level minor faults. The complex tectonics and steep stratigraphic dips present challenges in normalizing the two non-repeat seismic data sets.

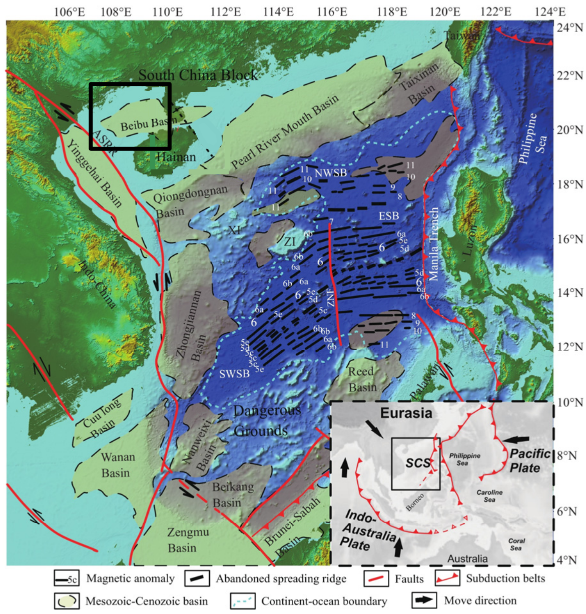


Figure 1. Regional geological structure in the area [24].

2.2. Time-Shifted Seismic Data

The survey (indicated by the blue square in Figure 1) contains two sets of seismic data: the first set is the towed streamer data acquired in 2004, and the second set is the OBC data acquired in 2021. The primary differences between these data sets lie in the acquisition parameters, particularly the source and receiver (Table 1).

Table 1. Towed streamer and OBC acquisition parameters.

	Acquisition Time	**2004**	**2021**
	Acquisition Geometry	**Towed Cable**	**OBC**
Source	Source type	Dual source air gun	Single source air gun
	Gun pressure(psi)	1800	2000
	Airgun capacity(cuin)	2500	4280
	Depth(m)	5	7
	Hypocentral distance(m)	50	--
	Shot interval(m)	25	25
Cable	Number	4	14
	Length(m)	4050	6000
	Depth(m)	6	Sea bottom
	Channel interval(m)	12.5	25
	Cable spacing(m)	100	200
	Sample interval(ms)	1	2
Record	Fold	37.5	420
	Channel number	324	240
	Record length(ms)	6000	8000
	Sample interval(ms)	1	2

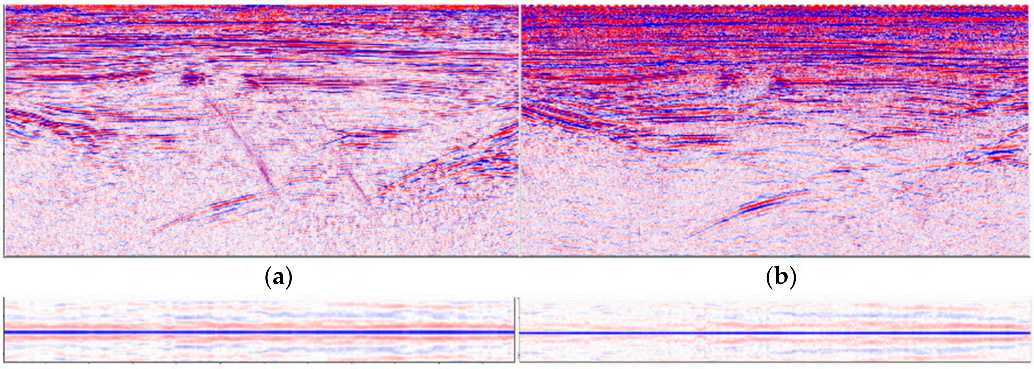
As a result of these differing acquisition methods and parameters, the characteristics of the two seismic data sets vary significantly.

3. Data Characteristic

OBC and towed streamer data differ significantly in both their data sets and seismic geometries.

3.1. Data Difference

The analysis and comparison of the two seismic data sets were conducted after applying noise, multiple waves, and ghost suppression separately. The differences between the data sets are evident in terms of SNR, amplitude, frequency, wavelet, time differences, and other factors (Figures 2–4). The towed streamer data exhibit weaker amplitude energy on the stacked seismic profile (Figure 2a,b), a broader wavelet width in auto-correlation data (Figure 2c,d), and a narrowed frequency band at 20 dB (Figure 3) compared to the OBC data.



