Velocity model building by wavefield-continuation imaging in the deepwater Gulf of Mexico

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Wavefield-continuation-based migration algorithms that downward extrapolate the 3D prestack wavefield (commonly known as "wave-equation migration") have been recently shown to produce better imaging results than Kirchhoff migration in many synthetic and real data cases (Popovici, 2000). Wavefield-continuation 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. In addition, wavefield-continuation methods handle multipathing naturally in contrast to Kirchhoff methods, focusing and defocusing effects of velocity variations are correctly modeled, antialiasing is handled implicitly, and amplitudes are consistent with the wave equation.

This study uses data over an extensive salt body in the deep Gulf of Mexico but concentrates on a subset of the entire 1215 km^2 data set consisting of two swaths of 160 and 64 inlines with 40 m line spacing and 1024 CMPs with 37.5 m spacing. CMP-fold is 48 and the recorded offset range 400-7400 m. Water depth is about 1800 m. Target lines A and B discussed below are the center lines of each swath (Figure 1).

When the salt body is absent, the local velocity structure is simple. The background sedimentary P-wave velocity model does not deviate significantly from a 1D linear Gulf of Mexico gradient—1700 m/s near the seafloor and reaching 3500 m/s at 12 750 m below sea level. The salt body is modeled as a constant velocity body with a P-wave velocity of 4500 m/s. The salt body sits in a depth range of 2300-8000 m and has a complicated shape that changes rapidly in both inline and crossline directions. The top of salt is characterized by steep flanks, narrow canyons, and a generally rugose surface topography (Figure 1). This initial velocity model is based on previous best-effort Kirchhoff processing of the entire data set.

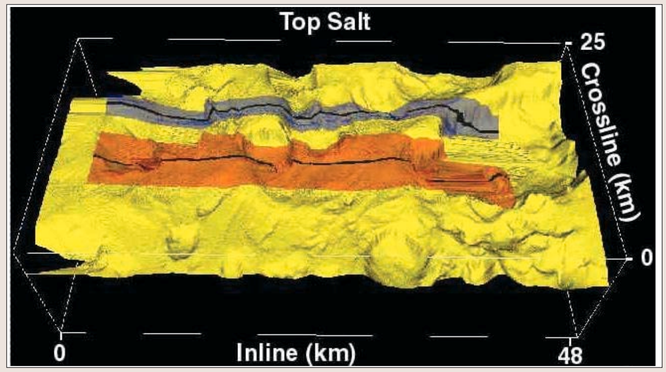

Figure 1. Perspective view of the top salt surface (yellow) of the Foldbelt Gulf of Mexico data set. Swaths A (orange) and B (gray) and their respective target lines (black) are used for this study.

Kirchhoff prestack depth migration. The prestack Kirchhoff migration used for this project employs a fast marching method (Sethian, 1996) to calculate 3D traveltime tables (Sethian and Popovici, 1999; Popovici and Sethian, 2002). Figures 2 and 3 show the two target lines, Kirchhoff migrated with the initial velocity model. Overall, the salt body is well imaged on line A, but the subsalt sedimentary reflectors are disrupted by strong migration artifacts ("smiles") in several locations (Figure 2a). A detailed view of the top salt reflector (Figure 4) reveals that it is not sharply defined everywhere, especially at steep flanks (Figure 4a) and within a narrow canyon (Figure 4b); parts of the more gently dipping top salt are blurred (Figure 4c). The base salt reflector is not clearly delineated in several locations below these problematic top salt areas (Figures 2a and 5). Disruptions in the top and base salt reflectors are even more obvious on line B, where the salt geometry is similar but appears more complicated in detail (Figure 3a). As we show in later sections, the deterioration in subsalt reflector continuity can clearly be traced to the problems in defining the shape of the overlying salt body (Paffenholz et al., 2002).

The image quality can be improved after migration by applying residual moveout corrections (RMO, see below), but the underlying imaging problem cannot be addressed in this way. To improve this area, the shape of the salt body must be delineated more accurately in the velocity model. The prestack Kirchhoff-migrated image can certainly be used to repick the salt body, but the blurry or missing salt reflector in the critical areas does not make it the ideal candidate for this procedure. Multiple raypath and focusing effects associated with the rugged top salt topography are better handled with wavefield-continuation methods. Beginning with the same initial velocity model, the image resulting from prestack wavefield-continuation migration will be a better starting point for determining the shape of the salt body.

