Imaging of complex structures by reflection seismic data: state-of-the-art and road ahead

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Abstract

Driven by hydrocarbon exploration in frontier areas (e.g. sub-salt), seismic imaging technology continues to make remarkable progress in imaging of complex structures. Recent advances in the areas of migration and velocity estimation are:

- 3-D prestack migration beyond Kirchhoff (wave-equation and beam migrations).
- Computation of Angle Domain Common Image Gathers for robust velocity estimation.
- Imaging by regularized iterative inversion.

Introduction

One of the main challenges for imaging seismic data in structurally complex areas is associated with the complexity of the wave-propagation phenomena that occur when large contrasts in propagation velocity are present. Important instances of these situations are the rugged salt bodies present in several deep-water sedimentary basins (e.g. Gulf of Mexico) and the basalt layers covering hydrocarbon-bearing sediments (e.g. Western North Sea).

In these areas, the standard imaging (migration) methods, which are based on the Kirchhoff integral, have both theoretical and practical shortcomings. Therefore, in the past few years substantial efforts have been spent in imaging methods based on wavefield continuation. These methods, often referred as *wave-equation* methods, have the potential of overcoming the limitations of Kirchhoff methods. However, they present practical challenges for 3-D imaging because of computational cost and irregularities in the acquisition geometries. Notwithstanding these issues, there are now several reported examples where better imaging has been achieved using wavefield-continuation methods instead of conventional Kirchhoff methods.

Recently there has been a renewal of interest in Gaussian-beam migration and related methods, with the aim of striking a compromise between computational cost and image accuracy. These methods can handle multipathing wavefields more effectively than Kirchhoff methods can, but they are less computationally expensive than wavefield-continuation methods and adapt easily to different acquisition geometries and/or image geometries (target oriented migration).

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In complex areas, the real challenge of seismic imaging is not as much in the migration step as in the estimation of the background velocity function. No matter how accurate a migration algorithm is, it will produce unsatisfactory images if the velocity function does not thoroughly describe the complex wave-propagation phenomena occurring during the actual experiment. Migration Velocity Analysis (MVA) is performed iteratively based on the velocity information contained in the Commmon Image Gathers (CIGs) extracted from the migrated image at previous iterations. As for the migration itself, conventional CIGs computed by Kirchhoff migration as a function of the data offset are prone to severe artifacts when the overburden is complex. Another important recent development has been the adoption of Angle Domain CIGs (ADCIGs) that decompose the image according to the aperture angle at the reflector, instead of the data offset at the surface. Several methods for computing and using ADCIGs for MVA have been developed for both Kirchhoff migrations and wavefield-continuation migrations.

Finally, another common problem linked with complex overburden, and/or 3-D irregular geometries is the incomplete illumination of target reflectors. To address illumination problems it is often necessary to go beyond simple migration and to perform iterative inversion of the data. Inversion can be computationally overwhelming and it is potentially unstable. Therefore, to be able to use inversion in practice we need to make substantial progress in constraining the inversion by appropriate regularization operators and speed it up its convergence by proper preconditioning operators.

Kirchhoff migration vs. wavefield-continuation migration

Wavefield-continuation methods can yield better images than Kirchhoff methods for depth-migration problems. They provide an accurate solution of the wave-equation over the whole range of seismic frequencies, whereas Kirchhoff methods are based on a high-frequency approximation of the wave equation. Furthermore, wavefield-continuation methods naturally handle multipathing of the reflected energy induced by complex velocity functions. In contrast, when multipathing occurs, Kirchhoff methods require the summation of the data over complex multivalued surfaces. This process can be cumbersome and prone to errors.

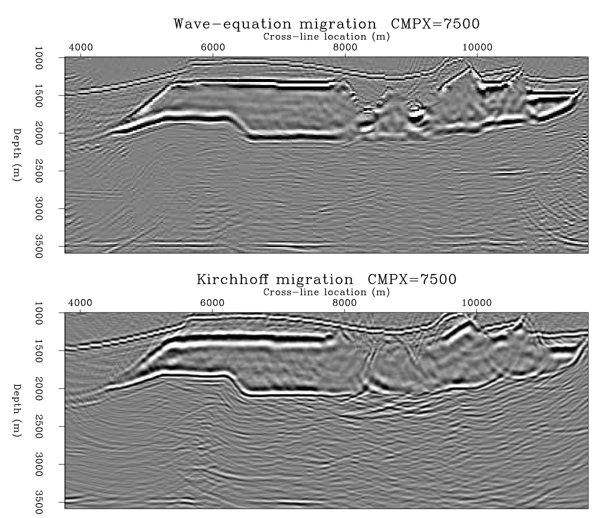

Figure 1: Sections of 3-D prestack migration results of a synthetic data set: wavefield-continuation migration (top), Kirchhoff migration (bottom).

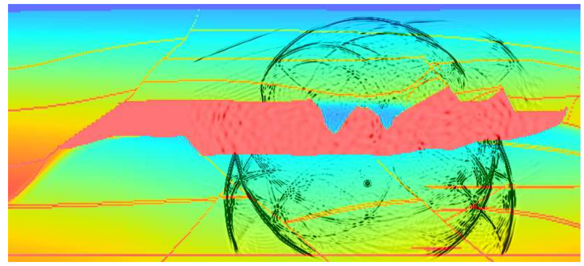

Figure 2: Snapshots of the wavefield at t=0 s and t=1 s, when the source is located below a salt body with a rugose top.

