ELIMINATION OF MULTIPLES FROM MARINE SEISMIC DATA USING THE PRIMARY-MULTIPLE INTERMEDIATE VELOCITIES IN THE τ-q DOMAIN

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ABSTRACT

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Removing seismic multiples is one of the essential steps in seismic data processing and is often carried out using the Radon transform (*intercept time (τ) and curvature (q)* domain). In this method, the normal moveout (NMO)-corrected CDP gathers using primary (signal) velocity are transformed into the *τ-q* domain where multiples can be separated from primaries, based on their curvatures, and muted. A drawback of using the primary velocity for NMO correction is that primaries and multiples often exhibit similar curvature in the *τ-q* domain, particularly at near offsets. We propose the use of velocity function intermediate between primaries and multiples for the NMO correction of the CDP gathers as input to *τ-q* domain to enhance primaries-multiples separation. The primary-multiple intermediate velocity approach is applied to synthetic and real short-streamer marine seismic data. A semblance-weighted Radon transform is used to reduce smearing in the radon space. The results showed more primary-multiple separation and better multiple removal.

KEY WORDS: seismic noise, multiples, Radon transform, seismic velocity, normal moveout correction.

INTRODUCTION

Coherent signals in the seismic data are categorized as desired signal, often referred as primary reflections, and the undesired noise, which masks the primary signals and includes ground roll, mode-converted waves and multiples. Seismic data processing is meant to remove the undesirable parts of the recorded signals while minimizing effects on the desirable signals.

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Multiples, as the name implies, are multiple reflections within one or many layers and appear at delayed times and obscure primary signals. Surface related multiples, peg leg multiple, and interbred multiples may have different ray geometry, but all have one common characteristic in that they exhibit a delayed time with respect to their primary.

Several methods were proposed to separate and attenuate multiples in seismic data, including stacking (Mayne, 1962), FK Filtering (Ryu, 1982) and Parabolic Radon (Hampson, 1986). Among these methods, parabolic radon is the most widely used. Hampson (1986) pointed out that when a CDP gather is NMO-corrected using the primaries velocities, multiples depict a parabolic curvature (the moveout property of multiples). Input to parabolic Radon entails a perfect transformation of CDP gathers from t-x domain into τ-q domain. Multiples are muted in the τ-q domain and muted gathers are transformed back to the t-x domain to obtain multiples CDP gathers free of multiples. Parabolic radon transform is reasonably successful in removing multiples provided the primaries velocities are estimated correctly (Foster and Mosher, 1992; Hampson, 1986; Russell et al., 1990; Sacchi and Porsani, 1999; Sava and Guitton, 2005). Advancement in Radon algorithms has been made to improve computational performance and efficiency (Ursin et al., 2009; Gholami and Sacchi, 2017).

Although the Radon transform is mostly used to attenuate surface as well as inter-bed multiples, it has some limitations. When the CDP gathers are NMO-corrected using the primary velocity, primaries and multiples often demonstrate similar curvatures in the τ-q domain, especially at short offset land and marine acquisitions and consequently separation of multiples becomes challenging. In this study, we investigate the application of intermediate velocity functions between primaries and multiples for NMO correction of data input to τ-q domain. The proposed approach has potential to enhance the separation between primaries and multiples.

Radon panel construction is prone to artifacts and smearing. The horizontal artifact is caused by the near-offset energy sharing, and the oblique smearing by the far-offset truncation (Cao and Bancroft, 2006). The smearing in the Radon domain decreases the ability to separate multiples energy from primaries. In order to reduce the smearing in Radon space, we used semblance-weighted radon, which is an iterative Radon algorithm, where more weights are given to clusters of maximum coherent energy that best match the input seismic data (Cao and Bancroft, 2006). The semblance-weighted Gauss-Seidel Radon method was introduced by Bradshaw and Ng (1987) and Ng and Perz (2004). For a particular time, the intermediate velocity is lower than the primaries velocity and higher than the multiples velocity. Unlike the conventional input to Radon, which entails primary velocities applied to CDP gathers, application of intermediate velocities result in over-corrected (negative q) primaries, and under-corrected (positive q) multiples. This enhances the separation between primaries and multiples and improves multiple removals in Radon space. We compare our results with the conventional radon attenuation practice, where multiples are modeled using the primaries velocity. We have tested this approach on synthetic seismic gathers and real marine seismic gathers acquired from relatively shallow water and contains strong water bottom multiples.

PARABOLIC RADON TRANSFORM

Hampson (1986) indicated that when a CDP gather is NMO-corrected using the primaries velocity, the multiples in the data depict residual parabolic curvature (*q*). These multiples can, therefore be separated from primaries using the Parabolic radon transform of the NMO-corrected CDP gather (Verschuur, 2013). The Parabolic radon [eq. (1)] is expressed as:

$$M(q, \tau) = \int_{-\infty}^{+\infty} d(x, t = \tau + qx^2)\, dx \quad , \qquad (1)$$

where q is the slope of curvature and τ is the two-way intercept time at the apex of the reflections in the t-x. The under-corrected multiples with positive curvature are muted in the τ-q domain and an inverse radon transform only transfers the remaining primaries into the t-x domain.

The parabolic radon transform in equation [(eq. (1)] can be expressed in frequency domain [eq. (2)], where the wave field is decomposed into plane waves, after which the result is inversely transformed from frequency to time (Verschuur, 2006):

$$M(q, f) = \int_{-\infty}^{+\infty} d(x, f)\, \mathrm{e}^{(-2\pi f q x^2)}\, \mathrm{d}x \quad , \qquad (2)$$

where f is the frequency, q is the curvature, and x represents the offset.

