Enhanced Angular Illumination from Separated Wavefield Imaging (SWIM)

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SUMMARY

In exploration geophysics, both primaries and multiples can be used for depth imaging. This is feasible after applying wavefield separation to generate up-going and down-going wavefields. The separated wavefields can be used as boundary data for migration using sea surface related multiples – Separated Wavefield Imaging (SWIM). The areal source (recorded down-going wavefield) in SWIM covers larger surface spread than the point source in primaries imaging. Therefore, SWIM can enhance the areal illumination of subsurface and angular illumination of a point in the subsurface, especially when shots sampling is coarser. Angle gathers are generated from imaging of primaries and SWIM. As expected, the SWIM angle gathers prove to be denser, and less affected by coarse source sampling than the primaries angle gathers. The concept is illustrated by using a wide azimuth (WAZ) field data example.

Introduction

Conventional wave equation migration extrapolates up-coming boundary data generated from primary reflections to image the subsurface. The use of sea surface related multiples for depth migration has been discussed by Berkhout and Verschuur (1994), Guitton (2002) and Whitmore et al. (2010). Imaging of multiples can be achieved by using the separated up-going and down-going wavefiled as receiver and source wavefields in depth migration. We refer to such method as Separated Wavefield Imaging (SWIM). Lu et al. (2011) presents the first 3D example (SEAM synthetic) of Separated Wavefield Imaging using multiples with towed streamer acquisition geometry. Lu et al. (2013) discusses the capability of the technology when applied to 3D field data examples.

When compared to primaries imaging, multiples imaging increases the subsurface illumination coverage of the migration. This is because multiples imaging uses an areal source (down-going wavefield), which is broadly distributed on the surface compared to the point source used by primaries imaging [Figure 1A]. The diagram illustrates how multiples imaging illuminates larger subsurface region (dashed circles) than primaries imaging (solid circles). In Figure 2, we demonstrate this concept using a 3D field data example (one shot). The one-shot image from multiples covers much broader subsurface region than the corresponding primaries image, which is consistent with the diagram in Figure 1A.

More significantly, multiples imaging improves angular illumination. Figure 1B shows the reflection angles from imaging one-shot of primaries and multiples. The diagram illustrates how at a single subsurface location, primaries imaging can only have one reflection angle; while multiples imaging can produce more than one reflection angles even when using only one shot.

In this paper, a 3D wide azimuth (WAZ) deep-water field data example is used to demonstrate the importance of multiples imaging to improving subsurface areal illumination and angular illumination. The finely sampled angle domain image gathers could be used for tomography and pre-stack post processing to improve the overall quality of depth migration.

Method

In shot profile wave equation migration, the imaging process is a combination of wavefield downward extrapolation and imaging condition (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. Multiples imaging propagates up and down-going wavefields as receiver and source wavefields, where boundary data are generated at the receiver locations via up-down wavefield separation. We employ an extrapolation method based on a Fourier Finite Difference operator. Primaries and multiples are imaged separately.

Up/down imaging principle is applied at the subsurface. We use a stable version of deconvolution imaging condition (Guitton et al. 2007) to suppress the cross talk generated from unrelated correlation of up and down-going wavefields:

$$I(\vec{x}) = \sum_{\vec{x}_s} \sum_{\omega} \frac{P_{up}(\vec{x}_s, \vec{x}, \omega) P^*_{down}(\vec{x}_s, \vec{x}, \omega)}{\left\langle P_{down}(\vec{x}_s, \vec{x}, \omega) P^*_{down}(\vec{x}_s, \vec{x}, \omega) \right\rangle_{\vec{x}} + \varepsilon(\vec{x}, \omega)} \quad (1)$$

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

In equation 1 and 2, $I(\vec{x})$ is the subsurface stacked image in depth, $I(\vec{x}, \vec{h})$ is the subsurface image gather in the offset domain; h is the source receiver half offset; P_{up} and P_{down} are the up and down-going wavefields; ε is a damping parameter to make the deconvolution imaging condition stable; $\langle \ \rangle_{\vec{x}}$ stands for smoothing in the image space. Subsurface offset gathers can be converted to angle domain after applying a radial-trace transform (Rickett and Sava, 2002).

