Maximize the value of DAS VSP using full wavefields

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Abstract

The acquisition of vertical seismic profiles (VSPs) using distributed acoustic sensing (DAS) has made VSP acquisition a robust technique and a cost-effective tool for reservoir imaging and monitoring. However, VSP acquisition also brings intrinsic challenges due to its limited spatial coverage. DAS recording typically produces data of suboptimal quality with directional sensitivity. Conventional reverse time migration imaging of primaries in DAS VSP data typically results in limited spatial coverage, particularly because events above the shallowest channel cannot be imaged at all. While it has been demonstrated that surface multiples can be complementary in imaging conventional streamer or ocean-bottom-node data, this paper shows that incorporating surface multiples as input for dynamic matching full-waveform inversion (FWI) can have a more significant impact in overcoming the intrinsic limitation and maximizing the value of DAS VSP surveys. Furthermore, the resulting FWI image from inversion has better amplitude fidelity.

Introduction

The 3D vertical seismic profile (VSP) technique has proved effective in reducing well placement risks and time-lapse monitoring of reservoirs, among other applications. The relatively new method of seismic acquisition using distributed acoustic sensing (DAS) has made the VSP technique more cost-effective and a viable solution for reservoir imaging and monitoring as techniques in DAS acquisition mature. DAS VSP data have been processed and analyzed to derive 3D impedance inside a small volume surrounding the DAS cable using data from a single survey (Kazei and Osypov, 2021) and to extract 4D responses using time-lapse data sets (Zwartjes et al., 2017; Kiyashchenko et al., 2020).

However, VSP surveys have limited spatial coverage, even though the limitation can be eased by longer arrays of DAS receivers and dense shot grids at the surface. Conventional processing using primaries usually can image only in a limited angle range in the vicinity around the VSP well/DAS cable. In particular, the well-known directional sensitivity of DAS acquisition results in better recorded signals when the direction of the wave motion deviates only slightly from the cable orientation. Because most DAS cables are deployed almost vertically (if not completely vertically), the wide-angle data from DAS VSP surveys are often less reliable with much lower signal-to-noise ratio (S/N). This limitation makes the reliable imaging scope even narrower when only primaries are used in imaging (Figure 1). Away from that narrow angle, the image quality decreases rapidly, and swing artifacts thus dominate the image away from the wellbore (Figure 1a). While the swing artifacts can be effectively suppressed (see blue arrows and structures within red ellipses in Figure 1) by using structure adaptive aperture during imaging defined at each imaging point (Hu et al., 2023), the resulting image (Figure 1b) recovers structures in a narrow scope, albeit cleaner. In addition, the primary reflection in a DAS survey cannot illuminate the area above the shallowest DAS channel, which prevents this area from being imaged using primaries only. For a typical survey in the Gulf of Mexico, the recorded usable data are often well below the sea bottom and could be up to a kilometer deeper for the data in this study (Chalenski et al., 2016).

Multiples have been utilized in imaging and full-waveform inversion (FWI) applied to non-DAS data acquired in streamer or ocean-bottom-node (OBN) surveys, where the extended illumination from multiples is complementary to that from primaries and can significantly improve the image resolution for especially shallow targets (Davydenko and Verschuur, 2014). The main challenge of including multiples in the input for imaging is the crosstalk among different orders of reflections. Lu et al. (2021) theoretically studied this issue and proved that crosstalk can be suppressed through iterations in least-squares imaging. The aim of this paper is to maximize the value of DAS VSP surveys by FWI image utilizing the full wavefields, including both primaries and multiples, to take advantage of the extended illumination of multiples, especially for imaging the area above the shallowest DAS channel of such surveys. Compared to migration images using primaries only, the resulting FWI image of the full wavefield in a DAS survey images structures above the DAS cable properly with better amplitude fidelity, which we will demonstrate through a 2D synthetic data test and 3D field data tests.

