Advances in subsurface imaging technology boost the search for elusive hydrocarbons

Frank Dumanoir,[1] Bin Wang and Simon Baldock, TGS (Houston) review the development of today's highly sophisticated seismic data processing and imaging technology and discuss the challenges ahead.

The remarkable improvements in data quality due to rapid advances in processing algorithms and computer technology over the past several years have been nothing short of phenomenal. The provision of 3D data cubes processed through pre-stack depth migration has given explorationists the ability to analyze and look for elusive reservoir targets in ever more complex geologic settings.

As in any complex scientific endeavor, many elements from different disciplines contribute to the overall goal. It is the synergy among diverse technologies, a foundation of experience and economic need that have driven and continue to fuel the search for understanding.

This article highlights a few of the key ingredients that have made the task of finding and producing hydrocarbons possible in previously unexplored areas. It is neither exhaustive nor deeply technical but merely provides a few examples of the progress made on depth migration processes, tomography, anisotropy, multiple prediction and attenuation, and velocity model building.

Depth migration processes

Certainly, the key area that has had the most effort and has achieved the greatest visibility in the past few years has been the substantial advancement in migration techniques. Combining migration techniques to efficiently address different and conflicting geophysical problems is now almost routine.

In their excellent paper, 'Seismic Migration Problems and Solutions', Sam Gray et al. (J. Etgen, J. Dellinger, D. Whitmore, www.seismo.unr.edu/ftp/pub/louie/class/757/migration-probs.pdf), the authors provide a historical perspective of the development of competing techniques and the relative merits and shortcomings of each in the ability to image the subsurface. The industry has evolved from advocating the use of one method over another to a philosophy of inclusion. We no longer defend Kirchhoff vs. wave equation, choosing instead to do both. This evolution is a direct result of plummeting computer costs.

Migration has evolved from being an expensive add-on option at the end of a (time) project to the step taking the lion's share of time and cost in any 3D processing project. It is now an integral part of building and refining the final result. It has revolutionized how a project is conducted by becoming an iterative process requiring the input of the processor as well as the interpretation of the earth scientist. The latter's input and understanding of the geologic framework are critical in the overall project flow and key to obtaining better results when interpreting interim image volumes in the elaboration of velocity models.

These days, imaging teams cannot rely on just one algorithm to provide an acceptable result. The present day tool box must have Kirchhoff based migration, which remains the workhorse of 3D PSDM. The key here has been the constant refinement of the algorithm to improve the accuracy of results and efficient handling of travel time tables. This is still the migration of choice for imaging steep dips and overhangs while maintaining adequate bandwidth of the seismic signal.

The beam migration variants of Kirchhoff have been around and discussed for a long time in the seismic industry. It is only in the last two or three years that they have become the tool of choice to quickly iterate data volumes in order to build velocity models in a reasonable time and at low cost. The Gaussian beam migrations can yield excellent results. This is an elegant solution to address the multipathing limitations of the conventional Kirchhoff algorithm with little or no penalty in the ability to image steep dips and turning waves while maintaining the target-oriented capabilities. This makes Gaussian beam migration an extremely versatile algorithm.

The faster versions, or fast beam migration algorithms, have to be used with care in order to neither overly influence the result nor risk removing primary energy. The interpreter has to be careful not to inject too much *a priori* information and end up with a result that is not data-driven.

There is no question that fast beam migrations have provided a significant leap forward in the quest for a quasi real-time interactive velocity model-building tool. This leaves little doubt that in a very short time (within a year?) we will have enough computing power within a workstation environment to allow the fast running of multiple 3D PSDM iterations. This gives the interpreter the ability to test numerous geologic hypotheses in days rather than weeks.

Wave equation migration algorithms have traditionally been the Great Hope for imaging, but high run-time costs

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and dip limitations have often overshadowed the technique's inherent ability to use exact velocity models to image subsalt events. This is clearly demonstrated in Figure 1. Wave equation migration is not affected by the multipathing problem that the Kirchhoff faces in salt areas and is able to handle high velocity contrast such as across salt/sediment boundaries. One of the limitations of wave equations, related to the geometric cost increase with frequency bandwidth, has been used to some advantage in model building iterations for complex salt geometry interpretation. These typically can be limited to 20 Hz bandwidth and still generate interpretable images of the salt interface.

It was not until fast implementations of wave equation migrations in 2003 that 3D wave equation PSDMs could be run in a reasonable time and at an acceptable cost. The efficiency came from combining point-source wavefields to form a line-source or area-source wavefield. This allowed full-volume 3D migrated cubes to be generated for velocity model building, definitely an advantage over the Kirchhoff target-line approach, which due to cost constraints was often too coarsely sampled to develop detailed velocity models. For velocity analysis, the imaging goals are different in that analysts are looking for image quality differences between velocity models.

In salt prone areas, the much shorter cycle time to get migration iterations has made running so-called subsalt WEM scans a reality. These are the modern equivalents of the old velocity scans used to pick velocities on land data. Using the 3D PSDM cubes migrated at a series of velocities at varied percentages around a reference velocity, the data is reinterpreted and the picks used to update the velocity model. This approach is especially useful when the subsalt signal is weak or subsalt events do not have enough aperture (or angle range), making the prestack picking of depth residual move-out (DRMO) unreliable. This provides a more accurate subsalt velocity model which can in turn be used in subsalt tomography.

Figures 2 & 3 selected from a suite of eight migration scans, clearly show that the original 100% velocity field was not ideal in focusing energy below the salt and that the 85% velocity field shows better sediment stack quality. In certain areas under the salt, the WEM scan method can be used to output gathers from data migrated at varying percentages around a reference velocity. Figure 4 illustrates how the gathers can be used to derive a more accurate velocity.

No discussion of depth migration algorithms would be complete without mentioning two-way wave equation migration or reverse-time migration (RTM), which is looked upon as the Holy Grail of migration. While theoretically the best method, cost remains one of the biggest handicaps. While initial results confirm the promise of this method, careful implementation is needed to avoid migration artifacts. It is also very unforgiving if the velocity is not known to a high degree of accuracy. This sensitivity of RTM to velocity accuracy could be explored in the future to develop a more accurate velocity model.

