Enhanced subsurface illumination from separated wavefield imaging

Shaoping Lu[1*], Dan Whitmore[1], Alejandro Valenciano[1] and Nizar Chemingui[1] **present applications of separated wavefield imaging to a deepwater wide-azimuth survey in the Gulf of Mexico and to a narrow azimuth data set from offshore Malaysia.**

In standard migration, up-going and down-going wavefields are mathematically extrapolated into the subsurface, where an imaging principle is applied. In the case of imaging primary reflections, the down-going wavefield is generated numerically by injecting the down-going response of a point source. The up-going wavefield at the surface is obtained by de-ghosting the recorded surface wavefield. In the case of dual-sensor streamer acquisition, the recorded data can be accurately deghosted and separated into up-going and down-going components (Carlson et al., 2007). These surface recordings contain not only primary seismic reflections, but also multiple scattered wavefields. When imaging primary reflections, the multiple scattered waves are noise that are typically attenuated in processing (e.g. surface-related multiple removal).

However, in the past decade we have seen more use of multiple reflections for imaging the subsurface instead of being discarded as noise (Berkhout and Verschuur, 1994; Guitton, 2002; Shan, 2003; Muijs et al., 2007; Whitmore et al., 2010). In the case of imaging surface-related multiples, the separated down-going component at each receiver location is injected as the source wavefield. Thus when imaging multiples, the separated down-going wavefield replaces the role of the source as used in imaging primary reflections. This down-going wavefield is effectively a source array with a virtual source at each receiver position. As in the case of primaries, in separated wavefield imaging (SWIM) of multiples, the separated down-going and up-going wavefields are extrapolated and the reflector image is constructed by an imaging principle.

To properly image the subsurface with the multiples, the down-going and up-going wavefields must both be recorded. Therefore, the streamer coverage, receiver density, source-receiver geometry and acquisition shooting direction as well as target depth and subsurface dip are controlling factors in the effectiveness of imaging with multiples (Lu et al., 2013).

In this paper, we show two applications of SWIM: one to a deep-water Wide Azimuth (WAZ) survey from the Gulf of Mexico and the other to a Narrow Azimuth (NAZ) dataset from offshore Malaysia.

Potential advantages of using multiples for migration

In typical marine acquisition, receivers are more densely sampled than sources along a line, and the cable spacing of a multi-streamer survey is denser than the sail-line spacing. As a result, when imaging multiples the down-going wavefield is much denser than the point source used in imaging primaries. In many cases, imaging multiples result in enhanced illumination and resolution in the subsurface. This is apparent in the case of shallow targets, where multiples illuminate the subsurface at smaller reflection angles than do primaries. This is illustrated by using single arrival rays in Figure 1. Within a one-shot physical experiment, multiples can travel through a broader subsurface region than primaries (Figure 1A). They can also produce additional angular illumination at each reflection point. Figure 1B shows how the plurality of 'virtual' sources from the multiples can illuminate from more than one angle the same reflection point, while the primaries can illuminate the same reflection point only once.

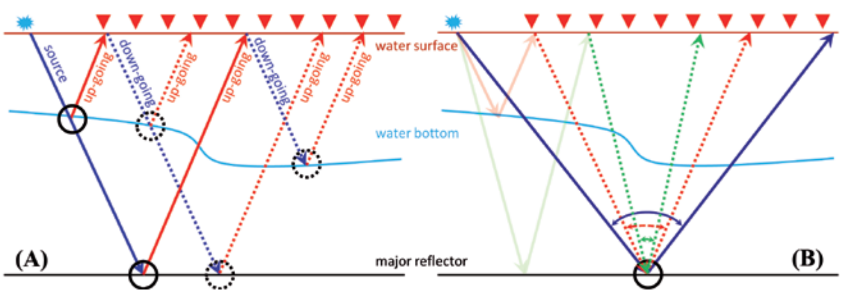

Figure 1 (A) Schematic diagram for trajectories of primary wavefield (solid lines) and multiple wavefield (dashed lines). Images from multiple reflection signals (dashed circles) illuminate a greater subsurface extent than images from primary reflection signals (solid circles). (B) At a subsurface reflector (solid circle), primary wavefield contains a single reflection angle (blue), while multiple wavefield contains more than one reflection angle (red and green).

