
Applications of Wave Imaging Technologies to Improve Deep Gulf Coast Prospecting

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EXTENDED ABSTRACT

The shallow section in the Gulf Coast normally exhibits a simple, depth-variable velocity profile, and prestack time migration (PSTM) methods generally produce drillable images. In recent years, however, an exciting frontier has opened in the deeper, pressured section, with low effective stress preserving reservoir quality. However, geopressure is a double-edged sword. Geopressured sediments typically exhibit seismic velocities below the compaction trend, and the associated velocity anomalies hamper seismic prospecting on PSTM images in two ways. The best known effect is the “time sag.” The second, more insidious effect is complex wavefield focusing, which reduces image crispness and blurs fault boundaries.

Prestack depth migration (PSDM) methods have been employed successfully for some time to overcome the effects of pressure-driven velocity anomalies. Typically, Kirchhoff PSDM algorithms have been used in the Gulf Coast. When the velocity complexity is severe, such as under Gulf of Mexico salt, Wave Equation PSDM (WEM) algorithms generally produce superior imaging results. Even away from the salt, WEM algorithms can more naturally handle the amplitude variations due to velocity focusing effects. Because of this, there is a good reason to use WEM for amplitude-versus-angle (AVA) analysis, but until recently, it was not known how to decompose efficiently WEM images into angle “gatherers.”

The key to unlocking the potential of PSDM is the accurate specification of depth migration velocities. We present a unique, two-stage velocity estimation workflow, utilizing wave equation focusing analysis and WEM angle gather update, and show how “extreme” velocity effort can yield significant improvements in Gulf Coast prospect delineation. We also illustrate the successful use of WEM angle gathers to accurately estimate rock physics attributes. We finally demonstrate that reverse-time migration (RTM), the most advanced imaging algorithm available, can greatly improve the imaging of steep fault planes and salt flanks.

High-Effort Wave Equation Velocity Update

In the early years of 3D prestack depth migration (PSDM), limitations in computer resources meant that PSDM was reserved for the final run, with velocity analysis using time migration (PSTM) methods. However, if lateral velocity variation necessitates the use of PSDM to image the subsurface, then in general a PSDM velocity estimation method is required to obtain an optimal migration velocity. Moreover, in areas (i.e., subsalt) where wave imaging methods, rather than ray-based methods, yield superior

image focusing, then velocity estimation techniques based on wave imaging should be more successful than ray-based velocity estimation techniques.

For land seismic processing in particular, we advocate a two-stage iterative velocity estimation scheme utilizing WEM. The first stage, Migration Velocity Focusing Analysis (MVFA), introduced by Higginbotham et al. (2008), utilizes the time-shift imaging condition for WEM (e.g., Sava and Fomel, 2006) to measure image focusing as a function of time. MVFA can detect errors in migration velocity under complex refractors such as salt (Brown et al., 2009) and is robust to large errors in migration velocity and irregular acquisition geometry.

The second stage is WEM Angle Gather update. By utilizing an efficient (Higginbotham et al., 2009; Macesanu et al., 2010) scheme to compute full-volume, true 3D angle gathers, we are able to measure residual curvature of events as a function of incidence angle, and backproject the velocity error to update the migration velocity model in a highly dense fashion.

In complex geology, an angle gather may not have recognizable residual moveout when the acquisition geometry is irregular or when the migration velocity is far from optimal. For this reason in particular, experience tells us that our two-stage workflow is necessary for land seismic applications.

Figure 1 is an example from the western Louisiana transition zone. A 3D migration velocity model obtained after multiple iterations of MVFA and WEM Angle Gather update is compared to a checkshot located 10 miles away. Three known zones of geopressure, causing velocity “inversions” in depth, are annotated with arrows. Our analysis correctly resolves these vertical features. Figure 2 is an example from South Texas. Eight MVFA iterations and 3 WEM Angle Gather updates were run to obtain a final migration velocity, which overlays the final WEM depth image. Notice the strong and well-known velocity inversion across the top Wilcox horizon, as well as abrupt lateral velocity contrasts across faults. In both examples, the angle gather updates were vertical updates, although the WEM angle gathers would make an excellent input to a reflection tomography scheme.

Reverse-Time Migration

Perhaps the simplest of all depth migration algorithms, reverse-time migration (RTM) is the most theoretically accurate, and also the most expensive. Continued commoditization of high-performance computing hardware has put RTM capabilities into the hands of even relatively small seismic processing firms.

