THE AMERICAN OIL & GAS REPORTER®

JULY 2020

The "Better Business" Publication Serving the Exploration / Drilling / Production Industry

CRAM Gathers Enhance 3-D Inversion

By Elive Menyoli

AUSTIN TX.–Elastic inversion from common reflection angle migration (CRAM) gathers can accurately capture lithology-driven lateral variations in reservoir properties, particularly in a strongly deformed and faulted geologic environment. Compared with angle gathers transformed from post-migration offset gathers, the intrinsic angle gathers from CRAM have three critical advantages:

- Reliable angle gathers greater than 40 degrees;
- A robust and reliable amplitude and phase preservation; and
- Regularly sampled gathers.

Many practitioners have shown that in order to obtain reliable density, compressional- and shear-wave velocities (Vp/Vs), Poisson ratio and total organic carbon (TOC) content from prestack simultaneous seismic inversion, seismic gathers with sufficient angle range greater than 40 degrees are required.

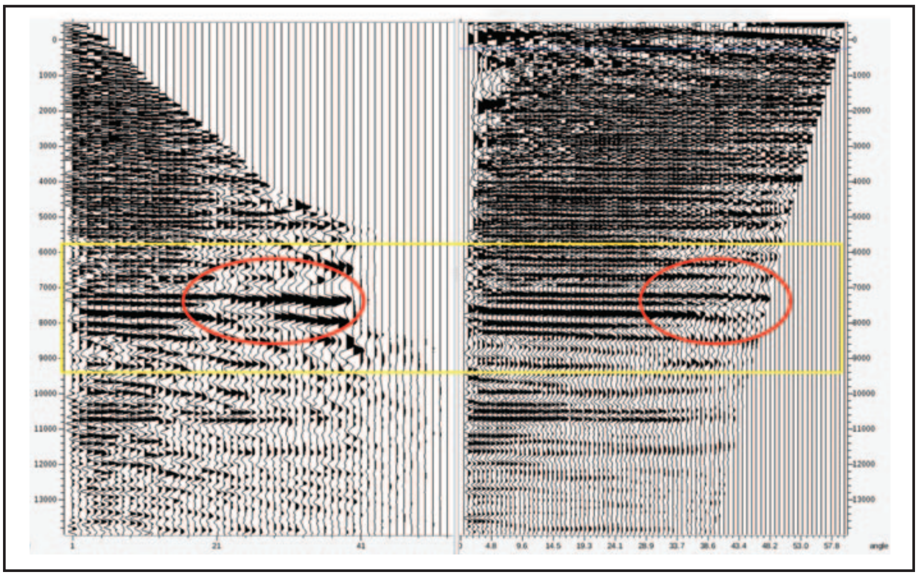
It has been shown in shale resource plays that the TOC content has a stronger influence on the density of the rock–and quite often density correlates to gamma ray curves (lithology predictor) or petrophysical properties such as porosity–than on velocities. However, the contribution of density to the overall seismic amplitude generally is present only on large angles greater than 40 degrees. Therefore, having a migration algorithm that naturally produces reliable large-angle gathers is critical.

The conventional Kirchhoff migration produces offset gathers that must later be converted into angle gathers prior to seismic inversion. Computing an accurate offset-to-angle conversion can be crucial to predicting subsurface lithology, particularly in shale plays with consolidated rocks that may have rapid lateral and vertical lithology changes.

Whereas a conventional normal move-out-based transform is increasingly inaccurate with increasing angles, especially in the presence of anisotropy, the CRAM-based method generates angle gathers directly using an intrinsic ray tracing procedure.

FIGURE 1

VTI Migrated Offset Gathers (Left) versus Common Angle Gathers (Right)



Generating CRAM Gathers

Unlike a conventional common shot or common offset Kirchhoff migration, which begins at the acquisition surface, common reflection angle domain migrations start at the depth image point. From each subsurface point, a fan of upgoing rays is shot at uniform emergence angle increments. This approach allows the direct application of correct summation weighting factors, resulting in continuous amplitude and phase-preserved image gathers for a wide range of reflection angles.

