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Common-azimuth prestack depth migration of a North Sea data set

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ABSTRACT

Common-azimuth migration accurately imaged in depth a marine 3-D prestack data set recorded in the North Sea. The comparison of the results of common-azimuth migration with the results of multiple 2-D in-line migrations show that common-azimuth migration correctly focused the reflections along the cross-line direction, as well as the in-line direction. Because common-azimuth migration takes into account the 3-D features of the velocity model it focuses sub-salt reflections better than 2-D migration.
Common-azimuth migration can be also used to extend the depth-focusing analysis methodology to 3-D. I hope that refinements in the velocity model achieved by depth-focusing analysis can even further improve the migration results presented in this report.

INTRODUCTION

Migration methods based on recursive downward continuation of seismic data have potential advantages over Kirchhoff-based migrations. Recursive methods are often more accurate and robust than Kirchhoff methods because they are derived from the full wave-equation and not from an asymptotic solution based on high-frequency assumptions. Kirchhoff migration methods have been shown to have difficulties to image accurately reflectors below complex structures (Geoltrain and Brac, 1993; Godfrey et al., 1993; ?). Multi-pathing of wave propagating through complex velocity models is the main culprit for this loss of accuracy. The negative effects of multi-pathing can be ameliorated by performing the Kirchhoff summation over the most energetic arrivals, or, even better, over multiple arrivals. However, these improvements are seldom bullet-proof, while they add significantly to the computational cost and code complexity of Kirchhoff migration.

Downward continuation methods are usually more computationally efficient than

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Kirchhoff methods for full-volume imaging, and they are straightforward to implement. In 3-D, the cost of Kirchhoff migration grows with the cube of the image depth, because the migration aperture typically grows linearly with depth. On the contrary, because of the recursive nature of downward continuation methods, their migration aperture increases with depth automatically, resulting in a much more attractive linear increase of cost with migrated depth. Unfortunately, 3-D surveys are typically recorded with a sparse coverage of the surface in both the source and the receiver domain, while wave extrapolation must be performed on a densely sampled grid to avoid aliasing of the wavefield. Because the wavefield sampling criteria are independent from the actual surface sampling of the recorded traces, a straightforward application of 3-D downward continuation to 3-D prestack data would thus result in a method that wastes a large fraction of the computations propagating dead traces and wavefield components that never contribute to the final image. Due to these large computational inefficiencies, downward continuation methods, to my knowledge, have never been used to perform 3-D prestack migration of realistically-sized field data. One notable exception being the migration of data sets recorded with unusual geometries, such as vertical marine cables (Roberts et al., 1996).

The migration results that I present in this paper have been obtained by prestack migrating a 3-D marine data set using a new downward continuation method (Biondi and Palacharla, 1995; **?**) that overcomes the computational problems of 3-D prestack downward continuation and actually produces full-volume images more efficiently than Kirchhoff migration. This method takes advantage of the narrow range of the source-receiver azimuth typical of marine data by selectively propagating only a portion of the whole prestack wavefield. It can be shown that from an imaging perspective the propagated portion of the wavefield is the main component of the wavefield. Although modern marine data sets are not exactly common-azimuth due to the use of multiple streamers and the occurrences of cable feathering, they can be transformed to common-azimuth by application of partial-prestack migration operators, such as AMO (Biondi et al., 1996a) or DMO followed by inverse DMO (Canning and Gardner, 1996a).

Common-azimuth downward continuation is not theoretically exact because it selectively propagates part of the wavefield; the error that it introduces depends on the amount of ray-bending caused by velocity variations. However, previous tests on synthetic data, which were generated assuming both strong vertical and lateral velocity gradients, showed that the method is robust with respect to velocity variations (Biondi and Palacharla, 1995; **?**). These encouraging results motivated the study presented in this paper. The data set used for the tests was collected in the southern sector of the North Sea and presents challenging depth migration problems caused by shallow velocity variations created by uneven thinning of a high-velocity chalk layer, and deeper velocity variations created by a high-velocity salt layer (Hanson and Witney, 1995). A typical in-line geological section of the area is shown in Figure **??**.

I compare the results of common-azimuth 3-D prestack migration with the results of multi-line 2-D depth prestack migration, where, for the purpose of this paper, I define multi-line 2-D migration as the combination of independent 2-D migrations of common-azimuth data as a set of parallel 2-D lines. The comparison with multi-line 2-D migration show that common-azimuth migration correctly focuses the energy in the cross-line direction, as well in the in-line direction. Reflectors in the target zone below the salt layer are focused and they seem to be correctly positioned. However, I think that the migration results of deeper reflectors could be improved by further refinements in the velocity model. I am planning to generalize the 2-D methodology of depth-focusing analysis (MacKay and Abma, 1992) to 3-D common-azimuth migration to estimate the necessary refinements in the velocity function. Further analysis on the data should also indicate whether multi-pathing affected the propagation of the reflected energy, and in the affirmative case, whether common-azimuth migration has the capability of improving the imaging of these reflections over Kirchhoff migration.

