Full wave-equation methods for complex imaging challenges

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Despite being at the end of a long and full Annual Meeting week, the workshop "Full wave-equation methods for complex imaging challenges," held 30 October 2009, drew an audience which filled the large meeting room. They were rewarded with a full day of presentations which mostly focused on emerging techniques for velocity model estimation rather than imaging itself: the consensus seemed to be that it is indeed there that the true imaging challenges lie. Nonetheless, significant contributions on the imaging side also demonstrated continuing progress in improving the quality and efficiency of imaging, and in interpreting the results.

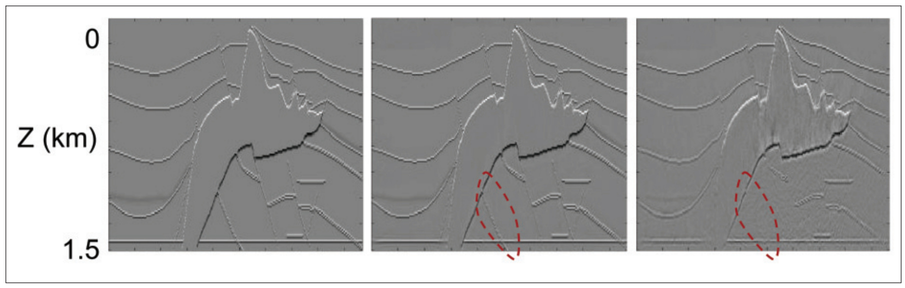

Figure 1. Phase-encoded sources and least-squares migration (LSM): 2D SEG /EAGE salt model (left) with results from 30 iterations of LSM with original data (center), and with data made by blending groups of 40 sources together (right).

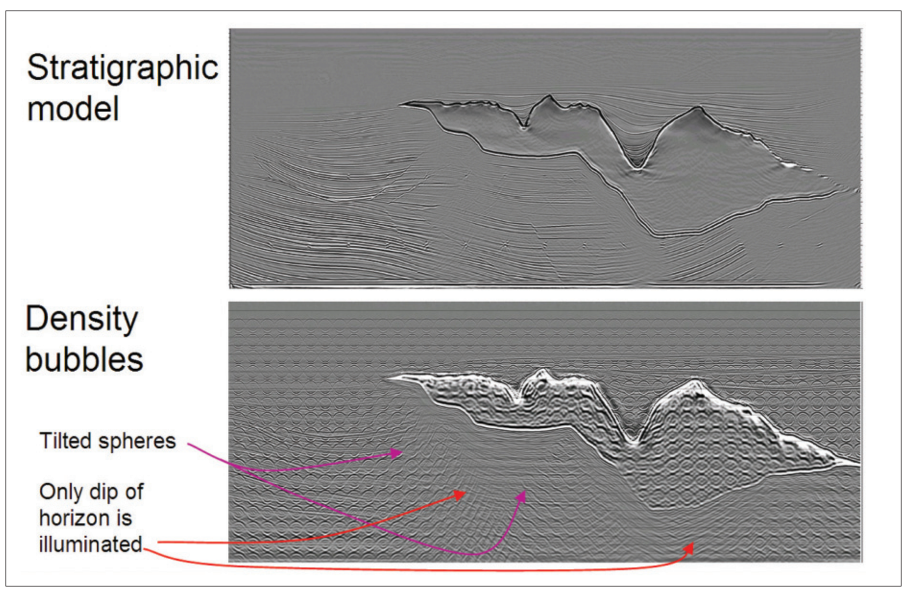

Figure 2. The use of density bubbles to represent dip-dependent illumination on Sigsbee. Note the reduction in illumination strength and dip range in some subsalt areas. (Courtesy of Tierra Geophysical).