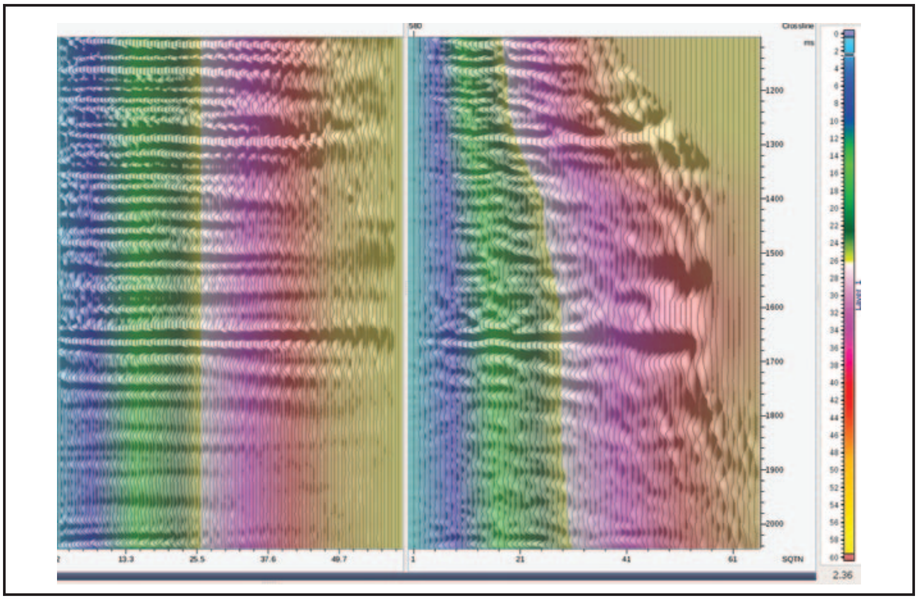
By shooting dense upgoing rays at uniform emergence angle increments, a uniform illumination is obtained directly at the image points from all directions (dips and azimuths), which is essential for the accurate reconstruction of angle image gathers that is required for seismic inversion.

Each event in the common image gather is constructed by summing all seismic data reflected from the image points with the same opening reflection angle. The relevant contributing data points are defined by the various ray paths from the image point. The illumination of the image points from all directions ensures uniform data sampling for building the image.

CRAM gathers are organized naturally

FIGURE 2

Angle of Incidence Overlaid on Migrated Angle Gather (Left) and Offset Gather (Right)



according to opening angles at each subsurface point, rather than according to source-receiver offset at the surface. Figure 1 compares an example of CRAM with a common offset Kirchhoff migration gather. Within the yellow-boxed zone, CRAM gathers are much cleaner, more continuous, and have better amplitude distribution.

CRAM gathers also are affected less by migration stretch at the far angles (area circled in red). This phenomenon is intrinsic to angle gathers and is another important advantage of CRAM migration. Avoiding migration stretch makes such angle gathers ideally suited for impedance inversion of elastic properties, even in complex geologic areas.

CRAM compensates equally for amplitude preservation and multiray path arrivals, and accounts for wavelet phase shift caused by caustics along the ray paths. Accounting for the total ray phase shift is important for keeping the wavelet phase stationary during propagation. Maintaining a stationary phase wavelet is one of the assumptions for seismic inversion.

It is worth noting that even in layer-cake geologic formations such as in South Texas, strong lateral and vertical velocity variations across fault boundaries may cause multiarrivals and ray caustics.

While CRAM gathers are organized in angles and depth, Kirchhoff gathers are organized naturally in offsets and depth. For inversion purposes, the Kirchhoff offset gathers must be transformed to angle gathers. Computing an accurate offset-to-angle transform is crucial to predicting subsurface lithology and fluid properties from seismic data.

The transformation from offsets to angles mostly uses analytical expressions that assume elastic properties vary only with depth and are laterally homogeneous (1-D assumption). With that assumption, Kirchhoff offset-to-angle transform becomes increasingly inaccurate as angles increase, especially in the presence of anisotropy.

Figure 2 is a display of a migrated seismic gather overlaid with the angle of incidence, and compares offset gathers and angle gathers. The amplitude distribution in the offset gather is quite different from the angle gathers, and is much noisier, especially at far offsets. Clearly, the offset gathers are less reliable in terms of amplitude preservation and may provide unreliable inversion output. In the offset gather, the reliable angle range for impedance inversion is no higher than 36 degrees. Beyond that, there is a significant migration stretch as well as prevalent noise.

Unfortunately, at angles less than 40 degrees, the Zoeppritz equation is relatively insensitive to changes in density. This often means that using such a range of angles for density inversion will not yield reliable results. In contrast, CRAM angle gathers show reliable amplitudes at angles up to 50 degrees, with more stability and less noise.