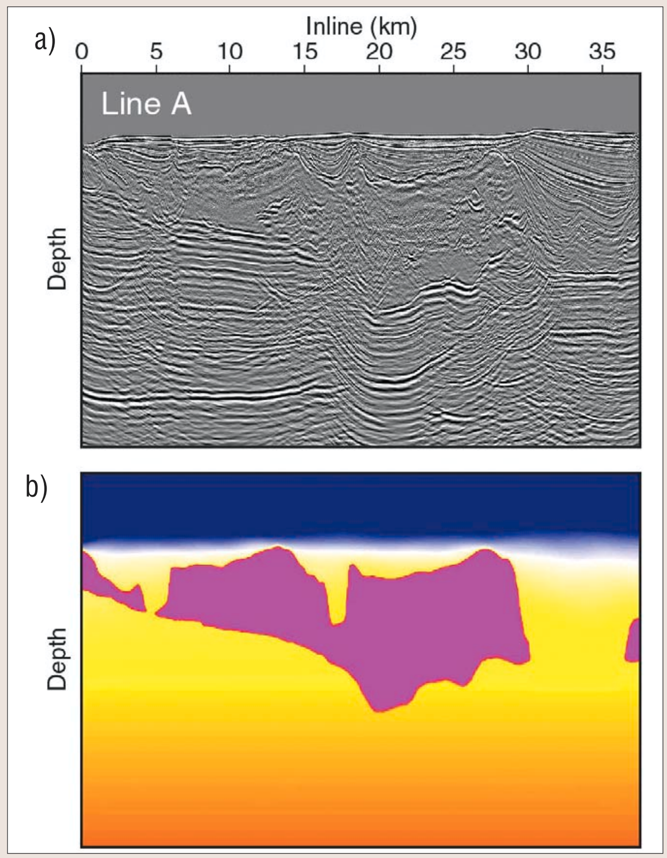

Figure 2. Kirchhoff-migrated target line A (a) and coincident section through the initial velocity model used for the migration (b).

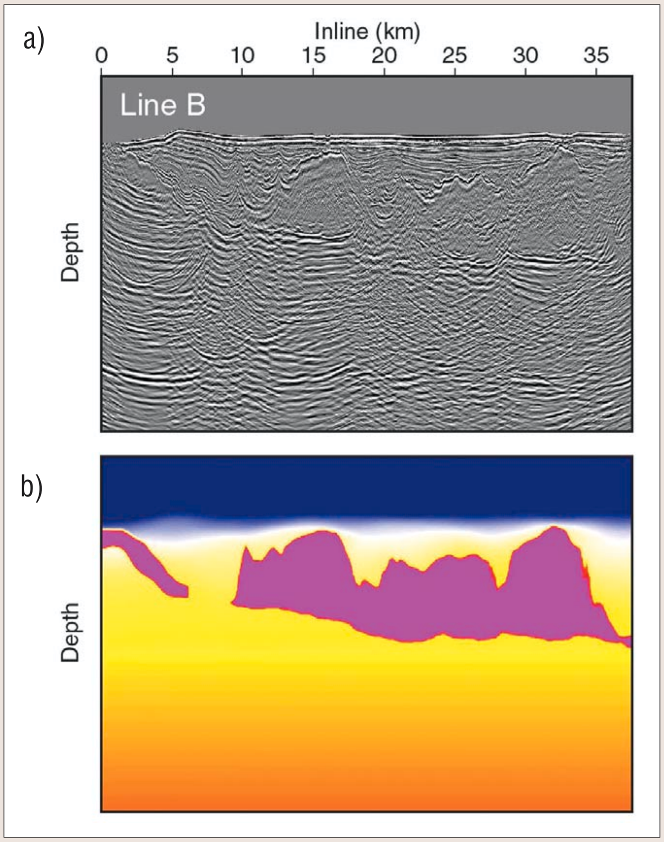

Figure 3. *Kirchhoff-migrated target line B (a) and coincident section through the initial velocity model used for the migration (b).*

