Processing converted-wave data in the tau-p domain: rotation toward the source and moveout correction

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ABSTRACT

The asymmetry of the converted-wave raypath is one of the main sources of complexity in the processing of multicomponent data. Such asymmetry is controlled by Snell's law, which also states that in an isotropic and flat layered medium the ray-parameter value p is preserved, even for converted-wave modes. In this study we propose processing converted-wave data in the ray-parameter domain offers a more suitable framework for dealing with this type of waves. Here, we address the problem of rotations toward the source in 2D media with dipping reflectors, converted-wave velocity analysis and NMO corrections. Results show that reversing the polarity of the traces to correct for the orientation of the horizontal components around the zero ray-parameter condition provides consistent polarities along all the events. Also, using an elliptical approximation to the PS-moveout in τ-p domain provides an alternative tool for velocity analysis and converted-wave moveout correction. Its implementation is very similar to conventional processing in the x-t domain. However, results show that in the τ-p domain the information in shallow events can be fully exploited. The ability of shallow events to reach wider reflection angles, and therefore larger ray-parameter values, makes them a good target for τ-p domain processing. An accurate algorithm for the τ-p transformation is required to avoid introducing numerical artifacts. We noticed that the polarity reversals present in the converted-wave events are a source of numerical artifacts. A new τ-p transformation algorithm, able to account for these polarity reversals and to avoid introduction of these artifacts, is required to provide cleaner data for further processing.

INTRODUCTION

Developments in acquisition of multicomponent data both on land and on the sea-floor enable us to use converted-waves in seismic exploration. The specifics of this wave-mode required us to revisit the concepts and ideas typically used in P-wave processing.

The most primitive form of seismic processing relies on our ability to stack seismic traces. Through stacking, operation that the signal/noise ratio of the data is improved and a seismic image can be computed. To produce a proper stack one must be able to correct reflection travel-times to a zero offset condition. This means removing the hyperbolic character of the reflection events by aligning all the amplitudes at their zero offset traveltime. The asymmetry of the converted-wave raypaths imposes an additional degree of complexity to this problem. Such asymmetry is the result of the difference in velocity between the downgoing P-wave and the upgoing S-wave. In spite of this, both legs of the converted-wave propagation still share the same ray-parameter value as dictated by Snell's law.

In 2D-3C seismic processing, rotation of the horizontal components toward the source is achieved by reversing the polarity of one end of the spread. However, the polarity of converted-wave arrivals may experience changes that may harm our ability to produce an optimum stack. This is evident in areas with some structural complexity. The reason for this is that the polarity change related to the directionality of the wavefield is shifted away from zero offset.

In this study we show how rotations toward the source and converted-wave NMO corrections can be performed in the ray-parameter domain. In this domain the directionality of the wavefield is accounted for, and rotations toward the source are properly achieved. Although still very simplistic, in conception it is a starting point for processing converted-wave data in a more suitable framework.

CONVERTED-WAVE PROCESSING IN THE RAY-PARAMETER DOMAIN

Rotation toward the source

In 3C data acquisition, geophones are planted in such a way that one of the horizontal components is oriented parallel to the receiver line direction, with the second perpendicular to the other. The horizontal component, parallel to the receiver line, is often referred to as the inline component and the perpendicular as the crossline component. In the case of 2D-3C acquisition using a split-spread configuration, the inline component of the receivers on one side of the spread will point toward the source while the receivers on the other side will point away from the source. This results in conflicting polarities between data recorded at positive and negative offsets.

In an isotropic geological model, with flat and homogeneous layers, PS-mode conversion presents radial symmetry around the source. This means that to solve the conflicting polarities of the data recorded on the inline component we just need to reverse the polarity of the traces recorded in one end of the spread.

