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157
Joint OBN and 3-D DAS-VSP data acquisition and processing in East China Sea

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ABSTRACT

This paper introduces the 3-D DAS- (Distributed Acoustic Sensing) VSP (Vertical Seismic Profiling) data simultaneously acquired by a downhole armored optical cable with an OBN (Ocean Bottom Node) data acquisition project in the East China Sea, and the results of 3-D DAS-VSP data imaging processing and interpretation. The usual 3-D VSP data imaging processing steps includes: observation system definition, preprocessing, first arrival picking, static correction, amplitude compensation, deconvolution, wavefield separation, velocity analysis and imaging. According to the characteristics of offshore 3-D VSP downgoing multiples, the offshore 3-D VSP downgoing multiple imaging technique has been innovatively developed, which greatly expands the 3-D DAS-VSP imaging range and improves the overall 3-D DAS-VSP imaging quality. The 3-D DAS-VSP downgoing multiple reflection wave imaging shows significant imaging quality improvement in comparison with the vintage 3-D OBC (Ocean Bottom Cable) data imaging. The tracing of the reservoir and formation boundary become much easier and more confident in both new OBN data imaging and 3-D DAS-VSP data imaging than in the vintage 3-D OBC data imaging. Borehole-to-surface joint seismic exploration is a 3-D seismic exploration method formed by the combination of surface seismic and VSP survey simultaneously. Using 3-D DAS-VSP data and borehole-to-surface jointly acquired seismic data, accurate time-depth relationship, formation velocity, deconvolution operator, spherical diffusion compensation factor, absorption attenuation factor and anisotropy parameters around the wellbore can be obtained. These parameters can be used to enhance significantly the surface 3-D seismic data processing.

Introduction

The Pinghu oil and gas field is in the middle of the Pinghu fault structural belt on the west side of the Xihu Sag in the Shelf Basin of East China Sea, bounded by the Pinghu main fault on the west side. The main fault of Pinghu is NNE trending and has an extension length of more than 100 kilometers, which plays an important role in controlling the formation of the Pinghu Formation in the Pinghu oil and gas field. The field is composed of eight large and small structures, including Fangheting, Bajiaoting, Wanghuting and Shuangzhaoting, among which Fangheting, Bajiaoting and Wanghuting are the main structures, all of which are controlled by drilling and tested for industrial oil and gas flow.

Fangheting structure is the largest structure in the field. The Huagang Formation trap of this structure is a complete anticline. The Pinghu Formation trap is also an anticline with a large trap area, and its east and west flanks are complicated by two faults, respectively. The Bajiaoting structure is in the descending wall of the Pinghu main fault to the north of the Fangheting structure. The Huagang Formation trap is also a complete anticline, trending northeast, and there are two high points. Well Pinghu No. 2 is in the northwest direction of the high point. The Pinghu Formation trap is a reverse traction semi-anticline controlled by the Pinghu main fault, with two high points.

The data quality of the existing OBC (Ocean Bottom Cable) seismic survey restricts the further in-depth reservoir evaluation and field development. The main problems faced by evaluation and development are:
(1) Target layer is deeply buried, and the imaging quality in the middle and deep layers is poor, which makes it difficult to meet the geological requirements for fine structural interpretation and identification of dominant reservoirs;
(2) The lateral variation of the reservoir is large, and the reservoir prediction is difficult;
(3) The acquisition method of towed streamer has poor imaging accuracy and low signal-to-noise ratio data;
(4) Noise interference of original seismic data is relatively serious, and main structure has a blank area of seismic data.

DAS-VSP survey is increasingly recognized as a viable alternative to geophone arrays for downhole seismic data acquisition (Chen et al, 2012). This paper introduces the 3-D DAS-VSP data simultaneously acquired by a downhole armored optical cable with an OBN (Ocean Bottom Node) data acquisition project in the East China Sea, and the results of 3-D DAS-VSP data imaging processing and interpretation. Borehole-to-surface joint seismic exploration is a 3-D seismic exploration method formed by the combination of surface seismic and VSP survey simultaneously (Jiang et al., 2016). Using 3-D DAS-VSP data and borehole-to-surface jointly acquired seismic data, accurate time-depth relationship, formation velocity, deconvolution operator, spherical diffusion compensation factor or true amplitude recovery factor (TAR value), formation absorption attenuation factor (Q value) and anisotropy parameters around the wellbore can be obtained. These parameters can be used to enhance significantly the surface 3-D seismic data processing. The borehole driven surface seismic data processing includes velocity model calibration and modification, static correction, deconvolution, demultiple processing, high frequency restoration, anisotropic migration, and Q compensation or Q migration, etc. Through borehole-surface joint seismic exploration, the accuracy and quality of seismic data volume can be improved, the signal-to-noise ratio and resolution of reflected waves of target layers can be enhanced, and the ability of the data to describe the geological target can be increased (Yu et al, 2020).

3-D OBN and 3-D DAS-VSP data joint acquisition

The exploration area is located about 280 kilometers southeast of Zhoushan City, Zhejiang Province, in the Pinghu Oil and Gas Field in the East China Sea. The sea floor of the work area is relatively flat, and the water depth is between 80 m and 100 m. There are two operating platform areas in the data acquisition area, namely the Bajiao Pavilion and the Fanghe Pavilion main platform. There are also oil and gas pipelines on the sea floor in the survey area. The project objectives are to provide high-quality basic data for high-quality characterization of deep oil and gas reservoirs, prediction of oil and gas properties of lithologic oil and gas reservoirs, fracture distribution of the fractured oil and gas reservoirs, and structural accuracy evaluation of remaining oil and gas reservoirs in micro-amplitude structures. The data acquisition requirements are: (1) the seismic reflection energy of the target layer is strong, and the SRN (Signal to Noise Ratio) and resolution meet the requirements of geological objectives; (2) improve the energy and SRN of deep formation data; (3) optimize the OBN survey design around the platform area to reduce the blank area of seismic data.

