Reverse time migration of transmitted wavefields for salt boundary imaging

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ABSTRACT

The imaging of steep salt boundaries has received much attention with the advent of improved wider azimuth acquisition designs and advanced imaging techniques such as reverse time migration (RTM), for example. However, despite these advancements in capability, there are cases in which the salt boundary is either poorly illuminated or completely absent in the migrated image. To provide a solution to this problem, we have developed two RTM methods for imaging salt boundaries, which use transmitted wavefields. In the first technique, downgoing waves, typically recorded in walkaway vertical seismic profile surveys, are used to image the salt flank via the generation of aplanatic isochrones. This image can be generated in the absence of an explicit interpretation of the salt flank using dual migration velocity models, as demonstrated on a 3D walkaway field data set from the Gulf of Mexico. In the second technique, we extend the basic theory to include imaging of upgoing source wavefields, which are transmitted at the base salt from below, as acquired by a surface acquisition geometry. This technique has similarities to the prism-imaging method, yet it uses transmitted instead of reflected waves at the salt boundary. Downgoing and upgoing methods are shown to satisfactorily generate an image of the salt flank; however, transmission imaging can create artifacts if reflection arrivals are included in the migration or the acquisition geometry is limited in extent. Increased wavelet stretch is also observed due to the higher transmission coefficient. An important benefit of these methods is that transmission imaging produces an opposite depth shift to errors in the velocity model compared with imaging of reflections. When combined with conventional seismic reflection surveys, this behavior can be used to provide a constraint on the accuracy of the salt and/or subsalt velocities.

INTRODUCTION

The imaging of steeply dipping or vertical salt flanks has traditionally been a challenging problem for the oil and gas industry. Hydrocarbon accumulations trapped up-dip from the basin and sealed by the salt require an image of the salt flank to accurately determine the reservoir extent and to ensure that hydrocarbon accumulations can be fully extracted. Poor imaging of the salt flank can be due to several factors including low or absent illumination during acquisition, an incorrect imaging velocity model, an unsuitable migration algorithm, or the absence of an impedance contrast across the salt boundary. In the case of the steeply dipping salt that surrounds the Mars Basin in the Gulf of Mexico, narrow and wide tow streamer data sets, as well as ocean bottom seismometer (OBS) acquisition, have failed to adequately illuminate the overhanging sides of the salt on either side of the basin (Figure 1). In this example, the 3D structure of the salt is complex, and the basin narrows to the west, and it is bounded by salt on three sides. This presents a challenge for velocity model building and imaging workflows because the salt is partially imaged from waves that have propagated through the salt on the opposite side of the basin. Accurately defining the salt in the velocity model is therefore critical to successful imaging of the salt flanks on either side of the basin and as well as for subsalt targets.

With the advent of full azimuth acquisition surveys, such as OBS, for example, we have seen improvements in image quality because greater source-to-receiver azimuths have provided better subsalt illumination. However, even OBS surveys can fail to image vertical salt flanks when the wave propagation travels beyond the node patch, as

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may be the case when the salt interface is steeply dipping. To mitigate these problems, we have formulated two imaging solutions using reverse time migration (RTM) with transmitted wavefields to fill the illumination gaps created when using surface reflection data alone. The first method takes a preexisting workflow for salt proximity imaging and applies RTM to provide an image of the salt interface using a downgoing wavefield recorded in a 3D vertical seismic profile (VSP) survey. The second method is a new application that provides an image of the salt flank via RTM of an upgoing transmitted wavefield, as recorded in a surface acquisition geometry.

Background

Imaging of salt boundaries can be achieved with different components of the seismic wavefield (Figure 2) including (1) directly with reflections or diffractions from the top and bottom of the salt (Figure 2a) (Hale et al., 1992; Anderson and Marcinkovich, 2006); (2) indirectly with reflections between the salt and surrounding strata, e.g., indirect prism waves (Figure 2b) (Dai and Schuster, 2013; Kudin et al., 2018); (3) directly using transmitted wavefields (Figure 2c) (McMechan et al., 1988; Sheley and Schuster, 2003; Zhao et al., 2004; O’Brien, 2005; Anderson and Marcinkovich, 2006; Mateeva et al., 2007; Roberts et al., 2009; Wu et al., 2012). McMechan et al. (1988) present a method to directly image the position of the salt interface without any prior knowledge of where the boundary between the salt and sediment interface was located. The authors migrate a traditional salt proximity survey from a single source location using their hybrid method incorporating ray tracing and the use of a one-way finite-difference migration. In their workflow, the ray tracing is applied to propagate the source wavefield from the surface down to the receiver for a VSP acquisition geometry. The top salt geometry is assumed to be known, and the salt velocity and extent are held constant below the level of the top salt. The use of ray tracing in this example is potentially problematic due to the strong velocity contrasts that typically result in large gaps in the ray coverage as well as being restricted to only a single travelttime arrival, i.e., no caustics. The use of a one-way wave-equation migration operator to back propagate the receiver wavefield provides the benefit of being able to image multiple wavefront arrivals; however, the dip coverage from the finite-difference implementation is also limited and cannot image horizontally propagating waves (Etgen et al., 2009; Liu et al., 2011; Diaz and Sava, 2016).

