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A tale of two realities: comparing physical and numerical modeling responses for a common physical model

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Summary

A physical model was constructed and surveyed in the CREWES physical modeling facility, to analyze seismic illumination and imaging of a complex structure where a high-velocity sill and dike complex near the surface masks and distorts the response from deeper structure (Henley and Wong, 2019; Henley and Wong, 2020; Wong et al, 2019). The survey data are difficult to process to a credible depth image without using a priori knowledge of the actual model structure. We use a manual 'bootstrap' process to obtain a reasonable depth image by incorporating our schematic knowledge of the actual model surfaces and physical properties to guide the depth imaging. We then use the velocity model verified by the depth imaging to create a Finite Difference numerical survey of the velocity model and compare the depth images from the numerical survey with those from the physical modeling survey for insight into full waveform inversion (FWI).

Method

The goal of FWI is to extract an accurate and detailed velocity structure of the earth from the observed seismic survey data. The process involves processing the seismic data to form the best possible depth image of the velocity structure (VID), then forward modeling the velocity to create a synthetic survey to compare to the original seismic data. From the image differences, adjustments to the velocity model are computed and applied for the next round of processing/forward modeling. Our work is somewhat different, in that we have some exact details of the physical model surveyed (a schematic plot showing the relative positions of all layer surfaces, and exact velocities and densities in each layer or feature), but no scaled digital representation of that schematic model. Hence, our study begins by merging the measured seismic data and the schematic model to create a velocity vs. depth (VID) model which fits the depth image of the survey data. This model is then used to create a numerical survey whose image can be compared to that from the physical model survey. Comparisons between the images give us insight about the accuracy of our VID model and the intrinsic differences between physical modeling (noises, mode conversions, etc.) and acoustic numerical modeling.

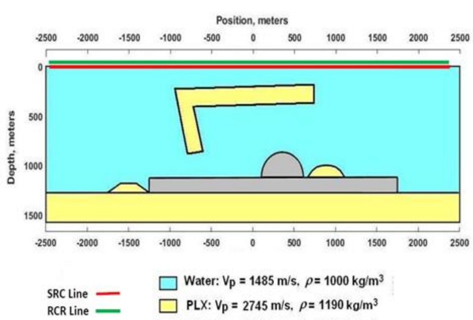

FIG. 1. Schematic of dike and sill model surveyed in the physical modeling tank.

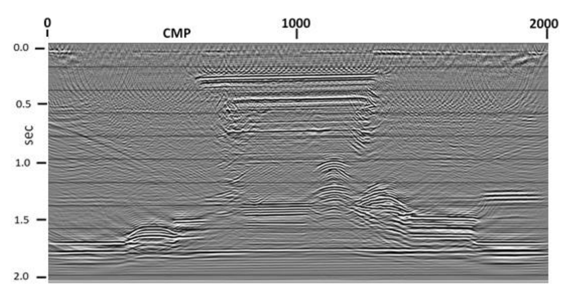

FIG. 2. Post-stack Kirchhoff time migrated image of the model after several iterations of NMO analysis.

Part I: processed seismic image + schematic = VID model + physical depth image

A schematic of the 'dike and sill' physical model created for study in the CREWES physical modeling facility is shown in Figure 1, with scaled dimensions of 5000 m by 1500 m and exact velocity and density values shown for each of the features in the model. A 2D CMP survey was performed over this model, using 101 shots, spaced at 50 m, into a fixed array of 1001 receivers, spaced at 5 m, to provide CMP spacing of 2.5 m, with a maximum fold of 100 (Wong et al, 2019). The seismic survey is processed to create the actual VID velocity model from the schematic as follows:

