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E-mail: hyxbe@263.net

The influence of irregular seafloor topography on the seismic wave field and migration imaging

Fuxing Han[1], Kun Wang[2], Jianguo Sun[1]*
[1] College for Geoexploration Science Technology, Jilin University, Changchun 130026, China
[2] Jilin Communications Polytechnic, Changchun 130012, China

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Abstract
One of the problems experienced in marine geophysical exploration is that the layered features in the migration imaging profile are blurred and the seismic energy reflected is weaker in the middle or lower parts. In this study we model the seismic wavefield records in the undulating seafloor when there is both a slight change and significant change in seafloor topography to analyze its influence on the seismic reflection data and migration imaging profiles. We compare and analyze the wave field records collected at the same point on the original and modified velocity models, and the cross-bonding resulting migration imaging profiles. The results show that whether the seismic reflection data collection is performed along the direction of the survey line or against the direction of the survey line, slight changes in the seafloor topography have little effect on the wave field records and the migration profile, while significant changes in the seafloor topography have great effect on both the wave field records and migration profile.

Key words: seafloor topography, seismic wave field, seismic reflections, migration imaging

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1 Introduction

In recent years, the growing global scarcity of land resources has forced resource exploration shifted from the land to the sea. China has invested a lot of effort and financial resources in marine oil and gas exploration which concentrated in the deep waters of Qiongdongnan Basin, located in the northern part of South China Sea. According to the previous geophysical studies (Tao et al., 2005; Li, 2006; Duan and Zhang, 2006), it is known that the area is characterized by a complex geological structure, with a sudden increase in water depth over a wide range, which changes from a few hundred meters to a few kilometers. As a result, the dip angle suddenly becomes steeper and the sea floor undulates strongly. This kind of structure influences the propagation of seismic wave field energy greatly, thereby affecting the imaging quality of seismic data significantly. Most 2D seismic profiles from this area have the following problems: (1) the structure of the sunken floor is not clear; (2) the basal surface cannot be imaged properly; (3) the reflection is disordered; (4) the signal to noise ratio in the middle and deep layers is low; (5) there are strong multiple waves; (6) the side waves have developed (Zhu et al., 2008; Deng et al., 2010).

Previous researchers have introduced a lot of improvements in data acquisition and processing, including: expansion of the air gun capacity (or air gun combination), adjusting the cable length and sinking depth, and changing the direction of acquisition (Yang and Li, 2010; Dan et al., 2011); stratifying the velocity of seawater according to temperature and salt structure (Munk, 1974; Song et al., 2010; Han et al., 2012); improving energy compensation in the middle-deep layer and improving the signal to noise ratio technology using 2.5D geometric diffusion compensation factor (Han et al., 2013); and pre-stack depth migration processing for rugged seafloor (Chen and Ge, 2005; Chang et al., 2008). All these efforts have indeed improved the quality of seismic data acquired from steep slopes in deep waters, but there is still a large gap in the imaging quality when compared with data acquired from shallow waters or flat areas. In the land seismic data processing, the velocity models obtained from velocity analysis are fixed in the migration process. This means that a velocity model does not change in the process of migration imaging. However, for the processing of marine geophysical exploration data, it is paramount to take into account that seawater is affected by wind-waves, turbulence, etc., and that the topography of the seafloor may change at different times and in different degrees. Therefore, if we still use the fixed velocity model derived from the original velocity analysis for migration imaging processing, errors are likely to occur. These errors can weaken the middle-deep image field energy and also blur the migration profile.

To further understand other factors that affect the migration image field energy in the middle-deep layer and improve the imaging quality of the migration profile, it is important to consider the impact of seafloor topography over time on wave field recording and migration imaging. For data acquired in marine geophysical exploration, we assume that the data acquired on the seafloor Model A from Time T_1 to T_i is DATA1. As time goes by, at a Time T_{i+1}, the seafloor topography changed because of correlative factors, such as waves. We take the seafloor after the change in topography to be Nodel B and the seismic data acquired on Model B from Time T_{i+1} to Time T_N as DATA2. However, during

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*Corresponding author, E-mail: sun_jg@jlu.edu.cn

normal data processing, we cannot know the changes in velocity model at Time T_{i+1}. We will use the seafloor Model A to perform migration imaging based on the two datasets, DATA1 and DATA2. This study will focus on how the change in seafloor topography would influence the wave field and the migration imaging.

2 Data model and methods

With regard to the influence of changes in the undulating seafloor on the wave field and migration image field, this study will establish two velocity models for analysis and discussion under the premise of ensuring that the stratum below the undulating seafloor is unchanged. (1) The velocity Model IA and the velocity Model IB when there is only a slight change in seafloor topography; (2) the velocity Model IIA and the velocity Model IIB when there is significant change in seafloor topography. The slight and significant change velocity models of the seafloor topography established here are mainly measured according to the difference between some acquired seismic wavefield records from South China Sea.

