3D High-Resolution Imaging Using Separated Wavefields

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SUMMARY

Conventional wave equation migration extrapolates upcoming boundary data generated from primary reflections to image the subsurface. In marine seismic data processing, sea surface related multiples are a major challenge. Particularly, when the water bottom is shallow, short period multiples are difficult to deal with. Acquisition footprint of seismic imaging is another issue for shallow water bottom geology, where the primary reflections do not have the complete illumination coverage to the shallow targets, including the water bottom. In this paper, we review a method of separated wavefield imaging using sea surface related multiples. We present a data processing work flow of separated wavefield imaging including up and down-going wavefield separation using dual-sensor data, wave equation migration of wavefield extrapolation and imaging condition, and a post processing step of amplitude balancing. A shallow water example from Asia-Pacific is tested, where the separated wavefield imaging generates remarkable high resolution 3D images. The separated wavefield image has greater area of subsurface illumination, which mitigates the strong acquisition footprint. The method and results can be useful to reduce well drilling geohazards.

Introduction

Conventional wave equation migration extrapolates upcoming boundary data generated from primary reflections to image the subsurface. The use of sea surface related multiples in wave equation depth migration has been discussed by Berkhout and Verschuur (1994) and Guitton (2002). Whitmore et al. (2010) demonstrates an approach of using one-way Wave Equation Migration (WEM) to propagate up and down-going wavefields and generate a subsurface depth image from sea surface related multiples. Lu et al. (2011) presents the first 3D case study (using SEAM synthetic full azimuth data) of separated wavefield imaging using multiples with towed streamer 3D acquisition geometry.

Source/receiver ghost events are generated by sea surface reflection. Deghosting of seismic data is a critical procedure to remove the spectral notches and generate high resolution broadband subsurface images. Acquisition and processing methods are required to remove the ghost wavefields. A method for receiver deghosting is dual-sensor (hydrophone and geophone) towed streamer acquisition, followed by up and down-going wavefield separation (Carlson et al., 2007). These separated wavefields can then be used for imaging.

Cross-line acquisition footprint is a common issue for shallow water towed streamer seismic imaging. Imaging of multiples helps to suppress the acquisition footprint. For each shot, imaging of primaries produces less subsurface illumination than imaging of multiples [Figure 1A]. To the extent that they are recorded, multiples imaging uses smaller reflection opening angles than primaries imaging [Figure 1B], and therefore can generate higher resolution images for the same offset distribution. In this paper, we present a shallow water case study from Asia-Pacific. Using up and down-going wavefields, we produce a high resolution 3D near surface image from sea surface related multiples. In this example, the multiples image generates more extensive subsurface illumination than the image using only primaries, and helps mitigate the acquisition footprint. The image from multiples can be combined with the image from primaries to create an overall better image.

Method

Dual-sensor towed streamer acquisition records both pressure and vertical component of particle velocity wavefields. Broadband up and down-going wavefields are separated by applying a frequency-wavenumber $P-Z$ summation algorithm to dual-sensor data.

In shot profile wave equation migration, the imaging process is a combination of wavefield downward extrapolation and imaging condition. The conventional depth migration backward propagates the upcoming data as receiver wavefield and forward extrapolates a synthetic impulse wavelet as source wavefield. Separated wavefield imaging propagates up and down-going wavefields as receiver and source wavefields. In this paper, we employ an extrapolation method based on a Fourier Finite Difference operator [Equation 1]. P is pressure wavefield; ω is temporal frequency; c is reference velocity; v is media velocity; $\nabla_{x,y}$ is spatial derivative; a and b are finite difference coefficients.

$$\frac{\partial P}{\partial z} = \pm i \left[\sqrt{\frac{\omega^2}{c^2} + \nabla_{x,y}^2} + \left(\frac{\omega}{v} - \frac{\omega}{c} \right) + \frac{\omega}{v} \left(1 - \frac{c}{v} \right) \frac{\frac{v^2}{\omega^2} \nabla_{x,y}^2}{a + b \frac{v^2}{\omega^2} \nabla_{x,y}^2} \right] P \quad ---- (1)$$

Up/down imaging principle is applied to subsurface source and receiver wavefields. Conventional wave equation depth migration uses cross correlation imaging condition [Equation 2]. We use a stable version of deconvolution imaging condition [Equation 3] (Valenciano and Biondi 2003; Guitton et al., 2007) to suppress the cross talk noise generated from unrelated up and down-going wavefields.

$$I(\mathbf{x}) = \sum_{\mathbf{x_s}} \sum_{\omega} P_{down}^{*}(\mathbf{x}, \mathbf{x_s}; \omega) P_{up}(\mathbf{x}, \mathbf{x_s}; \omega) \quad ---- (2)$$

$$I(\mathbf{x}) = \sum_{\mathbf{x_s}} \sum_{\omega} \frac{P_{down}^{*}(\mathbf{x}, \mathbf{x_s}; \omega) P_{up}(\mathbf{x}, \mathbf{x_s}; \omega)}{\left\langle P_{down}^{*}(\mathbf{x}, \mathbf{x_s}; \omega) P_{down}(\mathbf{x}, \mathbf{x_s}; \omega) \right\rangle_{(x,y)} + \varepsilon(\mathbf{x})} \quad ---- (3)$$

In equation 2-3, I is the subsurface image; ε is a damping parameter to make the deconvolution imaging condition stable; $\langle\ \rangle_{(x,y)}$ stands for smoothing in the image space in the x, y directions.