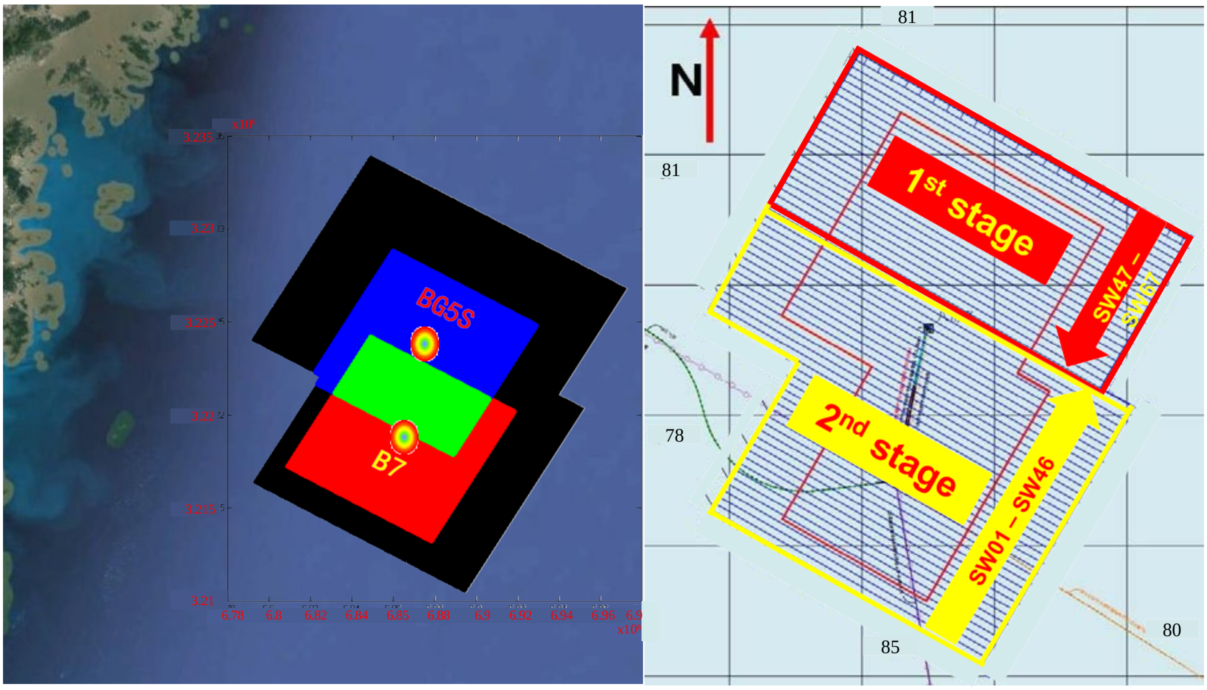


Figure 1. Joint 3-D OBN and 3-D DAS-VSP shots map (black: OBN shots cover area; red: Well B7 shots cover area; blue: Well B5 shots cover area; green: both wells joint shots cover area) (left); OBN acquisition shot swath stage plan (right).

As shown in Figures 1 and 2, the Pinghu 3-D OBN seismic data acquisition project designed 67 shot swath with a total of 261,192 shots, the full coverage area is 125.21 km2, the data area is 247.86 km2, and the actual number of shots completed is 26,1514 (322 shots more than the survey designed, and added more shots horizontally across the platform). The total number of released nodes are 18,504 (2,009 nodes repeatedly released in the second stage). The recording channels are 240 x 8=1,920, receiver spacing 50 m, minimum source-receiver offset 25.67 m, maximum offset 6,482.12 m, bin size 12.5 m x 25 m, and fold number 8 (h) x 80 (v) = 640. The inline shot spacing is 37.5 m and crossline shot spacing 50 m.

The simultaneously acquired 3-D DAS-VSP data used the same shots for the 3-D OBN survey when the OBN data were acquired. Two self-coupled armored optical cables with multiple high temperature rating single mode fibers were deployed inside casing in both wells B5 and B7. The length of downhole armored optical cable was 3,085 m and 3,537 m in wells B5 and B7 respectively. Each armored optical cable was connected to two DAS integrators on each platform to record two sets of 3-D DAS-VSP data, and the two data sets were stacked together for processing. The downhole receiver spacing is 1 m from sea floor to the bottom of the borehole. The armored optical cable recorded 62,473 shots inside Well B5 and 48,411 shots inside Well B7 respectively. The 3-D DAS-VSP data were recorded continuously 24 hours/day without affecting the OBN data acquisition, and the data were divided according to the GPS time of each airgun source shot after the 3-D DAS-VSP data acquisition completed.

