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Postmigration multiple prediction and removal in the depth domain

Bin Wang[1], Jun Cai[1], Manhong Guo[1], Chuck Mason[2], Sampath Gajawada[1], and Duryodhan Epili[2]

ABSTRACT

We have developed a new methodology for predicting and removing multiples in the postmigration depth domain based on wavefield extrapolation and attribute-based subtraction. The inputs for the multiple prediction are a 3D prestack depth-migrated stack volume and the corresponding migration velocity volume. The output is the predicted multiple model in the migration depth domain. In some cases, the strong residual top of salt multiple may be erroneously picked as the base of salt reflection. With the predicted multiple model available for comparison during the salt model building stage, there is a better chance of building an accurate salt model and avoid picking multiple events. In an effort to further improve the final migrated images, the predicted multiple model is used to remove residual multiples in the migration depth domain. A poststack wavefield extrapolation-based multiple prediction is used to identify and confirm the multiple events in the migration depth domain. Once multiple events are identified, an effective and efficient demultiple technique is applied to remove the residual multiples from the final migration. The key ingredient of this new demultiple methodology is the attribute-based subtraction. We describe the main steps of this methodology and demonstrate its effectiveness by showing some field data applications.

INTRODUCTION

Substantial progress has been made for predicting surface-related multiples in marine seismic data. There are two approaches for predicting multiples: 1) data-driven convolution based prediction called surface-related multiple elimination (SRME) (Verschuur et al., 1992; Berkhout and Verschuur, 1999; Baumstein et al., 2006; Dragoset et al., 2008; Cai et al., 2009) and 2) a model-driven approach such as wavefield extrapolation (WFE) based prediction (Riley and Claerbout, 1976; Morley, 1982; Tsai, 1985; Berryhill and Kim, 1986; Wiggins, 1988, 1999; Lu et al., 1999; Kabir et al., 2004; Pica et al., 2003, 2005). These two approaches were well summarized by Brown (2004) and Matson and Xia (2007).

Both SRME and WFE can in general predict the timing of multiples accurately. The accuracy of multiple predictions by SRME depends on source and receiver acquisition sampling and on how well the data regularization fills in missing traces. The WFE approach solves the sampling issue by modeling using the reflectivity model, which is typically based on a stacked migration image. The accuracy of WFE depends on the quality of the reflectivity model and the accuracy of the velocity model that is used to produce the migration image. However, both SRME and WFE alter the waveform of the multiples. Convolution based SRME changes the waveform by doubling the source wavelet spectrum in the frequency domain. In the convolution process, the seismic trace itself serves as a filter; therefore, the predicted multiple model has a narrower frequency bandwidth as compared with the multiples in the data. In addition, interpolated traces to generate missing source-receiver pairs at the bounce points under the water surface may not have the same waveform as the missing traces. WFE based approaches also change the waveforms unless one uses a perfect reflectivity model, which is impractical to obtain. In the WFE case, the reflectivity model (mostly the migration image) serves as a bandpass filter to the source wavelet. Because of these waveform changes, subtracting multiples from the data using the predicted multiples is still a challenging task.

One common approach for subtracting the multiples using the predicted multiples is adaptive subtraction (Verschuur et al., 1992). Adaptive subtraction tries to match the waveform of the predicted multiples to the waveform in the data in both amplitude and phase within a window. If the window is small enough to include only multiples, the window may not be large enough to provide enough statistics to design a reliable filter. On the other hand, if the window is too large, it may contain primaries and other noise which would limit the adaptation process. Another approach is based on pattern

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[1]TGS, R&D Department, Houston, Texas, USA E-mail: Bin.Wang@tgsnopec.com; James.Cai@tgsnopec.com; Manhong.Guo@tgsnopec.com; Sampath.Gajawada@tgsnopec.com.
[2]TGS, Imaging Services, Houston, Texas, USA E-mail: Chuck.Mason@tgsnopec.com; Duryodhan.Epili@tgsnopec.com.

matching (Spitz, 1999). One designs a prediction error filter (PEF) for the primary by deconvolving the PEF of the data with that of the predicted multiples. Comparison of adaptive subtraction versus pattern matching is well documented by Abma et al. (2005). They reported that a pattern matching technique tends to leave significant residual multiple energy and damages the primaries where the predicted multiples overlap the primaries.

Despite the great advances made in this area, multiple removal continues to be a major challenge in seismic data processing. Frequently, there are noticeable residual multiple reflections in the final migration image. There are numerous causes of these residual multiples. First, in the prestack SRME stage, the predicted multiple models are not accurate enough because of insufficient data acquisition or because the data regularization does not generate the bounce points as needed. Second, in order to preserve weak primary reflections, such as subsalt sediment reflections, the adaptive subtraction parameters are often deliberately set on the conservative side. These types of residual multiples are commonly found in shallow marine or land data. Third, in the case of fast-track volumes, there is often not enough time to apply complex full-scale 3D multiple removal techniques.