2D synthetic test

Using a 2D model (Figure 2a), synthetic data are generated using a VSP source-receiver geometry. The striking geologic features in the model include a salt body with dipping structure beneath and a steeply dipping fault nearby. Receivers in the simulated DAS VSP survey are arranged in a deviated well, and pressure data are simulated in the reciprocal acquisition geometry. Using primaries only, reverse time migration (RTM) images only the structures surrounding the well trajectory (Figure 2b). By using the full wavefields including multiples as input, least-squares RTM in the data domain (Zeng et al., 2014) yielded an image (Figure 2c) that is far better in terms of resolution and spatial illumination than the one using primaries. In this test, least-squares RTM using the full wavefield significantly improves the images of a VSP survey by taking advantage of extended illumination of the multiples. For the field data test, we often need to update the background model as well, so FWI will be chosen to invert the

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full wavefields for a high-resolution model and to derive FWI images afterward for imaging purposes.

3D DAS VSP field data test

The DAS VSP data set presented in this paper was acquired in the Gulf of Mexico, and an OBN survey was conducted at the same time using the same shots. We processed the raw DAS VSP data and did not have the OBN data to work with, only a legacy OBN RTM volume. Figure 3 illustrates the acquisition geometries. The shot carpet covers an area of 7.5 × 9 km near the surface. The average water depth is about 1.1 km. The DAS fiber was arranged in a well slightly deviated from the vertical direction with the fiber strapped to tubing. Four hundred eleven channels recorded usable data between the 2 and 4 km depth interval with the nominal channel interval at 8 m. The data recorded at shallower channels are too noisy due to field infrastructure and other well paths in close proximity above 2 km depth. Figure 3b shows one of the raw gathers where the downgoing direct arrivals and the first-order multiples can be identified clearly, along with noises including swell noises and tube waves. The data set went through simple time-domain preprocessing such as debubble and removing tube waves before being inverted in FWI as described in the following sections.

Update water layer and shallow sediment using direct and first-order multiples. An initial model is derived from a legacy study using the OBN data set. In the workflow centered at the dynamic matching FWI (Mao et al., 2020), the water layer and shallow sediment were first updated using two events only in the