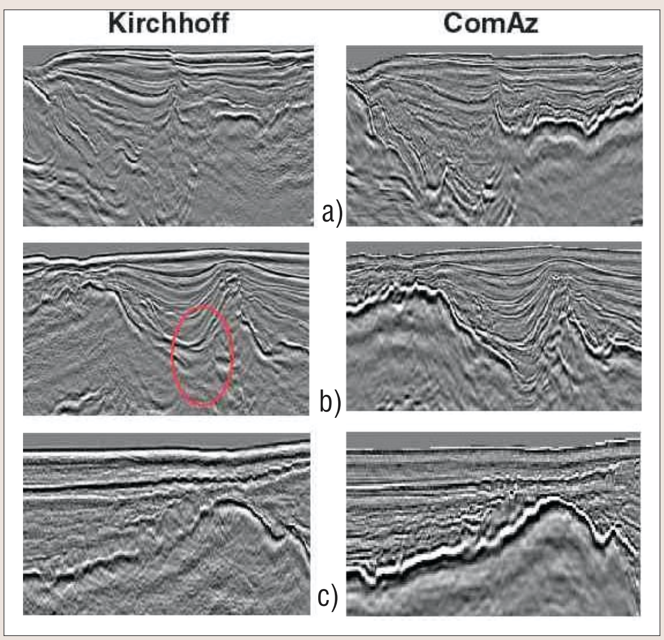

Figure 4. *Details of top salt reflector from line A comparing (left) Kirchhoff and (right) ComAz imaging. Note that ComAz gives better reflector continuity—(a) better imaging of sediments near the steep salt flank; (b) finer details in the rough top salt including the base of a narrow sedimentary channel (marked red); and (c) sharper definition of top salt and overlying sediments.*

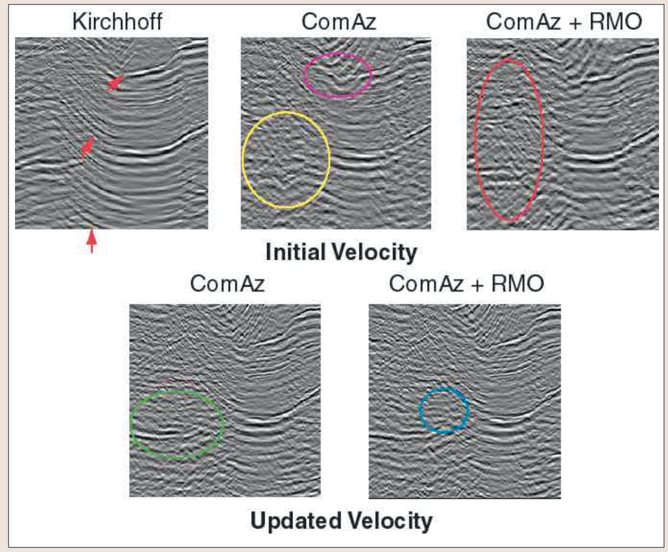

Figure 5. *Detail of base salt and subsalt reflections from line A. Note the strong Kirchhoff migration artifacts originating from the poorly imaged corner in the salt body (arrows). ComAz imaging with the same velocity model reduces these artifacts and defines the salt corner more clearly (magenta); however, some deeper reflectors (yellow) are still not imaged. Residual moveout (RMO) correction restores the subsalt reflector continuity (red). After updating the shape of the salt body in the velocity model, subsalt reflector continuity is improved (green). Further residual moveout corrections improve some subsalt reflectors (blue).*

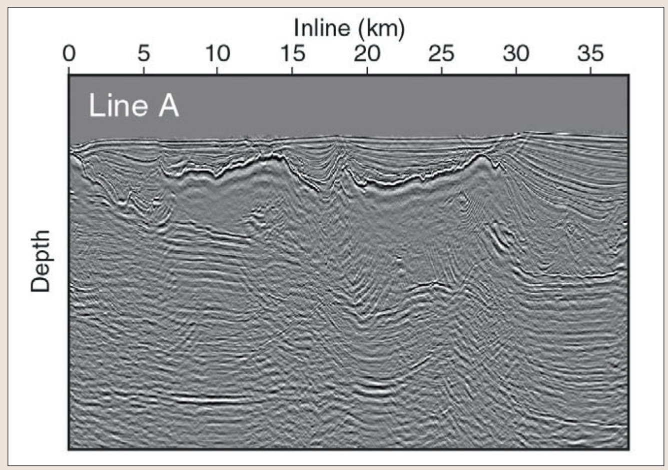

Figure 6. *Target line A, migrated with ComAz using the initial velocity model derived from Kirchhoff migration (Figure 2b). Note the improvements in sharpness and continuity of the top salt reflector compared to Figure 2a.*

Common azimuth wavefield-continuation migration. Common azimuth wavefield-continuation (Biondi and Palacharla, 1996) is a practical alternative to Kirchhoff migration for marine seismic data that is based on the full wave equation instead of asymptotic ray theory. The common azimuth downward-continuation operator restricts the full double square root (DSR) operator to zero crossline offset (four instead of five dimensions). This makes it well suited for marine seismic data that usually have limited azimuthal range. The common azimuth data are recursively evaluated at increasing depth levels, starting from the recorded data at the surface. For full-volume imaging, common azimuth migration (ComAz) is more efficient than equivalent Kirchhoff methods.