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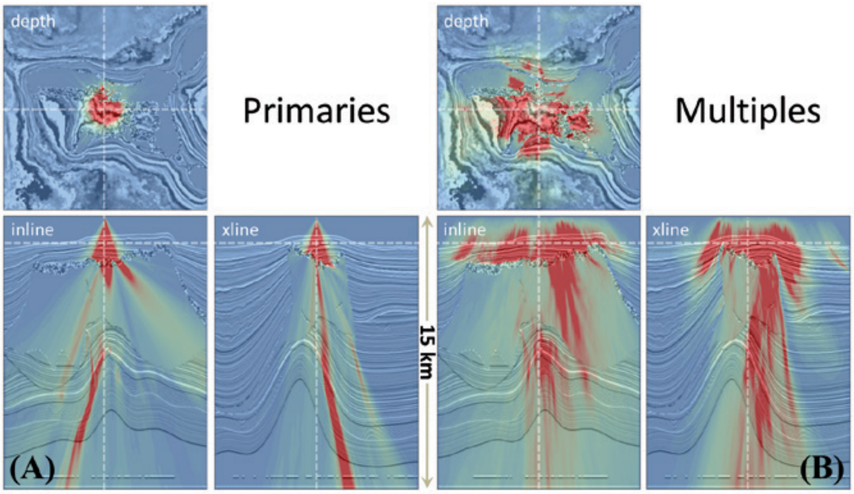

***Figure 2** Source illumination from imaging of primaries (A) and imaging of multiples (B) overlay the 3D SEAM reflectivity. The source power is generated from one shot using a point source for primaries and down-going wavefield as an areal source for multiples. The areal source wavefield in imaging of multiples illuminates a bigger subsurface region than the point source in imaging of primaries.*

A further demonstration of this can be seen by observing the illumination of the down-going wavefields for a point source and the down-going areal receiver array for a wide-azimuth configuration. In Figure 2, we demonstrate the subsurface illumination (source power from a common shot gather) in depth imaging of primaries and multiples using a realistic numerical model – the 3D SEAM synthetic. In shot profile migration, the lateral extent of the illumination zone is approximated by the source-receiver midpoint. When imaging with primaries, the illumination area is concentrated towards the common source location (Figure 2A), while in the case of imaging of multiples the subsurface region covered by the receivers in the surface is illuminated (Figure 2B).

Methodology

The basic principle of shot profile wave equation migration consists of extrapolating the source and receiver wavefields into the subsurface through a numerical operator, followed by the imaging condition to create a map of the reflectors (Claerbout, 1971). The conventional depth migration backward propagates the up-coming data as receiver wavefield and forward extrapolates a synthetic impulse wavelet as source wavefield. Separated wavefield imaging propagates up-going and down-going wavefields as receiver and source wavefields, where boundary data are generated at the receiver locations via up/down wavefield separation.

In the examples demonstrated here, we employed a one-way wave equation (WEM) Fourier Finite-Difference (FFD) operator for the wavefield extrapolation. The FFD dispersion relation approximation consists of three terms: a phase-shift, a thin-lens, and finite-differences. The 3D finite-difference operator is implemented using multi-way splitting that employs a different set of optimized coefficients along each splitting direction (Valenciano et al., 2009). This method shares the angle limitation of one-way propagators, but it is extremely efficient, especially in the anisotropy media of Tilted Transverse Isotropy (TTI). Besides, the operator can mimic wavefield propagation in acoustic or visco-acoustic media (Valenciano et al., 2011). These properties make our multi-way splitting FFD migration a good alternative for high-resolution (high-frequency) imaging.

It should be noted that, in imaging of multiples, receivers are used as secondary sources, and each seismic trace is a time series. When shot profile migration is applied, imaging of multiples is a blending migration process in both spatial and temporal domain. Therefore, during the application of the chosen imaging condition, events generated by the correlation of unrelated up and down-going wavefields appear as cross-talk in the images. The cross-talk may be partially reduced in the stacking process by utilizing acquisition with large data apertures in space and time (i.e., wide acquisition spread and long record length). Here, we discuss the use of an imaging condition that can assist in the reduction of cross-talk, but note also that more advanced inversion methods might be needed to fully remove the cross-talk.