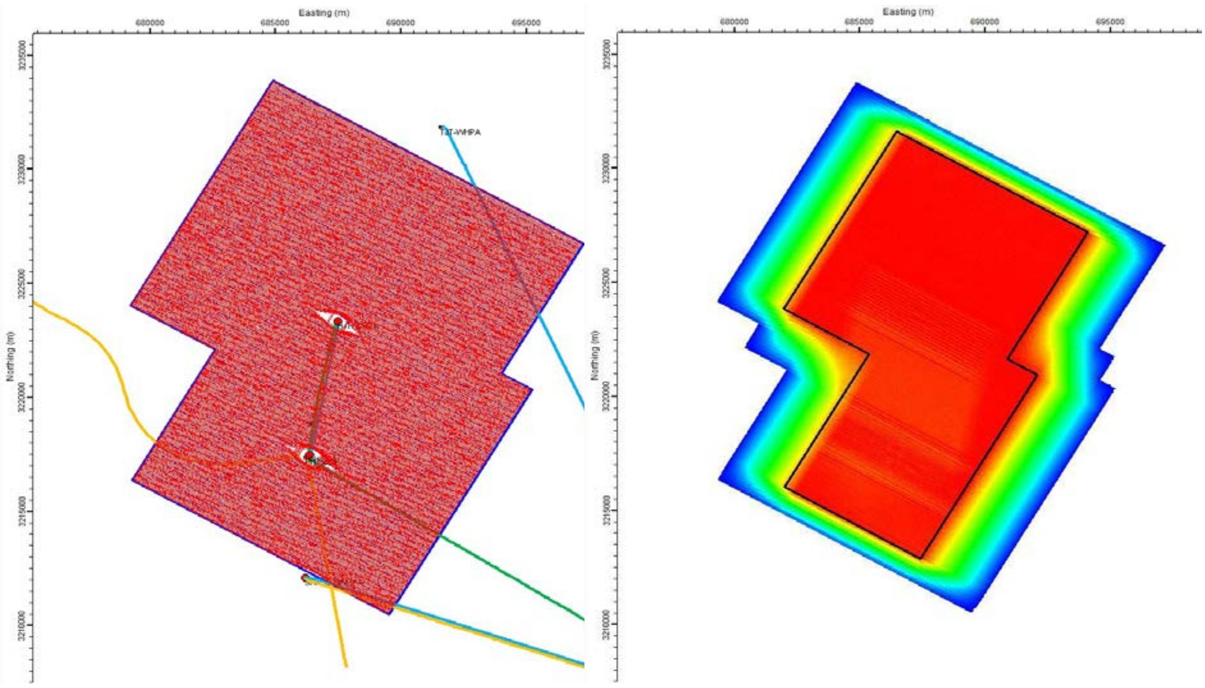


Figure 2. Actual OBN survey shot map (left) and full coverage fold map (right).

3-D DAS-VSP data processing

The raw 3-D DAS-VSP data quality analysis shows following features: (1) the single-shot raw data from near to far offset from both wells B7 and B5 have strong energy, high SRN, high dominated frequency and broad bandwidth. The low frequency energy is rich, the first arrival is clear, continuous and can be picked up easily, and the overall data quality is good; (2) the 3-D DAS-VSP data have different degrees of background noise, resonance interference, and some well sections have inevitable interference due to the surging of seawater; (3) the 3-D DAS-VSP data have abundant wave fields, and the multiple waves are relatively developed; (4) there is no difference in the comparison and analysis of the records for multiple optical cable re-entry to the well at different time, indicating that the stability of the acquisition equipment and parameter settings are not abnormal; and (5) the whole well high-density data meets the requirements of borehole seismic parameter calculation and accurate 3-D DAS-VSP imaging around the borehole.

DAS-VSP has the advantages of high density and full borehole coverage, but due to the poor coupling between the armored fiber optic cable and the casing wall, the cable ringing noise is strong. From Figure 3(a), the apparent velocity of ringing noise is close to the effective signal in the time domain, and it appears as a periodic pulse signal in the spectrum and periodic in the autocorrelation spectrum. Conventional denoising methods are difficult to remove effectively such noise.

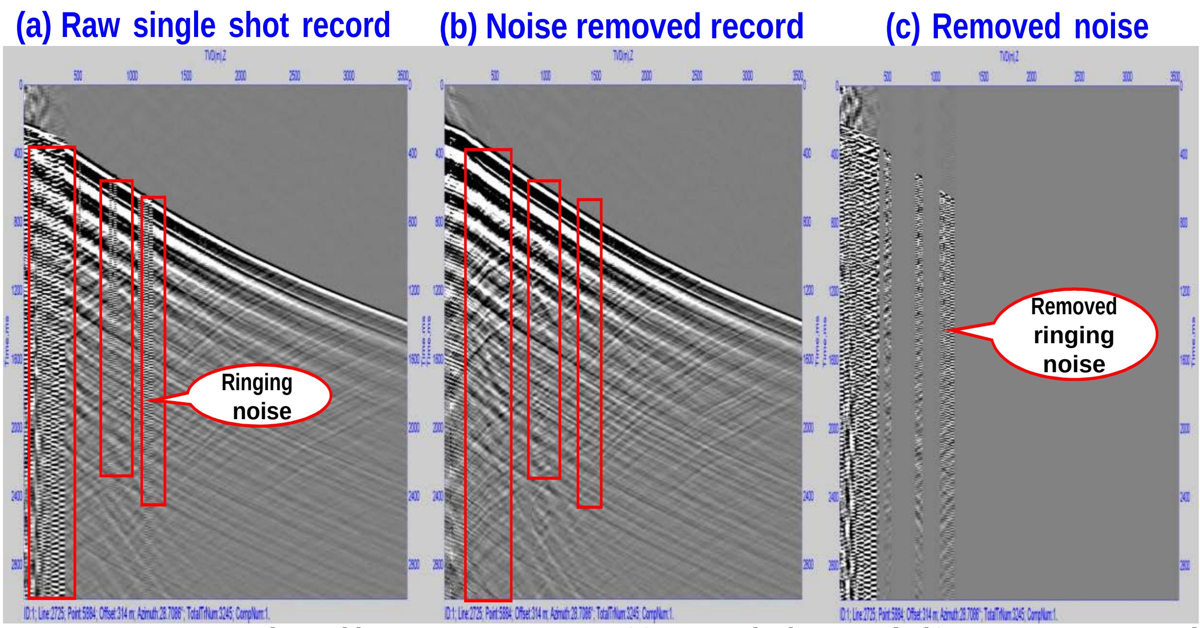


Figure 3. 3-D DAS-VSP data cable ringing noise remove: (a) raw single shot record; (b) Ringing noise removed record; (c) removed ringing noise.