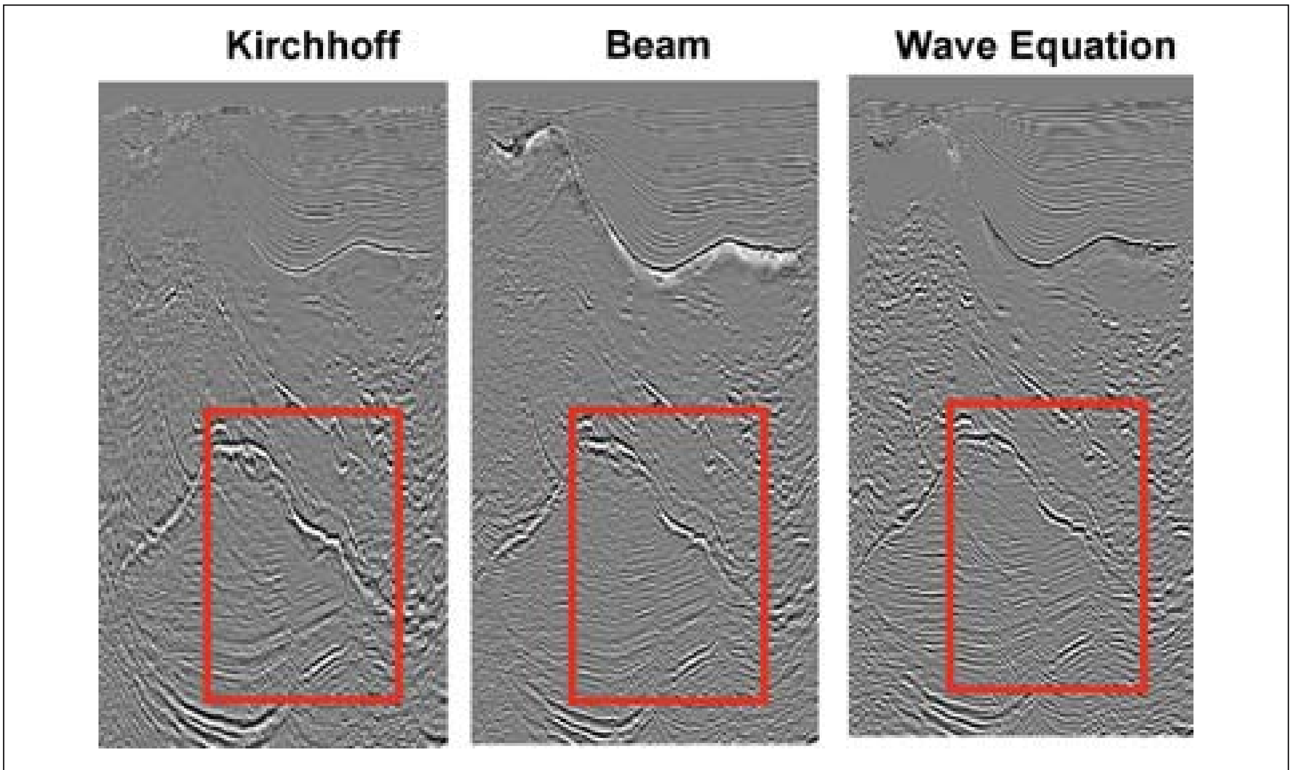
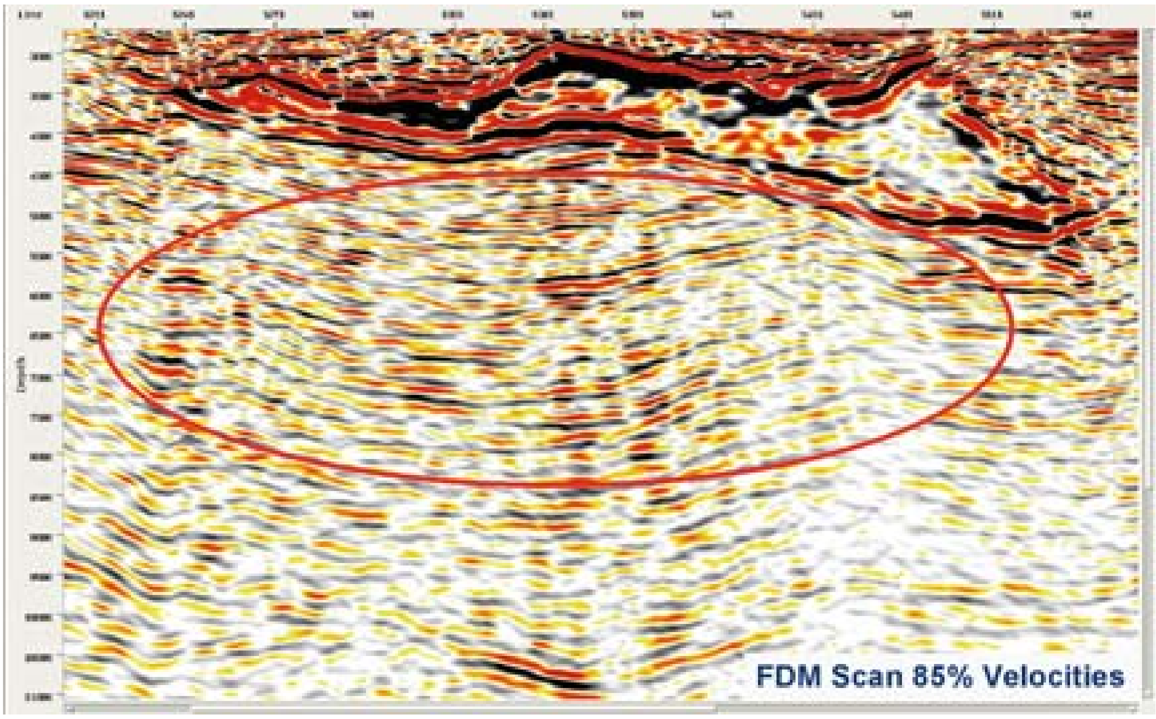


Figure 1.



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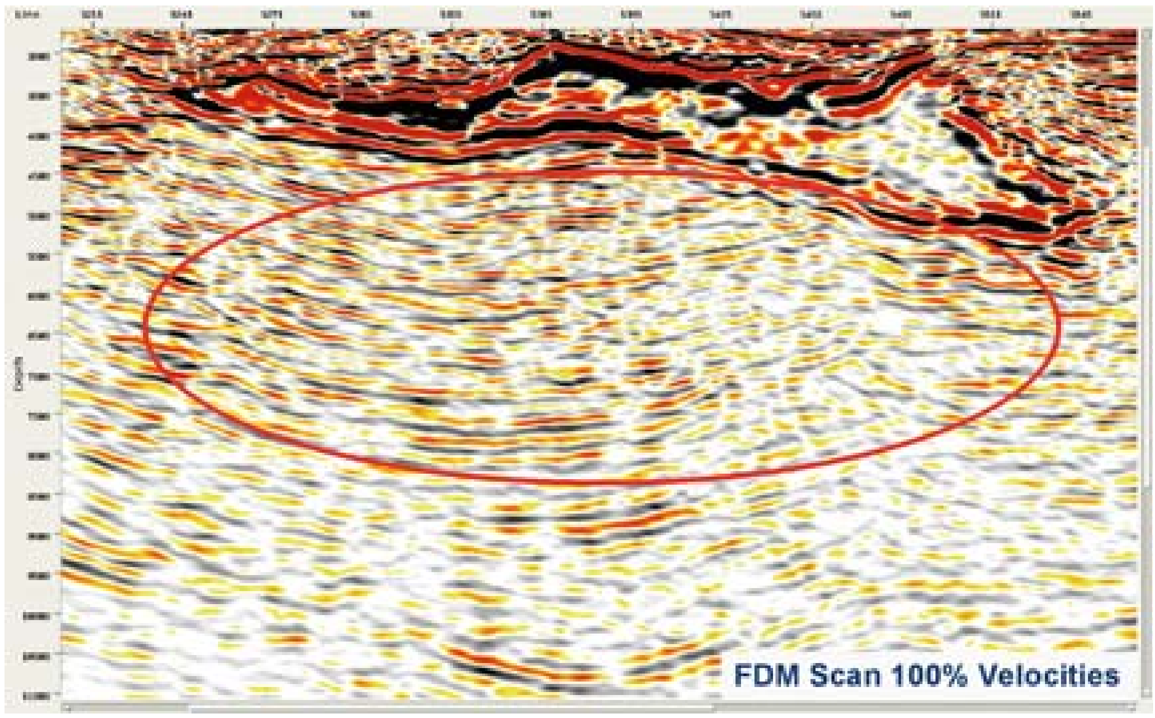

