Summary

Reverse Time Migration (RTM) is now the preferred option for subsalt imaging in deep water Gulf of Mexico, and its 3D angle gather output plays an important role in subsalt velocity updating and illumination compensation. We now present recently-developed RTM 3D dip gathers, which are common-image gathers (CIGs) generated through wavefield decomposition and grouped into the subsurface dip-azimuth angle domain. RTM 3D dip gathers offer an opportunity for subsalt illumination analysis. We propose to use sparsely-distributed density point diffractors in the subsalt region for illumination analysis via a modeling-migration procedure. A density model with point diffractors is used for forward modeling, followed by RTM with 3D dip gather output to determine the variable illumination coverage for all subsalt dip and azimuth angles, which can be used for acquisition design, e.g., in deciding the maximum offset. Furthermore, illumination scalars derived from the diffractor-based dip gathers are applied to RTM 3D dip gathers of real data to improve the signal-to-noise ratio (S/N) and compensate for dip-dependent illumination. Because no preconceived information about the subsalt structures is involved, this illumination compensation scheme is not interpretation-driven, resulting in enhanced subsalt images that are not biased towards interpretation preferences. We validate the workflow on a real wide azimuth dataset in the Gulf of Mexico.

Introduction

The value of common-image gathers in subsurface angle domain, namely the reflection-azimuth and the dip-azimuth angle domain, has been emphasized previously (Xu et al., 1998; Audebert et al., 2002; Sava and Fomel, 2003; Koren and Ravve, 2011). The reflection-azimuth angle gathers, particularly RTM 3D angle gathers (Xu et al., 2011), play an important role in subsalt imaging because of their applications in illumination compensation (Gherasim et al., 2010; Shen et al., 2011) and velocity updating (Liu and Han, 2010; Huang et al., 2011). The dip-azimuth angle gathers (hereafter called dip gathers) are generated by grouping subsurface reflections in all directions into dip-azimuth sectors (Browaeys, 2008; Koren and Ravve, 2011). The application of Kirchhoff dip gathers in illumination compensation has been discussed before (Qin et al., 2005; Ravve and Koren, 2011). In this paper, we introduce RTM 3D dip gathers for illumination analysis in subsalt imaging.

Point diffractors and their modified forms, such as density bubbles (Stork and Diller, 2009), have been used for resolution/illumination analysis (Xie et al., 2005). Acting as reflectors of all dip and azimuth angles, point diffractors in combination with RTM 3D dip gathers offer an opportunity to study the dip- and azimuth-dependent illumination coverage beneath a given overburden model by a given acquisition configuration, e.g., the maximum offset. Another application of RTM 3D dip gathers of point diffractors is in subsalt illumination compensation and noise attenuation. Although wide azimuth and full azimuth acquisitions (Michell et al., 2006; Roberts et al., 2011; Tim, 2011), together with advances in RTM (Zhang et al., 2007; Zhang and Zhang, 2009), have brought significant advancements in subsalt imaging in the GOM, we continue to see poor subsalt images of weak illumination in the presence of complex salt structures (Gherasim et al., 2010; Shen et al., 2011; Xu et al., 2011). Starting with a reflectivity model $M$ and a velocity model, a field acquisition acquiring seismic data $D$ can be simulated with a forward modeling operator $F$ in the form of

$$D = FM.$$
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Through the inverse process, the reflectivity model can be calculated from

$$M = F^{-1}D.$$  

However, the inverse operator $F^{-1}$ is very difficult to obtain, and it is usually replaced by the adjoint operator of $F$ in a standard migration

$$M' = F'D \sim M,$$

where $M'$ is the migrated image, and $F'$ is the migration operator. Because $F'$ is not the exact inverse of $F$, the reflectivity model $M$ is related to the migrated image $M'$ via

$$M = (F'F)^{-1}M'.$$

Given the power of today’s super computers, explicit illumination compensation through direct inversion for the illumination matrix $FF$ is not possible for 3D cases (Nemeth et al., 1999), and simplifications are made in practice. For example, illumination fold as a multi-valued field varying in space and direction was computed through a hit-count method (Audebert et al., 2002; Audebert et al., 2003), and illumination fold-scaling was applied to Kirchhoff dip gathers for dip-dependent illumination compensation (Qin et al., 2005). Based on the definition of the illumination matrix, illumination compensation requires simulating the field acquisition using forward modeling operator $F$, followed by migrations using operator $F'$. Illumination compensation via this forward modeling-migration procedure can be done with different weighting schemes. For example, illumination compensation is performed by forward modeling with interpreted horizons (i.e., for pre-defined dip-azimuth angles) and remigration for angle gather output using one-way wave equation migration or RTM (Gherasim et al., 2010; Shen et al., 2011). In this paper, we attempt to use RTM 3D dip gathers for the illumination analysis and compensation, where illumination compensation scalars derived from the synthetic data (generated by forward modeling with embedded point diffractors that are present as density abnormalities) are applied to field data within the dip-azimuth angle gather domain. Unlike illumination compensation using reflection-azimuth angle gathers where subsalt structures are assumed a priori (Gherasim et al., 2010; Shen et al., 2011), the proposed point diffractor scheme does not use interpreted subsalt horizons. This makes it a reliable illumination compensation approach, bearing minimal interpretation controls.

