MIGRATION OF TRANSMITTED ARRIVALS

by

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ABSTRACT

In this thesis I develop the novel theory of transmitted PS migration and show that PS transmitted arrivals in a Gulf of Mexico VSP data set can be migrated to accurately image a salt sheet even though the receiver array is below the transmitting boundary. I also show that migrating transmitted arrivals is effective in illuminating the base of an ore body invisible to PP reflections. In general, interfaces nearly perpendicular to wavepath propagation, and therefore invisible to PP reflections, can be imaged by migration of PS transmitted waves. These results suggest that migration of PS transmitted waves opens up new opportunities in imaging nearly vertical impedance boundaries that are typically invisible to conventional reflection imaging of crosswell and VSP data.

I also present a new interferometric method, denoted as reduced-time migration, which uses the arrival-time difference between the direct P-wave and subsequent events to increase migration accuracy. Reduced-time migration removes static time shifts in the data, decreases the focusing error due to an incorrect migration velocity model, and relocates reflection or PS transmission events to be closer to their true positions. Synthetic- and field-data examples for crosswell and VSP geometries show that reduced-time migration is noticeably more accurate than conventional migration. This suggests that reduced-time migration may improve the accuracy of migrated images for any data set with static problems or with uncertain knowledge of the migration velocity model.
For my beautiful wife Diane and new son Eli.
CONTENTS

ABSTRACT .................................................................................. iv
LIST OF FIGURES ................................................................. vii

CHAPTERS
1. INTRODUCTION AND OVERVIEW ....................................... 1
2. THEORY OF TRANSMISSION PS AND REDUCED-TIME MIGRATION .................................................. 3
   2.1 Transmission PS Migration Theory ................................... 3
   2.2 Reduced-Time Migration .................................................. 4
3. NUMERICAL TESTS ............................................................. 10
   3.1 Vertical Boundary Model ................................................... 10
     3.1.1 Forward Modeling ....................................................... 10
     3.1.2 Migration Results ....................................................... 12
   3.2 Salt Diapir VSP ............................................................... 22
     3.2.1 Forward Modeling ....................................................... 22
     3.2.2 Migration Results ....................................................... 22
4. FIELD DATA RESULTS ....................................................... 25
   4.1 Kidd Creek Crosswell ....................................................... 25
     4.1.1 Data Description ....................................................... 25
     4.1.2 Migration results ....................................................... 26
       4.1.2.1 SP Transmission Migration ................................... 26
       4.1.2.2 PP Reflection Migration ....................................... 26
   4.2 Gulf of Mexico VSP ......................................................... 32
     4.2.1 Data Description ....................................................... 32
     4.2.2 Migration Results ....................................................... 38
5. SUMMARY AND CONCLUSIONS .......................................... 48

REFERENCES .............................................................................. 50
# LIST OF FIGURES

2.1 Division of energy from an incident P-wave. The transmitted arrivals are extant in the receiver well, no reflections can be recorded. .......................... 5

2.2 Comparison of (a) PP reflection migration isochrons and (b) PS converted-wave isochrons in seconds. The PP isochrons form ellipses with the source and receiver as foci, while the PS converted-wave isochrons form oblate ellipsoid (egg shaped) isochrons. The tangents to the dashed portions of the isochrons denote the interfaces that can give rise to transmitted PS arrivals; solid lines indicate those for reflected waves. A transmission ray is shown in green and reflections in red. ................................. 6

2.3 (a) Homogeneous velocity model with source-receiver spacing of 1000 m and a depth of 200 m. The depth of reflectors (1) and (2) is 759 m and 1066 m, respectively. (b) Isochrons are governed by $\tau_{sr}^P + \tau_{rg}^P$. The direct wave (D) migrates to the line connecting the source and receiver. (c) Migration isochrons for (a) by the traces have been shifted by 0.2 s prior to migration. (d) Same as for (c) but reduced-time migration was used. ................................. 8

2.4 Comparison of the effect of velocity errors on conventional migration and reduced-time migration. (a) Identical to Figure 2.3a. (b) Migration isochrons for the true velocity model. (c) Conventional PP migration isochrons for the 110% velocity model. (d) Reduced-time PP migration isochrons for the 110% velocity model. Note, migration velocity errors introduce isochron distortions that are similar to those due to static shifts in the previous figure. ................................. 9

3.1 Vertical boundary model used to generate synthetic crosswell and RVSP data. Density is constant for the entire 100 m$^2$ model and a 1500 Hz Z-component source was used. Sources for both crosswell and RVSP simulations are on the left at one meter intervals (101 total). Receivers (101) at one meter intervals are distributed along the right for the crosswell simulation, and across the top for the RVSP simulation. ................................. 11

3.2 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. ................................. 13

3.3 Migration 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. ................................. 14
3.4 Similar to Figure 3.3 but reduced-time migration was used. Images (a) and (c) are identical to those in Figure 3.3. Notice how the migrated position of the boundary is much closer to the true positions in images (b) and (d) than for the standard migration images in Figure 3.3, validating the effectiveness of reduced-time migration.

3.5 Migration images for the RVSP experiment. The sources were on the left and the receivers were along the top, both emplaced at one meter intervals. Note that in (a) and (c) only a small portion of the vertical boundary is imaged due to the restricted RVSP geometry and refraction effects; Also wavepath migration has fewer artifacts than Kirchhoff migration.