Images are generated shot by shot and are stacked to form a composite image after migration. The subsurface power spectra are generated based on a boundary data spatial amplitude map. The stacked image is post processed using residual cable footprint removal and amplitude balancing.

Example

A field data example is tested with a 585km^2 area extracted from a full 3D dual-sensor towed streamer survey over the Tenggol Arch area in offshore Peninsula Malaysia. The dual-sensor survey is acquired using 12 cables with 4050m cable length and 75m cable spacing. The acquisition shot spacing is 18.75m and receiver spacing is 12.5m. Data is dealiased and resampled before migration to allow for migrations of 120Hz. Migrations are produced for frequencies of both 80Hz and 120Hz.

Up and down-going wavefield separation is applied in the shot domain to the surface data. The data consists of significant short period and long period multiples, which are from the shallow water bottom and other major impedance changes. When imaging the multiples, the separated wavefields have no demultiple applied, which means several orders of sea surface related multiples are used. Deconvolution imaging condition is applied to attenuate both the cross talk and noise from different orders of multiples. The up-coming wavefield after signature deconvolution, τ-p deconvolution and SRME (Verschuur, 1991) demultiple is used to produce the image from primaries with a cross correlation imaging condition.

Figures 2-4 show images of up to 80Hz migration. Figure 2 compares the inline images from primaries and from multiples in depth (0-3km). Inline images from one shot (colour regions) are on top of the 3D full stack images. The comparison shows that in the inline direction the multiples image has more extensive illumination than primaries from one shot, which is explained by the schematic diagram in Figure 1A. Figure 3 compares the cross-line images in two way travel time (0-1600ms). Image of multiples mitigates the strong sail line acquisition footprint in this direction. Figure 4 shows the depth slices at 105m of the test region (25km by 23.4km). The four plots are: (A) image from primaries that is contaminated by very strong sail-line acquisition footprint; (B) raw stack of image from multiples that mitigates the acquisition footprint from adjacent sail-lines (the image still has some residual amplitude footprint, primarily due to the lack of fold equalization of the input data); (C) subsurface power spectra that are generated from the surface data used to estimate imaged fold; (D) high resolution final image from multiples after amplitude balancing, which is largely free of sail-line acquisition footprint.

Conclusions

In this paper, we review and present a work flow of separated wavefield imaging using sea surface related multiples. Up and down-going wavefield separation is required to prepare boundary data as input of wave equation migration; deconvolution imaging condition is used to supress the cross talk and multiple noise. The separated wavefields are used to produce images of both multiples and primaries, where the multiples are instrumental in helping to suppress the acquisition footprint in the image. In the shallow water example from Asia-Pacific, the 3D separated wavefield image has remarkable high resolution in the near surface, with the acquisition footprint essentially removed. The method and results could be very useful to reduce well drilling geohazards.

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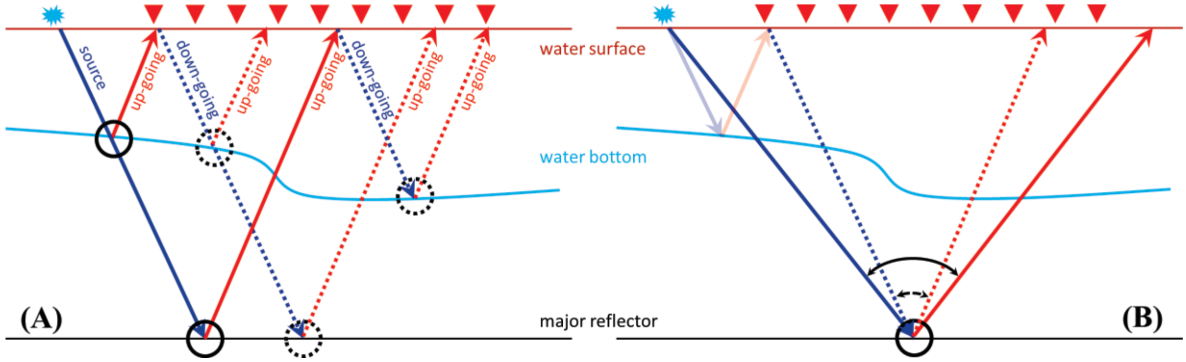