The research methods used in this study are as follows. We used finite difference method to generate synthetic seismic reflection dataset DATA1 on Model A from Time T_1 to T_i, at the Time T_{i+1}, seafloor topography had changed, and thus the velocity model changed to B. We generate synthetic seismic reflection data sets DATA1 on Model B from Time T_{i+1} to T_N. Then we processed the synthetic datasets; we name the migration profile obtained by the wave field record DATA1 on Model A as P1, the migration profile obtained by the wave field record DATA1 and DATA2 on Model A as P2, and the migration profile obtained by the wave field record DATA2 on Model B as P3. We compared and analyzed the migration Profiles P1, P2 and P3 to evaluate how the seafloor topography changes will influence the migration image profiles. The results can also help to determine whether this method is effective enough to solve the problems of weaker middle and deep energy and fuzzy horizons in marine geophysical exploration data processing. The research workflow used here is shown in Fig. 1.

3 Results and discussion

In the following, according to the research method and the processing flow, the influences on the wave field recording and the migration imaging will be analyzed in detail from the slight changes and significant changes in the undulating seabed.

3.1 *The influence of slight change on seafloor topography on wave field and migration imaging*

Firstly, we built the two velocity models, IA and IB, by taking the model size as 2 500×2 800 and the grid size as 2.5 m×2.5 m, the layer velocity is: sea water layer $v_1 = v_0\left\{1+\varepsilon\left[\mathrm{e}^{-\eta}-(1-\eta)\right]\right\}$ (Munk, 1974), $\eta = \dfrac{2(z-z_0)}{B}$, where z_0 is the position of the minimum value of the wave field, B is the width of the wave-guide, ε is the position of the minimum value of the migration profile, v_0 is minimum value of velocity, and B=1 000 m, z_0=1 000 m, $\varepsilon = 0.57\times10^{-2}$, v_0=1 500 m/s, v_2=2 300 m/s, v_3=2 800 m/s, v_4=3 250 m/s, v_5=4 000 m/s. Velocity Models IA and IB are shown in Figs 2a and b. For these two velocity models, IA and IB, we used our own 2-dimension, 8-order wave equation finite difference code to do the simulation. Respective wave field records were taken at the following shot points: (50, 2), (500, 2), (625, 2), (1000, 2), (1250, 2), (1500, 2), (1875, 2), (2470, 2), and the total number of traces of wave field records is 500, the trace space is 12.5 m, and the sampling interval is 2 ms.

The migration imaging profile of the respective wave field records taken at Points (500, 2), (625, 2), (1000, 2), (1250, 2), (1500, 2), (1875, 2) on Models IA and IB are shown in Fig. 3. The following is a detailed analysis of the impact on the migration imaging results when the seafloor topography changes slightly at a certain moment. For velocity Model IA, wave field records were taken at Points (500, 2), (625, 2), (1000, 2), (1250, 2), (1500, 2), (1875, 2) from Time T_1 to T_i. At the Time T_{i+1}, seafloor topography changed slightly, and the velocity model changed to IB, and wave field records were taken at Point (2470, 2) on Model IB. The wave field records of Models IA and IB, which were taken at Point (2470, 2) are shown in Fig. 4, while the migration results for the same point wave field are shown in Fig. 5. However, in seismic reflection data processing, we do not know to what extent the seafloor undulating topography changed from Model IA to Model IB at the Time T_{i+1}. When the wave field record taken at Point (2470, 2) on Model IB is used for migration imaging, the result is shown in Fig. 5b. The migration results obtained from wave field records acquired at Points (500, 2), (625, 2), (1000, 2), (1250, 2), (1500, 2), (1875, 2) on Model IA are shown in Fig. 6a. The migration results obtained from the wave field records acquired at the mentioned points on