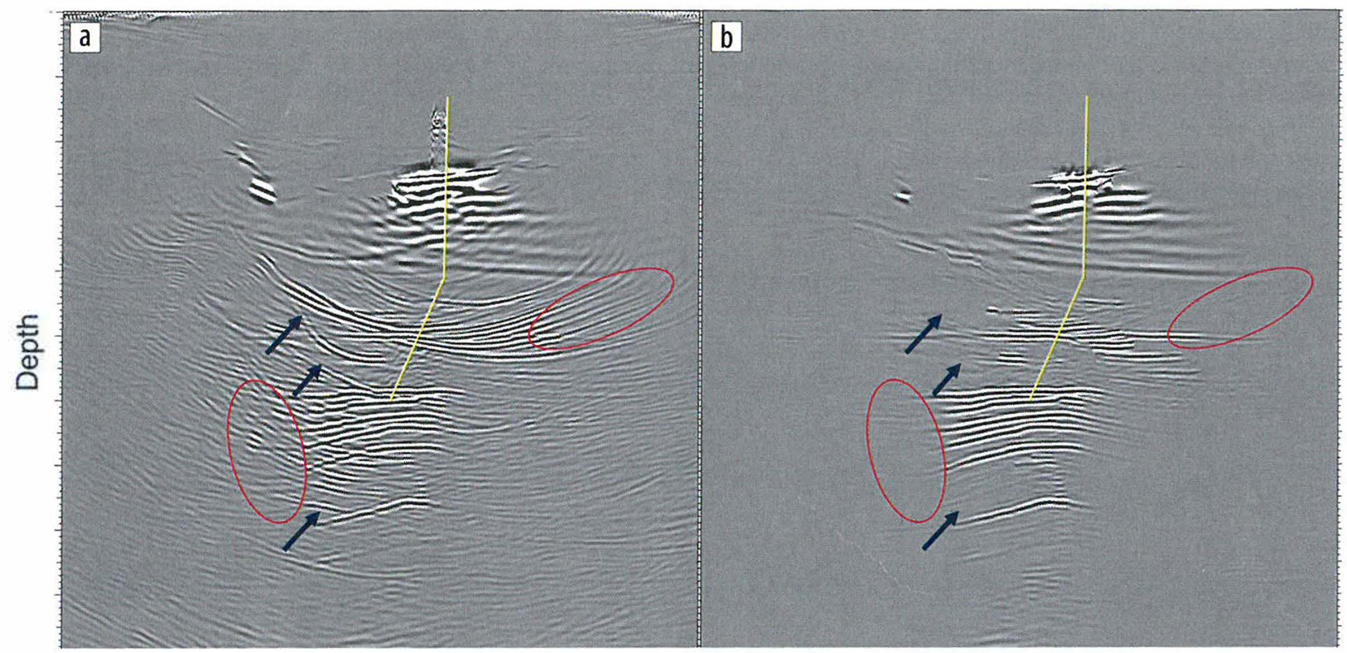

Figure 1. An example showing how swing artifacts can be suppressed by RTM with adaptive aperture (Hu et al., 2023) and a narrow imaging scope using DAS VSP data: the RTM image (a) without and (b) with adaptive aperture.

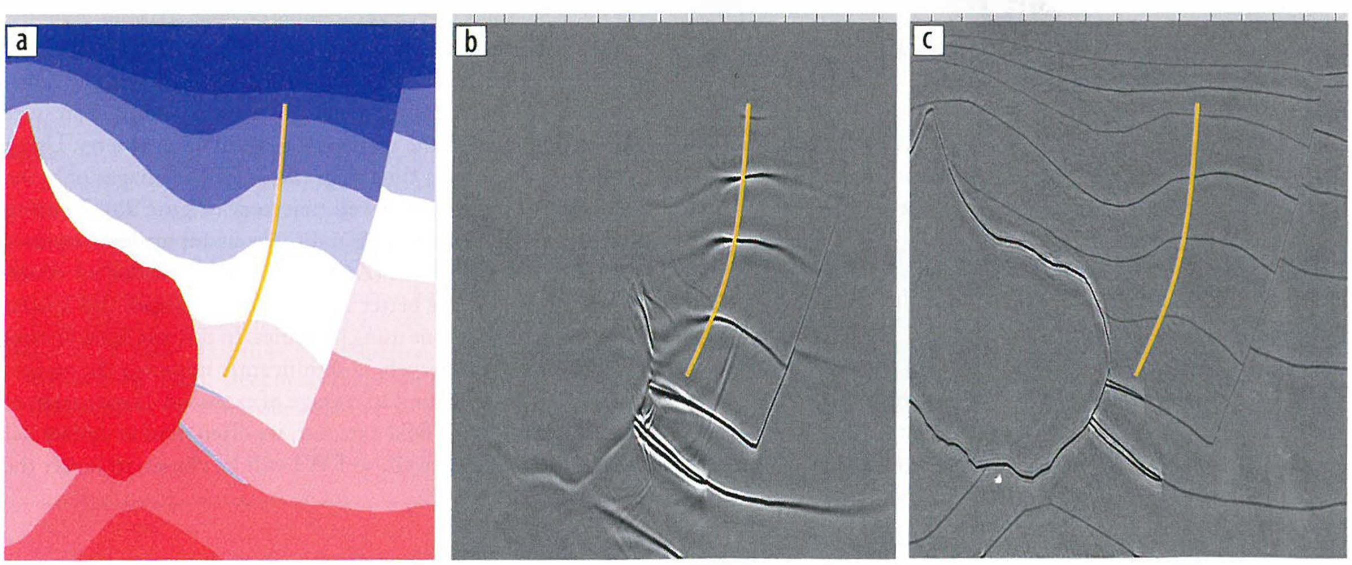

Figure 2. (a) The true V_P model, (b) the RTM image using primaries only, and (c) the image from least-squares RTM using full wavefields.

data after water static correction due to different tidal heights. To facilitate the static correction, the data were first regularized to 25 × 25 m grids. The two events to be inverted include the first arrivals that propagate through the water layer and shallow sediment and the first-order multiples that sample the water layer only as the ray diagrams show in Figure 4a. To facilitate the inversion using only these two events, muting tables for them are carefully prepared and quality controlled by cross-correlating the two events in the observed data with the corresponding events in the synthetic data to ensure only the good quality waveforms are used in the inversion. Two events in the five common receiver gathers recorded at the five shallowest channels were inverted up to 35 Hz in this step because first-order multiples recorded at shallower channels have better S/N (Figures 4b and 4c) in general.