Example

Imaging of primaries and imaging of multiples are applied to a 3D WAZ deep-water field data example. In this example, compared to primaries imaging, multiples imaging enhances subsurface areal illumination by using the extensively distributed down-going wavefield as the source wavefield. In Figure 3, depth slices from imaging of primaries and imaging of multiples at 3km below sea surface are compared (30km by 30km region). At this depth, salt boundaries are illuminated by both primaries and multiples. Inside the zoomed box, multiples imaging builds more continuous and clearer salt boundary images than primaries imaging. multiples imaging enhances subsurface illumination especially when complex structures are present (e.g. salt bodies).

Imaging of multiples improves angular illumination. The angular illumination depends on shot density; therefore shot sampling is important for generating rich angle fold. In marine streamer acquisition, the shot separation in crossline direction is typically several hundred meters. It is hard to have finely sampled angle gathers when imaging using primaries, especially at the 90-degree azimuth direction. By using an areal source (down-going wavefield), multiples imaging can have much improved "shot sampling" than primaries imaging. Therefore, multiples imaging generates much more finely sampled angle gathers than primaries imaging. Figure 4A displays the vertical profile of inline image from multiples imaging (0-8km from sea surface); and Figure 4B shows the corresponding angle gathers from multiples imaging (maximum angle from -25 to +25 degrees). In both the stack and angle images, multiples imaging illuminated structures from shallow to subsalt regions. Figure 5 displays the zoomed view of angle gathers inside the red-box region in Figure 4B. The gathers are displayed in both inline (zero degree azimuth) and crossline (90-degree azimuth) directions, maximum angle from -70 to +70 degrees. Figure 5B shows the angle gathers from primaries at 90-degree azimuth direction. As expected, there are only several angles illuminated, because the shot separation (sail line spacing) is 600 meters in this direction. In the inline direction, where the shot sampling is finer (150m shot separation) primaries generate acceptable angular illumination [Figure 5A]. Multiples imaging generates densely populated angle gathers in both inline and crossline directions [Figure 5C, 5D] when using much more densely sampled down-going wavefield as source wavefield. In both multiples imaging and primaries imaging, the maximum angle coverage of inline direction is larger than the cross line direction. This is because the streamer cable length is bigger than the cross line acquisition spread.

Using this 3D WAZ field data example, we have demonstrated that multiples imaging improves subsurface areal illumination and angular illumination. Multiples imaging generates much clearer salt boundary images than primaries imaging and angle gathers from multiples imaging are much more finely sampled than the angle gathers from primaries imaging.

Conclusions

We have applied Separated Wavefield Imaging (SWIM) for migration of sea surface related multiples. The separated up and down-going wavefields are required as boundary data for multiples imaging. A deconvolution imaging condition is used to supress the cross talk and multiple noise. Subsurface images and image gathers are created from imaging of primaries and imaging of multiples. Multiples imaging uses a densely populated areal source wavefield (down-going) and improves subsurface imaging coverage and angular illumination. Using a 3D WAZ field data example, we have demonstrated that multiples imaging improves salt boundary illumination and creates more finely sampled angle gathers. The densely populated angle gathers can be used for velocity model building and for pre-stack post processing to improve overall quality of depth migration.

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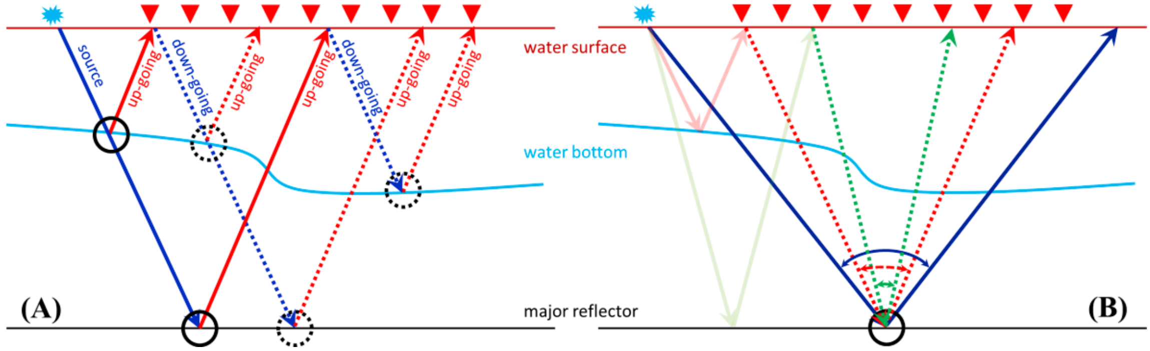