3.6 Reduced-time migration images of PS-waves for the RVSP experiment. Notice that the transmitting boundaries in (b) and (d) for reduced-time migration are imaged much closer to their true positions than for (b) and (d) in Figure 3.5.

3.7 SP migration for the RVSP experiment. Note that much more of the transmitting boundary is imaged than with PS transmitted waves (Figure 3.5). Wavepath image (d) has poor quality since the 90% velocity model led to the erroneous calculation of incidence angles.

3.8 Similar to Figure 3.7 but reduced-time migration was used. The location of the boundary image is less sensitive to migration velocity errors in (b) than for (Figure 3.7). The wavepath image still suffers from the incorrect calculation of incidence angles.

3.9 Migration images for reflected PP events in the RVSP experiment.

3.10 Similar to Figure 3.9 but reduced-time migration was used. The incorrect velocity model has less of an effect on the boundary location in (b) than for Figure 3.9.

3.11 (a) Salt diapir model used to generate synthetic seismograms. Figures (b), (c), and (d) show wavefield snapshots at 0.4 s, 0.7 s, and 0.8 s, respectively. (e) The unprocessed CSG is migrated with PS transmission migration. (f) Only transmitted PS events from the right salt flank are migrated.

3.12 Synthetic seismograms generated from the salt diapir model in the previous figure.

4.1 Kidd Creek P-wave velocity model assuming a 3.5 ms time delay. The inversion data residual is 0.086 ms. The source- (right) and receiver-well (left) locations are indicated by the solid black lines. The dashed lines represent the boundaries of the ore body as inferred from well information.

4.2 Common receiver gather for a receiver at a depth of 20 m. The gather has been bandpass filtered between 1000 and 6000 Hz.

4.3 The gather in the previous figure has been flattened to the direct P-wave traveltime and median filtered, and the direct S-wave and later events have been muted.
4.4 (a) Result from migrating the SP transmission events from the bottom of the ore body. Eight CRG's were migrated and stacked to produce this image; each CRG contained 140 traces. (a) Conventional SP transmission migration image. (b) The same data for (a) were migrated with reduced-time migration. (c) Result from migrating the PP reflection events from the top of the ore body with a convention migration algorithm. Seven CRG's were migrated and stacked to produce this image. (d) The same data for (c) were migrated with the reduced-time migration equation for PP reflections.

4.5 Offshore VSP acquisition geometry. The top image shows a plan view of the relative location of the sources to the well head, denoted by \( \odot \). 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. 

4.6 Shot gather for a source at 152 m with the Z-component at the top and the X-component at the bottom. The Y-component is not shown.

4.7 Top shows P-wave migration velocity model (left) and a velocity profile (right), bottom shows similar figures for the S-wave migration velocity model. The solid lines of the velocity profiles indicate the actual velocity distribution with depth and the dashed lines represent the smoothed velocity function used for migration.

4.8 A comparison of before and after reorientation of the seismograms in the XY-plane. The 3-component geophones were rotated until the energy in a small window surrounding the direct P-wave was maximized.

4.9 The rotation angle used to reorient the X- and Y-components (top). An X- and Z- rotation was also performed (bottom). After rotation the continuity of events was improved and transverse waves were largely removed from the Z-component.

4.10 Compare with Figure 4.6. Desired events were picked, flattened, median filtered, unflattened, and bandpass filtered to produce these gathers. FK filtering could not be used because single events have a large range of velocities some of the S-wave are aliased.

4.11 Migration of the gather shown at the top of Figure 4.10, the reflected P-waves. A synthetic zero-offset reflection section calculated solely from borehole velocities is shown on the left. There is good correlation with the base of salt and the strong event in the migrated gather.

4.12 Migration of the reflected PS transmitted wave gather shown at the bottom of Figure 4.10. There are strong events at both the base and top of the salt sheet.

4.13 Migration of transmitted PS arrivals (right). The traces of the synthetic depth section have been rotated 180 degrees from the previous two figures to emphasize the top of the 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 because corresponding events in Figure 4.12 (right) are flat.
4.14 Migration of reflected P-waves from a source position of 610 m. The active receivers range from depths of 3049 to 4482 m. ........................ 44

4.15 Migration image of reflected PS waves for a source at 610 m offset. ...... 45

4.16 Migration of transmitted PS waves. Notice that there are migrated events above to uppermost receiver (3049 m). The dipping events in this gather may be due to shear-wave anisotropy within the salt. ....................... 46

4.17 Comparison of wavepath and Kirchhoff migration for transmitted PS arrivals. The wavepath image contains much less noise and is richer in high wavenumber energy. .......................................................... 47
CHAPTER 1

INTRODUCTION AND OVERVIEW

Seismic migration is a powerful imaging method developed in the 1960’s (French, 1974) to reconstruct the reflectivity distribution from seismic reflection data. Originally developed for common depth point (CDP) data (Hu et al., 1988) it was extended in the 1980’s and 1990’s to image the reflectivity distribution from both vertical seismic profile (VSP) (Amundsen et al., 1993; Payne, 1994) and crosswell data (Qin, 1994). Although migration of PP reflections is effective in imaging horizontal or obliquely-dipping boundaries, it is notoriously ineffective in delineating near vertical interfaces such as salt flanks or ore body sides.

The inability to image steep flanks is a serious economic liability because oil or minerals are often adjacent to such boundaries. To solve the steep boundary problem I propose migrating the forward-scattered transmitted PS-waves to locate the transmitting boundary. Previous work on forward-scattering by Balch et al. (1991) showed that reverse-time migration of converted waves could image point diffractors in a physical model. This led to the further development of PS-reflection migration of crosswell data, but the imaging of PS transmitted waves remained unexplored.

