Salt Boundary Delineation by Transmitted PS Waves

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ABSTRACT

Interfaces nearly perpendicular to wavepath propagation, and therefore invisible to PP reflections, are well illuminated by migration of PS transmitted waves. Here I show that PS transmitted arrivals in a Gulf of Mexico VSP data set can be migrated to properly image a tabular salt body even though the receiver array is well below the transmitting boundary.

INTRODUCTION

Last year I showed that reduced-time migration can reduce the migration error associated with an incorrect velocity model and remove errors associated with an arbitrary data time shift (Sheley, 2000). In this paper I combine reduced-time migration with wavepath migration and investigate the feasibility of using transmitted PS waves to image a vertical boundary model and an offshore VSP data set.

REDUCED-TIME MIGRATION THEORY

In this section I will review reduced-time migration for both reflection (PP, SS, and PS) and transmission (PS, SP) arrivals (Sheley, 2000).

To illustrate reduced-time migration I’ll start with the conventional migration equation for PP reflections:

\[ m(r) = \int D(z_g, \tau_{sr}^P + \tau_{rg}^P)dz_g. \] (1)

The migrated image is denoted by \( m(r) \), \( D(z_g, t) \) represents the seismograms in a common-shot-point gather (CSG), \( \tau_{sr}^P \) is the travelt ime from the source to image
point, \( r \), at P-wave velocity, \( \tau^P_{sr} \) is the traveltime from the image point to the receiver at P-wave velocity, and \( z_g \) is the receiver depth.

The purpose of reduced-time migration is to decrease the effect of an incorrect P-wave velocity model or to eliminate the effect of an arbitrary time shift. To accomplish these tasks two time shifts are made to the migration equation (equation 1). The shifts are made by adding the direct wave observed traveltime (\( \tau_{sg}^{obs} \)) and subtracting the direct wave calculated traveltime (\( \tau_{sg}^{calc} \)) for a given source and receiver from equation 1:

\[
m(r) = \int D(z_g, \tau_{sr}^P + \tau_{rg}^P - \tau_{sg}^{calc} + \tau_{sg}^{obs}) dz_g. \tag{2}
\]

The effect of these shifts is to ensure that the direct P-wave is mapped to its exact location and all subsequent events closer to their true positions. It is evident that if \( \tau_{sg}^{calc} \) and \( \tau_{sg}^{obs} \) are equal in equation 2 then they will cancel reducing to equation 1.

To migrate converted events a straightforward modification of equation 2 is necessary. For example, to migrate P- to S-wave conversions we keep the first temporal term, \( \tau_{sr}^P \), and replace the second temporal term, \( \tau_{rg}^P \), with \( \tau_{rg}^S \), the traveltime for S-waves to propagate from an image point to the receiver. The resulting migration equation is given as:

\[
m(r) = \int D(z_g, \tau_{sr}^P + \tau_{rg}^S - \tau_{sg}^{calc} + \tau_{sg}^{obs}) dz_g. \tag{3}
\]

Equation 3 may be used to migrate both transmitted and reflected PS events, but I usually impose an incidence angle restriction.

**SYNTHETIC DATA RESULTS**

In this section I generate synthetic data and migrate it according to both the standard migration algorithm and the reduced-time migration algorithm.

**Forward Modeling**

The vertical boundary model in Figure 1 is used to generate both crosswell and RVSP seismic data. P-wave velocities are 5000 m/s and 5500 m/s, the P-to S-wave velocity ratio is 1.5, and a constant density is used. Parallel source and receiver wells are bracket the model for the crosswell simulation. The RVSP simulation uses the same sources as for the crosswell simulation but the receivers are along the top of the model. Synthetic seismograms were computed using
UTAM’s psvr4.f, a 2-D elastic wave modeling code, placing sources and receivers every meter. The grid point interval is 20 centimeters and the time interval is 20 microseconds. Source frequencies above 2000 Hz are often used in hardrock crosswell experiments; I chose a 1500 Hz vertical-component line source and 6000 time steps. The lines source is orthogonal to the model space and therefore geometric spreading occurs in only two dimensions. Both vertical- and horizontal-component data were generated and recorded. A common-shot gather for a source at 100 meters depth and receivers on the surface (RVSP) is shown in Figures 2 and 3. Seismograms from both crosswell and RVSP data sets are then migrated using both Kirchhoff and wavepath migration algorithms in combination with the reduced-time imaging condition.