ComAz requires a regularly sampled 4-D wavefield, which is computed from the recorded data set using azimuth moveout (Biondi et al., 1998). Azimuth moveout (AMO) is a partial prestack migration operator that transforms 3D prestack data with given azimuth and offset to equivalent data with different azimuth and offset. It can be understood as performing in one step a cascade of DMO and inverse DMO. AMO is applied after NMO; a final inverse NMO restores the data

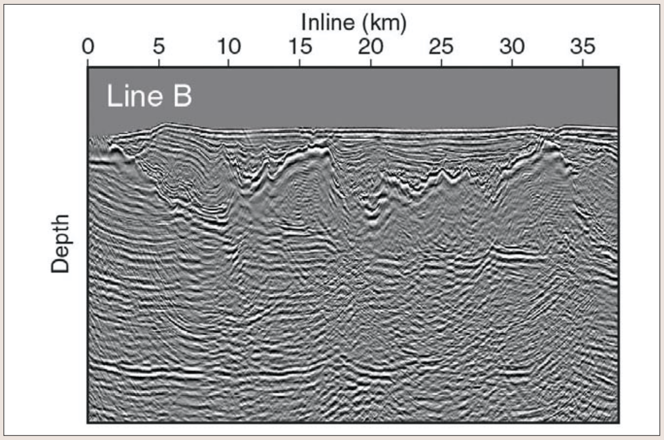

Figure 7. *Target line B, migrated with ComAz using the initial velocity model (Figure 3b) derived from Kirchhoff migration. Note the improvements in the top salt and the subsalt faults are compared to Figure 3a.*

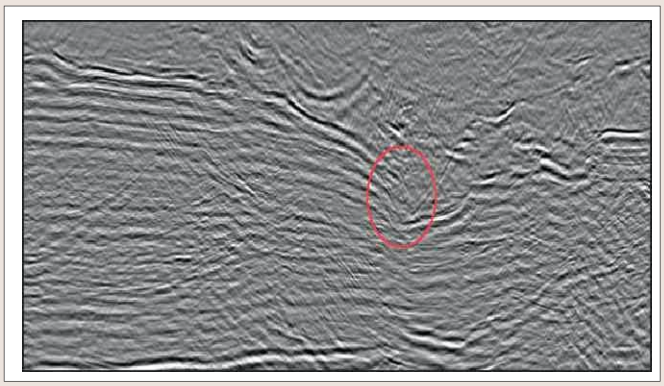

Figure 8. *Detail of the salt base from ComAz migrated swath A, 50 inlines away from the target line. Note the continuity of the base salt and sedimentary reflectors and the clear termination of the sediments against the salt keel (red).*

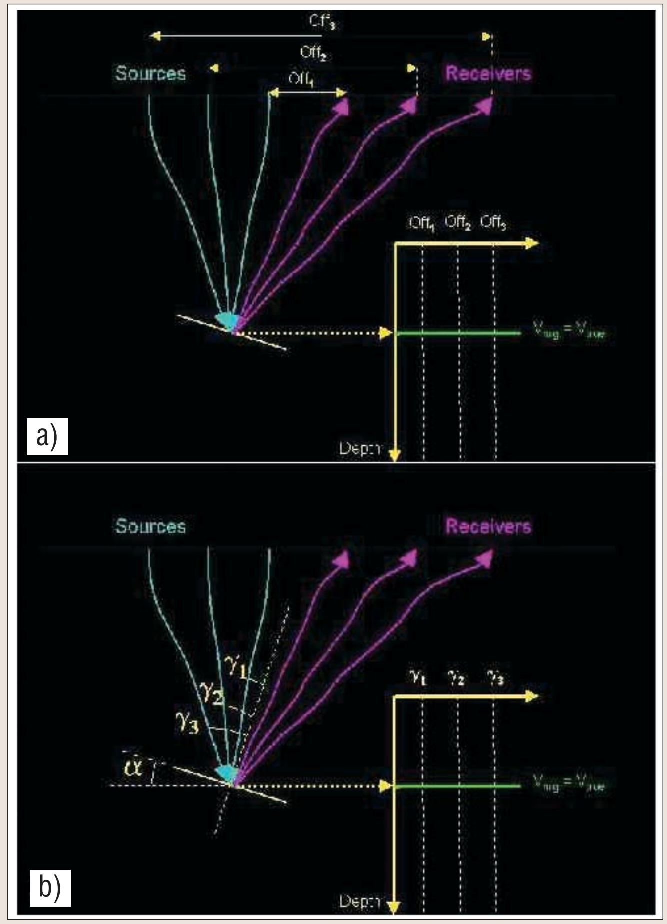

Figure 9. *Schematic comparison of (a) an offset domain common image gather (result of prestack Kirchhoff migration) and (b) an angle domain common image gather (result of common azimuth wavefield-continuation).*

