Application of RTM 3D angle gathers to wide-azimuth data subsalt imaging

Yan Huang¹, Bing Bai¹, Haiyong Quan¹, Tony Huang¹, Sheng Xu¹, and Yu Zhang¹

ABSTRACT

The availability of wide-azimuth data and the use of reverse time migration RTM have dramatically increased the capabilities of imaging complex subsalt geology. With these improvements, the current obstacle for creating accurate subsalt images now lies in the velocity model. One of the challenges is to generate common image gathers that take full advantage of the additional information provided by wide-azimuth data and the additional accuracy provided by RTM for velocity model updating. A solution is to generate 3D angle domain common image gathers from RTM, which are indexed by subsurface reflection angle and subsurface azimuth angle. We apply these 3D angle gathers to subsalt tomography with the result that there were improvements in velocity updating with a wide-azimuth data set in the Gulf of Mexico.

Introduction

In the past few decades, progress in three major areas has led to significant improvements in seismic subsalt imaging: better migration algorithms, better data acquisition, and improved velocity model building tools. Progress in each of these areas has improved seismic imaging and has also prompted technology advances in the other areas.

Kirchhoff migration and beam migration both use ray tracing to approximate seismic wave propagation. This method compromises migration accuracy, particularly in areas where strong variations exist in the velocity model, e.g., in the case of salt existence. The single-arrival assumption in standard Kirchhoff migration further degrades the image in areas where complicated wavefields exist, e.g., the subsalt regions. In recent years, wave-equation based migrations, particularly reverse time migration (RTM) (Baysal et al., 1983; McMechan, 1983; and Whitmore, 1983), has resulted in improvements in complex salt areas. In theory, RTM can image all acoustic wave information, including reflections, refractions, diffractions, multiples, prismatic events, etc. Its advantages include the accurate handling of rapid spatial velocity variation and imaging without dip angle limitations. For these reasons, RTM is the preferred prestack depth migration tool for imaging complex structures (Eigen et al., 2009; Zhang and Sun, 2009). Examples of success include the demonstration of Reasnor et al. (2009) that RTM produces better definition of steeply dipping salt flanks, greater detail of small salt overhangs, and fewer imaging artifacts in the Puma/Mad Dog area located in Green Canyon, Gulf of Mexico (GOM) when compared to the one-way wave-equation migration (WEM) and controlled beam migration (CBM). Also, Huang et al. (2010) show that, when compared to Kirchhoff migration, RTM produces superior base of salt and presalt images below the rugose top of salt in Santos Basin, Brazil.

In addition to advances in migration algorithms, strides in seismic acquisition have also played an important role in subsalt imaging. After the move from 2D to 3D surveys in the 1980s, the next big leap in marine acquisition is the wide-azimuth (WAZ) configuration. BP performed initial experimental marine WAZ seismic acquisitions at Mad Dog and Atlantis in 2005 (Michell et al., 2006; Clarke et al., 2006). Since then, WAZ acquisitions have surged in the Gulf of Mexico. In a typical WAZ towed streamer acquisition, additional source vessels are used to shoot at a large lateral distance in the crossline direction from the streamers behind the primary source vessel. This configuration results in a higher fold, wider crossline offset range and broader azimuth distribution for WAZ than for conventional narrow azimuth (NAZ) data. WAZ acquisition provides more uniform illumination of the subsurface and, thus, a better chance to image the complicated subsurface, such as subsalt areas. The abundant azimuthal information also improves the signal-to-noise ratio and the cancellation of multiples in the subsalt (Michell et. al, 2006; VerWest and Lin, 2007). Combining the rich-azimuth and highfold WAZ data with the precise migration algorithm, RTM, provides a better chance of generating high quality subsalt images.
With the WAZ acquisition and RTM imaging algorithm, an accurate velocity model is necessary to produce clear seismic images. In theory, tilted transverse isotropy (TTI) provides a more accurate velocity model and results in better images compared to isotropic and VTI (vertical transverse isotropy). Utilizing WAZ data and RTM also reinforces the application of a TTI model, because the rich azimuthal information in WAZ data generates better constraints in TTI tomographic velocity inversion, and TTI RTM provides superior subsalt images (Huang et al., 2009; Bowling, 2010). TTI RTM imaging on WAZ data has become the standard for subsalt imaging in the Gulf of Mexico in the last few years. Due to its superior images in complex salt geometry, RTM — especially TTI RTM — has been used in salt interpretation, which is an integral part of the model building in the Gulf of Mexico. Buur and Kuhnel (2008), Menyoli et al. (2009), and Ritter (2010) demonstrate the benefits of using RTM as the imaging tool in major salt interpretation steps, such as sediment flood, salt flood, and salt scenario studies. Tomographic velocity inversion is another important area in the velocity model building. To utilize RTM in this area, the crucial step is to generate common image gathers (CIGs).