The workshop started with Biondo Biondi of Stanford University presenting work from the Stanford Exploration Project on linearized inversion for enhanced imaging. In theory this amounts to applying the inverse of the Hessian, which is compounded from the migration operator followed by its adjoint, the demigration operator. This can compensate for uneven illumination and poor amplitude recovery by the basic migration operator. However, calculating the inverse operator explicitly is very expensive, so this has generally been avoided by doing iterative least-squares migration, in which the demigrated image is matched to the data. On the other hand, SEP has pioneered an alternative approach on the basis that the most significant entries in each row of the Hessian correspond to the spatial vicinity of the image point. Then model-space inversion can be run in a target-oriented fashion, reducing the computational load. Biondi showed how this can improve subsalt imaging, clarify time-lapse changes, and reduce cross-talk in images from data using simultaneous sources. In this last application, the Hessian is no longer compact and the reasons for working in the model space are less compelling.

The multisource + least-squares migration theme was picked up again at the beginning of the afternoon session by Gerard Schuster, who suggested that this could reduce the computational effort of reverse time migration (RTM) in 3D, at least. More generally, combining data records from multiple sources and using multisource preconditioning filters could deliver order-of-magnitude speed gains in the context of full-waveform inversion or migration velocity analysis, where the iterative inverse nature of the process would eliminate the cross-talk. However, as shown in Figure 1, some weak events seemed to be particularly hard to recover, presumably because the crosstalk is of similar amplitude. In the example shown, the 30-iteration "standard" LSM cost 90 times as much as standard RTM; the blended-source LSM was only around 2.5 times more costly, and even greater relative speedups have been observed in ongoing tests.

Sang Youg Suh (TGS-Nopec) addressed a different aspect of speeding up RTM by discussing several computational optimizations. An efficient implementation allows RTM to be used at several stages of the depth-imaging workflow, and he showed some examples of salt-model building from large-scale GOM projects.

Christof Stork (Tierra Geophysical) gave a different slant on illumination analysis by showing how modeling and migrating an array of density bubbles in the velocity model used for migration could give an immediately interpretable pictorial representation of the dip-dependent illumination. This is relatively inexpensive and can be superposed on the migration image to immediately improve understanding of the features (or absence thereof) in the image. He noted that this may be frequency-dependent in complex media (which would indicate the necessity for wave-equation propagators rather than rays for imaging and inversion). Stork also announced the availability of updated versions of some industry standard synthetic data sets, including the 3D SEG Salt Model and the 3D Ziggy Model, reducing illumination issues due only to the limitations of the acquisitions (Figure 2).

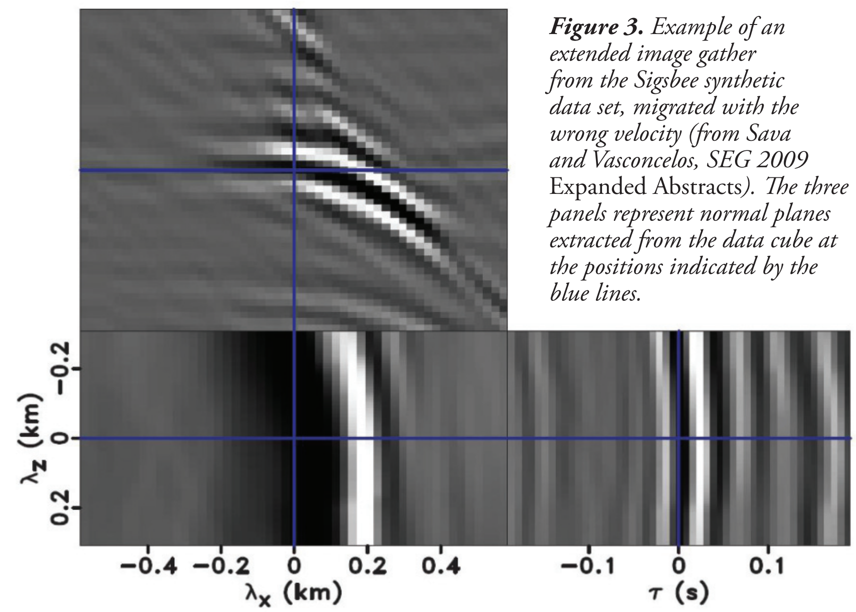

Figure 3. *Example of an extended image gather from the Sigsbee synthetic data set, migrated with the wrong velocity (from Sava and Vasconcelos, SEG 2009* Expanded Abstracts*). The three panels represent normal planes extracted from the data cube at the positions indicated by the blue lines.*