Significant residual multiples in a data set can cause problems with velocity model building and geological interpretation. The strong residual top of salt multiple event may be mistakenly picked as the base of salt reflection leading to an erroneous salt velocity model. During the velocity analysis stage, especially during subsalt velocity updating, residual multiples can make velocity picking very difficult, both for residual curvature picking on common image point (CIP) gathers and for subsalt scan picking. Additionally, residual multiples in the final migration image make seismic interpretation extremely challenging.

We have developed a new method for predicting and removing multiples in the postmigration depth domain. Our prediction technique is based on WFE (Pica et al., 2003, 2005; Stork et al., 2006; Matson and Xia, 2007), and is applied in the poststack mode, and the predicted multiple model is in the depth domain (Wang et al., 2009a, 2010). In general, the accuracy of the predicted multiple model using WFE depends on the accuracy of the velocity model. However, the velocity model used for creating the reflectivity model (mostly the migration image) is the same for the demigration/modeling step (Pica et al., 2005); therefore, even with an inaccurate velocity model, the demigration step reduces the kinematic error introduced during the migration stage and improves the accuracy, especially for near offset traces.

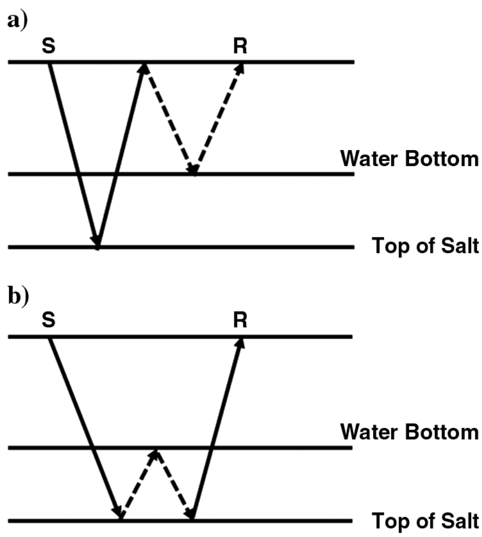

Figure 1. Multiple modeling is performed by adding a “round trip” to the primary: (a) water bottom peg-leg free-surface multiple; b) interbed multiple between water bottom and top of salt.

In addition to its efficiency, the poststack WFE is insensitive to velocity model errors, since the reflectivity model is kinematically consistent with the zero-offset image; therefore, the zero-offset demigration is kinematically undoing the migration and canceling out the errors. Pica et al. (2003) described an efficient method to use a constant velocity model to perform poststack migration and then perform zero-offset demigration and modeling to produce a zero-offset multiple wavefield in the time domain, and their demultiple method is intended to be applied at the preprocessing stage. Our approach is designed to be a postmigration processing tool to remove the residual multiples. It serves as a supplementary and additional demultiple step which is applied after the regular demultiple tools, such as 3D SRME, are applied in the preprocessing stage. Having a multiple model in depth for comparison was found to be very useful for salt model building and subsalt velocity updating to avoid picking a residual multiple event as base of salt. Artman et al. (2007) described a different way of producing a multiple model in the depth domain during migration.

In contrast to the typical multiple removal procedure (Verschuur et al., 1992), the multiple model predicted by the poststack WFE method may not be directly used in the subsequent subtraction step, and the commonly used adaptive subtraction may not be effective and suitable. One reason is that the wavelet shape and frequency content of WFE predicted multiples are significantly different from multiples existing in the data, and this makes a conventional adaptive subtraction approach very difficult. In this paper, we present a new method for multiple removal. The key ingredient of this new demultiple method is the attribute-based subtraction (Guo et al., 2008). Application to both marine and land data has proven this new technique to be very effective and efficient in enhancing the final image by reducing residual multiples.

POSTSTACK WFE MULTIPLE PREDICTION

A multiple event can be viewed as a primary event plus an additional round-trip in traveltime. As illustrated in Figure 1a, if the round trip (shown by the dashed line) is in the water column between the water bottom and free surface, it becomes a water bottom peg-leg multiple. Since the downgoing bounce point is on the free surface, it is called a free-surface multiple. On the other hand, if the downgoing bounce point is not on the free surface, but instead is on a subsurface reflection boundary such as the water bottom, it is called an interbed multiple. Figure 1b shows how an interbed multiple is generated between the water bottom and the top of salt; in this case, the round trip is between the water bottom and the top of salt.

The objective of this research is to generate a multiple model prediction in the postmigration depth domain that can be compared with the migrated image. Since this multiple prediction method operates in the poststack mode, it is extremely efficient.