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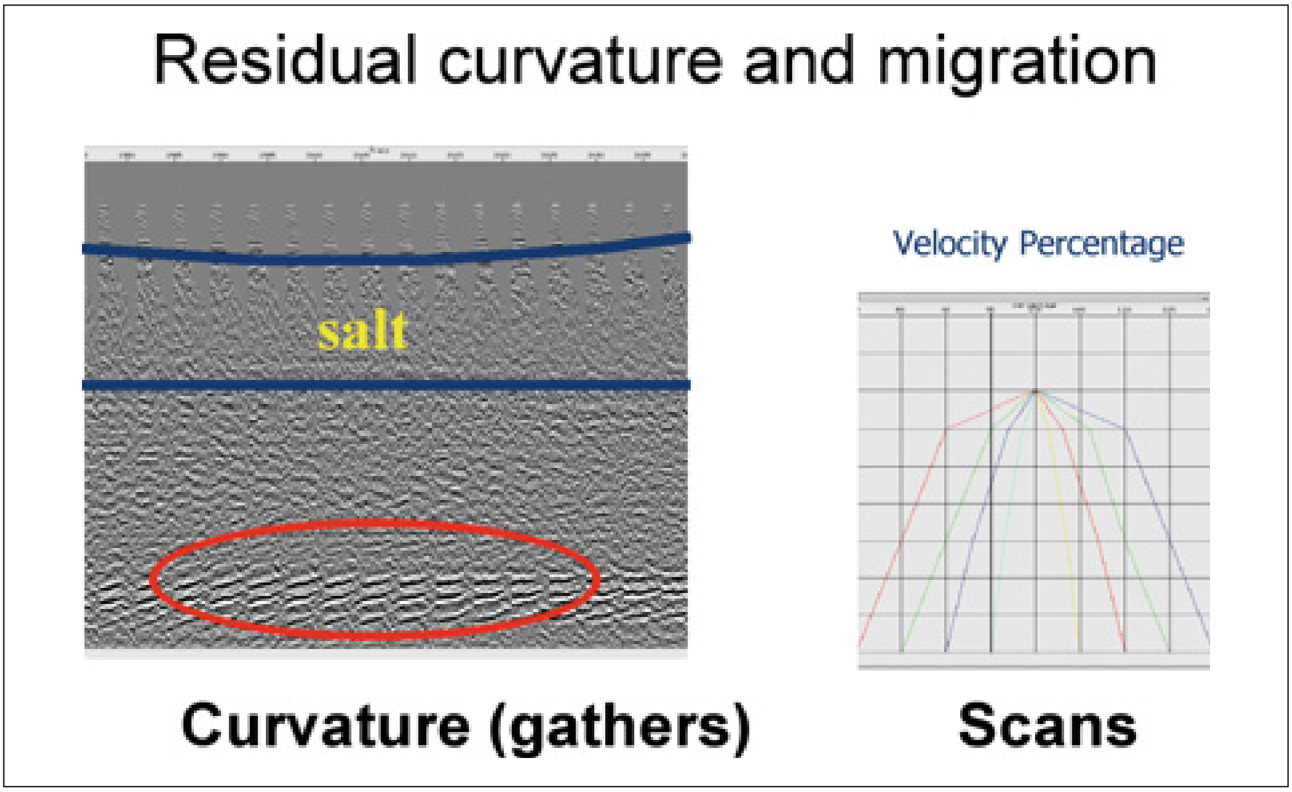

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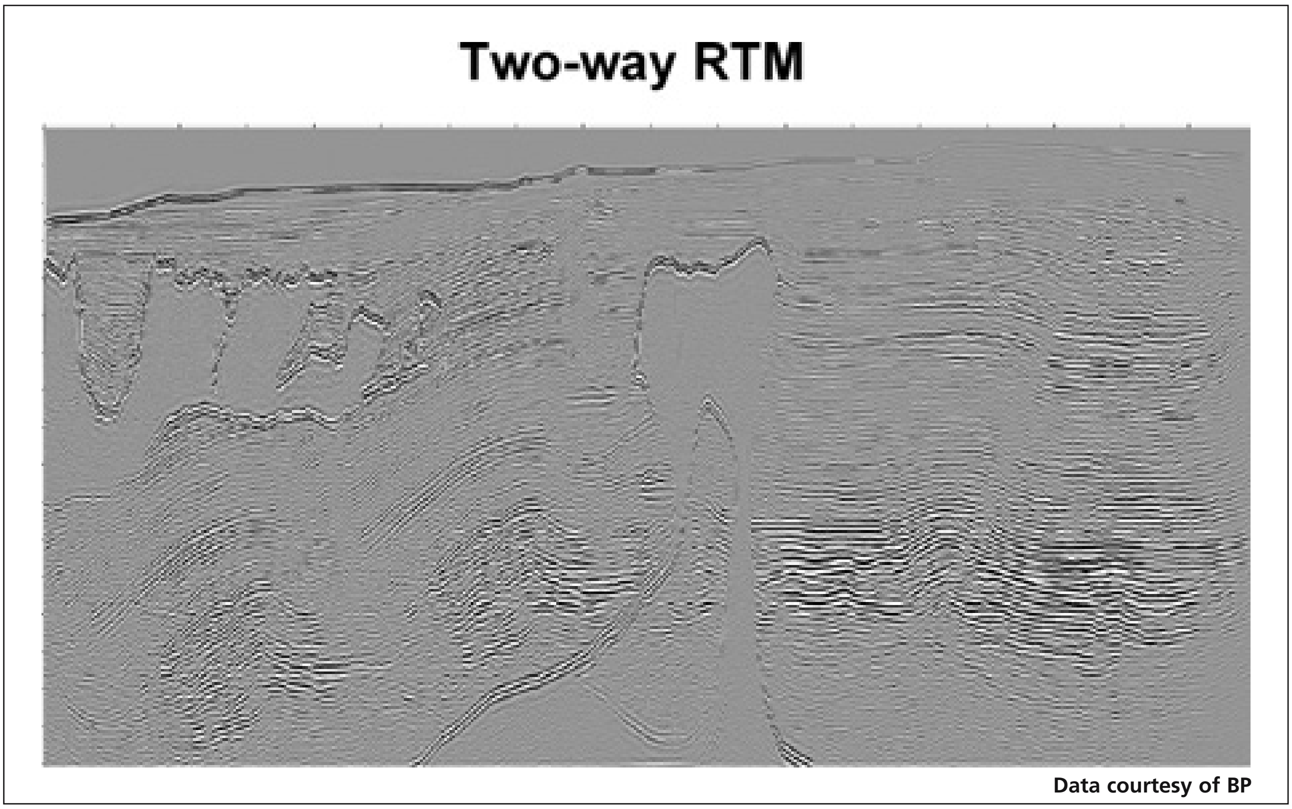
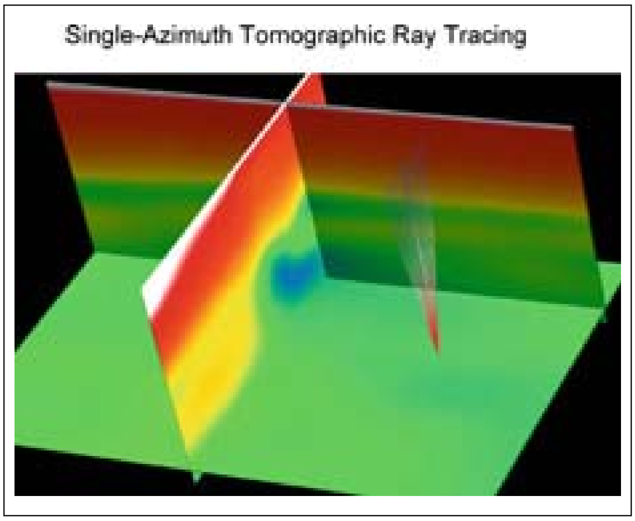


Figure 5.

Tomography

Volume-based, automated, high-resolution (grid) tomography has become an absolute necessity for accurate velocity estimation for PSDM. While it has been a standard part of depth imaging flows and velocity updating for several years, its use has been largely confined to refining the 3D velocity model in the supra-salt sediments. Using a multi-scale, iterative approach, long-wavelength features of velocity anomalies are derived first. Then, short-wavelength anomalies are gradually added from subsequent iterations.

Much effort has been aimed at reducing the grid size so that cells are small enough to sample shallow anomalies. A major advantage is to come up with a velocity model that takes into account anomalies, such as shallow gas clouds, which could have a strong impact on the deeper imaging.