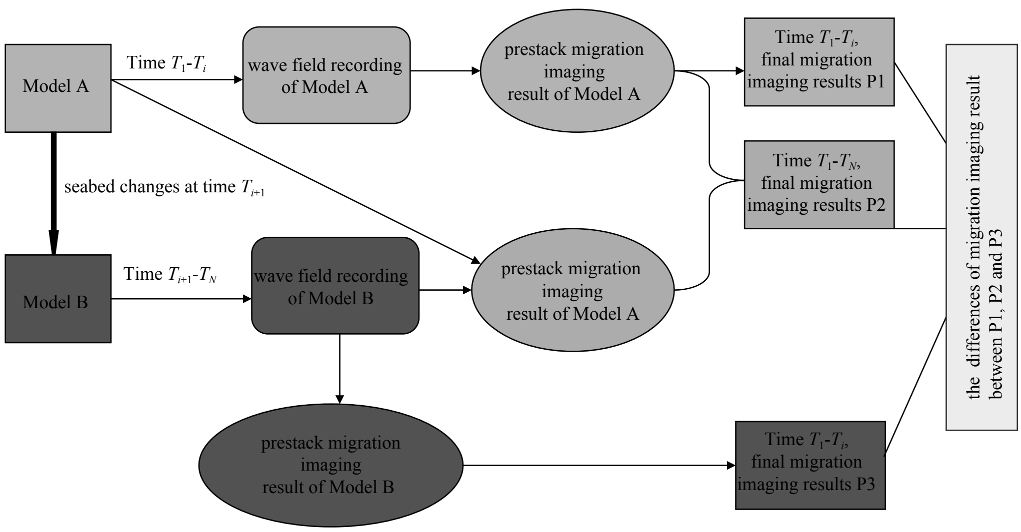

Fig. 1. The research workflow.

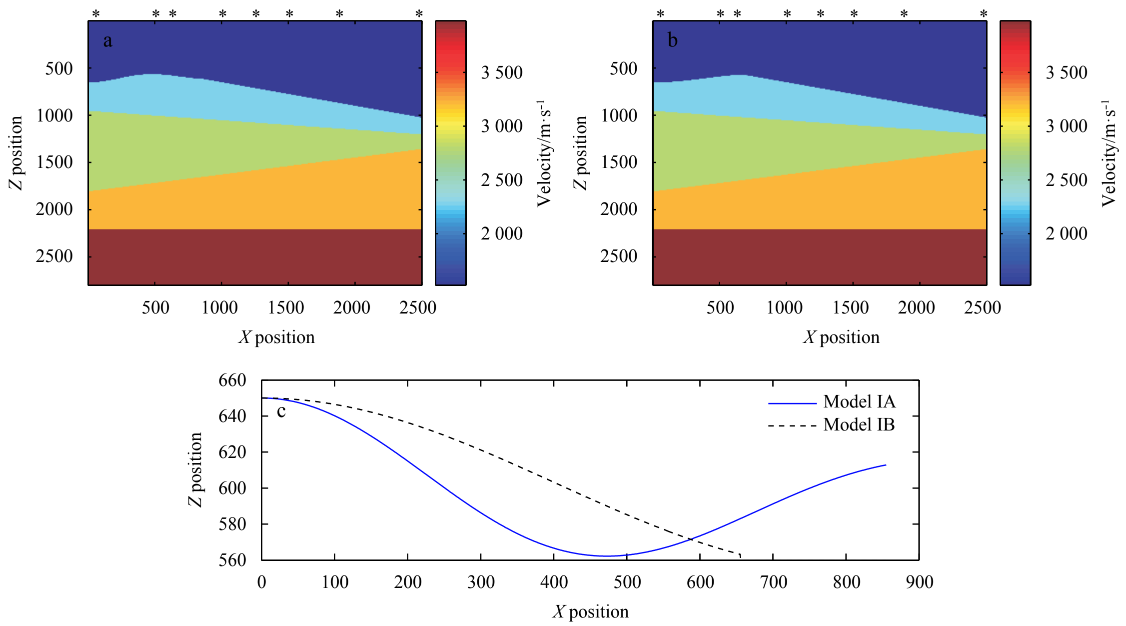

Fig. 2. Sketch map of velocity Models IA and IB, and the slight difference in the undulating seafloor. a. Velocity Model IA and shot point position, b. velocity Model IB and shot point position, and c. slight difference in the undulating seafloor on Models IA and IB. The full line and dotted line represent the sea surface before and after the change.