The remainder of the morning session was dedicated to four presentations on wave-equation migration velocity analysis (MVA). Paul Sava (CSM) and Ivan Vasconcelos (ION-GXT) both propounded the idea that this should be approached via high-dimensional (space and time) "extended image" gathers or points, as shown in Figure 3, and associated/adapted annihilators. Each point contains more information, or at least greater certainty of information than traditional, dense, single-dimensional gathers, so

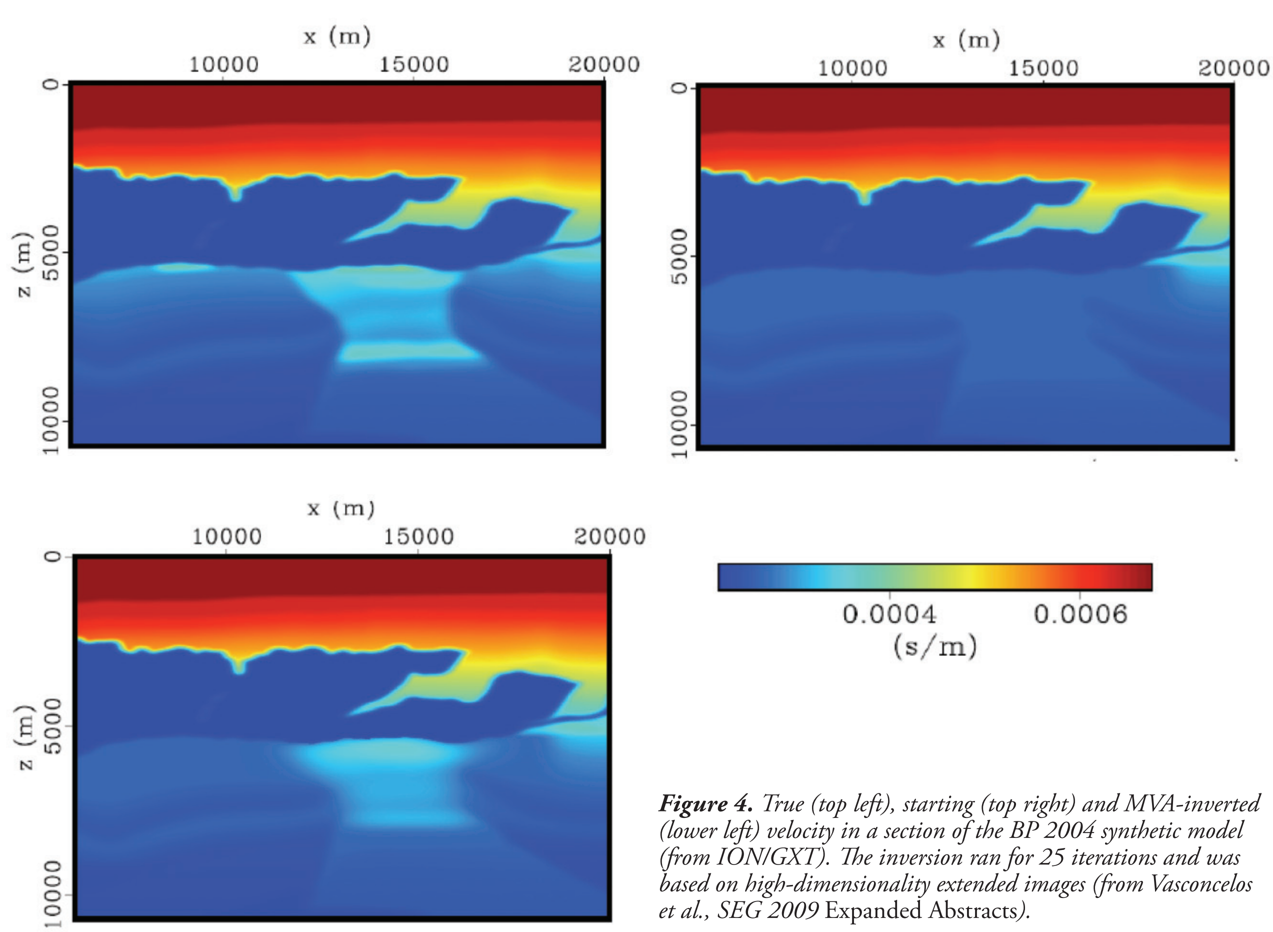

Figure 4. *True (top left), starting (top right) and MVA-inverted (lower left) velocity in a section of the BP 2004 synthetic model (from ION/GXT). The inversion ran for 25 iterations and was based on high-dimensionality extended images (from Vasconcelos et al., SEG 2009* Expanded Abstracts*).*

