# Trends in depth imaging: Observations from the 2002 SEG Annual Meeting

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In the rapidly evolving world of prestack depth migration (PSDM), the 2002 SEG Annual Meeting held in Salt Lake City, Utah, provided a useful forum to assess the state-of-the-art and necessary future directions for PSDM to better meet industry's needs in resolving complex subsurface environments. PSDM-related topics were heavily represented at the meeting with both contractor and oil company geoscientists presenting papers covering the full range of current issues. From these presentations certain themes and trends emerged which allow one to see through the confusion of today's PSDM implementation options and comparisons to isolate key areas of consensus in current practice as well as to identify the critical gaps remaining to be closed as industry moves down the path from ray-based (Kirchhoff) to wavefield-based schemes.

These trends can be summarized as follows:

- growing momentum from ray to wavefield approaches: "wave equation will win eventually"
- current wavefield economic shortcuts such as data decimation, aperture limits, or no gather output are rapidly declining in acceptability
- finely gridded gathers required to precisely define local velocity detail (e.g. top salt rugosity) with angle gathers prominently proposed by many PSDM providers
- integration of velocity model-building into the wave equation PSDM workflow is critical including the tight linkage to the interpreter and the geology
- 3-D tomography proposed as the velocity updating/inversion engine in complex regimes, although its current limitations in the presence of limited angle ranges and/or variable illumination were noted
- as complex imaging results improve, anisotropy corrections becoming standard to provide accurate spatial positioning of signal energy

The following sections attempt to encapsulate the key issues from the perspective of this author.

**Kirchhoff versus wave equation.** For many areas, the Kirchhoff-based approach remains a major industry workhorse with its robust proven workflows and favorable economics. However, it is clear that wavefield-based schemes have emerged as a major force for the more complex subsurface situations where multipathing of the signal energy cannot be properly refocused with current Kirchhoff approaches. Several presenters did show good results, even in certain subsalt cases, with Kirchhoff PSDM when great detail was paid to velocity model-building, traveltime solver selection, and rigorous use of antialiasing schemes, making the case that "Kirchhoff is sometimes hard to beat." However, Kirchhoff's most obvious deficiency in the face of energy multipathing typical of, for example, rugose salt conditions now clearly demands wavefield-based approaches in these situations and it is clear that "wave equation will win eventually" (Figure 1).

Several presenters discussed extensions of Kirchhoff to address multipathing but the jury remains out on whether these will ever be economically viable. Meanwhile, the current barriers in wavefield approaches are being actively addressed, specifically:

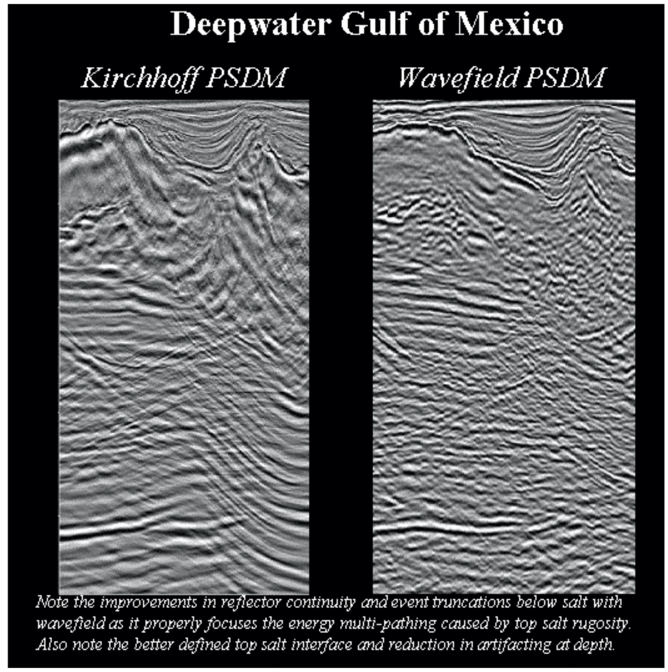


***Figure 1.** Kirchhoff versus wave equation: impact of strong top salt rugosity on below salt sedimentary interfaces.*

- how to improve the economics
- steep dip and amplitude fidelity
- accurate velocity model estimation

Finally, it should be noted that the Kirchhoff or wave equation decision is not necessarily an either/or situation. There is a strong case, at least in the near-term, for complementarity between the two imaging choices—the right method for the right problem.