A ringing noise attenuation technique based on TauP transform is proposed. First, TauP transform is used to transform DAS-VSP data into TauP domain, and then the linear prediction method is used to predict the periodic ringing noise. Finally, the predicted noise is subtracted from the original data, and realizes the separation of the effective signal and the ringing noise in the DAS data, to meet the needs of high-fidelity processing of the DAS-VSP data.

Figure 3 shows the effect of removing ringing noise in the Pinghu 3-D DAS-VSP data. After adopting the ringing noise attenuation technique of TauP transform, the ringing noise has been effectively attenuated and suppressed (b), and no effective reflection information can be seen from the removed noise (c).

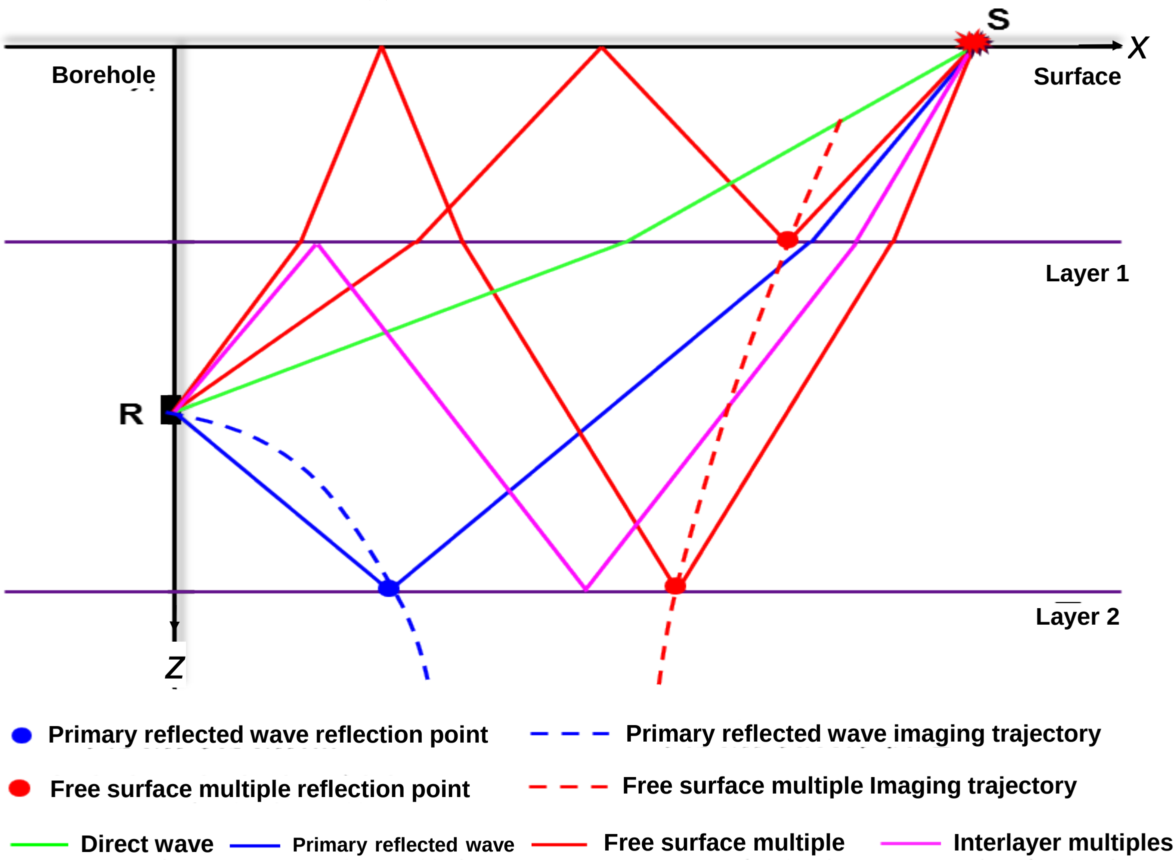


Figure 4. Various wave mode propagation paths recorded by a VSP survey.

The usual 3-D VSP data imaging processing steps includes: observation system definition, preprocessing, first arrival picking, static correction, amplitude compensation, deconvolution, wavefield separation, velocity analysis and imaging (Li et al., 2010). After the combined denoising processing, wavelet deconvolution, vector wavefield separation, anisotropic velocity modeling, correction of seismic migration velocity field, upgoing wave imaging, common receiver gather optimization imaging, downgoing wave imaging and other methods, the 3-D DAS-VSP data imaging processing has been performed. The main processing steps are: (1) Ringing noise suppression: suppressing ringing noise and abnormal amplitude interference, laying the foundation for the separation of upgoing and downgoing wavefields; (2) Signal deconvolution processing: use the downgoing wave to obtain wavelets for bubble suppression and wavelet zero-phase processing; (3) Wavefield separation: separate the upgoing and downgoing wavefields to expand the effective bandwidth of the data; (4) Shallow water multiple wave suppression: suppress the multiple waves of the water layer and highlight the real reflection characteristics of the formation; and (5) 3-D VSP migration: use the angle domain Gaussian beam migration method to process the 3-D DAS-VSP data to obtain high-precision 3-D DAS-VSP imaging results.