The method of McMechan et al. (1988) is further used by Roberts et al. (2009) on a 3D VSP data set acquired within the Gulf of Mexico. They overcome the dip restriction of the one-way method by performing a coordinate rotation to bring the dip range within the algorithm’s angular coverage. Following imaging, the data are rotated back to their initial position.

Under normal circumstances, a one-way method would suffice for most transmission imaging problems. However, the use of the...
dip unlimited, two-way wave equation avoids implementation issues associated with the one-way method and can inherently cope with complex propagation paths, for example, horizontally transmitted waves or headwaves that propagate at high angles to the salt boundary. Therefore, we solve the salt flank imaging problem using a two-way RTM algorithm for transmitted wavefields. In our solution, we follow the general workflow published by McMechan et al. (1988) but we present a mathematical solution to solve the salt imaging problem using reverse time imaging of a downgoing wavefield and demonstrate this on synthetic and a 3D walkaway VSP field data set from the Gulf of Mexico. In addition, a new solution is also provided to use transmission wavefields resulting from upgoing wave propagation, which includes a refraction leg, i.e., a refraction following a prior reflection event. We also show that when used in combination with a conventional reflection-based RTM, that errors in the average salt velocity or subsalt sediment velocity can be determined by comparing the alignment of the downgoing and upgoing wavefields, the correct salt velocity is one that aligns both wavefields. A mathematical explanation for the wavelet stretch, as noted on previous transmission images (Sheley and Schuster, 2003, Roberts et al., 2009), is also provided.

**METHODOLOGY**

The aplanatic surface

The fundamental methodology used by salt proximity surveys for the imaging of salt flanks is based on the definition of the aplanatic surface. This defines the locus of equal traveltime over which every point on the surface, the sum of the optical distances between two fixed points in space, has a constant value (Savarad, 2001). This was first discovered by the famous French mathematician Descartes in 1637, who could demonstrate the properties of the aplanatic lenses according to the sine law, where sines of incident and of refracted rays are in constant proportion. We refer to this today as the index of refraction, which is dependent on the refracting medium.

The aplanatic surface is a portion of a larger refraction isochron known as a Cartesian oval as graphically shown in Figure 3. In the figure, the inclined dashed interface separates the salt on the left side from the basin sediments on the right side. In this scenario, the velocity contrast between the salt at velocity \( v_1 \) and sediments at velocity \( v_2 \) is such that \( v_1 > v_2 \). In practice, this velocity contrast can be quite high (>3) in the Gulf of Mexico, particularly when the salt comes close to the seabed. If we trace rays (the normals to the wavefronts; Figure 3) from the source (S) on the left side, at velocity \( v_1 \), we get the traveltimes as indicated by the red lines shown in Figure 3. Likewise, if we trace rays from the receiver location (R) using velocity \( v_2 \), we get the traveltimes indicated by the blue lines shown in Figure 3. Where the raypaths intersect, the aplanatic surface is formed for all possible ray combinations (just one source/receiver pair, per this illustration). In practice, we would have many sources and/or receiver locations for a typical seismic acquisition survey and the best-fit line through the tangent to all aplanatic surfaces defines the refraction interface, or salt flank in our case.

Transmission imaging with RTM: Theory

In a two-way wave-equation implementation, as in RTM, the source and receiver wavefields propagate in all directions, thus enabling imaging of complex subsurface structures (Jones, 2014). In RTM, the source wavefield is propagated downward into the earth, whereas the receiver wavefield is time reversed and back propagated toward the reflector. An imaging condition is then applied to form the actual image. The zero-lag crosscorrelation imaging condition (Claerbout, 1971) is used

\[
I(z, x, y) = \sum_{t} \int P_s(t, z, x, y) P_g(t, z, x, y) dt,
\]

