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Improving Subsalt Imaging with Least-squares RTM - A Case Study At Kaskida Field, Gulf of Mexico

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Summary

Kaskida is a large three-way reservoir truncated by a salt weld and lying underneath a complex salt body. Inhomogeneous illumination from the complex overburden, which distorts the amplitude of reservoir reflectors and generates migration artifacts, has a detrimental impact on the seismic image at the reservoir level. The application of least-squares RTM (LSRTM) at Kaskida field demonstrates that it can effectively improve the signal-to-noise ratio (S/N) of the subsalt image by reducing migration artifacts, and it can also improve the reservoir amplitude fidelity by compensating for illumination effects caused by the overburden velocity and acquisition geometry. We further demonstrate that a more correct velocity model derived from reflection FWI (RFWI) improves LSRTM results by providing a better raw RTM image and more accurate illumination compensation. Finally, we compare common-image gathers (CIGs) from well-data synthetic modelling, raw RTM, and LSRTM and conclude that LSRTM improves the AVO response over raw RTM because of the offset-dependent illumination compensation and reduction in migration artifacts.

Introduction

RTM has become the migration method of choice for subsalt imaging. However, RTM is unable to fully recover the reflectivity for desired amplitudes and resolution, because it approximates the inverse of the forward wave-propagation with an adjoint operation. In addition, the image often contains strong migration artifacts. This shortcoming is well recognized by the imaging community, and it has propelled the emergence of least-squares RTM (LSRTM) (Tarantola, 1987). The often-cited benefits of LSRTM include more correct image amplitudes due to its ability to compensate for illumination loss caused by overburden and acquisition effects, more coherent images due to its ability to reduce migration artifacts, and higher image resolution due to its ability to remove the source signature and source/receiver ghost, as well as migration stretch. Classic LSRTM finds the solution through an iterative inverse approach (Schuster, 1993). The inversion often takes many iterations and thus is computationally expensive. In order to reduce the computational cost, image-domain single-iteration LSRTM methods have been proposed (Guitton, 2004; Lecomte, 2008). To better handle angle and frequency dependent illumination variations, Wang et al. (2016) extend Guitton's approach by introducing a curvelet-domain Hessian filter (CHF or LSRTM-CHF) between the raw migration, $m_0 = L^T d_0$, and its demigration/remigration, $m_1 = L^T L m_0$ to approximate the inverse of the Hessian operator $L^T L$ for the LSRTM solution:

$$\min_s \|C(m_0) - sC(m_1)\|^2 + \epsilon\|s\|^2, \tag{1}$$

where L^T is the migration operator, d_0 is data, C is the curvelet transform operator, s is the matching filter, and ϵ is a weighting factor for Tikhonov regularization. The LSRTM-CHF output is

$$m = C^{-1}\big(|s|C(m_0)\big), \tag{2}$$

where C^{-1} is the inverse curvelet transform operator and | | is used to remove the phase. They further extend the approach to work with surface-offset gathers (SOGs):

$$\min_s \left\|C(m_0) - sC\left(m_1^{sog}\right)\right\|^2 + \epsilon\|s\|^2, \tag{3}$$

$$m^{sog} = C^{-1}\left(|s|C\left(m_0^{sog}\right)\right). \tag{4}$$

The SOG-based LSRTM-CHF compensates for illumination effects on individual offsets, which can potentially give better AVO response.

One big assumption of LSRTM is that the velocity model is already accurate and will not be updated by LSRTM. However, in the real world, the velocity model is inevitably inaccurate. This causes problems for classic LSRTM, which assumes kinematic consistency between the synthetic data and recorded data. Although initially proposed to save computational cost, image-domain single-iteration LSRTM methods like CHF that try to find an inverse Hessian matching filter between the raw migration, m_0, and its demigration/remigration, m_1, are far less sensitive to velocity errors. This is because m_1 is generated through a demigration from m_0, followed by a remigration using the same velocity model, ensuring that m_1 always has the same kinematics as stack m_0. Of course, an accurate velocity model is still very important for CHF in that it provides a more accurate modelling of illumination patterns and, most importantly, a better initial raw RTM image.

In our data examples around the Kaskida oil field, we demonstrate that CHF produces cleaner images by reducing migration artifacts and higher amplitude fidelity by compensating for subsalt illumination imbalance. Furthermore, we prove that a better velocity model derived from RFWI indeed improves CHF results. Lastly, we show that the offset-dependent illumination compensation along with migration artifact reduction by SOG-based CHF deliver the promise to improve the AVO response.