However, in a geological model with dipping reflectors PS-mode conversion is not symmetrical and the polarity change is shifted away from the zero offset location. This shifting will depend on the magnitude of the dip. Therefore, in a multiple layers model with different dips, polarity reversals are expected to change their location with time. Figure 1 shows a three interface model with dips varying from 0° in the shallowest part, 5° in the middle, and 10° in the deepest part of the model. Synthetic converted-wave source gathers were simulated using ray tracing. Figure 2 (left) shows the inline component for a source gather located in the middle of the model (x=1500m). Amplitudes have been normalized to highlight the polarity changes. Notice how the polarities of the flat interface are symmetrical with respect to the zero offset. However, the location of that polarity change is different for the other two events.

Figure 2 (right), shows the result of reversing the polarity of all the traces recorded with negative offsets. Notice how this correction is effective for the flat shallow event but the other two events still present polarity problems. This results from the fact that the dipping interfaces have produced non-symmetrical wavefields. The actual location of this polarity change occurs around the normal incidence traveltime (fastest arrival) and not at the zero offset traveltime. For a flat reflector, the two traveltimes, zero offset and normal-incidence, are the same, but for dipping reflectors the two differ.

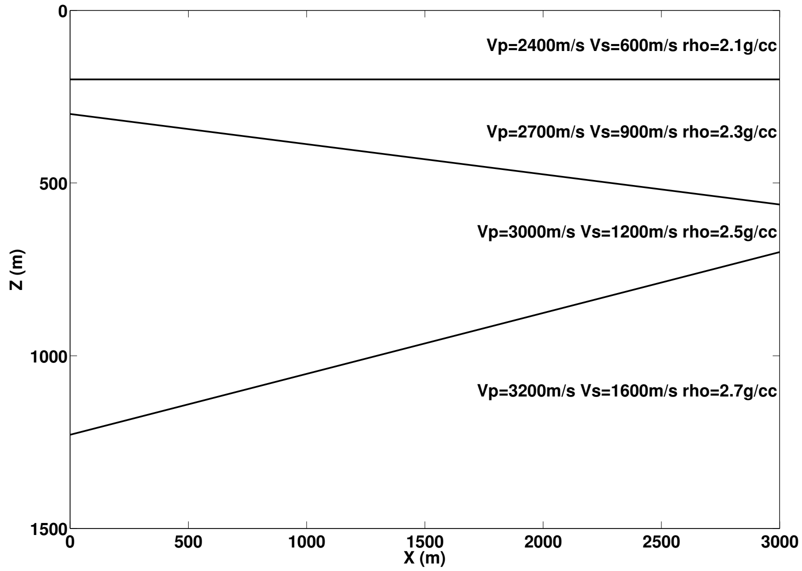

FIG. 1. Velocity model used to compute synthetic converted-wave traces via ray-tracing. The second and third reflectors present a dip of 5° and 10° respectively.