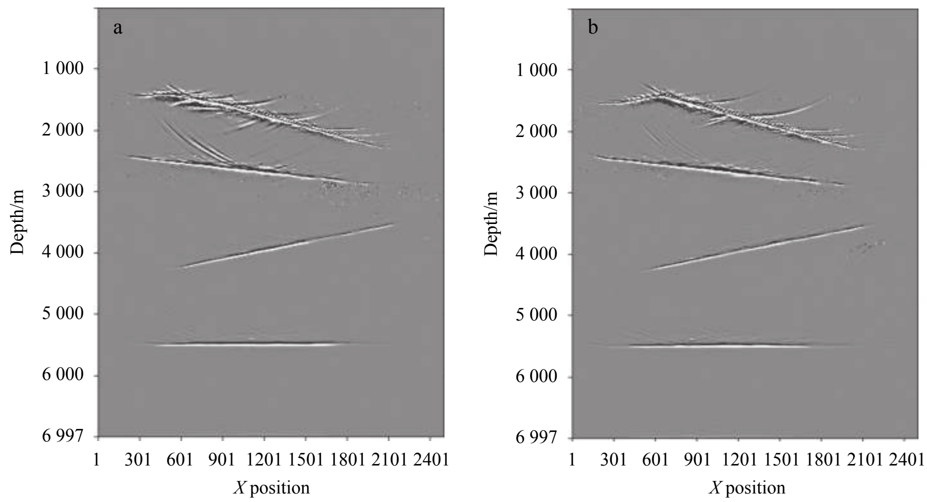

Fig. 3. The migration results of velocity Models IA and IB obtained from the wave field records taken at (500, 2), (625, 2), (1000, 2), (1250, 2), (1500, 2), (1875, 2). a. The migration result on Model IA obtained from the wave field records of velocity Model IA, and b. the migration result on Model IB obtained from wave field records of velocity Model IB.

Model IA and at Point (2470, 2) on Model IB are shown in Fig. 6b.

As shown in Fig. 4, it can be clearly seen from the wave field record taken at Point (2470, 2) under the condition that the underlying stratum of the Models IA and IB undulating seabed are completely identical, when the undulating seabed topography changes slightly. The wave field records of the two models have a slight difference between the positions of changes and far offset. Moreover, the energy difference near the source and middle-deep layers are not obvious.

It can be seen from the Figs 5, 3a, 6a and 6b that when the seismic reflection data is acquired from left along the direction of the survey line and the seafloor topography slightly changed in a small area, it will not influence migration results. The results of the seismic reflection data acquired against the direction of the survey line also draw the same conclusion. We will also discuss what kind of influence if there is a significant change in the seafloor topography at a certain time.

3.2 *The influence of significant change in the undulating seafloor on the wave field and migration imaging*

The following is a detailed analysis of the influence on wave field records when there is significant change in the undulating seafloor topography. By building two velocity Models IIA and IIB with size 2 500×2 400, and a grid size of 2.5 m×2.5 m, the resulting layer velocity is sea water layer $v_1 = v_0\left\{1+\varepsilon\left[e^{-\eta}-(1-\eta)\right]\right\}$, $\left(\eta = \dfrac{2(z-z_0)}{B}\right.$, where z_0 is the position for minimum value of the wave field, B is the width of the wave-guide, ε is the position of the minimum value of the migration profile, v_0 is the minimum value of velocity, and B=1 000 m, z_0=1 000 m, $\varepsilon = 0.57\times10^{-2}$,

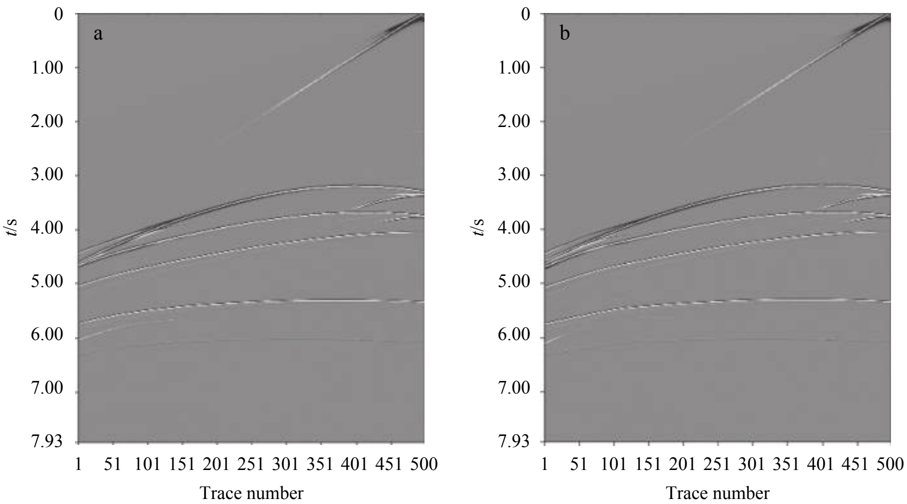

Fig. 4. The wave field records of velocity Models IA and IB taken at Point (2470, 2). a. Wave field record on Model IA, and b. wave field record on Model IB.