Field data examples

Complex overburden, such as salt bodies, often distorts reservoir images in terms of structural positioning, stratigraphic resolution, and amplitude fidelity. Kaskida oil field is one such example in the deep water of the Gulf of Mexico (GOM). The reservoir is a three-way closure structure of Paleogene play. The highly variant salt layers above the reservoir and the ambiguous salt shape with complex dirty salt and sutures nearby distort wave propagation and therefore the illumination of subsalt events. We applied the SOG-based CHF method at the Kaskida well area using a wide-azimuth streamer dataset. The input data underwent typical pre-processing to remove noise, ghost energy, multiples, etc. The RTM and LSRTM-CHF migration frequency was 15 Hz.

Figure 1 shows raw RTM images and LSRTM-CHF images near the well location in both the east-west and north-south directions. The raw RTM images contain strong migration artifacts and noise near the well, indicated by red arrows in Figures 1a and 1b. The three-way closure boundary events are not clearly imaged. LSRTM-CHF improves the images by suppressing migration noise and compensating for illumination of weak geological events, clarifying interpretation of reservoir structures. The highly dipping boundary of the reservoir closure (indicated by the red arrow in Figure 1d) becomes clearer after LSRTM-CHF.

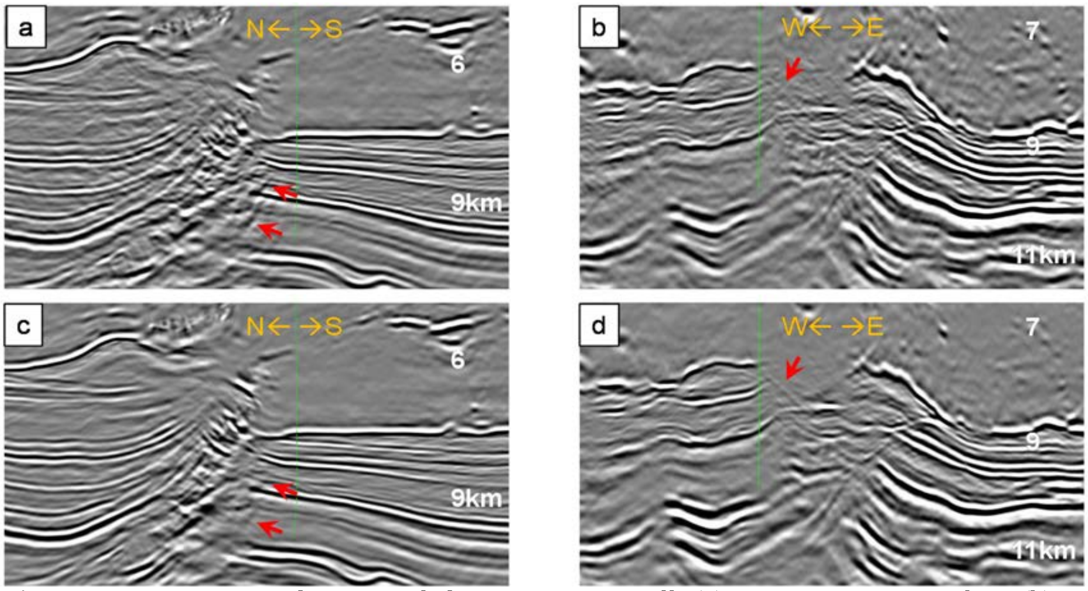

Figure 1 *LSRTM-CHF study over Kaskida, near KC-292 well: (a) raw RTM image N-S line; (b) raw RTM image E-W line; (c) LSRTM-CHF image N-S line; (d) LSRTM-CHF image E-W line.*

LSRTM reduces migration artifacts and compensates for illumination loss using the inverse of the Hessian, assuming the velocity model is correct. However, the performance of LSRTM is largely limited by the quality of the raw RTM image. It is very difficult, if not impossible, for any LSRTM method to recover subsalt events and structures that are completely missing on the raw RTM image due to insufficient input data or a poor velocity model. Moreover, the amplitudes of imaged events cannot be fully recovered if there is velocity error that causes poor focusing of events. In the GOM region, where salt structures are complex and subsalt imaging is often poor, the velocity building by traditional methods such as tomography is limited. To further improve the velocity model, we used a reflection-based full waveform inversion (RFWI) method (Chazalnoel et al., 2017, personal communication) to update the velocity. We then tested LSRTM-CHF again with the RFWI model. The results are compared in Figure 2 with a depth slice view at 9 km (close to the reservoir depth at Kaskida well KC-292). Comparing Figures 2a and 2b, we observed that LSRTM-CHF reduces migration noise and compensates for some weak subsalt events. However, some other events are still weak or even broken. RFWI improves the velocity model and better focuses the events, as indicated by red arrows in Figure 2 (comparing Figures 2a and 2c). LSRTM-CHF after RFWI further improves the images by noise suppression and illumination compensation (comparing Figures 2b and 2d).

