Joint imaging with streamer and ocean bottom data

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ABSTRACT

In the past we have shown that up-going and down-going (mirror) imaging can be combined in a joint inversion. We extend the method to joint-inversion of nodes and streamers data. Compared to conventional post-imaging merging, the joint inversion enhances resolution, suppresses migration artifacts, and more importantly, brings up the relative amplitude of true reflectors in the subsurface. We present a linearized inversion scheme for imaging narrow-azimuth and ocean-bottom data. We demonstrate the concept and methodology in 2D with a synthetic Marmousi model.

INTRODUCTION

Recent advances in seismic acquisition and imaging, and improved understanding of the relationships between seismic data and rock-fluid properties have contributed to the successful applications of time-lapse seismic to hydrocarbon reservoir monitoring. However, a complex network of in-sea and sub-sea installations often poses restrictions on seismic vessels near the production facility. Operators wishing to monitor production at these sites are faced with operational difficulties when using the conventional towed-streamer method. The negative impact of such restrictions has been mitigated with undershooting, which utilizes independent shot and streamer vessels to navigate around obstacles. However, even with undershooting, acquisition repeatability is difficult. For example, there are still missing short-offset illuminations, and azimuth distribution can be inconsistent between monitoring surveys.

Boelle et al. (2010) have proposed the use of autonomous ocean-bottom nodes (OBN) as a solution for imaging around obstacles. Figure 1 compares the source and receiver geometry between towed-streamer and OBN surveys along the crossline direction of the streamer survey. Autonomous receivers can be planted close to the production facility for acquiring infill time-lapse seismic data to complement streamer data and give a full picture of the target zone. Although it has the advantage of illuminating around the production facility, the OBN method has its own unique processing challenges.

One challenge is obtaining good up-down-separated data from a four-component recording of OBN data. In an ocean-bottom survey, the signal can be classified into an up-going primary and down-going mirror signal (Figure 2). Dash et al. (2009)

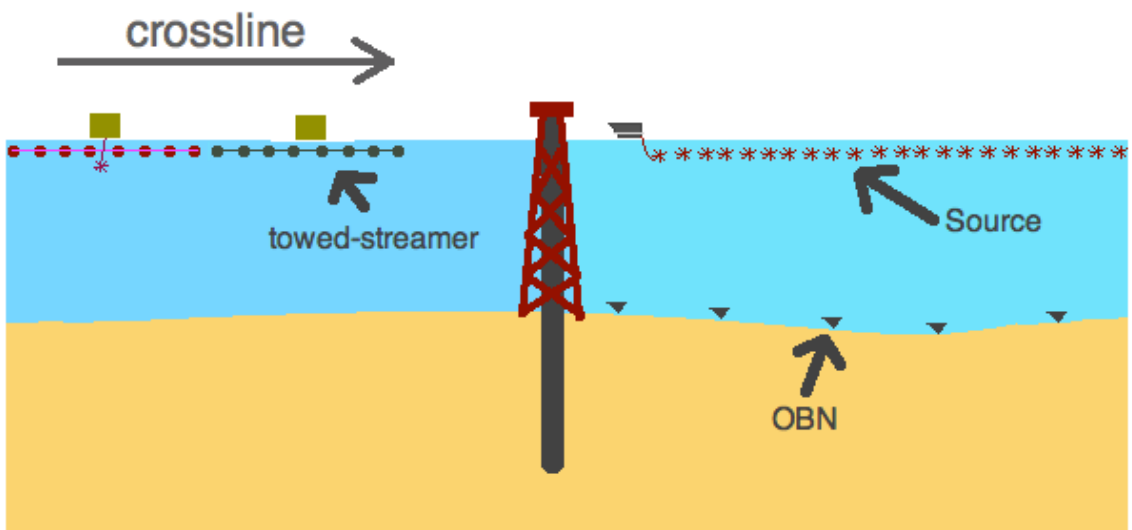

Figure 1: The source and receiver geometry of a towed streamer survey and an OBN survey along the crossline direction. [**NR**]

have used the down-going mirror signal in the migration of OBS data, which yields a wider illumination for sparsely spaced nodes. A reliable migration image requires the hydrophone signal to be decomposed into up- and down-going waves using the geophone and hydrophone recordings. In the case of imperfect up-down separation, there will be residual up-going energy or shear noise in the down-going mirror data. Such energy can give spurious artifacts in the migration image. The OBN image cannot completely replace the streamer image; instead, it is used to complement the streamer image.

Instead of treating the streamer and the OBN images separately, we propose an iterative linear least-squares inversion scheme that could coherently combine the information from the two images. The objective of the data processing is to put everything together and not overload the interpreter with alternative images. Combined ocean bottom nodes and streamer surveys offer the best of both methods: the economy of streamers and the ability of nodes to cover obstructed areas. Such an inversion can improve the structure and aperture of the seismic images by using two sets of signals. In the following sections, we will first discuss the theory of the joint linearized least-squares inversion, and then we show the results of applying our inversion scheme to a 2D Marmousi model.