In order to minimize the amplitude smearing on the conventional Radon panels, a least-squares formulation of the Radon methods was proposed by Thorson and Clarerbout (1985) and Hampson (1986). Hampson (1986) used a least-square method in minimizing the difference between the original and re-constructed data. This minimization is quantified using the root mean square (RMS) difference of the two data sets. This process is carried out in the frequency domain to be computationally efficient. The Radon panel consists of all possible curvatures and offsets, computed at each frequency component. The damped least square solution is then calculated [eq. (3)].

$$M = (\mathrm{L}\mathrm{L}^{\mathrm{H}} + \mu \mathrm{I})^{-1}\mathrm{L}\mathrm{d} \quad , \qquad (3)$$

where M is the transformed data and d is the original data, $L = e^{-2\pi fqx^2}$, and μ is the damping factor for stable inversion.

In this paper, we use the semblance-weighted radon (Bradshaw and Ng, 1987), which first transforms the data into the τ-q domain and runs a coherency scan to plot major clusters of energy into a new radon panel. The semblance of Common Depth Point in radon form is calculated in [eq. (4)].

$$S(\tau, q) = \frac{\sum_l \sum_h d(x, t = \tau + qx^2, h)\, dx}{N_h \sum_l \sum_h d^2(x, t = \tau + qx^2, h)\, dx} \quad . \qquad (4)$$

where S is the semblance in the τ-q domain, l is a window size and is usually a wavelet length; N_h are trace numbers involved in calculating semblance.

Semblance estimation does not depend on the amplitudes of the input seismic data, rather it is dependent on the degree of coherency of seismic events, which ranges from 0 to 1 as an indication of poorest-to-best fit of the reconstructed seismic data from Radon with the input data (Bradshaw and Ng, 1987). The weighted Radon transform [eq. (5)] for the parabolic trajectory is defined as follows:

$$M(\tau, q) = S(\tau, q) \sum_h d(x, t = \tau + qx^2, h)\, dx \quad . \qquad (5)$$

The transform undergoes repeated coherency scan from high-energy clusters to low energy in τ-q domain using Gauss-Seidel sparse matrix, for making the Radon panel. The process is iterative until the convergence is achieved. This prevents smearing in radon space.

SEISMIC VELOCITY ESTIMATIONS FOR MULTIPLES AND PRIMARIES

As seismic velocities of primaries and multiples are key parameters in designing the Radon transform, we have tested the constant velocity stacks and semblance plots methods for velocity analysis to select optimum velocity functions for data input to the Radon transform. Constant velocity stacks (CVS) is a well-established method for picking velocities, in which different constant velocity functions are applied to seismic events occurring at different times in the same CDP. The correct velocity functions corresponding to seismic event flattens these events. Higher velocities normally correspond to deeper events. Ideally, primaries with a specific velocity at different times are flattened and multiples are under-corrected. However, using CVS, where a single CDP is subjected to different velocity functions, enables primary events and their respective multiples both flattens. The multiples naturally appear at a delayed time. Both of these events depict coherency, which are shown in semblance plots. Thus uniform constant velocity stacks representing the local geology help discern primaries from multiples. Seismic semblance plot is a coherency tool for finding the maximum amplitude event. Semblance is normalized by a cross correlation function and displays the common signal power over the channels according to the specified lag pattern (Taner and Koehler, 1969). The power of this estimate is then computed by summing the amplitude squares within a specified time gate around the reference time (T_0) and this power is then displayed on the velocity spectra (Taner and Koehler, 1969).

APPLICATION OF PRIMARY-MULTIPLE INTERMEDIATE VELOCITY APPROACH TO SYNTHETIC DATA

For better separation of primaries and multiples in the t-x and τ-q domain, accurate velocity estimates are important. Using multiples' velocities for NMO correction yield greatly over-corrected primaries and a better separation from multiples, even at the near offsets. We have applied NMO corrections to synthetic gathers using primaries and multiples velocities (Fig. 1). The NMO-corrected gather using the primaries velocities showed under corrected multiples with a maximum moveout of 350 ms (Fig. 1b). The NMO-corrected gather using the multiples velocity showed overcorrected primaries with a maximum moveout of 550 ms (Fig. 1c). This means a better separation between primaries and multiples is achieved when multiples velocities are used for NMO correction (Fig. 1c).

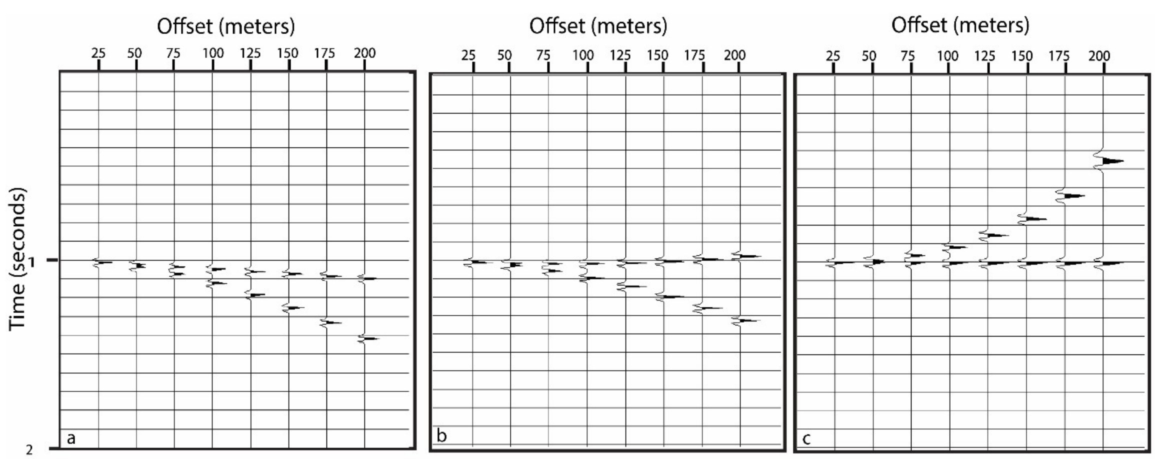

Fig. 1. A synthetic CDP gather before NMO correction (a) after NMO correction using primaries velocity (b) and after NMO correction using multiples velocity (c).