where \( P_s \) and \( P_g \) represent the source and receiver wavefields, respectively; \( t, z, x, y \) are the time, depth, and \( x, y \) coordinates, respectively; and \( I \) is the migrated image. Simply put, wherever the source and receiver wavefields coincide in space and time, an image will be formed, assuming there is an impedance contrast in the earth. For the simplest case of a two-layered medium, the image \( I(x_i, x_j) \) produced by a source/receiver pair will be an isochrone surface (Schneider, 1971, 1978)

\[
I(x|x_i, x_j) = \frac{A}{|x-x_j|} \delta \left( \frac{|x-x_i|}{v_s} - \frac{|x-x_j|}{v_g} \right),
\]

and it has similar functional form for reflection and transmission RTM. Here, \( x_i \) is the location of the source, \( x_j \) is the location of the receiver, \( v_s \) is the velocity of the medium used to propagate the source field \( P_s \) (the source leg), \( v_g \) is the velocity of the medium used to propagate the receiver field \( P_g \) (the receiver leg), \( \tau \) is the traveltime of the reflection or refraction event, and \( A = s_0 d_0/16 \pi^2 \) is an amplitude proportional to the spectral amplitudes of the delta source \( s_0 \) and recorded event \( d_0 \). The image along a profile oriented through the source and receiver positions is a Cartesian oval, which becomes elliptical for reflection events (\( \tau > |x_i-x_j|/v_s, v_s = v_g \)) and an aplanatic curve for transmission events (\( |x_i-x_j|/\max(v_s, v_g) \leq \tau \leq |x_i-x_j|/\min(v_s, v_g) \)). Stacking isochrones of equation 2 by summation over different positions of sources and receivers pro-

![Image](https://pubs.geoscienceworld.org/geophysics/article-pdf/84/2/S71/4662069/geo-2018-0182.1.pdf)
roduces an image of the interface that can have an arbitrary dip (Baysal et al., 1983; McMechan, 1983; McMechan et al., 1988; Bleist et al., 2001). The latter illustrates the benefit of using RTM versus imaging with one-way propagators, and it becomes particularly important for the second proposed method of transmission RTM imaging with upgoing scattered wavefields, when the initially reflected and then refracted wavefield can propagate in arbitrary directions.

It is interesting to note that images formed by reflection RTM and transmission RTM respond differently to inaccuracies in the velocity model. Consider the example shown in Figure 4. If we assume some incorrect velocity of the top medium and denote it with \( v'_2 \), then the isochrone of reflection RTM becomes

\[
L \frac{v'_2}{v_2} = |x - x_g| + |x - x_s|,
\]

where \( L \) is the distance traveled for the reflected ray, which is fixed for given locations of the source, receiver, and interface. It is clear from equation 3 that if the assumed velocity \( v'_2 \) is greater than the true velocity \( v_2 \), then isochrone ellipses will have larger axes. This will result in correlated images of the reflecting layer being pushed further away from \( x_s \) and \( x_g \); i.e., the image of the reflector will be formed deeper than the true position of the reflector.

In the case of transmission RTM, the response of Cartesian ovals to errors in migration velocity is shown in Figure 5. One can see that if the salt velocity \( v'_2 \) is too slow relative to the true salt velocity \( v_2 \), then the isochrone’s upper edge is pushed downward below the edge of the real location of the interface (Figure 5a). For the correct salt velocity, the isochrone’s upper surface will be aligned exactly on the boundary (Figure 5b), whereas if the velocity is too high, then the isochrone’s upper edge will be pushed upward above the real location of the interface (Figure 5c). As previously mentioned, the summation of aplanatic surfaces will form an image of the interface if there are sufficient sources and receivers and that this interface will move up or down if the velocity is too fast or slow. This effect can be observed from the following simple test using the geometry shown in Figure 5. Let us assume that the slower (sediment) velocity is correct, i.e., \( v'_1 = v_1 \), whereas the faster (salt) velocity \( v'_2 \) is incorrect by \( \Delta v_2 \):

\[
v'_2 = v_2 + \Delta v_2.
\]

This velocity model should result in a different (incorrect) position of the imaged interface, which will appear shifted by some distance \( \Delta L \). We can find a relation between \( \Delta v_2 \) and \( \Delta L \) using the expression \( t_{ref} = (L_1/v_1) + (L_2/v_2) \) for the refraction event and equation 2 for the aplanatic surface:

\[
\frac{L_1}{v_1} + \frac{L_2}{v_2} = \frac{|x - x_g|}{v_1} + \frac{|x - x_s|}{v_2 + \Delta v_2},
\]

\[
\frac{L_1}{v_1} + \frac{L_2}{v_2} = \frac{L_1 + \Delta L}{v_1} + \frac{L_2 - \Delta L}{v_2 + \Delta v_2},
\]

from equation 6, we thus get

\[
\Delta L \approx \frac{v_1}{v_2 - v_1} \frac{L_2}{v_2} \Delta v_2.
\]