In this paper, we are interested in using RTM to handle the complex overburden for wave propagation and in using ray-based tomography to update the subsalt velocity, especially in anisotropy media. We first review different types of CIGs for wide-azimuth data and discuss the advantages of RTM 3D angle-domain CIGs. Second, we briefly introduce how to produce RTM 3D angle gathers. Then we demonstrate the application of RTM 3D angle gathers to subsalt TTI tomographic velocity updating. We use a WAZ data set from the Gulf of Mexico to illustrate how the proposed method helps to improve subsalt model building and image quality.

**COMMON IMAGE GATHERS FOR WIDE AZIMUTH DATA**

A common image gather (CIG) consists of a set of migrated traces at the same image location, with each trace representing a different subset of the data. Within a CIG, the same event from different traces will be imaged at the same depth, i.e., observed events will be flat if the correct velocity model is used in the migration. When events on the CIGs are not flat, the velocity model can be updated by analyzing the curvature of the events (Etgen, 1988; Al-Yahya, 1989; Stork, 1992; Kosloff et al., 1996; Zhou et al., 2003).

Conventionally, surface offset-domain CIGs (ODCIGs) are generated from ray-based migrations such as Kirchhoff and beam migration. An ODCIG contains traces migrated from different source-receiver offsets, usually ignoring azimuthal information for NAZ data. For WAZ data processing, the ODCIGs can be extended to 3D surface vector offset gathers by offset-X and offset-Y binning (Li, 2008). Using these gathers, one can distinguish information from different source and receiver pairs with a fixed distance and azimuth direction. With a growing trend to acquire multiple WAZ data sets, as well as to coprocess all existing NAZ data with WAZ data to further improve subsurface sampling and illumination, an even larger amount of data are added in the seismic processing. In these cases, 3D surface azimuth/offset gathers are sometimes used to combine all available data sets with varying azimuthal information. WAZ acquisition significantly increases the cost of generating ODCIGs simply because of the increase of data fold.

However, the quality of ODCIGs, or other CIGs indexed by surface attributes, suffers from migration artifacts due to the migration ambiguity caused by multiple raypaths (Nolan and Symes, 1996; Xu et al., 2001). When geology is complex, the appearance of migration artifacts hinders velocity analysis. Xu et al. (2001) suggests that a solution in 2D is to generate the CIGs indexed by a subsurface reflection angle or opening angle.

Generating surface ODCIGs using wave-equation based migration (WEM or RTM) has prohibitively high computational cost (Ehinger et al., 1996). Alternatively, it is possible to generate subsurface ODCIGs with less effort. Sava and Fomel (2003) exploit this fact to propose a two-step approach for producing subsurface CIGs: first generate local subsurface offset gathers, then convert them to subsurface angle-domain CIGs (ADCIGs). This approach is computationally efficient for 2D isotropic migrations (Sava and Fomel, 2003), but becomes complicated and computationally intensive in 3D (Fomel, 2004; Pell and Clapp, 2007). Sava and Fomel (2006) next propose an alternative, which is to produce time shift CIGs and then convert them to ADCIGs. However, the method is based on an isotropic media assumption, and the final angle gathers from this approach lack azimuthal information. There are many research efforts on ADCIGs generated from either subsurface offset gathers or time shift gathers and its applications on velocity updating (Biondi and Symes, 2004; Biondi, 2007; Wang, 2009). Most of them use 2D ADCIGs. The quality of these ADCIGs generated from an intermediate domain is limited by the conversion from one data domain to the other, because the conversion itself is constrained by interpolation and sampling theory.

