Benefits of full-azimuth and ultralong-offset data for subsalt imaging in the deepwater Gulf of Mexico

Yunfeng (Fred) Li, Qiaofeng Wu, Minshen Wang, and Tony Huang, CGG

Abstract

In deepwater regions of the Gulf of Mexico, the ability to image subsalt structures has improved significantly with wide-azimuth data, reverse time migration, and anisotropic tomography and imaging. However, subsalt imaging, such as imaging steeply dipping salt flanks and subsalt three-way closures, still remains difficult in areas with complex salt geometry. Moreover, limited subsalt illumination provides insufficient incident angles for residual curvature tomographic analysis. Full-azimuth and long-offset acquisition configurations are the latest acquisition technologies designed to address these subsalt challenges. An improved subsalt imaging and tomography updating using staggered acquisition provides full-azimuth data coverage and ultralong offsets.

Introduction

In the past decade, seismic streamer acquisition in the deepwater Gulf of Mexico (GOM) has evolved from narrow-azimuth (NAZ) to multiazimuth (MAZ) and wide-azimuth (WAZ) acquisition. Today, multiple WAZ surveys cover the same key areas in the GOM. The development of tilted-transverse-isotropic (TTI) reverse time migration (RTM) also extracts additional value from WAZ data.

However, subsalt imaging quality remains poor under complex salt structures because of illumination limitations and residual multiple contamination (Figure 1). To enhance azimuthal coverage, combining WAZ and multiple NAZ surveys with different shooting directions can improve the subsalt image incrementally. However, WAZ and WAZ/NAZ combinations are still short of full azimuthal coverage, and with limited offset ranges (shorter than 9 km), they are unlikely to provide good illumination under complex salt geometry or to image steeply dipping subsalt structures. Furthermore, limited azimuth and offsets do not provide sufficient incident angles for subsalt residual curvature analysis and velocity updates.

In subsalt exploration, long-offset data have been proved to benefit image quality (Wombell et al., 1999). In the Gulf of Mexico, 2D acoustic and elastic modeling have been used to demonstrate that data with ultralong offsets of as much as 20 km can improve subsalt images (Li et al., 2010). To overcome imaging challenges in the deepwater GOM, several full-azimuth (FAZ) and long-offset acquisition schemes have been proposed. Ocean-bottom node surveys are similar to the ideal FAZ and long-offset acquisition (Beaudoin and Ross, 2007). Circular shooting is proposed to acquire FAZ and long-offset data (Buia et al., 2010). Mandroux et al. (2013) present a staggered-acquisition configuration. By shooting orthogonal directions, it forms full-azimuthal coverage of as much as 10 km and ultralong offsets as great as 18 km (Figure 2).

Figure 3 shows the imaging improvement of the staggered FAZ and ultralong-offset acquisition (Keathley Canyon, GOM) over the conventional WAZ acquisition with similar preprocessing and the same TTI velocity model derived using FAZ and long-offset data. Several factors contribute to the improvement, but here we examine the contribution of full azimuth and ultralong offsets to subsalt imaging.

First, to understand the benefits of full azimuth in salt-body delineation and subsalt imaging, we compared salt-flood RTM and salt-body RTM imaging to WAZ and FAZ.
Second, we compared RTM 3D angle gathers (Han and Xu, 2011) between the conventional-offset range (as much as 9 km) and the ultralong-offset range (as much as 18 km) and evaluated the results of subsalt tomography with RTM 3D angle gathers from ultralong offsets.

**Full-azimuth contribution for delineation of salt body and improved subsalt imaging**

In the Gulf of Mexico, we should not underestimate the importance of an accurate model in the suprasalt section, but we often notice that correct delineation of the salt body can play an even bigger role in subsalt image quality. Without an accurate definition of salt geometry, the subsalt image becomes distorted and poorly resolved. In regions with complex salt, WAZ data do not always provide enough illumination to accurately delineate the salt geometry.