Besides the improvement on the stack images, the SOG-based LSRTM-CHF reduces the strong illumination footprint on the raw RTM SOGs, as shown in Figure 3. Overall, the amplitudes across different offsets become more balanced. Some far offset events in the RTM gathers are quite weak due to low S/N, and LSRTM-CHF was unable to generate much uplift in those instances. RFWI improves the velocity model, resulting in flatter and more focused gathers, as seen in the blue ovals in Figures 3a-d. Additionally, LSRTM-CHF enhances these event amplitudes to a stronger level and gives improved offset gather quality in the subsalt area.

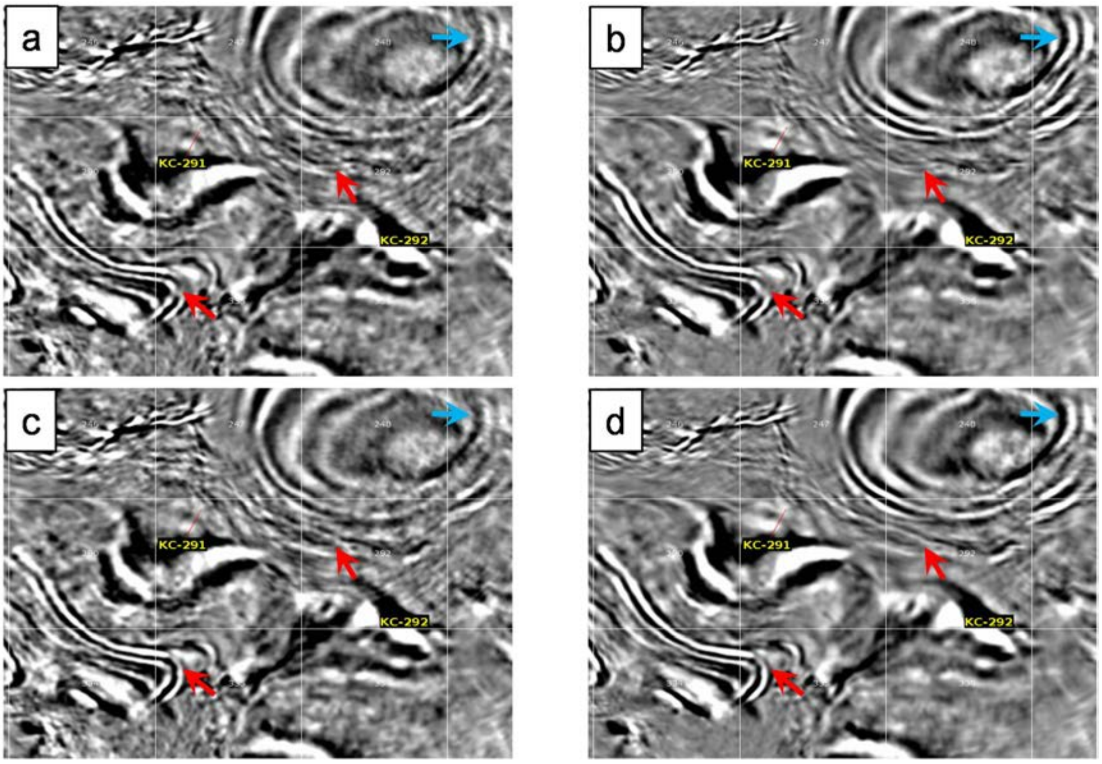

Figure 2 *Kaskida depth slice view at 9 km: (a) raw RTM image before RFWI; (b) LSRTM-CHF image before RFWI; (c) raw RTM image after RFWI; (d) LSRTM-CHF image after RFWI.*

