Is depth imaging a commodity? The impact of new imaging technologies and Web-based collaboration

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Prestack depth imaging—consisting of both velocity/depth model building and prestack depth migration (PSDM)—is increasingly becoming the rule rather than the exception when the goal is to more clearly reveal a subsurface complicated by structure or velocity.

The growth of depth imaging was initially fueled and cost-justified by the extreme risk presented by subsalt exploration targets such as those found in the deep water Gulf of Mexico. Depth imaging is now being applied around the world, both onshore and offshore and during both exploration and production phases, to remove obscuring effects produced by a diverse range of geologic and geophysical conditions. Recent case studies illustrate that salt, reefs, thrusts, normal faults, low signal-to-noise ratio, gas clouds, slump zones, shale, and basalt can all result in velocity complexity and imaging challenges that only prestack depth imaging can address effectively. An example of the recent application of 3-D depth imaging in the onshore Gulf of Mexico illustrates the improvement gained relative even to prestack time migration (Figure 1).

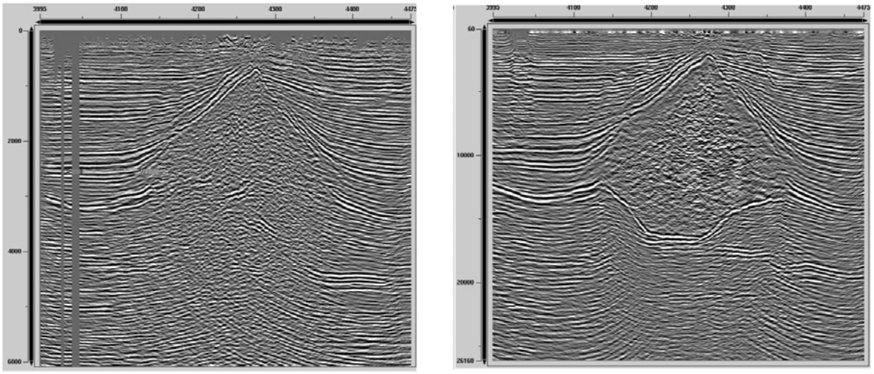


Figure 1. (left) Prestack time-migrated in-line, with only vague hints of a discontinuous base of salt. (right) Prestack depth migration showing a strongly continuous base of salt and coherent subsalt reflectors.

3000m - Class 3 Sand - Elastic Properties

	Velocity	Density	Poisson	Shear
Unit Above	2900	2.27	.35	1393
Gas Sand	2800	1.98	.17	1766
Wet Sand	3100	2.43	.28	1714