The earthquake community also uses PS arrivals to image certain reflector boundaries. Using a layered model assumption, earthquake seismologists use P and S transmitted waves from earthquakes to image the Moho, denoting the method as the receiver-function technique (Langston, 1977). Later, Chávez-Pérez (1997) and Chávez-Pérez and Louie (1996; 1998) used forward-scattered P-waves from recorded earthquakes to infer the presence of deep fault-zone diffractors. Chávez-Pérez (1997) proposed using either forward-scattered S-waves or P-SV events to image diffractors but was unable to successfully do so.

Although these previous researchers utilized PS transmission data, they did not exploit its most useful feature: namely, imaging vertical interfaces with VSP or crosswell data. I will expand on this previous work and define a Kirchhoff migration operator for
transmitted converted waves and use it to successfully image transmitting boundaries in both synthetic and field data. This overcomes, to a large degree, the inability of seismic methods to image vertical boundaries.

Other major problems in migration include an incorrect migration velocity model and static shifts in the data. Static shift problems are particularly acute in the mining industry where errors in source initiation time or indeterminate well locations lead to defocusing of the migration image. To mitigate these problems I introduce a new interferometric technique that decreases the sensitivity of migration to velocity model errors and removes static errors; I denote this method as reduced-time migration. I validate reduced-time migration with both synthetic and field data, and show that it can be applied to both transmission and reflection arrivals to improve image quality. By combining these two tools, transmission migration and reduced-time migration, several of the major problems that have long plagued crosswell and VSP migration are now mitigated.

In chapter 2 of this thesis I define both transmission migration and reduced-time migration and show that the imaging-time error will always be less for reduced-time migration. I then test these techniques on synthetic data (chapter 3) and field data (chapter 4). Lastly in chapter 5, I present a summary and conclusions.
CHAPTER 2

THEORY OF TRANSMISSION PS AND REDUCED-TIME MIGRATION

In this chapter I develop the theory for both migration of transmitted PS waves and reduced-time migration. Reduced-time migration removes data time shifts and mitigates errors due to incorrect velocities, while PS transmission migration images the vertical boundaries using transmitted PS waves.

2.1 Transmission PS Migration Theory

Converted-wave migration migrates either reflected or transmitted mode-converted events to their place of conversion at the reflecting or transmitting boundary. Compared to PP reflection migration the advantage of migrating transmitted converted waves in crosswell and VSP surveys is that boundaries roughly parallel to the wells can be imaged, as demonstrated in Figure 2.1. To demonstrate this capability Figure 2.2 shows several migration isochrons, the curves along which PP reflections (Figure 2.2a) and converted PS-waves (Figure 2.2b) will be smeared by Kirchhoff migration. Each technique is suitable for imaging boundaries tangent to the migration isochrons. For a single trace and a homogeneous medium PP reflection migration smears along isochrons that form concentric ellipses, while, PS migration smears along isochrons that form oblate ellipsoids. The region near the tip of the oblate ellipsoids (dashed lines in Figure 2.2b) is where the P-waves convert to transmitted S-waves, which is the event this thesis will exploit in imaging vertical boundaries. Note, there are no vertical tangents between the wells for the PP reflection isochrons, meaning that such boundaries are invisible to PP reflection imaging. Contrast this with the many vertical or near-vertical tangents for the transmitted PS-wave isochrons.

Similar to PP-reflection migration, the migration algorithm for transmitted PS arrivals, in a single trace of crosswell or VSP data, consists of three steps: 1.) Calculate the traveltime $\tau_{sr}^P$ for P-waves to propagate from the source to an image point using the
P-wave velocity, 2.) Calculate the traveltime $\tau_{rg}^S$ for S-waves to propagate from an image point to the receiver using the S-wave velocity, 3.) Smear the amplitude from the trace at time equal to $\tau_{sr}^P + \tau_{rg}^S$ to the image point denoted by $r$:

$$m(r) = \int h(s, r, g) s(z_g, \tau_{sr}^P + \tau_{rg}^S) dz_g,$$

(2.1)

where $m(r)$ is the migration image at $r$, $s(z_g, t)$ is the seismic trace recorded at the depth denoted by $z_g$ and

$$h(s, r, g) = \begin{cases} 
1 & \text{if } s\bar{r} \text{ and } \bar{r}g \text{ form a transmitted ray}, \\
0 & \text{otherwise},
\end{cases}$$

is the threshold filter that distinguishes transmitted rays from reflected rays. Migrating the data in this manner requires determining both the P- and S-wave velocity models. Figure 2.2b shows the isochrons for $\tau_{sr}^P + \tau_{rg}^S$, the imaging condition for both PS reflection (solid lines) and transmission PS-waves (dashed lines). If $\tau_{rg}^S \rightarrow \tau_{rg}^P$ then equation 2.1 is appropriate for PP reflection migration, with the associated isochrons shown in the Figure 2.2a.

The importance of Figure 2.2 is that the tangents to the transmission PS-wave isochrons are vertical or nearly vertical, while those for PS reflected waves or PP reflections have less dip between the wells. This means that PS transmission migration is appropriate for imaging steep dips compared to the limitation of imaging only shallower dips by PP and PS reflection migration.