Figure 4 illustrates how full-azimuth data can help the delineation of a salt body. Figure 4a shows a salt-flood RTM image with single-direction staggered acquisition (WAZ coverage). Using the same salt-flood model, Figure 4b shows the salt-flood RTM image with both orthogonal directions from staggered acquisition (FAZ coverage). Blue arrows and circles in Figures 4a and 4b show that full azimuth reduces the imaging ambiguity at the base of salt (BOS), which helps to delineate the salt body.
Using a similar approach, we compared salt-body RTM imaging with one-direction input (WAZ, Figure 4c) and two-orthogonal-direction input (FAZ, Figure 4d). FAZ acquisition not only improves the signal-to-noise ratio in the overhang region (blue circle), but it also provides additional illumination in the subsalt region and better images the dipping events (blue arrow).

Illumination benefits from ultralong-offset data

In the rose diagram (Figure 2b), the staggered-acquisition configuration provided full azimuthal coverage of as much as 10 km and ultralong offsets as great as 18 km. To understand the impact of ultralong offsets on subsalt imaging, we migrated the data with the same velocity model but with different offset ranges. Figures 5a and 5b compare RTM images using a conventional offset range (as much as 9 km) and ultralong offsets (as much as 18 km). The ultralong offsets permit better imaging of subsalt event truncations underneath the salt and better continuity of subsalt events.

Figures 5c and 5d show a similar comparison for the RTM 3D angle gathers. Although the 9-km offset data provide incident angles less than 25°, the ultralong-offset data provide incident angles as large as 50° (Figure 5d). The curvature of the angle gathers, which is not easy to characterize using 9-km offset, is much clearer with 18-km offset (blue arrows), as shown in Figure 5d. Thus, larger subsalt incident angles from ultralong-offset data allow us to capture subsalt velocity errors.

Moreover, ultralong offsets provide illumination benefits. We generated illumination patterns from 9-km-offset RTM angle gathers and 18-km-offset RTM angle gathers (Figure 6). The illumination plots show the subsalt ray coverage. In Figure 6a, the 9-km-offset inputs leave some areas poorly illuminated because of salt complexity. However, in Figure 6b, the 18-km-offset inputs provide greater illumination, allowing for better RTM subsalt imaging. The ultralong-offset RTM angle gathers, therefore, have a better opportunity to reveal velocity errors in poorly illuminated areas.

Subsalt velocity updating with ultralong offsets

To test the benefit of the larger incident angles and better illumination in RTM 3D angle gathers provided by ultralong offsets, we used the angle gathers as input to tomography for the subsalt velocity update (Han and Xu, 2011). Figures 7a and 7b show RTM stacked images and 3D angle gathers migrated with an initial subsalt velocity. The angle gathers show the down-curving events beneath the salt, requiring lower salt-exit velocity. Deeper subsalt events, in which the RTM 3D angle gathers curve up, require higher velocity. After subsalt tomography that used curvatures on these ultralong-offset 3D angle gathers, Figures 7c and 7d show improved stacked images and flatter angle gathers. Importantly, the velocity after tomography generally follows subsalt geology.

Moreover, the velocity update not only is observed in areas of good illumination, but it also improves the velocity in complex areas. As a result of the updated subsalt velocity
model, subsalt events are more focused and continuous. After tomography, the angle gathers show events with extended angle coverage from 40° to 50° at a depth of about 10 km, indicative of a well-informed velocity update. Figure 7e shows how the velocity after tomography matches the sonic log more closely.

Conclusion

We have demonstrated that FAZ acquisition helps both the delineation of salt bodies and subsalt imaging. Ultralong offsets also provide better subsalt illumination, which improves imaging in otherwise poorly imaged areas below complex salt. Ultralong-offset RTM 3D angle gathers contain large incident angles, which helps subsalt velocity updating. Our example showed that RTM 3D angle gathers using ultralong offsets contain valuable information for residual curvature tomographic analysis in the subsalt region. The updated velocity after tomography using ultralong-offset RTM 3D angle gathers reveals an improved subsalt final image and flatter gathers. Tomographic velocity also closely matches the sonic log at the well location.

References


Han, W., and S. Xu, 2011, High resolution velocity model for imaging complex structures: 73rd Conference and Exhibition, EAGE, Extended Abstracts, B010.


Acknowledgments: We thank CGG for permission to publish this work.

Corresponding author: fred.Li@cg.com