Migration Results

In this section I present the results of migrating the synthetic data described in the previous section. Prior to migration I isolated the PS transmission events by muting all other arrivals. Using no restriction on incidence angles, Kirchhoff and wavepath PS migrations were applied to the isolated events of the crosswell model for both the true velocity (Figures 4a and 4c) and for a 90% velocity model (Figures 4b and 4d). The events are migrated to their actual position for the true velocity model and to an incorrect position for the 90% velocity model as expected. I then adjusted the computer codes to compute equation 3, the reduced-time migration equation for transmission PS arrivals. Results for reduced-time PS migration are shown in Figure 5. For the 90% velocity model the location of the transmitting boundary is much closer to the true boundary position when using reduced-time migration. It is also evident that, as Sun has shown (Sun, 1999), wavepath migration reduces migration artifacts by migrating energy only to the Fresnel zone of the specular reflection point.

The results for synthetic RVSP data are similar. Figures 6 and 7 show the results for conventional and reduced-time migration of transmitted PS waves. Figures 8 and 9 show the results for transmission SP waves.

Note, that much more of the boundary is imaged by migrating the SP waves than by migrating the PS waves. This is due to the fact that the velocity contrast for the SP waves is greater that that for the PS waves and hence the SP waves are refracted more. Also note that the boundary in the wavepath migration images, Figures 8d and 9d, lack continuity. Since the wavepath algorithm uses the model velocity and the apparent velocity of an event to calculate the incidence angle and since the examples in Figures 8d and 9d use an incorrect velocity model
the calculated incidence angle is incorrect. Therefore the calculated Fresnel zone
does not coincide with the actual focusing point. This was not a problem for
the crosswell or RVSP PS migrations since the events were being migrated to a
location much closer to the receivers, which rendered incidence angle information
less important. In other words, even though the incidence angle was incorrect a
portion of the Fresnel zone still coincided with the energy focusing point.

FIELD DATA RESULTS

In this section I will present a description and the results from an offshore
VSP data set donated by a generous sponsor.

Data Description

The data consists of three 3-component gathers at offsets of 500, 2000, and
5000 ft from the well head (Figure 10). The 500 ft offset gather consist of 82
receiver stations from depths of 8700 to 12750 ft at 50 ft intervals. The 2000 and
5000 ft offset gathers contain 95 receiver stations, each between depths of 10000
and 14700 ft, again at 50 ft intervals. Sample gathers are shown in Figure 11 and
interpreted in Figure 12. The vertical axis is depth in kft and the horizontal axis
is time from 1.2 to 3.0 seconds. The upper figure shows the vertical component
primarily containing direct and reflected P-waves. A horizontal component (X)
for the same shot offset is shown in the lower figure; this shot gather records
reflections and transmissions from both P- and SV-waves. A P-wave velocity
model is generated from well information (Figure 13 top-left). An S-wave ve-
locity model was estimated from near vertically incident PS transmission and
reflection events (Figure 13 bottom-left). A P- to S-velocity ratio of 1.6 and 2.7
was used for the salt and sediment, respectively. Prior to migration, the data
were reoriented by maximizing the P-wave energy (Ahmed, 1987). This was first
done on the X- and Y-components, maximizing the energy on the X-component
direct wave (Figures 14 and 15), then on the Z- and X-components, maximizing
the Z-component direct wave energy. The events with the desired moveout veloc-
ity were picked and flattened. The flattened gathers were median and bandpass
filtered and unflattened. Figure 16 shows the isolated reflected P-waves (top)
and transmitted S-waves (bottom) for the 500 ft offset gather.