Well-To-Seismic Ties

Prior to performing impedance inversion, seismic data must be preconditioned. The following steps were applied to the data shown in this article: multiples suppression, increased signal-to-noise ratio (median filtering), spectral balancing, enhanced signal bandwidth with inverse Q, higher-order gather flattening, and wavelet unstretch.

A critical component of any seismic inversion is wavelet extraction. Before wavelet extraction, it is imperative to calibrate the seismic to the well markers and remove any seismic-to-well mis-ties that may exist. Furthermore, a good calibration is needed for building background models for the impedance inversions.

A well tie tomographic approach was used for the seismic-to-well calibration. The approach uses the depth mis-ties to globally update the seismic velocity model and anisotropic parameters to minimize mis-ties. This approach helps to minimize the stretching and squeezing per well, which often is required at the wavelet extraction stage.

Because it is a tomographic approach, it honors the correct ray path and accounts for any lateral displacement, as opposed to vertical stretching only, which is the common approach. It also ensures that the seismic data globally match all available wells in the project.

It is only after this step that the seismic

FIGURE 3

Resolution of Inversions from CRAM Gathers (Far Right) versus Kirchhoff Gathers (Center)

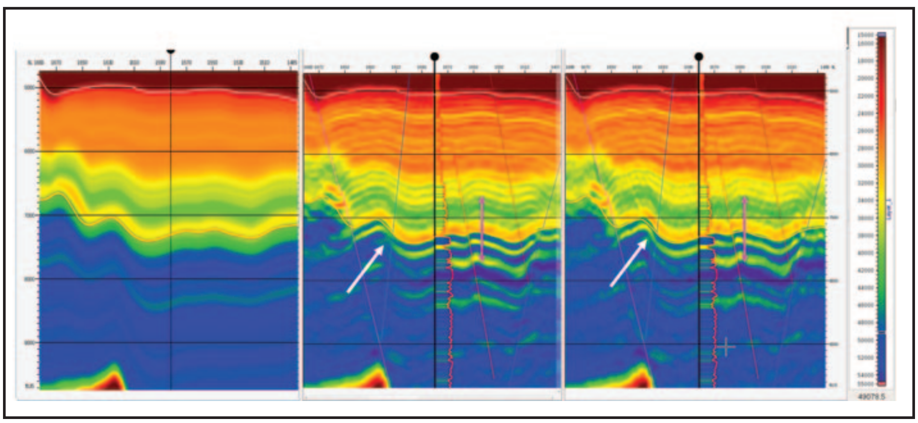


FIGURE 4

P-Impedance Inversion with Zero Phase Wavelet for Kirchhoff (Left) versus CRAM (Right)

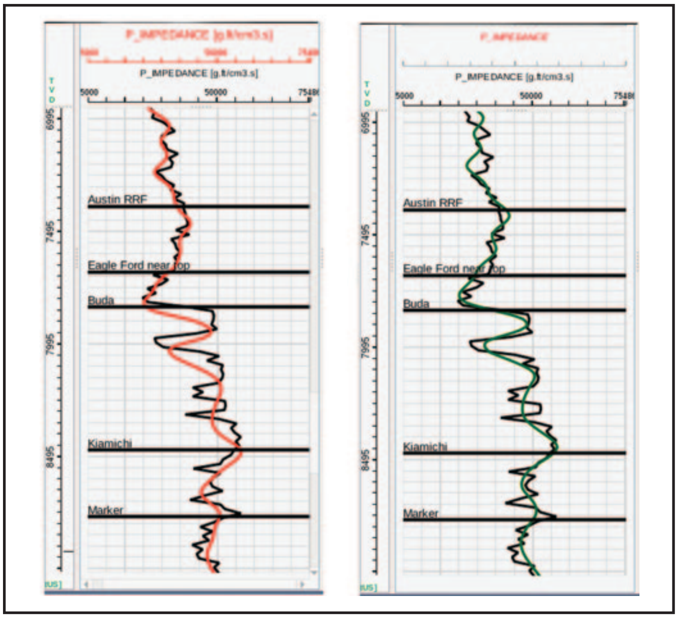
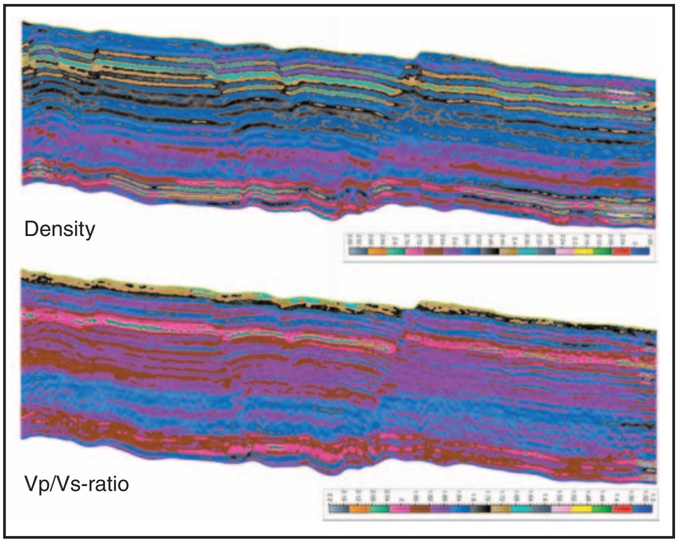