- Source-oriented coherent noise is removed with RT filtering (Henley, 2003) on source gathers.
- Signal wavelet is shortened, spectrum broadened with Gabor deconvolution (Margrave et al, 2011).
- Reflections from tank sides and bottom are removed by median filtering and subtraction on common-offset gathers.
- NMO analysis is performed iteratively on CMP supergathers, using both manual and automatic semblance picking, resulting in VRMS velocity field.
- The CMP stack is formed, and post-stack Kirchhoff time migrated image is created using the 'best' NMO velocity field (VRMS). (See Figure 2)
- With a velocity editing tool, horizons are picked on the post-stack time migrated image corresponding to *every single* boundary in the schematic in Figure 1.
- Using the same velocity editing tool, all the regions bounded by the picked horizons are filled with the known V_p values from the schematic to form the VIT velocity field. (Figure 3)
- The VIT velocity field is converted to VID, using simple 1D conversion. (Figure 4)
- With the velocity editing tool, distortions in the boundaries in the VID model are removed to create the best estimate VID model. (Figure 5)
- Pre-stack Kirchhoff depth migration creates the seismic depth image which is overlaid on the VID model to confirm the correctness. (Figure 6)
- VID is used to update VIT and VRMS velocity fields.
- CMP stack and post-stack Kirchhoff time migration are performed using the new velocities and the images compared with previous images for additional validation.

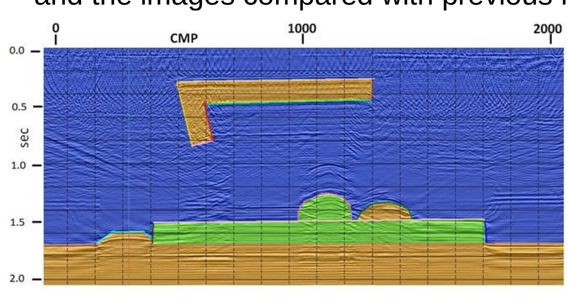

FIG. 3. Schematic boundaries fitted to reflections and other features of the post-stack time migrated image—this is the first estimate of the VIT model.

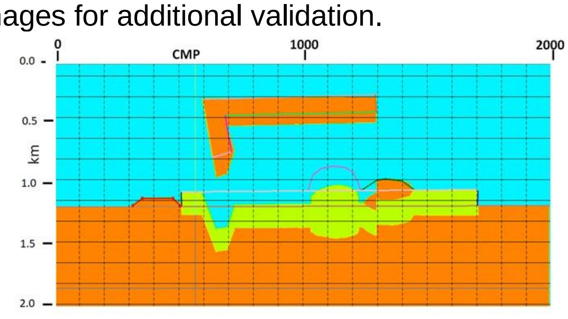

FIG. 4. VIT velocities from Figure 3 converted directly to VID using 1D conversion—systematic under-estimation of values distorts boundaries. Re-picked boundaries are outlined.

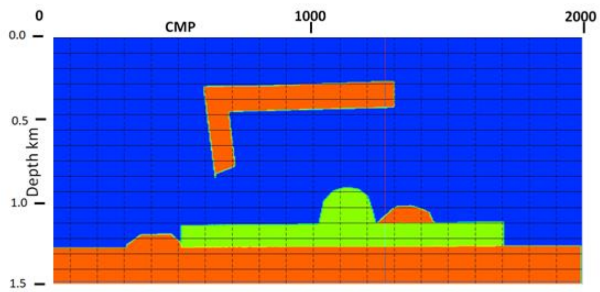

FIG. 5. Corrected VID model from editing Figure 4.

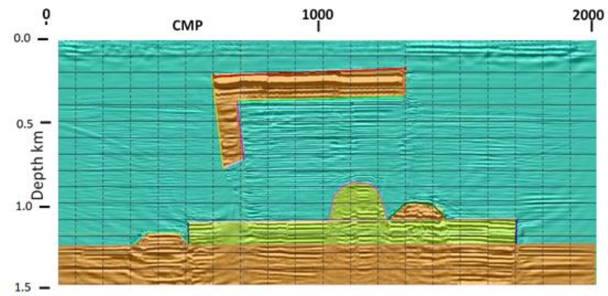

FIG. 6. Physical model data after pre-stack Kirchhoff Depth migration using VID model in Figure 5, With VID model overlaid to check fit.