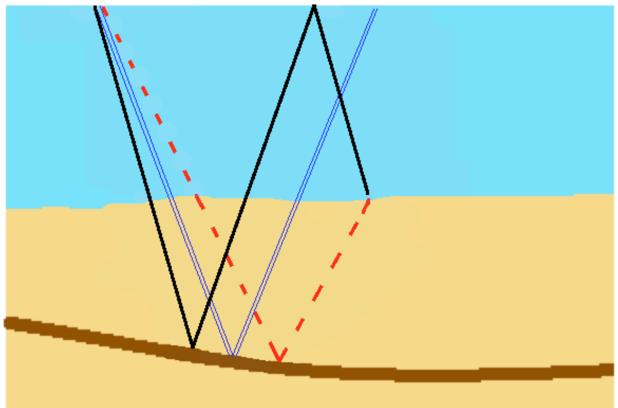

Figure 2: Three main modes of imaging. Up-going ocean bottom data in dashed-red, mirror ocean-bottom data in solid-black, and streamer data in double-line blue. Notice the subsurface reflection point is different for each mode given the same offset distance between the source and the receiver. [**NR**]

THEORY

Linearized Inversion

We pose the imaging problem as an inversion problem by linearizing the wave-equation with respect to our model ($m(\mathbf{x})$). Assuming that the earth behaves as a constant-density acoustic isotropic medium, we linearize the wave equation and apply the first-order Born approximation to get the following forward modeling equation:

$$d^{mod}(\mathbf{x}_r, \mathbf{x}_s, \omega) = \sum_{\mathbf{x}} \omega^2 f_s(\omega) G(\mathbf{x}_s, \mathbf{x}, \omega) m(\mathbf{x}) G(\mathbf{x}, \mathbf{x}_r), \tag{1}$$

where d^{mod} represents the forward modeled data, ω is the temporal frequency, $m(\mathbf{x})$ represents the reflectivity at image point $\mathbf{x}$, $f_s(\omega)$ is the source waveform, and $G(\mathbf{x}_s, \mathbf{x})$ is the Green's function of the two-way acoustic constant-density wave equation. Note that G is actually ω dependent. It is important to point out that the adjoint of the forward modeling operator is the migration operator:

$$\mathbf{m}_{mig}(\mathbf{x}) = \sum_{\mathbf{x}_r, \mathbf{x}_s, \omega} \omega^2 f_s^*(\omega) G^*(\mathbf{x}_s, \mathbf{x}, \omega) G^*(\mathbf{x}, \mathbf{x}_r) d(\mathbf{x}_r, \mathbf{x}_s, \omega). \tag{2}$$

The inversion problem is defined by minimizing the least-squares difference between the synthetic and the recorded data: One can use various types of propagators to formulate the Green's function. In our study, we use the two-way propagator. In this case, the migration operator is equivalent to reverse time migration (RTM). The inverted image ($m(\mathbf{x})$) is better than the migration image in the sense that its forward-modeled data fits the recorded data. Next, we discuss how to apply linearized inversion to jointly image with streamer and OBN data.

Joint imaging

Linearized inversion can combine different sets of data that share the same model. In Wong et al. (2010), we show that up-going and down-going (mirror) imaging can be combined in a joint inversion. We now extend the method to joint-inversion of nodes and streamers data. The fitting goal is:

$$0 \approx \begin{bmatrix} \mathbf{L}_{str} \\ \mathbf{L}_{OBN\downarrow} \end{bmatrix} \mathbf{m} - \begin{bmatrix} \mathbf{d}_{str} \\ \mathbf{d}_{OBN\downarrow} \end{bmatrix}, \tag{3}$$

where $\mathbf{L}$ is the forward-modeling operator that corresponds to equation 1. The subscripts $_{str}$ and $_{\downarrow}$ denote streamer and OBN-mirror, respectively. Our goal is to obtain a final image that consistently explains the two data sets.

The major benefit of joint inversion is that it attenuates the migration artifacts caused by spurious energy in the original recorded data. Spurious energy can occur due to imperfect pre-processing. For example, even with the most advanced multiple-removal methods, surface and internal multiples energy can still be present in the field data. For OBN, there is an additional challenge of removing the shear and up-going energy in the mirror signal. Next, we will look at a 2D synthetic study based on the Marmousi model.

SYNTHETIC EXAMPLE

Figures 4 (a) and 4 (b) shows the velocity and reflectivity models used. The model is 2.8 km deep and 8 km wide with a spacing of 10 m. To simulate a monitoring survey, we assume there is an existing production structure that spans the location from x=3950-4000 m. The water depth is about 1000 m. Figure 3 shows a plane map view of the streamer survey and the OBN survey.