As shown in Figure 4, in comparison with surface seismic, the VSP wavefield is more abundant, with not only upgoing reflected waves, but also downgoing reflected waves with wider illumination. Generally, the downgoing reflected waves include free surface multiples, interlayer multiples, etc. Figure 4 shows two reflective layers, one observation well, and S is the source and R is the receiver. The direct wave, primary reflected wave, free surface multiples and interlayer multiples propagate along green, blue, red and pink line respectively. The propagation path of the primary reflected wave is from the shot point S to the reflection point of the reflective layer then to the receiving point R. The propagation path of free surface multiples is from shot point S to the reflection point of reflection layer, from here to reflection point of free surface (surface), and then to the receiving point R. Receiver R can receive not only the free surface multiples of the underlying formation, but also the free surface multiples of the overlying formation. Comparing the positions of the reflection points, the lateral distribution of the multiple reflection points of the free surface is wider and the vertical distribution is shallower. After the downgoing reflected wave imaging processing, the reflection imaging above the receiving point R can be achieved, and the lateral imaging range has been broadening.

The free surface multiple reverse time migration method (Liu et al., 2011, Liu et al., 2012, Wang, et al., 2014, Liu et al., 2015) is used in the 3-D DAS-VSP data imaging processing. Ferguson et al. (2005) derived the Fourier integral equation of one-way wave field continuation from the scalar wave equation and gave the explicit expression of angular frequency domain. Based on the method of single-pass pre-stack depth migration of primary reflected waves and the propagation characteristics of free surface multiples, the imaging can be realized only by modifying the wavefield continuation method. The free surface multiple wave one-way wavefield continuation imaging method can be described as:

Step 1: Rearrange the Z components of the VSP data into CRG (Common Receiver Gather) domain data set;
Step 2: Forward continuation of the source wavelet to the surface. Set the source wavelet at the receiver point R in the borehole. The wavefield of the source wavelet extends upward continuation layer by layer (step Δz), and the continuation formula from z to $z\text{-}\Delta z$ is:

$$\psi_s(x, z+\Delta z, \omega = \psi_s(x, z, \omega) e^{-ik_z \Delta z}\ ) \qquad (1)$$

where $\psi_s(x, z, \omega)$ is the source wavefield in the angular frequency domain at depth z, and k_z is the wave number in the z direction. Here, the wavefield continuation operator can be a split-step Fourier operator, a Fourier finite difference operator, or a generalized screen operator, etc.;

Step 3: Continuation one step in the reverse direction. The CRG wavefield extends downward from the surface layer by layer (step Δz) according to formula (2).

$$\psi_r(x, z+\Delta z, \omega) = \psi_r(x, z, \omega) e^{ik_z \Delta z} \qquad (2)$$

where $\psi_s(x, z, \omega)$ is the wavefield of the free surface multiple in the angular frequency domain at depth z, and k_z is the wave number in the z direction.

Step 4: Continuation forward by one step. The source wavelet wavefield of the second step is extended downward from the surface layer by layer (step Δz) according to formula (3).

$$\psi_r(x, z-\Delta z, \omega) = \psi_r(x, z, \omega) e^{ik_z \Delta z} \qquad (3)$$

where $\psi_s(x, z, \omega)$ is the wavefield of the free surface multiple in the angular frequency domain at depth z, and k_z is the wave number in the z direction.

Step 5: Extract imaging values. Cross-correlate the wavefields extended in the 3rd and 4th steps and take the zero-time imaging value. Repeat steps 3, 4, and 5 until reaching the maximum depth.

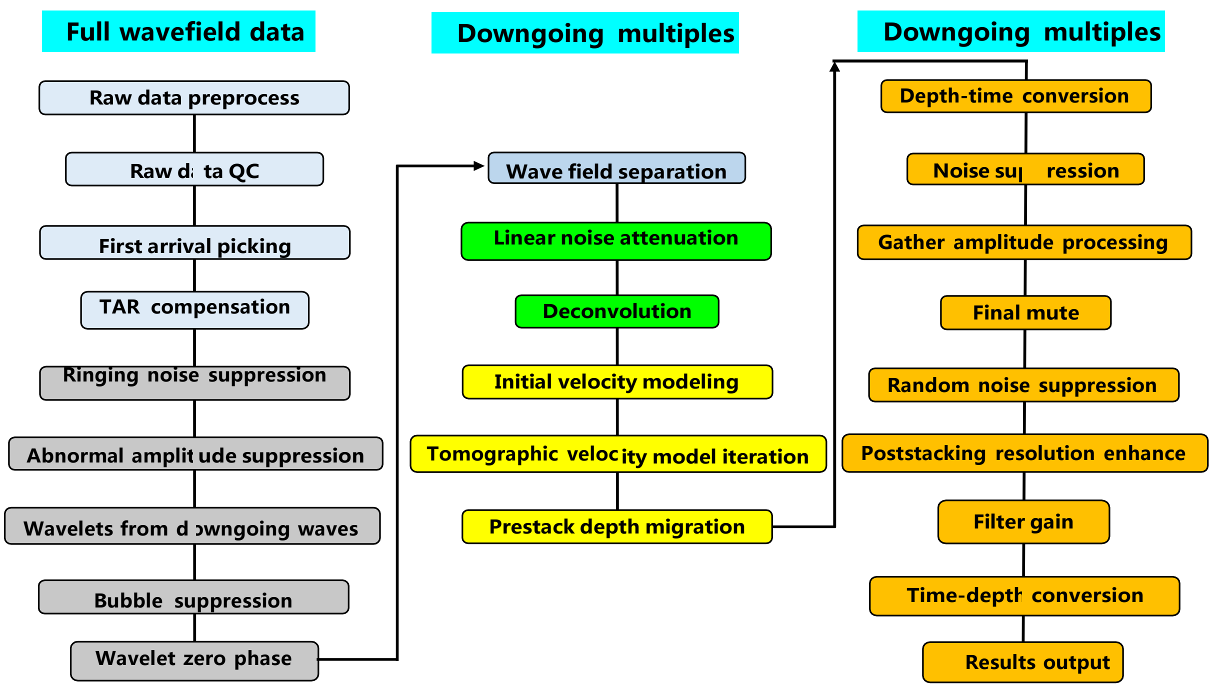
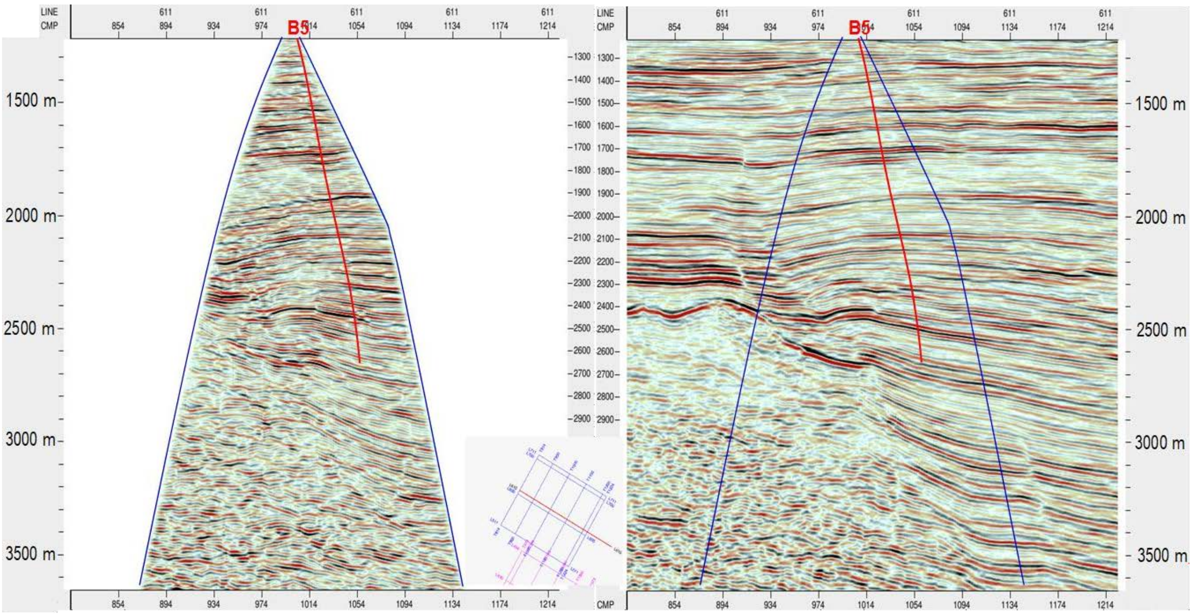