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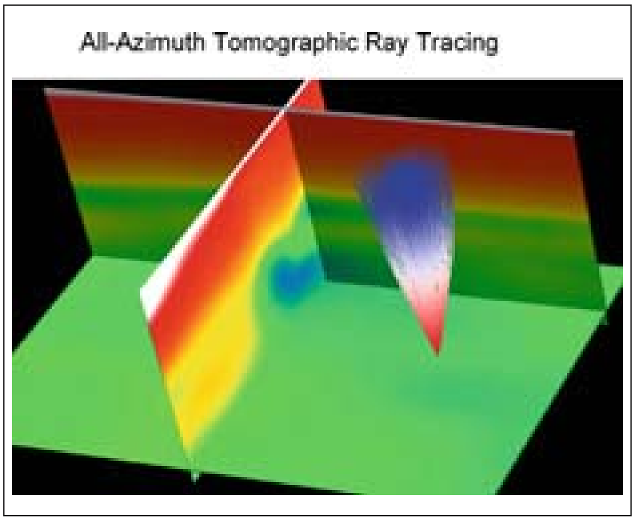

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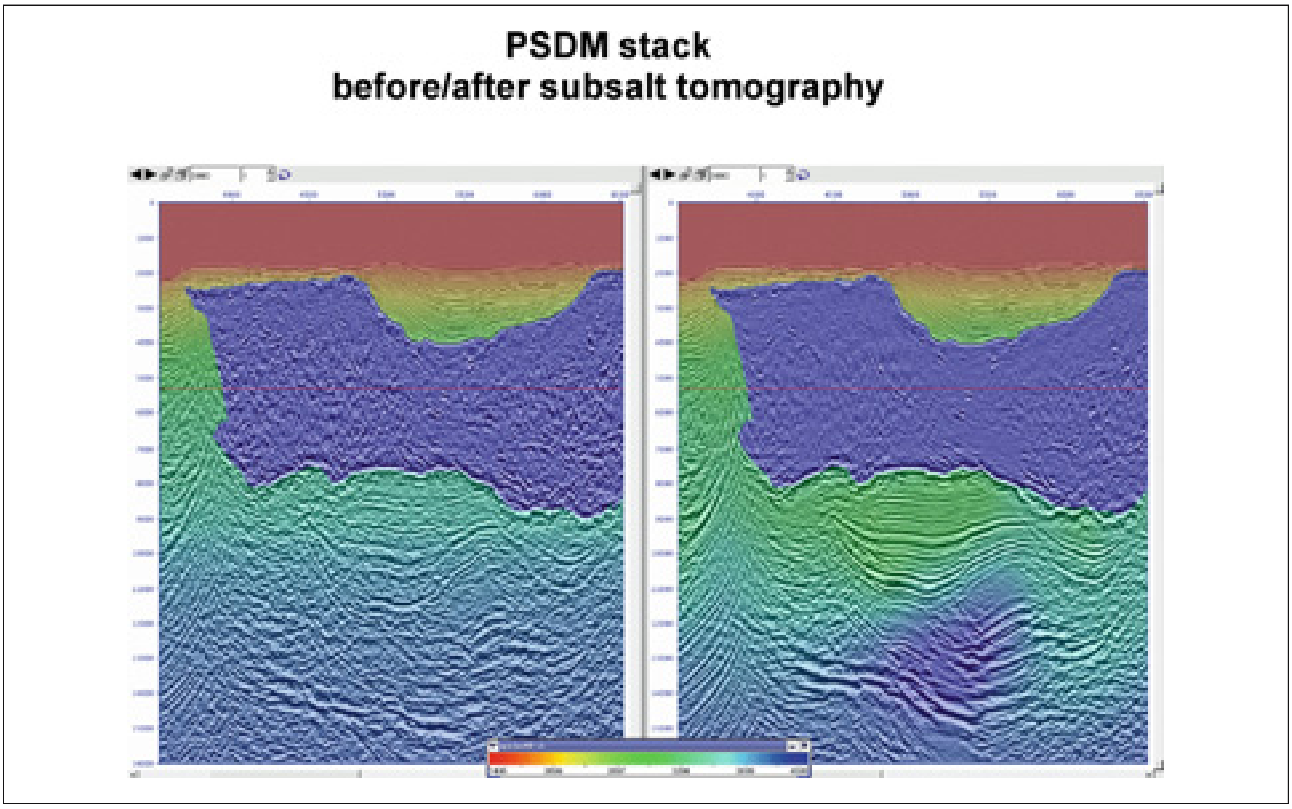


Figure 8.

Most approaches have to mask out the salt and its influence on raypaths in order to converge on a solution. The problem has been that the velocities below and around salt bodies are critical to the building of an accurate model. With the increasing use of wide azimuth acquisition techniques, it becomes necessary to go to all-azimuth ray tracing instead of the traditional single-azimuth ray tracing (Figures 6 & 7). This is especially suitable and perhaps necessary for OBC surveys and the emergence of wide-azimuth/multi-azimuth marine acquisition techniques. Figure 8 shows examples of subsalt tomography and the result on the enhanced subsalt image in the Gulf of Mexico.

Anisotropy

The quest continues on many fronts to refine algorithms to make them quicker and better able to cope with complex geology. A case in point is anisotropy. Today's state-of-the-art migration algorithms are able to take anisotropy into account. One of the challenges is the anisotropic parameter estimation. The key has been the ability to estimate Epsilon and Delta using scan methods extrapolated from known reference points provided by well logs. Auto-picking is then used to adjust the velocity field accordingly.

This is probably one of the more frustrating aspects of processing faced by interpreters and, particularly, development geophysicists, who often find that their wells don't match the seismic, being anywhere from 5% to 15% off. The seismic is usually too deep, which has important financial implications, especially when imaging smaller traps in greater relief. Figures 9 and 10 show examples of an Epsilon and Delta cube scan, and the method is used to auto-pick the 'ε' and 'δ.' Results are shown using a specially modified version of the SEG-EAGE 3D model. The final anisotropic WEM images using the exact model and the estimated model from Epsilon-Delta scans are extremely close (Figures 11 and 12).

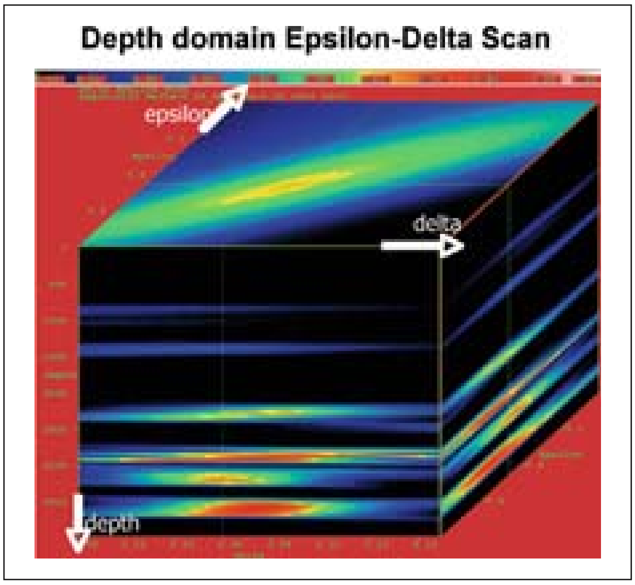


Figure 9.

Multiples

If only processing and accurate imaging simply required migration! Unfortunately, nature is not so simple or kind to us. Any migration effort will be wasted if the frontend processing of the data is not able to improve the S/N ratio to an acceptable level and--most importantly--attenuate if not completely eliminate the multiple energy inherent in any real data. There are basically two main tools available today to address this: SRME and Radon.