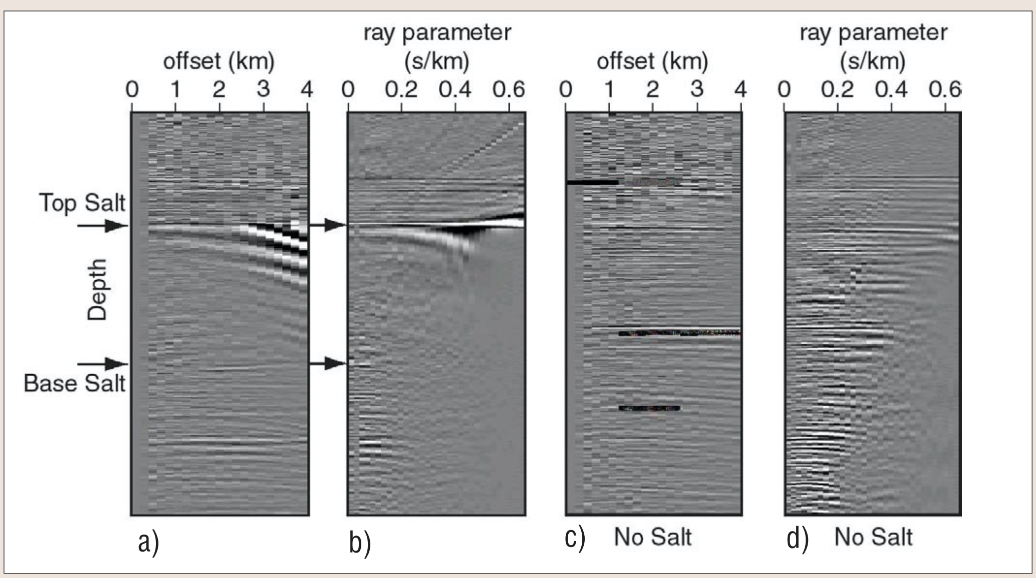

Figure 10. *(a) Offset domain (Kirchhoff) CIG and (b) angle domain (ComAz) CIG with salt present; (c) offset domain CIG and (d) angle domain CIG without salt present.*

in the new, regular geometry suitable for ComAz.

Figures 6 and 7 show the ComAz images of target lines A and B, migrated with the same velocity model as the Kirchhoff images. A comparison with their Kirchhoff counterparts (Figures 2a and 3a) shows improvement in the top salt reflector definition (Figure 4) but similar deterioration in the base salt and subsalt reflectors (Figure 5). Clearly the same velocity model is not optimal for both types of migration. The success of the next step, repicking the shape of the saltbody, however, hinges on the fact that the ComAz image is sharper, more continuous, and reveals more details of the top salt topography. Figure 4 compares the Kirchhoff and ComAz imaged top salt in detail and shows that the latter is superior. Furthermore, artifacts in the Kirchhoff image generated by sharp corners at the base of the salt body are clearly reduced in the ComAz image (compare Figures 5 and 8).

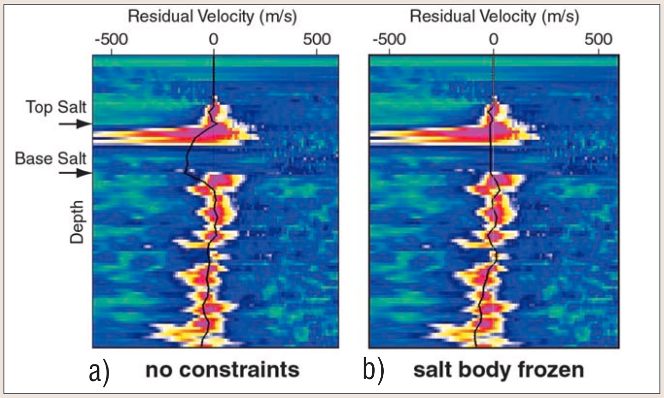

Figure 11. *Residual velocity semblance spectra and automatic residual pick (black); (a) salt body included into picking, (b) salt body excluded from picking.*