Migration Results

In this section I present the results from migrating the offshore VSP data
described in the previous section. For each of the three gathers I migrated the PP reflections (upgoing P-wave using equation 2), PS reflections (upgoing S-wave using equation 3 with an incidence angle constraint), and PS transmissions (downgoing S-wave using equation 3 with an incidence angle constraint). The grid spacing for my migration was 10 ft in both the offset and depth directions (in hindsight a more coarse discretization in the offset direction may have been appropriate). Conventional migration as well as reduced-time migration were applied although no significant difference could be determined between the two. I find that the velocity models (Figure 13) accurately describe the true earth velocity. The average time difference between the calculated direct-P traveltime \( \tau_{calc} \) and the picked direct-P traveltime \( \tau_{obs} \) was about 6 ms (6 data time samples). Since there is little difference between the two I will only show the reduced-time examples.

I will first show the results for the 500 ft offset gather followed by the 2000 ft offset gather. For comparison I generated a synthetic seismogram (Figure 17 left) based solely on the well log velocity function (Figure 13).

Using a Kirchhoff migration algorithm (equation 2) I migrated the 500 ft offset Z-component gather with isolated P-wave reflections (Figure 16) to obtain the reflection section shown in Figure 17. The prominent event at 10400 ft is the base of salt and correlates with the same event in the synthetic seismogram. A similar event can be found a bit higher in the reflected PS image, Figure 18. This figure shows another event at 9200 ft which correlates with the top of salt. The transmitted PS migrated image (Figure 19) shows a strong event at 9200 ft which correlates well with the top of salt. In this figure I reversed the polarity of the synthetic seismograms to accentuate the top boundary of the salt. Also, in this figure the reader may notice that the events below the top of salt dip steeply to the right. Since the geologic interfaces in this region are assumed to be flat and appear to be so in the other migrated sections, I assume that this dip may be caused by salt anisotropy. A supporting argument could be that the previous image (Figure 18) contains the Y-component while this image contains the X-component.

Figures 20, 21, 22, contain, respectively, the reflected P, the reflected PS, and the transmitted PS migrated images for a source offset of 2000 ft. In Figure 22 notice the prominent events at 10400 ft, the base of salt, in the reflected images. Notice the quasi-correlation between the top of salt, above the uppermost receiver at 10000 ft, and the prominent event in the migrated section. Finally in Figure 23 I show a comparison between wavepath and Kirchhoff migration for transmitted
PS arrivals from sources at 2000 ft offset. Note that although they contain most of the same coherent events that the wavepath image contains much less noise. Also, the events in the wavepath image have a higher wave number than their counterparts in the Kirchhoff image.

**DISCUSSION AND CONCLUSION**

I have shown that the effect of an incorrect P-wave migration velocity on converted-wave migration can be diminished by using a reduced-time migration algorithm. Results from synthetic and field data show that PS transmitted arrivals in VSP data can be migrated by this technique to reconstruct the transmitting boundary. The Gulf of Mexico VSP data were successfully used to reconstruct the top and bottom of the tabular salt body even though the top of the salt body was above the receiver array. Also, if the PS transmission events are isolated a reflection-free migration image may be obtained.

**ACKNOWLEDGMENTS**

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**REFERENCES**


Figure 1: Vertical boundary model used to generate synthetic crosswell and RVSP data. Density is constant for the entire 100 m² model and a 1500 Hz Z-compressional source was simulated. The left half of the model has P- and S-wave velocities of 5000 and 3333 m/s, respectively. The right half of the model has P- and S-wave velocities of 5500 and 3666 m/s, respectively. Sources for both crosswell and RVSP simulations are on the left at one meter intervals (101 total). Receivers for the crosswell simulation are on the right and across the top for the RVSP simulation, 101 receivers at one meter intervals are used for both.
Figure 2: Synthetic RVSP seismogram for a source at 100 m depth. The source frequency is 1500 Hz, receiver spacing is 1 m, and the total record length is 0.06 seconds.
Figure 3: Same as Figure 2 with prominent modes identified.
Crosswell: PS Migration

Figure 4: Migrated images for the crosswell experiment. The sources were on the left and the receivers on the right. The PS transmitted waves were isolated by muting. Images (a) and (c) use the true velocity model while (b) and (d) use a velocity 10% slower than the actual velocity model.
Crosswell: Reduced-Time PS Migration