The reflection coefficient, in shot record wave equation migration, can be estimated as the deconvolution of the receiver by the source wavefield (Claerbout, 1971). However, for practical reasons and primarily stability, the imaging condition is usually implemented as cross-correlation of the receiver and the source wavefields as follows:

$$I(\vec{x}) = \sum_{\vec{x}_s} \sum_{\omega} P_{up}(\vec{x}_s, \vec{x}, \omega) P^*_{down}(\vec{x}_s, \vec{x}, \omega) \quad (1)$$

where P_{up} and P_{down} represent the up-going and down-going wavefields respectively at an image point $\vec{x}$. The up/down wavefields are initiated using a common source $\vec{x}_s$ and represented in the frequency domain ω.

While this cross-correlation imaging condition (Equation 1) is stable and kinematically correct, it cannot produce true relative amplitudes and is susceptible to cross-talk when

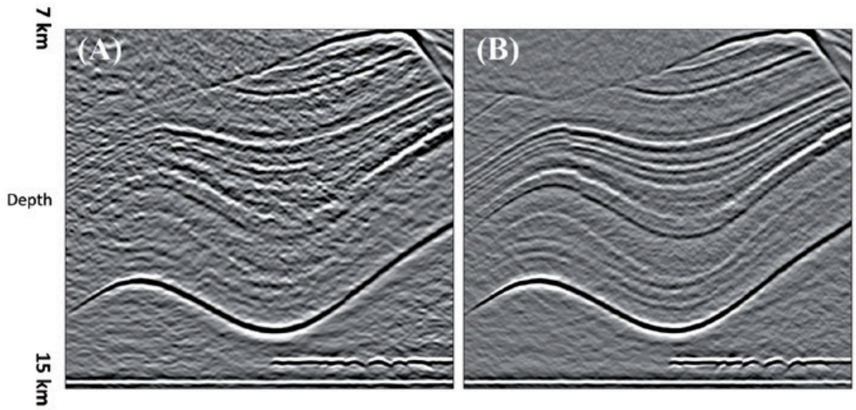

Figure 3 Inline images from multiple wavefield using cross correlation imaging condition (A) and deconvolution imaging condition (B). The deconvolution imaging condition suppresses cross-talk and provides a higher signal-to-noise ratio image.

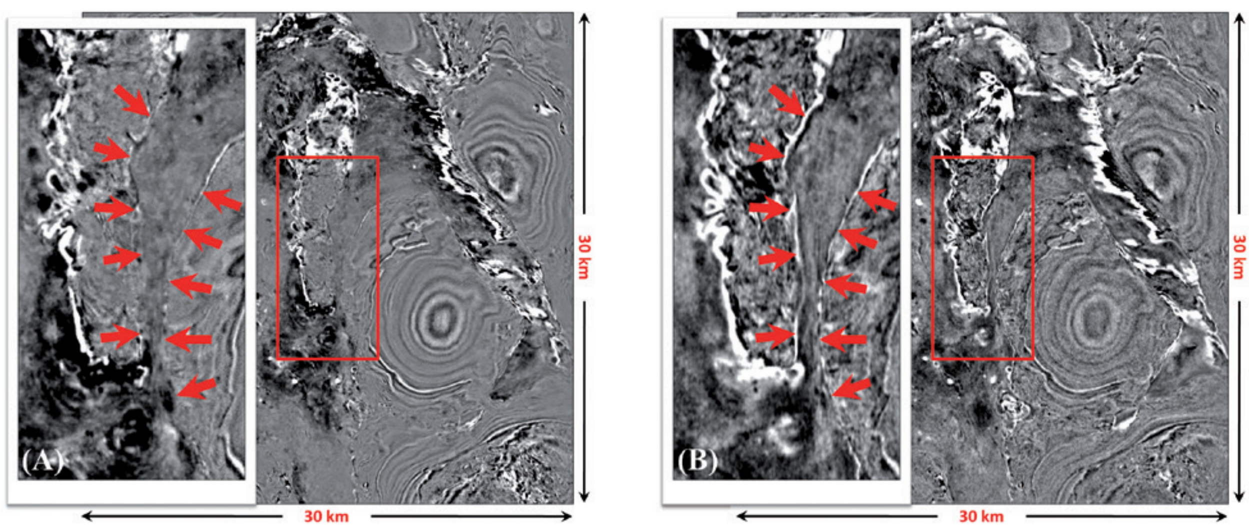

Figure 4 Depth slices (3000 m below sea surface) from imaging of primaries (A) and imaging of multiples (B). Imaging of multiples improves illumination of complex top salt structures (indicated using arrows inside the red box).