Figure 3 a shows a snap shot of the streamer survey during undershooting. In our 2D synthetic study, we create synthetic data along with shots and receiveres lined along the crossline direction, cutting through the production platform. Shots run from 0 to 8000 m on the sea surface at an interval of 350 m along the 2D line. There are 8 receivers to the left and to the right of each shot, spaced at 50 m apart. This geometry captures the same sub-surface illumination range as a dual-shot towed-streamer survey along the crossline direction. The towed-streamer cannot be within 500 m from the platform, which leads to illumination gap. We create two additional shots undershooting near the platform.

For the OBN survey, receivers are placed from x=2000 to 6300 m at the ocean-bottom with a 400 m spacing. The shot carpet spans the entire model along the

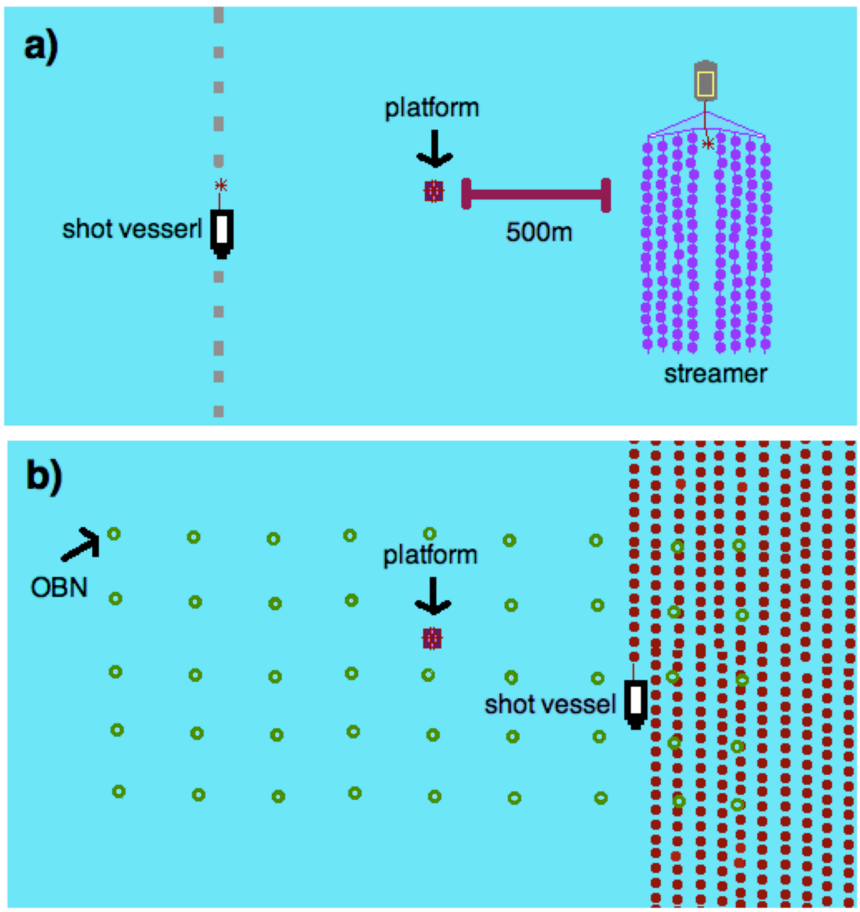

Figure 3: (a) Plane map view of streamer survey during undershooting. Streamer must be at least 500m from the platform. (b) Plane map view of OBN survey. The shot carpet (red circles) is much denser than the receiver grid (green open cicles). [**NR**]

sea surface except in the area within 50m of the platform. For the OBN data, we forward-modeled the down-going mirror signal only. We added 10 percents of the up-going signal as noise to the data to simulate imperfect up-down separation.

Figure 4 (c) and 4 (d) show the reverse-time migration (RTM) image of the streamer survey and the OBN survey, respectively. By comparing with the original model, we can see different kinds of artifacts in the two results. The streamer image looks noisy in general because of the sparse shot spacing. The area beneath the obstruction is poorly illuminated. The OBN image is less noisy because of the dense shot carpet. However, there is a spurious event at depth z=1200 m. This spurious reflector is caused by imperfect up-down separation. In addition, the dipping reflector near x=5500 m and z=2400 m is not well illuminated in the OBN image.

For comparison, we individually perform linearized inversion on the two data sets. The resulting images are shown in (a) and (b) of Figure 5. We can see an overall improvement from the migration image in (c) and (d) of Figure 4 to the inversion image in (a) and (b) of Figure 5. In general, we can see that the inverted images contain higher resolution and better amplitude information than the migrated images. Linearized inversion can discrimmiate certain artifacts and remove them from the image. For example, the annotate artifacts in Figure 4 c) are suppressed in 5 (a). For the OBN survey, one noticeable improvement is the wider illumination. In the next section, we will explore the effect of joint inversion on the output image.