**Economics and wavefield choices.** A primary barrier to widespread use of wavefield-based PSDM has been the high cost due to the computational intensity of wavefield algorithms. A mechanism to achieve acceptable results at acceptable prices with shot profile schemes, an early wavefield implementation entry, was to "decimate" the data volume (e.g. using every fifth shot) and/or to limit the aperture used. It was clear at the SEG meeting that this approach is rapidly declining in acceptability for two reasons: (1) recognition that shot profile decimation, aperture constraints, and lack of gather output are inhibitors to optimal image quality; and (2) emergence of faster, accurate wavefield schemes which also naturally output gathers essential for detailed velocity information (see below).

An early industry complaint was that wavefield schemes didn't provide steep dip definition equivalent to Kirchhoff

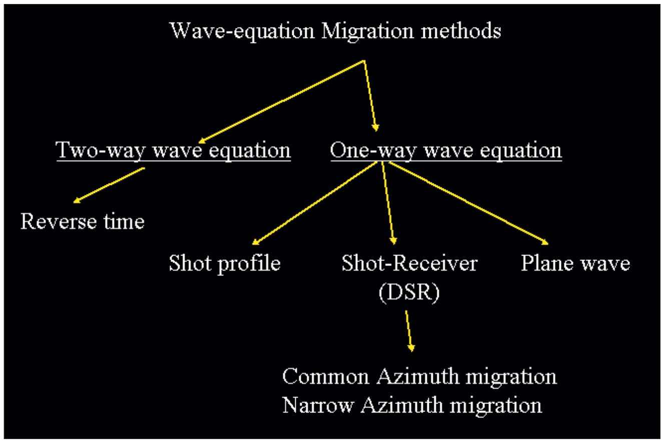


*Figure 2. Alternative implementations of wave equation migration.*

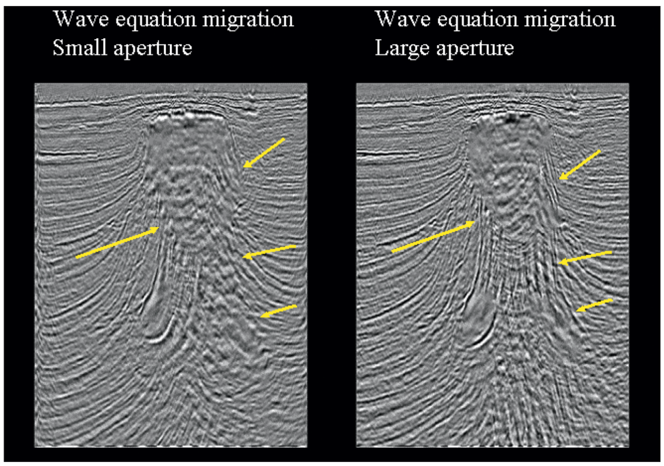


*Figure 3. Migration aperture comparison. Note the recovery of ultra-steep dips when full aperture is invoked.*

schemes. From several comparisons at the meeting, it is clear that when equivalent apertures are used, equivalent dips can be preserved. The difference is more an issue of adherence to the physics of the problem (i.e. rigor of implementation) than a ray versus wavefield issue.

The lack of gather availability (in an economic manner) from shot profile schemes disallows the fine-grain detail required in the velocity field for complex areas and/or rugose salt environments as demonstrated by several SEG presenters. One company reported its efforts to output offset gathers from shot profile at a factor of 6 or more in computational requirement, and angle gather output, while faster, was still a factor of 2 or 3 increase.

The introduction of efficient wavefield schemes adapted for streamer environments and based on source-receiver input data domain rather than shot gather domain now allows performance in the same range as Kirchhoff schemes. These source-receiver domain approaches provide full volume migration outputting gathers naturally. Output of angle gathers is gaining prominence as a practical mechanism where detailed residual curvature estimates can be used to update the field effectively. A series of presenters proposed a variety of source-receiver scheme alternatives (Figure 2) producing well-imaged results, although the issue was clouded by comparisons where implementation choices frequently tended to favor the implementation being proposed.