COMMON-AZIMUTH DEPTH MIGRATION TEST

In this section I describe the details of the application of common-azimuth migration to the North Sea data set, and compare the results of 3-D common-azimuth migration with multi-line 2-D prestack migration.

Migration algorithms

The program that I used to migrate the data implements the common-azimuth downward continuation operator presented in previous reports by Biondi and Palacharla (?). The continuation operator is derived in the frequency-wavenumber domain, but, because it is applied to depth migration, it is implemented using a mixed space-wavenumber domain migration scheme. In particular, I implemented the method using a straightforward generalization of phase-shift plus interpolation (PSPI) (Gazdag and Sguazzero, 1984) to common-azimuth migration because of its simplicity and computational efficiency; other choices, such as split step (Stoffa et al., 1990) would have probably been just as effective. The design a frequency-space (Fx) representation of the common-azimuth downward continuation operator would be a worthwhile effort, after common-azimuth migration has been proven effective and accurate to image a wide-class of 3-D data sets.

The results of multi-line 2-D migrations were computed by a simple modification of the common-azimuth migration program; the well known 2-D double square root operator (Claerbout, 1985) was substituted for the common-azimuth operator. The multi-line 2-D migration program is slightly faster than the full 3-D program. Because it propagates energy only along the in-line direction, it does not require repeated forward and inverse FFTs along the cross-line midpoint axis to take into account the velocity variations along the cross-line direction.

Data set and preprocessing

The data set used for the tests was recorded in the southern sector of the North Sea. A typical in-line geological section of the area is shown in Figure **??**. An in-line section showing the velocity model superimposed onto a wiggle plot of the migrated image is shown in Figure **??**. The geological section indicates shallow velocity variations created by variable thickness in the low-velocity Tertiary sediments and in a high-velocity Cretaceous chalk layer. The reflections from the complex three-dimensional faulting in the Jurassic and Triassic formations just above the salt swell are affected by these shallow velocity variations. The exploration targets are the reflectors immediately below the salt. The correct positioning and the full focusing of the reflections from the target require prestack depth migration. McKay and Abma (1992) used a 2-D data set recorded above a similar geological setting to test their depth-focusing velocity analysis methodology; they provide a detailed description of the geological setting and its effects on depth imaging.

Although the geology in the area has predominant dips in the in-line direction, there are few interesting 3-D effects that require full 3-D migration to be properly taken into account. The fault blocks and the lithological boundaries in the Jurassic and Triassic layers are rotated with respect to the in-line direction, generating reflections with uneven azimuth. Both the top of the salt and the dolomite intrusions have complex reflector geometry that require 3-D migration. Further, because of the 3-D nature of the velocity model, full 3-D depth migration is needed to properly image the mildly dipping reflectors at the bottom of the salt layer.

The data were acquired using a flip-flop double-source and triple streamer acquisition configuration and affected by cable feather. Therefore, the original data geometry is not exactly common-azimuth and the data need to be transformed to a regularly sampled "equivalent" common-azimuth data set before migration. The transformed data set had the same sampling of the nominal sampling of the acquisition; that is, 9.75 m in the in-line direction, and 25 m in the cross-line direction. The offset axis was sampled with a 80 m interval; this coarse sampling introduced some aliasing along the offset axis, which seems to have caused only minor artifacts in the migration. I used this coarse sampling to reduce the migration computation time, and limit the size of the data set that needed to be handled. Tests with finer sampling of the offset axis are needed to determine more reliably the impact of offset aliasing on the results. To fully take into account the deviations of the source-receiver azimuth from the nominal common azimuth, AMO (Biondi et al., 1996b) should be applied to compute the common-azimuth data. But, for this initial test I used a simple horizontal binning and interpolation procedure that placed the traces at the correct midpoint, and normalized the interpolated output by the bin fold. The coarse sampling of the output offset axis implied some offset mixing, thus I applied NMO before the binning-interpolation procedure, and applied inverse NMO afterward.

Both the stacking velocity function used for NMO and inverse NMO, and the interval velocity function used for migration were provided by Conoco. The interval