Two ways in which the industry is trying to come up with 3D multiple prediction are:

- Purely data-driven convolution-based 3D SRME
- Wavefield extrapolation based 3D multiple prediction

Even with advances in 3D SRME implementation, the technique is able to reduce the multiple content to manageable

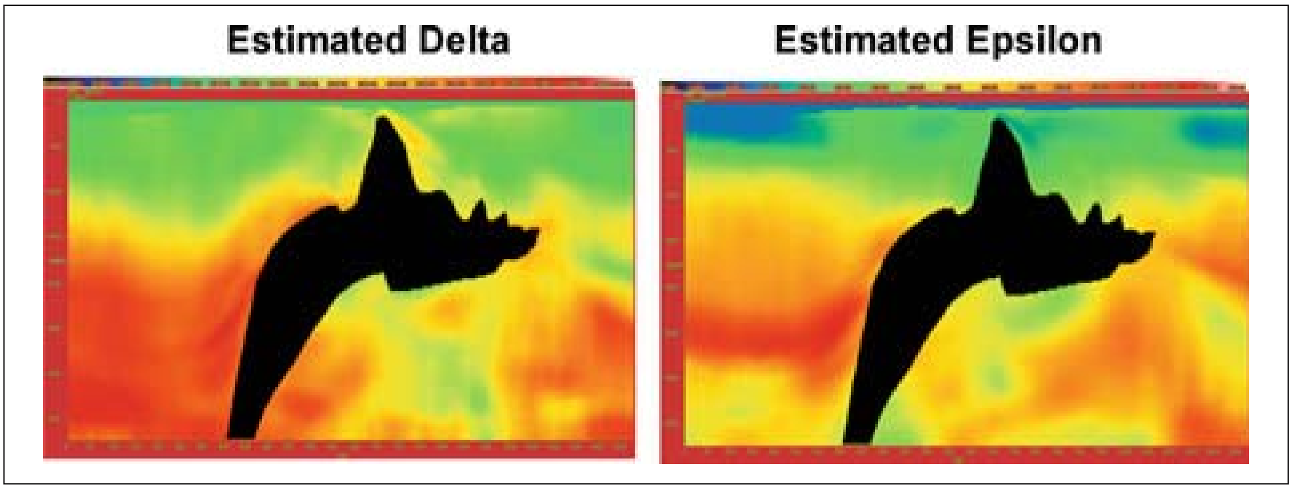
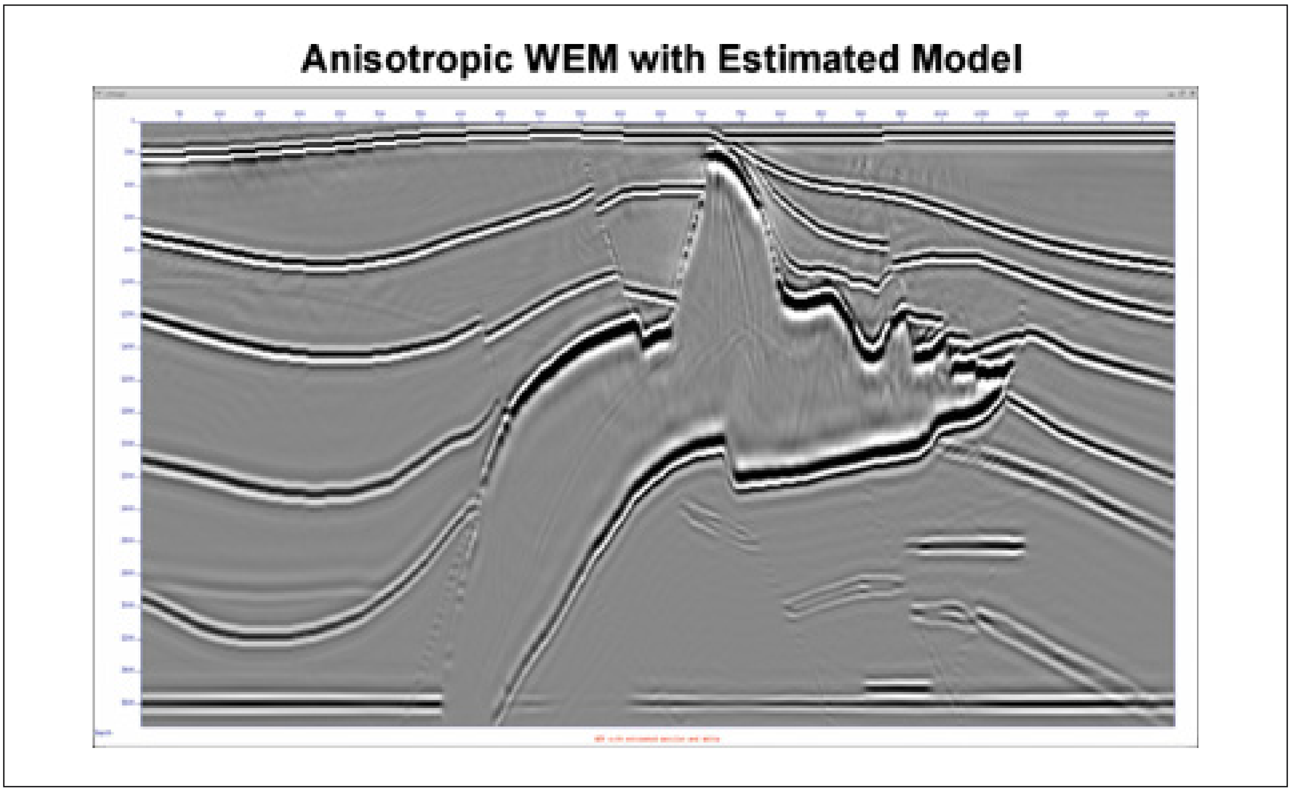


Figure 10.



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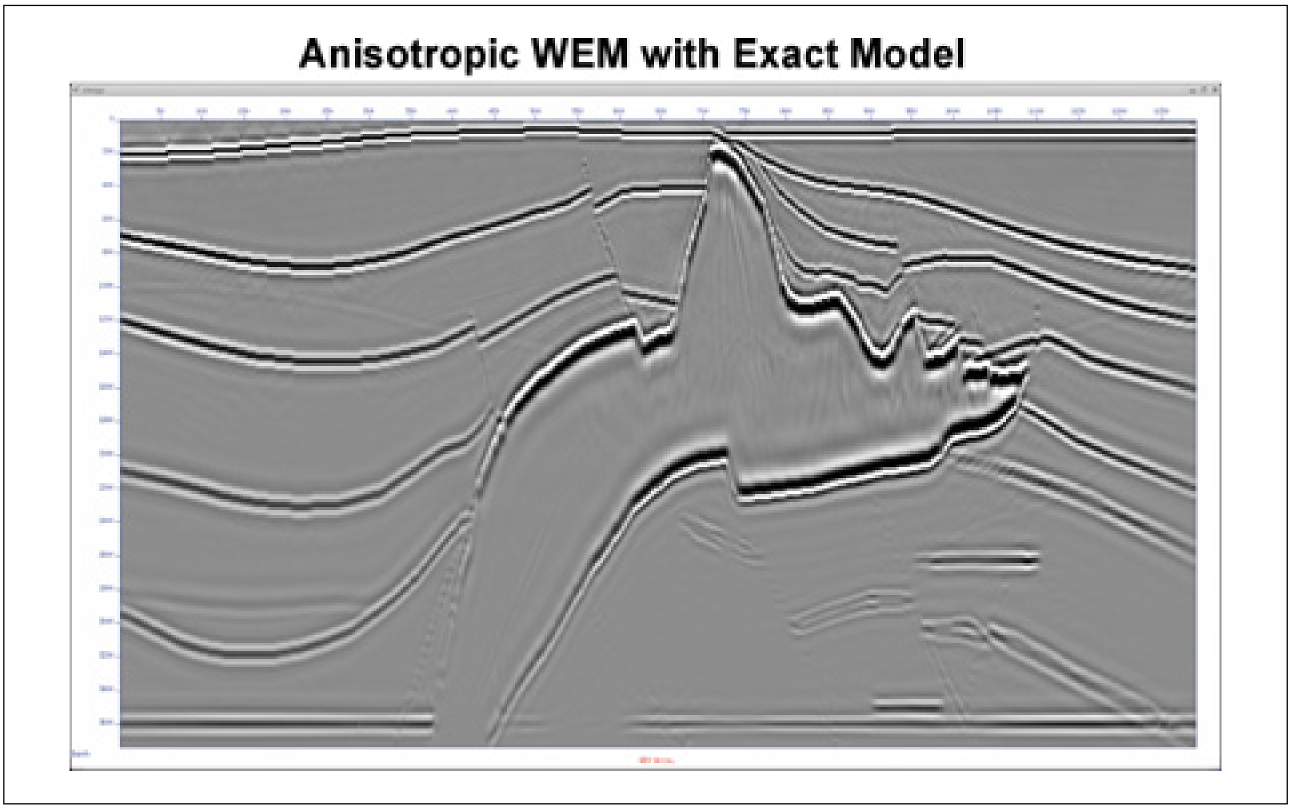