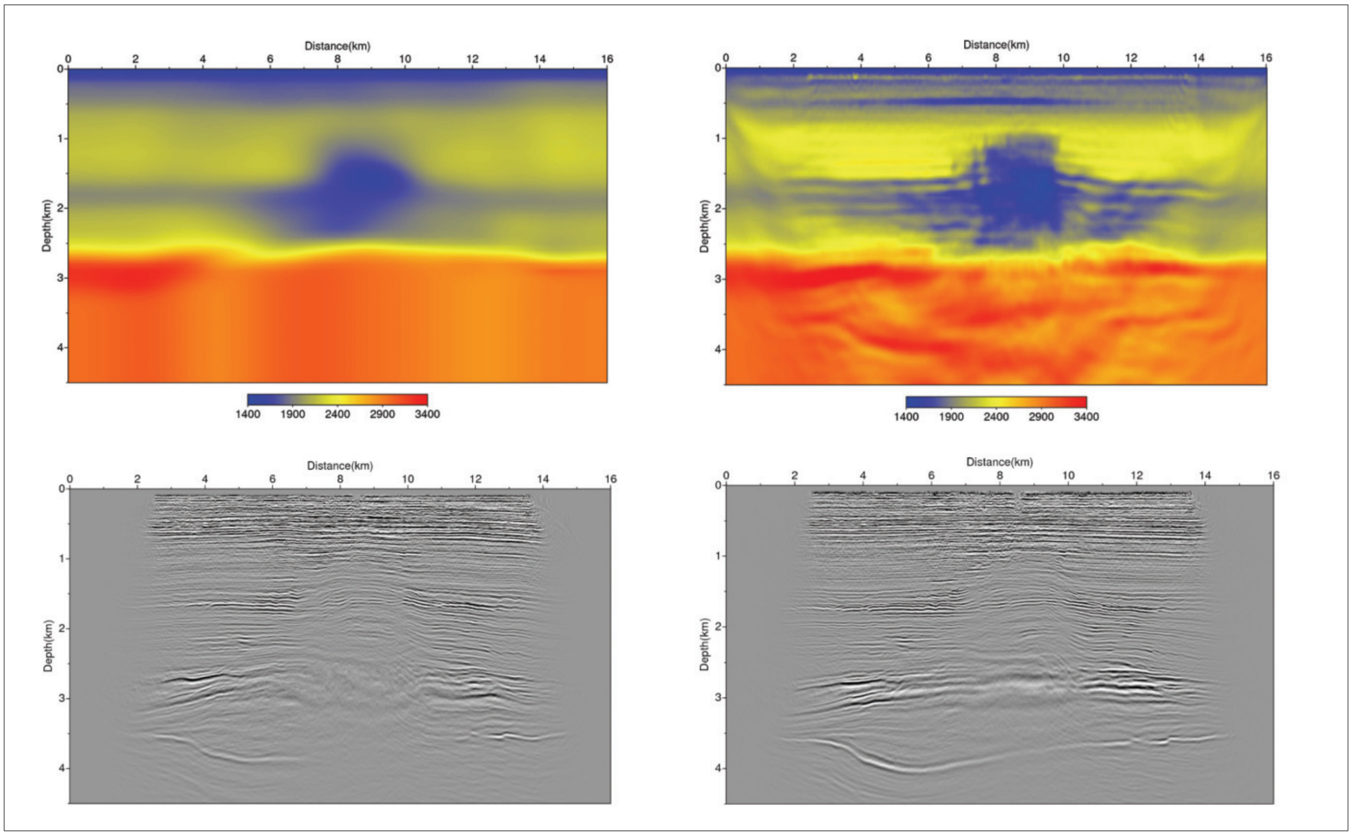

Figure 5. *Initial (top left) and inverted (top right) velocity models, and associated PSDM images (bottom left and right, respectively) from Valhall. (Courtesy of BP, from Sirgue et al., EAGE 2009* Extended Abstracts.*)*

while, individually, they could be quite expensive to calculate due to their dimensionality, this could be done at relatively sparse analysis points to avoid excessive overall cost. The new annihilators would generate "better" sensitivity kernels, with fewer/weaker side lobes and therefore an objective function with a gradient with fewer artifacts and which would presumably generate updates which converge faster while retaining the robustness of, for example, a simple DSO-type algorithm.

Vasconcelos showed, as an example, a subsalt zone from the 2004 BP 2D model; the sediment velocity variations were well-recovered, but this still took 25 iterations, although since the inversion was applied in a target-oriented way, the cost for such a calculation presumably remains reasonable (Figure 4).

On the other wing of the WEMVA tendency, Robert Soubaras (CGGVeritas) and Hongbo Zhou (Repsol) formulated their inversion to maximize semblance or coherence rather than minimize the action of an annihilator on the (extended) image. Zhou prefers objective functions based on coherence rather than data misfit because of the difficulty of even formulating the forward problem (wave equation, source terms, etc.) sufficiently precisely. Therefore modeled amplitudes are (unpredictably) wrong; however, the kinematics of forward-modeled data are now relatively robust and accurately represent the model. Therefore an objective function in the image domain using the redundancy of the data by comparing independent images should allow robust inversion of real data, even if it may converge more slowly and deliver less resolution than classic FWI for synthetic data.

Soubaras, too, acknowledged the difficulty of stably employing FWI to extract broadband velocity and density from real data, even with an "accurate" wave equation, although the theoretical advantage of this when compared to the implicit separation of velocity and reflectivity (in, e.g., MVA) is non-negligible and worth pursuing. Furthermore, the "refraction tomography" option of FWI, working with the early arrivals, makes it the tool of choice when the acquisition geometry is favorable.

The discussion at the end of the morning was mostly consensual; speakers agreed that, while the calculation of explicit sensitivity kernels in MVA would allow greater flexibility and control of the inversion compared with the adjoint-state methods generally used, this would add significantly to the already not inconsiderable computational expense (comparable with FWI). It was suggested that applying adjoint-state methods in ray-based tomography might give insight into what could be lost thereby in WEMVA. There was also discussion about what gathers should be calculated, and with what offsets, in an imperfectly/unknown medium: responses emphasized the importance of understanding the dip structure, as far as possible, since time-lag analysis showed that this alone typically carries less information than time and space lags. Vasconcelos commented that compressive sampling ideas could help in limiting the amount of work that was needed, and Stork emphasized that successful MVA depended upon illumination.

