3-D wave-equation prestack depth migration

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Summary

Many people call the 3-D prestack wave-equation methods "Kirchhoff killers" because of the improved images and faster processing time. However, the two methods will coexist peacefully and will be used in complementary fashion. Kirchhoff migration is efficient for generating sparse CRPs for velocity analysis and target migration, while full volume wave-equation migration is efficient for generating the final image and offers better accuracy.

While at present time 3-D Kirchhoff depth migration represents the state-of-the-art processing technique for 3-D prestack imaging, wave-equation based migrations algorithms that downward extrapolate the wavefield have the potential of becoming superior imaging alternatives to Kirchhoff migration. Common azimuth migration is a wave-equation based 3-D prestack depth migration, using a phase-shift split-step with multiple reference velocities downward continuation formulation. I present imaging comparisons of 3-D Kirchhoff prestack depth migration and wave-equation common-azimuth migration. I conclude that wave-equation imaging offers superior resolution to standard Kirchoff.

Introduction

Common-azimuth migration (COMAZ) is a novel 3-D prestack wave-equation migration algorithm originally proposed by Biondi and Palacharla (1994; 1996), as an alternative to Kirchhoff migration for marine seismic data. Recursive methods such as COMAZ have certain intrinsic advantages over Kirchhoff methods:

- Recursive methods are potentially more accurate and robust because they are based on the full wave-equation and not on an asymptotic solution based on ray theory.
- Wave-equation methods handle multi-pathing naturally, while Kirchhoff methods do not.
- Focusing and defocusing effects of the velocity variations are correctly modeled by wave-equation methods.
- Anti-aliasing is handled implicitly.
- There is no need for traveltime interpolation, analysis of traveltimes grid error or traveltime shot spacing, or massive disk storage of traveltime tables.
- Common Image Gathers for velocity analysis and residual NMO before stack.
- Faster than Kirchhoff for full volume.

The disadvantage over Kirchhoff is that target lines are imaged at the same cost as the full volume, since COMAZ is a full wave downward continuation method. As such, Kirchhoff should be used in tandem with COMAZ, the former for initial velocity model building, the latter for full volume final imaging.

Short Review of Common Azimuth Migration

The full prestack downward continuation operator is expressed in the frequency-wavenumber domain by the Double Square Root (DSR) dispersion relation

$$\begin{aligned} k_z &= \sqrt{\frac{\omega^2}{v(\mathbf{s},z)^2} - \frac{1}{4}\left[(k_{mx}-k_{hx})^2 + (k_{my}-k_{hy})^2\right]} \\ &+ \sqrt{\frac{\omega^2}{v(\mathbf{r},z)^2} - \frac{1}{4}\left[(k_{mx}+k_{hx})^2 + (k_{my}+k_{hy})^2\right]}, \end{aligned} \qquad (1)$$

where ω is the temporal frequency, k_{mx} and k_{my} are the midpoint wavenumbers, and k_{hx} and k_{hy} are the offset wavenumbers; $v(\mathbf{s},z)$ and $v(\mathbf{r},z)$ are the propagation velocities at the source and receiver location.

By limiting the wavefield to have a common azimuth, the crossline direction component of the offset wavenumber k_{hy} becomes zero, and the stationary phase solution for the integral in dk_{hy} (Biondi and Palacharla, 1996) gives an expression for k_{hy} function of the other variables: $k_{mx}, k_{my}, k_{hx}, \omega, v(\mathbf{s}, z), v(\mathbf{r}, z)$:

$$\hat{k}'_{hy}(z) = k_{my} \frac{\sqrt{\frac{1}{v(\mathbf{r},z)^2} - \frac{1}{4\omega^2}\left(k_{mx} + k_{hx}\right)^2} - \sqrt{\frac{1}{v(\mathbf{s},z)^2} - \frac{1}{4\omega^2}\left(k_{mx} - k_{hx}\right)^2}}{\sqrt{\frac{1}{v(\mathbf{r},z)^2} - \frac{1}{4\omega^2}\left(k_{mx} + k_{hx}\right)^2} + \sqrt{\frac{1}{v(\mathbf{s},z)^2} - \frac{1}{4\omega^2}\left(k_{mx} - k_{hx}\right)^2}}. \qquad (2)$$

This expression is then introduced in equation 1 and used for downward continuation and imaging of seismic wavefields. The 4-D seismic wavefield is regularized using azimuth moveout (Biondi et al., 1994; Biondi et al. 1998) to become $Data(t, cmp_x, cmp_y, h)$ where cmp_x and cmp_y are the common-midpoint coordinates, and h represents the offset.