(**a**) (**b**)

(**c**) (**d**)

Figure 2. Amplitude and wavelet of the two data sets. ((**a**): Towed streamer data-stacked profile; (**b**): OBC–stacked profile; (**c**): towed streamer data auto-correlation; (**d**); and OBC auto-correlation).

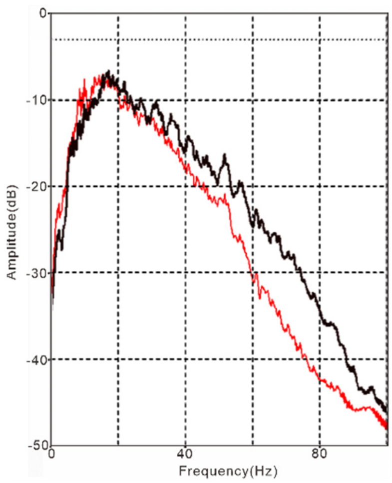
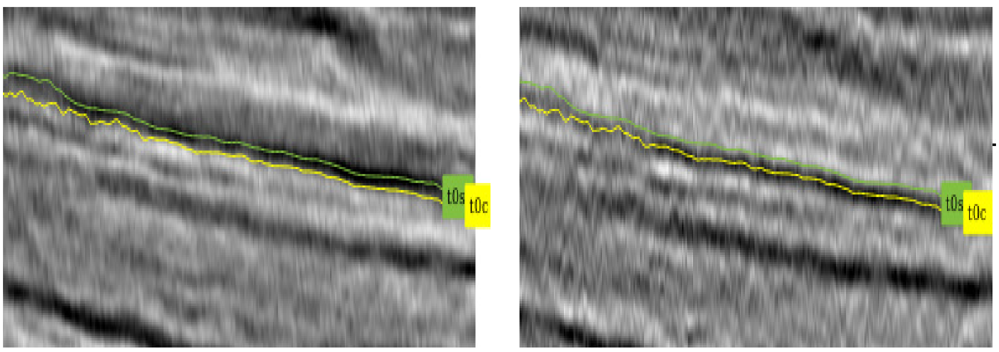


Figure 3. Frequency content of the two raw data sets (red: towed streamer data; black: OBC data).



(**a**) (**b**)

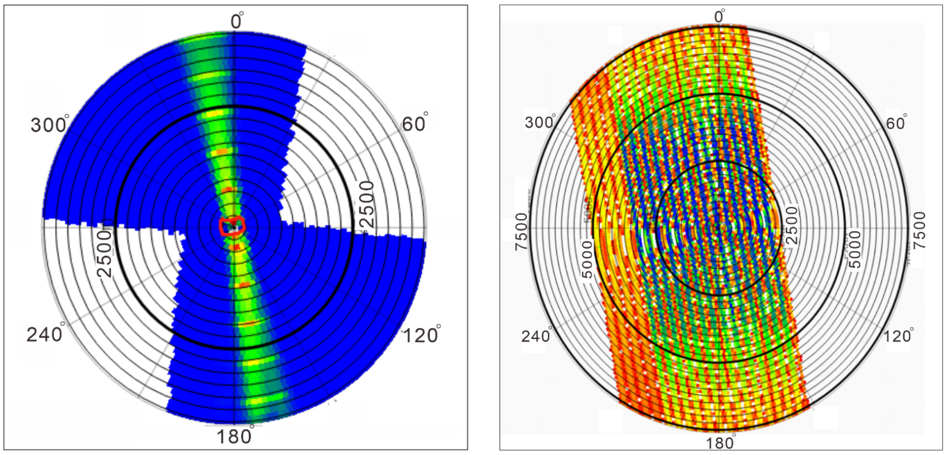
Figure 4. The time difference in the two data sets. ((**a**): Towed streamer data; (**b**): OBC data).

The time difference between the two is shown in Figure 4: the same horizon tracked on the stacked pre-stack time migration (PSTM) profile of OBC data (yellow horizon) is deeper than that of the towed streamer data (green horizon).

These differences significantly impact the time-shifted comparison. Therefore, the frequency, amplitude, wavelet phase, and time difference in the two data sets must be processed for consistency before a time-shifted comparison is made.