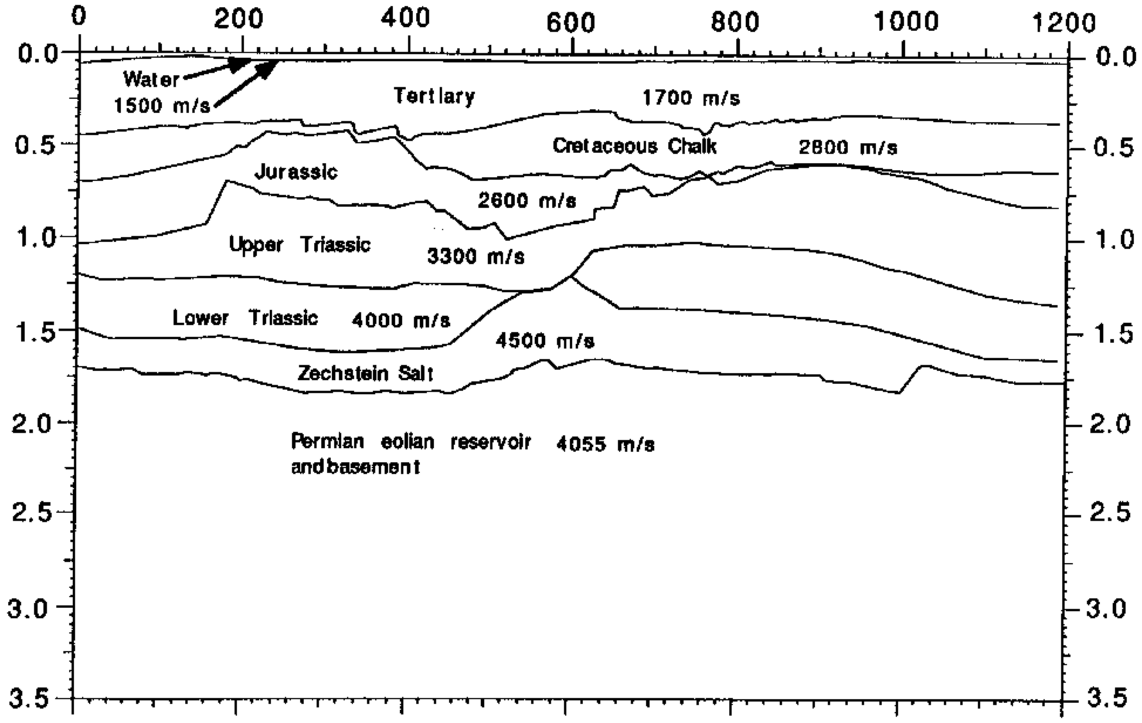

Figure 1: Geological in-line section and corresponding velocities of layers. From (Hanson and Witney, 1995). biondo2-geoltr [NR]

velocity model was derived by a tomographic procedure that used a 3-D migrated volume to define lithological boundaries (Hanson and Witney, 1995). The velocity model can thus be used as an indirect check of the geometric correctness of the migrated images; that is, that common-azimuth migration correctly positions in depth the reflectors.

The velocity model was the same for both the 3-D and the multi-line 2-D migration. In both cases I used five reference velocities in the PSPI algorithm. Preliminary tests showed that, if only three reference velocities were used in the PSPI algorithm, migration would poorly focus the reflectors. Possibly, it would be beneficial to increase the number of reference velocities even further; more tests in this direction are needed. For downward continuation, the interval velocity was linearly interpolated to the dense sampling of the image (8 m depth, 9.75 m in-line, 25 m cross-line) from a sparser grid (40 m depth, 187.5 m in-line, 200 m cross-line). No smoothing was applied to the interpolated velocity.

Migration results

The superposition of the migrated results onto the velocity model (Figure ??) shows that common-azimuth migration successfully imaged the reflectors and correctly po-