RADON APPLICATION TO SYNTHETIC DATA USING THE INTERMEDIATE VELOCITY APPROACH

The conventional radon filtering uses the primaries velocities for NMO correction and therefore, cannot separate multiples effectively, particularly at near offsets (Fig. 1b). Using multiples velocity will result in better separation, and preserves most of the multiples as flat events, along with the near offset primaries (Fig. 1c). In this case, both near offset primaries and multiples are associated with near-zero curvature in Radon space. This potentially leads to loosing primary events when muting multiples in Radon space. Therefore, a better alternative is to use intermediate velocities between primaries and multiples. This practice still ensures better separation between primaries and multiples, and results in fewer primary-multiples event, falling near the smaller *q* region in Radon space.

A synthetic example of radon application, when primary velocities are used for the NMO correction is shown in Fig. 2. In this case, the primary event is corrected, whereas multiples remain under corrected. The moveout difference between the two events at 300 m offset is 720 ms. The positive curvatures (*q*) of multiples are muted, and transformed back in t-x domain. Some of the positive *q* values are kept intact, as they account for inaccurate RMS velocities that leaves primary events under-corrected. Moreover, as the moveout between primaries and multiples is less at near offsets, muting smaller qs inevitably removes primaries. It is evident that this practice of preserving primaries results in preserving remnant multiple energy (Fig. 2c).

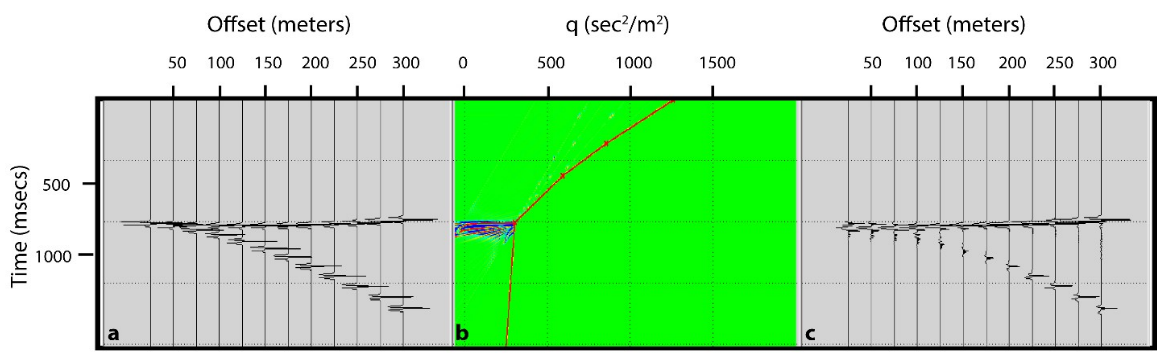

Fig. 2. A synthetic gather with primary event flattened using primary velocity leaving multiples under-corrected (a), muting of positive *q* in Radon space (b), filtered gather with remnant multiples (c).

Radon multiples attenuation of the above synthetic gather (Fig. 2) using intermediate velocities for NMO correction is displayed (Fig. 3). In this case, over-corrected primaries and under-corrected multiples are observed. The moveout difference between primary and multiple events at 300 m offset is 824 ms, which is 104 ms more than where using primary velocity for NMO correction. Since using intermediate velocities for NMO does not result in flattening the primaries or the multiples, it is expected that least amount of energy falls near 0 *q*'s in the τ-q domain, which allows muting more near zero *q's*. However, in order to preserve the very near offset primaries, 0 *q* and smaller positive *q* values will not be muted, and this results in a better removal of multiples and preservation of more primaries (Fig. 3c).

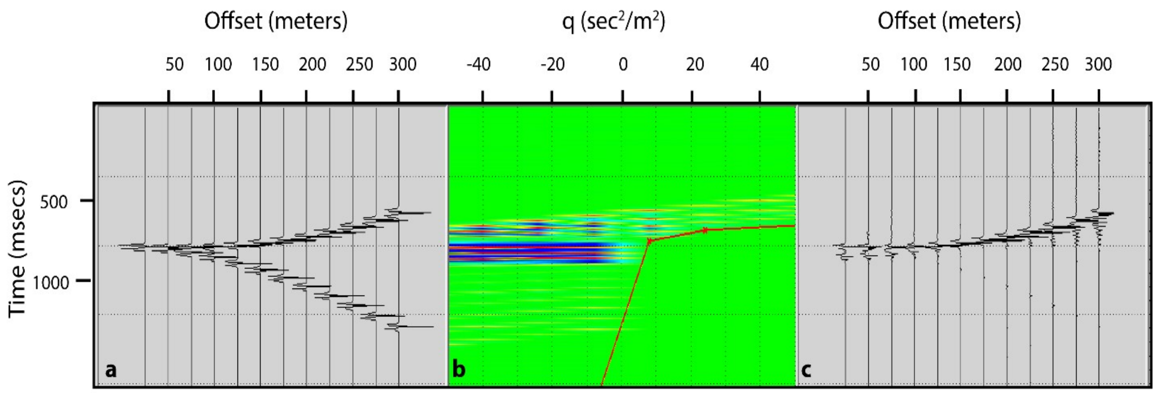

Fig. 3. A synthetic gather with primary event over-corrected and multiples under-corrected using intermediate velocity (a), muting of positive *q* in radon space (b), filtered gather (c).

RADON APPLICATION TO MARINE DATA USING THE INTERMEDIATE VELOCITY APPROACH

The seismic dataset used in testing the Radon transform parameters are short streamer data acquired for imaging the shallow part of the sub sea. The streamer length was 3200 m and the shot and receiver intervals were 25 m. The shallow marine seismic data is "Mobil Viking Graben Line 12", an open source data released for the 1994 SEG workshop, SEG file publication, No. 4 (Keys and Foster, 1998). If reliable velocity functions are used to create semblances, using NMO-corrected super-gathers (multiple CDP's merged together), multiples can be differentiated from primaries based on their velocity trends in the velocity semblance.