RTM 3D dip gathers

The RTM 3D dip gathers we use in this paper are generated by the algorithm developed by Xu et al. (2011) which performs directional wavefield decomposition among four subsurface angles, namely the reflection-azimuth angles $(\theta_2, \phi_2)$ and the dip-azimuth angles $(\theta_1, \phi_1)$ (Figure 1a). At the imaging condition, RTM 3D angle gathers (Figure 1d) are formed by summation over the dip-azimuth angle $(\theta_1, \phi_1)$ plane and output to the reflection-azimuth angle $(\theta_2, \phi_2)$ domain. As an extension to RTM 3D angle gathers, RTM 3D dip gathers (Figure 1c) are formed through summation over the reflection-azimuth angle $(\theta_2, \phi_2)$ plane (Figure 1a) and output to the dip-azimuth angle $(\theta_1, \phi_1)$ domain. The RTM 3D dip gather at a given CDP location is a group of traces sorted by dip-azimuth binning. The amplitude of each trace changes vertically with subsurface structure and illumination variations along the z direction (Figure 1c). The dip angle $\theta_1$ is measured from the vertical direction to

Figure 2: Illumination coverage shown using RTM 3D dip gathers of point diffractors. a) subsalt reflector image with 9km cable. b) RTM 3D dip (between -90° to 90°) gathers at the yellow line location in a. c) subsalt point diffractor image with 9km cable. d) RTM 3D dip gathers at the yellow line location in c. e) subsalt reflector image with 15km cable. f) RTM 3D dip gathers at the yellow line location in e. g) subsalt point diffractor image with 15km cable. h) RTM 3D dip gathers at the yellow line location in g. Dips of reflectors at marked (cross symbols) locations (in a and e) are mapped onto diffractor dip gathers in d and h respectively. The dashed blue line regions contain dips that can be illuminated by 15km cable but not the 9km cable.
the reflector normal vector $\mathbf{K}$, coinciding with the migration vector determined by the source and receiver wavefield propagation directions $\mathbf{K}_s$ and $\mathbf{K}_r$ respectively (Figure 1a) (Xu et al., 2011). The azimuth $\phi_1$ for RTM 3D dip gathers is measured counterclockwise from the positive x axis to the surface projection of the reflector normal vector $\mathbf{K}$ (Figure 1a). It is different from the azimuth $\phi_2$ for RTM 3D angle gathers, which refers to the angle between the plane formed by $\mathbf{K}_s$ and $\mathbf{K}_r$ and the plane formed by $\mathbf{K}$ and the x axis (Figure 1a) (Xu et al., 2011).

2D synthetic data

Using the velocity model shown in Figure 1b and subsalt reflectors that we introduce as density contrasts, we generate two synthetic datasets using isotropic acoustic wave-equation forward modeling to simulate 2D acquisitions of 9km and 15km cables (Figure 2a and e, respectively). We generate two additional datasets with subsalt density point diffractors at 600m×600m spacing, also simulating 9km and 15km cable acquisitions (Figure 2c and g, respectively). Surface-related multiples are not modeled in any of the four forward modelings. We run RTMs with aperture equal to the cable length in order to output dip gathers with azimuth = 0° and dips between -90° to 90°. While reflectors of given dips form hot spots in dip gatherings due to their directional preference (Figure 2b and f), point diffractors react equally to incidences in all directions and appear as flat events consisting of all illuminated dips (Figure 2d and h). The horizontal amplitude variation of diffractor dip gathers can thus be viewed as a dip-dependent illumination index, with higher amplitude indicating better illumination. Stack images of subsalt reflectors show that dipping reflectors are better imaged with the 15km cable length (Figure 2e) than the 9km cable length (Figure 2a). This suggests that subsalt illumination improves with increased cable length. For comparison, a subsalt reflector of ~25° dip at the location marked with the cross-symbol in Figure 2a and e is mapped (using similar symbols) onto the reflector/diffractor dip gathers of corresponding cable lengths (Figure 2b, d and f, h). The mapped event falls into dim zones in both dip gathers of 9km cable data (Figure 2b and d); however, the event is not in dim zones in the 15km cable data (Figure 2f and h). Comparisons between the dip gatherings of the reflector and point diffractor models (Figure 2b versus d and Figure 2f versus h) show that certain dips of subsalt events at gather locations (yellow lines on stack images) are poorly illuminated, even for the 15km cable acquisition. Strong amplitudes of negative dips in the diffractor dip gathers (Figure 2d and h) hint that noises with dips opposing those of subsalt reflectors will be favorably illuminated and may lead to poor S/N under the simulated acquisition configurations. The dashed line regions in Figure 2d and h contain all dips that benefit from the enhanced illumination coverage provided by a 15km cable acquisition (Figure 2e and g) in comparison to a 9km acquisition (Figure 2a and c). These observations indicate that RTM 3D dip gathers of point diffractors can be used to quantitatively study the dip-dependent (dip- and azimuth-dependent for the 3D case) subsalt illumination coverage and thus may be useful for acquisition design evaluation and area-specific subsalt illumination analysis.