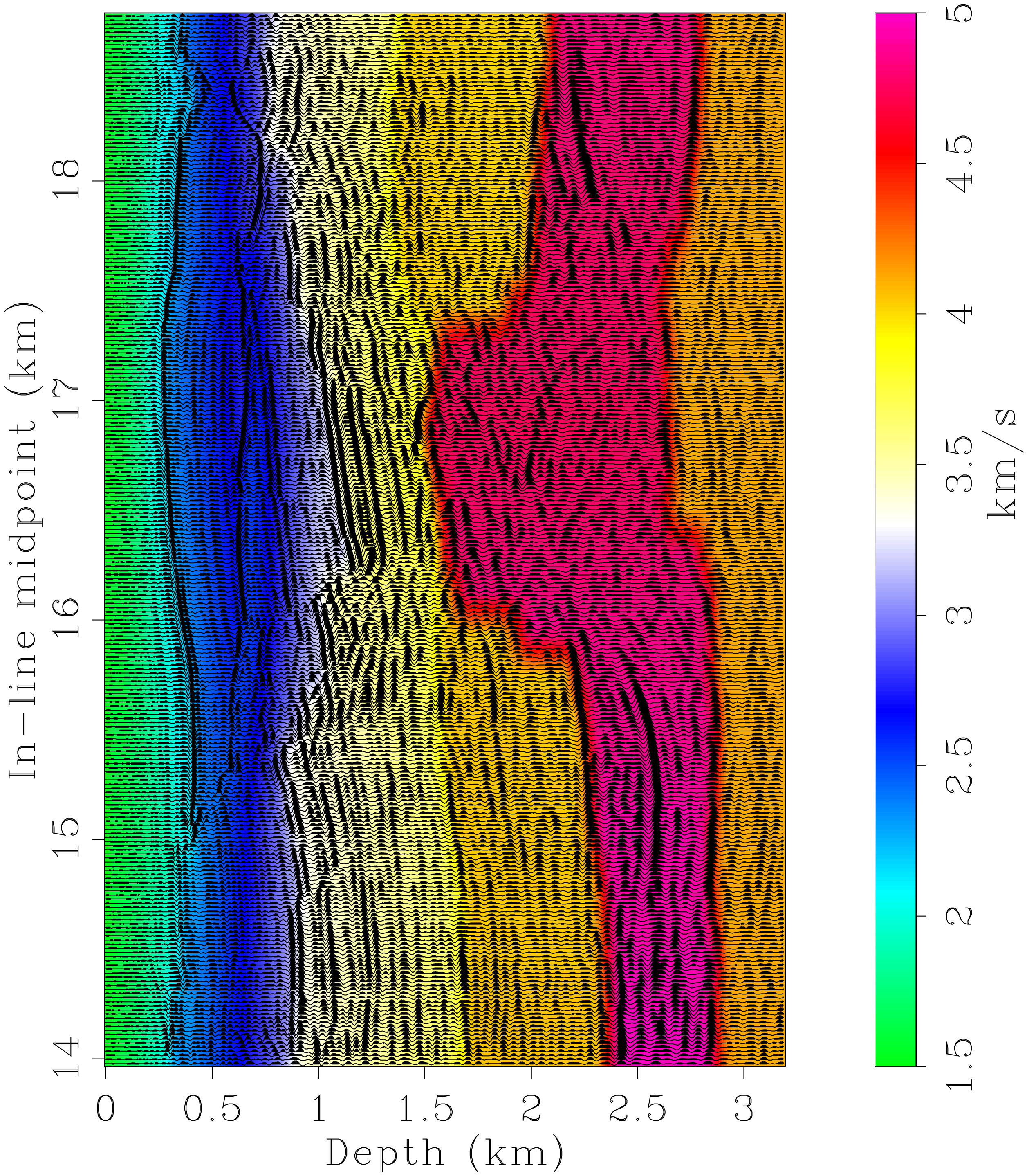

Figure 2: Migrated section superimposed to velocity model (CMP Y=19.8 km) $\boxed{\text{biondo2-veldata19800}}$ [CR]

sitioned them in depth. The migrated salt boundaries overlap quite precisely with the salt boundaries identified by the sharp variations in the velocity model. The target reflectors below the salt layer are also well imaged, though it seems that their focusing could be improved by further refinements of the velocity function. When the same velocity function used for common-azimuth migration was used for 3-D prestack Kirchhoff depth migration small residual moveout corrections of the migrated CRP gathers were required to maximize the image energy.

The accuracy of common-azimuth migration can be analyzed in more detail by plotting smaller sections of the data, and compare the results of full 3-D prestack migration with multi-line 2-D prestack migration. The difference between the two results are mostly visible in the cross-line sections, where the lack of focusing in the multi-line 2-D migration results manifests itself. In the following sequence of figures I show three cross-line sections located at the left-edge, in the middle, and at the right edge, of the central fault system. Figure **??** shows the comparison of the common-azimuth migration (left) and of the multi-line 2-D migration (right) for the same cross-line. The most obvious differences between the two sections are in the reflections from the boundary between the Jurassic and the Triassic formations, located at about 1.1 km in depth. Common-azimuth correctly positioned the lithological boundary, while multi-line 2-D migration mispositioned the boundaries by several hundred meters and did not properly focus the reflector. The lack of focusing in the cross-line direction prevents multi-line 2-D migration from properly imaging the top of the salt layer, visible in Figure **??** at a depth of about 1.6 km. Unfocused diffractions are clearly visible in the multi-line 2-D migration results (right panel in the figure). On the other hand, common-azimuth migration (left) nicely images the roughness at the top of the salt. A similar situation is shown in the cross-line sections of Figure **??**. Common-azimuth migration correctly focuses the diffractions caused by the uneven top of the salt, as well as the diffractions caused by the shallow faults visible at the top-right corner of the sections.

The lack of cross-line focusing in the multi-line 2-D migration is also evident in the depth slices shown in Figure **??**. These depth slices, taken at a depth of 1.096 km, clearly show the reflections from the boundary between the Jurassic and the Triassic formations around the in-line midpoint location of 16 km. This is the same event previously shown in the cross-line sections of Figure **??**. Examining this depth slice we can verify that common-azimuth migration correctly positions the reflection at the true boundary between the formations, while multi-line 2-D migrations mispositions the boundary, even transforming it in a bowtie-shaped event around the cross-line midpoint location of 19 km. The set of faults cutting across the broad reflection located between 16.5 km and 17 km in the in-line direction is also more sharply imaged by common-azimuth migration than by multi-line 2-D migration.