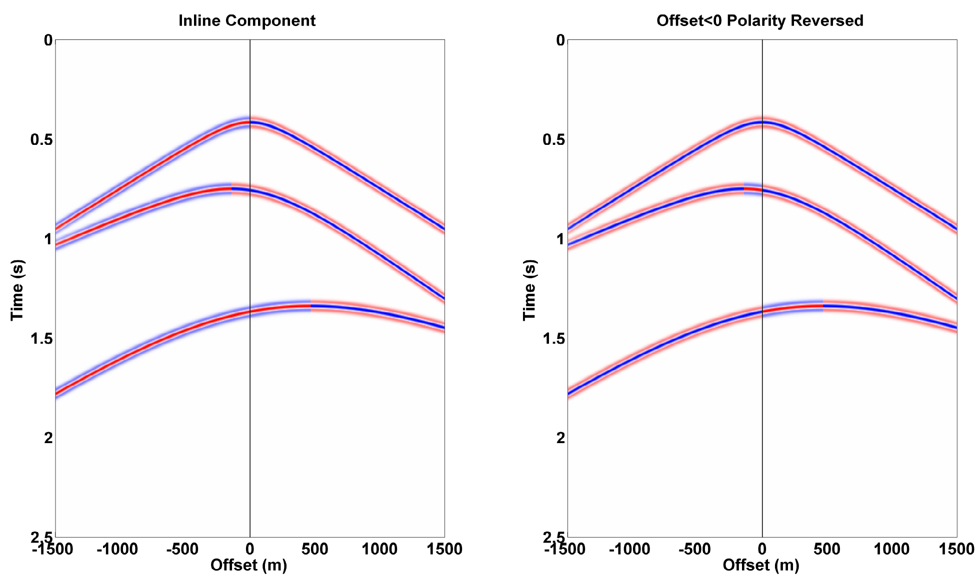

FIG. 2. (left) inline component gather for a source located in the middle of the model ($x = 1500$m). Location of the polarity reversal characteristic of horizontal component data is shifted away of the zero offset for dipping interfaces. (right) result of reversing the polarity of traces recorded at negative offsets. Notice that polarities are inconsistent along the events.

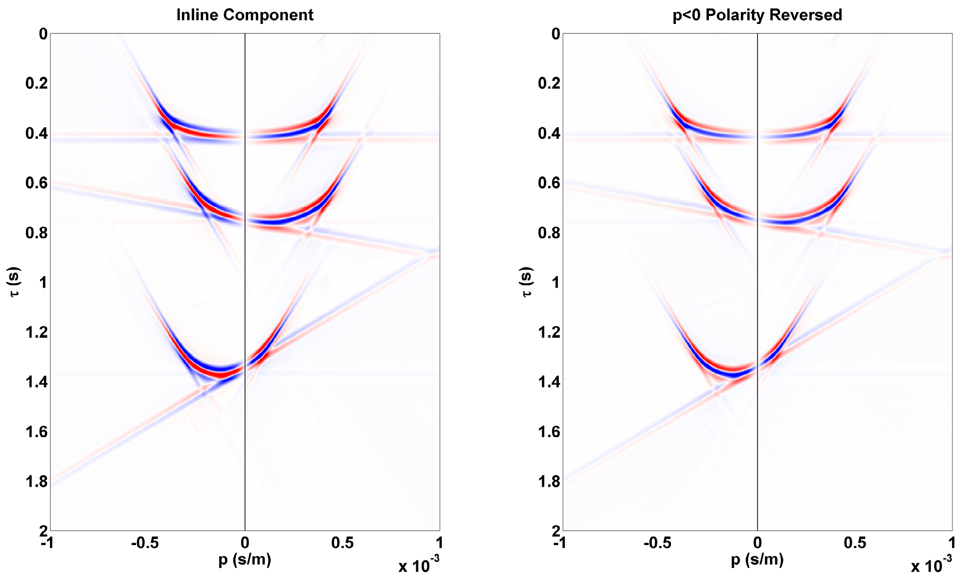

FIG. 3. (left) Source gather 1500 transformed to the τ-p domain. Notice that the polarity reversals are now aligned around the zero ray-parameter value. (right) result of reversing the polarity of all the traces with $p < 0$. All the events now display a consistent polarity.

One way to determine the location of the polarity change of the event is by use of a τ-p transform. The apex of the events corresponds to the part of the wavefield with zero-slope, ($dt/dx = 0$). This slope, by definition, represents the horizontal slowness, or ray-parameter p. Therefore, instead of doing the polarity correction around the zero offset condition, here we propose doing it around the zero ray-parameter condition.

Figure 3 (left) shows the result of transforming the source gather shown in Figure 2 (left) to the τ-p domain. Notice how the polarity change of all the events is now aligned around the zero ray-parameter value. Figure 3 (right) shows the result of reversing the polarity of all the traces with a p-value less than zero. Notice how all the events now display a consistent polarity for all the ray-parameter values.