In addition to the aforementioned indirect methods, ADCIGs can be produced directly by decomposing the wavefields at the image location into their local directional components before the imaging condition is applied (Soubaras, 2003; Wu et al., 2004). However, this method has thus far been limited to one-way wavefield propagators in isotropic media and has only been applied to 2D data, due to its high cost. Xu et al. (2011) propose an approach to generate 3D ADCIGs from RTM. This algorithm: (1) is formulated on the framework of amplitude-preserving RTM; (2) is valid in transversely isotropic media with tilted symmetry axis (TTI); and (3) produces CIGs indexed by a reflection angle and azimuth angle. During wave propagation in RTM, the wavefields from the source and the receiver are stored locally. A local windowed antileakage Fourier transform (ALFT) (Xu et al., 2005; Xu et al., 2010) is then applied to pick the wavenumbers with significant energy. The cross-correlation imaging condition is applied to those high energy wavenumber components, allowing the image to be decomposed according to an azimuth angle and reflection angle.

As mentioned above, direct generation of RTM 3D angle gathers handles anisotropy and provides subsurface azimuthal information. For WAZ data acquired over complex subsurface geology, the azimuthal information is crucial for velocity updating. Traditionally, the ADCIGs are only indexed by reflection angle, while completely omitting azimuthal information. Though they are not a problem for NAZ data, they do not fully utilize the WAZ data, which has rich subsurface azimuthal coverage in complex structures to aid model building and anisotropy parameter estimation (Zhang et al., 2010). Also, direct generation of RTM 3D angle gathers removes the need for the intermediate — domain. As a result, the artifacts introduced during the CIG conversion are eliminated. This improves the reliability of event picking for tomography.
In summary, RTM 3D angle gathers are generated before the imaging condition by decomposing the wavefields into local directional components; they are indexed by subsurface reflection and azimuth angles. They take advantage of the rich azimuthal information from the WAZ acquisition and the high imaging accuracy of RTM to produce reliable CIGs for anisotropic model building.

**GENERATING RTM 3D ANGLE GATHERS**

Xu et al. (2011) provides the details in formulating the RTM 3D angle gathers by first introducing the asymptotic form for 3D true amplitude angle-domain CIGs and then adjusting the formula for common shot RTM with a crosscorrelation imaging condition. The following steps summarize the procedure for generating RTM 3D angle gathers:

1. Calculate the source wavefield \( p_s \) and receiver wavefield \( p_r \) using an RTM wave propagation engine.
2. Conduct a 4D temporal/spatial Fourier transform to both the source and receiver wavefields, i.e., forward in time for the source wavefield and backward in time for the receiver wavefield, to express the wavefields in the frequency/wavenumber domain.
3. In the vicinity of the image location \( \mathbf{x} \), apply the imaging condition,
   \[
   I_s(\mathbf{k}, \theta_0, \varphi_0) = \sum_\omega \delta(\theta - \theta_0)\delta(\varphi - \varphi_0) \times p_F(\mathbf{k}, \omega)p_B(\mathbf{k}r, \omega),
   \]
   to the wavefields, and decompose the image by reflection angle \( \theta \) and azimuth angle \( \varphi \), according to
   \[
   \begin{cases}
   \cos \theta = \frac{k_\mathbf{k}_n}{|k_\mathbf{k}_n|} \\
   \cos \varphi = \left(\frac{(n_\mathbf{k}_r \times \mathbf{n}) \cdot (\mathbf{k}_r \times \mathbf{k}_s)}{|k_\mathbf{k}_r| |\mathbf{n} \times (\mathbf{k}_r \times \mathbf{k}_s)|}\right),
   \end{cases}
   \]
   where \( \mathbf{n} = (1, 0, 0) \) is a unit vector. The wavenumber vectors \( \mathbf{k}_s \) and \( \mathbf{k}_r \) are the wave propagation phase directions at \( \mathbf{x} \) for the wavefields from the source location \( s \) and the receiver location \( r \), respectively, and \( \mathbf{k} = \mathbf{k}_s + \mathbf{k}_r \). Figure 1 illustrates the reflection and azimuth angle definition in RTM 3D angle gathers. In Figure 1, the yellow surface represents a subsurface reflector, and the blue dashed arrow marks the normal direction.
4. In the vicinity of \( \mathbf{x} \), apply a 3D inverse spatial Fourier transform on \( I_s(\mathbf{k}, \theta_0, \varphi_0) \), to obtain the RTM 3D angle gather \( R_s(\mathbf{x}, \theta_0, \varphi_0) \) using the following equation:
   \[
   R_s(\mathbf{x}, \theta_0, \varphi_0) = w(\mathbf{x}, \theta_0) \sum_\mathbf{k} I_s(\mathbf{k}, \theta_0, \varphi_0)e^{i\mathbf{k}\cdot\mathbf{x}},
   \]
   where \( w(\mathbf{x}, \theta_0) \) is the true amplitude migration weight for angle gathers. For isotropic media, Xu et al. (2011) prove
   \[
   w(\mathbf{x}, \theta_0) = \frac{\delta(\theta_0 - \theta)\delta(\varphi_0 - \varphi)}{\sin \theta_0 \sin \varphi_0}.
   \]