The FWI theme was picked up more emphatically in the

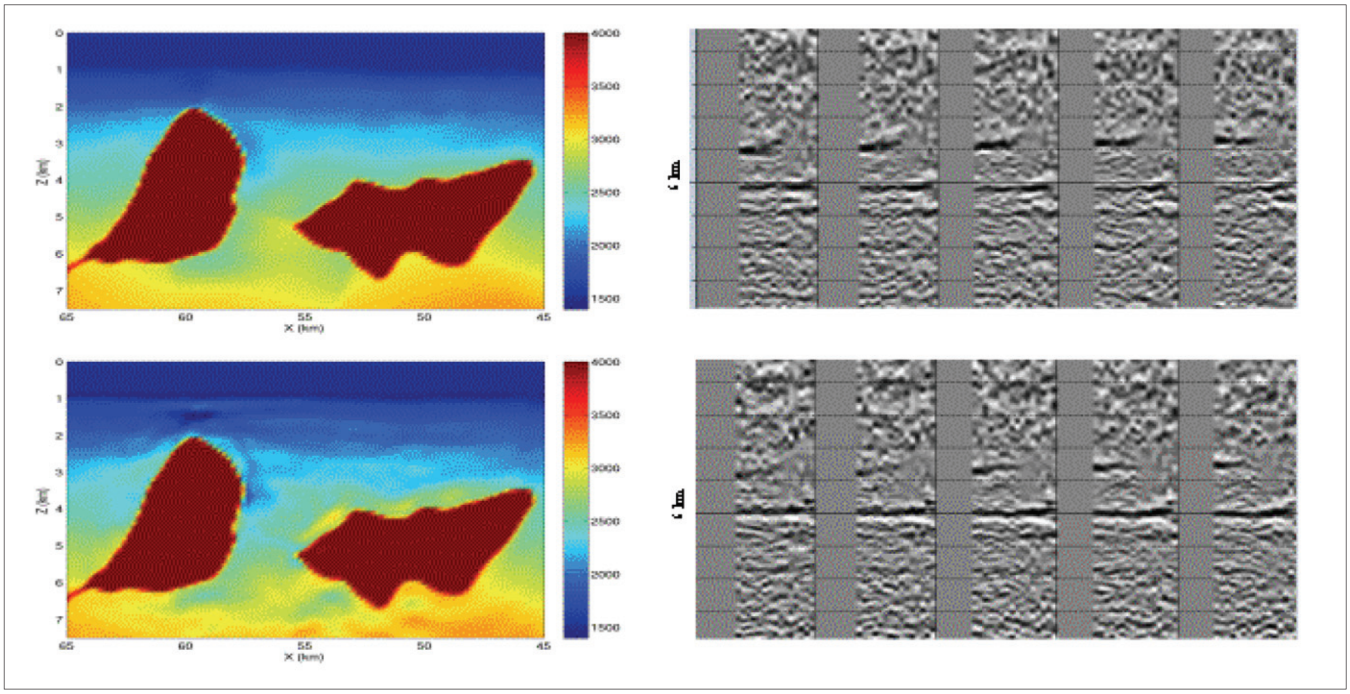

Figure 6. *Starting model (top left) and final model (bottom left) from Shell's application of FWI to Deimos.*