Thus, if \( v_2 > v_1 \) then \( \Delta L \) will have the same sign as \( \Delta v_2 \). In other words, if the assumed velocity \( v'_2 \) is greater than the true velocity \( v_2 \), then the image of the reflector will be formed shallower than its true position, which is opposite to the direction that the image is shifted in reflection RTM, as previously discussed. This is an interesting property of imaging with transmitted waves: Transmission RTM and reflection RTM shift the apparent image of the salt bottom in opposite directions if the assumed salt velocity is incorrect. This property may be used to provide quality control of the velocity model and is illustrated later with synthetic example 3.

It is also interesting to illustrate the behavior of transmission RTM image in the case in which the subsalt sediment velocity is wrong. Let us assume that the sediment velocity \( v'_1 \) is incorrect and is faster than the true sediment velocity \( v_1 \) by \( \Delta v_1 = v'_1 - v_1 \). Equation 7 then becomes

\[
\Delta L \approx \frac{v_1 v_2}{v_2 - v_1} \left( \frac{L_1}{v_1} \Delta v_1 + \frac{L_2}{v_2} \Delta v_2 \right).
\]

By omitting small second-order terms \( \Delta L \Delta v_1 \), \( \Delta L \Delta v_2 \), and \( \Delta v_1 \Delta v_2 \), one can derive from equation 8

\[
\Delta L \approx \frac{v_1 v_2}{v_2 - v_1} \left( \frac{L_1}{v_1} \Delta v_1 + \frac{L_2}{v_2} \Delta v_2 \right).
\]

Figure 4. (a) The correct model is composed of salt and sediment layers. In RTM with transmitted waves, we use different velocities for different legs of RTM (b and c) (see the main text for details).

Figure 5. Cartesian ovals generated for (a) too-low salt velocity, (b) correct salt velocity, and (c) too-high salt velocity. For a correct medium velocity, the Cartesian oval will be positioned at the interface between two media (b). However, if the velocity is too low or too high, the Cartesian oval is not aligned with the interface.
One can see from equation 9 that either faster salt ($\Delta v_2 > 0$) or sediment ($\Delta v_1 > 0$) velocities result in a transmission RTM image of the salt bottom forming shallower ($\Delta L > 0$) than its true position.

**Transmission imaging with RTM for VSP acquisition: Using the direct downgoing wavefield**

The RTM workflow for imaging the salt flank with the transmitted wavefield, which propagates directly from source to receiver, is graphically shown in Figure 6a. We start with a source-to-receiver geometry such that wave propagation from the surface (S) to the receiver (R) will refract at the salt flank (Figure 6a). The RTM solution is split into a forward propagation of the source wavefield and a backward propagation of the receiver (the recorded) wavefield. The forward source propagation is performed using a salt flood velocity model; i.e., the salt is extended beyond its base and encloses the receiver position (Figure 6b), and the top salt geometry is known in this example. In principle, the lower boundary of the salt flood velocity model should be extended far enough away from the likely location of the salt flank to ensure that imaging can be performed with a constant salt velocity and that there is no refraction of the downgoing wavefield between the top salt and receiver array. Next, the recorded wavefield is backward propagated using the sediment velocity only, i.e., with no salt interfaces in the model (Figure 6c). A zero-lag crosscorrelation imaging condition is then applied at each time step to form the image (Figure 6d). The forward and backward wavefields correlate at the base salt (Figure 6e, orange line). In practice, it would require several receivers to image the region covered by the orange line as depicted in Figure 6e. To ensure that there is no cross contamination between transmitted and reflected arrivals, it is recommended to separate the two wavefields and mute later arrivals so that the impact of the transmitted wavefield can be clearly seen. However, even when this is performed, there will still be a reflected wavefield as part of the RTM forward source propagation. These reflections will correlate with the backward-propagated receiver wavefield to generate an image at locations of strong velocity contrast within the migration velocity model. This might be undesirable, as is the case for an incorrect interpretation of the salt; however, it does serve a useful purpose in providing an estimate of the illumination coverage at the interpreted interface, as will be shown in the “Results” section.