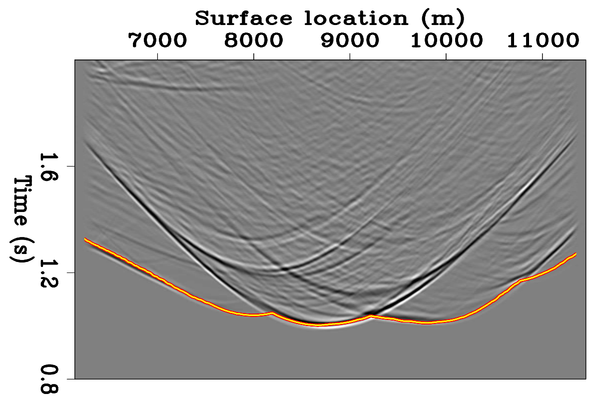

Figure 3: Wavefield recorded at the surface, corresponding to the wave modeling shown in Figure 2.

The following example illustrates a case in which the severe multipathing of the wavefield makes wavefield-continuation methods advisable. Figure 1 compares the images obtained by 3-D prestack migration with a wavefield-continuation method (top) and a Kirchhoff method (bottom) using a synthetic data set. The improvements achieved by the wavefield-continuation migration in the sub-salt image are evident. In the top image there are several reflectors that are not visible in the bottom image. Furthermore, several imaging artifacts that degrade the bottom image are not present in the top image.

The superior image quality achieved by wavefield-continuation migration can be understood by analyzing the results of wavefield modeling in the vertical section corresponding to the images shown in Figure 1. Figure 2 shows two snapshots of the wavefield taken at times t=0 and t=1 second, when the source is located below the salt body. Figure 3 shows the wavefield recorded at the surface. Notice the complex multipathing of the wavefield and the multi-branching of the Green function. The line superimposed on the wavefield represents the time-delay function computed using a finite-difference solution of the Eikonal equation. In this case, the Eikonal solution is a poor approximation of the "true" Green function.

Angle-domain Common Image Gathers

Conventional CIGs are parametrized according to the offset and azimuth of the data at the surface. When multipathing occurs these conventional CIGs can be affected by strong artifacts that diminish their utility for velocity estimation (and amplitude analysis). Angle-domain CIGs (ADCIGs) are more robust than conventional offset-domain CIGs. At the basis of angle-domain CIGs is a reflector-centered parametrization (reflection opening and azimuth angles) of the prestack image in place of the conventional surface-centered parametrization.

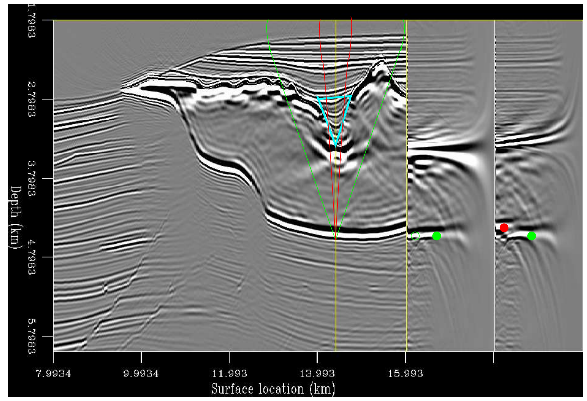

Figure 4: Migrated image of a synthetic data set: the left panel is the stacked image, the middle panel is ADCIG computed when the migration velocity function is correct, and the right panel is the ADCIG computed when the migration velocity is too low in the triangular region delimited by the cyan line superimposed onto the stacked image (left panel).

The robustness of ADCIGs assure that useful velocity information is available even in complex situations. Figure 4 shows an example where both the ADCIG computed using the correct velocity (middle panel) and the ADCIG computed using the wrong velocity (right panel) are clearly interpretable and provide useful velocity information.

Imaging by regularized iterative inversion

Target reflectors are often poorly illuminated because complex overburden distorts the propagating wavefield (e.g. under salt edges) and/or because of incomplete acquisition geometries (e.g. narrow-azimuth marine acquisition). In these situations, simple migration may produce images that are strongly affected by artifacts and have uneven amplitudes. Several researchers are investigating whether iterative inversion can compensate for this transmission effects. The normalization of the migrated image by a factor that takes into account the uneven illumination of reflectors is a first step toward inversion. The iterative inversion of the modeling operator is a more expensive, but potentially more powerful, approach. To avoid instability the inversion must be regularized. A physically meaningful constraint is to favor smoothness along the reflection angle of the image in the ADCIGs.

Figure 5 shows a comparison of the image obtained under a salt edge by simple migration (left), normalized migration (middle), and iterative regularized inversion (right).

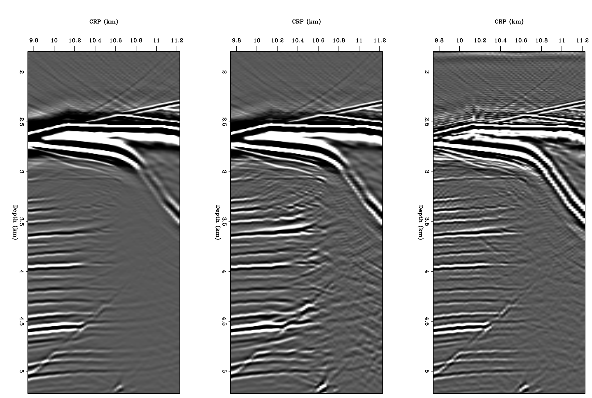

Figure 5: Images obtained by a) migration b) normalized migration c) regularized iterative inversion (Courtesy of Marie Clapp - SEP).