FIGURE 5

Density and Vp/Vs Ratio Volume Inverted from CRAM Gathers



data is ready for wavelet extraction and impedance inversion. Another advantage of this tomographic approach is that careful ties between the well logs and the seismic minimize the need to change the phase of the wavelet and improve the chances of obtaining a zero-phase wavelet, which in turn will yield markedly improved inversion results.

Inversion Results

The inversion process uses the three-term Fatti approximation to generate P-impedance, S-impedance and density volume. Figures 3 and 4 show a comparison of the inversion results using both migrated offset gathers and CRAM gathers.

Figure 3 contains the background P-impedance model (left), the inverted P-impedance using offset gathers (middle), and the inverted P-impedance using CRAM gathers (right). The overall trends in both inversion techniques are maintained, but the CRAM results show better resolution. This is evident in the interval between Austin Chalk and Top Buda away from the well.

Because the data preconditioning is the same for both types of gathers, the differences in the results is attributed to a lack of reliable large opening angles. The lateral heterogeneity seen in the CRAM products could be related to variations in the lithofacies.

While both techniques replicate what generally is observed in the wells at a broader scale, the detailed analysis in Figure 4 shows how the results from the offset gather do not match the measured log impedance below the Buda formation.

Above the Buda, the inversion results match the log results very well, but there is a shift below it at depth. This can be attributed to the far offset stretch or to the fact that the Kirchhoff migration does not produce a stationary wavelet with depth, since it uses only a single ray path arrival. To the contrary, CRAM does not show a deterioration in results with depth.

If there are more than two ray paths that pass through caustics, then the phase rotation from those ray paths will not be accurately accounted for. This phenomenon may cause the phase to vary with depth. In contrast, CRAM accounts for multiple ray path arrivals, as well as all possible phase shifts caused by caustics. For that reason, the inversion from CRAM angle gathers fits very well both at the Buda formation itself, and above and below the Buda formation.

After inverting for P-wave impedance, S-wave impedance and density volume, one can easily calculate mu-rho, lambda-rho and Vp/Vs volumes.

Figure 5 shows density and Vp/Vs sections. As expected, CRAM density and Vp/Vs ratio show higher resolution. With a reliable density volume, other important petrophysical attributes necessary for reservoir characterization, such as lambda-rho and mu-rho, can be computed. For instance, the product of Young's Modulus and density can be computed confidently. This is a property that can show areas containing material with a tendency to fracture.

The results from this South Texas onshore dataset show that performing simultaneous seismic inversion from CRAM angle domain gathers is optimal and straightforward. Obtaining such reliable inversion results will allow interpreters to confidently move to any next level, such as geostatistical inversion or machine learning probabilistic facies classification, for example.

Generating CRAM angle domain gathers has several advantages, including the fact that trustworthy angle traces can be produced for up to 50 degrees, and these traces are less affected by migration stretch. Such high-quality angle traces enhance confidence in density inversion and other derived attributes. ❐

Editor's Note: The South Texas data presented in this article is provided courtesy of Seitel Inc.

ELIVE MENYOLI

Elive Menyoli has more than 15 years of experience in the oil and gas industry. Prior to joining Emerson, he worked at Marathon Oil and Total E&P USA, in deepwater projects. Menyoli holds an M.S. in physics from the University of Goettingen, Germany, and a Ph.D. in geophysics from the University of Hamburg, Germany.