Joint Inversion

A joint inversion is performed in a least-squares sense with the objective goal described in equation 3. Panel (c) of Figure 5 shows the image after joint inversion. Notice that the joint image is better than the streamer inversion image around the platform area (x=3950-4000 m), as shown in (c) and (a) of Figure 6, respectively. Moreover, the joint image is better than the OBN inversion image for the dipping reflectors, as shown in (b) and (c) of Figure 7.

In our example, the joint image is able to attenuate, but cannot completely remove the spurious artifact caused by residual up-going energy in the OBN mirror signal. One reason for this is that the streamer data are not well illuminated in that area. Figure 8 compares the energy between the synthetic observed, the forward-modeled, and the residual data for one common-receiver gather in the OBN survey. The forward-modeled data is generated by applying $L_{OBN\downarrow}$ to the final inverted model m after 30 iterations. We can see that most of the energy in the synthetic observed data is explained by the forward-modeled data. Also, notice that the relative amplitude of the residual up-going energy (near 2.3 sec) becomes higher.

DISCUSSION

Our synthetic study shows improvements of the joint inversion image over migrating or inverting either signal alone. There are several considerations that need to be addressed when applying these results to field data.

One consideration is related to the matching of the streamer and the OBN images, because the two surveys are acquired with different sources. Naturally, this leads to different wavelets in the data. Careful deconvolution is needed to make sure the wavelet in the image is consistent between the two surveys. Note that the two data sets are not required to have exactly the same frequency band but only the same phase (e.g., zero-phased).

Another consideration when applying this method to field data is the relative position of the reflectors between the two images. Due to different weather conditions, the water velocity can be different between the two surveys. If the water velocity and static correction is not properly adjusted, the sea-bottom reflector between the two images might not be the same. In addition, errors in positioning sources and receivers can also cause mismatch between the two images. If the mismatch is not severe, one can consider applying warping in the image space (Boelle et al., 2010; Hale, 2011; Ayeni, 2011) by estimating appropriate shifts to obtain a good match. For conjugate-gradient type inversion, this simple technique requires warping when applying the migration operator:

$$\begin{aligned} \Delta\mathbf{m} &= \Delta\mathbf{m}_{str} + \mathbf{W}\Delta\mathbf{m}_{OBN}, \\ &= \mathbf{L}_{str}^T\mathbf{r}_{str} + \mathbf{W}\mathbf{L}_{OBN}^T\mathbf{r}_{OBN}, \end{aligned} \tag{4}$$

where $\mathbf{W}$ is the forward warping operator that will match the OBN image update $\Delta\mathbf{m}_{OBN}$ with the streamer image update $\Delta\mathbf{m}_{str}$. $\Delta\mathbf{m}$ is the total image update. In the modeling direction, we apply unwarping before forward-modeling the gradient:

$$\begin{aligned} \Delta\mathbf{r} &= \Delta\mathbf{r}_{str} + \Delta\mathbf{r}_{OBN}, \\ &= \mathbf{L}_{str}\Delta\mathbf{m}_{str} + \mathbf{L}_{OBN}\mathbf{W}^{-1}\Delta\mathbf{m}_{OBN}, \end{aligned} \tag{5}$$

where $\Delta\mathbf{r}$, $\Delta\mathbf{r}_{str}$ and $\Delta\mathbf{r}_{OBN}$ search the total, streamer, and OBN search directions. $\mathbf{W}^{-1}$ is the unwarping operator.

The computational cost of linearized inversion is higher than that of migration by a factor proportional to twice the number of iterations. For OBN surveys, such additional computational cost can still be affordable. This is because the number of pre-stack calculations needed equals the number of OBN receivers in the survey. The number of migrations needed is substantially smaller than that in a towed-streamer survey. However, for towed-streamer surveys, the computational cost can be substantial. Recently, Dai et al. (2011) suggested using phase-encoding in the linearized inversion, which can reduce the computational cost substantially at the expense of introducing crosstalk into the image. In the future, we plan to combine not only the streamer and the OBN mirror signal, but to combine all 3 modes to produce one coherent image. The three modes are OBN primary, OBN mirror, and streamer data sets:

$$0 \approx \begin{bmatrix} \mathbf{L}_{str} \\ \mathbf{L}_{OBN\uparrow} \\ \mathbf{L}_{OBN\downarrow} \end{bmatrix} \mathbf{m} - \begin{bmatrix} \mathbf{d}_{str} \\ \mathbf{d}_{OBN\uparrow} \mathbf{d}_{OBN\downarrow} \end{bmatrix}. \tag{6}$$

CONCLUSION

Joint inversion can coherently combine the information from the narrow-azimuth towed-streamer and ocean-bottom data. We demonstrate the result with a 2D synthetic Marmousi model. The results show that the joint image is better than the streamer inversion image around the platform area. In addition, the joint image is better than the OBN image for dipping reflectors.