3.2. Differences in Seismic Geometry

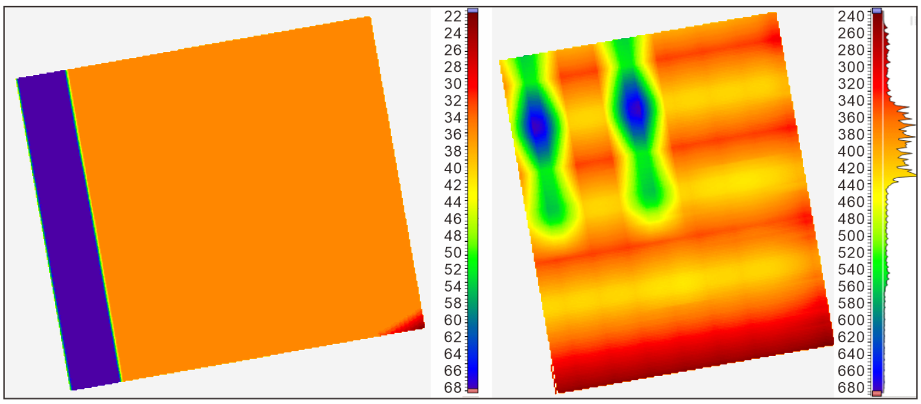
The towed streamer data and OBC differ in terms of fold and azimuth due to their distinct seismic geometries. The azimuth range of the towed streamer is relatively narrow, primarily concentrated at 154°–180°and 334°–360°, whereas the OBC data have a broader azimuth range, concentrated at 130°–210° and 290°–10° (Figure 5).



(**a**) (**b**)

Figure 5. Azimuth of two data sets. ((**a**): Towed streamer data; (**b**): OBC data).

The fold of the OBC data are significantly higher, for the most part around 420, compared to just 40 for the towed streamer data (Figure 6). These differences pose challenges for time-shifted comparisons, making seismic geometry normalization crucial for achieving consistency in time-shifted seismic processing.



(**a**) (**b**)

Figure 6. Fold of two data sets. ((**a**): Towed streamer data; (**b**): OBC data).

4. Key Technology of Consistency Processing

Based on the differences in amplitude, frequency, wavelet, time difference, and seismic geometry, the two data sets underwent consistency processing, which is defined in the following section.

4.1. Data Consistency Processing

Consistency processing was applied following noise, ghost, and multiple wave suppression of the two data sets. First, the vertical amplitude difference between the data sets was reduced through spherical diffusion compensation, followed by amplitude consistency correction performed to eliminate the horizontal amplitude difference. The two data sets were then matched-filtered to improve the frequency and wavelet alignment in the target layer, with the towed streamer data adjusted to more closely resemble the OBC data. Finally, the time difference between the two data sets was eliminated by static correction. After consistency processing, the amplitude, frequency, and auto-correlation wavelet characteristics were more closely aligned between the two data, with the time difference eliminated at the yellow line of the stacked profile (Figures 7 and 8).

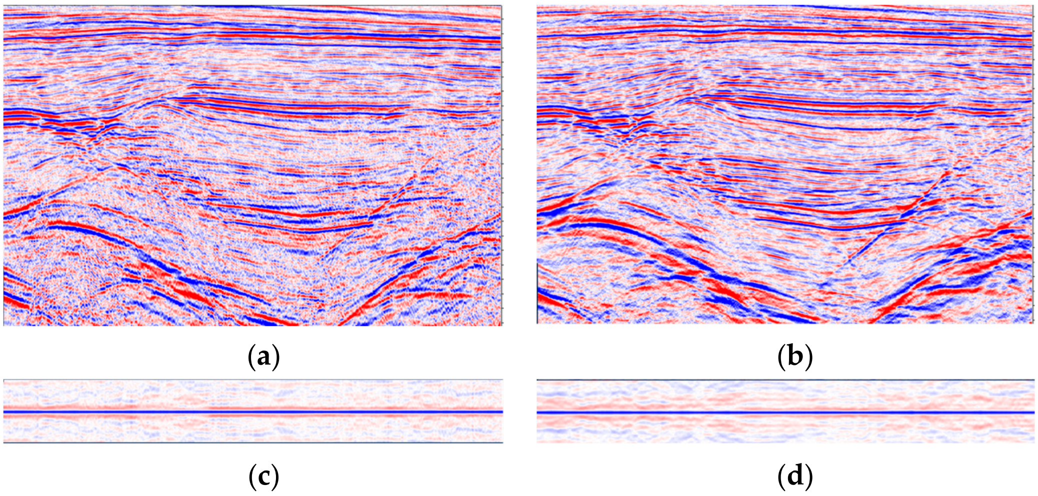


Figure 7. Amplitude, time difference, and wavelet of two data sets. ((**a**): Towed streamer data-stacked profile; (**b**): OBC–stacked profile; (**c**): towed streamer data auto-correlation; and (**d**): OBC autocorrelation).

