Subsalt Imaging with Converted Waves

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Summary

Converted-wave energy is significant in both standard towed-cable and ocean-bottom cable (OBC) acquisition geometries. We present a 2-D modeling study designed to investigate the use of converted-wave energy to image geological structure below high-velocity salt layers. Rock physics properties typical of Gulf of Mexico oil bearing environments were used to numerically generate synthetic data sets. The synthetic data sets were generated by elastic ray tracing, acoustic modeling, and elastic modeling. These modeling results were analyzed to determine the conditions under which significant amounts of energy are converted from P-wave propagation to S-wave propagation, and to gain an understanding of the nature of these conversions so that they can be used for optimal reservoir imaging and characterization. We investigated converted waves for both towed-cable and OBC acquisition. Substantial energy and information can be obtained from OBC data for reservoir characterization in difficult to image areas where the reservoir rocks may not have a good P-wave impedance contrast with surrounding host rock (MacLeod et al., 1999) or when imaging is obscured by phenomena such as gas clouds (Thomsen et al., 1997).

The modeling study allowed us to corroborate the rock physics predictions based on the Zoeppritz equations. Migration of symmetric-mode converted-wave data illustrates the advantages and feasibility of converted-wave imaging.

Modeling and Ray Tracing

Five different models were used in this study, but for brevity results from only two are discussed in this abstract. Figure 1 is an elastic modeling result obtained for a simple flat layered earth model simulating marine towed-cable geometry. The model consists of a salt slab embedded in a sedimentary halfspace overlain by a 500 meter water column. To facilitate discussion, the labeling convention of the events ignores the water column leg, and the "P" for the water column has been dropped from the notation (ie. the event labeled PSSP should really be labeled PPSSPP, but the outer P's corresponding to the water column have been dropped). The PSSP arrival in Figure 1 represents a reflection off the bottom of a salt layer, and is clearly very energetic and significant despite the mode conversions and transmission through the water-sediment interface.

Ray tracing allowed us to clearly identify the kinematics of significant reflection events. These events are labeled in Figure 1 and include:

- P-wave reflections off the top and bottom salt (PP, and PPPP, respectively).
- The bottom-salt converted mode reflection corresponding to P-wave propagation in the sediments and S-wave propagation in the salt (PSSP), This represents an important imaging target.

The headwave event seen splitting off from the PP reflection denotes the point at which the P-wave critical angle is reached for the top-salt reflector. At this point the PP reflection energy splits into a post-critical reflection and a headwave. The PPPP arrival energy begins to decrease significantly at the P-wave critical angle, while the PSSP arrival energy begins to increase. This verifies the rock physics prediction that the maximum P to S conversion begins at the P-wave critical angle (Purnell and Ogilvie, 1996).

The OBC modeling results are displayed in Figure 2. The converted-wave PSSP event remains strong and significant, but there are now additional S-wave arrivals in the data, including:

- The top-salt converted mode reflection corresponding to P-wave propagating downward to the top of salt, and conversion to S-wave upon reflection (PS).
- The bottom of salt converted mode corresponding to P-wave propagation to the bottom-salt reflector and S-wave propagation back to the surface(PPSS).

The strength of these additional S-wave arrivals is indicative of the added subsurface information that can be attained from OBC data versus standard towed-cable data. This synthetic OBC gather

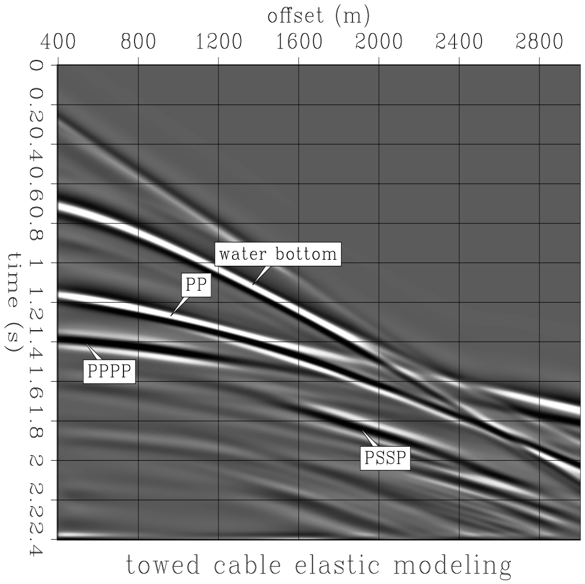

Figure 1: Elastic modeling results for towed-cable acquisition marine 1-D model. To facilitate comparison, the P-wave leg in the water column has been eliminated from the conversion notation in the labels. The PSSP bottom-salt reflection is energetic and represents an important imaging target

represents only one component of the elastic wavefield. In practice, actual OBC data records multi-component (4C) data, vastly increasing the amount of potential information that can be used for imaging.