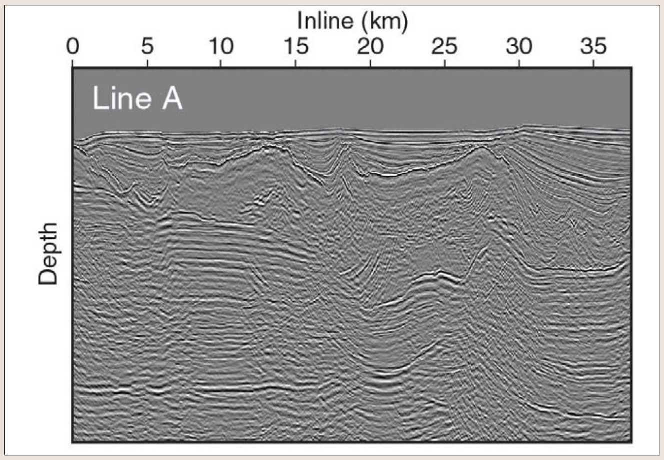

Figure 12. *ComAz-migrated target line A after applying residual moveout corrections: subsalt reflectors become more continuous (compare with Figure 6).*

Improving the wavefield-continuation image. Before we repick the salt body for remigration, we enhance reflector continuity by correcting for residual moveout in the image gathers produced by the wavefield-continuation migration. Residual moveout correction uses the technique of migration velocity analysis on the common image gathers (Liu et al., 2001) to remove residual curvature from the migrated arrivals before stack. The migration velocity analysis used here is essentially an implementation of the Dix method for postmigration data (Deregowski, 1990).

In contrast to Kirchhoff migration, common azimuth wavefield-continuation produces common image gathers (CIGs) in the ray parameter (angle of incidence) domain, not the offset domain (Figure 9). An advantage of angle domain gathers is that they show more clearly than offset domain gathers the narrowing of the data aperture with depth after the seismic signal passes through the high-velocity salt body (Figure 10) due to the fixed offset range at the surface. The broadening and upward curvature of the top salt reflection at high ray parameters indicate the emergence of the salt headwave, which will be muted before stacking.

For residual moveout correction, we calculate semblance spectra for a subset of CIGs (Figure 11a). The generally small deviations of the semblance peaks from the zero residual velocity line outside the salt confirm that the simple background velocity model for the sediments is probably accurate enough. From the semblance gathers, residual velocities are picked automatically (excluding the water layer and the salt body, Figure 11b). Properly smoothed, the velocity residuals are then applied to all CIGs as a hyperbolic moveout correc-

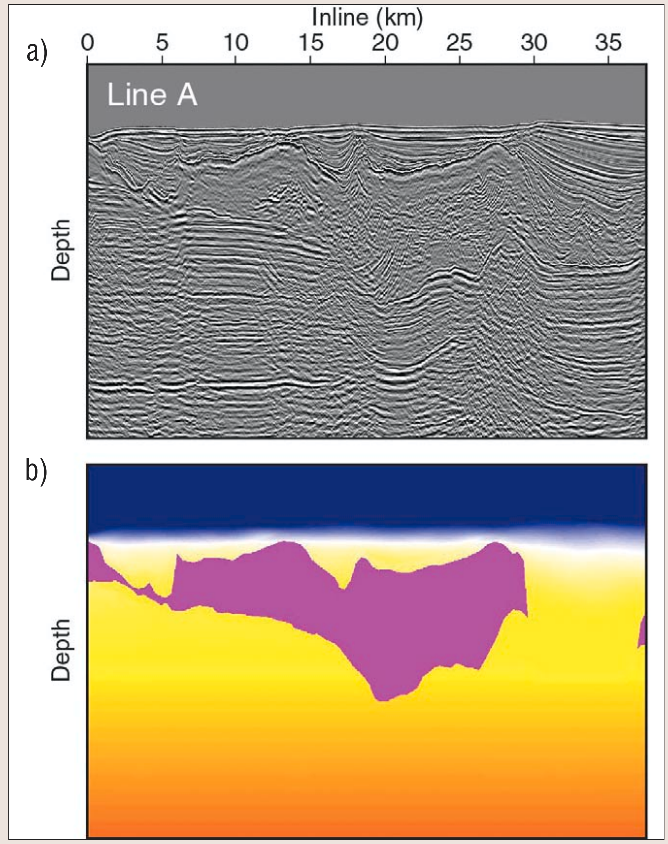

Figure 13. *ComAz-migrated target line A (a) and coincident section through the updated velocity model used for the migration (b). Base salt and subsalt reflectors become more continuous after the better delineation of the top salt surface.*