The process of selecting the appropriate NMO velocities was the same by evaluating both the CVS and semblance. Because the tested data is relatively shallow, the difference between the primaries and multiples is less pronounced. The dominant multiples energy is at water velocity of 1500 m/s (Fig. 4).

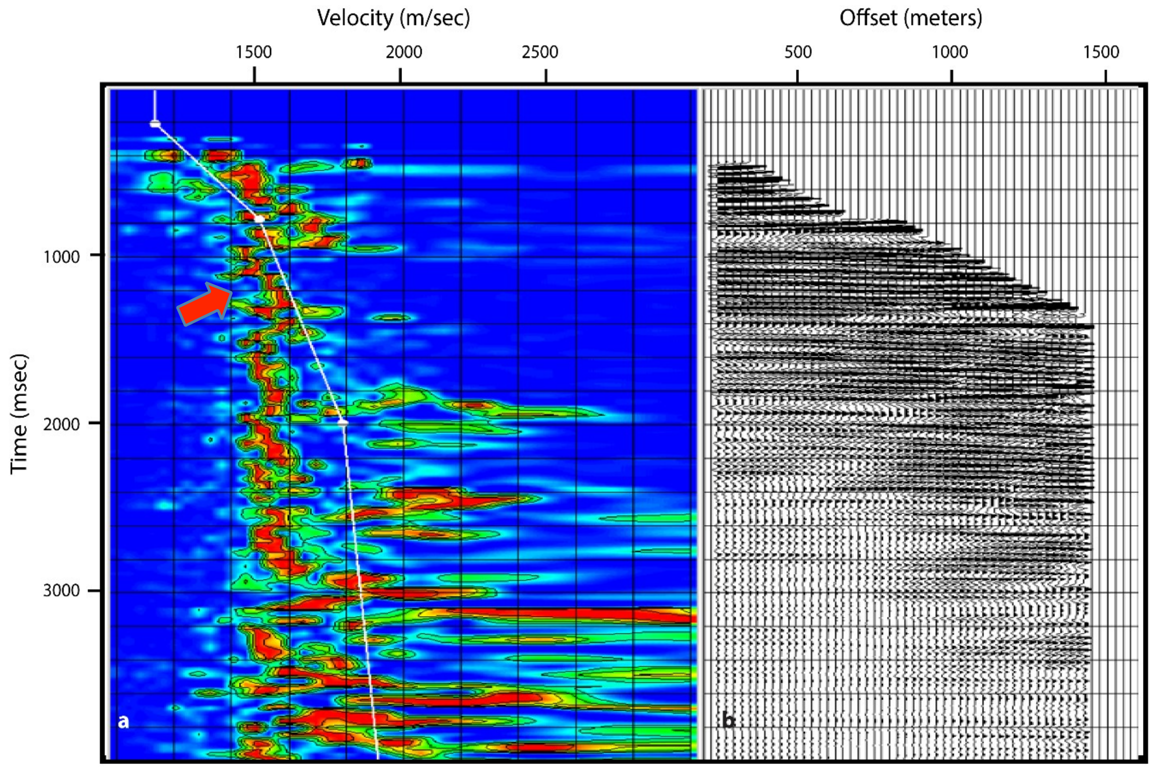

Fig. 4. Semblance plot (*a*) and super gathers (*b*), with primaries velocity picked and NMO applied. Velocity trends of water bottom multiples and inter-bed multiples are indicated by the red arrow in the semblance display.

The strong water bottom reflections are associated with strong multiples, which can be seen appearing below the primaries in the semblance plot. Also, interbed multiple energy forming coherent events are seen (Fig. 4 and Fig. 5). NMO correction using the picked velocity functions is applied to the tested CDP gathers that flatten primaries and left multiples under-corrected, depicting positive curvature. The NMO-corrected gathers are modelled inside the *τ-q* domain by predicting curvature range and interval. Accuracy of the *τ-q* model was tested by transforming back modeled gathers from Radon space to the t-x domain and subtracting from the original gathers. The process is repeated iteratively until the difference between the modeled gathers and original gathers is minimum and the final model gather attained the optimum curvature interval, and range. Fewer *q*-values lead to inaccurate transformation of CDP gathers from t-x domain to *τ-q* domain. An optimum *q*-values range of -50 to 3000 with an increment of 12 *q*. Therefore, a total number of 250 *q* values with a maximum data frequency range of 100 Hz was used to construct a new *τ-q* domain to transform the data and prevent aliasing (Fig. 6).