To demonstrate the usage of point diffractor-based RTM 3D dip gathers in illumination compensation, we re-run forward modeling of subsalt reflectors with a 15km cable, but this time with surface-related multiples modeled as well. We generate dip gathers (similar to Figure 2f but with multiples) using RTM and the raw stack is shown in Figure 3a. Due to the unbalanced subsalt illumination coverage, the amplitude along any given reflector varies significantly, and subsalt events appear to be broken at many locations (Figure 3a). Although multiples are not honored by the migration velocity and imaging condition, they appear as...
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high-amplitude noise cutting across primaries in the stack (e.g., within the blue circle in Figure 3a), likely due to the illumination preference for the negative dips as shown by Figure 2h. We convert the amplitude information from the diffractor dip gatherings (Figure 2h) to dip-dependent illumination scalars and apply them to the multiple-contaminated reflector dip gatherings. After illumination compensation, the amplitude along any given subsalt reflector becomes more homogeneous, with many broken events now continuous. Multiple-related noise is also attenuated with more balanced illumination coverage among dips after compensation, resulting in cleaner subsalt image (blue circle in Figure 3b).

3D wide azimuth data

We now test the illumination compensation workflow on wide azimuth data from the Walker Ridge area in the Gulf of Mexico. Similar to the 2D case, we perform 3D forward modeling to simulate the wide azimuth field acquisition with point diffractors introduced into the subsalt. After forward modeling, we run RTMs to produce 3D dip gatherings for both the field data and the forward modeling-derived data. The stacked images of raw RTM 3D dip gatherings of the field data are shown in Figure 4a (inline) and c (crossline). Illumination scalars, derived from the diffractor 3D dip gatherings as a function of dips and azimuths, are applied to the field data dip gatherings. The post-illumination compensation images are shown in Figure 4b (inline) and d (crossline). Without introducing artifacts, subsalt sediments with event-consistent amplitudes are revealed from background noise by the illumination compensation in both the inline (Figure 4a versus b) and crossline directions (Figure 4c versus d). In particular, the dipping reflector at ~10km depth is significantly more coherent and extends further towards the salt keel (Figure 4a versus b).

Conclusions

Through a modeling-migration procedure, we proposed a scheme to use RTM 3D dip gatherings of point diffractors for subsalt illumination analysis. Because we are able to analyze full-spectrum dip-dependent illumination coverage through a single forward modeling-migration loop, this method may be useful in acquisition design evaluation and subsalt illumination analysis in general, with potential to reduce relevant computational cost and human effort. RTM 3D dip gatherings of point diffractors can also be useful to interpreters for evaluating interpretation hypotheses – they may enable better judgement of ambiguous subsalt events by separating structures that can be illuminated from those that cannot. We showcased through 2D synthetic and 3D wide azimuth examples that point diffractor-based RTM dip gatherings can also be used for dip-dependent illumination compensation and can be effective in enhancing subsalt S/N, leading to improved subsalt images. Other than the overburden model and salt geometry, this new illumination compensation approach does not use additional interpretation-based information, which reduces the chance of introducing artifacts during illumination compensation.

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![Figure 4: Dip-dependent illumination compensation on Walker Ridge wide azimuth data. a) RTM 3D dip gather raw stack, inline view. b) RTM 3D dip gather post-illumination compensation stack, inline view. c) RTM 3D dip gather raw stack, crossline view. d) RTM 3D dip gather post-illumination compensation stack, crossline view. Yellow lines mark the locations of the orthogonal lines.](image-url)
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