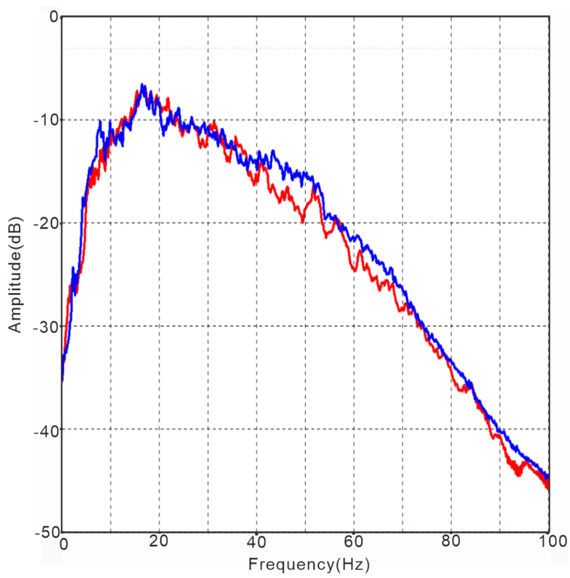


Figure 8. Frequency content of two data sets after consistency processing. (Red: towed streamer data; blue: OBC data).

4.2. Seismic Geometry Consistency Processing

The azimuth and fold differences introduced by the seismic geometry also require normalization. Given that the two data sets are acquired in an area with a complex geological structure, geometry consistency processing utilizes a multi-mode approach to thoroughly evaluate the validity of the time-shifted seismic response under different modes. The normalized patterns for the three modes are illustrated as follow:

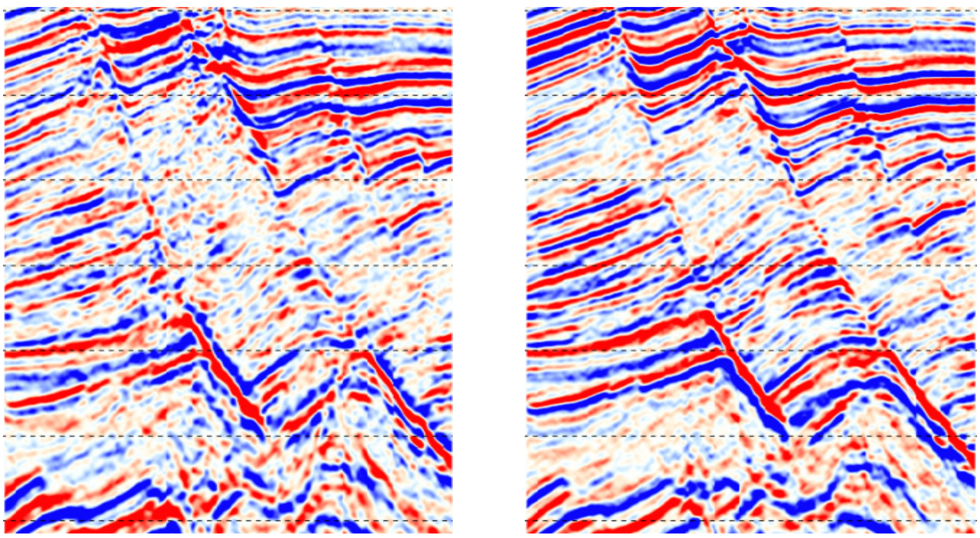
Mode I: Time-shifted seismic processing in a completely non-repeated acquisition mode, where the two seismic geometries are not normalized. The reliability of the time-shifted target layer comparison is assessed by processing the two data sets to a state where the marker layer is comparable.

Mode II: seismic geometry is strictly repeated by selecting data that match the shot point, receiver, azimuth, and offset, thereby achieving a complete repeat of time-shifted seismic processing.

Mode III: Seismic data normalization based on data reconstruction. This approach extends the fold and azimuth of all the towed streamer data and aligns the azimuth and offset intersection of OBC data with towed streamer data, making the two seismic geometries comparable.

4.2.1. Seismic Geometry Consistency Processing of Mode I

A time-shifted comparison based on the stacked data after PSTM of the OBC and towed streamer data reveals a clear imaging gap at the steep dip structure of the target layer between the two data sets due to the wide azimuth and far-offset OBC (Figure 9).