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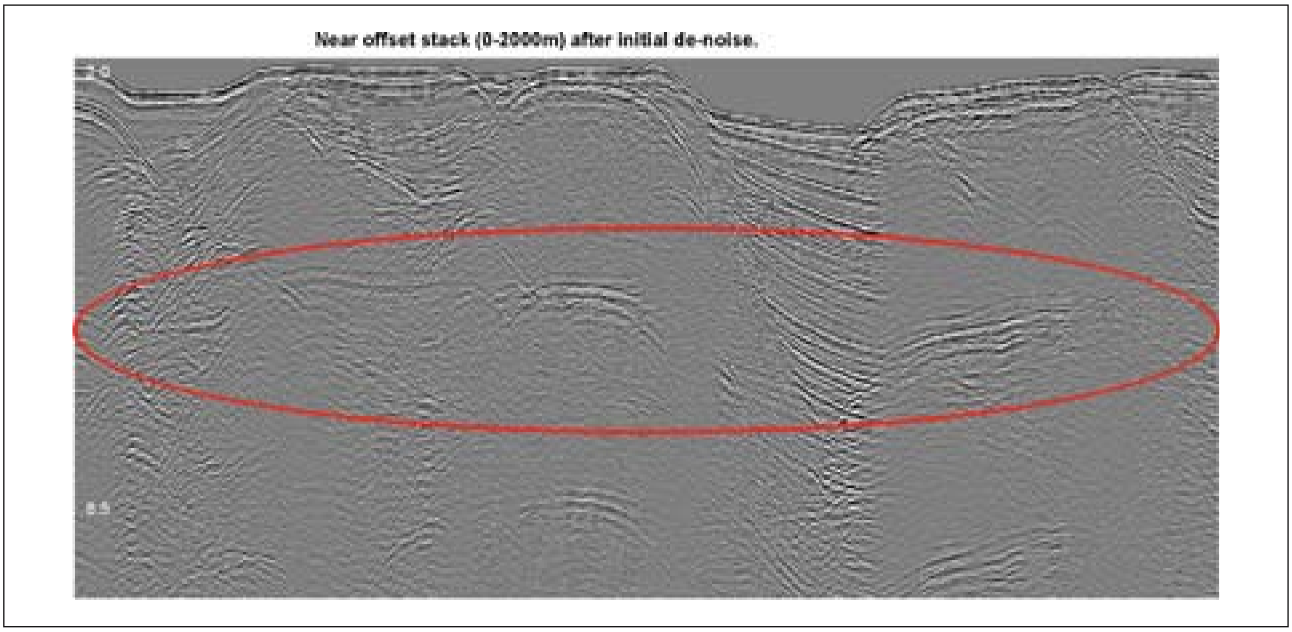

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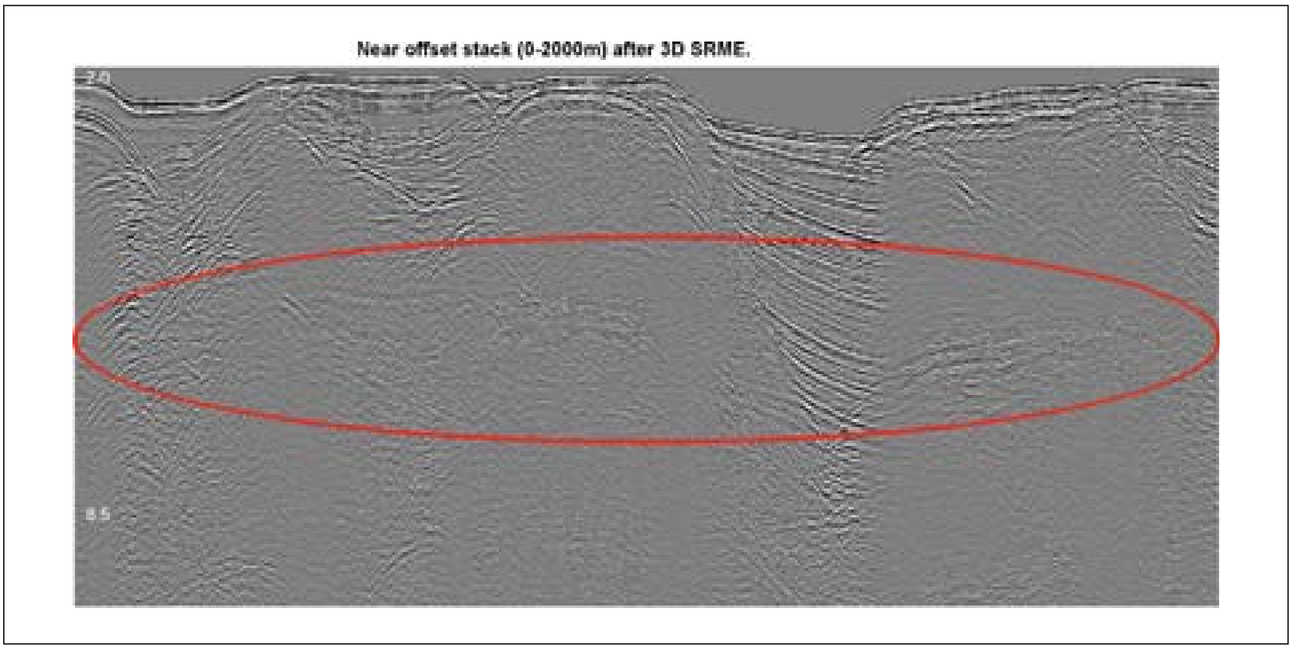
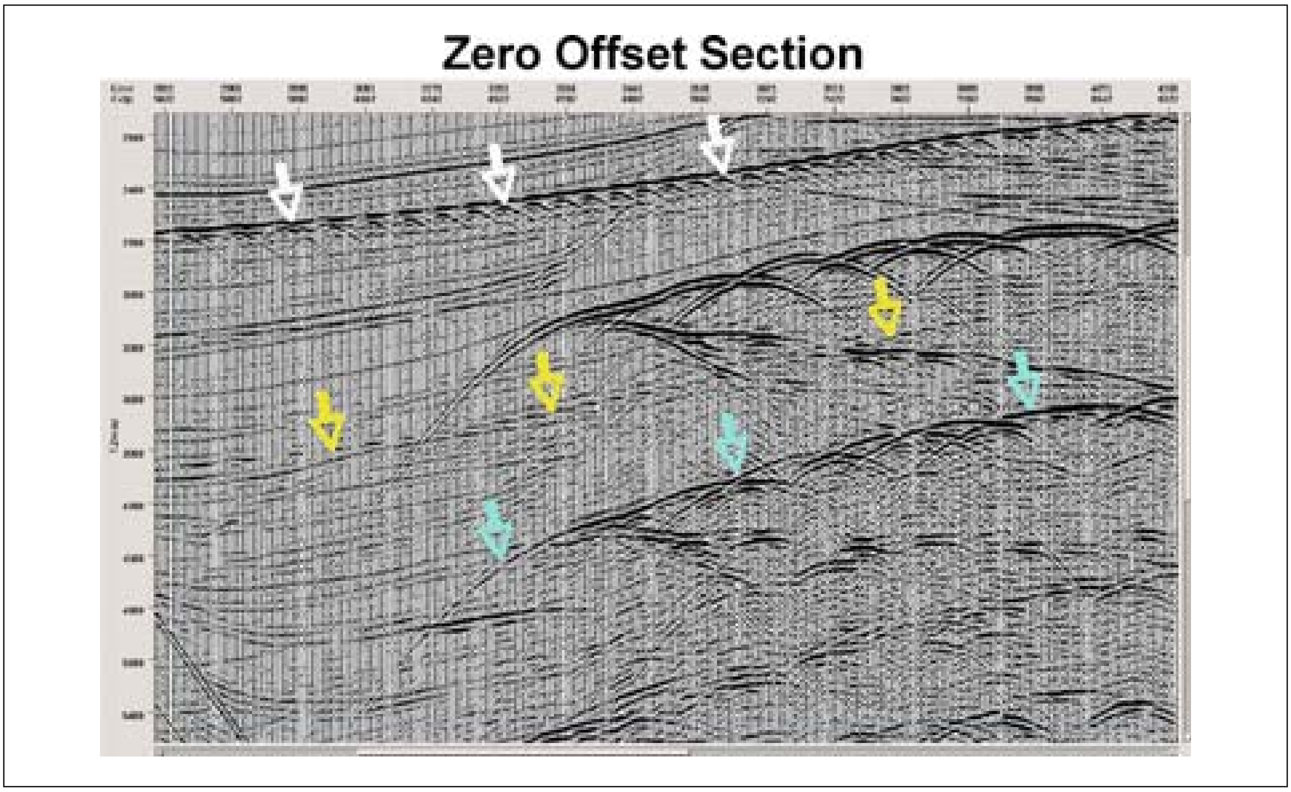