Figure 5: Similar to Figure 4 but reduced-time migration was used (equation 3). Images (a) and (c) are identical to those in Figure 4. Notice how the migrated position of the boundary is much closer to its true position in images (b) and (d) than for their counterpart images in Figure 4, validating the effectiveness of reduced-time migration.
Figure 6: Migrated images for the RVSP experiment. The sources were on the left and the receivers were along the top, both at one meter intervals. Note that in (a) and (c) although the true position of the boundary is obtained only a small portion of it is actually imaged due to the restricted RVSP geometry and refraction effects. Also note that wavepath migration has less artifacts than Kirchhoff migration.
RVSP: Reduced-Time PS Migration

Figure 7: Reduced-time migrated images of PS waves for the RVSP experiment. Notice that the transmitting boundary in (b) and (d) for reduced-time migration is imaged much closer to its true position than for (b) and (d) in Figure 6.
RVSP: SP Migration

Figure 8: SP migration for the RVSP experiment. Note that much more of the transmitting boundary is imaged than with PS transmitted waves (Figure 6). Also, note that image (d), the wavepath image, has such poor quality since an incorrect incidence angle was calculated due to the 90% velocity model.
Figure 9: Reduced-time SP migration for the RVSP experiment. The incorrect velocity model has less of an effect on the boundary location in (b) than for the previous figure (Figure 8b). The wavepath image still suffers from the incorrect incidence angle calculation.
Figure 10: Offshore VSP acquisition geometry. The top image shows the relative location of the sources to the well head. Since the source was on a ship there is some scatter in each offset’s source location. The bottom two figures show the relative location of the receiver array to the source position for the different offsets.
Figure 11: Shot gather for a source at 500 ft with depth in kft along the vertical axis and one-way traveltime along the horizontal axis. The Z-component is at the top and the X-component is at the bottom. The Y-component is not shown.
Figure 12: Interpreted shot gather for a source at 500 ft. Similar to Figure 11 with a juxtaposed interpretation of the various events.
Figure 13: Top shows P-wave migration velocity model (left) and a velocity profile (right), bottom shows similar figures for the S-wave migration velocity model. For the velocity profiles the solid line indicated the actual velocity distribution with depth and the dashed line represents the smoothed velocity function used for migration.
Figure 14: A comparison of before and after reorientation of the seismograms in the XY-plane. The energy in a small window surrounding the direct P-wave was maximized.
Figure 15: The degree of rotation used to reorient the X- and Y-components. An X- and Z-rotation was also performed but is not shown. After rotation the continuity of events was improved and transverse waves were largely removed from the Z-component.
Figure 16: Desired event velocities were picked, flattened, median filtered, unflattened, and bandpass filtered to produce these gathers. Since single events have a large range of velocities and aliasing of some of the S-waves FK filtering could not be used. It appears that the chosen method has worked adequately to isolate the desired events.
Figure 17: Migration of the gather shown in the top of Figure 16, the reflected P-waves. A synthetic gather calculated solely from borehole velocities is shown on the left. There is good correlation with the bottom of salt and the strong event in the migrated gather.
Figure 18: Migration of the reflected PS transmitted wave gather shown at the bottom of Figure 16. Once again notice the correlation of the strong event with the base of salt in the migrated gather.
Figure 19: Migration of transmitted PS arrivals (right). The synthetic seismograms have been rotated 180 degrees from the previous two figures to emphasize the top of salt boundary. Notice the excellent correlation between the top of salt in the synthetic and migrated traces. The dip of the lower events may be due to anisotropy since corresponding events in Figure 18 (right) are flat.
Figure 20: Migration of reflected P-waves from a source position of 2000 ft. The active receivers range from depths of 10000 to 14700 ft.
Figure 21: Migration image of reflected PS waves for a source at 2000 ft offset.
Figure 22: Migration of transmitted PS waves. Notice that there are migrated events above to uppermost receiver (10000 ft). The dipping events in this gather may be due to shear-wave anisotropy within the salt.
Figure 23: Comparison of wavepath and Kirchhoff migration for transmitted PS arrivals. Notice that although they contain most of the same coherent events that the wavepath image contains much less noise. Also, the events in the wavepath image have a higher wave number than their counterparts in the Kirchhoff image.