Figure **??** compares the results of common-azimuth migration (top) and multi-line 2-D migration (bottom) when imaging the salt layer and the target reflectors below it. The salt boundaries are fairly well imaged by common-azimuth migration, including the bottom of the salt and part of the salt flanks. I expect that a dip-preserving

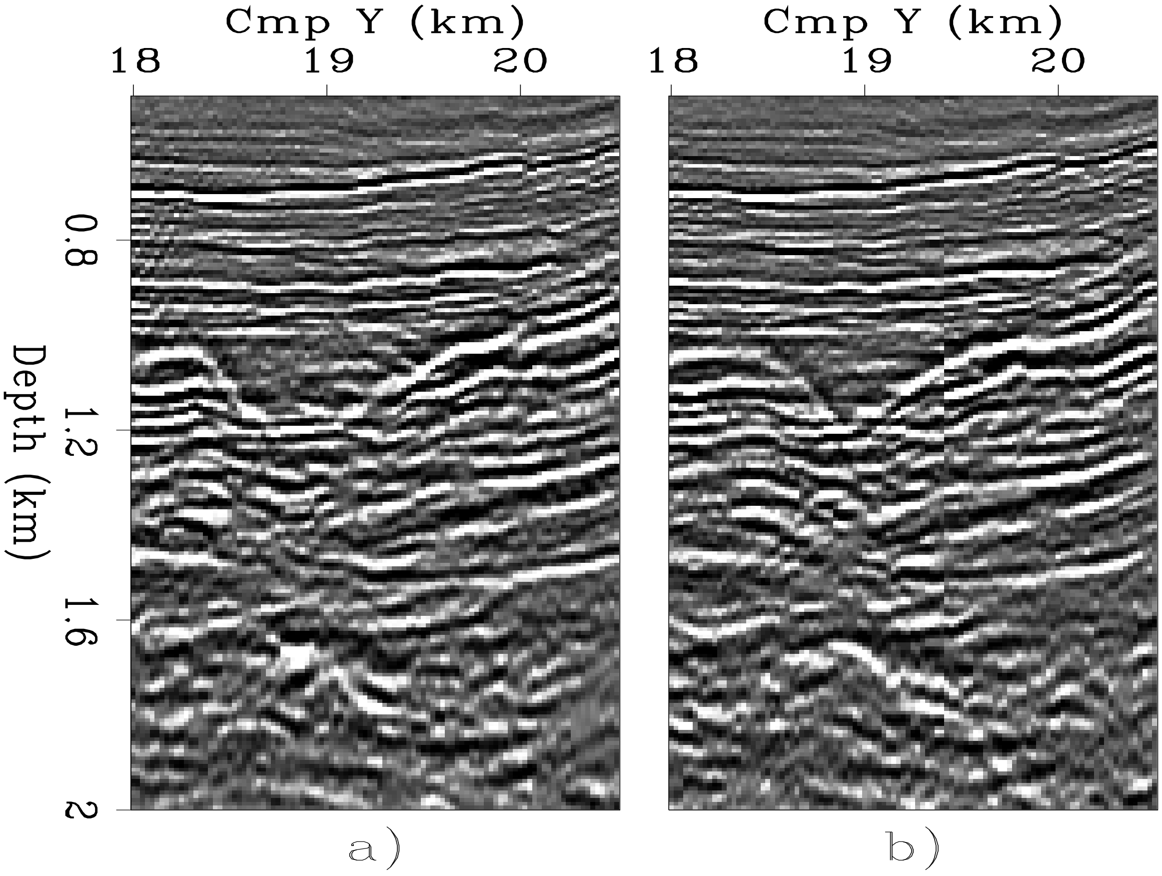

Figure 3: Migrated cross-line sections (CMP X=16.088 km) obtained by a) 3-D common-azimuth migration, b) multi-line 2-D migration. biondo2-x16088 [CR]

transformation to common-azimuth that includes AMO in the processing sequence would improve the imaging of the steeply dipping salt flanks. The reflectors below the reservoir are well imaged, although with uneven amplitudes. Refinements in the velocity model may improve the imaging of these reflectors. On the contrary, the multi-line 2-D migration poorly images the bottom of the salt layer and the reflector below the salt. The salt flanks are almost totally lost in the multi-line 2-D migration image as well. Two effects play a role to cause the large differences between the two migrations when imaging reflectors that have a fairly mild cross-line dip component. First, the large width of the cross-line migration aperture at this depth makes the images very sensitive to cross-line dips. Second, common-azimuth migration correctly takes into account the cross-line velocity variations because it correctly propagates the wavefield in the cross-line direction as well in the in-line direction. On the contrary, multi-line 2-D migration constrains the wavefield to propagate along the vertical in-line planes, and cannot fully honor the 3-D nature of the velocity function.