Since the polarity correction was done in the τ-p domain, an inverse transform needs to be applied to get the data back to x-t. The result of back-transforming the corrected gather to x-t is shown in Figure 4. Notice how the polarity of the events is now consistent at all offsets. The stack, produced by gathers corrected using this method, should provide a better stacking power than those with partially corrected polarity.

Despite having the correct polarity, the amplitude values around the apex of the events in Figure 4 have been distorted. The weak linear events, apparent in the transformed data, are numerical artifacts produced by the polarity changes. Prior to reversing the polarity of the traces, the artifacts displayed opposed polarities. This means that without applying any polarity change, the linear events should stack to zero during the back-transformation, and the original data should be recovered. However, after applying the polarity correction these artifacts display a consistent polarity. As a result, they will stack to a non-zero amplitude during the back-transformation. To solve this problem, a τ-p algorithm able to handle polarity changes without introducing numerical artifacts, is needed to fully recover the original amplitude values in the near-offsets.

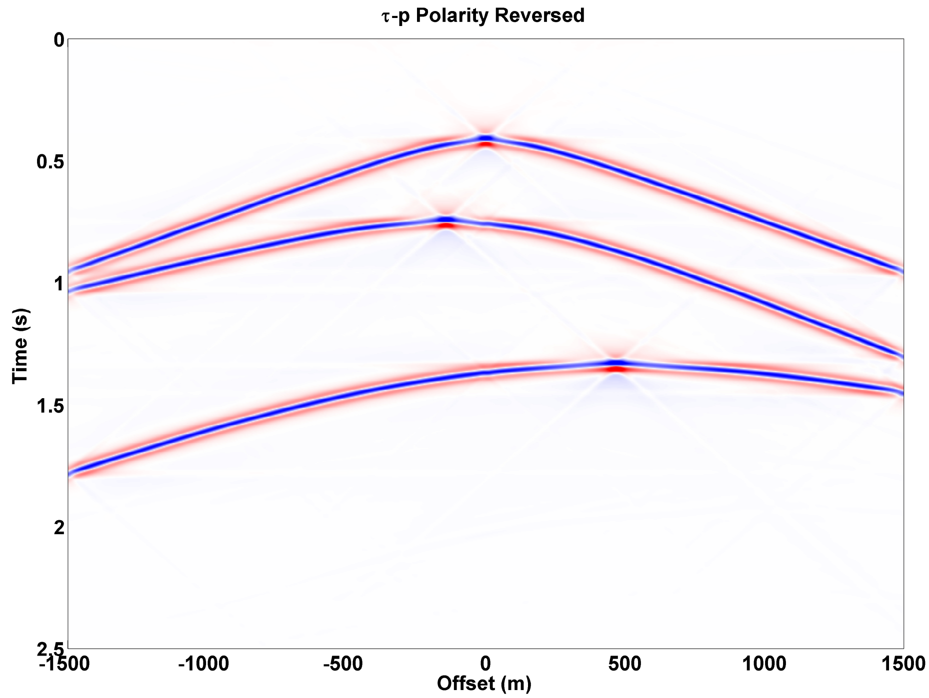

FIG. 4. Back-transformation of the τ-p polarity corrected data to x-t. The polarity of the events have been fully corrected. However, amplitudes around the zero offset value have been distorted.

Although near-offset polarities have been distorted we think that the τ-p corrected data should still provide better stacked traces. Another option to deal with the problem caused during the back-transformation is to apply the NMO correction directly on the τ-p gather. In the next section we explain how this goal can be achieved.