The input volumes for this method include the 3D migration image cube and the corresponding migration velocity model. The output is the predicted multiple model in the postmigration depth domain. Figure 2 shows the flow chart of this prediction method. The method consists of the following major steps:

1) Perform a poststack wave-equation based demigration to get an estimate of the zero-offset (post-stack-time) wavefield (Wang et al., 2005), using the depth migration image as the reflectivity model, and the migration velocity model.
2) Obtain an estimate of the multiple model wavefield in the time domain, using the demigrated wavefield as input and adding a round-trip forward WFE.
3) Convert the predicted time-domain multiple model to the multiple model in the postmigration depth domain, using wave-equation migration (WEM) with the same migration velocity model.

Figure 3 is an example of utilizing the above three steps of multiple prediction on a Gulf of Mexico 3D data set. Figure 3a is the migration velocity model in depth. Figure 3b is the final depth migration image, which shows significant residual multiples. Figure 3c shows the predicted multiples in the migration image domain.

If some key interpretation horizons from the depth-migrated volume are available, such as water bottom or TOS, an alternative approach is to use these horizons instead of the seismic migration volume to predict multiples in horizon form. This is illustrated in Figure 4.

MULTIPLE MIGRATION IMAGE AS AN AID TO INTERPRETATION

It is possible to identify multiple reflections by comparing the migration image with primary and residual multiple events to the migration image of only predicted multiple events. This is particularly useful during the salt model building stage.

The examples shown in Figures 3 and 4 illustrate that the top of salt water bottom peg-leg multiple may contaminate the base of salt interpretation. Clearly, near the picked base of salt, there is a strong top of salt multiple. In the example shown in Figure 3, at this location the top of salt is very close to the water bottom. The sediment velocity right above the top of salt is very low; therefore, the velocity contrast across the top of salt is high and generates a strong top of salt multiple. It is difficult to remove this multiple during the standard time-domain demultiple processing. With the predicted multiple model shown in Figures 3c and 4c as a guide, the picking of top of salt multiples as base of salt horizons during the salt model building stage could be avoided.

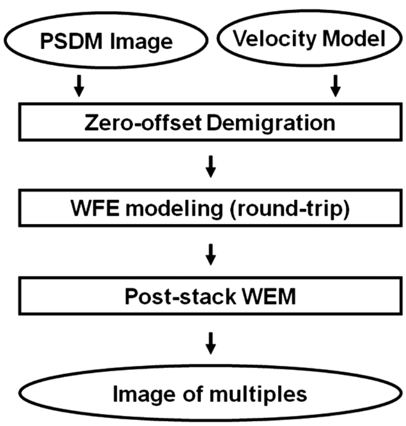

Figure 2. Flow chart showing multiple modeling in migration depth domain using migrated image and velocity model.

Reverse time migration (RTM) is a very useful tool for imaging complex areas such as subsalt; Wang et al. (2009b) show how RTM can also be used for subsalt velocity analysis using a scan-based approach. However, because it is an interpretation driven process, conflicting subsalt events create problems for subsalt scanning. Figure 5a is an RTM image, with steeply dipping, conflicting events in the deep subsalt area. After performing multiple prediction in the migration depth domain (Figure 5b), we can see that in the highlighted area the event dipping to the right is actually noise caused by strong multiples swinging into the shadow area directly below the salt body. There is no one-to-one correspondence between the predicted multiples and the residual multiples left in the migration image. This is because some of the multiples were already removed by the regular time-domain demultiple process.

RESIDUAL MULTIPLE REMOVAL BY ATTRIBUTE-BASED SUBTRACTION

We use a new subtraction approach based on the attributes of the predicted multiples; namely, dip and average absolute value (AAV)

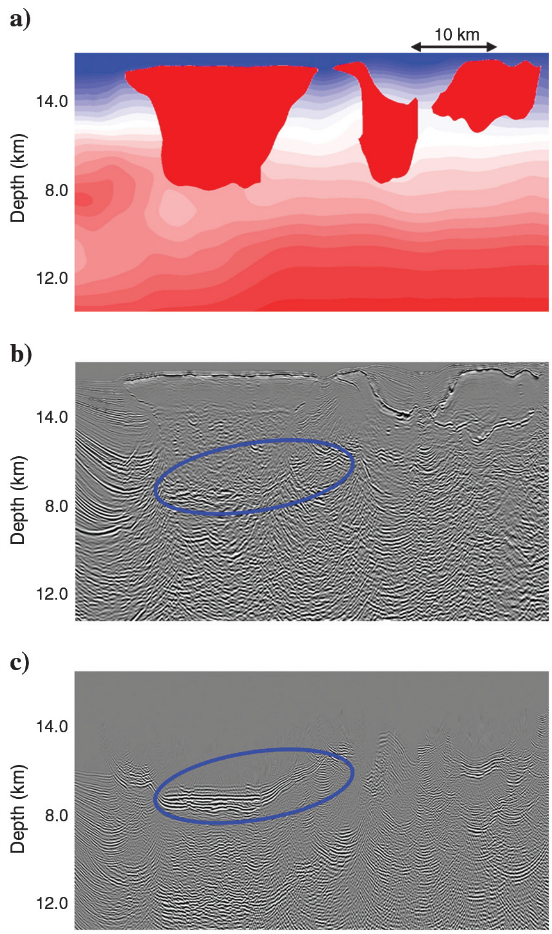

Figure 3. This illustrates the multiple prediction using a migration image as the reflectivity model where the multiples interfere with base of salt picking. (a) velocity model; (b) final migration image; (c) multiple model based on poststack WFE.