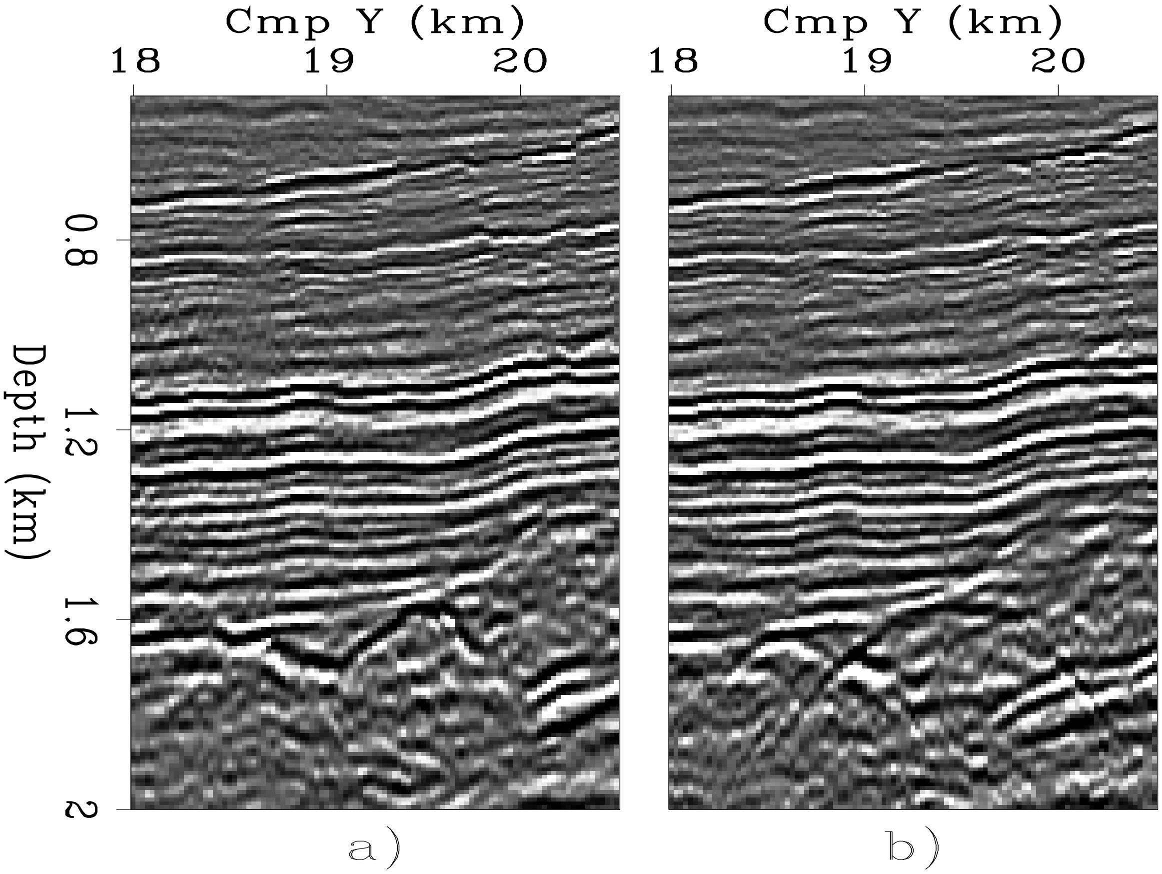

Figure 4: Migrated cross-line sections (CMP X=16.566 km) obtained by a) 3-D common-azimuth migration, b) multi-line 2-D migration. biondo2-x16566 [CR]

CONCLUSIONS AND FUTURE WORK

Common-azimuth migration was successful in prestack depth imaging a 3-D marine data set recorded over a complex geological area. The results presented in this paper showed that common-azimuth migration is a viable method for efficient full-volume imaging of modern 3-D marine data sets. Further improvements in the migration results are expected when AMO, instead of simple binning, is used to transform the recorded data to "effective" common-azimuth data prior to migration.

The encouraging results from the test presented in this paper open new promising directions of investigation. Because of the potential advantages of downward continuation methods in handling multi-pathing, it would be worthwhile to develop a comparative study of the accuracy of common-azimuth migration and Kirchhoff migration in presence of multi-pathing. Further, a generalization of depth-focusing velocity analysis to 3-D marine data would yield a velocity estimation methodology that might have wide applications to the data sets for which common-azimuth migration proves to be accurate.