Practically speaking, RTM combines the best attributes of one-way WEM algorithms (natural handling of amplitude focusing effects and sharp lateral velocity variations) and Kirchhoff algorithms (ability to image steep or overturned dips). However, RTM is very sensitive to velocity errors and anisotropy, as the energy which illuminates the steep or overturned reflectors takes a long travel path through the earth, and often propagates at or near the horizontal.

In Figure 3, we show how a pseudospectral (Fourier domain) RTM algorithm can image the overturned flanks of the Spindletop salt dome, where a straight-ray PSTM algorithm could not. Curved-ray PSTM algorithms may image these salt flanks, because the illuminating energy does not pass through salt. Actually, we feel that the biggest imaging benefit from RTM in the Gulf Coast may be the improved imaging of complex, highly-faulted geology near the salt flanks, which at great depths (>10,000 ft) represent the best remaining prospects against mature salt domes. The ability to directly image deep fault plane reflections certainly benefits Gulf Coast prospecting, where the accurate visualization of fault blocks can make or break a prospect.

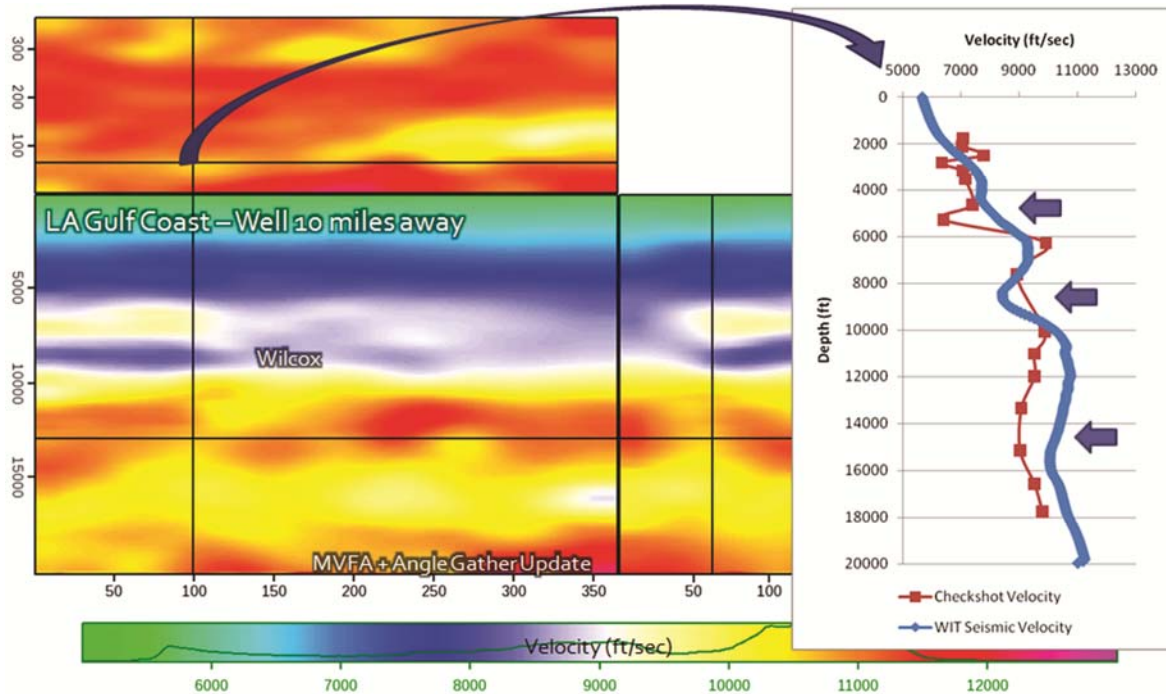


Figure 1. Louisiana transition zone velocity estimation example. The 3D cube displays a velocity model obtained via multiple iterations of MVFA and WEM angle gather update. On the 2D graph to the right, the migration velocity (blue) is compared to a checkshot-derived velocity (red) about 10 miles away.

Attribute Inversion of WEM Angle Gathers

AVO (amplitude-versus-offset) prospecting has been a cornerstone of prospect generation and reservoir de-risking in sedimentary basins like the Gulf Coast for many years. However, the scientific basis of almost all AVO work rests on linearizations of the Zoeppritz equations about linear perturbations in elastic properties like V_p , V_s , and density. The resulting AVO equations are actually written in terms of incidence angle at the reflector; in practice offset and angle are connected by a $V(z)$ assumption. From the previous examples, we see that in the Gulf Coast, the $V(z)$ assumption is often violated, and sometimes severely, scrambling the offset-to-angle mapping.