Converted-wave NMO Correction

Tessmer and Behle (1988) derived an approximation for converted-wave moveout (equation 1) based on a Taylor series expansion of the traveltime equation. In the equation, t_{c_0} represents the zero offset converted-wave traveltime, x is the source-receiver offset, and V_c is the converted-wave RMS velocity. This equation represents a hyperbolic approximation to the converted-wave moveout. It should be noted that its convergence is not as fast as in the case of PP reflections, but it works well for offset/depth ratios close to 1.0 (Tessmer and Behle, 1988).

$$t_c = \sqrt{t_{c_0}^2 + \frac{x^2}{V_c^2}}. \tag{1}$$

In the τ-p domain, hyperbolic events are transformed into ellipses. Equation 2 was derived by Schultz and Claerbout (1978) to explain the shape of the ellipses in this domain. There, τ_0 represents the intercept time at normal incidence, p is the ray-parameter, and v is the moveout velocity of the event.

$$\tau = \tau_0 \sqrt{(1 - p^2 v^2)}. \tag{2}$$

In this study we use equation 2 to approximate the moveout of converted-wave events transformed into the τ-p domain. Figure 5 shows a summary of the implementation of equation 2 into the velocity analysis and stacking stages of the converted-wave processing.

After applying the polarity correction explained in the previous section the data were sorted in asymptotic conversion point (ACP) gathers. The gather displayed in Figure 5 correspond to the ACP gather located in the middle of the model ($x = 1500$m). Equation 2 is then used to remove the moveout of the events using constant velocity functions to compute a stacking power panel. There, we can observe what velocity values provide the best moveout correction for each event. The time-velocity function represented by the dashed line is then picked and applied to the ACP gather. The τ-p NMO-corrected gather in Figure 5 shows how equation 2 effectively removes the moveout of the events for a significant range of p values. Although the interfaces are known to be dipping we can observe a good level of flatness in the events after NMO correction. The dashed lines in the NMO-corrected gather represent the mute functions applied before stacking. The last panel in Figure 5 displays a stacked section of the ACP gathers around ACP 1500. We can see how this correction not only performs well for the ACP 1500 but also for the ACP's around it. The mini-stacked section shows very well the dip of the events.

It is important to note the shape of the mute function used to stack the traces. As we can see in the NMO-corrected gather the range of p values useful after muting is wider for shallower events than for deeper events. This results from the ability of shallow events to reach wider reflection angles, which translates into larger ray-parameter values. Compared to what we would expect in x-t domain, the useful range of offsets after muting is generally narrower for shallow events than for deep events. In other words, in the x-t domain the shape of the live zone after muting widens downward while in τ-p it widens upward. This may have an impact on our ability to produce optimum stacks for shallow events. We think that NMO corrections in the τ-p domain may outperform corrections in x-t for shallow events.