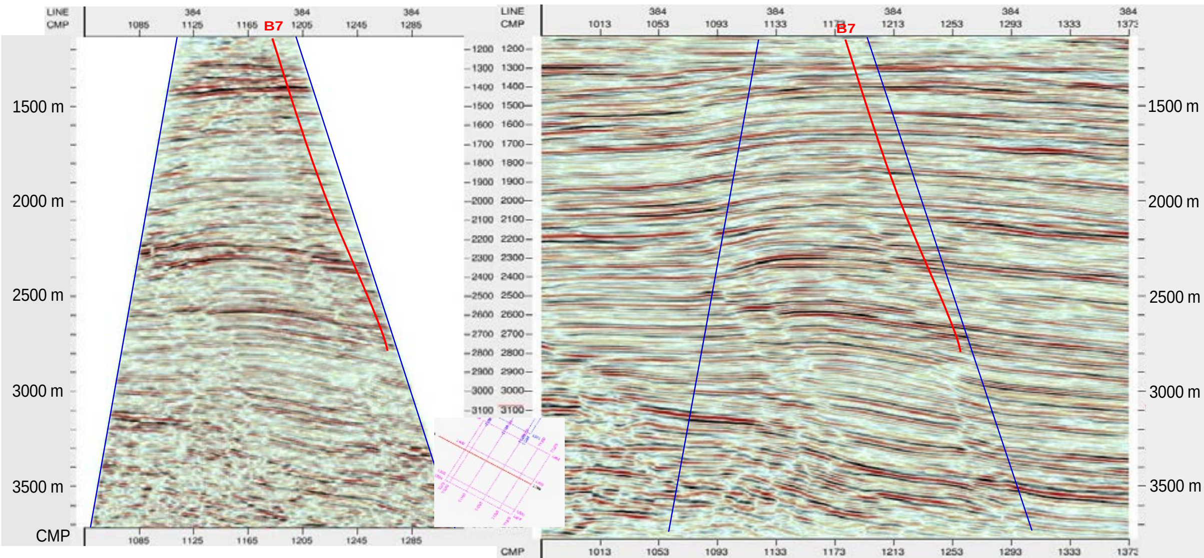
Figure 5. 3-D DAS-VSP data downgoing multiple reflection wave imaging processing workflow.

Because both wells B5 and B7 are deviated wells and the source must be 500 m away from the platform, the 3-D DAS-VSP upgoing reflection wave imaging has limited aperture and coverage area, the downgoing multiple waves were used to perform the 3-D DAS-VSP data imaging to increase the imaging coverage area. Figure 5 is the 3-D DAS-VSP data downgoing multiple reflection wave imaging processing workflow.



B5 3-D DAS-VSP upgoing wave imaging **B5 3-D DAS-VSP multiple wave imaging**

Figure 6. Borehole B5 3-D DAS-VSP data imaging comparison: Upgoing reflection wave imaging (left) vs downgoing multiple reflection wave imaging (right).



B7 3-D DAS-VSP upgoing wave imaging **B7 3-D DAS-VSP multiple wave imaging**

Figure 7. Borehole B7 3-D DAS-VSP data imaging comparison: Upgoing reflection wave imaging (left) vs downgoing multiple reflection wave imaging (right).