imaging with multiples. In contrast, the stabilized deconvolution imaging condition (Guitton et al., 2007)

$$R(\vec{x}) = \sum_{\vec{x}_s}\sum_{\omega} \frac{P_{up}(\vec{x}_s,\vec{x},\omega)P^*_{down}(\vec{x}_s,\vec{x},\omega)}{\left\langle P_{down}(\vec{x}_s,\vec{x},\omega)P^*_{down}(\vec{x}_s,\vec{x},\omega)\right\rangle_{\vec{x}} + \varepsilon(\vec{x}_s,\vec{x},\omega)} \quad (2)$$

creates an estimate of the subsurface reflectivity $R(\vec{x})$ and provides a reduction in cross-talk by including a stabilisation term $\varepsilon(\vec{x}_s,\vec{x},\omega)$ to the denominator that is smoothed in the space domain $\langle\ \rangle_{\vec{x}}$.

The effect of the deconvolution imaging condition is demonstrated when applied to the SEAM synthetic example (Lu et al., 2011). We compare a section of the images from multiples that are generated using either the cross-correlation (Figure 3A) or deconvolution (Figure 3B) imaging conditions. The deconvolution imaging condition produces amplitudes closer to the reflection coefficient, and overall, a higher signal-to-noise ratio image.

Equation 2 can be generalized to the prestack image domain by extending the image to create subsurface prestack offset gathers $I(\vec{x},\vec{h})$. They are computed by deconvolving the shifted subsurface up/down wavefields ($\vec{h}$ is the source-receiver half offset) as:

$$I(\vec{x},\vec{h}) = \sum_{\vec{x}_s}\sum_{\omega} \frac{P_{up}(\vec{x}_s,\vec{x},\omega,\vec{x}+\vec{h})P^*_{down}(\vec{x}_s,\vec{x},\omega,\vec{x}-\vec{h})}{\left\langle P_{down}(\vec{x}_s,\vec{x},\omega,\vec{x}-\vec{h})P^*_{down}(\vec{x}_s,\vec{x},\omega,\vec{x}-\vec{h})\right\rangle_{\vec{x}} + \varepsilon(\vec{x}_s,\vec{x},\omega)} \quad (3)$$

The resulting subsurface offset images can be transformed to the angle domain through a radial-trace transformation (Rickett and Sava, 2002).

WAZ field data application

As mentioned earlier the effectiveness of imaging with multiples depends strongly on the overall streamer coverage, the receiver density and the source-receiver geometry. The more free-surface multiple information can be collected by the chosen receiver array geometry the more the final image can be potentially improved. It is for this reason that the SWIM technology is particularly advantageous in improving subsurface illumination when used with WAZ survey geometries.

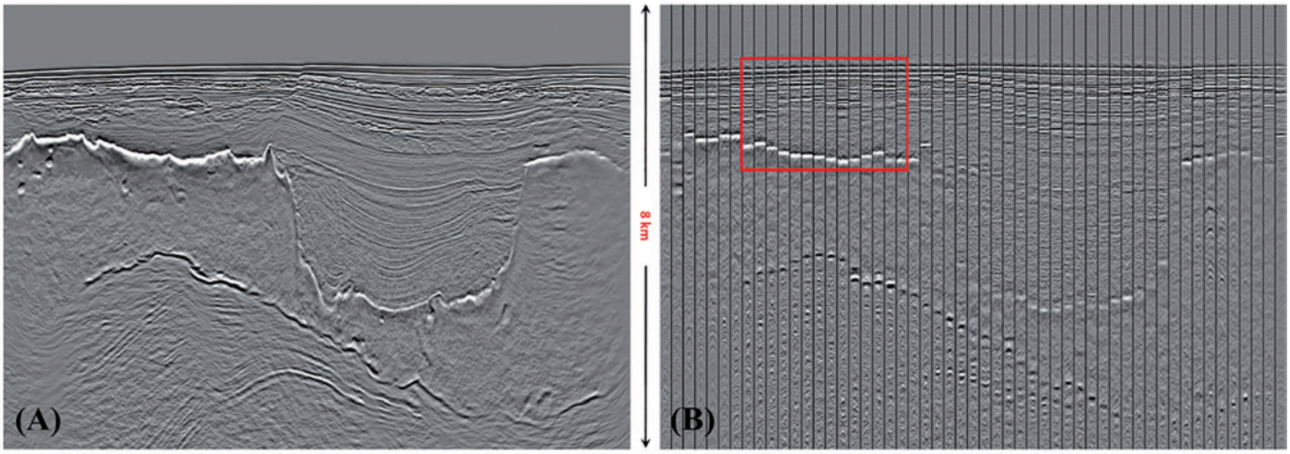

Figure 5 Vertical profile of post-stack image (A) and the pre-stack angle domain image (B) from imaging of multiples. The angle gathers are in the least favourable direction (90-degree azimuth), and are displayed from -25 to +25 degrees.