**Transmission imaging with RTM for surface acquisition: Using upgoing scattered wavefield**

The RTM workflow for imaging of the salt base with the transmitted wave scattered from a deeper reflector is shown in Figure 7. The scattered wavefield is generated using Born modeling on a reflector taken from the regular reflection RTM image (Dai and Schuster, 2013). The scattered wavefield is forward propagated in a sediment-only velocity model, whereas the backward propagation of the receiver field is performed using a salt flood velocity model. The scattered forward source wavefield and direct backward receiver wavefields are then crosscorrelated with zero-lag time to form an RTM image. Because velocities of receiver and source legs are correct for the salt base, a strong correlation is expected to form at the true location of the salt-sediment interface. In the next section, we illustrate the performance of the transmission RTM imaging on synthetic and field data.
RESULTS

Example 1: Synthetic test for a downgoing VSP wavefield

To test the RTM implementation for salt proximity imaging, a simple synthetic model was constructed (Figure 8). The velocity model includes a constant velocity salt body (4500 m/s) enclosed within a $v(z)$ velocity gradient above the deep horizontal reflector. The VSP geometry to test is indicated by the red source to receiver shown in the figure. This is representative of a walkaway VSP acquisition geometry with a source positioned at the surface and a receiver down the borehole. In this example, we only model one source-to-receiver pair, whereas, in practice, there would be a spread of sources at the surface and several receivers within the well.

The results of the imaging tests are shown in Figure 9. We compare two cases. In the first example, we image the direct arrival from source to receiver using conventional RTM with the correct migration velocity model. RTM with a zero-lag crosscorrelation imaging condition generates an image wherever the source and receiver wavefields coincide (Jones, 2014) (Figure 9a). Much attention has been paid to removing low-wavenumber artifacts from the crosscorrelation of source and receiver wavefields at nonreflecting locations along the wave path (Fletcher et al., 2005; Guitton et al., 2006; Yoon and Marfurt, 2006; Zhang and Sun, 2009; Liu et al., 2011). In our examples, we have filtered the images to remove backscattered energy at the lowest wavenumbers only, using a second derivative (Laplacian) filter, so that the details of the imaging methods can be observed. Filtering of the migrated image can result in image artifacts if not performed carefully (Zhang and Sun, 2009). In the example in Figure 9a, we see an image of the wave path from source to receiver and a clear image at the location of the salt flank as indicated by the arrows. The areal extent of the salt interface, as seen in the figure, is directly related to the illumination coverage from the VSP acquisition geometry. In Figure 9b, we follow the method of McMechan et al. (1988) and forward propagate the source wavefield with the salt flood velocity model and back propagate the receiver wavefield with the sediment flood velocity model. Crosscorrelation of the two wavefields has generated a Cartesian oval exactly per the theory previously outlined (see Figure 3 for comparison). In Figure 9b, the aplanatic curve lies along the upper portion of the Cartesian oval and is aligned with the dipping salt interface. For just one source-to-receiver location, there is no image formed of the dipping interface itself; to achieve this, we would have to sum contributions from several different source or receiver positions.

As previously mentioned, the tangent to the aplanatic curves for several source or receivers will line up at the correct position of the salt interface if the velocity model is correct. If there are errors in the velocity model, then we can expect that the image will not align and may produce a false position of the salt interface. This is shown in Figure 10, for the case of a 10% lower salt velocity (Figure 10a), for the correct salt velocity (Figure 10b), and for 10% too high salt velocity (Figure 10c). When the salt velocity is too low, the transmission image formed is deeper that the true depth of the interface (Figure 10a), and the image of the interface covers a smaller lateral distance than when the salt velocity is correct (Figure 10b). Correspondingly, when we include a too-high salt velocity in the model (Figure 10c), the image is shallower and covers a larger lateral distance than for the correct model (Figure 10b). It is also worth noting that in each test case, we also see image artifacts from the lack of cancellation at the edges of the illuminated aperture as shown by the images of the rotated Cartesian ovals, as expected. These can be blanked from the data or reduced if additional sources or receivers are available for the imaging.

Example 2: 3D VSP field data set

We now apply the downward transmission imaging workflow to a 3D walkway VSP survey from the Gulf of Mexico acquired around a development well within the Mars Basin (Figure 11). There are two VSP spirals shown in the image; for purposes of this test, we will only use the red spiral as indicated in the figure. The survey was acquired...
to image the up-dip extent of the basin as it approaches the salt flank (see also Figure 1). There are 30 receivers positioned at 10 m intervals within the borehole, and a conventional air-gun source array was towed around the well at the surface. The data have been processed to remove noise and multiples, and the downgoing and upgoing wavefields have been separated using radon dip filtering (see Table 1 for the processing workflow used). An enlarged view of the shot-points for the 3D VSP spiral is shown in Figure 12. The center of the spiral is positioned at the surface location of the well. The tear-drop-shaped gap in the coverage immediately to the right of center is the position of the Mars platform.