5000m - Class 2 Sand - Elastic Properties

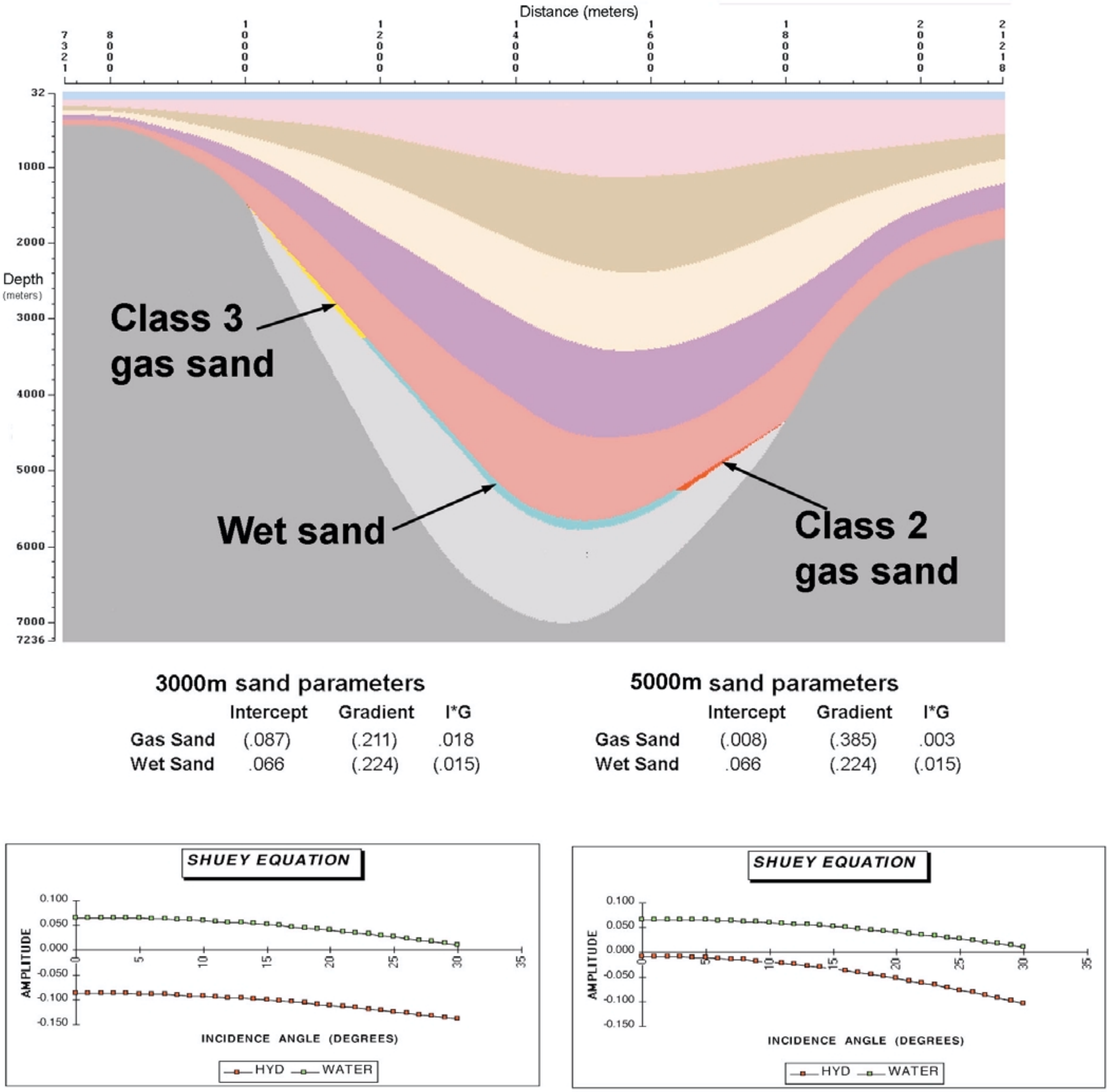
	Velocity	Density	Poisson	Shear
Unit Above	2900	2.27	.35	1393
Gas Sand	2950	2.20	.12	1939
Wet Sand	3100	2.43	.28	1714

Figure 2. Elastic properties for two model sands.

Growth in the application of depth imaging has been most pronounced during the past three years and has several causes. Advances in velocity model building and migration have produced significant gains in image quality. In addition, imaging price/performance has improved profoundly through the use of clustered, parallel supercomputing: networked groups of tens or hundreds of very powerful yet affordable personal computers and workstations. These enhancements to quality, turnaround, and value have encouraged oil companies to expand their use of depth imaging both geographically and geologically to make leasing and drilling less risky and less expensive. As more projects have been completed and case studies have been published, more oil companies have become exposed to depth imaging and have in turn adopted it as a key to reduce risk.

Given the greater availability and application of depth imaging, it is reasonable to consider whether depth imaging has become a commodity. We feel that the term “commodity” in this context implies two conditions. First, the technology would be readily available from a variety of sources at a comparable price. Second, with the same data as input, depth-imaging results obtained from one supplier's technology would be practically indistinguishable from those obtained through the use of all others; that is, images would be so similar that there would be no substantive difference in interpretation.

While rapidly improving computing price/performance has made depth imaging more affordable, there is to date no evidence that the various depth-imaging implementations produce substantially similar or “commodity” results. Quite the contrary, the difference in image quality is typically significant and can be dramatic. Recent advances in imaging and com-



3000m sand parameters

	Intercept	Gradient	I*G
Gas Sand	(.087)	(.211)	.018
Wet Sand	.066	(.224)	(.015)

5000m sand parameters

	Intercept	Gradient	I*G
Gas Sand	(.008)	(.385)	.003
Wet Sand	.066	(.224)	(.015)

Figure 3. (top) Two model sands pinched out against a synclinal structural model; (bottom) expected AVO response of the two sands. The shallow sand (yellow) is on the left, and the deep sand (red) is on the right.

munications technologies and in associated business practices have raised the bar on the quality to be obtained from depth imaging and have therefore widened the gap between the images being delivered today and what a commodity result would imply. We have chosen three recent advances to discuss in this light: amplitude-preserving Kirchhoff PSDM, wave equation PSDM, and Web-based collaboration.