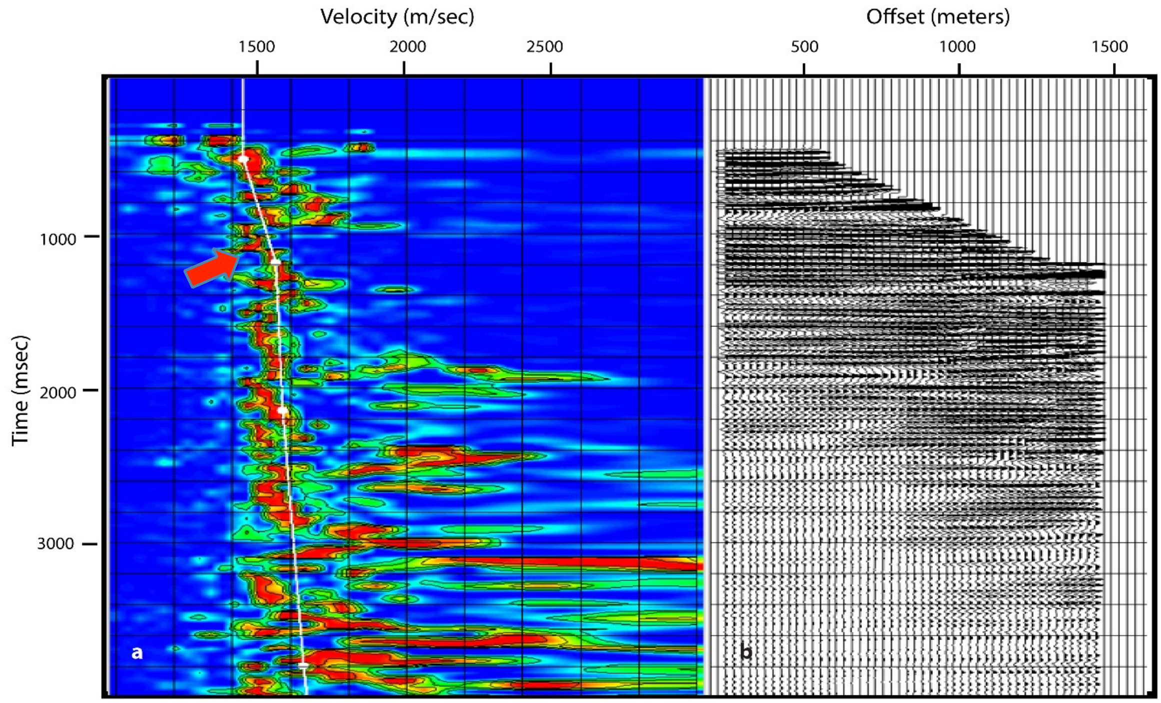

Fig. 5. Semblance plot (*a*) and super gathers (*b*), with intermediate velocity picked and NMO applied. Velocity trends of water bottom multiples and inter-bed multiples are indicated by the red arrow in the semblance display.

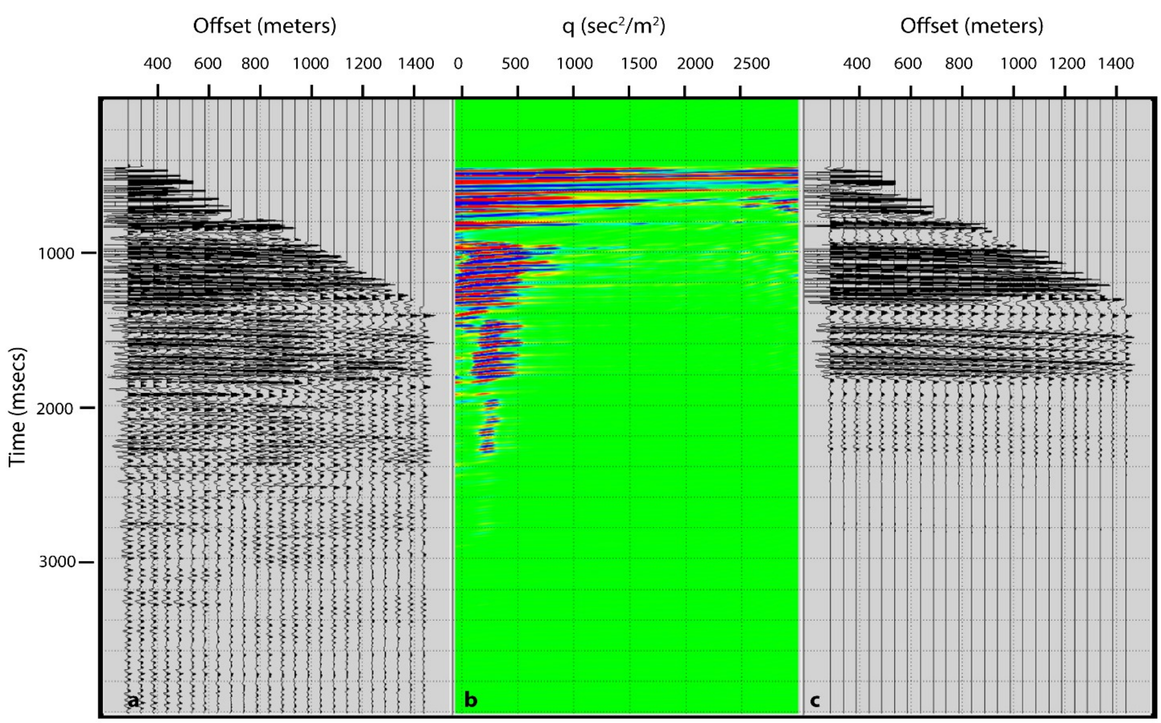

Fig. 6. Original CDP with NMO correction applied using primaries velocity (*a*), Radon transform with-50 to 3000 p-values (*b*) and inverse radon transform back to CDP(*c*) after muting multiples.

The final model is used in the τ-q domain to select curvature associated with multiples. Multiples can be muted in the Radon space. However, it is better to model the multiples in Radon space and transform back to t-x domain to be subtracted from the original gathers. This helps in mitigating artifacts created, while muting multiples in the τ-q domain.

Since primaries velocity is used, multiples depict positive q-values. The positive q-values are selected within the τ-q domain (Fig. 7). Primaries and multiples are hard to differentiate at shallow depths, therefore q-values associated to shallow events were not removed in order to avoid muting primaries along with multiples. Because it is often difficult to reach velocity functions that completely flatten all the primary events, some residual moveout result in under-correction (positive curvature). Muting zero and some positive curvatures of deeper events is not recommended, irrespective of moveout difference between primaries and multiples. Therefore, we select maximum q values at shallower time, and taper it down to small q values at greater depths (Fig. 6). The modeled positive q-values (Fig. 7) are transformed from the τ-q domain to the t-x domain to be subtracted from the original gathers. As discussed in our synthetic example, this practice is prone to preserve some multiples energy.