### 2.2 Reduced-Time Migration

Reduced-time migration is defined as temporally shifting the traces by the traveltime of the observed direct arrival $\tau_{sg}^{obs}$, and then migrating the reduced data, i.e.,

$$m(r) = \int s(z_g, \tau_{sr} + \tau_{rg} + \tau_{obsg}^{obs} - \tau_{sg}^{calc}) dz_g,$$

(2.2)

where $\tau_{sg}^{calc}$ is the direct traveltime computed from the velocity model. This $\tau_{sg}^{calc}$ term is used to adjust the migration operator to account for reduced-time data. If the exact velocity model is known then $\tau_{sg}^{obs} = \tau_{sg}^{calc}$ and this equation does not differ from the conventional Kirchhoff migration equation. However, if there is an unknown source static time shift $\delta t_{sg}$ in the traces then $\tau_{sg}^{obs} - \tau_{sg}^{calc} = -\delta t_{sg}$, which is the negative value of the unknown static shift. Thus, equation 2.2 eliminates this static error by reshifting the traces by $-\delta t_{sg}$.
Figure 2.1. Division of energy from an incident P-wave. The transmitted arrivals are extant in the receiver well, no reflections can be recorded.
Figure 2.2. Comparison of (a) PP reflection migration isochrons and (b) PS converted-wave isochrons in seconds. The PP isochrons form ellipses with the source and receiver as foci, while the PS converted-wave isochrons form oblate ellipsoid (egg shaped) isochrons. The tangents to the dashed portions of the isochrons denote the interfaces that can give rise to transmitted PS arrivals; solid lines indicate those for reflected waves. A transmission ray is shown in green and reflections in red.
The focusing error due to a static shift in the trace is illustrated in Figure 2.3. Figure 2.3a shows the model where a single trace is assumed to contain three events: a direct P-wave denoted as D, a reflection R1 from layer one, and a reflection R2 from layer two. This trace is migrated to give the section shown in Figure 2.3b, where the direct wave energy has been smeared along a line connecting the source with the receiver, and reflection energy is smeared along the correct ellipses. If the trace is now given an erroneous static shift \( \delta t_{sg} \), the direct wave D is now incorrectly smeared along the jagged ellipse shown in Figure 2.3b, while the reflections are smeared along incorrect ellipses. However, reduced-time migration eliminates this error as shown in Figure 2.3d because the term \( \tau_{sg}^{obs} - \tau_{sg}^{calc} = -\delta t_{sg} \) compensates for the unknown static shift.

Reduced-time migration also mitigates errors due to erroneous migration velocities. In the case of a migration velocity error the erroneous time shift to the data is in the traveltime calculation of the imaging condition where:

\[
\tau_{sr} + \tau_{rg} = \tau_{sr}^{correct} + \tau_{rg}^{correct} + \delta t_{sr \text{g}}. 
\]

(2.3)

Here, the \( \text{correct} \) superscript refers to the calculated traveltimes in the correct model, and \( \delta t_{sr \text{g}} \) is the error in computing \( \tau_{sr} + \tau_{rg} \) with an incorrect velocity model. Note, if \( r \) is a point on the direct wave ray then \( \tau_{sg}^{obs} - \tau_{sg}^{calc} = -\delta t_{sr \text{g}} \) in equation 2.2 and the direct wave is migrated correctly along the direct ray. However, if \( r \) is elsewhere, then \( \tau_{sg}^{obs} - \tau_{sg}^{calc} \neq -\delta t_{sr \text{g}} \) so the reflectors are still migrated incorrectly. But, the associated \"static shift\" error is reduced because \( |\tau_{sg}^{obs} - \tau_{sg}^{calc}| < |\delta t_{sr \text{g}}| \). This is illustrated in Figure 2.4 where the correct migration image is given in Figure 2.4b, while migration with an incorrect velocity model results in Figure 2.4c. Note, the direct wave is now incorrectly migrated to an ellipse and the reflections are migrated deeper than their reflecting boundaries. With the incorrect velocity model, reduced-time migration (Figure 2.4d) migrates the direct wave D to its proper position and migrates the reflection events, R1 and R2 closer to their reflecting boundaries than with conventional migration. This is because the compensation factor \( \tau_{sg}^{obs} - \tau_{sg}^{calc} \) in equation 2.2 reduces the value of the \"velocity static shift\" factor \( \delta t_{sr \text{g}} \) in equation 2.3.

The next chapter will use numerical examples to illustrate the feasibility of imaging vertical boundaries by migration of PS transmitted arrivals. It will also show how reduced-time migration can decrease focusing errors due to static shifts and velocity errors.
Figure 2.3. (a) Homogeneous velocity model with source-receiver spacing of 1000 m and a depth of 200 m. The depth of reflectors (1) and (2) is 759 m and 1066 m, respectively. (b) Isochrons are governed by $\tau_{sr}^P + \tau_{rg}^P$. The direct wave (D) migrates to the line connecting the source and receiver. (c) Migration isochrons for (a) by the traces have been shifted by 0.2 s prior to migration. (d) Same as for (c) but reduced-time migration was used.
Figure 2.4. Comparison of the effect of velocity errors on conventional migration and reduced-time migration. (a) Identical to Figure 2.3a. (b) Migration isochrons for the true velocity model. (c) Conventional PP migration isochrons for the 110\% velocity model. (d) Reduced-time PP migration isochrons for the 110\% velocity model. Note, migration velocity errors introduce isochron distortions that are similar to those due to static shifts in the previous figure.
CHAPTER 3

NUMERICAL TESTS

In this chapter synthetic data are generated for a vertical boundary model and a salt diapir model. The data are then migrated to image the converting boundary, demonstrating the ability of PS-transmission migration to image such features.