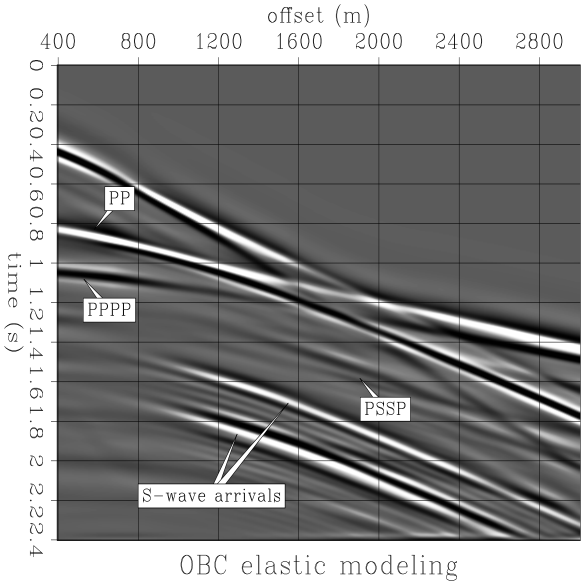

Figure 2: Elastic modeling results for ocean bottom cable (OBC) acquisition marine 1-D model. To facilitate comparison, the P-wave leg in the water column has been eliminated from the conversion notation in the labels. Strong converted S-wave arrivals are present in the wavefield because the geophones are located on the ocean bottom.

The 1-D model study is useful for determining the nature and significance of mode conversion, but the imaging objectives that could most benefit from the use of converted-wave energy are those with complex structure. Therefore, we generated synthetics corresponding to a complex salt structure. We used the same petrophysical parameters as the 1-D study, but replaced the tabular salt body with a salt body based on a transect through the SEG/EAGE velocity model. Ray tracing and elastic modeling results for a representative shot gather are displayed in Figure 3. The ray tracing results are shown on the left, and the elastic modeling results are shown on the right.

Converted wave imaging

Multiples and multivalued arrivals are also abundant in the elastic modeling results, complicating event identification. Despite the complicated nature of the wavefield, comparison to the ray tracing allows for the ready identification of numerous significant primary and converted-wave events. The complexity of the wavefield attests to the need for including converted-wave energy in the imaging process, and the desire to recover all available petrophysical information from the complete wavefield.

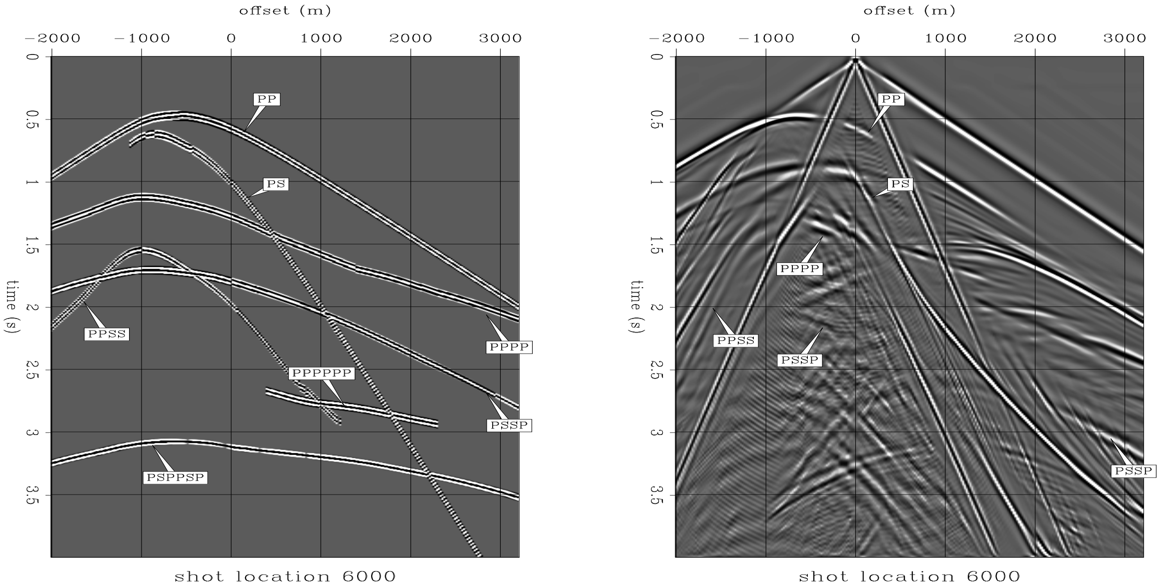

Figure 3: Left: Ray tracing. Right: Elastic modeling. Results are for the SEG/EAGE-shaped salt body embedded in sedimentary halfspace.