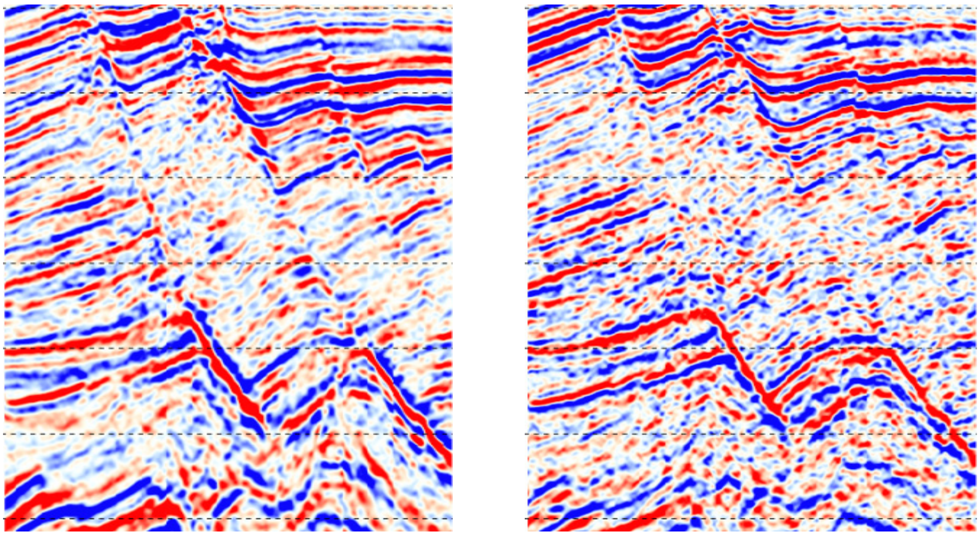


(a) (b)

Figure 9. Stacked data after PSTM of Mode I. ((**a**): Towed streamer data; (**b**): OBC data).

4.2.2. Seismic Geometry Consistency Processing of Mode II

Due to the far-offset and far-array of the OBC data, the offset and off-line distance of OBC data are limited, and the receiver point spacing of the towed streamer data is reduced to achieve the intersection of the two data sets. This reduction decreases the fold of the intersection data, with the towed streamer data reduced by 50% from 40 to 20 and the OBC data reduced from 420 to 20, leading to a poor SNR. A time-shifted comparison of the stacked data after PSTM reveals that the image quality of OBC data is significantly poorer compared to that of the towed streamer data (Figure 10), which hinders effective time-shifted comparisons.

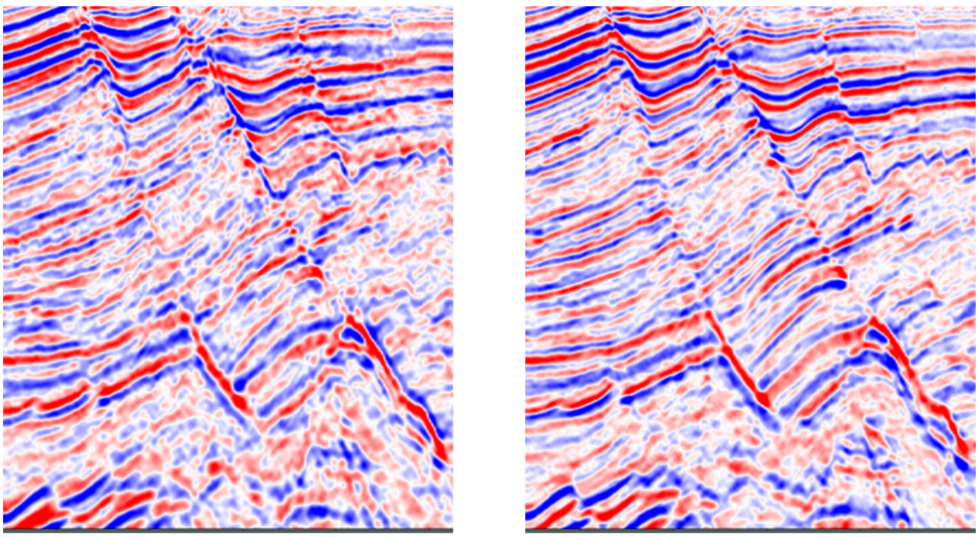


(**a**) (**b**)

Figure 10. Stacked data after PSTM of Mode II. ((**a**): Towed streamer data; (**b**): OBC data).