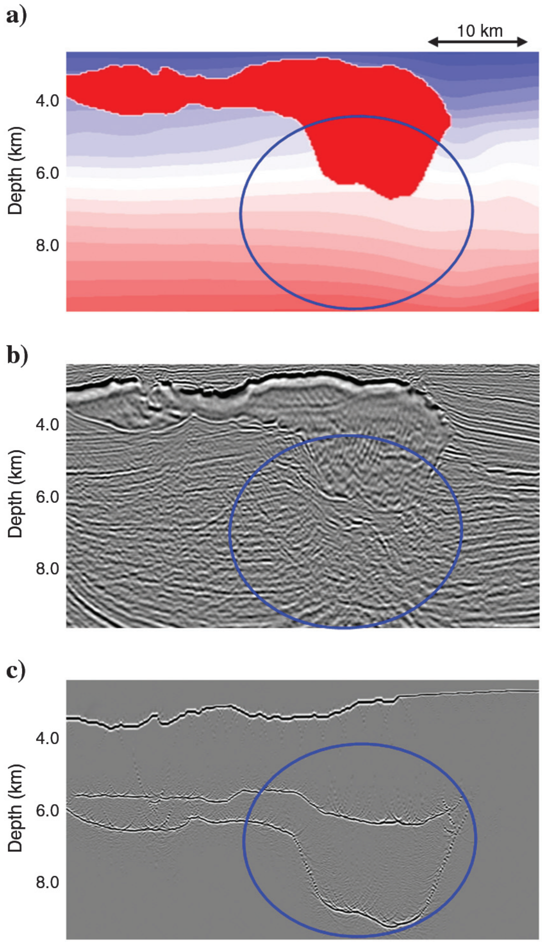

Figure 4. Example of multiple prediction using interpreted surfaces to build the reflectivity model: (a) velocity model; (b) final migration image; (c) multiple model based on horizon-based reflectivity.

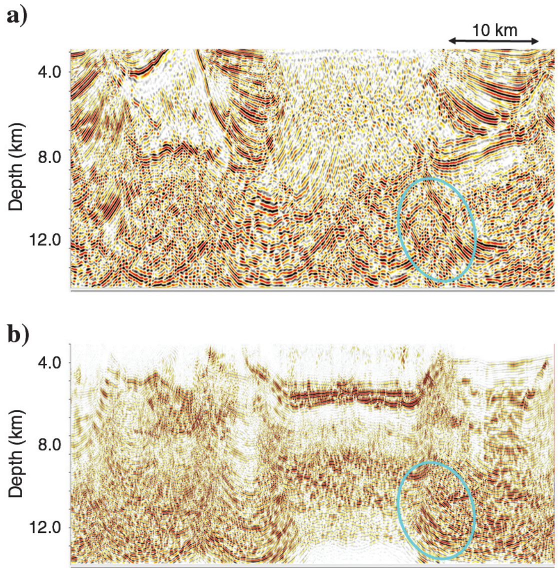

Figure 5. The predicted multiples can be used as an aid to interpretation helping to differentiate between migration swing and legitimate dip: (a) RTM image; (b) predicted multiple model in depth.

along the dip. Instead of subtracting adapted or matched multiples, we subtract multiples directly estimated from the data using the dip and AAV of the predicted multiples. This approach avoids the matching process which may have been the main source of the problems with previous approaches.

Figure 6 shows a flow diagram of the new method using the dip and AAV of the events in the data and in the predicted multiples. It consists of two steps. In the first step, we determine whether a given sample in the data belongs to a primary or a multiple. In the second step, we estimate the multiples in the data and subtract them from the data.

We use dip scanning to determine the dips of the events in the data containing primaries, multiples and other noise and the dips of the events in the predicted multiples. Next, the dips of the events in the data are compared to the dips of the events in the predicted multiples to separate the dips of the primaries. If the dip at a sample point in the data is sufficiently different from the dip at the same sample location in the predicted multiple, we consider the sample in the data as a primary. On the other hand, if they are similar, we regard the sample in the data as a multiple. In addition, we use AAV as another criterion to distinguish the primaries from the multiples particularly when the dips are similar. Because of spurious noise in the predicted multiples, the dip at a sample point in the predicted multiples can be similar to the dip at the same location in the data, but the AAV along the dip in the predicted multiples should be much smaller than the AAV along the same dip in the data. In this case, we regard the sample as a primary.