Part II: VID model + FD acoustic modeling + processing = numerical depth image

After creating the VID model of the physical tank model and verifying its fidelity against processed physical model data, we created a synthetic simulation of the physical modeling process by applying a finite difference acoustic modeling algorithm (Kelly and Marfurt, 1990) to create a numerical 2D CMP survey, whose images can be compared to those from the actual physical survey. The numerical survey uses the same acquisition geometry as the actual survey. Figure 7 is a shot gather from the physical modeling survey, and Figure 8 is the corresponding shot gather from the numerical modeling survey, with the same pre-processing applied (RT filter, Gabor deconvolution). The following processing produces a depth image from the numerical modeling survey:

- RT filter to remove coherent source energy.
- Gabor deconvolution to broaden spectrum, sharpen wavelet.
- CMP stack and post-stack Kirchhoff time migration using VRMS determined in Part I.
- Pre-stack Kirchhoff depth migration using VID determined in Part I (Figure 9).
- Overlay the numerical depth image on the VID model to confirm the match. (Figure 10).

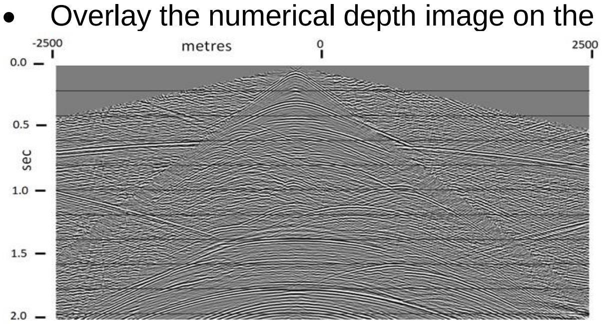

FIG. 7. Shot gather from source location 451 of the Physical model survey. RT filtering and Gabor Deconvolution have been applied

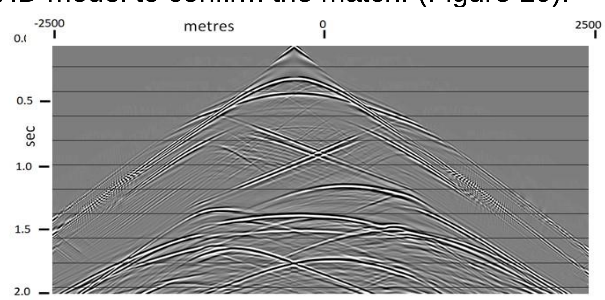

FIG. 8. Shot gather from source location 451 of the FD acoustic numerical model survey. RT filtering and Gabor Deconvolution have been applied.

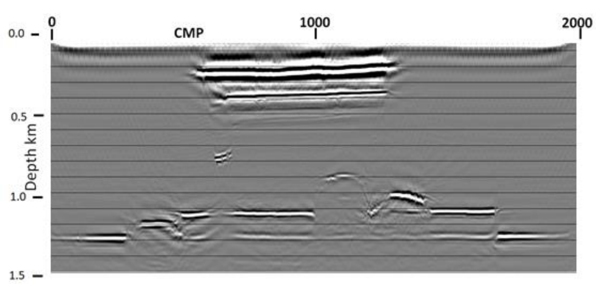

FIG. 9. Pre-stack Kirchhoff depth migration of FD acoustic Numerical model survey

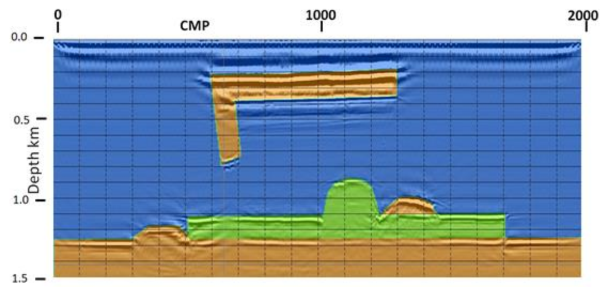

FIG. 10. Pre-stack Kirchhoff depth migration overlaid on the VID model derived from Part I and used for both the forward modeling and the pre-stack Kirchhoff depth migration.