Before imaging is applied, we perform an additional processing step to isolate only that portion of the wavefield that propagates through the salt to the receiver, i.e., the downgoing salt-only wavefield. This was achieved by ray tracing a vertically transverse isotropic velocity model using the exact source and receiver locations from the field geometry. Sources were selected whose raypaths formed a direct arrival through the salt; all other paths, i.e., sediment only, or combinations of sediment and salt paths had their sources removed for the imaging step. The use of ray tracing to select the data is potentially problematic below the salt; however, some crosstalk can be tolerated if it does not degrade the image too much. The portion of the data set that was selected for imaging is shown in red in Figure 12.

The RTM image, using the correct velocity model and using synthetically generated data from the field source and receiver geometry, is shown in Figure 13. This test, therefore, allows one to establish the illumination coverage for the 3D VSP geometry to see what extent of the base salt and salt flank can be illuminated. In Figure 13a, the RTM image of the wavefield transmission for one source-to-receiver pair is shown. You can see that an image has been formed along the interfaces with the largest velocity contrasts in the model; these are the water bottom, top, and base salt interfaces, as indicated by the arrows in Figure 13a. In comparison, the image using the known model but with all the sources that contribute to a direct salt arrival is shown in Figure 13b. As seen in the figure, a large portion of the top salt has

![Figure 11](https://pubs.geoscienceworld.org/geophysics/article-pdf/84/2/S71/4662069/geo-2018-0182.1.pdf)

**Figure 11.** Location map of the 3D VSP data set used to test the refraction imaging method. Two 3D VSP spirals (red and blue) are positioned at the western end of the Mars Basin. The top salt interpretation is shown in green. The yellow line represents the location of a 2D walkway VSP survey not used in the current study.

![Table 1](https://pubs.geoscienceworld.org/geophysics/article-pdf/84/2/S71/4662069/geo-2018-0182.1.pdf)

**Table 1.** 3D VSP processing workflow used to prepare the field data set for transmission imaging with RTM.

3D VSP processing sequence
1) Receiver reorientation
2) Select vertical component
3) Spherical spreading correction
4) Multifrequency denoise
5) Model-based designature of air-gun array
6) Wavefield separation, e.g., P and S, upgoing and downgoing wavefields
7) Deabsorption, constant $Q$ value
8) Shot regularization
9) Model-based free-surface demultiple
10) Direct salt arrival selection, based on ray-traced arrivals
been imaged by the correlation of the reflected, forward-propagated source and back-propagated receiver wavefields. In comparison, a much smaller portion of the base salt and salt flank has been imaged (Figure 13b). The illumination coverage is therefore better for the top than the base salt, as expected. The receivers are positioned very close to the salt boundary and therefore are only able to record a smaller angular range compared to the angular coverage for the top salt. Positioning the receivers further away from the salt flank would have provided a more extensive imaging of the base salt; however, salt flank imaging was not considered when the well was originally designed.

To test the workflow for better imaging the salt flank, we generated a salt flood velocity model to move the position of the salt edge beyond the borehole receivers as was graphically shown in Figure 6b. This model was used to forward propagate the source wavefield. Correspondingly, a sediment-only velocity model was used to back propagate from the downhole receivers. After application of the imaging condition, the transmission image was created as shown in Figure 14a. An image of the salt flank has been recovered. For comparison purposes, the conventional image of the upgoing RTM is shown in Figure 14b. The image generated from the upgoing wavefield effectively terminates at the approximate salt boundary position, but it becomes quite unreliable toward the edges due to the limited spatial coverage of the data. Therefore, it is not possible with any certainty to know the true up-dip extent of the basin sediments without imaging the salt flank. If we take a closer look at the downgoing image, there are several features in common with the earlier synthetic test from Figure 13. At position 1, the flank is not imaged, due to the lack of offset coverage between the downhole position and the dipping salt flank, which was also noted in Figure 13b. There is not enough illumination coverage in the selected data set to image this area from the VSP geometry. This might be improved by adding back the shots that have raypaths that reflect from the salt down to the receiver (the purple area in Figure 12). At positions 2 and 3 in Figure 14a, an image of the steep salt flank is created. This was achieved where there was no explicit base salt in the velocity model, and the recumbency in the salt flank has been imaged, which was not previously seen on the image from the surface acquisition data (see Figure 1).