In the second step, assuming the waveform does not change much over a few traces, we estimate the primaries by averaging over a few traces along the dip. We then subtract the estimated primaries from the data to obtain a new data set that contains all the multiples and some residual primaries that were not properly accounted for in the previous estimation step. Using the dips of the events in the predicted multiples, we estimate or reconstruct the multiples from the new data set by averaging over a few traces along the dips of the multiples. These estimated multiples are subtracted from the data.

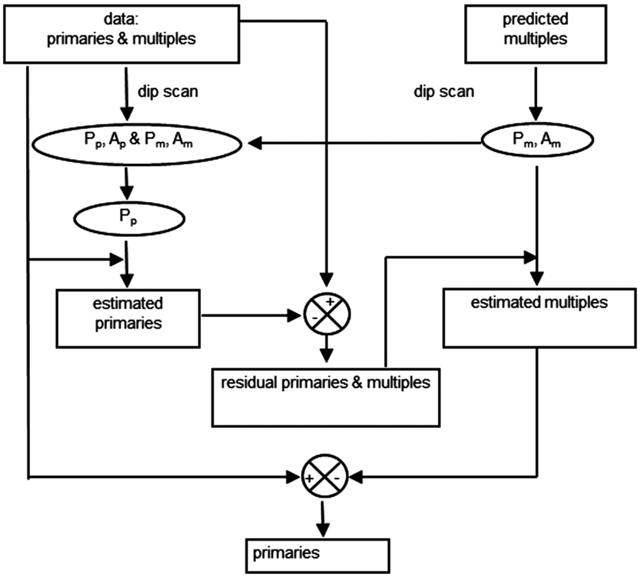

Figure 6. A flow diagram of attribute-based subtraction. *P* denotes the dip, and *A* denotes AAV. The subscripts *p* and *m* correspond to the primary and multiple, respectively.

Reconstructing the multiples using the data set from which most primaries are removed allows for a more reliable estimation of the multiples in the data.

Note that instead of generating a filter that will try to match the predicted multiples to the multiples in the data, we directly determine the multiples in the data using the dips of the predicted multiples. In other words, we use the predicted multiples only to determine the dips of the multiples in the data, thereby avoiding a step of matching the waveform of the predicted multiples to that of the multiples in the data.

For most of the applications, we directly apply the attribute-based subtraction described above. Sometimes we can also combine it with filtering in the frequency and wavenumber (*f*-*k*) domain to help further preserve the primaries by taking advantage of frequency separation between the high-frequency multiples and lower frequency primaries; therefore, the demultiple methodology consists of the following two steps:

1) Mild demultiple using *f*-*k* filtering.
2) Attribute-based multiple subtraction.

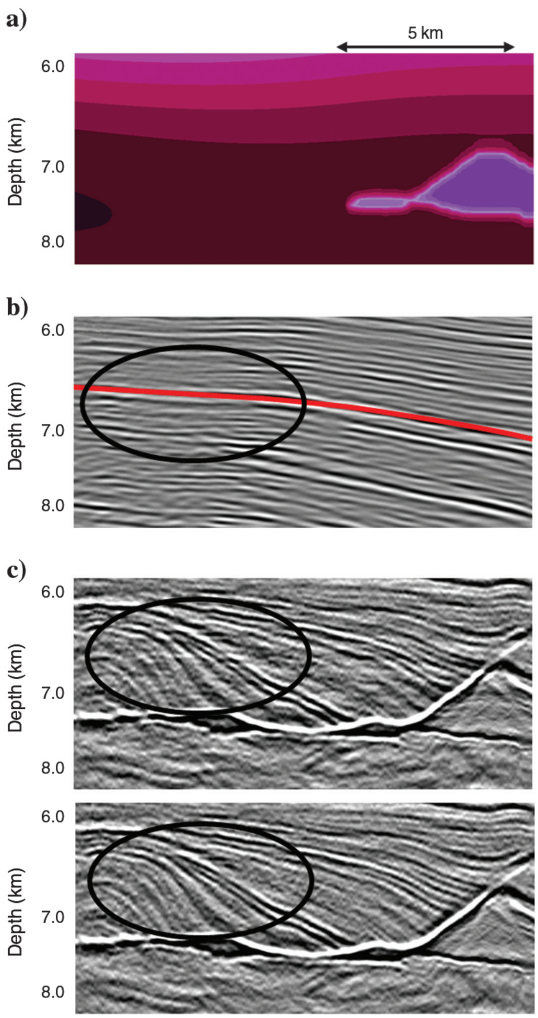

Figure 7. The multiple model (b), with flattening surface in red, is created using the velocity model (a) and migrated image (c). Attribute-based subtraction results in the postmigration demultipled output d).