Figure 14.

levels only when used in conjunction with some other methods. The data-quality problem is exacerbated in salt-prone areas where data is masked underneath the salt formations or spurious signals are generated that must be dealt with before any velocity and migration work can be done (Figures 13 and 14).

A promising new area being explored is multiple modelling by wavefield extrapolation. The following figures show examples of multiple attenuation on synthetic data using wavefield extrapolation.

The promise of this method in the handling of difficult multiple contamination in data is also expected to become a more important factor as wide-azimuth and multi-azimuth data become more prevalent. WFE applied in the common-shot domain provides an accurate and efficient way to attenuate surface-related multiples (Figures 15 and 16). This is especially the case for wide-azimuth acquisition, where 'supershots' can be built by collecting together the many individual shots fired in a common location.



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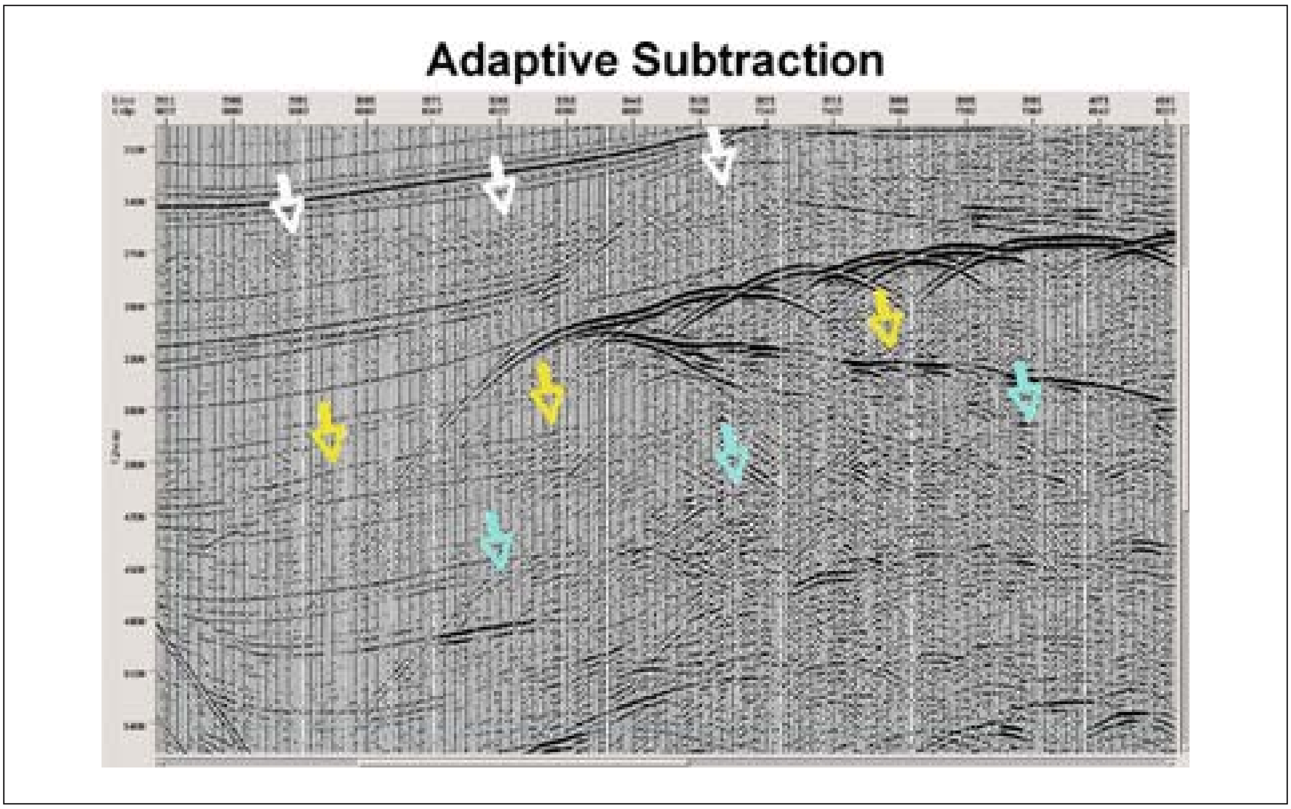