3.1 Vertical Boundary Model

A vertical boundary model is used as a feasibility test and to gain insight into both PS transmission migration and reduced-time migration. Both crosswell and reverse vertical seismic profile (RVSP) data are generated and migrated.

3.1.1 Forward Modeling

The vertical boundary model in Figure 3.1 is used to generate both crosswell and RVSP 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 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 a 2-D elastic wave modeling code, placing sources and receivers at one meter intervals. The model grid size is 20 centimeters and the time interval is 10 microseconds. Although 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 line 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 Figure 3.2. Seismograms from both crosswell and RVSP data sets are then migrated using both Kirchhoff (French, 1974; Gardner, 1974) and wavepath migration algorithms (Sun and Schuster 1999a; 1999b; 2000) in combination with reduced-time migration.
Figure 3.1. 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-component source was used. Sources for both crosswell and RVSP simulations are on the left at one meter intervals (101 total). Receivers (101) at one meter intervals are distributed along the right for the crosswell simulation, and across the top for the RVSP simulation.
3.1.2 Migration Results

Prior to migration PS transmission events were isolated by muting all other arrivals. Using no restriction on incidence angles, Kirchhoff and wavepath PS migrations were applied to the PS events for both the true velocity (Figures 3.3a and 3.3c) and for a 90% velocity model (Figures 3.3b and 3.3d). The PS events are migrated to their actual position for the true velocity model and to an incorrect position for the 90% velocity model. Reduced-time migration was also applied to the transmission PS arrivals. Results for reduced-time PS migration are shown in Figure 3.4 where the location of the transmitting boundary for the 90% velocity model is much closer to the true boundary position. It is also evident that, as shown by Sun and Schuster (1999a; 1999b; 2000), wavepath migration reduces artifacts by migrating energy only to the Fresnel zone of the specular reflection point.

The results for synthetic RVSP data are similar to those for crosswell data. Figures 3.5 and 3.6 show the results for conventional and reduced-time migration of transmitted PS-waves. Figures 3.7 and 3.8 show the results for transmitted SP waves. In addition to transmitted events, reflected PP-waves were migrated by both Kirchhoff and wavepath techniques (Figure 3.9) and reduced time migration was used (Figure 3.10) to mitigate the incorrect migration velocity errors.

Note, much more of the boundary is imaged by migrating the SP waves than by migrating the PS-waves. This is because the velocity contrast for SP waves is greater than that for PS-waves, hence, the SP waves are refracted more to give a wider target illumination. Also note that the vertical boundary in the wavepath migration images, Figures 3.7d and 3.8d, lack continuity. The wavepath algorithm calculated an erroneous incidence angle from the incorrect migration velocity. 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 errors less important.
Figure 3.2. 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 3.3. Migration 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 3.4. Similar to Figure 3.3 but reduced-time migration was used. Images (a) and (c) are identical to those in Figure 3.3. Notice how the migrated position of the boundary is much closer to the true positions in images (b) and (d) than for the standard migration images in Figure 3.3, validating the effectiveness of reduced-time migration.
RVSP: PS Migration

(a) Kirchhoff 100% Velocity

(b) Kirchhoff 90% Velocity

(c) Wavepath 100% Velocity

(d) Wavepath 90% Velocity

Figure 3.5. Migration images for the RVSP experiment. The sources were on the left and the receivers were along the top, both emplaced at one meter intervals. Note that in (a) and (c) only a small portion of the vertical boundary is imaged due to the restricted RVSP geometry and refraction effects; Also wavepath migration has fewer artifacts than Kirchhoff migration.
Figure 3.6. Reduced-time migration images of PS-waves for the RVSP experiment. Notice that the transmitting boundaries in (b) and (d) for reduced-time migration are imaged much closer to their true positions than for (b) and (d) in Figure 3.5.
RVSP: SP Migration

a.) Kirchhoff 100% Velocity 
b.) Kirchhoff 90% Velocity 

c.) Wavepath 100% Velocity 
d.) Wavepath 90% Velocity 

Figure 3.7. SP migration for the RVSP experiment. Note that much more of the transmitting boundary is imaged than with PS transmitted waves (Figure 3.5). Wavepath image (d) has poor quality since the 90% velocity model led to the erroneous calculation of incidence angles.
Figure 3.8. Similar to Figure 3.7 but reduced-time migration was used. The location of the boundary image is less sensitive to migration velocity errors in (b) than for (Figure 3.7). The wavepath image still suffers from the incorrect calculation of incidence angles.
RVSP: PP Reflection Migration

a.) Kirchhoff 100% Velocity

b.) Kirchhoff 90% Velocity

c.) Wavepath 100% Velocity
d.) Wavepath 90% Velocity

Figure 3.9. Migration images for reflected PP events in the RVSP experiment.
RVSP: Reduced-Time PP Reflection Migration

Figure 3.10. Similar to Figure 3.9 but reduced-time migration was used. The incorrect velocity model has less of an effect on the boundary location in (b) than for Figure 3.9.
3.2 Salt Diapir VSP

A salt diapir model is used to generate a single VSP shot gather. The synthetic seismic data are migrated with PS transmission migration to locate the diapir flanks.