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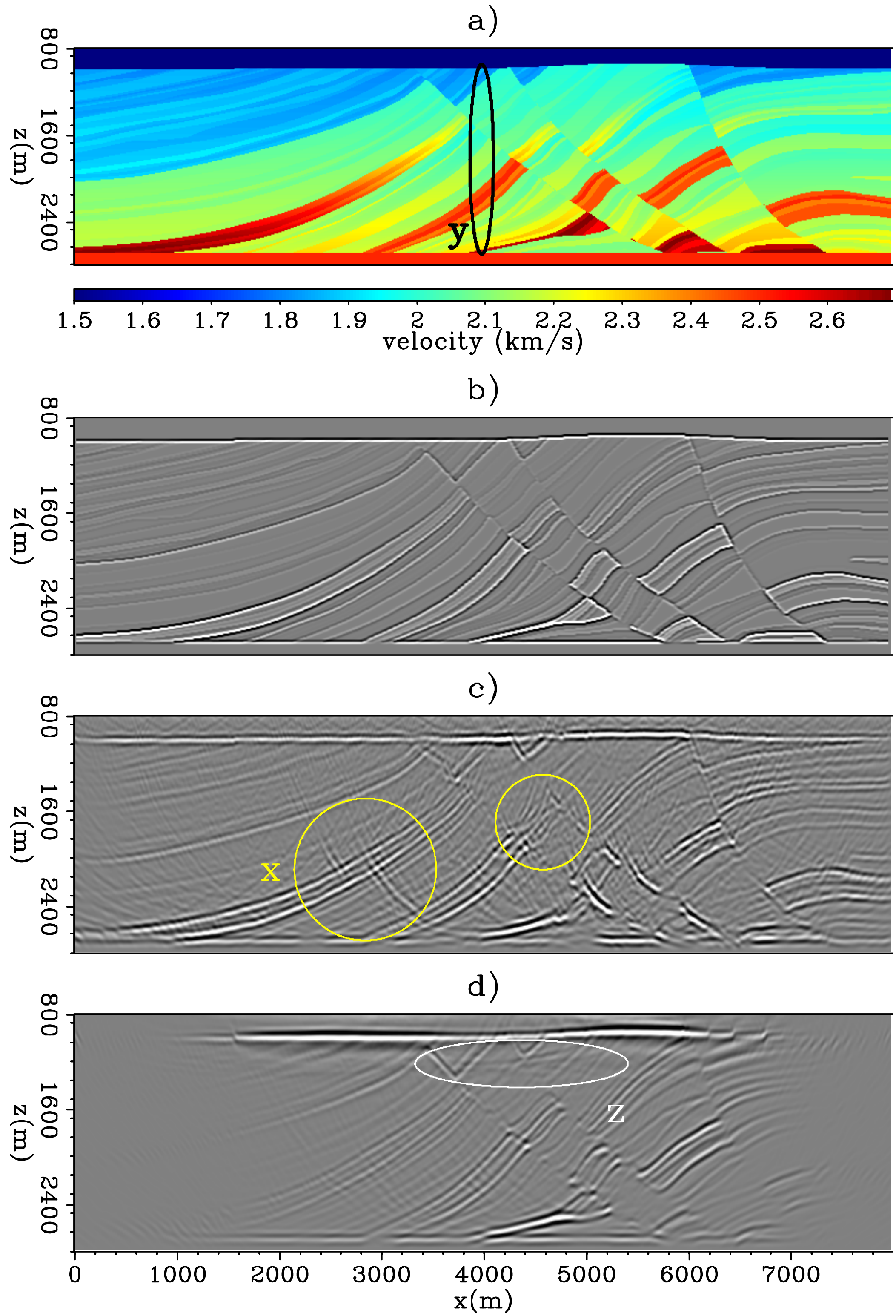

Figure 4: (a) The velocity model, (b) the reflectivity model, (c) the streamer RTM image, and (d) the OBN RTM image with mirror imaging. Even with undershooting, the streamer image shows some artifacts (x) near the production structure (y). The residual up-going OBN energy in the down-going OBN data create some artifacts (z). [**CR**]