Imaging with Kirchhoff Depth Migration

We now turn our attention to using the observed converted-wave energy for depth imaging of complex geological structure. To represent a realistic imaging challenge, we model a complicated distribution of elastic parameters and subsurface reflectors. For the symmetric mode conversions, we migrate converted wave data by replacing the P-wave salt velocity with the S-wave velocity in the salt. This means that all the arrivals corresponding to propagation modes with an S-wave leg in the salt and P-wave everywhere else (ie. PSSP and PSPPSP) will be properly positioned and all the other modes (Such as pure P modes and PPSS, PPPSSS etc.) will be mispositioned.

The bottom of salt is well imaged in Figure 4. The dotted line in the figure corresponds to the bottom of salt in the velocity model, and it matches the migrated event perfectly. This is not surprising based on the relative transmission coefficient for the P to S conversion at top of salt and the fact that only two conversions are required, thereby minimizing energy loss at interfaces. This is an example of a correctly imaged PSSP event. The P-wave and S-wave positioning is an important indicator of velocity accuracy, carrying critical and useful information about geology and lithology (Tatham, 1982).

Two clearly imaged PSPPSP events are the sand lens and the cross-cutting fault. The PSPPSP sand lens image is weaker than the mispositioned P sand lens image because of the additional conversions that the energy must go through to illuminate the reflector. The PSPPSP image of the cross-cutting fault is a great imaging success because it is not visible at all as a P event. The subsalt anticline is distorted by cross-cutting artifacts and stronger mispositioned P-image of the anticline, but it is faintly visible just below the mispositioned P-image. The image can be further improved by post-migration image enhancement (such as AGC and muting).

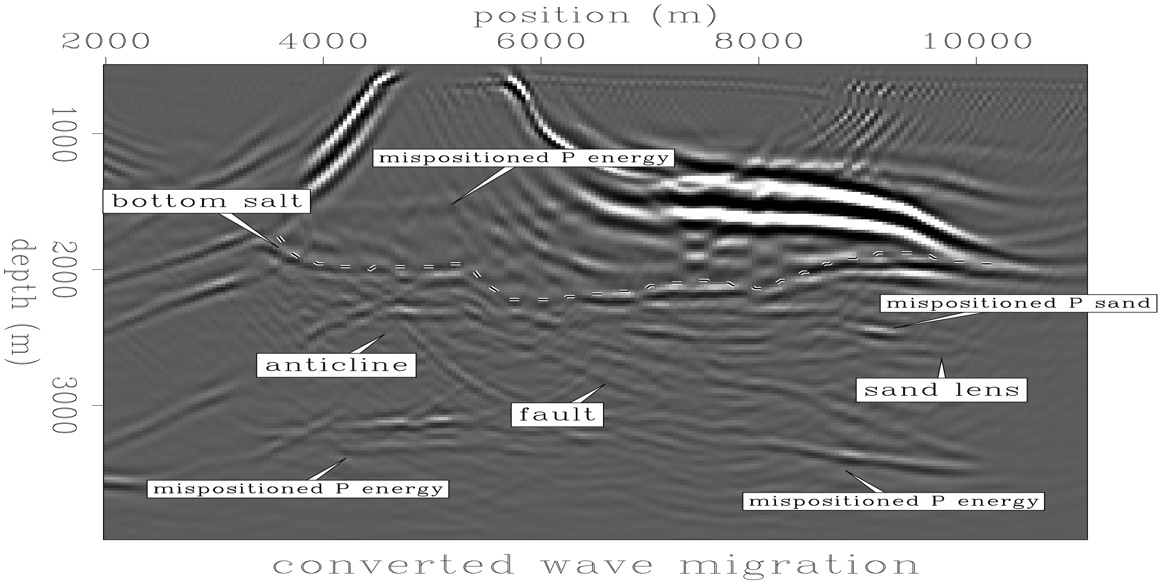

Figure 4: converted-wave migration of SEG/EAGE 2-D synthetic data. The bottom of salt, cross-cutting fault, subsalt anticline, and sand lens are imaged.

Conclusions

Through modeling, ray tracing, and migration, we demonstrate the utility of converted wave energy for imaging in two distinctly different and complementary data acquisition modalities: towed-cable, and OBC. We obtained very encouraging results in imaging the bottom of salt and *subsalt* for a very complex 2-D geological model using converted-wave propagation through the salt.

References

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