afternoon, with three examples of applications to real 3D data, and two others with additional points of interest around the method. Rene-Edouard Plessix (Shell) and Uwe Albertin (BP) showed some significant areas of agreement, although a sample of two is perhaps too small to define an industry trend. Both presented inversions of ocean-bottom data, where the extension of the seismic spectrum at the low end compared to conventional streamer data reduces the likelihood of "cycle-skipping" between the modeled and observed data, and therefore makes the inversion more robust with respect to the starting model, and both worked essentially in the frequency domain. In both cases the relatively small number of (fixed) receiver positions helped keep the overall cost under control via designation of these as sources and application of reciprocity. Both studies were relatively shallow compared to the offsets acquired, so it seems likely that the inversions were dominated by the refraction tomography mode, although the rather deeper Shell study had regions where reflection-type FWI took over. Both studies essentially inverted the low-frequency, "background" velocity model, although BP pushed up to 7 Hz, whereas Shell, did not show results beyond 3 Hz. Nonetheless, they both showed appreciable improvement in the quality of the imaging, despite starting from models that were essentially smoothed versions of the models derived and used in their standard depth migration workflows, partly because both fields contained features which pose problems for conventional imaging: a gas cloud for BP (Valhall) and salt for Shell (Deimos). Figure 5 shows a section through BP's result on Valhall, which demonstrates a considerable increase in the level of detail in the model, and a clear improvement in the image. Furthermore, the FWI was able to invert the model with much reduced acquisition footprint, compared to the reflection tomography, clearly revealing a surprising amount of detail in the gas cloud and shallow geology. A taste of Shell's result is given in Figure 6; the update in the velocities around the salt bodies appears to improve the quality of the gathers. Both fields were thought to be anisotropic (VTI) but the inversions were run in essentially "passive" anisotropic mode only. Plessix fixed the η parameter and inverted for the NMO velocity, accepting that surface data alone is insufficient to estimate vertical velocities and thus image at the correct depth; Albertin showed that inverting the velocity with their previously-derived anisotropy parameter values gave good well ties. The extremely encouraging results shown in these presentations gave strong indications that the long-held-out promise of FWI for exploration seismology may finally be beginning to be realized.

The third real-data application of FWI was shown by Denes Vigh (WesternGeco), who addressed a more challenging problem in deepwater subsalt Gulf of Mexico subsalt exploration with surface streamer data. The targets are typically much deeper here than in the North Sea, and offsets are limited to 8–9 km, so a large part of the model is only potentially sampled by reflected energy, and even with wide-azimuth data there are surely areas with limited illumination. Furthermore, the bandwidth of recorded frequencies is also rather narrower than for ocean-bottom data. Nonetheless, migration images post-FWI showed areas which seemed to be distinctly improved relative to the initial images, which were obtained with a conventional PSDM workflow. The FWI seemed, in particular, to have updated some features of the salt model, increasing the complexity of the flanks and adding inclusions (Figure 7). Vigh emphasized the importance of careful QC (and interpretive input) at each iteration. He also discussed FWI in anisotropic environments; it is essential to allow for this; synthetic examples showed good results, but mostly from