Figure 1 (A) *Schematic diagram for subsurface reflection of primaries (solid lines) and sea surface related multiples (dashed lines). In wave equation migration, red lines are used as receiver wavefield; blue lines are used as source wavefield. Imaging from multiples (dashed circles) has greater extent of illumination than imaging from primaries (solid circles).* ***(B)*** *To image the same reflector (solid circle) by a single shot, primaries imaging (solid lines) uses a larger reflection opening angle than multiples imaging (dashed lines); therefore multiples produce a higher resolution image than primaries.*

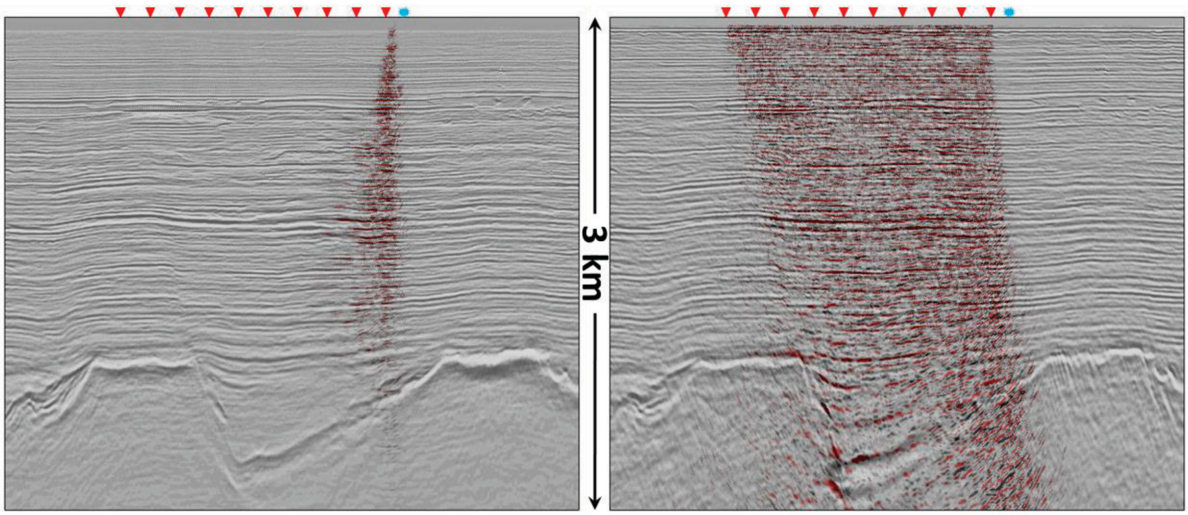

Figure 2 *Inline images from primaries (left) and from multiples (right) in depth from 0 to 3km. Images from one shot (colour regions) on top of the 3D full stack images (grey) show that imaging of multiples has greater extent of subsurface illumination than imaging of primaries. Stars indicate the source location; triangles display the receive geometry.*

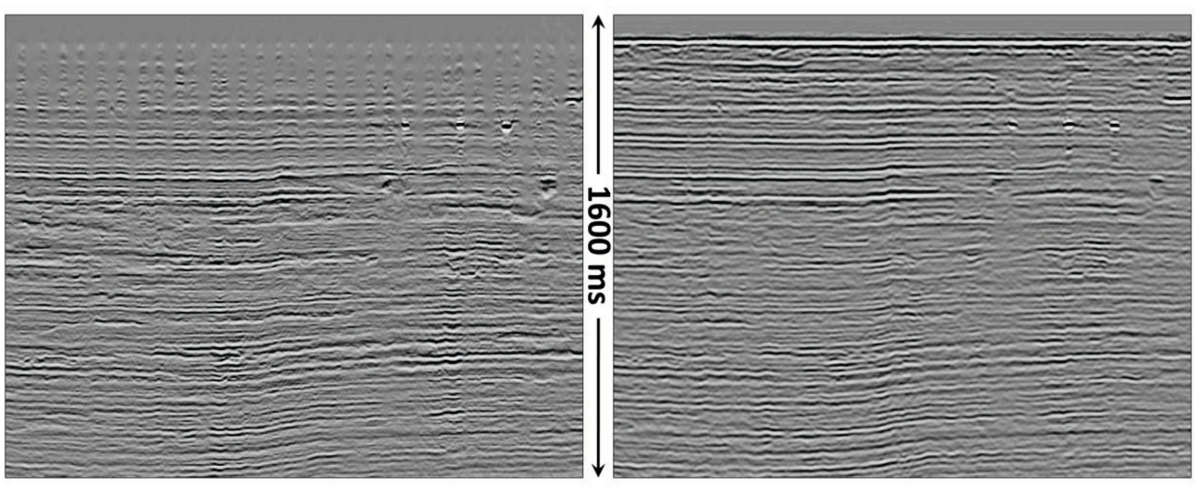

Figure 3 *Cross-line images from primaries (left) and from multiples (right) in two way travel time from 0 to 1600ms. Imaging of multiples mitigates the acquisition footprint in this direction and generates a very high resolution image including detail information of the water bottom reflection.*