As described in an earlier section, we utilize an efficient (Higginbotham et al., 2009; Macesanu et al., 2010) scheme to compute full-volume, true 3D angle gathers. The angle information is computed at the reflector and is more accurate than the simple $V(z)$ offset-to-angle transformation. Rather than AVO analysis, we really should be doing AVA, or amplitude-versus-angle analysis.

Higginbotham et al. (2010) described an advanced inversion scheme for AVA parameters, which uses the entire angle gather, not just “far/mid/near stacks,” and which presents an iterative scheme to recover a “mudrock line” which best fits the data volume, subject to constraints.

Figure 4 illustrates Higginbotham et al.’s (2010) technique applied to compute the “fluid factor” over the best-producing well (4.6 BCFE [billion cubic feet equivalent] since 1994) in the survey area. After iterative velocity analysis, described in Figure 2, a final WEM was run, outputting incidence angle gathers at every surface location, with a

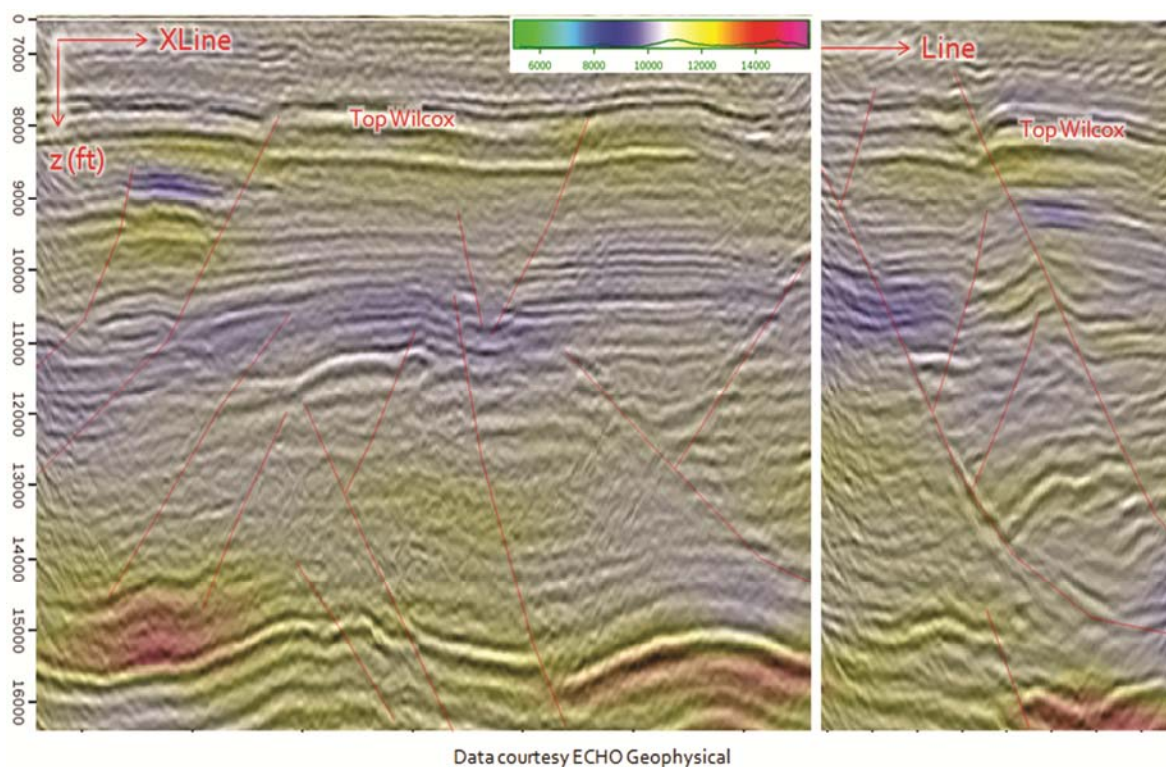


Figure 2. South Texas WEM imaging and velocity estimation example (best viewed on electronic copy of abstract). The WEM depth image is overlain by the final migration velocity (8 MVFA iterations, 3 WEM Angle Gather updates). The colorbar denotes the velocity in ft/sec and the top Wilcox horizon is labeled.

sampling of 4 degrees and a maximum angle of 48 degrees. Five iterations of the iterative attribute estimation scheme were run, producing a collection of reflectivity attributes, including the fluid factor, which was the most striking. Notice on the fluid factor reflectivity image how the fault block containing the prospect “lights up” well above the background amplitude on the WEM image.