To illustrate this we have applied the TTI anisotropic SWIM technique to a WAZ dataset acquired in the deep-water Gulf of Mexico. Figure 4 shows a comparison of depth slices from imaging of primaries only and imaging with multiples at three kilometre below the sea surface. The SWIM image shows a better lateral definition of the rugose top salt geometry due to the improved illumination. The close-up images in Figure 4 confirm that SWIM produces more continuous and clearer salt boundary images than primaries alone.

Figure 5A shows an inline of the SWIM cube, in which structures from the shallow to the deep subsalt regions are very well illuminated, especially the steep salt flanks and small scale sediment inclusions. The significantly improved illumination provided by SWIM can be best accessed in pre-stack domain by looking at angle gathers. Whereas the subsurface illumination using primaries is limited by the shot density, which in turn is controlled both by the shot and sail-line spacing (which is typically several hundred metres), the sampling of the free-surface multiples used in SWIM is determined by the receiver and cable spacing, which is typically much denser than the shot and sail-line spacing. Imaging with multiples therefore generates much more finely sampled angle gathers, especially in the cross-line direction. Figure 5B shows the angle gathers from SWIM in the least favourable direction at 90-degree azimuth. The improvements in the angular illumination from imaging with multiples are not limited only to the shallow section.

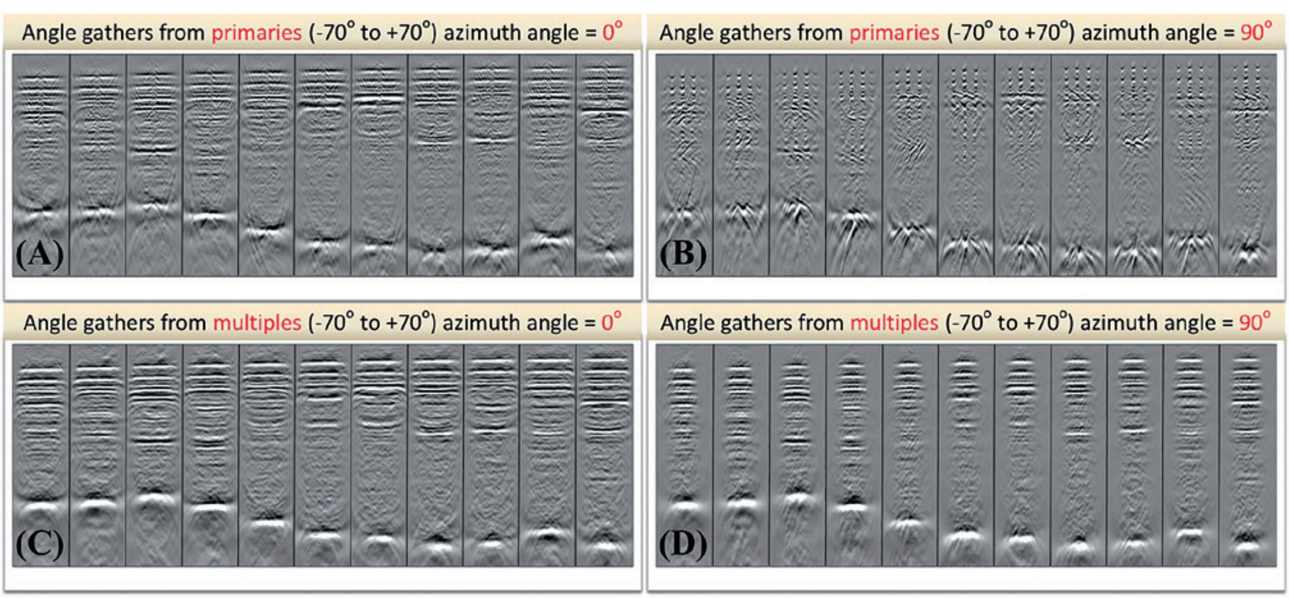

Figure 6 Angle gathers from imaging of primaries and imaging of multiples. The gathers are from the red box area in Figure 5B. The poor angular illumination in the gathers from imaging of primaries is due to the coarse shot sampling. Gathers from imaging of multiples are finely sampled in both inline and cross-line directions.