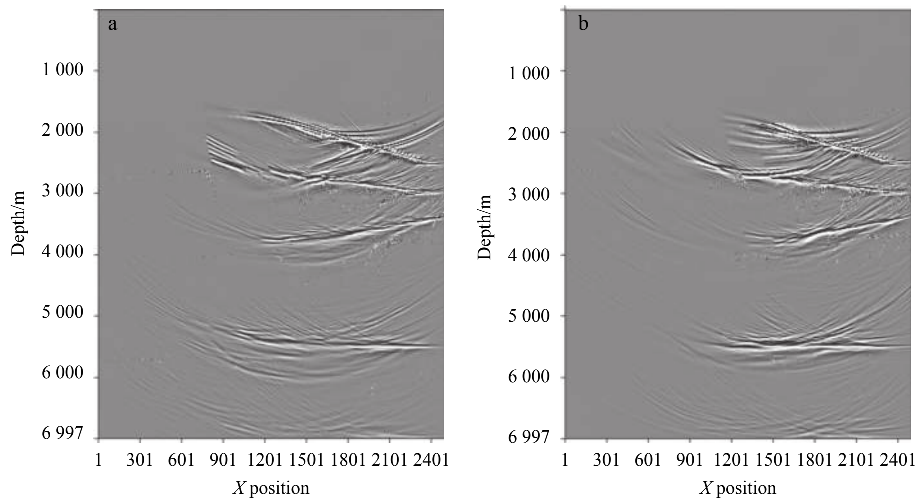

Fig. 5. The migration results on Models IA and IB obtained from wave field records acquired at Point (2470, 2) on Model IB. a. The migration result on Model IB obtained from the wave field record of velocity Model IB, and b. the migration result on Model IA obtained from the wave field record of velocity Model IB.

v_0=1 500 m/s, v_2=2 300 m/s, v_3=2 800 m/s, v_4=3 500 m/s, v_5=4 250 m/s. Velocity Models IIA and IIB, obtained when there was significant change in the undulating seafloor are shown in Fig. 7. For velocity Model IIA, and Model IIB with significant change in seafloor topography at a certain time, we used our own 2D 8-order wave equation finite difference code to do the simulation. Respective wave field records were acquired at shot points (50, 2), (250, 2), (725, 2), (1000, 2), (1250, 2), (1500, 2), (2000, 2), (2250, 2), and the total number of traces of wave field records is 500, the trace space is 12.5 m, and the sampling interval is 2 ms.

For velocity models IIA and IIB, respective wave field records were acquired at Points (725, 2), (1000, 2), (1250, 2), (1500, 2) for migration imaging, and the generated migration imaging profile is show in Fig. 8. The following is a detailed analysis of the influence on imaging results when the seafloor changes significantly at a certain time. For velocity Model IIA, wave field records were acquired at Points (500, 2), (625, 2), (1000, 2), (1250, 2), (1500, 2), (1875, 2) from T_1 to T_i. At a Time T_{i+1} the seafloor topography changed significantly, and thus the velocity model changed to IIB. The wave field records of Models IIA and IIB were acquired at Points (2000, 2) and (2250, 2) and are shown in Fig. 9. The migration results of Models IIA and IIB obtained from the wave field records acquired at these two points are shown in Fig. 10. However, during seismic reflection data processing, we do not know to what extent the seafloor undulating topography changed from Model IIA to Model IIB at the Time T_{i+1}. When migration imaging of Model IIA is performed based on the wave field records acquired at Points (2000, 2) and (2250, 2), the result is shown in Fig. 10b. The migration results obtained from the wave field records collected at (725, 2), (1000, 2), (1250, 2) and (1500, 2) on Model IIA are shown in Fig. 11a. The migration results obtained from the wave field records acquired at Points (725, 2), (1000, 2), (1250, 2), and (1500, 2) on Model IIA, and at Points (2000, 2) and (2250, 2) on Model IIB are shown in Fig. 11b.

It can be seen from the wave field records in Fig. 9 that when the shot point is at (2000, 2) and (2250, 2), on the point far offset, there are obvious differences in the records of the two models.