4.2.3. Seismic Geometry Consistency Processing of Mode III

Mode I exhibits a significant imaging difference between the two data sets, while the SNR of the intersection OBC data in Mode II was severely degraded. To address the challenges of the time-shifted seismic target layer, characterized by a large depth and complex structure, the data reconstruction method was employed. This method processes the OBC seismic data at the azimuth and offset intersection part, along with all the towed streamer data, to ensure consistency in the SNR, fold, offset, and azimuth of the two data sets. After data reconstruction, the SNR and imaging quality of both data sets were improved and almost consistent (Figure 11).



(**a**) (**b**)

Figure 11. Stacked data after PSTM of Mode III. ((**a**): Towed streamer data; (**b**): OBC data).

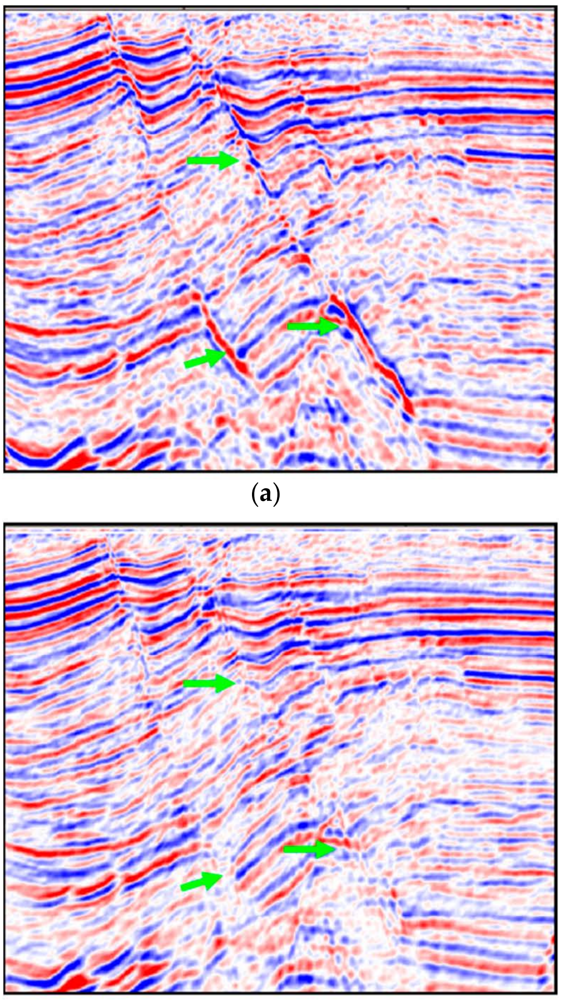
A comparison of the three modes reveals that Mode I has a clear imaging gap at the steep dip structure of the target layer, making it unsuitable for time-shifted comparisons. Although the offset and azimuth of the two data sets are normalized in Mode II, it is not ideal for the time-shifted comparison because the SNR of OBC data are far from the towed streamer data due to the excessive reduction in OBC data fold; Mode III, which normalizes offset and azimuth through data reconstruction, enhances the consistency between the two data sets, making them suitable for time-shifted comparisons.

5. Time-Shifted Comparison with Actual Reservoir Drilling

The two seismic data sets were compared using three modes after they were made consistent, including processing for amplitude, frequency, wavelet, time difference, and seismic geometry. The maximum trough amplitude attribute along the target layers was then extracted to compare the attribute characteristics of the two data sets. In this area, complex faults, particularly the reflection waves from the steep dip fault (also known as the fault surface wave), could impact the accuracy of the time-shifted comparisons, necessitating their elimination.

5.1. Elimination of Fault Surface Wave

Since the target layer is located in the fault region (as indicated by the green arrow shown in Figure 12a), the maximum trough amplitude attribute extracted along the layer is significantly influenced by the fault surface wave, resulting in noticeable striation anomalies on the amplitude attribute map (indicated by the green arrow and circle in Figure 13a). After filtering out the fault surface wave, the profile was imaged without any visible fault surface wave (as shown in Figure 12b), and the striation feature in the amplitude attribute was eliminated (as indicated by the green arrow and circle in Figure 13b).



(**a**)

(**b**)

Figure 12. Fault surface wave on stacked section. ((**a**): Before elimination; (**b**): after elimination).