According to the characteristics of offshore 3-D VSP downgoing multiples, the offshore 3-D VSP downgoing multiple imaging technique has been innovatively developed, which greatly expands the 3-D DAS-VSP imaging range and improves the overall 3-D DAS-VSP imaging quality.

The resolution of the downgoing multiple wave imaging is low, so the downgoing multiple wave Q-migration was introduced to reduce the influence of absorption attenuation and improve the multiple-wave imaging resolution. As shown in Figures 6 and 7, there are two 3-D DAS-VSP data imaging results: one is the depth migration imaging based on upgoing wave data (left), the other one is the depth migration imaging based on downgoing multiple wave data (right), and the final migration velocity model is an updated velocity field using anisotropic velocity modeling (Sun et al., 2009).

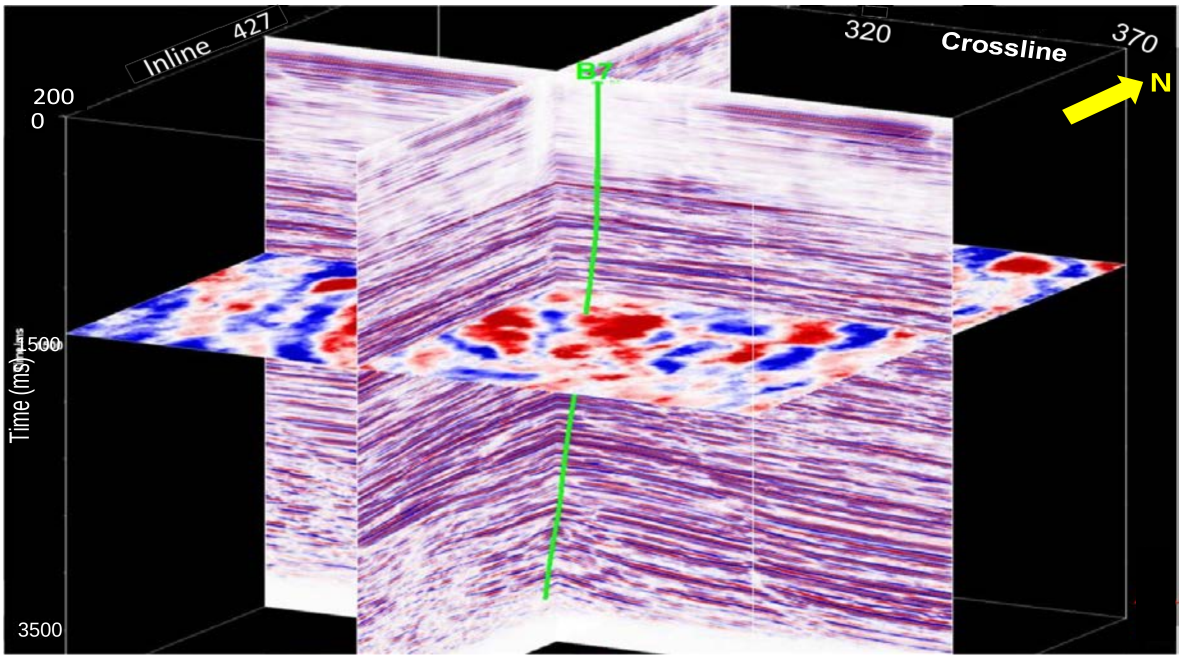


Figure 8. 3-D view of the Pinghu 3-D DAS-VSP downgoing multiple reflection wave imaging in Borehole B7.

Figure 8 is the 3-D view of the Pinghu 3-D DAS-VSP downgoing multiple reflection wave imaging result in Borehole B7. This 3D volume imaging data can be used to guide the 3D structure interpretation and generate 3D attribute data volume for reservoir characterization around the borehole. Since the downgoing multiple reflection wave imaging expanded the coverage area, this imaging result can be used to map the detailed reservoir structure and characterize fluid distribution near the bottom of the borehole.

Figure 9 shows the comparison of newly acquired 3-D OBN data imaging, 3-D DAS-VSP upgoing wave imaging and 3-D DAS-VSP downgoing multiple reflection wave imaging in Borehole B7. The blue lines define the 3-D DAS-VSP upgoing wave imaging coverage area.

The yellow lings in Figure 9(c) is the coverage area of the 3-D DAS-VSP downgoing multiple reflection wave imaging.