Summary and Conclusions

We highlighted the performance on Gulf Coast onshore field data of three advanced wave imaging technologies which are perceived to only apply in a sub-salt environment. We finally summarize how each technology has reduced exploration risk.

High-Effort Wave Equation Velocity Update

It is self-consistent to use a wave equation based velocity update if the final migration is a WEM or RTM. Figure 2 proves that, in “fault shadow” provinces, (a) velocity indeed varies from fault block to fault block, and (b) high-effort depth migration velocity analysis can measure it. Figure 1 shows how the migration velocity obtained with the techniques presented matches the regional trends seen in checkshot data.

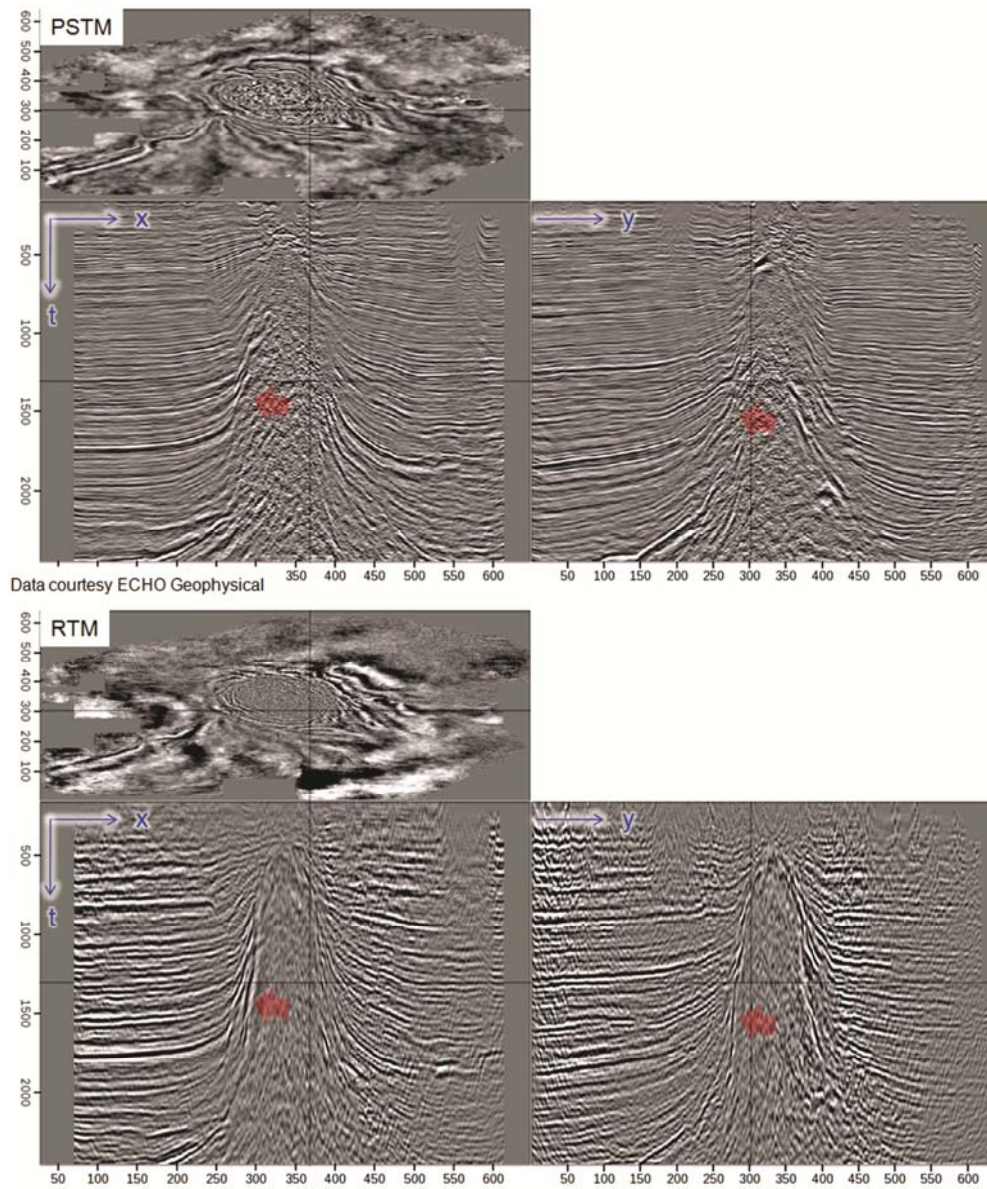


Figure 3. (Top) PSTM image of Spindletop salt dome. (Bottom) RTM image, converted to time for comparison. Red arrow highlights overturned salt flank.