Amplitude-preserving Kirchhoff PSDM. Because the Kirchhoff method is today the most commonly applied PSDM, an often-asked question is: "What is a good Kirchhoff implementation?" Rather than answering this question directly, one is often forced to answer a somewhat different question: "Which Kirchhoff implementation is the best?" The answer to this question is quite obvious when one can compare output from different implementations for the same input data, as is usually done by oil companies when screening contractors for projects. Of course, this answer can hardly be generalized for all data sets and it gets muddier if the comparison has involved real data where the quality of the result reflects as much the skill of the imager as the implementation of the Kirchhoff algorithm. But here we will venture to answer the first question.

The purist will answer that a good Kirchhoff implementation should take into account all propagation effects such as geometrical spreading and transmission losses, all acquisition geometry effects, all possible raypaths, and it should be true amplitude. But everyday practitioners who use the migration output to support drilling or leasing decisions are somewhat less ambitious. For them, at a minimum, a

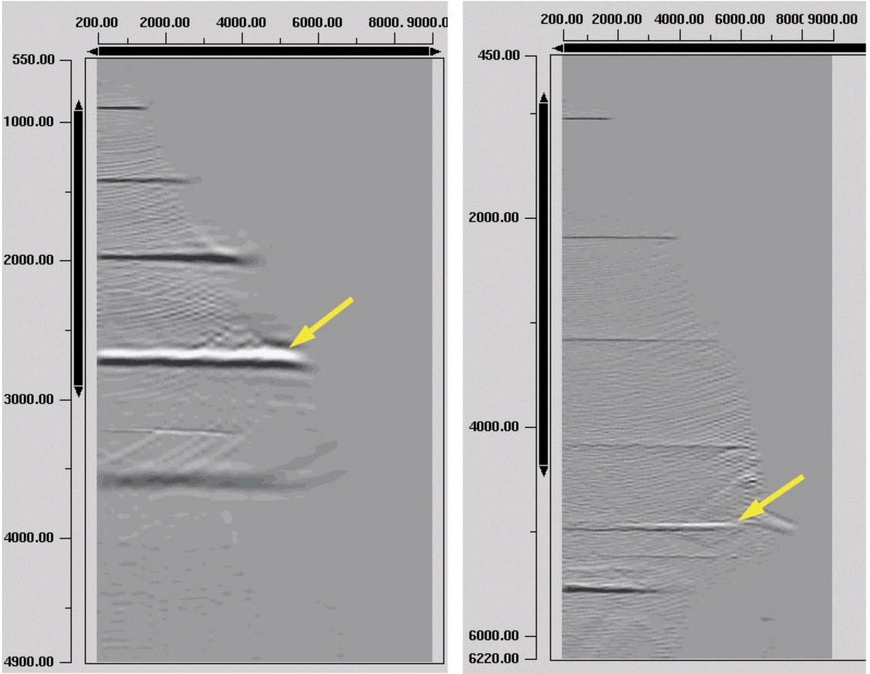


Figure 4. Common image point depth gathers; 3000 m Class 3 sand on the left and 5000 m Class 2 gas sand on the right.

good Kirchhoff implementation should image the data in the right spatial location, it should generate noise well below the detectable level relative to the signal for well-sampled data, and it should preserve amplitude.

To achieve even the less ambitious goals of everyday practitioners, a large number of implementation details must be addressed, and overlooking any of them can have a detrimental effect on the quality of the output. Certainly, accuracy of traveltime calculations in its different modes (maximum energy, shortest path, first arrival, etc.) and algorithmic noise (traveltime interpolation, antialias filtering, etc.) is of paramount importance but for reasons of brevity we will concentrate on the rather recent development of amplitude preservation.

A well-implemented Kirchhoff algorithm should preserve amplitude. To further qualify this statement, we mean that the resulting depth gathers should be as well suited for AVO analysis as those produced by prestack time migration (PSTM). Of course, we need to be mindful that both PSTM and PSDM gathers are meaningful only in areas where the velocity of the overburden is smoothly varying. In such areas, a Kirchhoff PSDM algorithm that does not introduce random or systematic amplitude errors will produce gathers that can be quantitatively analyzed for hydrocarbon signatures via impedance inversion or crossplotting.