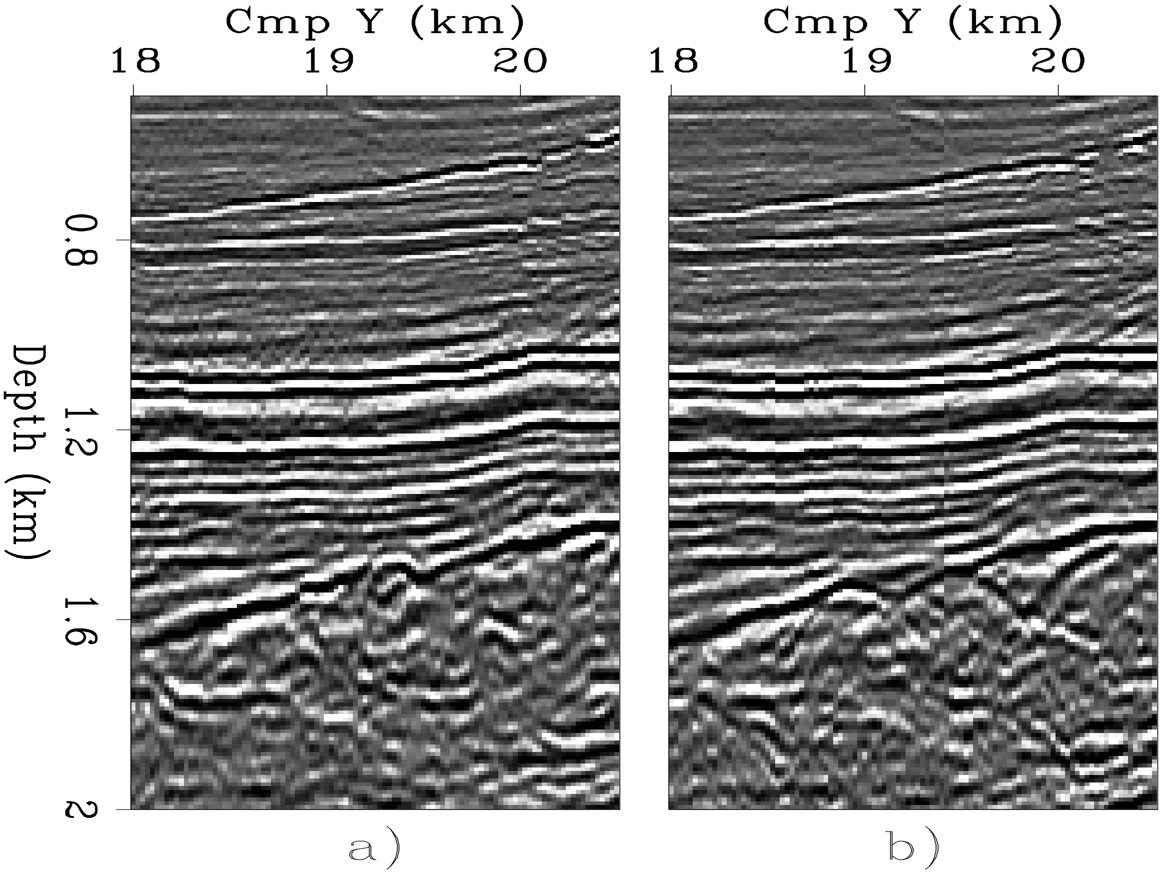

Figure 5: Migrated cross-line sections (CMP X=16.82 km) obtained by a) 3-D common-azimuth migration, b) multi-line 2-D migration. biondo2-x16820 [CR]

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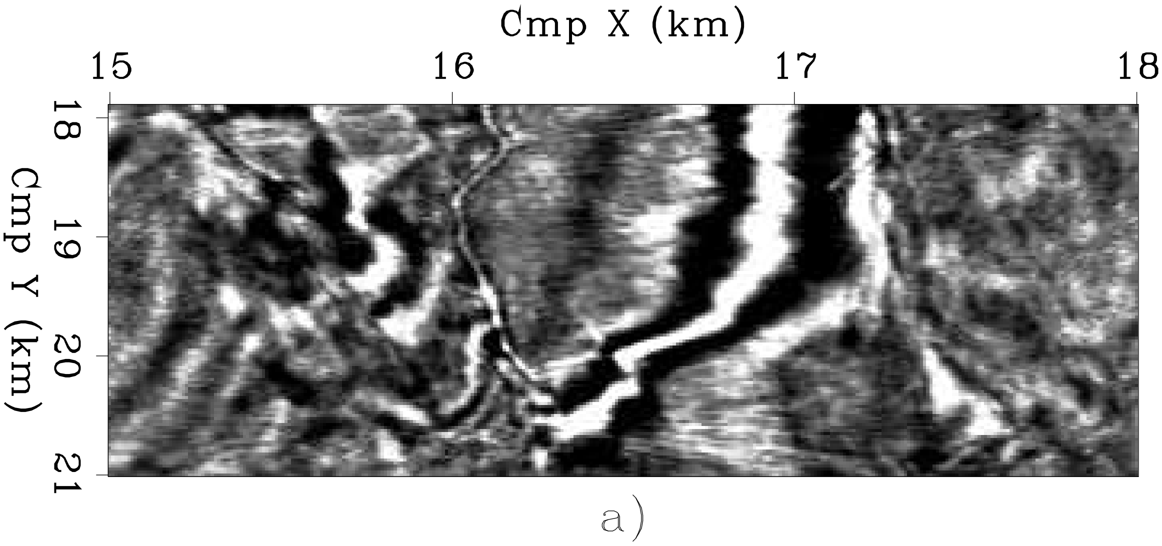