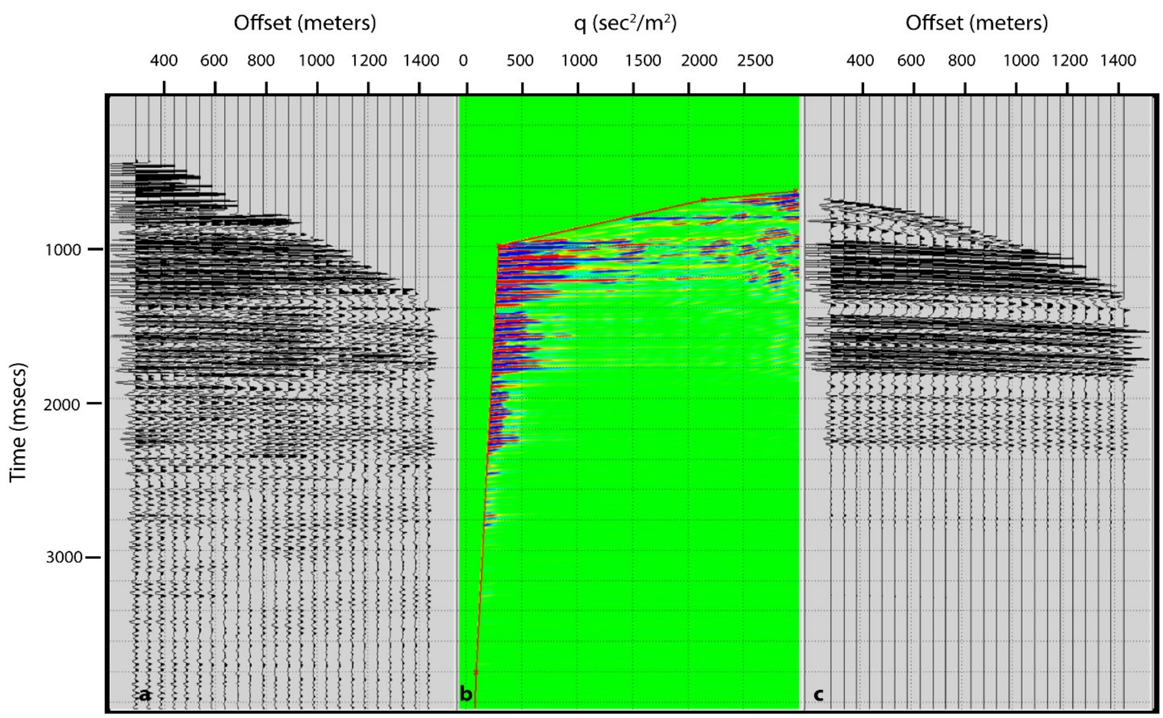

Fig. 7. Original CDP with NMO corrected using primary velocity (*5a*), Radon transform with p values model associated to multiples (*5b*) and inverse Radon transform back to CDP with multiples only (*5c*).

The intermediate velocity between primaries and multiples is used for enhanced separation between primaries and multiples, in preparing CDP gathers, as input to radon. With the intermediate velocity applied, the primaries are overcorrected depicting negative curvature, and multiples are under-corrected with positive curvature. This new velocity is then used for NMO correction on CDP gathers, and are tested. Testing entailed making best estimate of *q* values ranges and interval. Again, the transformation is validated by subtracting the original NMO -corrected CDP gather with this new velocity, from the gather obtained after transformed back from the radon space. In our case, *q* range of -3000 to 3000 was used of 250 *q* values and frequency range of 100 Hz (Fig. 8). An important aspect of this approach is that intermediate velocity leads to least amount of *q* values that fall in the zero curvature region (Fig. 9). This prevents modeling near zero curvatures *q* as there are primary and multiples events at shorter offsets with almost no curvature difference.

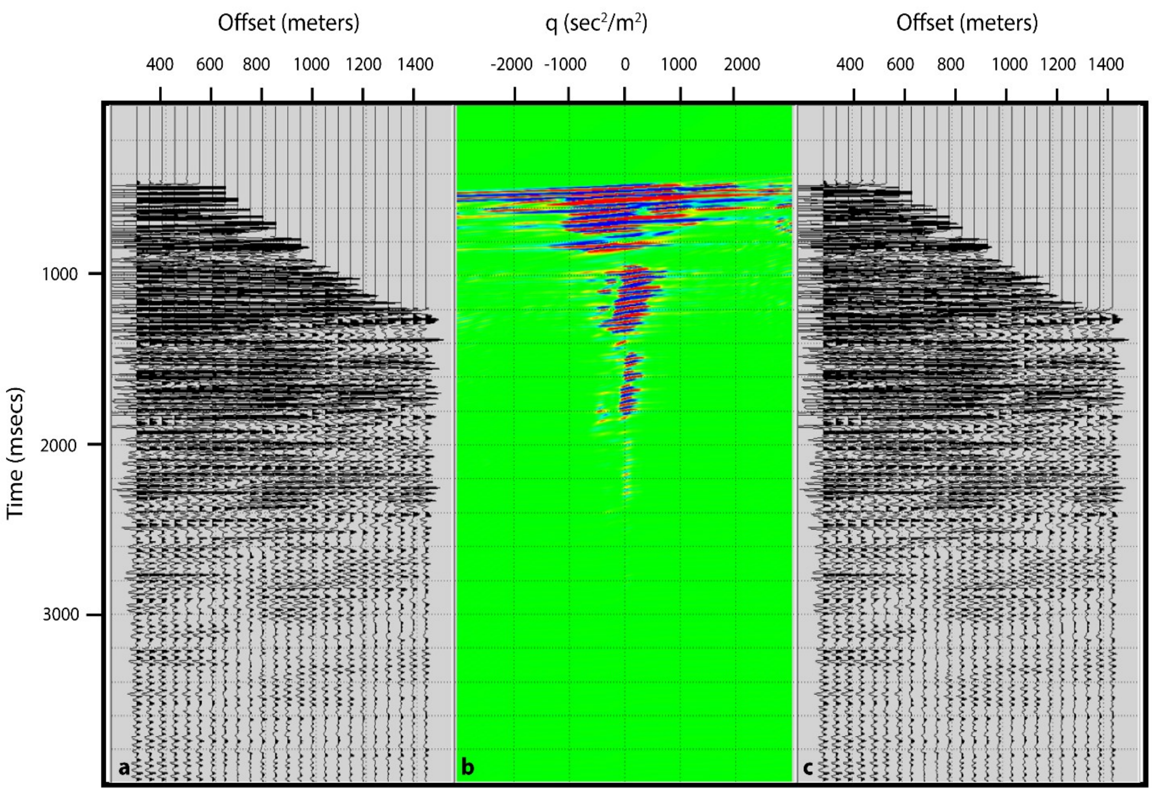

Fig. 8. Original CDP with NMO correction applied using primaries velocity (a), Radon.