From the procedure it is not difficult to see that generating the RTM 3D angle gathers needs intensive computation. In step 1, the amount of calculation for the wave propagations is the same as for conventional RTM. However, to generate RTM 3D angle gathers, the additional 4D Fourier transform (step 2) and angle decomposition in wavenumber domain (step 3) make the procedure computationally intensive. To reduce the extremely high computation cost and make the RTM 3D angle gathers feasible for use in practical seismic processing, Xu et al. (2011) analyze the computational cost and provide a solution to speed up the process while maintaining the accuracy. As a brief summary, first, the wavefields are decomposed in overlapping local spatial windows, and the dispersion relationships on the wave vectors are used to constrain the decomposition and convolution. Because, within a local window, the range of the slowness vector norms, is usually much smaller than the global range, the use of a local window not only reduces the cost of 3D convolution, it also allows for a more efficient use of dispersion relationships, which is related to the minimum and maximum values of the slowness vector norms. Second, introducing an oversampling scheme in ALFT reduces the effects of the Gibbs phenomenon and preserves angular resolution. Third, the computation increases by the oversampling scheme can be controlled by using a small number of most energetic wavenumbers to represent the wavefield. Despite the fact that it still needs significantly more computation than a conventional RTM, this scheme makes generating RTM 3D angle gathers feasible with current computer power and preserves calculation accuracy.

**RTM 3D ANGLE GATHERS FROM WAZ DATA**

We use a WAZ data set from the Gulf of Mexico to illustrate the advantages of RTM 3D angle gathers. The WAZ acquisition configuration had a maximum offset of \( \pm 8.5 \) km in the inline direction and \( \pm 4 \) km in the crossline direction (seven tiles, each with a width of 1.2 km). A rose diagram (Figure 2a) is used to depict the fold distribution with respect to surface azimuth and offset for this WAZ data. It displays the relative fold in a polar coordinate system where the radius axis is offset and the angular coordinate is azimuth. The rose diagram highlights the rich azimuthal information embedded in the data. More than half of the azimuth/offset space is covered by the WAZ acquisition. Figure 2b shows one RTM 3D angle gather in the center of a deep basin. It contains six azimuth angle sectors with 30° increments and reflection angles from 0° to 40° with 2° increments. Overall, energy is well-distributed among all the azimuth sectors, except at 90° where the surface offset range is the narrowest. The events in the shallow section are well illuminated across a wide

Figure 1. An illustration of reflection and azimuth angle for RTM 3D angle gathers. \( \mathbf{n} \) is the normal direction of the subsurface reflector, \( \theta \) is the reflection angle and \( \varphi \) is the azimuth angle at the imaging point.
range of reflection angles. Because of the combination of velocity gradient and surface offset limitation, the reflection angle range progressively decreases with depth.

To demonstrate the rich azimuthal information inherent in WAZ data, we use the WAZ center tile to mimic an NAZ acquisition. The rose diagram shown in Figure 3a is also calculated based on the center tile. The surface azimuthal coverage is mostly concentrated within ±10° for the center tile, especially in the middle and far offsets. On the other hand, in the full tiles WAZ (Figure 2a), middle and far offsets can reach ±50° surface azimuthal coverage. Next, we produce RTM 3D angle gathers using only the WAZ center tile. As expected, the energy from an NAZ acquisition is primarily concentrated in the 0° azimuth sector with slight spreading into adjacent sectors. RTM 3D angle gathers contain subsurface azimuthal information, which is different from the surface azimuth shown in the rose diagram. However, the two sets of information are related and, depending on the complexity of the velocity model, the subsurface azimuth distribution may show the imprint of the surface azimuth distribution. Based on this comparison, 3D CIGs are essential for accurately evaluating migrated WAZ data.

**SUBSALT TOMOGRAPHY USING RTM 3D ANGLE GATHERS**

In the preceding sections, we demonstrated that RTM can produce CIGs indexed by a subsurface reflection angle and azimuth angle, which are suitable for WAZ data. In this section, we focus on how to use such CIGs in tomographic velocity model building and discuss the advantage and effectiveness of angle-domain tomography.