After FWI inversion, the significantly improved normalized cross-correlation shows that the synthetic data and observed data are much better matched (Figure 5b) compared to that using the initial model (Figure 5a). Further comparison on the waveform matching confirms the kinematic improvement of the water velocity, which results in better matching in the waveforms of the first-order multiples after model update (Figure 5c).

Model update using full wavefields. With the water layer and shallow sediment fixed, the model is subsequently updated by inverting the first arrivals in all data. This is to make sure that the whole background model is kinematically correct. Using the updated background model as the initial, the full wavefields were inverted up to 25 Hz in FWI with water layer fixed. Figure 6a shows the final model and the FWI image derived from it (Figure 6b). Compared to the RTM image of the OBN data (Figure 6c), which was acquired at the similar time and using the initial model, the FWI image reconstructs comparable overall structures, with many of the small-scale features in the shallow sediment in the FWI image matching those in the OBN RTM image well. However, as expected, some subsalt structures are more coherent in the FWI image derived using DAS data than the counterparts in the OBN RTM images (green arrows near the salt body in Figures 6b and 6c). The structures are compared at one more location in Figure 8 in 3D perspective (green arrow in Figures 8b and 8c). The overlay of FWI model and FWI image in Figure 8a shows that the velocity anomalies in the FWI model conform to the geologic structures.

Compared to the RTM image using primaries only (Figure 7a), the FWI image (Figure 7c) recovers structures in a much wider scope, especially in the shallow sediment, that are completely missed in the primary-only image. By mirrored RTM imaging using the full wavefields (Figure 7b), the shallow sediments have the chance to be imaged; however, artifacts due to crosstalk show up in the image (e.g., the event indicated by the red arrow in Figure 7b). The crosstalk due to interference between different orders of multiples in the FWI image has been suppressed well in the waveform inversion.

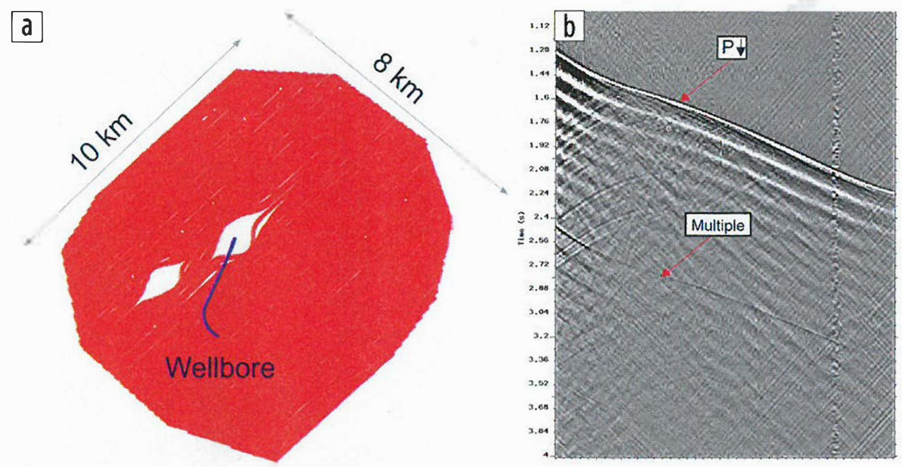

Figure 3. (a) The source-receiver geometry of the 3D DAS VSP survey and (b) a raw shot gather. In (a), the red dots indicate the shot positions and the blue dots the DAS receiver positions. Downgoing P waves and multiples are indicated in (b).