COMAZ is not only a 3-D prestack imaging tool, but can be used without any modification to image, 2-D postack and prestack data, as well as 3-D poststack data. Examining equation 1 we observe that in the absence of a crossline term and an offset term, the equation becomes a 2-D zero-offset downward continuation operator. In the absence of the 3-D crossline term, but keeping the inline offset term, the operator becomes a 2-D prestack downward continuation operator identical to the one used by Popovici (1996) for DSR split-step migration. Keeping the 3-D crossline term, but without the offset term, the operator becomes a 3-D poststack operator. Therefore, COMAZ can be used in a multitude of situations, as an extremely versatile imaging tool.

Wave-equation Imaging

The wave-equation common-azimuth migration was tested in the SEG/EAEG 3-D salt dome C3 dataset. The classic narrow-azimuth dataset C3 consists of 50 lines with 160 meters crossline spacing, 95 shots per line, 80 m shot spacing, 8 streamers spaced at 40 m, 68 groups per streamer with 40 m group spacing. The dataset is comprised of a total of approximately 2.5 million traces, 6.4 Gbytes. Figures 1 and 2 show comparisons of 3-D Kirchhoff prestack depth migration and wave-equation migration. The traveltimes used by the 3-D Kirchhoff depth migration were computed using the Fast Marching Method (Sethian and Popovici, 1999), a first arrival with headwave killer eikonal solver that is unconditionally stable, fast and accurate. In both depth slices the wave-equation migration image has better event resolution than Kirchhoff. Both methods image the global structure, the salt flanks, the regional fault, and the smaller semicircular faults, but the wave-equation migration image has less migration artifacts and better detail resolution. In Figure 2 the salt structure around the two lower-right semicircular faults is imaged in higher detail than Kirchhoff, as well as the salt flanks around the zone with low velocity that cuts through the salt dome.

Figure 3 shows 2-D prestack Kirchhoff depth migration and wave-equation migration imaging of the Marmousi dataset. The Marmousi synthetic dataset is based on a real geologic model from the Cuanza basin in Angola (Bourgeois et al, 1991). The challenge in imaging this dataset is to delineate the structural trap and the oil/gas contact in the second, deep anticlinal structure. The first arrival propagation used to build traveltimes for Kirchhoff migration is responsible for not delineating the second, deeper anticlinal area. Better Marmousi target imaging with first arrival traveltimes is possible using semirecursive migration (Bevc, 1997). Using wave-equation migration the second anticline as well as the oil/gas contact are accurately imaged, because the multiple arrivals are implicitly handled by the wave-equation migration.

Conclusions

I present imaging comparisons of 3-D Kirchhoff prestack depth migration and wave-equation common-azimuth migration. I conclude that wave-equation imaging offers superior resolution to standard Kirchoff due to several intrinsic advantages: it is based on a full wave-equation solution, it handles multi-pathing, has implicit operator antialiasing, no errors are introduces by traveltimes interpolation, and is faster than Kirchhoff for full volumes.

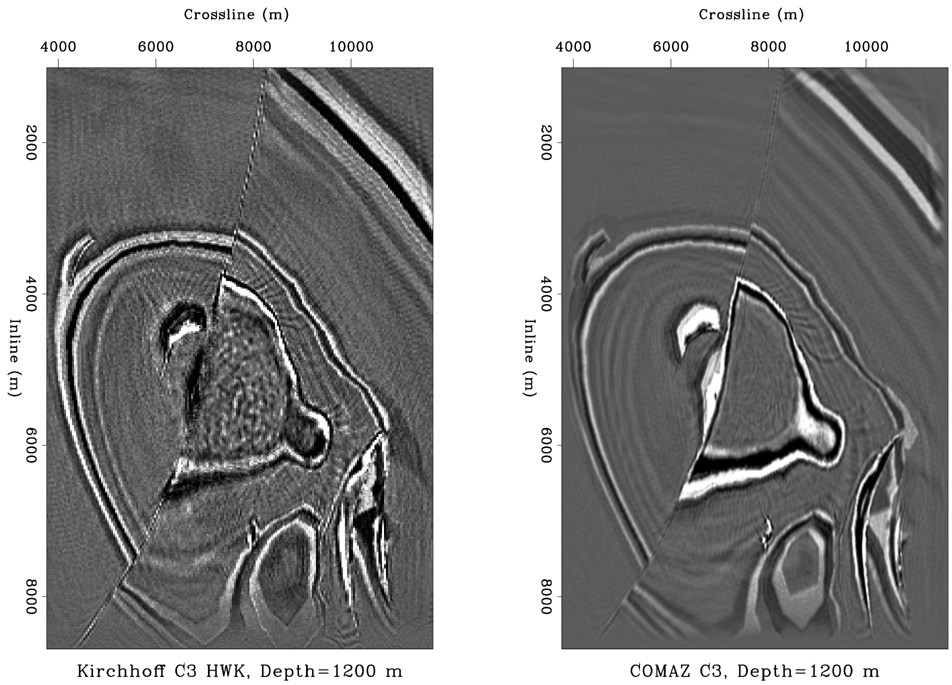

Figure 1: Comparison of 3-D depth migration slices at 1200 m. Left, Kirchhoff depth migration. Right, wave-equation migration. Wave-equation migration offers better resolution.