Postmigration tomography uses the curvature of picked reflection events on CIGs to guide the velocity updating. At each image location, the moveout curvatures of the events are picked on the CIG. Using the dip information determined from the stacked image, a bottom-up ray tracing from the reflection point to the recording surface is performed. Conventionally, 2D or 3D ODCIGs generated from ray-based migrations are used for tomographic inversion. However, with complicated salt geometry (rugose top of salt or base of salt), ray-based migrations usually poorly image the structures below salt. The full-wave propagation of RTM can handle the rapid velocity variations caused by the complex salt geometry better than ray-based imaging methods. This allows RTM to produce CIGs that are more reliable than those produced by ray-based migration.

Using ODCIGs for subsalt tomography has a further limitation. Because these gathers are indexed in surface parameters, the specular ray pairs shot from the subsurface upward to the recording surface must be captured by actual source and receiver locations to conform the offsets and azimuths of the actual acquisition (Liu and Han, 2010). This poses a problem for subsalt velocity updating because the raypaths must go through the salt. Complicated salt geometry and rapid velocity changes at salt boundaries cause ray

---

**Figure 2.** (a) The rose diagram for all the seven tiles of a WAZ data in the Gulf of Mexico. (b) An RTM 3D angle gather with reflection angle from 0° to 40° and six azimuth angles (0°, 30°, 60°, 90°, 120°, and 150°, from left to right).  

**Figure 3.** (a) The rose diagram for only the central tile of a WAZ data in the Gulf of Mexico. (b) An RTM 3D angle gather using the central tile, with reflection angle from 0° to 40° and six azimuth angles (0°, 30°, 60°, 90°, 120°, and 150°, from left to right).
tracing to become inaccurate, in turn degrading the reliability of the tomographic inversion. Figure 4a shows an example of ray tracing from a subsalt location, with rays going through the salt layer and reaching the surface. The yellow lines are the raypaths calculated based on the velocity. The blue dashed ovals highlight the areas of unstable ray behavior across both the top and base of salt. On the other hand, for subsurface angle gathers, the subsurface reflection angle information is provided in the angle gathers themselves, and the subsurface azimuth angles are supplied by the CIGs in the 3D case (or assumed to be 0° in the 2D case). For subsalt tomography, where only the velocities below salt are to be determined, the ray tracing can be limited to the subsalt area; ray segments above the base of salt are not needed. Therefore, upgoing raypaths can be stopped at the base of salt, and the ray information can be combined with the subsurface reflection angle information in the angle gathers to provide the subsalt velocity updating. Figure 4b shows well-behaved raypaths confined to the subsalt area where the velocity model has relatively gentle lateral variation. This enables a good combination of wave-based imaging with ray-based tomographic inversion.

For NAZ data, 2D ADCIGs, which are inherently insensitive to surface or subsurface azimuths, will provide nearly the same (incomplete) information for velocity updating as 3D ADCIGs. However, for WAZ data, which has rich azimuthal coverage, ignoring the subsurface azimuthal information is neither adequate nor correct. Also, the process of converting subsurface offset gathers or time shift gathers after applying the imaging condition (used when generating conventional ADCIGs) is constrained by sampling theory. Problems such as undersampled output or an insufficient subsurface offset range will degrade the resolution of these ADCIGs. In principle, then, RTM 3D gathers offer a better choice for subsalt tomography using WAZ data. Finally, the 2D ADCIG conversion is based on an assumption of isotropy. The converted angle range may not be trustworthy in the areas displaying strong anisotropy. However, the 3D CIG honors local anisotropy. As a conclusion, RTM 3D angle gathers provide a superior tool for subsalt tomographic inversion.

**EXAMPLE OF TTI SUBSALT TOMOGRAPHY**

The study area is at the boundary of Garden Banks and Keathley Canyon, in the Gulf of Mexico. The data were acquired by WAZ acquisition and were first processed by a VTI flow. In the reprocessing, we used ODCIGs from controlled beam migration (CBM) (Ting and Wang, 2008) to build a TTI model in the sediment area. Then we interpreted the salt geometry after TTI tomography. Next, we took advantage of RTM 3D angle gathers to build a TTI subsalt velocity.