Transform with-3000 to 3000 p-values (*b*) and inverse Radon transform back to CDP(*c*).

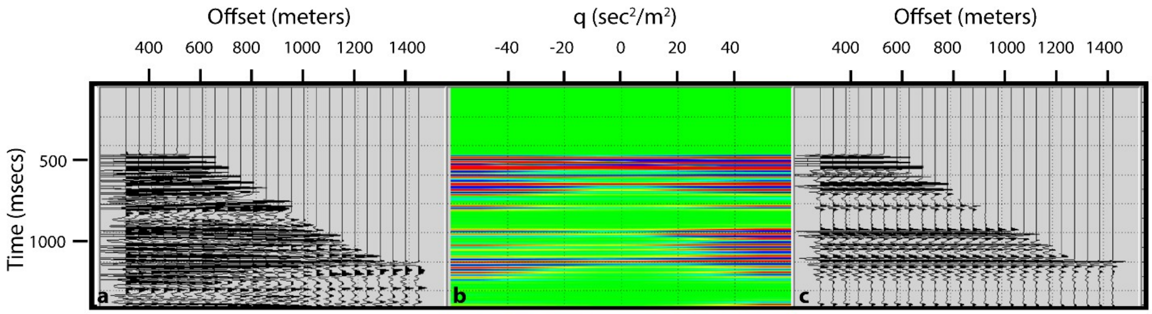

Fig. 9. Zoomed Original CDP with NMO corrected using intermediate velocity (*8a*), Radon panel (*8b*) and inverse radon transform back to CDP (*8c*). Notice intermediate velocity picked, results in least *q* values around 0 in radon space (τ-q).

Once perfect q range and increments are estimated, we select positive *q* values associated to multiples. Since using intermediate velocity assists in better separation, we are able to use more near *q* values to be added as multiples. However, for near offset, we keep the practice of not modeling zero q values, as in conventional radon approach discussed above. The modeled multiples are shown in Fig. 10.The multiples models in both cases are transformed back in the time space domain and are subtracted from the original CDP gathers. The two datasets are then analyzed by inspecting their semblances (Fig. 11) and shot gathers (Fig. 12).

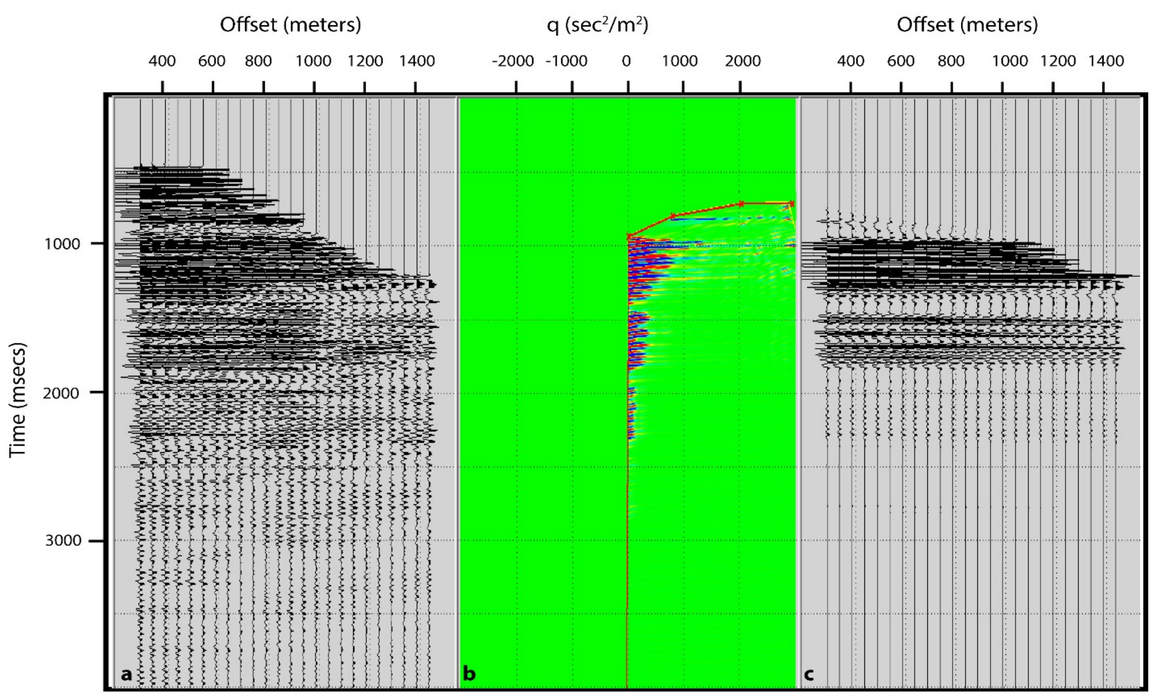

Fig. 10. Original CDP with NMO corrected using multiples velocity (9a), Radon panel (τ–q) with positive q selected to model multiples (9b) and inverse Radon transform back to CDP with multiples only (9c).