The key point was made by one presenter that, just as an exact implementation of Kirchhoff is equivalent to a full wavefield implementation, proofs have been presented showing that, when fully implemented, there is an exact equivalence between the shot gather data domain implementation and the shot-receiver data domain approach. Hence, the critical issue for all schemes is more related to the rigor of implementation undertaken with each approach and the economics of the approach when implemented with the necessary rigor to solve the subsurface problem at hand.

Currently, the industry is rapidly trending toward the shot-receiver schemes which offer favorable economics, availability of gathers, and, when properly implemented, can offer the steep dip imaging and necessary amplitude fidelity for many of today's complex subsurface problems.

**Dips and amplitudes.** Several presentations appeared to suggest that Kirchhoff is still the comfort tool for imaging very steep dips, but, as noted above, the issue is more related to adherence to physical principles (especially aperture) and rigor of implementation of the particular algorithm selected. One company presented a Kirchhoff versus wavefield comparison that showed steeper Kirchhoff dips, but they openly acknowledged that their aperture for Kirchhoff had a radius of 15 km while the wavefield example was restricted to 6 km because economics of running an ultra-wide wavefield aperture was restrictive. Figure 3 shows that when full aperture is invoked, the steepest dips are indeed preserved by the wavefield PSDM method.

Regarding amplitude fidelity, it is clear in complex situations that the standard Kirchhoff implementation cannot refocus multipathed energy and, hence, cannot be expected to have proper amplitude integrity. For wavefield schemes, the algorithmic implementation needs to include all relevant amplitude terms in the solution—at least five terms should be considered, according to one presenter. Another inhibitor to amplitude preservation discussed by several presenters was variable illumination across the target reflector, and several illumination compensation schemes were proposed.

From the SEG meeting, several elements emerged which need to be considered when rating wavefield results for amplitude and/or steep dip preservation:

- is full aperture being used?
- is variable illumination an issue?
- are all relevant amplitude terms included in solution?
- are all relevant frequencies and/or reference velocities properly parameterized?
- is velocity detail captured in the model, or is it being smoothed out?

Again, in this context, the emergence of wavefield source-receiver based methods provides benefits:

- the full input data volume is the effective aperture
- gather output allows velocity detail to be incorporated

Finally, in the case of overturned beds, certain presenters made the point that current one-way downward continuation schemes cannot resolve the problem. Several innovative solutions were proposed including coordinate rotation schemes, next generation "bottoms-up" or two-way continuation schemes, and reverse time migration methods, all of which are being actively researched, but economically the latter two don't appear to be likely near-term options.

**Velocity model-building.** The velocity model as always is the key determinant in successful subsurface imaging. The 2002 SEG meeting highlighted several valuable pointers as the trend to more widespread use of wavefield-based PSDM methods continues.