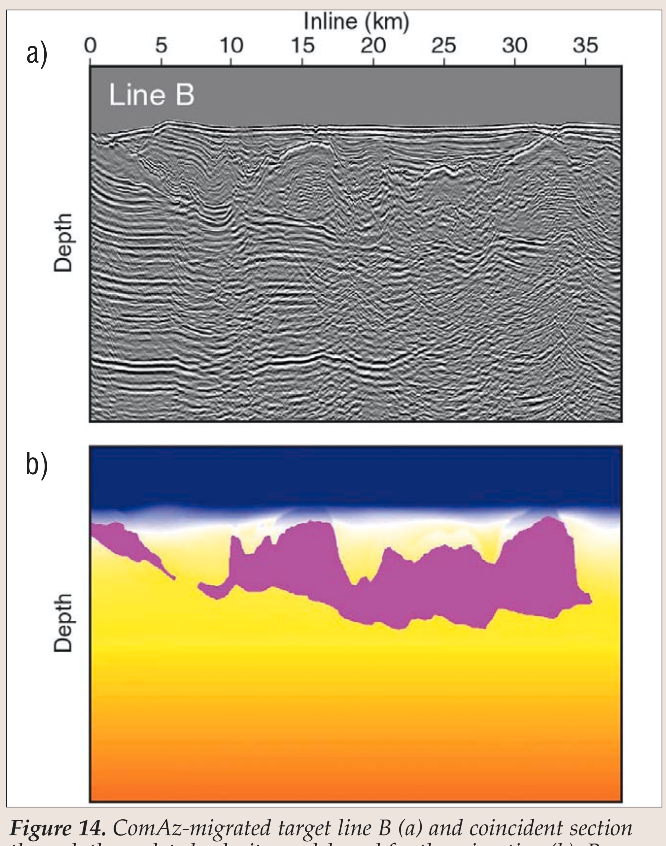

Figure 14. *ComAz-migrated target line B (a) and coincident section through the updated velocity model used for the migration (b). Base salt and subsalt reflectors become more continuous after the better delineation of the top salt surface.*

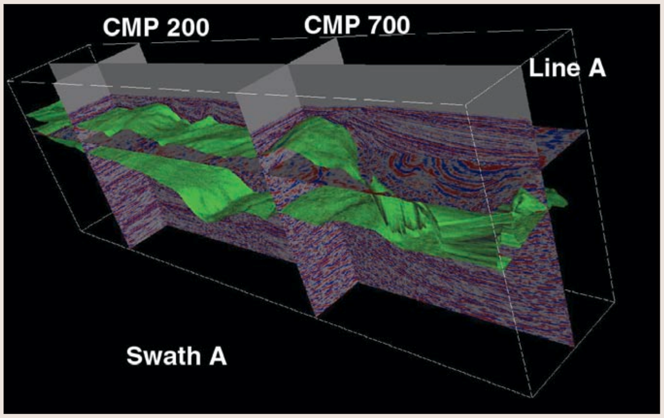

Figure 15. Perspective view of swath A, ComAz-migrated with the updated velocity model. Top and base salt surfaces in green.

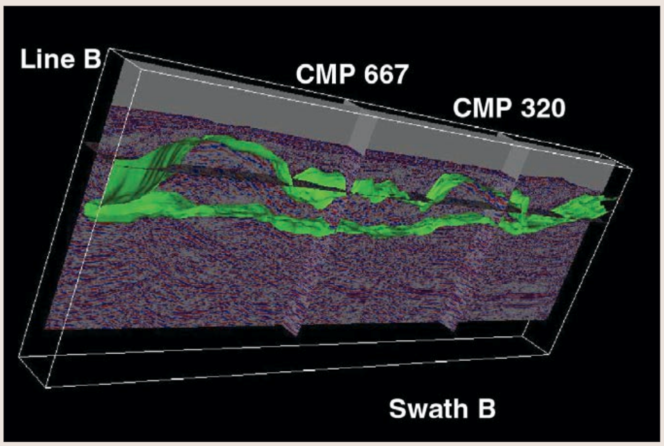

Figure 16. Perspective view of swath B, ComAz-migrated with the updated velocity model. Top and base salt surfaces in green.