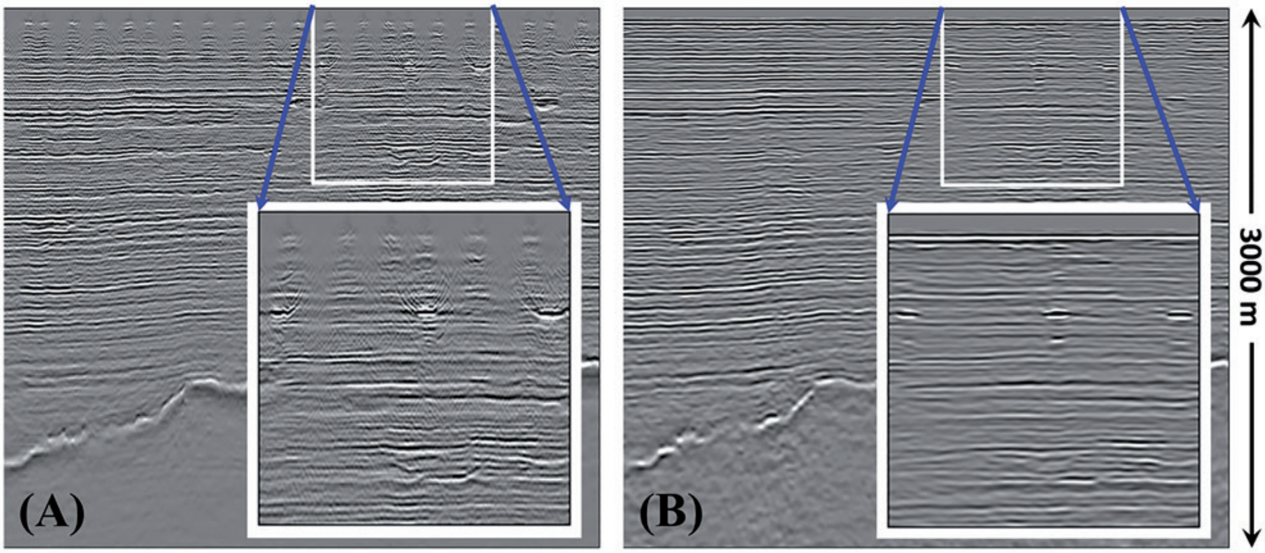

Figure 7 *Images from primaries (A) and from multiples (B) in the cross-line direction. The image from primaries is contaminated by a very strong acquisition footprint. The image from multiples shows significant improved illumination in the shallow subsurface.*