3.2.1 Forward Modeling

To further test the effectiveness of PS transmission migration, synthetic data were generated for a salt diapir model (Figure 3.11a). The seismograms, shown in Figure 3.12, were generated with a 2D elastic forward modeling code using a homogeneous background velocity of 3000 m/s and a salt velocity of 5000 m/s. A P-to-S velocity ratio of 2.2 is assumed for the entire model. A source was placed far below the surface (520 m) and 2700 m from the receiver well; there are no free surface reflections. Figures 3.11b, 3.11c, and 3.11d show three snapshots of the wavefield at 0.4, 0.7 and 0.8 seconds respectively. These images illustrate the presence and relative strength of the PS transmitted waves and show how complex data can become for even a simple model.

3.2.2 Migration Results

The CSG generated in the previous section is now migrated using PS transmission migration (equation 2.1). Migration of the unprocessed synthetic seismograms yields Figure 3.11e. No attempt was made to isolate the transmitted PS arrivals and no incidence angle or layer dip restrictions were used. It is clear that some parts of the salt flank boundary are well imaged despite the presence of coherent migration noise. Migrating additional shot gathers will increase the signal-to-noise ratio, causing the coherent noise to destructively interfere and the transmission PS energy at the diapir boundary to constructively interfere.

Next, the transmitted PS-wave traveltimes from the right salt flank were picked and the picked traveltimes were convolved with a source wavelet to generate traces containing only PS transmission events. These seismograms were then migrated to generate the migration image shown in Figure 3.11f. It is evident that the migration image of the transmitted PS waves corresponds well with the salt flank of the actual model. It should be noted that the exact velocity was used to generate the final migration section. Also, no incidence angle or dip constraints were imposed during migration, which would have reduced the migration artifacts. This test supports my conjecture that PS transmitted waves can be migrated to delineate salt flank boundaries.
Figure 3.11. (a) Salt diapir model used to generate synthetic seismograms. Figures (b), (c), and (d) show wavefield snapshots at 0.4 s, 0.7 s, and 0.8 s, respectively. (e) The unprocessed CSG is migrated with PS transmission migration. (f) Only transmitted PS events from the right salt flank are migrated.
Figure 3.12. Synthetic seismograms generated from the salt diapir model in the previous figure.
CHAPTER 4

FIELD DATA RESULTS

Applying converted-wave and reduced-time migration to crosswell and a VSP field data yields dramatic results. Converted-wave migration illuminates the base of an ore body and the top of a salt sheet, both invisible to conventional migration of PP reflections. Also, an unknown data time shift in the crosswell example is eradicated by reduced-time migration.

4.1 Kidd Creek Crosswell

The Kidd Creek mine, near Timmins, Ontario, Canada, is a volcanogenic sulfide deposit consisting primarily of rhyolite, basalt, diorite, ultramafics, argillite, and massive sulfides. Previous work proved the feasibility of imaging massive sulfide deposits with seismic reflections (Meng and McGaughy, 1996; Hu, 1999). Here I migrate both PP reflection and SP transmission events to image the sulphide body. I also show the benefits of applying reduced-time migration to these data.

4.1.1 Data Description

The Kidd Creek crosswell data were collected by Noranda Mining and Exploration using boreholes drilled from inside the copper-zinc sulfide mine. The boreholes intersect an ore body as evidenced by cores from each hole. These seismic data are ideally suited for the reduced-time migration method since there exists an unknown time delay and/or well location error in the seismograms. In an attempt to mitigate the problem Hu (1999) proposed that a constant time shift be applied to the traces. He estimated this delay to be 3.5 milliseconds by assuming a constant background velocity and minimizing the data residual. After applying the data time shift, the first arrival traveltimes were inverted to generate the velocity model shown in figure 4.1. Since the velocity tomogram does not correlate well with the empirically based model the tomogram is assumed to be in error. Nevertheless, it is used here as the migration velocity model to prove the utility of the
reduced-time migration. Since the S-wave first arrivals are not distinct throughout the
data set they were not picked and inverted to generate an S-wave velocity model. Instead
I assume a constant P-to-S velocity ratio of 1.7.

4.1.2 Migration results

PP reflections and SP transmissions are migrated and compared to the results from
reduced-time migration. In chapter 3, wavepath migration was shown to be sensitive to
the velocity model errors and since both the P- and S-wave Kidd Creek velocity models
are incorrect I do not attempt to use wavepath migration here.

To process the data I resorted to the common receiver gather (CRG) domain, picked
the first-arrival traveltimes, flattened the direct-P arrivals, and then picked the residual
times to further flatten the direct P-wave. After flattening, I applied an eleven-point
median filter to accentuate the reflection and transmission events, muted all but these
events, and unflattened the events back to their original positions. A sample gather after
bandpass filtering is shown as Figure 4.2 and median filtering is as Figure 4.3.

4.1.2.1 SP Transmission Migration

By applying conventional converted-wave migration to the muted and time-shifted
CRG’s the transmitted SP waves, which appear as PS transmissions in the CRG’s, are
migrated near the ore-body boundary estimated by Noranda (Figure 4.4a). A restriction
on incidence angles was used to limit the angle between the image point and the line
connecting the source and receiver to be less than twenty degrees. That is, the conversion
takes place mostly along the tips of the oblate ellipsoids in Figure 2.2. This restriction
helped to reduce migration artifacts.

The reduced-time migration algorithm was then applied to the seismograms without
applying the 3.5 millisecond time shift. The result, given in Figure 4.4b, migrates the
events much closer to the inferred boundary than with conventional migration. More-
over, the intersection of the boundary with the borehole and the intersection of the SP
transmitted wave with the direct P-wave correlate well.