Figures 2-4 show an example that illustrates the validity of amplitude-preserving PSDM. Two sands with different elastic properties (Figure 2) are modeled to pinch out against a synclinal structure (Figure 3, top). The expected AVO response of the two gas-filled sands is shown at the bottom of Figure 3. The shallow sand (yellow) is a Class 3 sand with a very strong zero-offset reflectivity and a mild increase in amplitude with offset. The deeper sand (red) is Class 2 with virtually zero-offset reflectivity but a very large AVO gradient.

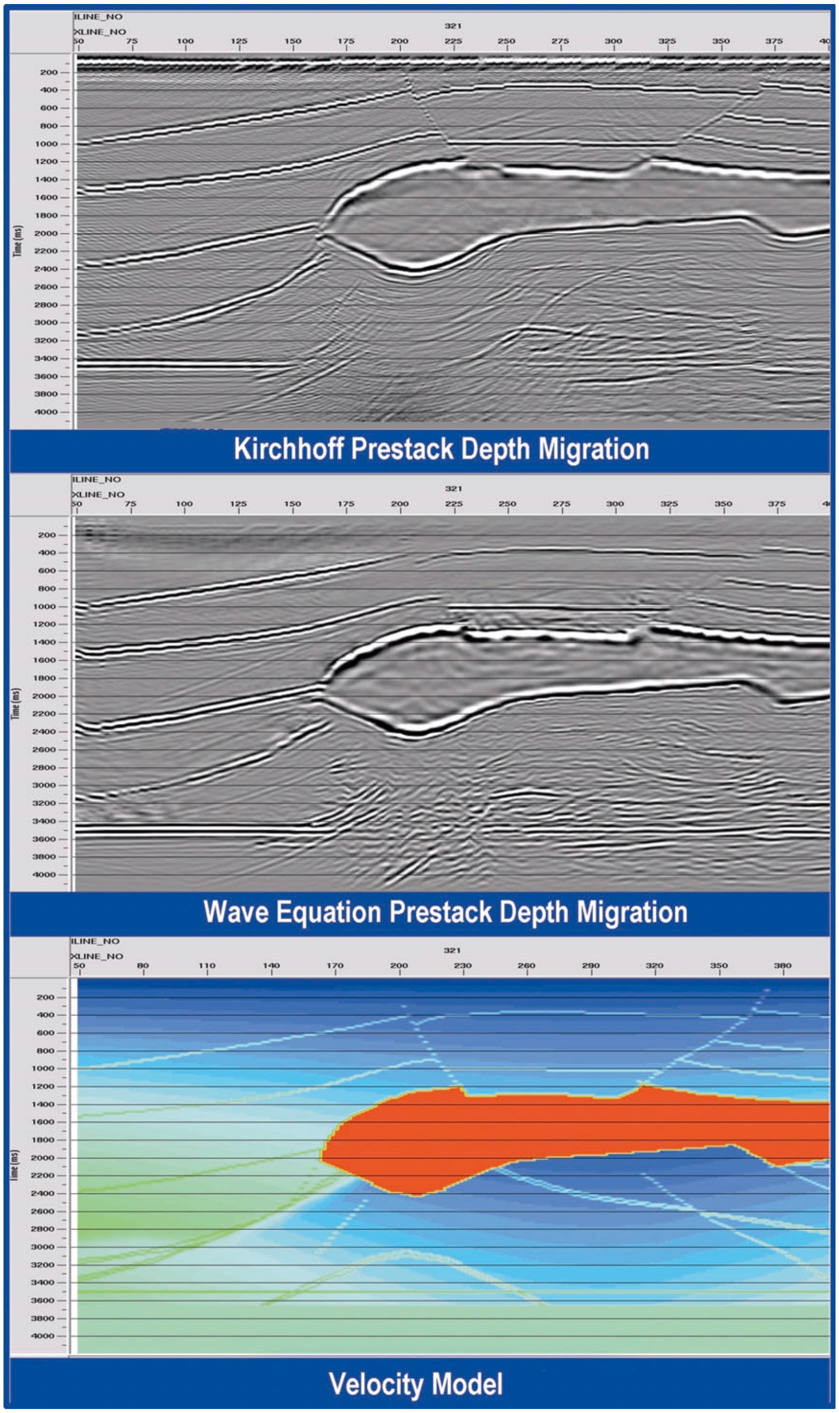
Synthetic elastic ray-traced data generated from this model have been prestack depth migrated. Figure 4 shows common image point gathers from the shallow and the deep sands. Note that the amplitude response matches the theoretical response for both sands. The shallow sand displays a large zero-offset amplitude and a mild AVO gradient. In contrast, the deep sand displays virtually no reflection amplitude at zero offset and a very large AVO gradient.