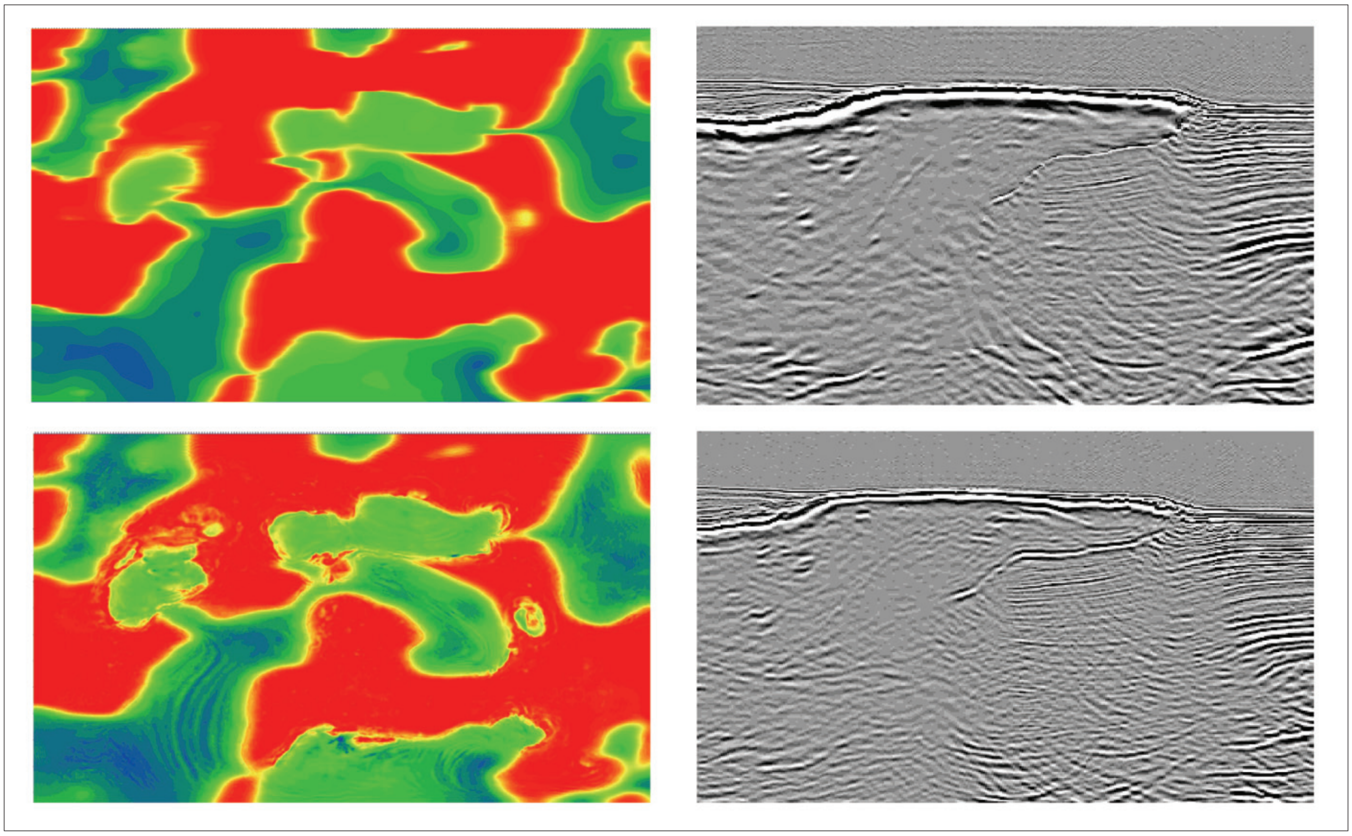

Figure 7. *Depth slice through WesternGeco's starting (top left) and inverted (lower left) velocity models and (right) inlines from the corresponding RTM images.*

starting models which seemed to be smoothed versions of the true models. How these might be obtained was not discussed and remains an issue in the application of FWI.

Stephen Kelly (PGS) presented FWI of 2D data acquired using the PGS proprietary dual-sensor streamer (Geostreamer), which also allows the extension of the data bandwidth compared to conventional streamer data, in particular allowing deep tow to access low frequencies without the ghost notch disrupting the medium-high part of the spectrum. Data preconditioning allows 2D inversion, and they invert for both (P-wave) velocity and density, using a Gardner-type relation to constrain the density. Illumination compensation is applied to the gradient and Kelly observed that the use of a Cauchy or Sech norm resulted in gradients with fewer artifacts, and better balance between the subsalt and the rest, than the standard L2 norm.

The final presentation of the afternoon was by Joe Meng (ConocoPhillips), who demonstrated the use of Hale's structure-oriented smoothing filter to constrain/condition FWI gradients on some synthetic data examples. This accelerates convergence and appears to improve the recovery of the low-frequencies by imposing consistency between the velocity updates and the image, and may therefore be a very useful tool in the practical application of FWI when acquisition and other conditions are less than ideal.

The afternoon discussion was dominated by the startling results from the 3D real data inversions and, overall, this workshop gave the impression that we are at the point of moving to the next level in velocity estimation for complex imaging. Methods based on the wave equation are now (close to) taking their places in industrial practice alongside the corresponding imaging techniques, even if they are yet far from standard. Nonetheless, we may expect that these methods will continue to evolve for many years to come. We also saw that wave equation imaging techniques, while much further advanced than the velocity estimation tools, are still advancing, and may continue to do so for some time to come.

As a final note, many of the presenters authored, or coauthored one or more papers related to their presentations in this workshop for publication in the SEG 2009 *Expanded Abstracts*. Several also contributed to articles in the supplement to the November-December 2009 issue of Geophysics, "Advances in Seismic Imaging and Inversion," which also contains many other articles pertinent to the theme of this workshop. TLE

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