For the *f*-*k* filtering step, we first define a 3D surface which follows the main dipping trend of the multiples (Figure 7b). We flatten the multiple events by performing a static shift using the picked surface making the multiple events more or less zero dipping, and then apply a gentle *f*-*k* filter to reduce the multiple content. In the *f*-*k* domain, energy from the multiple is separated from the primary by its dip and relatively higher frequency.

After the *f*-*k* filtering step, the majority of the multiples are removed, and the data is ready for the second attribute-based subtraction step. Though the input volumes are 3D, the demultiple process operates in a 2D line-by-line mode; therefore, it is extremely efficient. For better dip separation, the migration volume can be sorted to the crossline direction before the demultiple process. Figure 7c is the final migration volume, which is contaminated by residual multiple events. Figure 7a is from the corresponding 3D migration velocity volume. Figure 7b is the multiple model predicted by the poststack WFE. As shown in Figure 7b, the red curve shows the interpreted surface which follows the dip trend of the multiple events. Figure 7d is the result after applying the described demultiple procedure.

Shown by Figure 8, the demultiple method can be effectively used to remove the residual multiples in the final migration image.

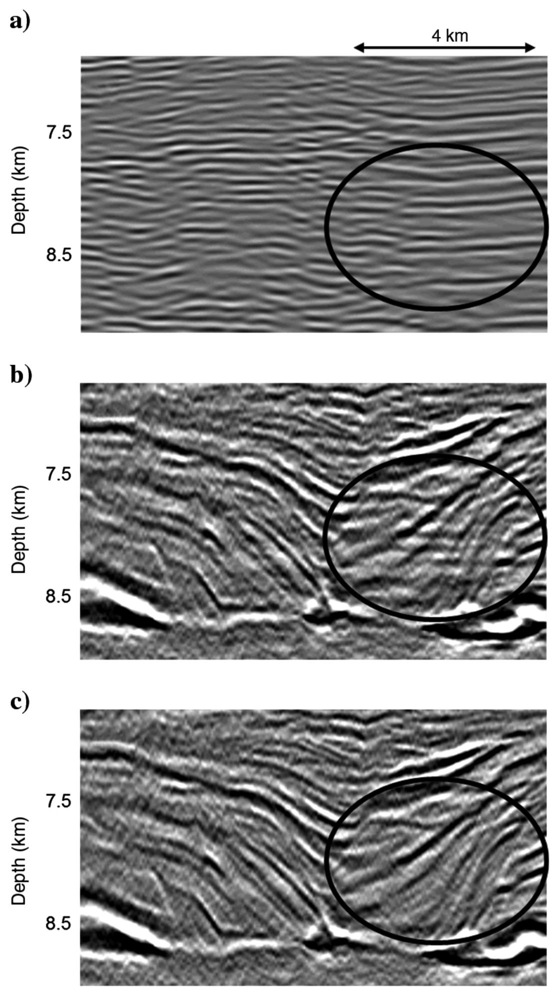

Figure 8. Using the multiple image (a), attribute-based demultiple is applied to the original migration image (b), resulting in the postmigration demultipled image (c).

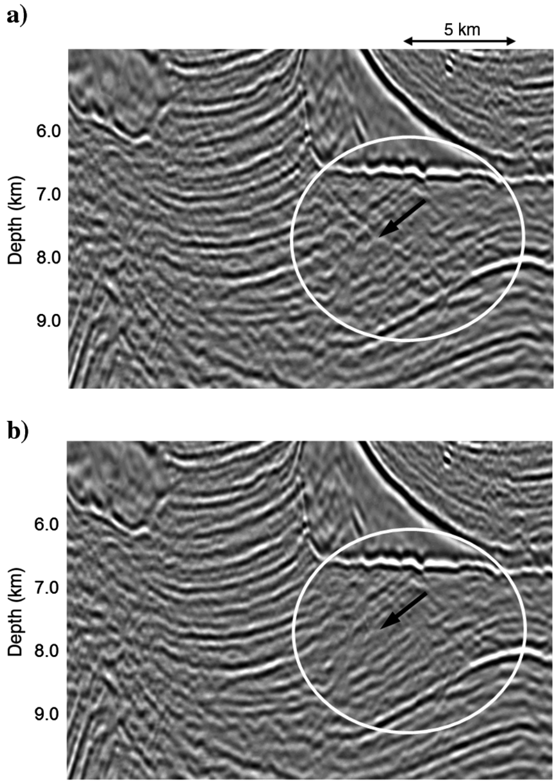

Figure 9. Horizon-based multiple prediction was used to model the discrete top of salt multiple. Comparison of the original image (a) and the migration image after postmigration demultiple (b) shows a clear improvement in primary continuity.