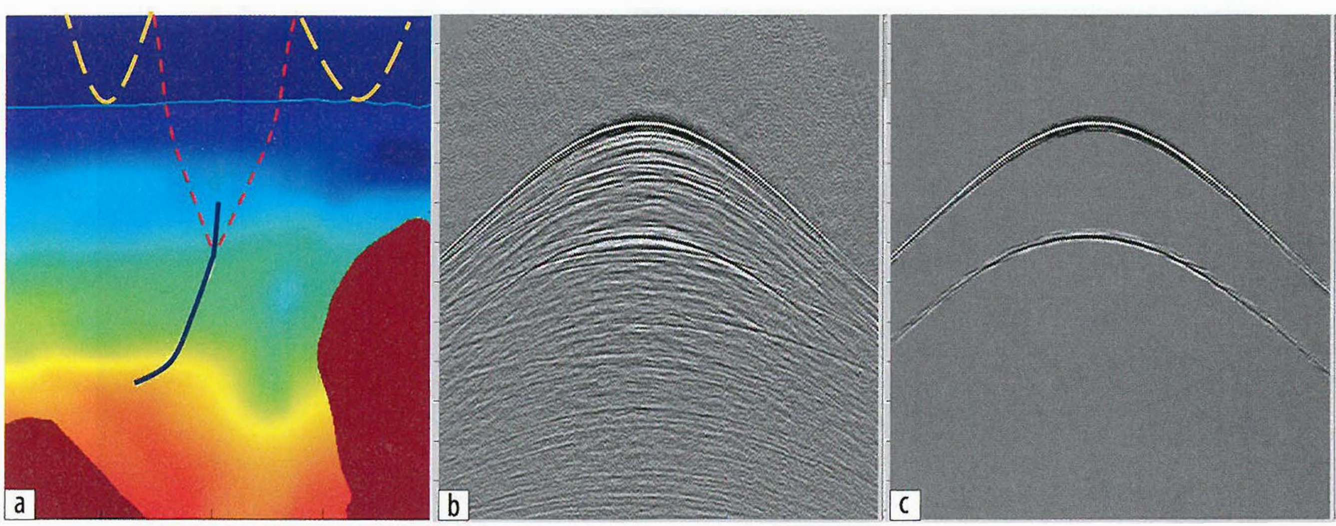

Figure 4. The initial model used for FWI and ray diagrams (a) for the first arrivals (red) and first-order multiples (yellow), (b) a part of a common receiver gather, and (c) the gather after muting such that only first arrivals and first-order multiples remain.

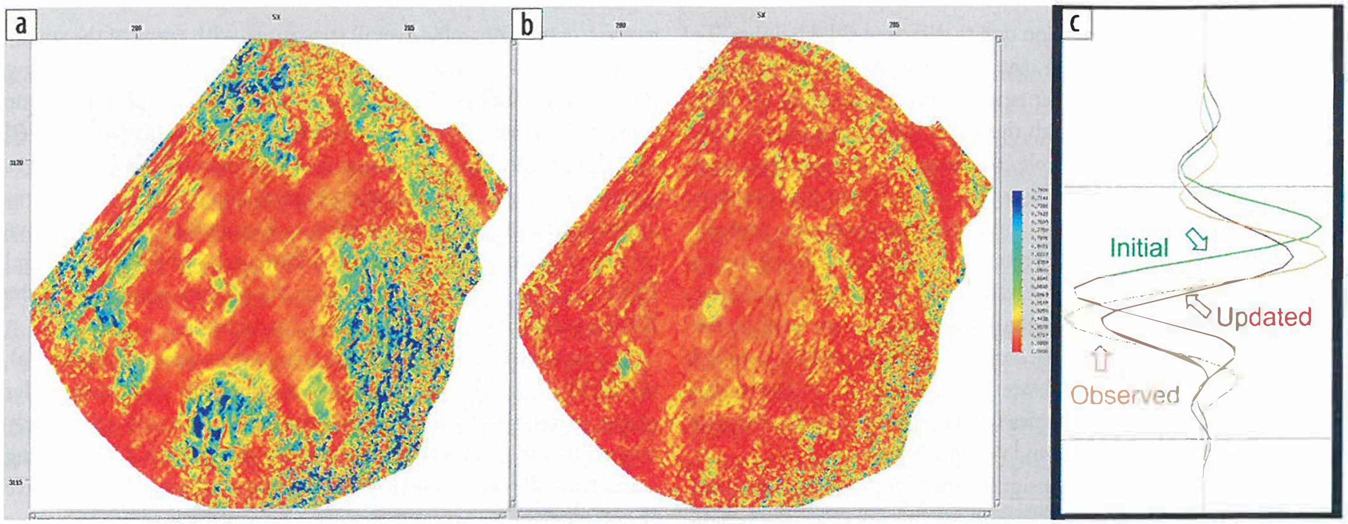

Figure 5. The cross-correlation map as a function of shot locations (a) before and (b) after the FWI model update, and (c) an example of the waveform matching of first-order multiples before and after the model update.