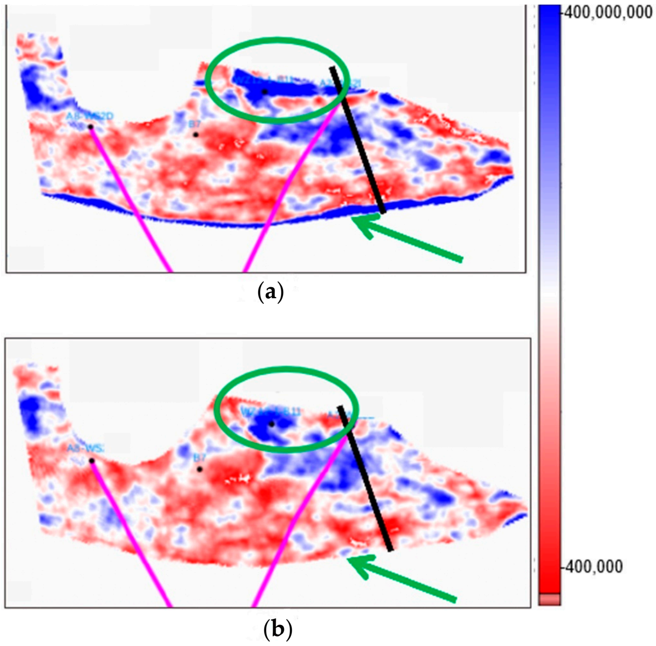


Figure 13. Fault surface wave on maximum trough amplitude attribute plan. ((**a**): Before elimination; (**b**): after elimination. The purple lines are drilling tracks. The color is the value of the maximum trough amplitude).

5.2. Time-Shifted Comparison Method

After eliminating the fault surface wave, the maximum trough amplitude attribute along the layer was extracted from the two data sets. Two comparison methods—the difference method and the ratio method—were applied (Figure 14). The results indicate that the ratio method clearly reveals the reservoir changes compared to the difference method. Therefore, this paper adopts the ratio method for the time-shifted comparison.

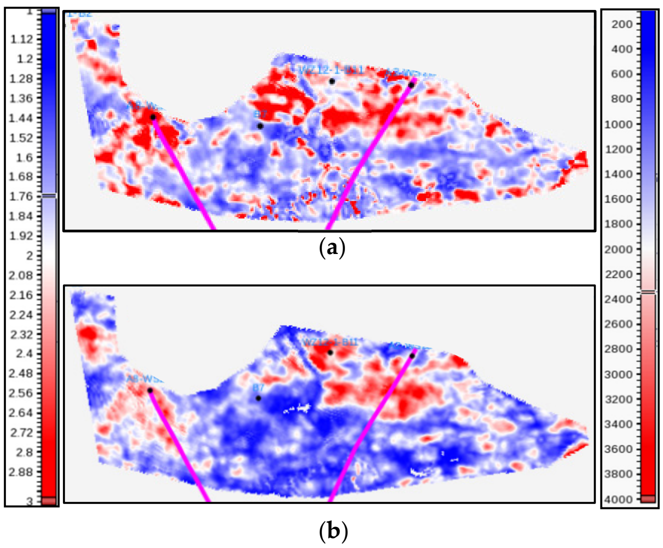


Figure 14. Time-shifted comparison. ((**a**): Ratio method; (**b**): difference method. The purple lines are drilling tracks. The left graphic symbol is the ratio of the two; the right graphic symbol is the difference between the two).

5.3. Comparison of Time Shifts for Three Modes

After eliminating the fault surface wave from the normalized seismic data of the three geometry modes, the maximum trough amplitude attribute was extracted from the target layer for each mode. The amplitude attribute ratio method was used for time-shifted comparison analysis. The analysis (indicated by the green circle in Figure 15) shows that the imaging quality of the OBC data in Mode I was significantly better than that of the towed streamer data, resulting in a larger amplitude ratio. In contrast, the low quality of the OBC imaging in Mode II led to poorly regularized time-shifted contrast noise. In Mode III, the amplitude increased with good regularity in the well gas injection area, showing significant amplitude enhancement and consistent imaging in the gas injection region of the well.