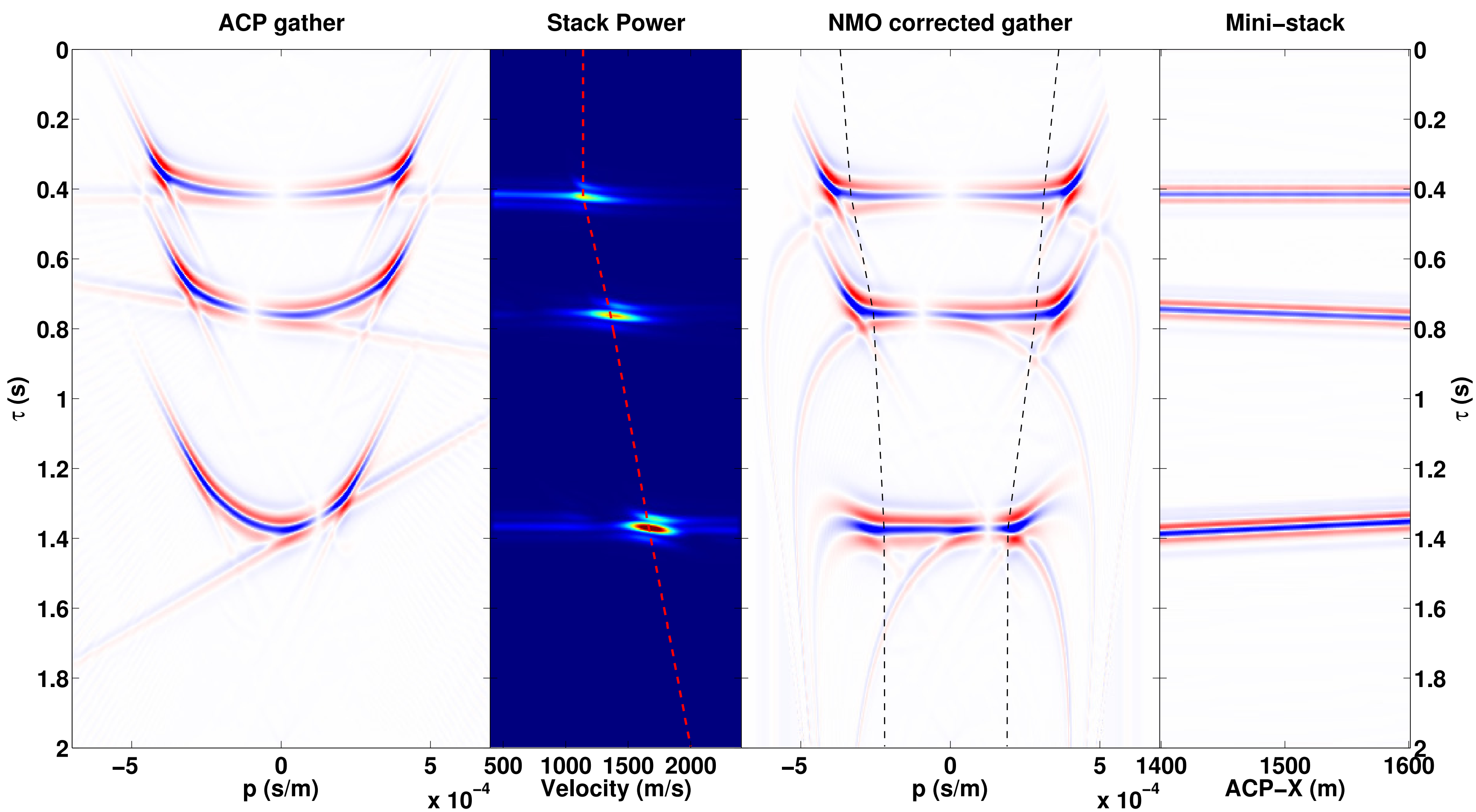

FIG. 5. Velocity analysis and NMO correction of converted-wave data in τ-p domain.

CONCLUSIONS

This study proposes a framework to process converted-wave data in the τ-p domain is proposed in this study. The polarity correction due to rotation of the horizontal components toward the source can be performed in τ-p. There; the imprint of the dip of the interfaces on the moveout can be accounted for. Therefore, polarity corrections around the zero ray-parameter condition instead of the zero offset conditions may lead to a more appropriate polarity correction.

Converted-wave NMO corrections can also be applied in the τ-p domain. The elliptical approximation to the τ-p moveout can be used for both velocity analysis and moveout removal. NMO-corrected gathers showed a good level of flatness that, combined with a proper polarity correction, yields an optimum stacking power. The shape of the live amplitudes zone, after muting, widens upward, enabling a wide range of p-traces to be used during the stack of shallow events. As a result, velocity analysis and NMO corrections in τ-p domain may provide a more suitable framework for processing shallow events.

Our main concern resides on the invertability of the τ-p transform. In the case of converted-waves the presence of polarity changes along the events introduces a new source of numerical artifacts. To address this problem a new τ-p algorithm, able to handle polarity changes without introducing numerical artifacts, needs to be developed.

ACKNOWLEDGEMENTS

The authors thank the sponsors of CREWES for continued support. This work was funded by CREWES industrial sponsors and NSERC (Natural Science and Engineering Research Council of Canada) through the grant CRDPJ 461179-13. We also thank Roy Lindseth and Andreas Cordsen for their suggestions and assistance with proof-reading.

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