Reverse-Time Migration

RTM is commonly perceived as a “salt-only” algorithm. While we have shown a convincing salt flank example in Figure 3, we feel that the improved imaging of fault planes and fault terminations make RTM eminently applicable for nearly any Gulf Coast example. While RTM is costly, it adds little additional burden if run only as the final migration, because our iterative velocity analysis scheme may require 10 or more WEMs.

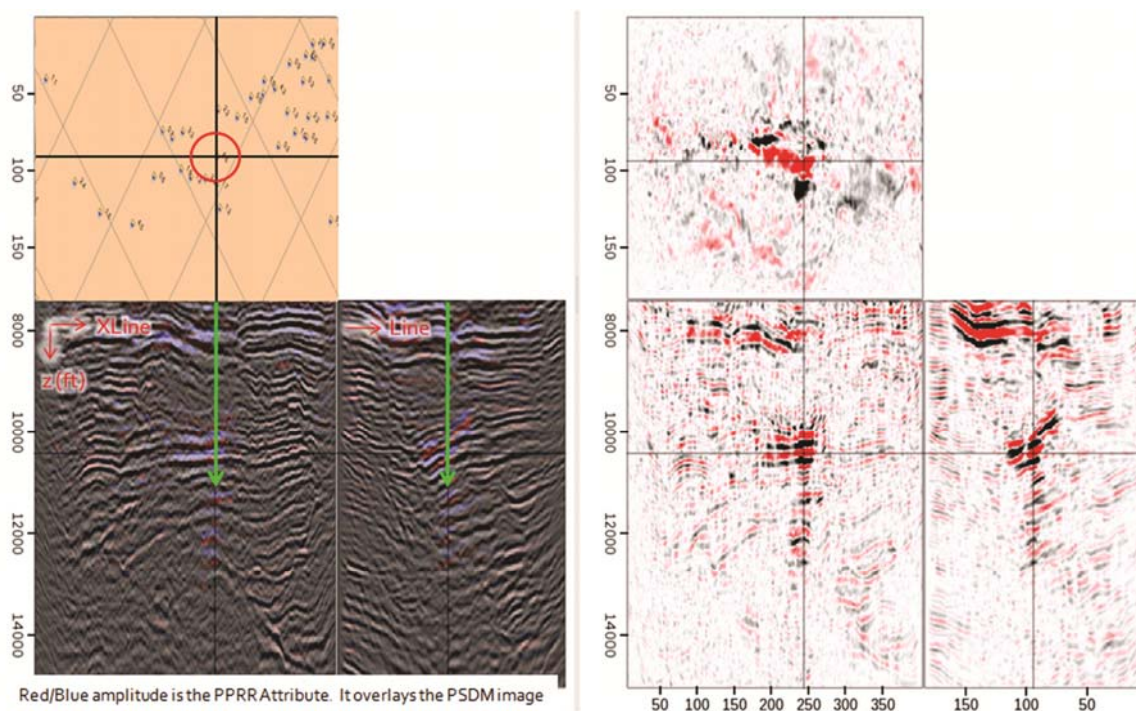


Figure 4. (Left) WEM image of West George West data. Crosshairs are centered on the location of Samson Resources’s Nelson #8 well, which has produced 4.6 BCFE of gas and condensate since 1994. The highlighted fault block has produced over 15 BCFE in total. (Right) Fluid factor reflectivity attribute obtained by Higginbotham et al.’s (2010) “iterative attribute engine”; crosshairs also centered on the Nelson #8 well.

Attribute Inversion of WEM Angle Gathers

Wave equation migration techniques are believed to handle amplitudes more naturally than Kirchhoff algorithms in many cases. The traditional impediment to using WEM for AVA work was the lack of readily obtainable angle gathers. **Figure 4** proves that our efficient WEM angle gathers, combined with Higginbotham et al.’s (2010) attribute inversion scheme, can produce a high-quality fluid factor attribute over a known strong producing well.

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