With amplitude-preserving Kirchhoff migration, there is absolutely no reason why one should have to migrate twice, once in time for AVO analysis and once in depth for accurate positioning. Significant time and money can be saved during both the processing and interpretation phases of a project if such an amplitude-preserving algorithm is employed. The resulting unified framework of structural and stratigraphic interpretation significantly enhances the value of both and ultimately benefits the economics of exploration and production. Although not yet widely available, amplitude-preserving Kirchhoff PSDM produces images clearly distinguished from those of more conventional Kirchhoff approaches.

Wave-equation PSDM. While some algorithms employed for imaging the wavefield in 3-D are simple extensions of the same algorithms in 2-D (Kirchhoff, common shot), others (common azimuth, common angle/ray parameter) are the result of fairly recent theoretical advances that attempt to reduce the dimensionality of the problem in 3-D to less than five dimensions (NX_shot, NY_shot, NX_image, NY_image, NZ_image) by making certain approximations. With the exception of Kirchhoff, 3-D migration methods are typically referred to as wave equation migration (WEM) methods because they employ a downward continuation engine (phase shift, phase shift plus interpolation, split Fourier, explicit or implicit finite difference, Fourier finite difference, reverse time, etc.) that is based on a band-limited solution to the wave equation.

To analyze various WEM algorithms for their differences would involve a theoretical discussion that is beyond the scope of this paper. We can say that these algorithms have limitations that usually pertain to the velocity model, the direction of data acquisition, or other theoretical approximations. For example, some algorithms assume constant velocity, others a laterally invariant earth, while others can accommodate arbitrary velocity variations. Some algorithms assume strike or dip shooting while others can accommodate arbitrary acquisition. Finally, some algorithms are dip-limited while others have errors that depend on azimuth or frequency.

WEM algorithms implicitly accommodate multiple raypaths, preserve amplitude, and properly handle the difficulties associated with the high-frequency approximation of the Kirchhoff algorithm such as shadow zones and caustics. On the other hand, WEM algorithms require regular or regularized data and cannot produce target output unless the full wavefield has been imaged. However, for those cases for which the theoretical assumptions of a WEM algorithm are satisfied, it is reasonable to expect that such an



Kirchhoff Prestack Depth Migration

Wave Equation Prestack Depth Migration

Velocity Model

Figure 5. (a)Kirchhoff PSDM output; (b) wave equation PSDM output; note the noise reduction below the salt keel; and (c) velocity model for Line 321, 3-D SEG/EAGE salt model.

algorithm will produce better quality than Kirchhoff.

An example of a situation in which a WEM algorithm can outperform Kirchhoff is found in the subsalt Gulf of Mexico. In those cases where the top or base of salt are very rugose, the high velocity contrast between the salt and the surrounding sediments introduces multipathing and focusing effects that can be better handled by WEM methods. By way of example, consider line 321 from the 3-D SEG/EAGE salt model synthetic of Figure 5. Figure 5c shows the velocity model with the salt body, outlined in red, exhibiting a base keel. Figures 5a and 5b show the images obtained from 3-D Kirchhoff and wave equation prestack depth migration methods respectively. Note that in Figure 5a the Kirchhoff image shows high frequency reverberant noise that mimics the base salt below the keel and completely masks the flat subsalt reflector. Such noise is quite often observed in real data. In contrast, the wave equation migration does not suffer from such noise and even though due to focusing effects the flat reflector below the salt keel is somewhat weaker, its interpretation is nevertheless unambiguous.

It is only in the past several months that WEM has become commercially available from a limited number of suppliers for production-scale processing, but it is already evident that under appropriate circumstances it produces images superior to those obtained through conventional or even amplitude-preserving Kirchhoff. In other words, WEM does not produce commodity results. Still, such methods do not come without a price: They can be much more compute intensive and therefore can be more costly than Kirchhoff. Kirchhoff PSDM—especially an amplitude-preserving algorithm—can be the appropriate choice when the imaging challenge does not require WEM or when turnaround or cost are overriding concerns.