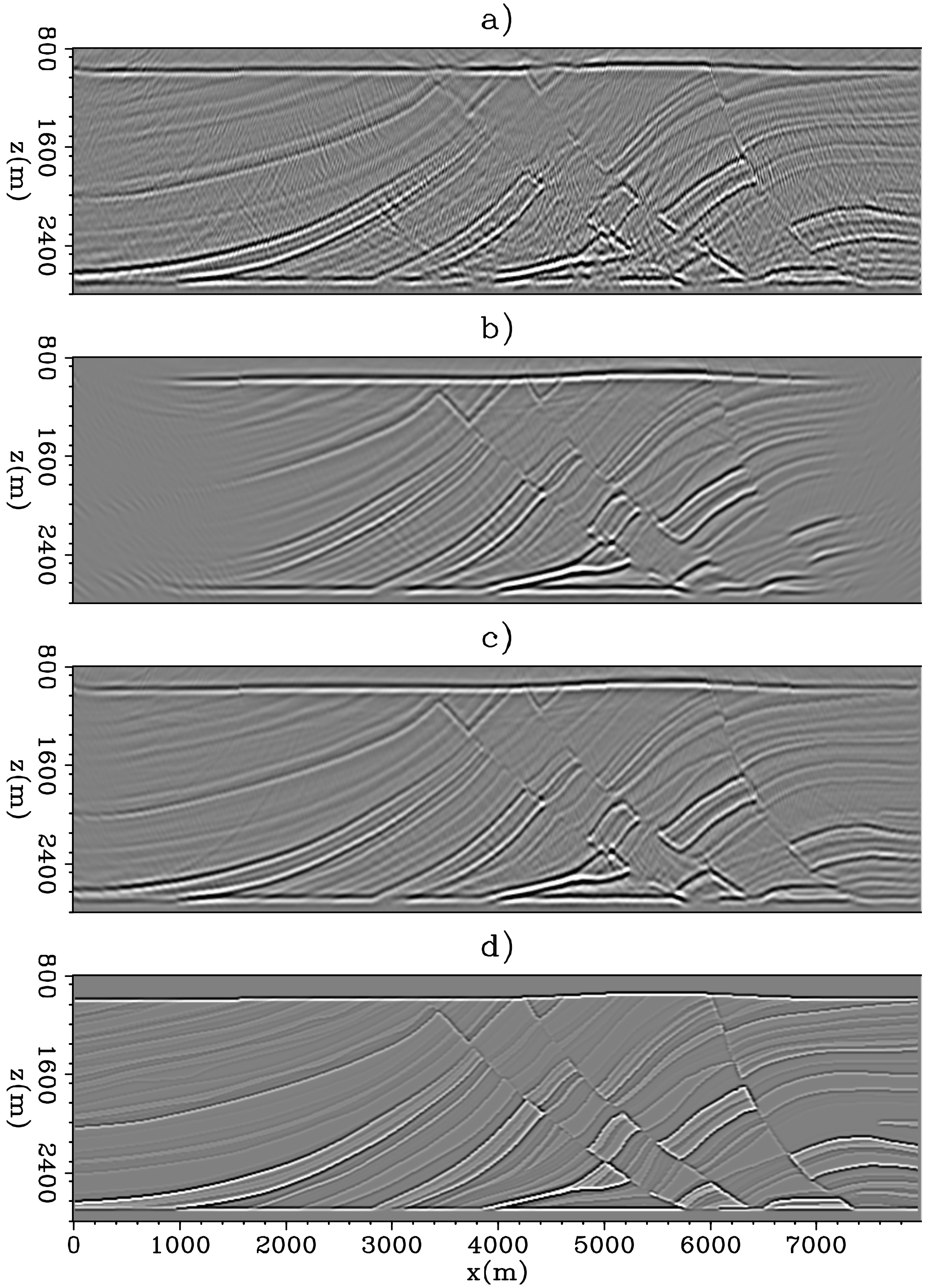

Figure 5: (a) The inverted streamer image, (b) the inverted OBN image, (c) the jointly inverted image, and (d) the reflectivity model. Notice the joint image coherently combines the information between the individually inverted images. [**CR**]