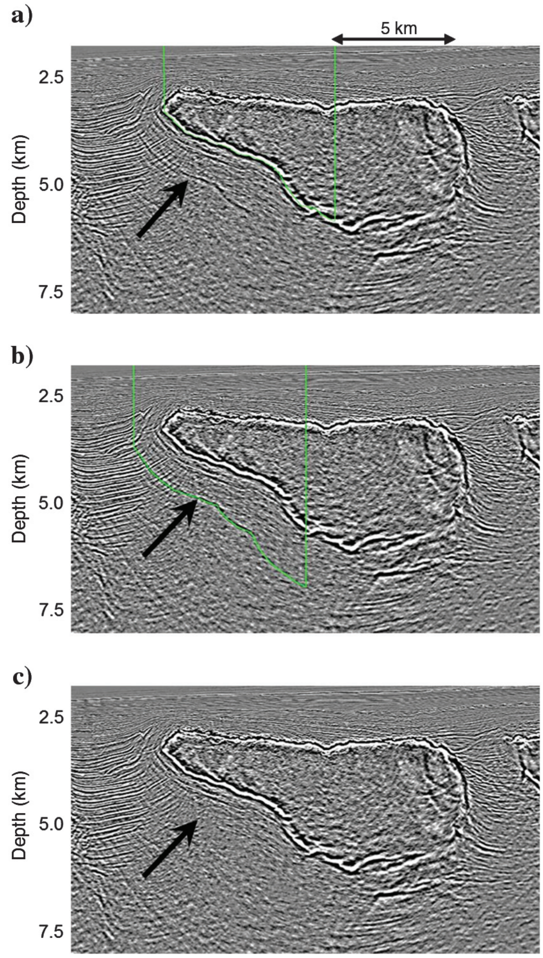

Figure 10. Ray-based multiple prediction is used to project the base of salt reflection (a), to its multiple image location (b). Interactive demultiple application (c) effectively removes the BOS multiple.

The flattish residual multiples in the original migration image are evident in Figure 8b. Figure 8c shows the results after applying the demultiple technique to the migrated image. Figure 9 shows another example of residual multiple removal from the final migration image by this postmigration demultiple technique. In this example, the horizon-based multiple prediction is used. The water bottom peg legs of top of salt and base of salt multiples are effectively removed, and primary reflectors are well behaved after the multiple removal.

INTERACTIVE DEMULTIPLE IN THE POSTMIGRATION DEPTH DOMAIN

As described in the previous sections, the poststack WFE multiple prediction is able to use either a whole migration image or a set of interpreted horizons/surfaces to build a reflectivity model for multiple prediction in the postmigration depth domain. If the residual multiples are only related to a few major multiple generating surfaces, we can also use ray tracing for the multiple prediction, which is more efficient. Very similar to poststack WFE, ray tracing based on the Runge-Kutta method is used first to predict the traveltime for the primary reflection from the base of salt, then the round-trip traveltime between the free-surface and water bottom is predicted. Next, the round-trip traveltime is added to the primary traveltime to get the traveltime of the multiple event; then ray tracing is used again to predict the location of the multiples in the postmigration depth domain.

Figure 10 is an example of the removal of a strong base of salt multiple using ray-based prediction. Figure 10a shows the base of salt multiple which is roughly parallel to the base of salt. Figure 10b shows the predicted base of salt multiple event in the postmigration depth domain. Figure 10c is the migration image after the attribute-based subtraction using the predicted base of salt multiple shown in Figure 10b. Since the ray-based multiple prediction is very efficient, we call this process of residual multiple removal using multiple surfaces predicted by ray-tracing "interactive demultiple."

CONCLUSION

We have developed a new and efficient multiple removal method that operates in the poststack mode in the migration depth domain. Comparison of a multiple prediction model with the final migration image provides interpreters with useful information, reducing the potential for misinterpretation of residual multiple events as true subsurface structures; therefore, our approach can aid in salt model building, in particular, where a multiple of the top of salt could be erroneously picked as a base of salt event.

In the technique outlined here, conventional adaptive subtraction is not used for the subtraction step, and the predicted multiple model is not directly used in the subtraction. Instead, the attributes of the predicted multiples, such as dip, frequency, amplitude and location are used in the subsequent attribute-based subtraction. By combining the multiple prediction method with the attribute-based subtraction method, we are able to reduce residual multiples effectively in the final migration images.

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REFERENCES

Abma, R., N. Kabir, K. H. Matson, S. Mitchell, S. A. Shaw, and B. McLain, 2005, Comparisons of adaptive subtraction methods for multiple attenuation: The Leading Edge, **24**, 277–280.

Artman, B., G. Alvarez, and K. Matson, 2007, Image-space surface-related multiple prediction: Geophysics, **72**, No. 2, S113–S122.