4.1.2.2 PP Reflection Migration

Hu (1999) used conventional PP reflection migration to successfully image the top
boundary of the ore body. I repeat the process here and compare it to PP reflection
migration using the reduced-time imaging condition. I found a strong reflection event
from the top boundary in seven CRG's. These gathers were processed, as described in
the previous section, by median filtering and muting. After applying the 3.5 millisecond
data shift to the traces the gathers were migrated using the PP reflection migration.
Without this time shift the reflection energy is either not migrated or is smeared far from
its location on the ore boundary. The result is given as Figure 4.4c. A dip restriction was
used to limit reflector dip to between 25 and 30 degrees.

Reduced-time migration was then applied to the unshifted data. The result, given
in Figure 4.4d, migrates the events much closer to the inferred boundary than with
conventional migration. Moreover the intersection of the boundary with the borehole
correlates well with the seismic data. Reduced-time migration without the 3.5 millisecond
time shift gives a more reliable image that does conventional migration with the time shift,
and the combination of SP transmission and PP reflections almost completely illuminates
the ore body boundaries.
Figure 4.1. Kidd Creek P-wave velocity model assuming a 3.5 ms time delay. The inversion data residual is 0.086 ms. The source- (right) and receiver-well (left) locations are indicated by the solid black lines. The dashed lines represent the boundaries of the ore body as inferred from well information.
Figure 4.2. Common receiver gather for a receiver at a depth of 20 m. The gather has been bandpass filtered between 1000 and 6000 Hz.
Figure 4.3. The gather in the previous figure has been flattened to the direct P-wave traveltine and median filtered, and the direct S-wave and later events have been muted.
Figure 4.4. (a) Result from migrating the SP transmission events from the bottom of the ore body. Eight CRG’s were migrated and stacked to produce this image; each CRG contained 140 traces. (a) Conventional SP transmission migration image. (b) The same data for (a) were migrated with reduced-time migration. (c) Result from migrating the PP reflection events from the top of the ore body with a convention migration algorithm. Seven CRG’s were migrated and stacked to produce this image. (d) The same data for (c) were migrated with the reduced-time migration equation for PP reflections.
4.2 Gulf of Mexico VSP

I now describe the results of applying PS transmission migration to offset VSP data acquired in the Gulf of Mexico. The objective is to use PS transmission events to image the top and base of a tabular salt sheet.

4.2.1 Data Description

An offset VSP experiment was carried out by an anonymous seismic contractor in the Gulf of Mexico. A plan view of the survey configuration is shown in the top of Figure 4.5. The data consists of three 3-component gathers at offsets of 152 m, 610 m, and 1524 m from the well head (Figure 4.5 top). The 152 m offset gather consist of 82 receiver stations from depths of 2652 m to 3887 m at 15.2 m intervals (Figure 4.5 bottom-left). The 610 m and 1524 m offset gathers contain 95 receiver stations each between depths of 3049 m and 4489 m, again at 15.2 m intervals (Figure 4.5 bottom-right). Sample gathers are shown in Figure 4.6 with prominent modes labeled. The vertical axis is depth in meters 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 4.7 top-left), and an S-wave velocity model was estimated from near vertically incident PS transmission and reflection events (Figure 4.7 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 for the X- and Y-components, maximizing the energy on the X-component direct wave (Figures 4.8 and 4.9), then on the Z- and X-components, maximizing the Z-component direct wave energy. The events with the desired moveout velocity were picked and flattened. The flattened gathers were median and bandpass filtered and unflattened. Figure 4.10 shows the isolated reflected P-waves (top) and transmitted S-waves (bottom) for the 152 m offset gather.
Figure 4.5. Offshore VSP acquisition geometry. The top image shows a plan view of the relative location of the sources to the well head, denoted by °. 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 4.6. Shot gather for a source at 152 m with the Z-component at the top and the X-component at the bottom. The Y-component is not shown.
Figure 4.7. Top shows P-wave migration velocity model (left) and a velocity profile (right), bottom shows similar figures for the S-wave migration velocity model. The solid lines of the velocity profiles indicate the actual velocity distribution with depth and the dashed lines represent the smoothed velocity function used for migration.
Figure 4.8. A comparison of before and after reorientation of the seismograms in the XY-plane. The 3-component geophones were rotated until the energy in a small window surrounding the direct P-wave was maximized.
Figure 4.9. The rotation angle used to reorient the X- and Y-components (top). An X- and Z- rotation was also performed (bottom). After rotation the continuity of events was improved and transverse waves were largely removed from the Z-component.
4.2.2 Migration Results

For each of the three gathers described in the previous section the PP reflections, PS reflections, and PS transmissions were migrated with reduced-time migration. The grid spacing for the migration model was 3 m in both the offset and depth directions. Conventional migration as well as reduced-time migration were applied to these data although no significant difference could be determined between the two. I find that the velocity models accurately describe the true earth velocity. The average time difference between the calculated direct-P traveltime ($\tau_{sg}^{\text{calc}}$) and the picked direct-P traveltime ($\tau_{sg}^{\text{obs}}$) was about 6 ms (6 data time samples). Since there is little difference between the two I only show the reduced-time examples.

I first show the results for the 152 m offset gather followed by the 610 m offset gather. For comparison I generated a synthetic migration section (Figure 4.11 left) based solely on the well log velocity (Figure 4.7).