Figure 1, (A) *Schematic diagram for imaging of primaries (solid lines) and imaging of multiples (dashed lines). Images from multiples (dashed circles) cover greater subsurface extent than images from primaries (solid circles).* ***(B)*** *At a single subsurface reflector (solid circle), there is a single reflection angle generated from primaries imaging (solid lines); while there can be more than one reflection angles generated from multiples imaging (dashed lines).*

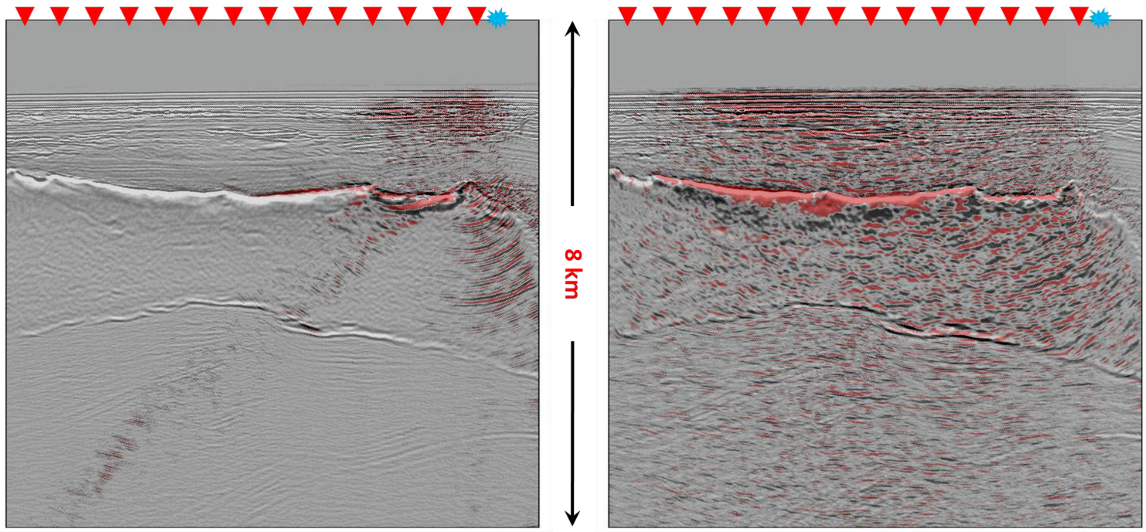

Figure 2, *images generated from one shot data (color) on top of the stacked images (grey) from a 3D WAZ field data example. When using one shot data, multiples imaging (right) creates larger subsurface illumination coverage than primaries imaging (left), which is consistent with Figure 1A.*

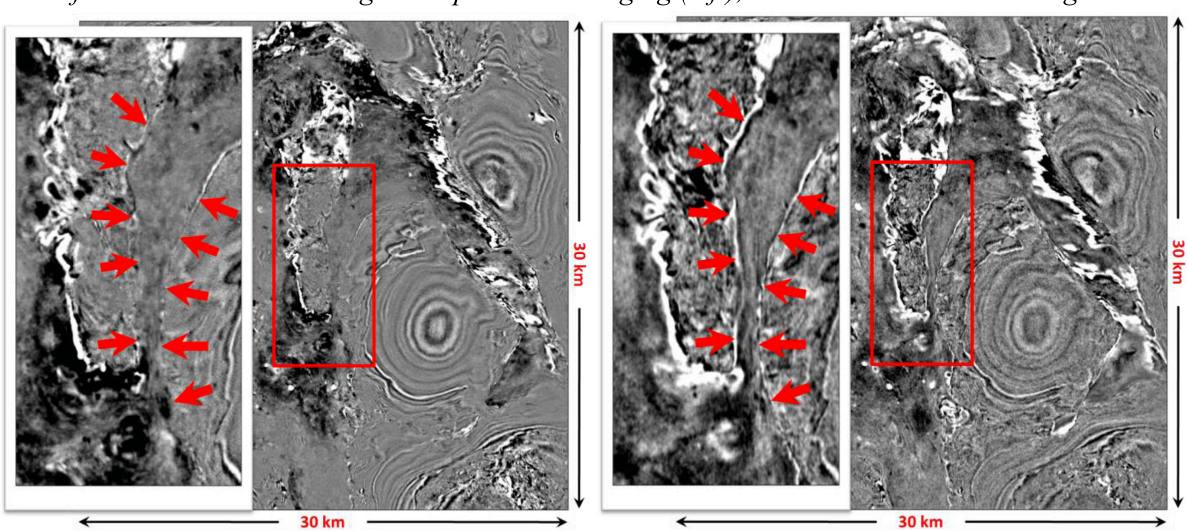

Figure 3, *depth slices (3km below sea surface) from imaging of primaries (left) and imaging of multiples (right). Multiples imaging builds more continuous and clearer salt boundary reflection images than primaries imaging (indicated by red arrows inside the zoomed region).*