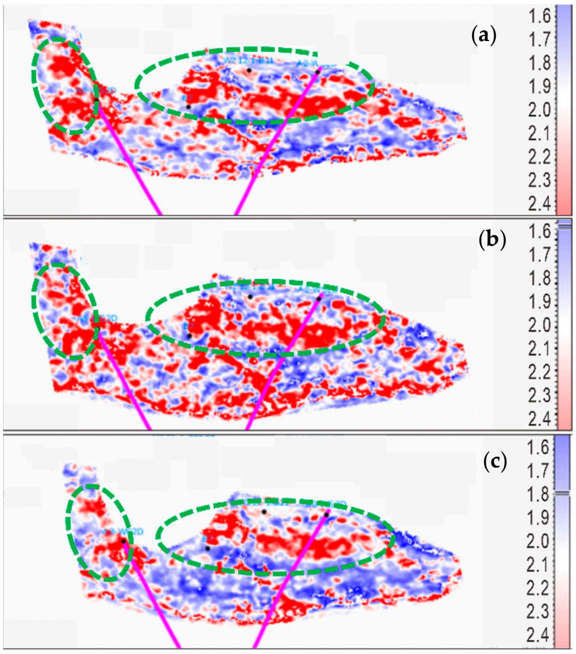
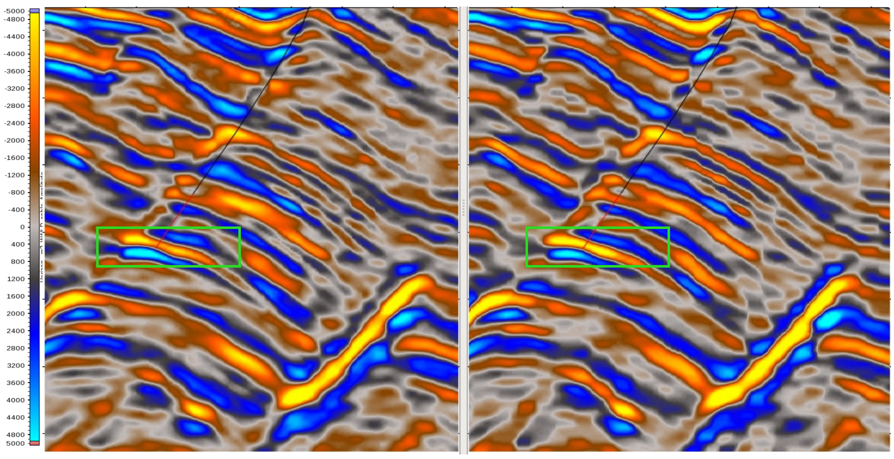


Figure 15. Time-shifted comparison of three modes ((**a**): Mode I; (**b**): Mode II; and (**c**): Mode III. The purple lines are drilling tracks. The graphic symbol is the ratio of the two attributes).

5.4. Comparison with Actual Drilling

The actual reservoir well was drilled for gas injection, resulting in a fluid-to-gas transition. This change altered the wave impedance of the layers, leading to an enhancement of the seismic reflection through amplitude (indicated by the green square in Figure 16). The effects observed in the time-shifted comparison were consistent with the outcomes of actual drilling.



(**a**) (**b**)

Figure 16. The amplitude of the two data sets. ((**a**): Towed streamer data; (**b**): OBC data).

6. Discussion

This study presents a sort of recipe for processing two data sets that are collected using different parameters, which can be used for time-shifted seismic monitoring. This marks the first time that multi-component data and towed streamer data have been used together for consistency processing in a time-shifted seismic correlation. Compared with traditional consistency processing methods for seismic geometry, this study adopted a multi-mode normalization method and applied data reconstruction to the normalization process. This approach achieved effective processing results and aligns well with the actual drilling conditions.

7. Conclusions

In this paper, a non-repetitive time-shifted seismic monitoring method was applied to the 2021 OBC data and 2004 towed cable data. First, the differences in amplitude, frequency, wavelet, and time differences between the two data sets were processed for consistency. Then, the three modes of seismic geometry normalization were compared, and Mode III (the data reconstruction method). including the normalization for the offset, azimuth, and SNR ratio, was preferred. Finally, the maximum trough amplitude attributes were extracted from both data sets across the three modes, and the time-shifted comparison was analyzed using the ratio method and difference method after eliminating the fault surface wave. The conclusions are given as follows:

(1) The differences in amplitude, frequency, wavelet, and time difference between the OBC and towed streamer data were effectively normalized through consistency processing.
(2) Data reconstruction technology proved superior to other methods when comparing the offset, azimuth, and SNR of the multi-mode normalized data.
(3) After eliminating the fault surface wave, the maximum trough amplitude attribute was extracted from the two seismic data sets of the target layer and analyzed using the ratio method and the difference method, where the former more accurately reflected the time-shifted changes associated with gas injection during drilling.
(4) Mode III (the data reconstruction method) entailed comparison yield results that aligned more closely with the fluid replacement caused by the actual gas injection, which is characterized by regionally strong wave impedance changes in both seismic profiles and planes. This alignment is consistent with the distribution of residual oil.
(5) After consistency processing, the OBC and towed streamer data were suitable for time-shifted seismic monitoring research, providing a reliable foundation for future, non-repetitive, time-shifted seismic comparison studies. This approach also offers a methodological basis for future CCS monitoring technology.

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