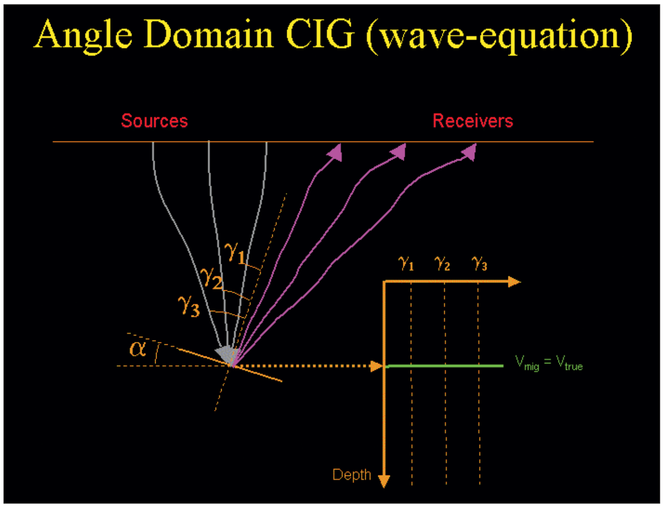


***Figure 4.*** *Gather energy is organized by reflection angle.*

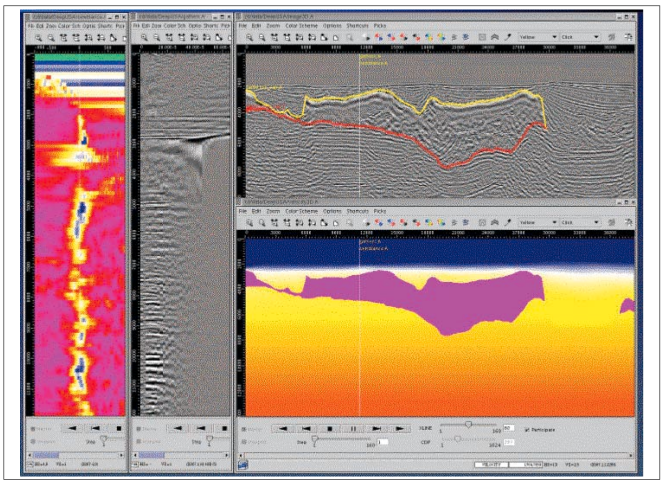

***Figure 5.*** *Interactive graphical aid for rapid model QC/validation showing angle gather with semblance.*

The prevalence, because of prior economics, of the use of velocity models derived from Kirchhoff migrations to drive a final wave equation PSDM was shown to result in suboptimal image quality in complex and salt rugosity environments. The fine detail required for quality wavefield imaging is typically not included in the Kirchhoff-derived model due to inherent smoothing and/or coarse grid derivation of the model. Fortunately, the introduction of faster, full volume wavefield solutions now allows fine-grained wavefield-derived velocity models to be developed to allow the full potential of the wavefield method to be applied to our most complex subsurface problems. From the series of both contractor- and oil company-presented papers in Salt Lake City, a clear consensus emerged at this meeting regarding the most effective approach to velocity modeling in today's wavefield PDSM world.

- need to fully represent high acoustic impedance contrast and/or short wavelength velocity variation details in the model. "Exact knowledge of the salt shape is crucial in order to focus subsalt events."
- full volume depth migrated data required with finely sampled velocity analyses (25 × 25 m, not 500 × 500 m). Angle CIGs gaining favor (Figure 4)
- automated picking tools required to deal with high volume of velocity information with interactive graphical aids to easily and quickly high-grade results (Figure 5)
- gridded, not layered, models—more natural, easier to control, well-resolved representation
- model updating flexibility required with 3D tomography becoming a standard tool in most complex areas (although tomography is greatly inhibited at depth by illumination variability and/or limited opening angle ranges)
- interpreter involved at all key decision stages for subregional context and geologic plausibility
- inclusion of anisotropy corrections for spatial positioning

On a cautionary note, one leading industry presenter made the observation that "Velocity model construction cannot be considered a commodity; it is not a solved problem." This is particularly true in the deep subsurface, especially below salt, where decreasing resolution with depth because of limited angle and/or offset coverage, the presence of shadow zones and/or poor data quality leave significant velocity versus depth ambiguity unresolvable by current methods. Thus, as we provide clearer subsalt images because of improving algorithmic capability, we are left with the dilemma of accurate spatial positioning of the clarified energy, resolvable only with a detailed and unambiguous velocity model. This remains an industry technical challenge to be prioritized as we move forward.

**Summary observations.** The depth imaging component of the 2002 SEG meeting was more evolutionary than revolutionary in nature, but it did allow several key trends to be clearly identified. These are of value to the practicing geoscientist required to make key decisions for selection of appropriate PSDM implementations and/or contractors to resolve their company's complex subsurface problems, reducing company risk and maximizing the likelihood of economically finding recoverable hydrocarbon reserves. An overview of this author's key points follows:

- Kirchhoff is still the weapon of choice for lower raypath complexity regimes, although certain fast wavefield schemes can now provide solutions in the same economic range.
- Wavefield methods are essential in multipathing complex geology. Full volume imaging with common image gather output is required. Angle gathers preferred.
- Implementation rigor differentiates currently available algorithmic alternatives as industry climbs the learning curve for efficient, high fidelity wavefield imaging.
- "Wave equation will win eventually."
- Velocity model-building must be high detail, fine-grained, with fully integrated, automated tools including full gather availability.

Key challenges remain in at least the following areas:

- Continuing improvements in economics and implementation choices for wavefield methods.
- Extending amplitude and steep dip preservation
- Deriving velocity models that provide accurate spatial positioning of fully imaged energy at depth

The reader is encouraged to review the many interesting papers addressing the depth imaging topic published in the SEG 2002 *Expanded Abstracts*, where many of the issues mentioned above are discussed in much greater detail. TLE

*Acknowledgments: Unocal and Apache/SEI are gratefully acknowledged for their permissions to show the seismic data included in this article.*

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