It can be seen from the Figs 10 and 11 above that there is obvi-

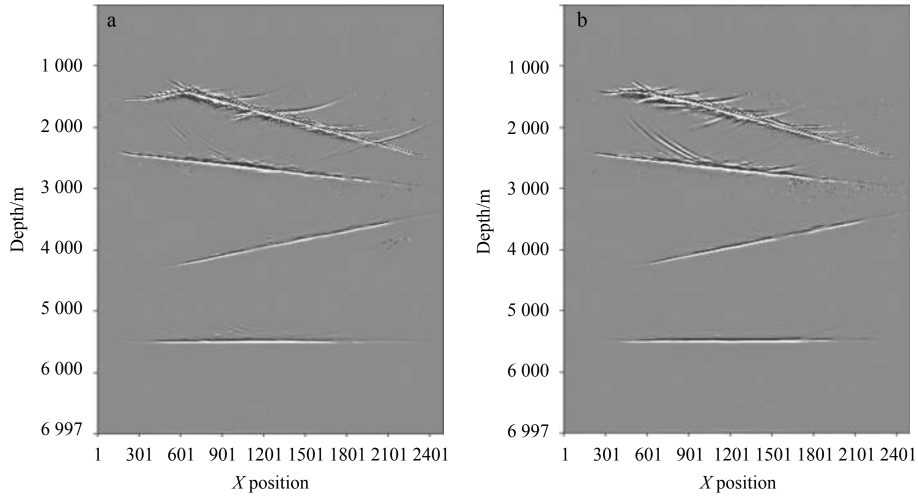

Fig. 6. The migration stack profile of the offset results of the wave field records of Model IA acquired at source Points (500, 2), (625, 2), (1000, 2), (1250, 2), (1500, 2), (1875, 2) and the offset results of the wave field records of Models IA and IB acquired at source point (2470, 2). a. The offset results of the wave field records of Model IA acquired at source Points (500, 2), (625, 2), (1000, 2), (1250, 2), (1500, 2), (1875, 2), (2470, 2) on the velocity Model IA; and b. the offset results of the wave field records of Model IA acquired at source Points (500, 2), (625, 2), (1000, 2), (1250, 2), (1500, 2), (1875, 2) and the offset results of the wave field record of Model IB acquired at source Point (2470, 2) on the velocity Model IA.

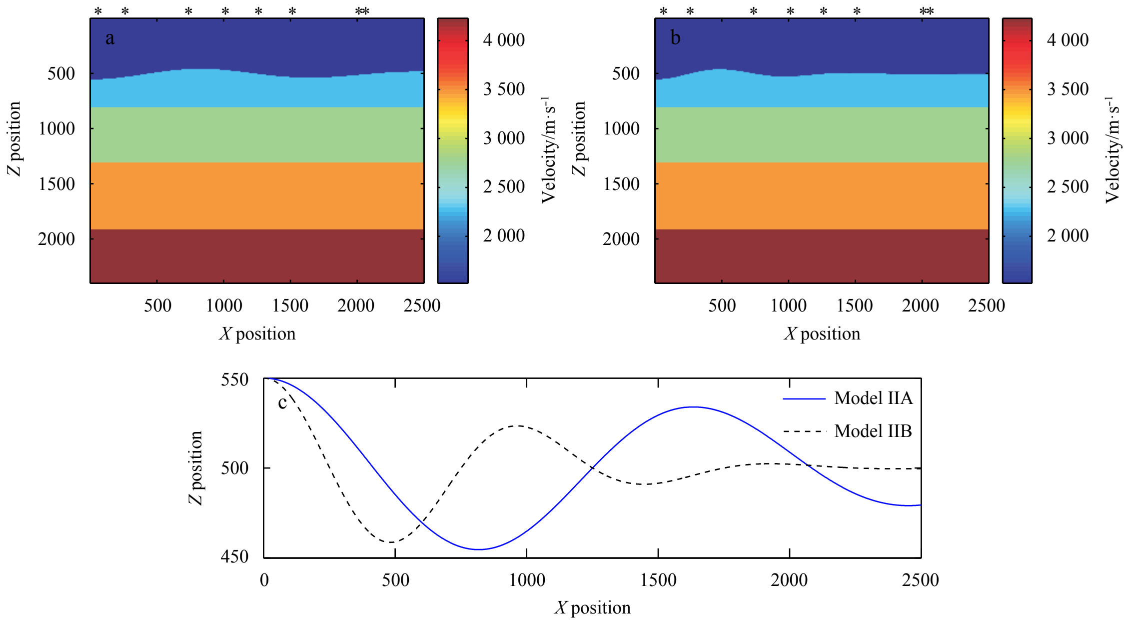

Fig. 7. Sketch map of velocity Models IIA and IIB when there is significant in the undulating seafloor. a. Velocity Model IIA and shot point position, b. velocity Model IIB and shot point position, and c. significant difference in the undulating seafloor on Models IIA and IIB.

ous change in the undulating seafloor as a whole. When seismic reflection data is acquired along the direction of the survey line, there is a corresponding obvious difference between the individual migration results and results of the whole stack on Models IIA and IIB based on wave field records acquired at shot point position (2000, 2) and (2250, 2). If we use the wrong velocity model in analysis, the middle-deep layers will be severely deformed. This is illustrated in Fig. 11b where it can be seen that using the wrong model will have significant influence on the image field energy and the clarity of middle-deep layer. Analysis performed on seismic reflection data acquired against the direction of the survey line also drawn the same conclusion.

4 Conclusions

In this paper, we try to find an explanation as to why migration imaging is blurred, and field energy is weaker in middle-deep layers when acquired the seismic reflection data from the undulating seafloor at certain times. We then analyzed and discussed the influence of both slight and significant changes on the seafloor topography on wave field records and migration imaging profiles. The following conclusions can be drawn from this study.