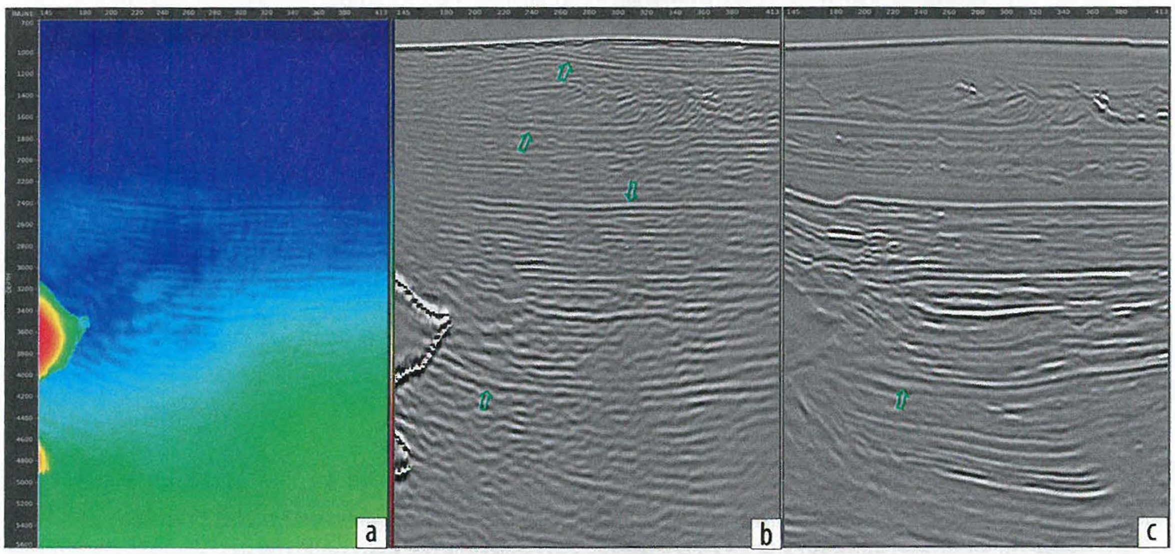

Figure 6. (a) The FWI updated model, (b) the FWI image derived from using the model in (a), and (c) the RTM image using the OBN data set.