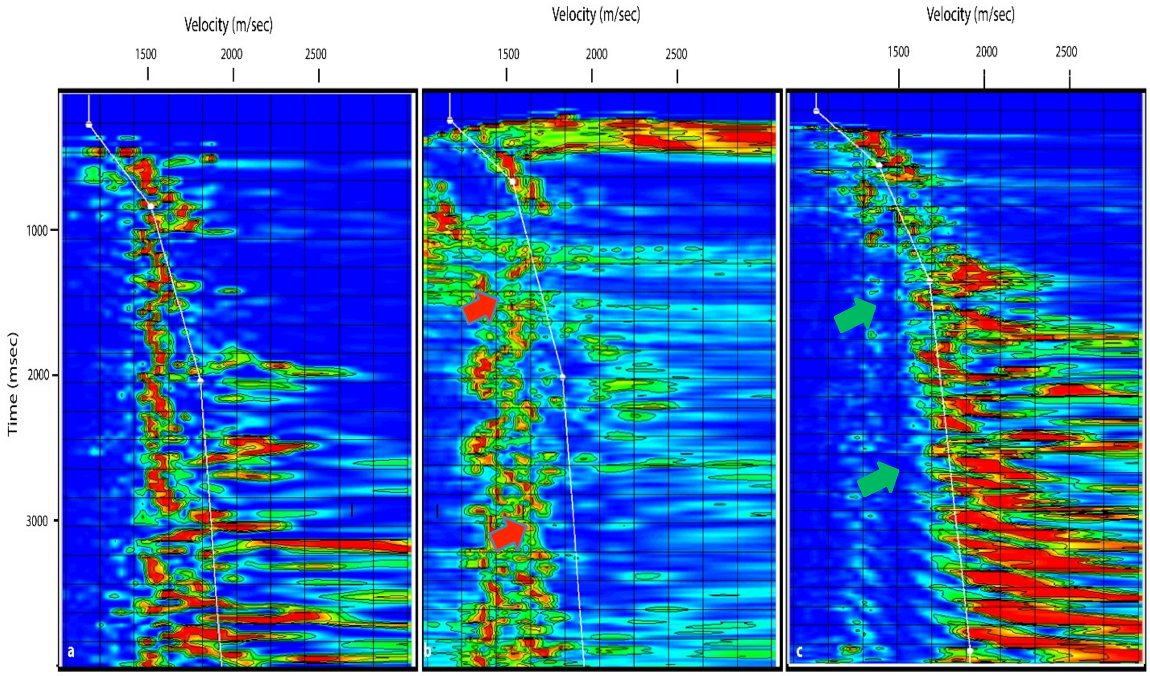

Fig. 11. Original Semblance (10a), Semblance created after conventional radon depicting artifacts and remnant multiple energy (red arrows-10b), semblance created after multiples modeled filtering. Multiples are removed (10c).

DISCUSSION AND CONCLUSIONS

Parabolic radon is velocity and curvature dependent. The best estimate of velocities and curvature are typically achieved by constructing reliable seismic semblance plots, for identifying primaries and multiples events. Semblance windows should be sufficiently sampled to distinguish noise, in this case multiples, from primaries. The weighted semblance radon can provide high resolution and is often preferred**.** For short-streamer data sets, the standard radon muting practice preserved shallower events with larger positive *q* values, and muted deeper events with more moveout or positive *q* values. Applying primaries velocities to shallower marine data with a short streamer length, results in smaller moveout time between primaries and multiples. Therefore, smaller *q* values are not modeled, which results in preserving smaller positive *q*-values even at depth. As demonstrated from synthetic data examples, this practice is prone to preserving significant multiple energy. However, the second approach in which CDP gathers are NMO-corrected using intermediate velocity functions between primaries and multiples, showed more distinction between over-corrected primaries and under-corrected multiples. Subsequently, better modeling of multiples is attained with relatively lesser potential to include primaries, in radon space. This approach results in a better attenuation of multiples, especially for short offset acquisition.

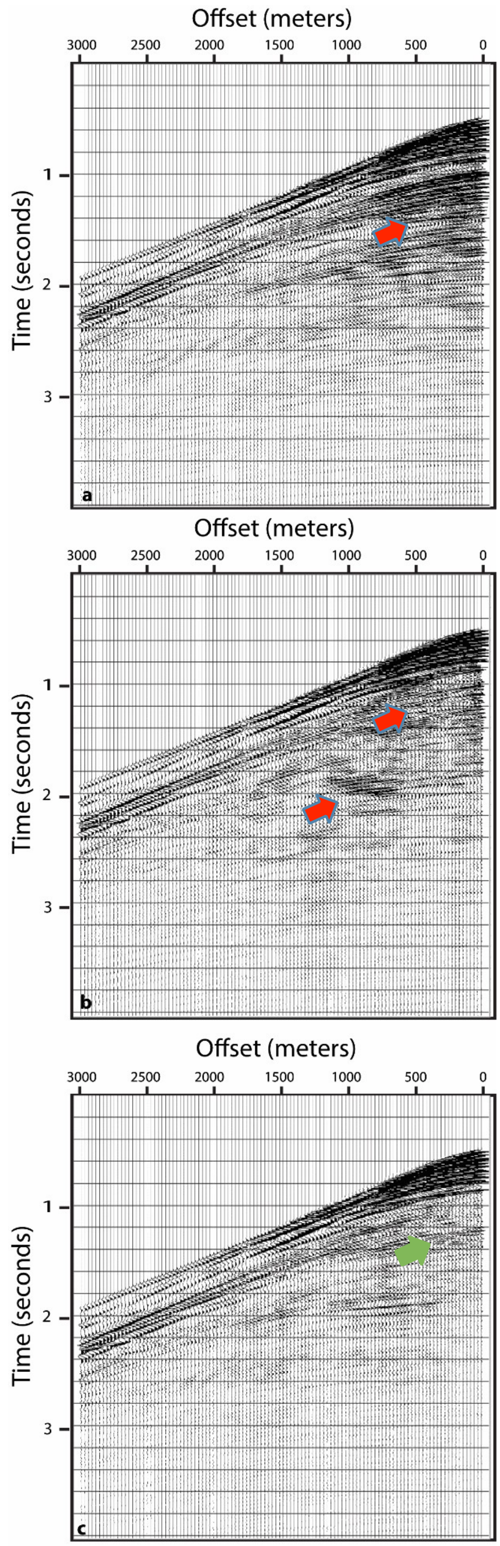

Fig. 12. Original shot gather depicting surface multiples (11a-*red arrow*), shot gather filtered using conventional Radon, depicting remnant multiples (11b-*red arrows*) and shot gather filtered using multiples modeled radon, with multiples removed *(green arrow*-11c).

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