Part III: compare responses

Although we have not established a feedback mechanism for updating the VID model based on differences between the physical and numerical model images, as in full-on FWI, we can display the differences and discuss which ones are intrinsic (due to differences between the actual physical environment for the modeling survey and the numerical environment for the FD modeling).

Results and discussion

First, we compare Figures 7 and 8, two corresponding source gathers from the physical and numerical modeling surveys, respectively. We can find comparable reflection events on both gathers; but the two gathers differ considerably in appearance, nevertheless. Although the physical model has only a limited number of discrete reflecting surfaces, we see numerous coherent events filling the space between known reflections. These are almost certainly various reverberations and mode-converted events created and propagated in the physical modeling tank, since even in the simulated marine environment, P-waves impinging on hard surfaces can lead to mode-converted waves in the solid, which are re-converted as they emerge into the water. In addition, there are coherent events with apparent hyperbolic moveout originating in the physical modeling apparatus, *external to the model itself*, that also manifest themselves on source gathers. The numerical modeling, on the other hand, uses an acoustic algorithm which does not support mode conversions, and which is strictly 2D (the physical model has basically 2D geometry, but its wave amplitudes are, in fact, 3D). As well, only velocities were used in the finite difference algorithm, so while the kinematics of the seismic events are correct, their amplitudes are not. Nevertheless, when we compare Figures 6 and 10, we see that the pre-stack depth-migrated images of both the physical modeling and the numerical modeling fit the common VID model reasonably well. This model was used only to migrate the physical model data; whereas it was used both to create and migrate the numerical model data.

Figure 11 shows the squared differences between the depth images created from the physical model and the numerical model, and Figure 12 shows small windows of the matched waveforms from the two images before subtraction.

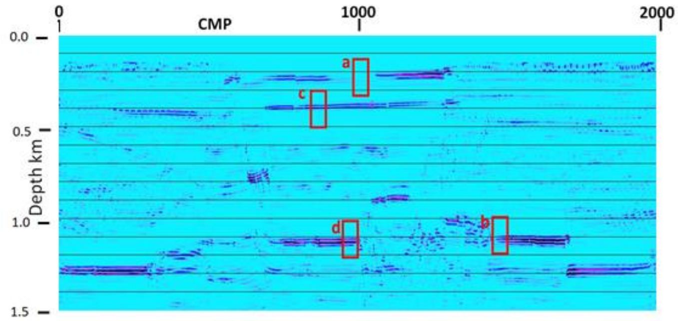

FIG. 11. Misfit function (squared differences) between physical model image in Figure 6 and numerical model image in numerical model survey in Figure 9.

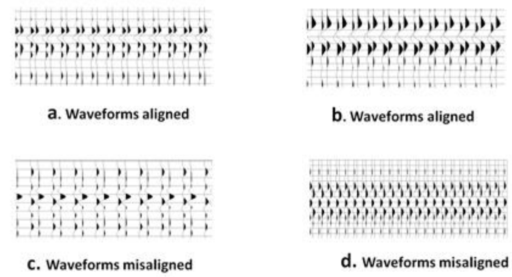

FIG. 12. Zoom of waveforms from zones marked on the misfit function in Figure 11.

On the image misfit function shown in Figure 11, we focus on four small regions where the images seem to fit relatively well, or relatively poorly. Small selections of traces from the actual images before subtraction are shown in Figure 12. Where the images appear to match relatively well, as in regions a. and b., we note that these parts of the images correspond to surfaces in the model which have only water above them, whereas the mismatches correspond to surfaces with other model interfaces above them, the more intervening interfaces, the greater the mismatch. This implies a possible systematic depth error in one or more of the VID interfaces, and provides a possible hint for how to update the model—by adjusting complete interfaces in depth.

Acknowledgements

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