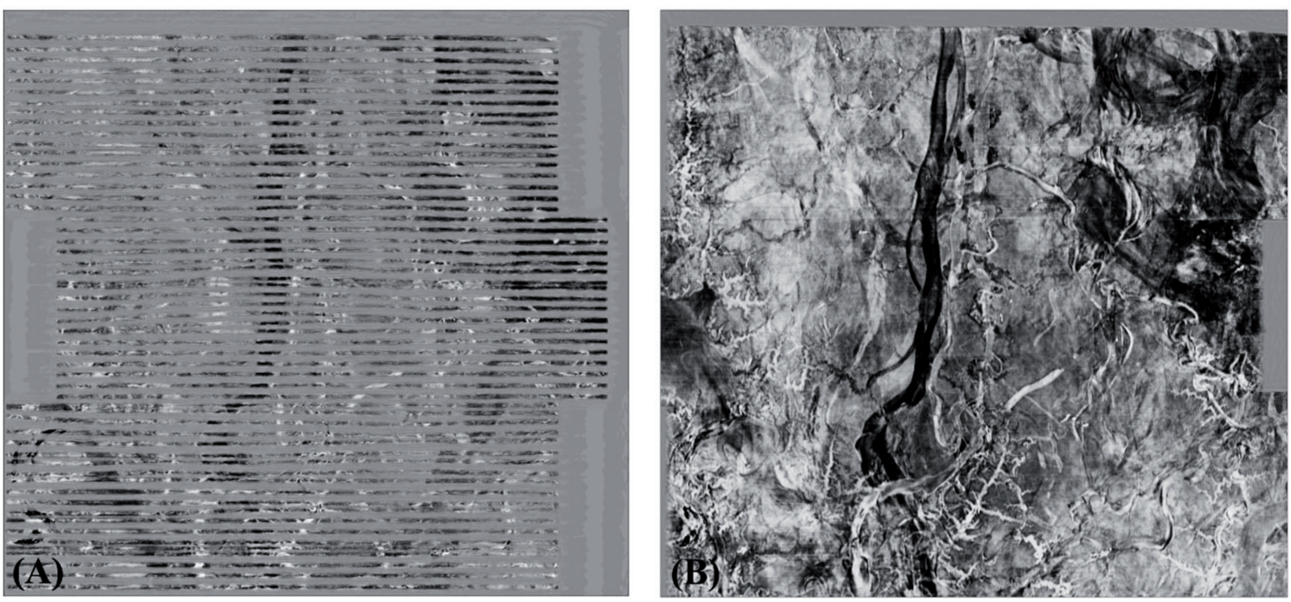

Figure 8 *Depth slices at 105 m below sea surface from imaging of primaries (A) and imaging of multiples (B). The image from multiples not only includes greater coverage of the subsurface at this depth but the image also includes details that are not present in the primary wavefield image. Imaging of multiples enhances subsurface imaging illumination and resolution.*

Figure 6 shows a zoom view centered on the water bottom, sediment and top salt. In the plots, the angle gathers are displayed in inline (zero-degree azimuth) and cross-line (90-degree azimuth) directions with maximum angles ranging from -70 to +70 degrees. The zero-degree azimuth angle gathers from SWIM (Figure 6C) is much more finely sampled than the gathers from imaging with primaries only (Figure 6A). Moreover, in the 90-degree azimuth direction only very few reflection angles are imaged (Figure 6B), while SWIM enables the creation of densely populated angle gathers that are easier to interpret (Figure 6D).

NAZ field data application

While separated wavefield imaging (SWIM) benefits from large streamer array utilized in WAZ survey geometries, it also improves the resolution of shallow subsurface targets when applied to narrow azimuth (NAZ) data. Acquisition footprint and poor near-surface image resolution present ongoing challenges in particular in shallow water environments when only primaries are used for imaging. In order to improve the image resolution, high-density 3D (HD3D) acquisition survey geometries can be designed comprising denser sail-line spacing and richer near offset information.

However, this inadvertently increases the cost of both acquisition and data processing. As has been discussed above, free-surface multiples provide a significantly wider and denser sampling of shallow reflectors than is possible with primaries arrivals. Separated wavefield imaging therefore provides a possible low-cost alternative to high-density acquisition geometries in shallow water environments.

We illustrate the near-surface image improvements from SWIM using a NAZ dataset from offshore Malaysia. Within a 25 km by 23.4 km testing area, 49 consecutive sail-lines of dual-sensor streamer data are imaged utilizing up- and down-going wavefield estimates. Figure 7 shows cross-line sections through the depth image for (A) the primary only image and (B) and the SWIM image. Significant gaps are visible in the primary only image of the very shallow overburden caused by the limited illumination fold due to the large sail-line separation and the required mutes to eliminate refracted energy arrivals.

In contrast, the SWIM images provide a complete near-surface image (Figure 7B). These significant image improvements are confirmed on a shallow depth slice at 105 m below the sea surface (Figure 8). The SWIM data (B) provides a shallow channel image of unseen clarity and structural detail.

Conclusions

Free-surface multiples contain valuable information about the subsurface that can be used to improve the subsurface image instead of discarding multiples as unwanted noise. In dual-sensor towed streamer acquisition, the recorded data can be accurately deghosted by separating the data into up-going and down-going components. These up-going and down-going wavefield components form the natural input for shot profile wave equation migration. In separated wavefield imaging (SWIM) the down-going wavefield is used as a virtual areal source, resulting in images with increased angular illumination. The use of the multiples also improves the extent of the subsurface image and its resolution. Significant near-surface image improvements are observed for both wide-azimuth and narrow azimuth geometries.

The process of imaging with multiples can create crosstalk, which can be partially mitigated by using improved deconvolution imaging conditions, but is still subject to ongoing and active research.

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