We use RTM to generate 3D CIGs. There are three azimuth sectors with center azimuths at 0°, 60°, and 120°. The reflection angle range is from 0° to 31°, with a 1° increment. Figure 5a shows an RTM image before the subsalt tomography. The yellow oval marks a concave feature right below a local high base of salt. The subsalt events underneath this feature are broken (indicated by yellow arrows) and can be misinterpreted as faults. In Figure 5b, the RTM image after the subsalt tomography is displayed. The broken events are healed, and the structures connect continuously. Figure 6a and 6b shows the velocity models before and after the subsalt tomography, respectively. In general, low velocities are observed right below a base of salt and can be caused by overpressure. A local low velocity zone can be seen that corresponds to the concave feature directly beneath the base of salt marked with a yellow oval. The RTM 3D angle gather at a location marked with the yellow line in Figure 6 is extracted from both before and after subsalt tomography and displayed in Figure 7a and 7b. The RTM 3D angle gather before the updates has inconsistent curvature trends in different azimuth sectors (Figure 7a). With the help of TTI tomography, the flatness of the subsalt events in all three azimuth sectors are much improved (Figure 7b).

The stacked image and RTM 3D angle gathers from another location are shown in Figures 8 and 9, respectively. In the stack, events are more continuous and better focused in the deep section, around 12 km, marked with a yellow oval in Figure 8. Also, the subsalt events around 8 km are flatter after the tomographic updating (Figure 8b), where an obvious sag can be observed before the updates (Figure 8a). In the RTM 3D angle gathers, the events after the updates are flatter and better focused in all three azimuth sectors in Figure 9b, indicating that a better velocity field was obtained through an angle-domain subsalt TTI tomography.

Although RTM 3D angle gathers give promising subsalt updating results with ray-based tomography inversion, in some areas they still cannot provide a clear subsalt image (Figure 10). Lack of illumination, incorrect sediment velocity, or misinterpretation of salt

Figure 4. (a) Ray tracing going through a salt body can be unstable. (b) Ray tracing in a subsalt area does not suffer from instability.
Figure 5. (a) An RTM image before subsalt tomography using RTM 3D angle gathers. Yellow arrows indicate broken events in the subsalt area. (b) An RTM image after subsalt tomography using RTM 3D angle gathers. The subsalt events indicated by the yellow arrows become continuous.

Figure 6. (a) A velocity model overlaid on the stacked image before subsalt tomography. (b) A velocity model overlaid on the stacked image after subsalt tomography using RTM 3D angle gathers. A low-velocity zone is observed underneath the base of salt, especially in a concave feature marked with a yellow oval.

Figure 7. (a) An RTM 3D angle gather before subsalt tomography. Inconsistent curvature trends show in different azimuth sectors. The gather location is marked with a yellow line in (b). The RTM 3D angle gather at the same location after subsalt tomography. Overall, the events are flatter in all the azimuth sectors when compared to (a).
geometry may lead to poor subsalt imaging. When the energy of the subsalt image is too weak to generate enough consistent events in RTM 3D angle gather for curvature picking, tomography fails to provide reliable inversion results.

CONCLUSION

A 3D angle gather with RTM is a superior choice for prestack depth imaging in complex geological areas. Compared with conventional offset-domain CIGs, angle-domain CIGs suffer much less from migration artifacts and improve the performance of tomography. With wide-azimuth acquisition providing richer azimuthal information in the seismic data, RTM 3D angle gathers retain the localized subsurface information with respect to azimuth and reflection angle and take care of anisotropy in the migration medium.

Subsalt imaging remains a challenge in the Gulf of Mexico exploration. Our experiments demonstrate that RTM 3D angle gathers, together with angle-domain tomography, provide the method of choice to estimate velocity in subsalt areas, and, hence, improve the subsalt image quality.
ACKNOWLEDGMENTS

We thank Weishan Han and Jinjun Liu for their help with the subsalt tomography and Jerry Young for constructive suggestions and discussion. We are grateful for Sam Gray’s review of the paper and Kristin Johnston’s help on editing the paper. We also thank CGGVeritas for permission to publish this paper.

REFERENCES


Queries

1. In the sentence beginning “Also, direct generation of RTM 3D angle gathers” did you intentionally include a dash between the words “intermediate” and “domain?”

2. In the sentence beginning “Third, the computation increases by the oversampling scheme can be controlled,” in the phrase “by using small number of most energetic wavenumbers” should “small number” be made plural? Or should an “a” be added before “small number?”

3. Was this paper presented at an SEG AM? If so, please include this in the reference list?

4. Should Huang’s second article title read as “Challenges in presalt depth imaging of the deepwater Santos Basin, Brazil” or “Challenges in presalt depth imaging of the deepwater Santos Basin, Brazil”?