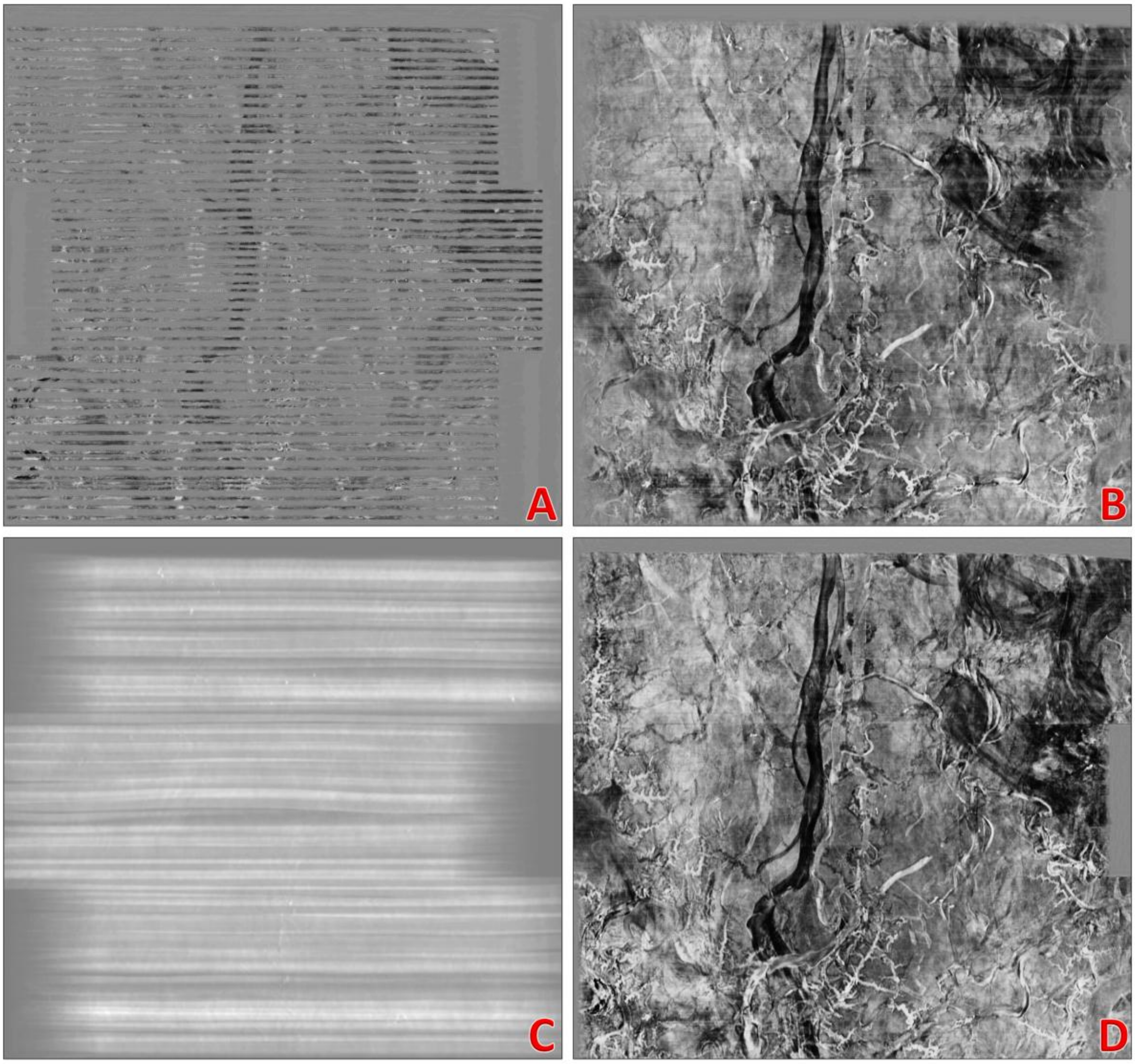

Figure 4 *Depth slices at 105m of the test region (25km by 23.4km):* ***(A)*** *the image from primaries shows strong acquisition footprint;* ***(B)*** *raw stack of image from multiples still has some residual amplitude footprint;* ***(C)*** *subsurface power spectra are generated from the surface data and consistent with residual amplitude footprint;* ***(D)*** *high resolution final image from multiples after amplitude balancing is largely free of sail-line acquisition footprint.*

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