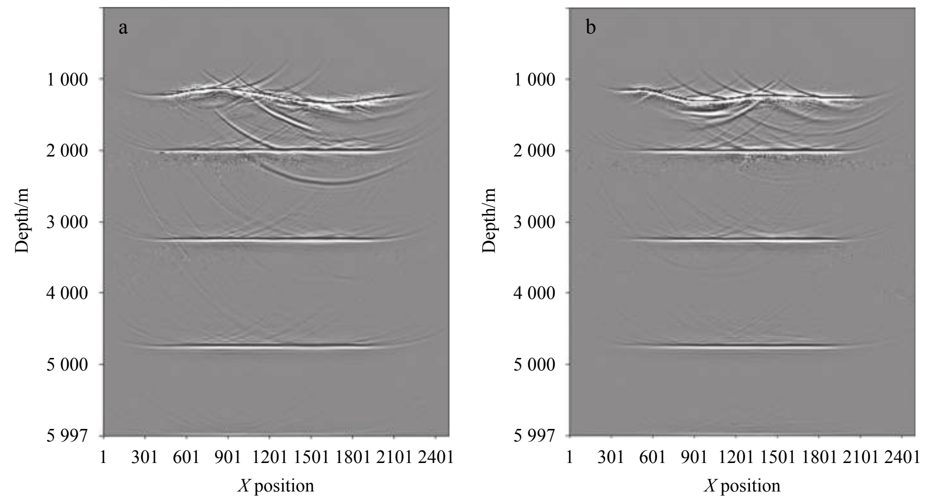

Fig. 8. The respective offset results of the wave field records acquired at 750, 1000, 1250, 1500 points on Models IIA (a) and IIB (b).

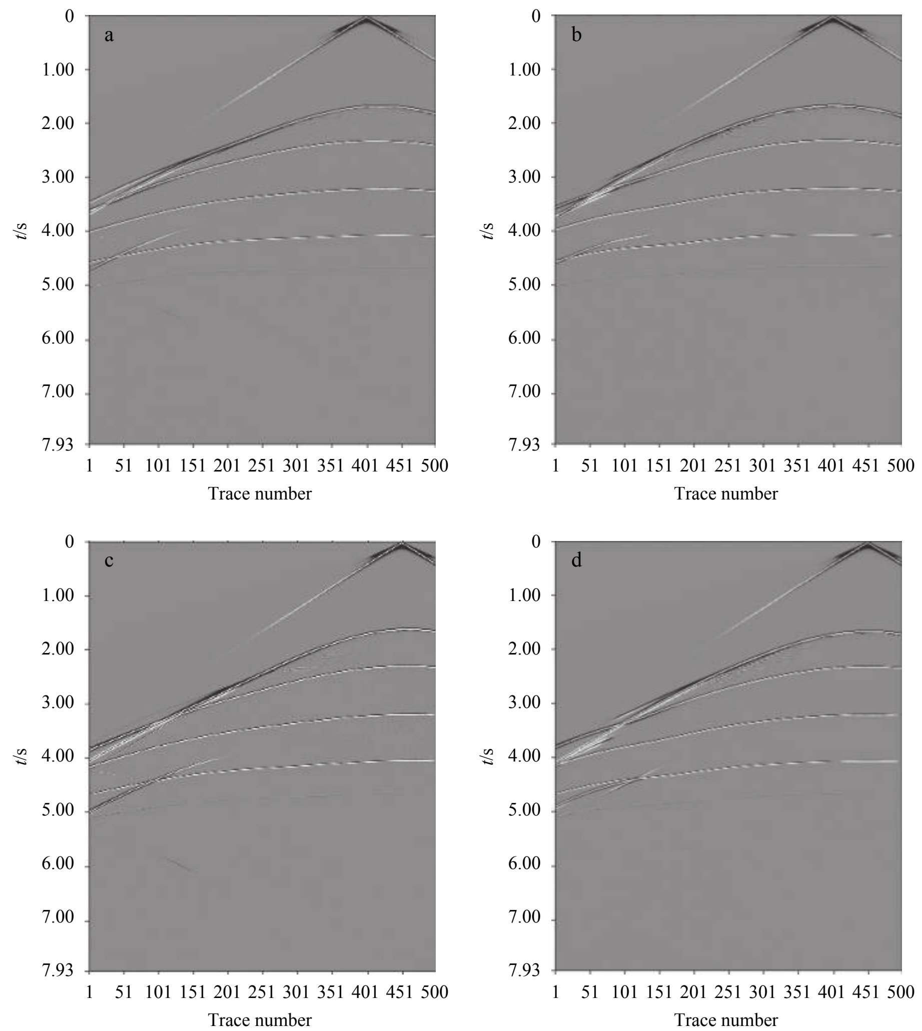

Fig. 9. Wave field records at source point (2000, 2) (a, b), and at (2250, 2) (c, d) on Models IIA (a, c) and IIB (b, d).

(1) For the velocity model with slight change, by comparing the wave field records acquired at the same point on original Models IA and IB, it can be seen that there is a slight difference at the point far offset and a slight influence on the energy level in the middle-deep layers.