Example 3: Synthetic test for an upgoing wavefield

The final example we show is designed to illustrate the imaging of an upgoing reflected wavefield that is then transmitted at the base salt as recorded by a surface acquisition geometry. We use the velocity model defined in Figure 8 for this test and the acquisition geom-

![Figure 12. Source locations for the 3D VSP survey used in our study. The sources have been separated based on whether they contain direct downgoing salt rays (red symbols) or sediment-only raypaths (blue symbols) or a combination of both (purple symbols).](image)

![Figure 13. Velocity model with RTM transmission image overlaid for (a) single source-to-receiver path and (b) for all sources that contain the direct downgoing salt arrival (see Figure 12). The red line at the top of (b) indicates the shot spread from the selected sources. The RTM image was formed using the known velocity model in both cases. The arrows indicate areas where an image is formed at the main impedance contrasts: water-bottom, top salt, and base salt. The P-wave velocity scale for both plots is shown on the right.](image)

![Figure 14. (a) The RTM refraction image generated from the VSP downgoing wavefield for all shots that have a direct salt path. (b) This is compared with the RTM image of the reflected upgoing wavefield. The features in the transmission image that are highlighted include (1) the illumination gap, (2 and 3) images of the salt flank formed when no base salt was present in the velocity model. The dashed line is the well path, and the green area along the well indicates the receiver coverage.](image)
etry shown by the blue source-to-receiver path, as shown in the figure. The conventional reflection RTM image with this model is displayed in Figure 15a, and we see that the salt boundary has been well-imaged. If we now perform imaging for the transmitted upgoing wavefield scattered from the deeper reflector, we achieve the image shown in Figure 15b, which provides an image for most of the base salt at least where the model is illuminated, as indicated by the arrows in the figure. You can also see that with this method, we have some strong image artifacts at each end of the salt. These are due to mismigration of the internal salt multiples and prism waves that are reflected from the underside of the base salt.

As with the previous workflow, we now test the upgoing method in the presence of a velocity error. Because the upgoing wavefield has a bigger portion of its travel path through the sedimentary section (compared with the downgoing VSP method), we test the upgoing transmission migration using a velocity error, which is introduced into the source-side forward-scattered wavefield. Figure 16a shows the image after including a 10% reduction in the subsalt sediment velocity. This can be compared with the correct velocity model image (Figure 16b) and the image with a 10% increase in the subsalt sedimentary velocity (Figure 16c). As was noted in the previous method, a decrease in velocity moves the event deeper than the true position of the salt boundary, whereas an increase in migration velocity moves it shallower.

**DISCUSSION**

The transmission imaging workflow of McMechan et al. (1988) using backward and forward focusing of VSP data has been shown to form an image when the position of the salt interface is unknown.
depth of the receivers in the borehole and their proximity to the salt. Sources located immediately above the receivers do not illuminate the salt boundary, which can only be imaged by some offset to the side. However, the recorded offset is limited by the maximum radius of the shot spiral, i.e., 6 km, and the proximity of the receivers to the salt; this narrows the range of recordable paths that illuminate the salt interface. Moving the receivers further away from the salt face, increasing the number of receivers, or raising the receivers shallower in the well would provide for a better transmission image. Some of the illumination issues may also be improved by using the geophone’s horizontal components within the borehole, which will most likely record horizontally propagating waves from the salt flank. The horizontal components were not extensively analyzed in our study, and this remains an opportunity for future work.

One critical assumption that has been made throughout this paper is that the salt is homogeneous and therefore has constant velocity. Zong et al. (2015) analyze the composition, density, velocity, and stress effects of a variety of rock salt samples and determine that, in the Gulf of Mexico, the salt is largely isotropic with a very small increase in velocity with depth. However, this does not account for the case when sediment is trapped within the salt during formation or the chemistry of the salt under evaporitic conditions may result in variability in composition from pure halite. These errors are assumed to be no worse than demonstrated previously and are likely to be only a few percent in error. Although this requires further validation, the impedance contrast with the neighboring sediments is still large resulting in strong wavefield refraction across the salt/sediment boundary.

Another assumption fundamental to the method of transmission imaging with the downgoing and upgoing methods is that the interpretation and location of the top salt is correct. For our VSP field data set, the top salt has been constrained by prestack depth imaging using several towed-streamer and OBS data sets with constraints from well logs. We therefore have high confidence in the interpretation of the top salt, but this might not be the case for other areas.

As has been shown for the two methodologies presented, if the velocity model is incorrect then the Cartesian oval and hence aplanatic surface will be displaced relative to the true base salt boundary position for the transmission RTM. This is in the opposite sense to a conventional RTM of reflection wavefield. A comparison of the two images should therefore indicate if there is a velocity error in the migration model. Figure 17 shows the comparison of the reflection RTM image and the transmission RTM image spliced toward the center of the salt body. In both cases, the correct migration velocities were used but the transmission result followed the dual velocity migration previously discussed. The base of salt is aligned between the reflection and transmission RTM images. One significant difference in the images is that the transmission image appears to have a much lower frequency content than the reflection image. This is due to the different correlation lengths used in the imaging condition, and it effectively results in a stretched wavelet for the transmission image. A detailed explanation is provided in Appendix A. Another difference is noted in the polarity flip between the two images due to the difference in reflection and transmission coefficients for the two migration applications.