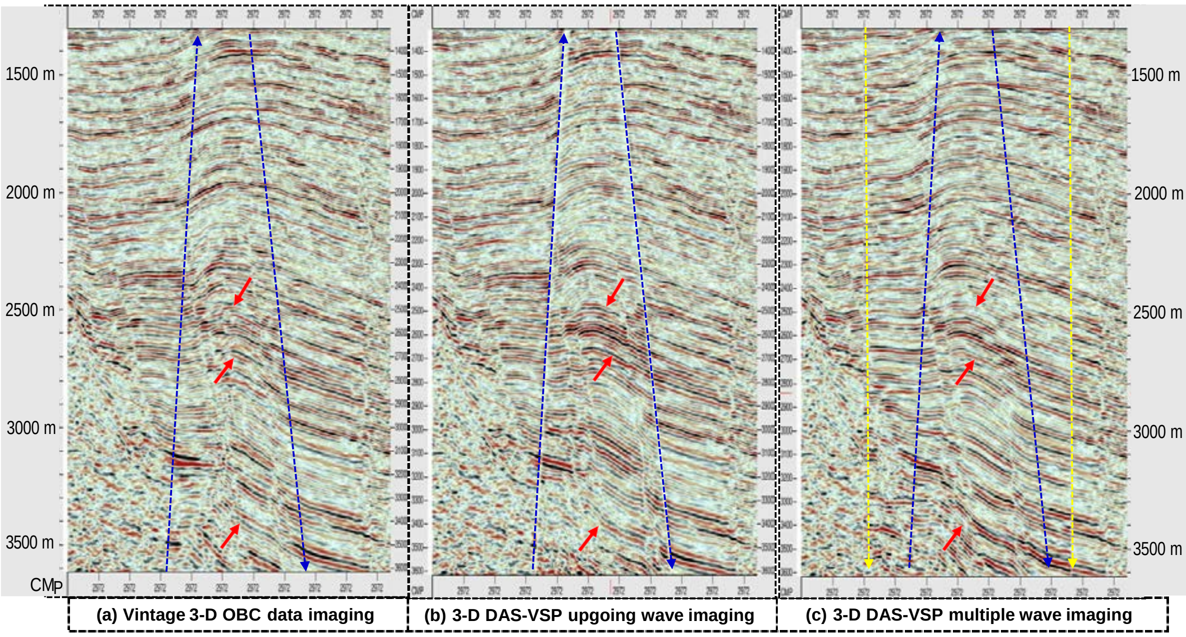


Figure 9. Comparison of vintage 3-D OBC data imaging, 3-D DAS-VSP upgoing wave imaging and 3-D DAS-VSP downgoing multiple reflection wave imaging in Borehole B7.

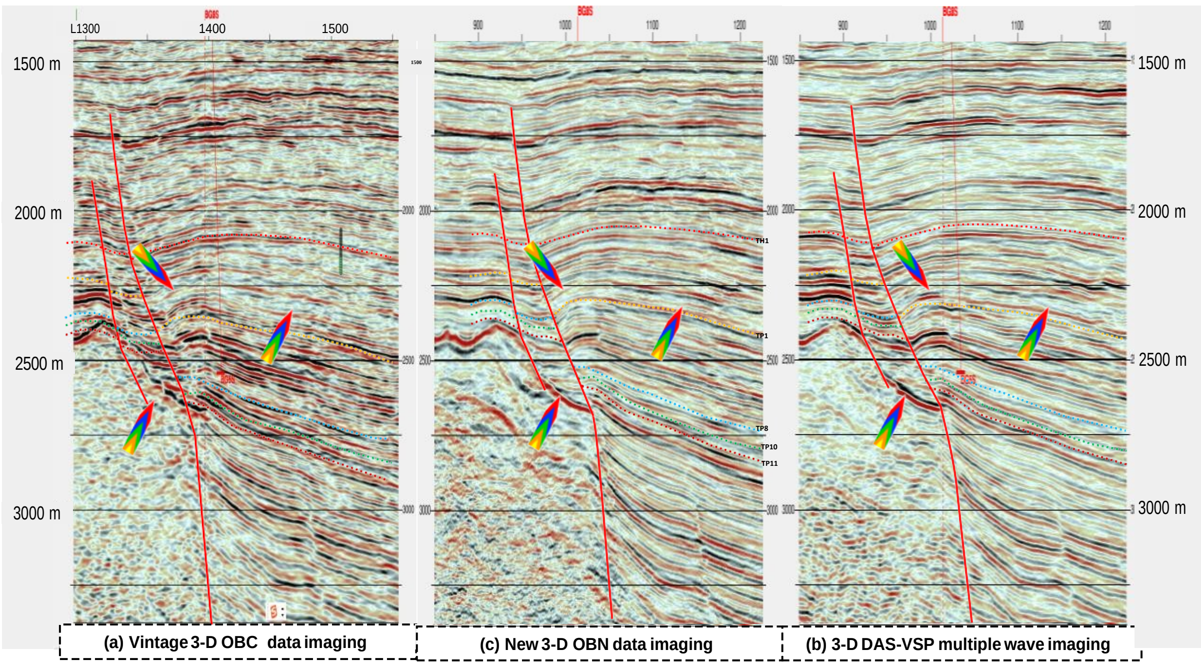


Figure 10. Comparison of vintage 3-D OBC data imaging, new 3-D OBN data imaging and 3-D DAS-VSP downgoing multiple reflection wave imaging in Borehole B5.

The comparison of vintage 3-D OBC data imaging, new 3-D OBN data imaging and 3-D DAS-VSP downgoing multiple reflection wave imaging in Borehole B5 is shown in Figure 10. The 3-D DAS-VSP downgoing multiple reflection wave imaging (Figure 10(c)) shows significant imaging quality improvement in comparison with the vintage 3-D OBC data imaging. The tracing of the reservoir and formation boundary become much easy and more confident in both new OBN data imaging and 3-D DAS-VSP data imaging than in the vintage 3-D OBC data imaging.

Conclusions

DAS-VSP survey is increasingly recognized as a viable alternative to geophone arrays for downhole seismic data acquisition. The borehole and surface joint seismic exploration technique is a 3-D seismic exploration method formed by the combination of surface seismic and borehole seismic data acquisition simultaneously. Using the zero offset VSP data simultaneously acquired with surface seismic data, the accurate time-depth relationship, velocity, TAR value, absorption attenuation factor and anisotropy parameters can be obtained. These parameters can be applied to the surface seismic data processing to improve significantly the amplitude preservation of seismic data, resolution and imaging accuracy. We introduced the 3-D DAS-VSP data simultaneously acquired by a downhole armored optical cable along with an OBN data acquisition project in the East China Sea, and the 3-D DAS-VSP data imaging processing and interpretation results. The 3-D DAS-VSP downgoing multiple reflection wave imaging shows significant imaging quality improvement in comparison with the vintage 3-D OBC data imaging. The tracing of the reservoir and formation boundary become easier and more confident in both new OBN data imaging and 3-D DAS-VSP data imaging than in the vintage 3-D OBC data imaging.

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