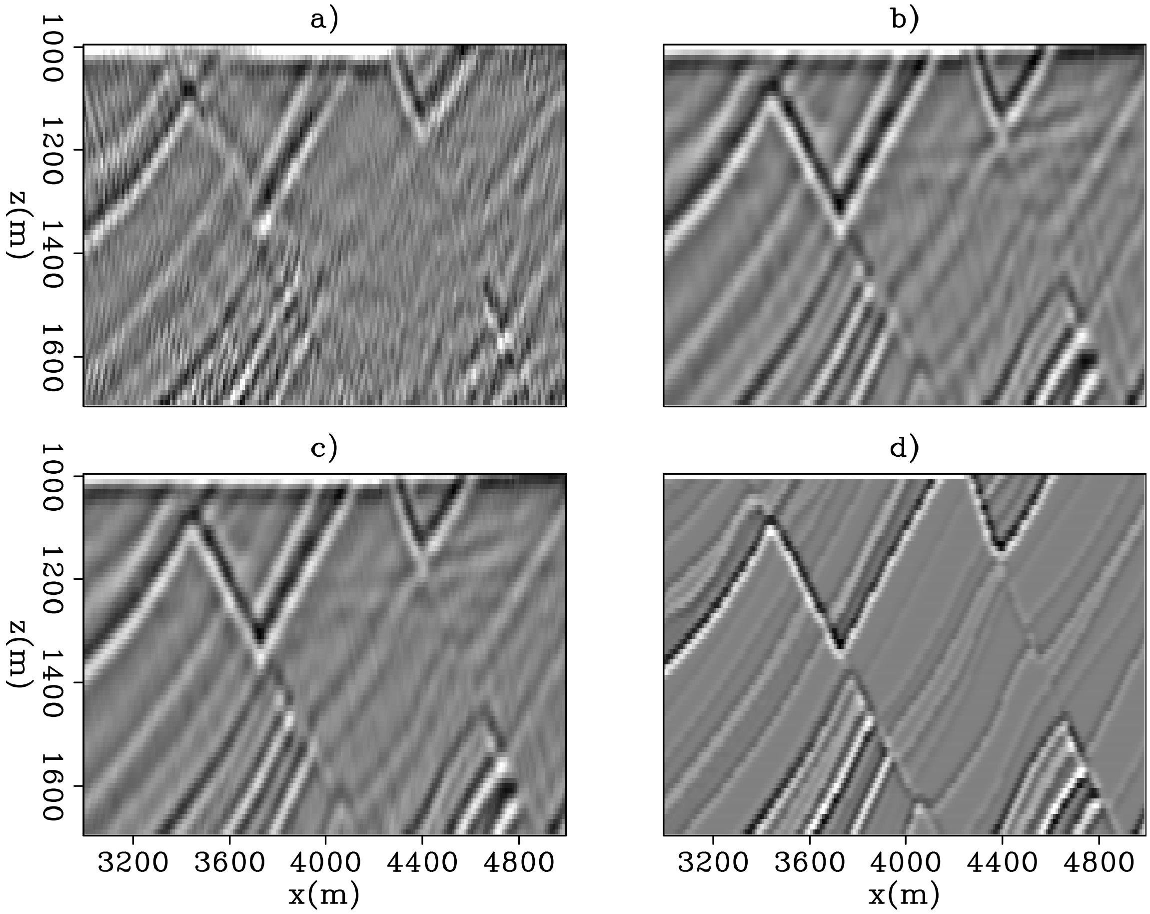

Figure 6: A zoomed section from x=3000-5000 m and z=50-750 m among (a) the streamer inversion image and (b) the OBN inversion image, (c) the joint inversion image and (d) the reflectivity model. The platform is located at horizontal position of x=3950-4000 m. In this region, most of the useful information comes from the OBN mirror data. The joint image is able to attenuate but cannot completely remove the spurious artifact caused by residual up-going energy in the OBN mirror signal. [**CR**]