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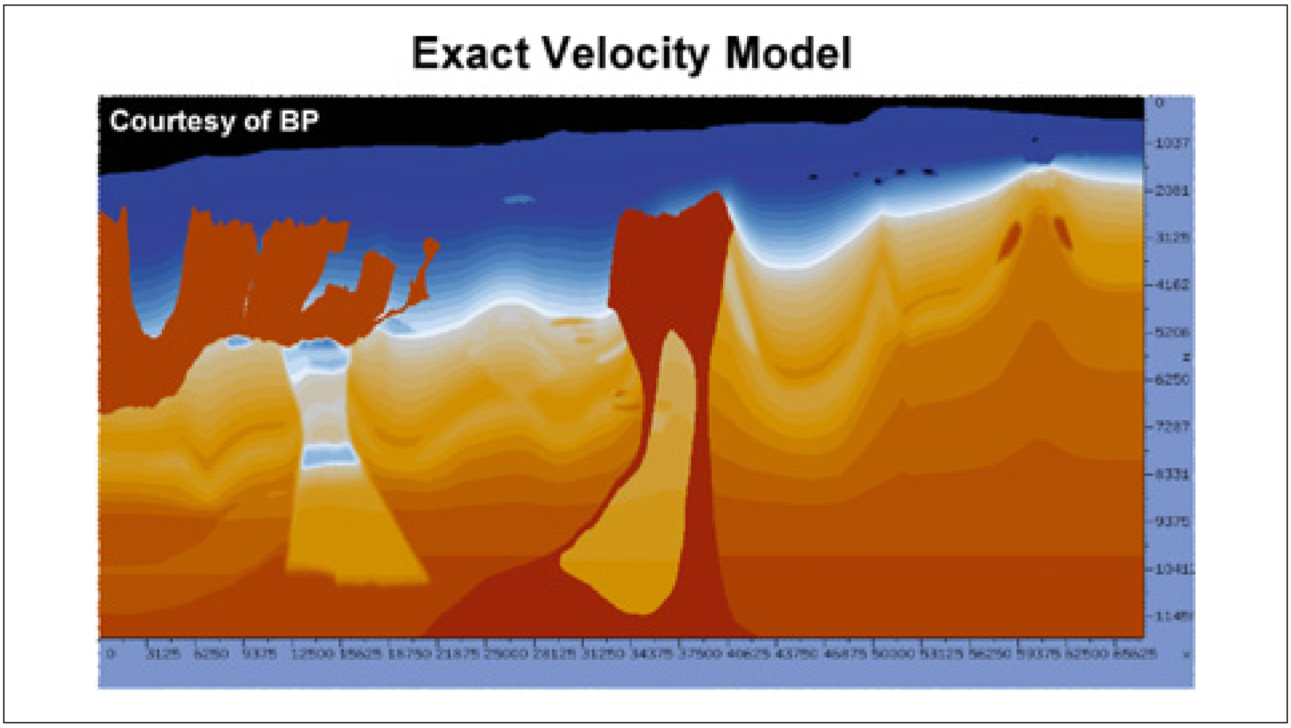

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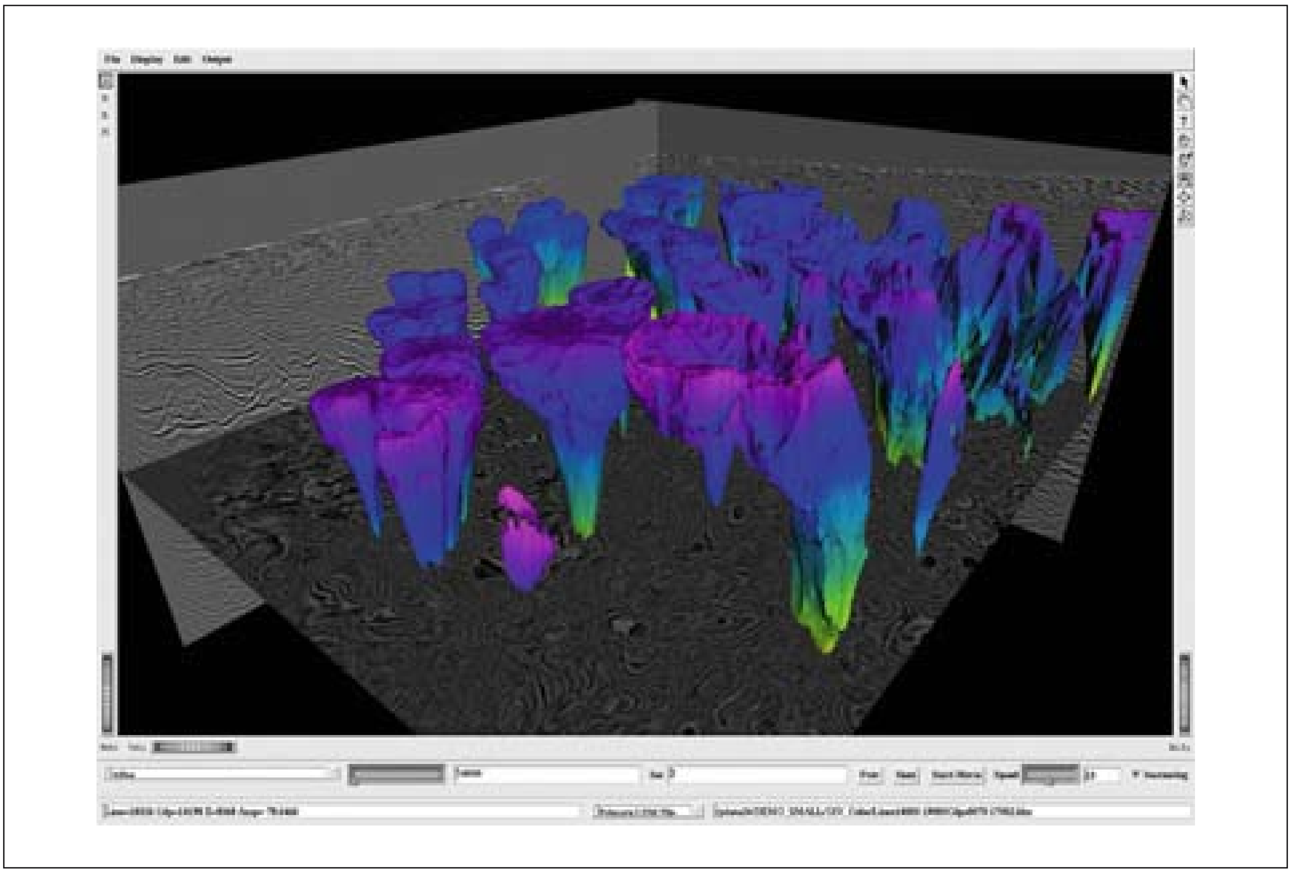

Figure 18.

Velocity model building - the next big challenge?

The industry can rightly claim that signal processing algorithms have improved at a breakneck pace and are able to address most signal-related issues faced in modern data. Velocity model building (VMB) and estimation is still an area that will require a large effort and all the ingenuity the industry can muster to continue improving subsurface imaging.

The recent BP-AIT velocity model (Figure 17), results of which have been widely circulated, serves as a strong reminder of the work that needs to be done. It demonstrated that, while migration algorithms are on the right track as witnessed by some good results, once the velocity model was known the elaboration of the correct velocity model proved to be an extremely difficult problem.

With all the tools summarized above at the industry's disposal, VMB should be the new frontier to conquer. Despite a lot of talk of velocity 'estimation' or of so many different velocities to deal with - stacking, RMS, average, interval, and geologic (well log) - for years, velocity picking has been the stepchild of processing. Yet most improvements in reprocessing often come precisely from better velocity estimation. This is one area in the processing chain where the experience and knowledge of the analyst are of prime importance. Efforts continue to develop automatic-picking routines that *should* be more efficient and accurate than human picking. These very often require some form of guide functions to converge on solutions.

Because surface seismic methods do not provide necessary and sufficient information to explicitly define velocities, the industry will continue to rely on an interpretative and iterative methodology to arrive at satisfactory models to generate subsurface images (Figure 18).

Summary and conclusions

Other important segments of seismic technology development impact imaging efforts today. This profession is closely linked to and continues to benefit from the continuing improvements in computer power, disk storage capacity, and reductions in cost per gigaflop. These key ingredients allow the application of complex processes to ever-expanding 3D data sets. The onset of wide-azimuth and multi-azimuth acquisition schemes, which have shown promise in improving hard-to-image targets below salt and in complex geologic settings, have brought seismic technology to the threshold of another order-of-magnitude increase in raw data sizes.

While these will no doubt help drive exploration in the 21st Century, continued success will rely on maintaining substantial commitment to investing in high-end imaging technology in order to develop the new tools that will allow generation of the best possible images of the subsurface in the quest for energy.

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