Collaboration, the Web, and business processes. The quality of depth images depends on the migration implementation and also on the velocity model that feeds it. Although velocity model building tools vary from one imple-

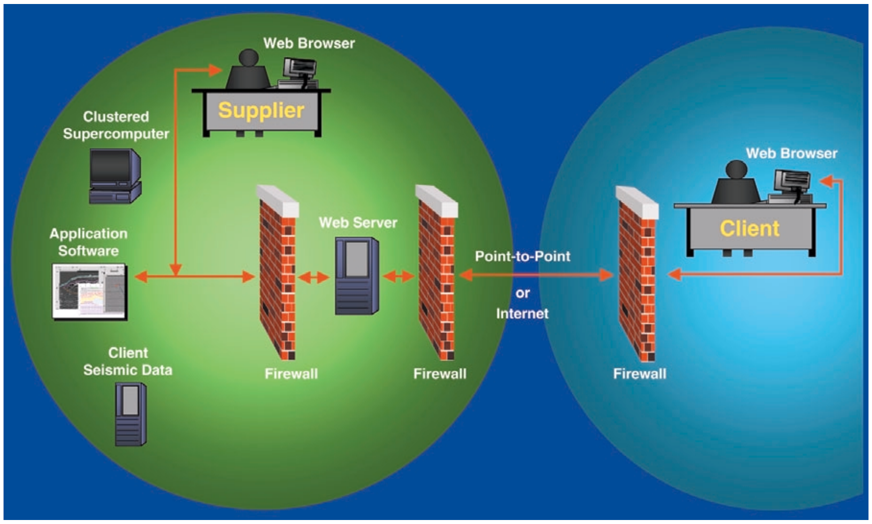


Figure 6. Key components of Web-based collaboration.

mentation to another and can make a difference in the quality of the derived model, these tools alone do not ensure its quality. Unlike the approach used in more conventional time processing, the process of building a velocity model for prestack depth migration is highly interpretive and depends on the explorationist's knowledge of the area. It also depends upon the skill and experience of a specialized processor—the depth imager—who must also have an interpreter's eye but know how to use the very specialized software and hardware tools of depth imaging to produce a high-quality result within a tightly constrained time period. Depth imaging can be described as interpretive processing, and very few people possess all the skills and experience—let alone the time—necessary to the task. More typically, depth imaging involves collaboration between at least two people: the oil company interpreter (or "client") and the depth imager (or "supplier").

This need for collaboration poses some significant challenges, the most important of which are not technical. Velocity model building for prestack depth imaging is iterative and episodic, requiring several periods of collaboration to build the velocity model, review the interim depth results, and modify the velocity model prior to the next phase of migration. The timing of these collaborations is sometimes difficult to predict far in advance. Given the demands on the interpreter's time, it is often problematic to bring the depth imager and interpreter together, especially without interrupting the interpreter's train of thought or other activities. Collaboration is especially an issue when the interpreter or imager must travel to a different location to collaborate, as is typically the case when the project is outsourced to an external service provider or when the in-house imaging team is in a different building or city.

Because a barrier to the convenience and effectiveness of this collaboration is a threat to the quality of the depth image, there is an increasing industry focus on improving this process. The most recent and promising advance in collaboration augments, and in some cases replaces, traditional face-to-face meetings with interactive, desktop sessions conducted over the World Wide Web. Figure 6 is an example of such a system. Using a standard Web browser, interpreters and depth imagers are able to interactively collaborate with each other and their colleagues and partners, jointly reviewing and interpreting the velocity model and seismic data, each without leaving the office.

With the Web as the portal to such collaboration, these sessions can be conducted between people anywhere in the world if they have an Internet connection. They can be in the office, the home, or even on vacation using wireless access. While it is obvious that this makes collaboration possible between people who might otherwise have to fly or drive long distances to meet—or who might not be able to meet at all—desktop collaboration can even alleviate the distraction and time associated with travel across a city the size of Houston or London. This is a key benefit of the Web-based approach: making it possible to increase the frequency and effectiveness of collaboration while minimizing the impact to the client's focus and schedule. The ultimate result can be a significant improvement in the quality of the subsurface image.