(2) For the velocity model with significant change, by comparing the wave field records acquired at shot Points (50, 2), (250, 2), (2000, 2) and (2250, 2) on both Models IIA and IIB, it can be

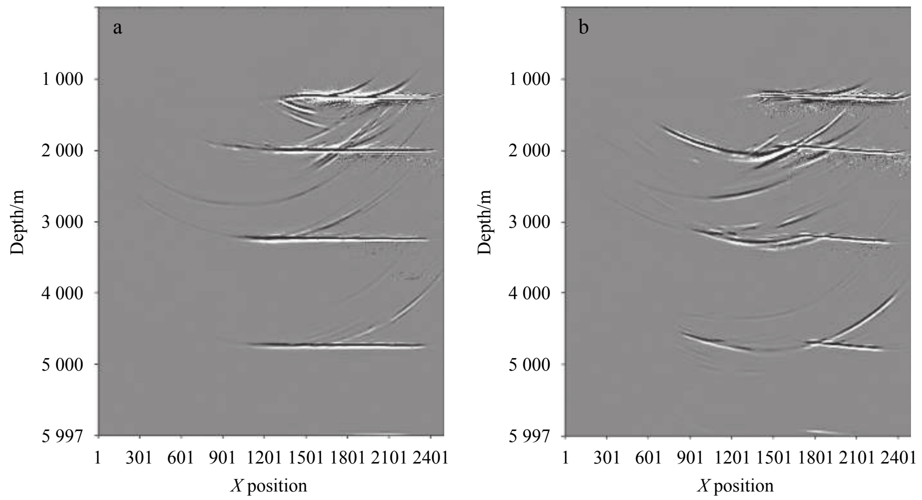

Fig. 10. The offset results of the wave field records of model IIB acquired at source Points (2000, 2) and (2259, 2) on Models IIB (a) and IIA (b).

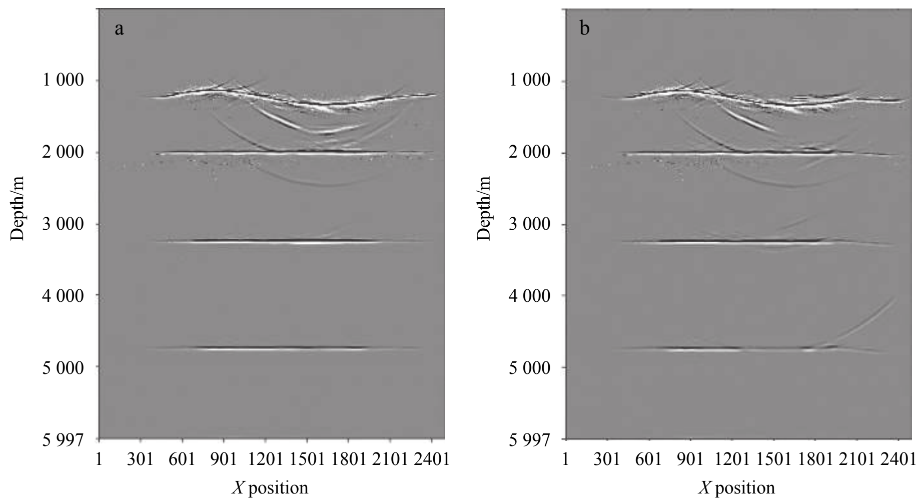

Fig. 11. The migration stack profile of the offset results of the wave field records of model IIA acquired at shot Points (725, 2), (1000, 2), (1250, 2), (1500, 2) and the offset results of the wave field records of Models IIA and IIB acquired at source Points (2000, 2) and (2250, 2). a. The offset results of the wave field records of model IA acquired at shot Points (725, 2), (1000, 2), (1250, 2), (1500, 2), (2000, 2), (2250, 2) on the velocity Model IIA; and b. the offset results of the wave field records of Model IIA acquired at source points shot Points (725, 2), (1000, 2), (1250, 2), (1500, 2) and the offset results of the wave field record of model IIB acquired at shot point position (2000, 2), (2250, 2) on the velocity Model IIA.

seen that there is an obvious difference in the distant trace and in the energy of the middle-deep layers.

(3) For the velocity model with slight change, whether seismic reflection data is acquired along the direction of the survey line or against the direction of the survey line, there is no difference between the profile of the single shot record on the original model and the model with changes. Therefore, the difference in the whole overlay profile is not significant.

(4) For the velocity model with significant change, whether seismic reflection data is acquired along the direction of the survey line or against the direction of the survey line, there is obvious difference between the profile of the single shot record on the original model and the model with changes. By comparing the results, it is clear that if the wrong model is used, the middle-deep layers will be blurred and severely deformed and influence the image field energy in the entire stack profile as a result.

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