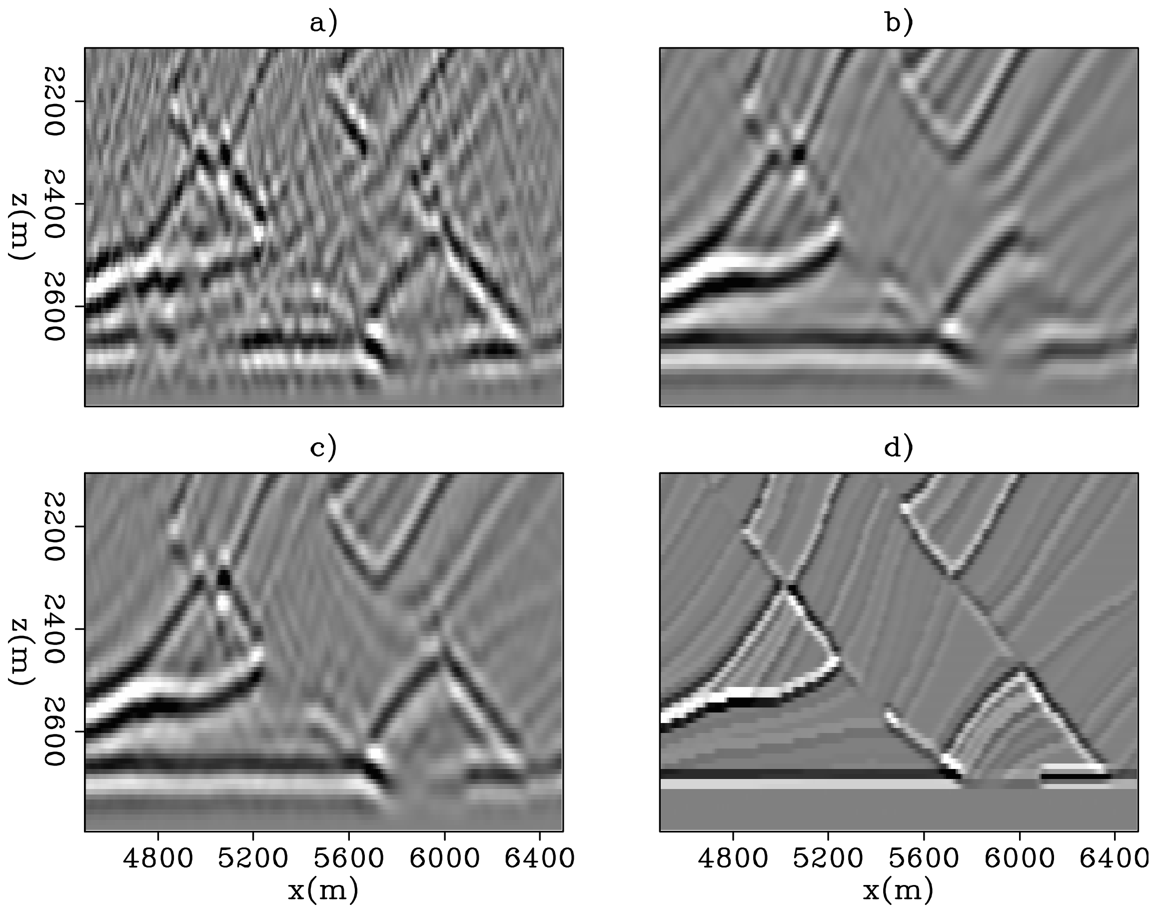

Figure 7: A zoomed section from x=4500-6500 m and z=1300-2000 m among (a) the streamer inversion image, (b) the OBN inversion image, (c) the joint inversion image and (d) the reflectivity model. Although the streamer image looks noisy, joint inversion can properly include the dipping reflector from the streamer image to produce a better joint image. [**CR**]

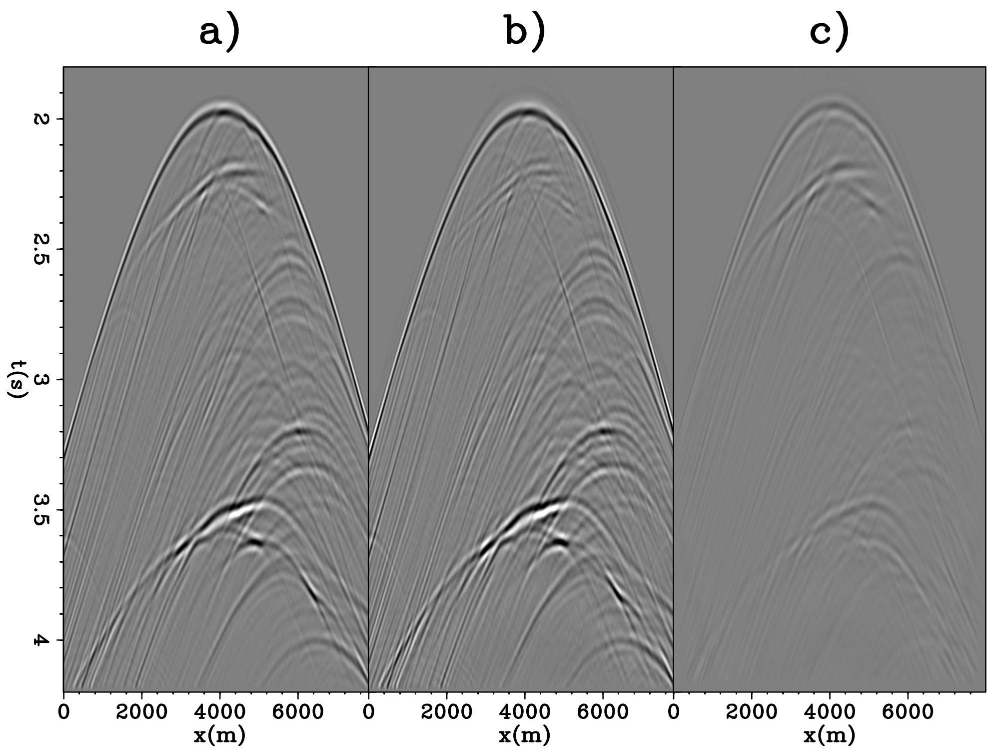

Figure 8: (a) The synthetic observed data, (b) the forward-modeled data, and (c) the data residual for one common receiver gather in the OBN survey. All data are clipped at the same bound. Notice that the relative amplitude of the residual up-going energy becomes higher in the data residual. By incorporating more data to produce a single model, joint inversion can help discrimminate between signal and noise in the data. [**CR**]