The infrastructure for Web-based collaboration must provide a means for remotely serving data and a variety of software applications, the communications bandwidth necessary to an interactive experience, and tight network security to prevent unauthorized access to the data and the computing environment. In this example, an Application Service Provider (ASP) model is used in which applications such as velocity model building software execute on centralized server computers typically at the supplier's office. The software is served on user demand over private, point-to-point networks or the Internet to collaborators using Web browsers on "thin client" computers such as personal computers or workstations. The collaborators can interactively swap control of the remotely executing software, with all actions of the currently active collaborator—such as cursor motion, menu pulldowns, or text entry—visible in near-real time to other collaborators.

The degree of interactivity depends significantly on available bandwidth, but in this example even relatively slow 56 kbps modem dial-up connections can be sufficient for remote data QC prior to the ensuing phase of migration. Integrated audio- and videoconferencing can add significantly to the effectiveness of Web-based collaboration but, of course, their bandwidth requirements must be taken into account. The necessary bandwidth is widely available and affordable to oil companies across the globe; this is particularly true in North America, Western Europe, and parts of Asia Pacific and the Middle East. Because bandwidth is expanding worldwide at an astonishing rate, oil companies in other locations will soon have improved access to desktop collaboration.

Security is a critical and special consideration in Web-based collaboration because seismic data and their associated interpretations are clearly some of the most valuable and confidential data owned or licensed by oil companies. This example implements multiple firewalls, multiple levels of authentication and authorization, and SSL 128-bit encryption. Applications served during collaboration also have been redeveloped to ensure that authorized users are unable to see other companies' data, nor even listings of other project names or files. Finally, a client may choose to implement a point-to-point network rather than the Internet to reach the supplier. This can result in more predictable, even dedicated bandwidth for collaboration and an even more secure connection.

Communications technology and the Web can be critical components of collaboration during depth imaging, but they are not sufficient. The business processes of the interacting individuals and organizations must typically change as well. Changes to the supplier's distribution process are implicit because an evolving velocity/depth model and the resulting depth images are key deliverables to the client. This process may replace but is more likely to augment delivery mechanisms already in use. If the supplier of the software for remote model building and visualization also licenses these products for more traditional (i.e., noncollaborative) use, the supplier will likely be required to change the product development process to maintain multiple versions of the software. This could involve a remotely served version preventing unauthorized access to other companies' projects, and a locally executing version providing users with freedom to browse their own company-networked file systems.

Perhaps most importantly, there must be willingness by all involved to upgrade their communications infrastructure and processes. This must be true of corporate processes and personal processes: the supplier and client must have the skills and be willing to communicate more frequently and effectively than traditional time-processing projects have required. If the project demands the highest fidelity seismic images to reduce leasing or drilling risk, the highest quality depth-imaging tools and processes must be brought to bear. This realization is helping improve the art and architecture of communication between the supplier and receiver of depth-imaging solutions.

Summary. Is depth imaging a commodity? We believe that the current evidence strongly suggests not. Recent advances in amplitude preserving Kirchhoff and wave equation PSDM as well as Web-based collaborative technologies and associated business processes can be responsible for significantly differentiating the quality of results obtained from depth imaging. The pace of this innovation is accelerating. Because depth images are presently improving in quality every

(Continued on p. 543)

(Donihoo, from p. 496)

6-12 months, it will likely be some time before the industry can expect a commodity result from this most interpretive and rapidly evolving form of seismic processing.

Suggested reading. "Aspects of true-amplitude migration" by Albertin et al. (SEG 1999 *Expanded Abstracts*). "Efficient 2.5-D true-amplitude migration" by Dellinger et al. (GEOPHYSICS, 2000). "Subsalt imagery and structure recognition using Pre-SDM" by Docherty et al. (*World Oil*, 1999). "Depth imaging dynamics" by Donihoo (*Hart's E&P*, 2000). "True-amplitude seismic migration: A comparison of three approaches" by Gray (GEOPHYSICS, 1997). "The Shell 3-D prestack migration benchmark" by Kuiper and Kikker (*Journal of Seismic Exploration*, 1998). "The impact of migration on AVO" by Mosher et al. (GEOPHYSICS, 1996). "3-D true-amplitude finite offset migration" by Schleicher et al. (GEOPHYSICS, 1993). "Regional multi 2-D prestack depth migration: A subsalt case history from deepwater GOM" by Willacy (*TLE*, 1999).

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