Using Kirchhoff migration I migrated the 152 m offset Z-component gather with isolated P-wave reflections (Figure 4.10) to obtain the reflection section shown in Figure 4.11. The prominent event at 3171 m is the base of salt reflection and correlates with the same event in the synthetic section. A similar event can be found somewhat higher in the reflected PS image, Figure 4.12. This figure shows another event at 2805 m which correlates with the top of salt. The transmitted PS migration image (Figure 4.13) shows a strong event at 2805 m which correlates well with the top of salt. In this figure I reversed the polarity of the synthetic section 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 4.12) contains the Y-component while this image contains the X-component.

Figures 4.14, 4.15, 4.16, contain, respectively, the reflected P, the reflected PS, and the transmitted PS migrated images for a source offset of 610 m. In Figure 4.16 notice the prominent events at 3171 m, the base of salt, in the reflected images. There is a good correlation between the top of salt, above the uppermost receiver at 3049 m, and the prominent event in the migrated section. Figure 4.17 shows a comparison between the wavepath and Kirchhoff migration images for transmitted PS arrivals from sources at 610 m offset. Although the Kirchhoff images contain most of the same coherent events the
Figure 4.10. Compare with Figure 4.6. Desired events were picked, flattened, median filtered, unflattened, and bandpass filtered to produce these gathers. FK filtering could not be used because single events have a large range of velocities some of the S-wave are aliased.
wavepath image contains much less noise. Also, the events in the wavepath image have a higher wave number, indicating better focusing, than their counterparts in the Kirchhoff image.
Migrated Shot Gather: 152 m Offset

Synthetic Seismograms

Reflected PP

Figure 4.11. Migration of the gather shown at the top of Figure 4.10, the reflected P-waves. A synthetic zero-offset reflection section calculated solely from borehole velocities is shown on the left. There is good correlation with the base of salt and the strong event in the migrated gather.
Figure 4.12. Migration of the reflected PS transmitted wave gather shown at the bottom of Figure 4.10. There are strong events at both the base and top of the salt sheet.
Figure 4.13. Migration of transmitted PS arrivals (right). The traces of the synthetic depth section have been rotated 180 degrees from the previous two figures to emphasize the top of the 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 because corresponding events in Figure 4.12 (right) are flat.
Figure 4.14. Migration of reflected P-waves from a source position of 610 m. The active receivers range from depths of 3049 to 4482 m.
Figure 4.15. Migration image of reflected PS waves for a source at 610 m offset.
Figure 4.16. Migration of transmitted PS waves. Notice that there are migrated events above the uppermost receiver (3049 m). The dipping events in this gather may be due to shear-wave anisotropy within the salt.
Figure 4.17. Comparison of wavepath and Kirchhoff migration for transmitted PS arrivals. The wavepath image contains much less noise and is richer in high wavenumber energy.
CHAPTER 5

SUMMARY AND CONCLUSIONS

In this thesis I developed and tested two novel techniques for crosswell and VSP seismic imaging: Transmission PS migration and reduced-time migration. Transmission PS migration complements PP reflection migration by illuminating nearly vertical boundaries. In addition, reduced-time migration, was proposed to decrease the imaging-time error associated with either an incorrect migration velocity or a constant time shift.

In chapter 3 I showed that for a synthetic crosswell experiment PS transmission arrivals may be migrated to locate a vertical boundary parallel to the boreholes, a boundary that is invisible to PP reflections. It was also demonstrated that the reduced-time imaging condition introduced in chapter 2 could be applied to these data to decrease the focusing errors due to an incorrect migration velocity. Wavepath migration was applied to the crosswell data to reduce the migration artifacts by limiting the migration to the Fresnel zone at the specular transmission point.

Utilizing the synthetic RVSP data I applied PS and SP transmission migration as well as PP reflection migration to locate the vertical boundary. Due to the velocities chosen SP transmission migration was able to image approximately two-thirds of the boundary, PP reflection migration one-half of the boundary, and PS transmission migration one-third of the boundary. As for the crosswell simulation, the reduced-time imaging condition migrated the energy more accurately than conventional migration for an incorrect velocity model. To account for errors in the migration velocity model, wavepath migration should smear migrated energy along several Fresnel zones.

A salt diapir model was used to test the feasibility of migrating PS transmission events for a more complex model. Although PS transmission migration of the entire shot gather delineated the diapir flanks, migrating only the PS transmission events illuminates the diapir flank more clearly.

In chapter 4, PS transmission migration of the Kidd Creek crosswell data and the Gulf of Mexico VSP data demonstrated the feasibility of imaging the transmitting boundaries.
The use of reduced-time migration with the Kidd Creek data clearly showed better focusing and more accurate imaging than images obtained with conventional migration. Applying reduced-time migration to the Kidd Creek data illustrated that in the presence of an unknown time shift transmitted SP arrivals and reflected PP arrivals can be used to accurately image the transmitting and reflecting boundaries. For these data, the base of the ore body would have remained unimaged without the availability of PS transmitted arrivals.

The Gulf of Mexico VSP data were successfully migrated to reconstruct the top and bottom of the tabular salt body even though the top of the salt body was above the receiver array. This further illustrates the utility of migrating transmitted PS arrivals to illuminate boundaries invisible to PP reflections.

In summary, migration of transmitted converted waves and reduced-time migration are two new tools that can be used to reduce imaging error and illuminate nearly vertical boundaries, or "dark" parts of salt flanks, ore bodies, and other targets.
REFERENCES