If we assume that the top salt is correctly interpreted and the suprasalt velocity model is correct, then the misalignment of the base salt would suggest that either the salt velocity is incorrect or in the case of the transmission migration that either the salt or sediment (or both) velocities are incorrect. Because the error in the salt velocity is typically small, the sedimentary velocity estimation is likely to be the bigger source of error. Alignment between the conventional and transmission images may provide an additional quality control for velocity model-building workflows if both data sets are available. We summarize the relative changes in the base salt geometry to velocity error for the reflection and transmission methods in Figure 18.

CONCLUSION

We have presented the theoretical and practical implementations of applying wave equation transmission imaging using RTM for the imaging of steep salt flanks. These methods do not require any previous salt flank interpretation and only an approximate window around the direct arrival event; therefore, they are quite robust in the presence of multivalued arrivals typical of the subsalt domain. The methods have been demonstrated to be somewhat sensitive to velocity error, proximity to the salt body, and impedance contrasts across the salt boundary. Velocity errors from an incorrect sediment or salt velocity produce the opposite change in depth to that expected from conventional reflection-based RTM images. This principle can be used to infer if the velocity of the salt or subsalt sediment is incorrect. In addition, the frequency content is generally lower on transmission images (from wavelet stretch) due to the difference in the transmission and reflection coefficients.

Image artifacts due to incorrect imaging of internal salt multiples, reflection prism waves, and the use of a finite source-to-receiver

Figure 18. Interpretation summary of the changes to base salt depths between reflection and transmission RTM images. (a) Reflection migration = salt velocity too slow, transmission migration = salt or sediment velocity too slow. (b) Reflection migration = velocity correct, transmission migration = velocity correct. (c) Reflection migration = salt velocity too fast, transmission migration = salt or sediment velocity too fast.
coverage may be present in transmission images. This can be minimized by muting later arrivals before imaging.

Based on the work presented, we consider three main applications in which these transmission methods can be used (1) to provide additional imaging at high impedance contrasts (this would require separation of the wavefields), (2) for imaging salt boundaries where the salt/sediment interface is unknown and poorly imaged with existing data sets, and (3) to provide a constraint on the salt and/or sediment velocity when used in conjunction with conventional reflection RTM.

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DATA AND MATERIALS AVAILABILITY

Data associated with this research are confidential and cannot be released.

APPENDIX A

EXPLANATION FOR WAVELET STRETCH

From Figures 14 and 15, one can see that the transmission image of the base salt appears to be of lower frequency that the standard reflection RTM images. To explain the frequency differences, let us consider a wavefield propagating along the z-axis and falling normally at an interface (Figure A-1). In the figure, \( P_i \), \( P_r \), and \( P_t \) are the incoming, reflected, and transmitted components, respectively, and \( k_z = \omega/v \), \( k_z^i = \omega/v_i \).

In regular RTM, we are crosscorrelating wavefields \( P_i \) and \( P_r \), i.e.,

\[
I_{\text{ret}} \sim P_i P_r^* = e^{ik_z z} (e^{-ik_z z})^* = e^{2ik_z z}.
\]

Although in RTM with transmitted waves, we are crosscorrelating wavefields \( P_i \) and \( P_t \) or

\[
I_{\text{trans}} \sim P_i P_t^* = e^{ik_z z} (e^{ik_z z})^* = e^{2ik_z z}.
\]

From these two equations, one can see that the correlation length in the former case is proportional to

\[
l_1 = \frac{1}{2k_z} = \frac{v_2}{2\alpha},
\]

whereas in the latter case, the correlation length is proportional to

\[
l_2 = \frac{1}{k_z - k_z^i} = \frac{v_1 v_2}{v_2 - v_1}.
\]

By dividing equations A-3 and A-4, we can compare how much of the wavelet will be stretched during RTM of transmitted waves as compared with RTM of reflected waves:

\[
\frac{2v_1}{v_2 - v_1} l_1.
\]

In other words, the wavelet will be stretched

\[
\frac{2v_1}{v_2 - v_1} = 2.3.
\]

So, the wavelet will be stretched 2.3 times compared with standard RTM for this example.

REFERENCES