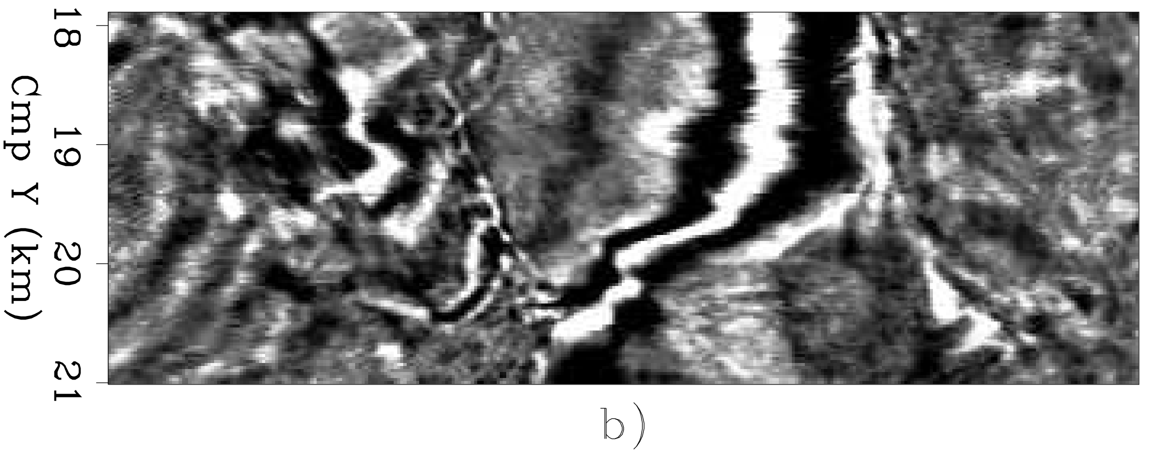

Figure 6: Migrated depth slices (Z=1.096 km) obtained by a) 3-D common-azimuth migration, b) multi-line 2-D migration. biondo2-z1096 [CR]

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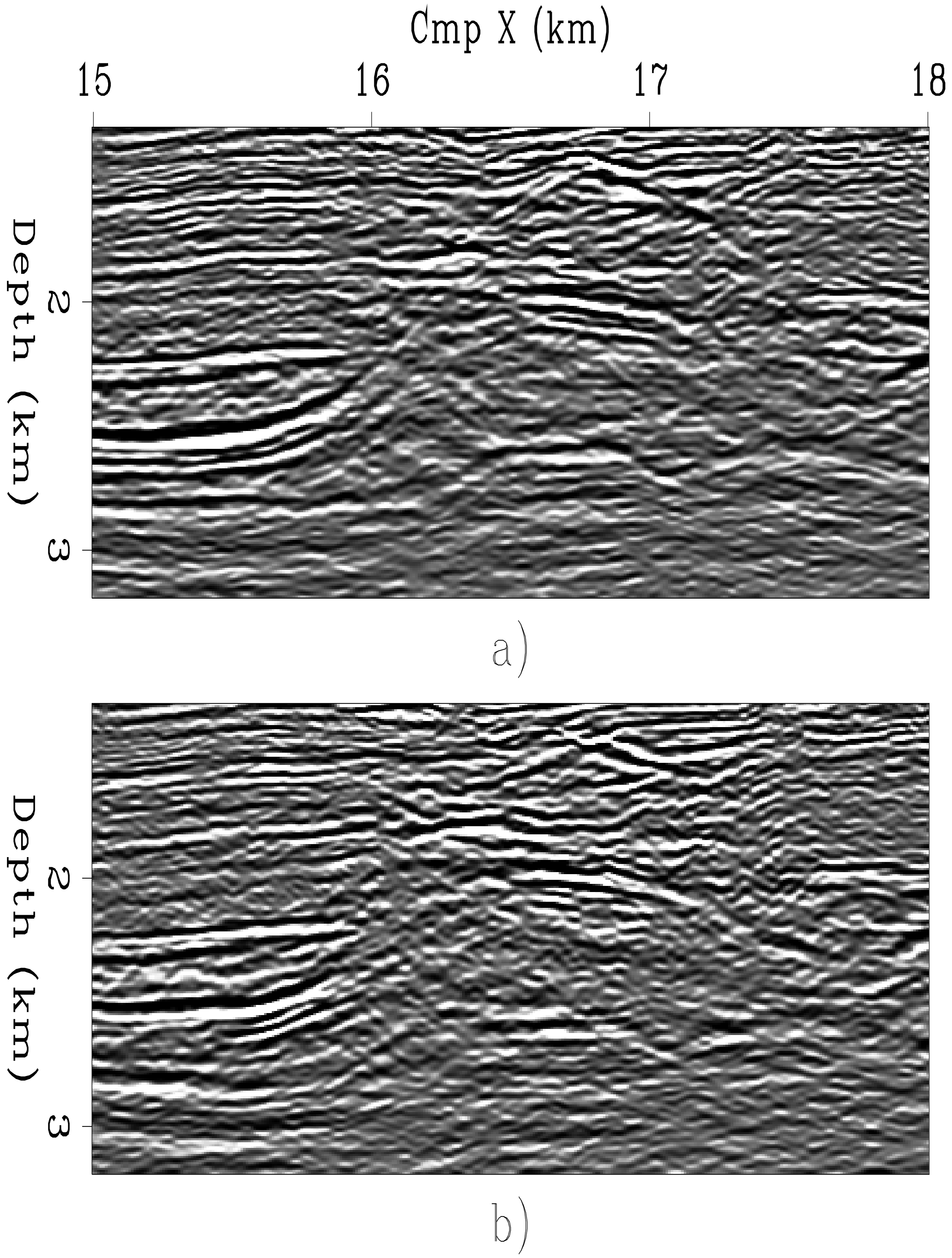

Figure 7: In-line sections (CMP Y=20 km) obtained by a) 3-D common-azimuth migration, b) multi-line 2-D migration. $\boxed{\text{biondo2-y20000}}$ [CR]

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