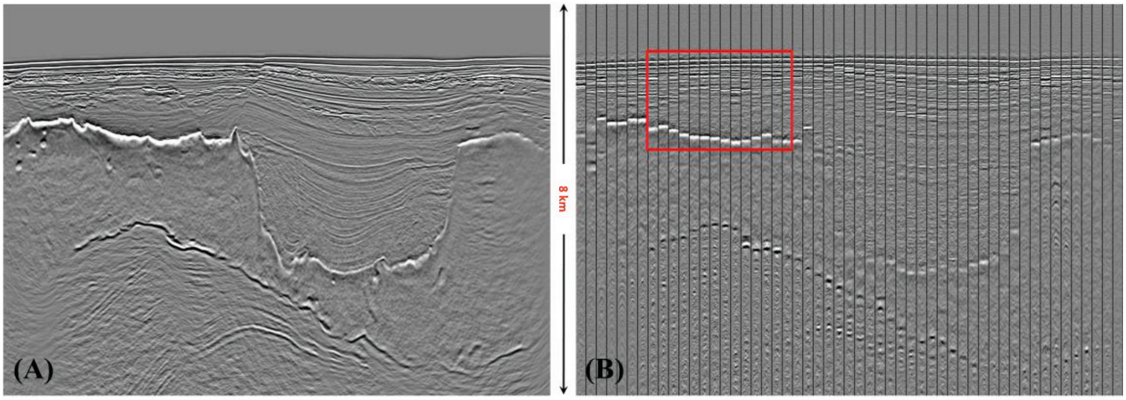

Figure 4, *vertical profile of inline image from multiples (A), and the angle gathers from multiples (B). The gathers are at the 90-degree azimuth direction, and maximum angle from -25 to +25 degrees.*

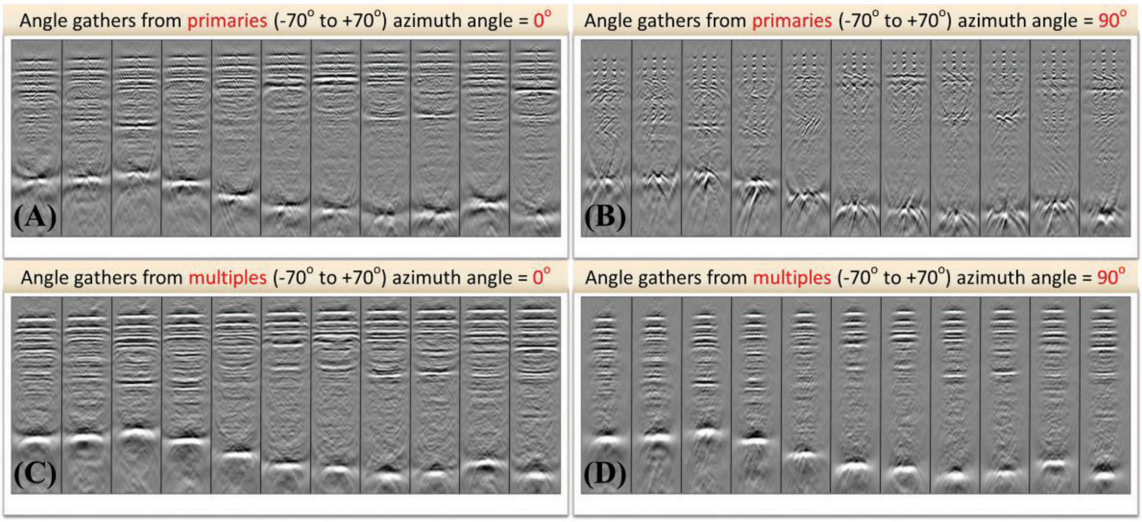

Figure 5, *angle gathers from imaging of primaries and imaging of multiples. The region corresponds to the red box area in Figure 4B. The gathers from primaries imaging have illumination issues due to the sparse shot spacing, especially at the 90-degree azimuth direction in panel (B). Gathers from multiples imaging (C, D) are finely sampled in both inline and cross line directions.*

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