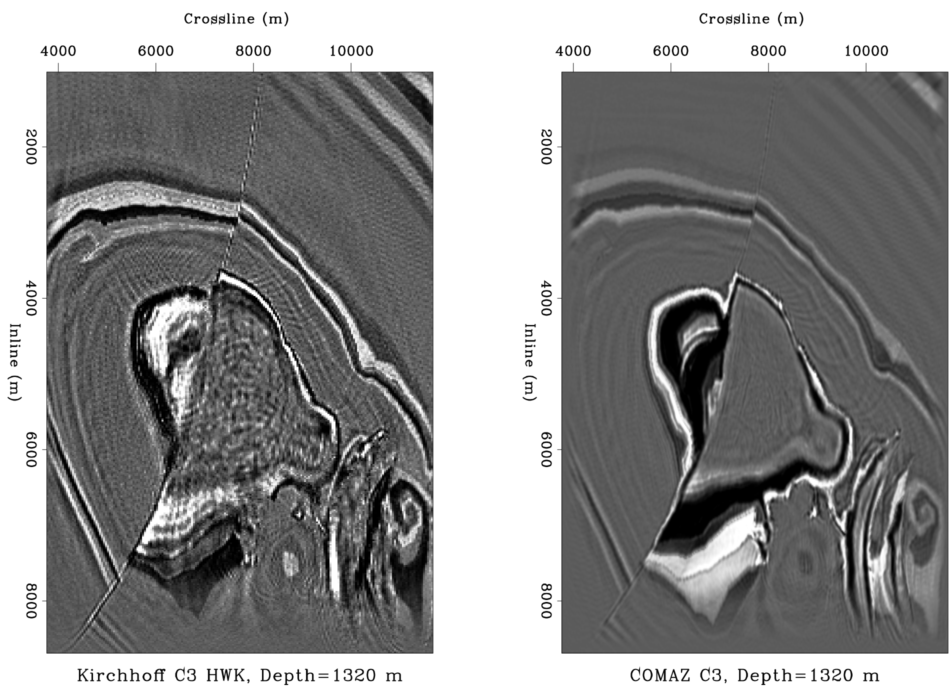

Figure 2: Comparison of 3-D depth migration slices at 1320 m. Left, Kirchhoff depth migration. Right, wave-equation migration. Wave-equation migration offers better resolution.

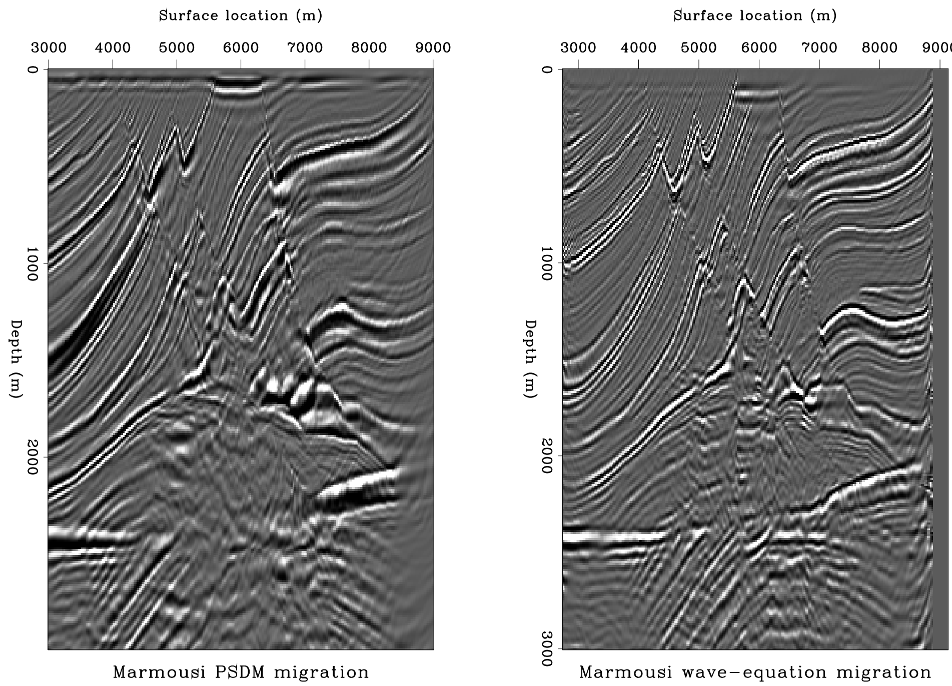

Figure 3: Comparison of 2-D Marmousi: Left, Kirchhoff depth migration. Right, wave-equation migration. The wave-equation multi-pathing image correctly the target anticline.

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