Baumstein, A., D. L. Hinkley, K. D. Andersen, and T. G. Farrington, 2006, Attenuating diffracted multiples with 3D SRME — A feasibility study: 68th EAGE meeting, F021.

Berkhout, A. J., and D. J. Verschuur, 1999, Removal of internal multiples: 69th Annual International Meeting, SEG, Expanded Abstracts, 1334–1337.

Berryhill, J. R., and Y. C. Kim, 1986, Deep-water peg legs and multiples — Emulation and suppression: Geophysics, **51**, 2177–2184.

Brown, M. P., 2004, Least-squares joint imaging of multiples and primaries: Ph.D. thesis, Stanford University.

Cai, J., M. Guo, S. Sen, S. Dong, R. Camp, and B. Wang, 2009, From SRME or wave-equation extrapolation to SRME and wave-equation extrapolation: 79th Annual International Meeting, SEG, Expanded Abstracts, 3313–3316.

Dragoset, B., I. Moore, M. Yu, and W. Zhao, 2008, 3D general surface multiple prediction: An algorithm for all surveys: 78th SEG Annual International Meeting, SEG, Expanded Abstracts, 2426–2330.

Guo, M., Y. Kim, S. Sen, J. Xu, J. Xie, and B. Wang, 2008, A new multiple subtraction method using the attributes of predicted multiples: 78th Annual International Meeting, SEG, Expanded Abstracts, 2451–2455.

Kabir, N., R. Abma, and G. Xia, 2004, 3D wavefield extrapolation based demultiple in Ormen Lange: 74th Annual International Meeting, SEG, Expanded Abstracts, 1245–1248.

Lu, G., B. Ursin, and J. Lutro, 1999, Model-based removal of water-layer multiple reflections: Geophysics, **64**, 1816–1827.

Matson, K. H., and G. Xia, 2007, Multiple attenuation methods for wide azimuth marine seismic data: 77th Annual International Meeting, SEG, Expanded Abstracts, 2476–2479.

Morley, L., 1982, Predictive multiple suppression: Ph.D. thesis, Stanford University.

Pica, A., and M. Manin, 2003, Fast zero-offset surface multiple modeling in 3D: 73rd Annual International Meeting, SEG, Expanded Abstracts, 1957–1960.

Pica, A., G. Poulain, B. David, M. Magesan, S. Baldock, T. Weisser, P. Hugonnet, and P. Herrmann, 2005, 3D surface-related multiple modeling, principles and results: 75th Annual International Meeting, SEG, Expanded Abstracts, 2080–2083.

Riley, D. C., and J. F. Claerbout, 1976, 2D multiple reflections: Geophysics, **41**, 592–620.

Spitz, S., 1999, Pattern recognition, spatial predictability, and subtraction of multiple events: The Leading Edge, **18**, 55–58.

Stork, C., J. Kapoor, W. Zhao, B. Dragoset, and K. Dingwall, 2006, Predicting and removing complex 3D surface multiples with WEM modeling — An alternative to 3D SRME for wide azimuth surveys?: 76th Annual International Meeting, SEG, Expanded Abstracts, 2679–2682.

Tsai, C. J., 1985, Use of autoconvolution to suppress first-order long-period multiples: Geophysics, **50**, 1410–1425.

Verschuur, D. J., A. J. Berkhout, and C. P. A Wapenaar, 1992, Adaptive surface-related multiple elimination: Geophysics, **57**, 1166–1177.

Wang, B., M. Guo, C. Mason, J. Cai, S. Gajawada, and D. Epili, 2009a, Wave-equation based residual multiple prediction and elimination in migration depth domain as an aid to seismic interpretation: 79th Annual International Meeting, SEG, Expanded Abstracts, 3123–3126.

Wang, B., C. Mason, M. Guo, J. Cai, S. Gajawada, and D. Epili, 2010, Interactive demultiple in the post-migration depth domain: 80th Annual International Meeting, SEG, Expanded Abstracts, 3436–3439.

Wang, B., C. Mason, M. Guo, K. Yoon, J. Cai, J. Ji, and Z. Li, 2009b, Subsalt velocity update and composite imaging using reverse-time-migration based delayed-imaging-time scan: Geophysics, **74**, no. 6, WCA159–WCA167.

Wang, B., F. Qin, F. Audebert, and V. Dirks, 2005, A fast and low cost alternative to subsalt wave equation migration perturbation scans: 75th Annual International Meeting, SEG, Expanded Abstracts, 2257–2260.

Wiggins, J. W., 1988, Attenuation of complex water-bottom multiples by wave equation-based prediction and subtraction: Geophysics, **53**, 1527–1539.

Wiggins, W., 1999, Multiple attenuation by explicit wave extrapolation to an interpreted horizon: The Leading Edge, **18**, 46–54.