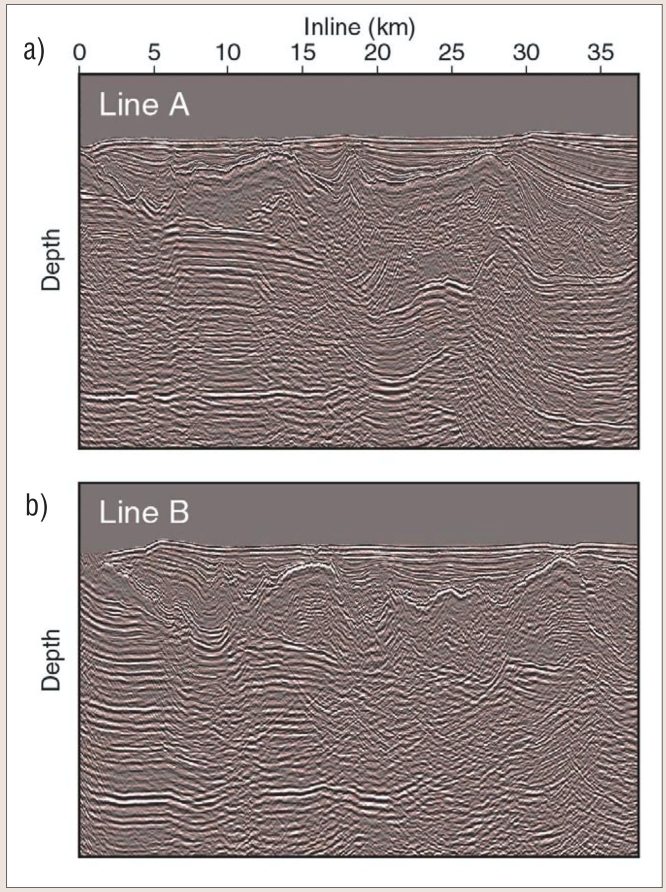

Figure 17. ComAz migrated target lines A and B, migrated with updated velocity model and after residual moveout corrections. Improvements on Figures 13 and 14 are marginal (see Figure 5) because the migration velocities are now closer to a correct model.

tion (Figure 12). The termination of the subsalt sediments against the salt keel and therefore the definition of the base of salt is improved and the strong subsalt reflector at approximately 10 000 m is more continuous.

Repicking the shape of the salt body. Because the velocity structure of the Gulf sediments is fairly simple and the salt body can be well approximated by a constant velocity body, the main improvements in image quality will come from a better delineation of the salt body in the migration velocity model. The sharper salt body image achieved by the common azimuth wavefield-continuation migration enables us to pick the shape of the salt body in more detail. We then insert the new salt body into the background (sedimentary) velocity model and remigrate (Figures 13 and 14).

After remigration, the top salt reflector is both sharper and more continuous. Because of the large velocity contrast between sediments and salt, even subtle changes in the shape of the salt body can lead to drastic improvements in the continuity of base salt and subsalt reflectors. Repicking and remigration is an iterative process, and we show here only the final product after two iterations (Figures 15 and 16).

After arriving at a final velocity model, a subsequent residual moveout correction improves the image only marginally because the velocity model is closer to convergence (Figure 17).

Conclusions. We have demonstrated that wavefield-continuation migration by a common azimuth method (ComAz) dramatically improves the imaging of complicated salt/sediment interfaces compared to Kirchhoff migration methods. The initial velocity model derived from previous best-effort Kirchhoff processing does not provide an optimal velocity model for wavefield-continuation migration. Consequently, velocity model building by iterative wavefield-continuation migration is crucial for an optimal image. The ComAz image reveals more details of the top salt topography and suppresses migration artifacts generated at sharp corners of the salt body. The resulting better delineation of salt bodies in the migration velocity model leads to better continuity of subsalt target horizons and sharper fault definition.

Suggested reading. "Azimuth moveout for 3D prestack imaging" by Biondi et al. (GEOPHYSICS, 1998). "3D prestack migration of common-azimuth data" by Biondi et al. (GEOPHYSICS, 1996). "Common-offset migrations and velocity analysis" by Deregowski (*First Break*, 1990). "3D migration velocity analysis for common image gathers in the reflection angle domain" by Liu et al. (SEG 2001 *Expanded Abstracts*). "SIGSBEE 2 a synthetic subsalt data set—image quality as function of migration algorithm and velocity model error" by Paffenholz et al. (EAGE 2002 *Extended Abstracts*). "3D wave-equation prestack depth migration" by Popovici (SEG 2000 *Expanded Abstracts*). "3D imaging using higher order fast marching traveltimes" by Popovici et al. (GEOPHYSICS, 2002). "3D traveltime computation using the fast marching method" by Sethian and Popovici (GEOPHYSICS, 1999). TLE

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