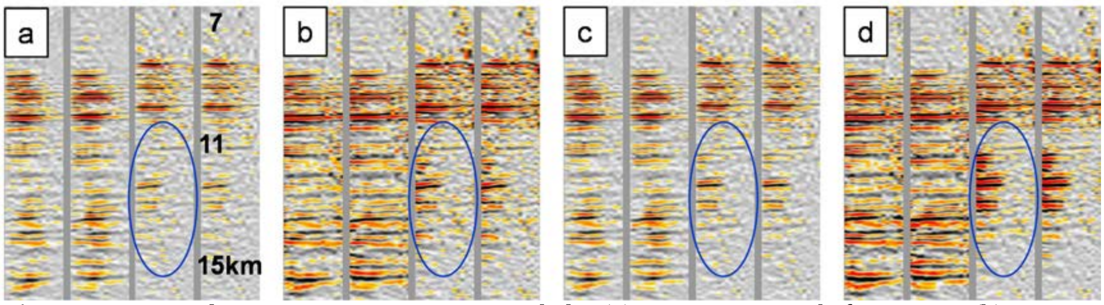

Figure 3 *RFWI and LSRTM-CHF SOGs over Kaskida: (a) raw RTM SOGs before RFWI; (b) LSRTM-CHF SOGs before RFWI; (c) raw RTM SOGs after RFWI; (d) LSRTM-CHF SOGs after RFWI.*

In order to further investigate the illumination compensation effect on different offsets by the SOG-based LSRTM-CHF method, we performed AVO analysis using the pre-stack common-image gathers (CIGs) after RFWI at the KC-292 well location. Figure 4a shows one CIG from synthetic modelling, raw RTM, and LSRTM-CHF. The synthetic CIG was derived from well data. The Paleocene marker event at the well is selected, and its AVO curves are plotted in Figure 4b. The raw RTM CIG suffers from a strong footprint pattern: weak at both very near and far offsets but strong at middle offsets, and its AVO is obviously deviated from the synthetic AVO. LSRTM-CHF effectively reduces migration noise and compensates for illumination distortion across different offsets and thus gives a better AVO response that more closely matches the synthetic AVO. This enhanced amplitude fidelity by LSRTM-CHF could potentially benefit seismic inversion near the reservoir.

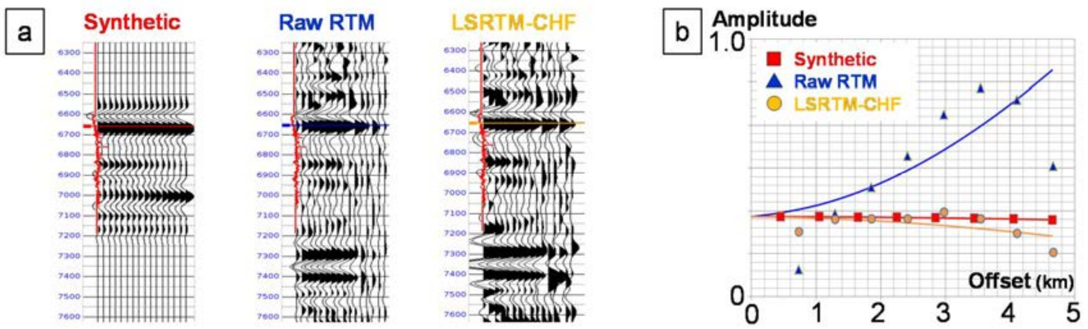

***Figure 4** AVO analysis at Kaskida well KC-292: (a) one CIG from synthetic, raw RTM, and LSRTM-CHF; (b) AVO curves at the Paleocene marker event indicated by the line on the gathers.*

Conclusions and discussion

The LSRTM-CHF study over Kaskida shows cleaner reservoir structures and enhanced amplitude fidelity by reducing migration artifacts and compensating for illumination imbalance caused by complex salt bodies and acquisition geometry. With the improved velocity model derived from RFWI, LSRTM-CHF provides more benefits on both the stack and offset gathers. Offset-dependent illumination compensation and migration artifact suppression by SOG-based CHF improve the AVO response of RTM CIGs.

While LSRTM-CHF is theoretically less sensitive to velocity errors than classic iterative LSRTM, a good velocity model improves LSRTM-CHF results by providing a better raw RTM image and a more accurate modelling of illumination patterns. We note that many other factors, such as non-focusing due to velocity error, transmission loss, as well as elastic effects that cannot be addressed by methods using acoustic Born modelling, can prevent CHF from giving correct amplitudes. Good AVO matching between well-data synthetic modelling and CHF CIGs indicates that, in this case, illumination distortion is the dominant cause of the deviation of the raw AVO from the synthetic AVO. This deviation is mostly corrected by CHF, which is not necessarily true for other cases.

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