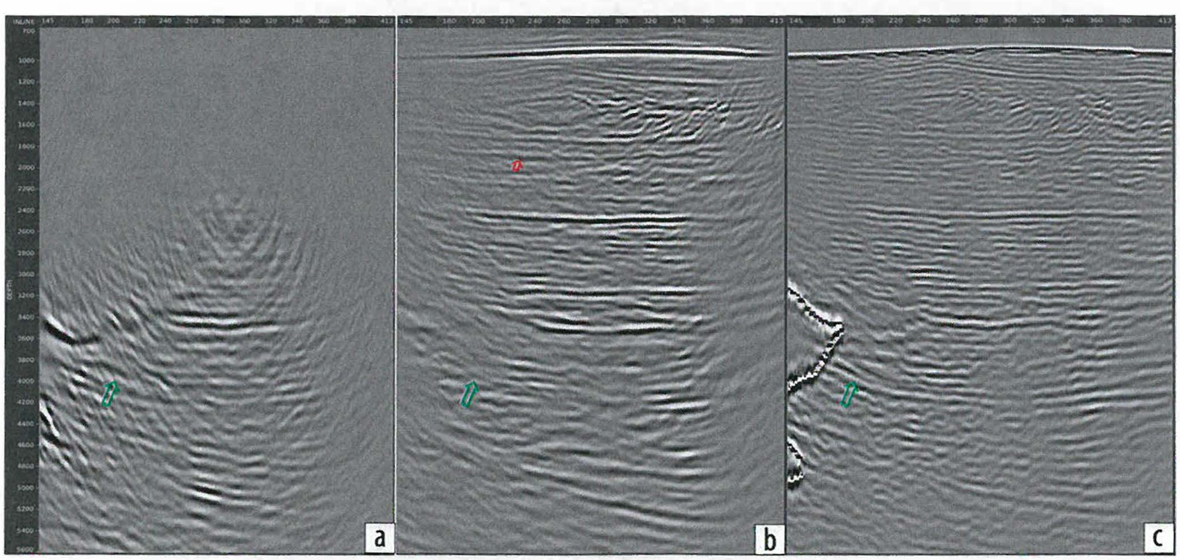

Figure 7. (a) The RTM image using primaries only, (b) the mirrored RTM image using downgoing waves, and (c) the FWI image, all from using the FWI updated model shown in Figure 6a.

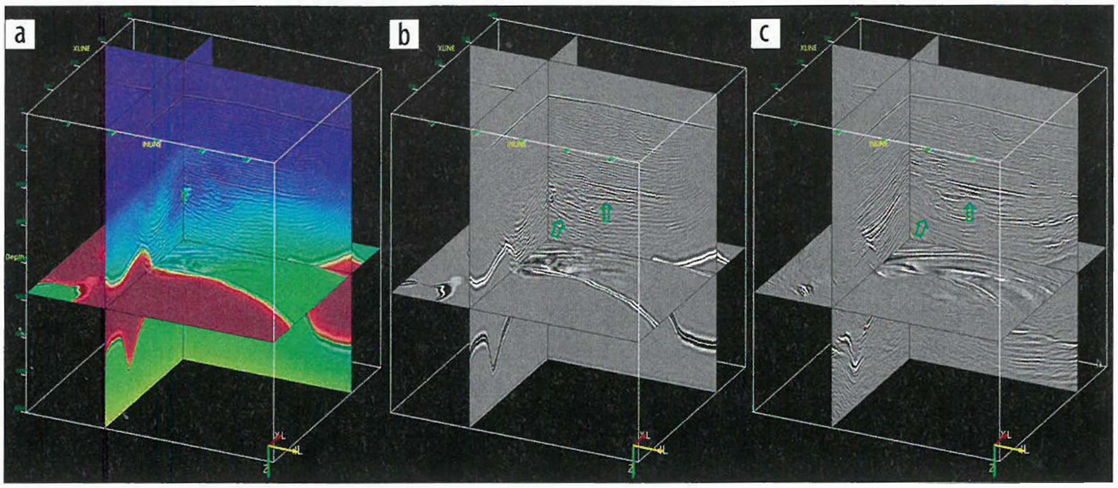

Figure 8. (a) The FWI image overlaid with the FWI model, (b) the FWI image, and (c) the OBN RTM image in 3D perspective.

Discussions and conclusions

This paper describes a workflow implemented to invert full wavefields in DAS VSP data, especially to overcome the shortcoming of limited illumination in VSP data acquisition. The full wavefields include both primaries and multiples and have better illumination than the data that include primaries only. The DAS channels at 8 m intervals provide enough sampling folds for the structures, and the 40 m of gauge length in DAS recording yielded data with a reasonably good S/N. FWI has been performed in the reciprocal acquisition geometry for efficiency purposes. The DAS receiver response is absorbed into the source simulation, including the source wavelet. The FWI method applied in this study is largely insensitive to the directional amplitude variation in DAS data because the observed waveforms are matched dynamically by the synthetic ones (Mao et al., 2020). Crosstalk resulting from interference between different orders of reflections is successfully suppressed by inversion. The workflow in this study consists of three sequential steps, from updating the water layer and shallow sediments using selected events to updating the whole model in full resolution using full wavefields, with FWI applied at each step. The final model is well validated because the derived FWI image from it can be cross-checked well against a legacy OBN RTM image using non-DAS data even for small-scale features in the shallow sediments, while some deeper subsalt structures are more coherent in the former than in the latter RTM image. This successful utilization of the full fields maximizes the value of DAS VSP data acquisition. Future study could extend the inversion into elastic FWI (Liu et al., 2024). TLE

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Data and materials availability

Data associated with this research are confidential and cannot be released.

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