Vertical Image Projection, an effective data preconditioning for seismic inversion

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Summary

The dip-dependency of the wavelet on migrated images can cause significant inaccuracies in the inverted impedances obtained from conventional inversion approaches based on 1D vertical convolutional modelling. Although the inaccuracies are dominant on the steeply dipping events, low-dip events may also suffer if they are contaminated with cross-cutting steep migration artefacts and smiles. An efficient, effective and reversible data pre-conditioning approach is proposed that corrects for dip-dependency of the wavelet and is applied to migrated images prior to inversion. The method consists of integrating with respect to the total wavenumber followed by differentiation with respect to the vertical wavenumber. This process is equivalent to applying a deterministic dip-consistent correction that projects the data from the total wavenumber to the vertical wavenumber axis. The proposed vertical image projection methodology reduces the impact of migration artefacts and improves inverted impedances in both synthetic and real data examples.

Introduction

It is well known that the seismic wavelet on migrated images is aligned normal to the structural dip, while pre-migration the wavelet is aligned vertically (e.g., Chun et al., 1981). However, the post migration processes applied to seismic images are often assumed blind to this effect and assume the wavelet is still aligned vertically. Neglecting this effect may have significant impact on the quantitative interpretation of seismic data particularly in geologically complex areas and with data containing noise and migration artefacts.

Several approaches have been suggested to tackle the issue of dip-dependency of the wavelet. These approaches include the application of pre-migration spectral shaping (Lazaratos and David, 2009), modifying forward modelling in the inversion algorithms and accounting for ray direction (van der Burg et. al., 2009), applying a dip-consistent correction in the forward convolutional modelling (Cherret, 2013) and creating extended gathers in orthogonal dip domain (Khalil et. al., 2015). In parallel, efforts have been made to deconvolve the wavelet at the migration stage through least-squares migration and point spread function (PSF) deconvolution and depth-domain inversion (Fletcher et. al., 2012). The latter approaches accounts for illumination issues and make quantitative interpretation much easier by removing the wavelet but have the disadvantage of heavy computational and storage costs.

Instead of modifying imaging or inversion algorithms we propose efficient, effective and reversible data pre-conditioning to correct for dip-dependency of the wavelet applied post-migration and before quantitative interpretation. The method involves integrating data with respect to the total-wavenumber followed by differentiation with respect to the vertical wavenumber. This is equivalent to applying a deterministic dip-consistent correction that projects the data from the total wavenumber to the vertical wavenumber axis, hence the name Vertical Image Projection (VIP). Since in conventional impedance inversion the seismic image will be integrated vertically, the differentiation in the vertical wavenumber direction applied in VIP will be reversed and the resulting impedance values will come out corrected for dip-dependency of the wavelet. In the following sections the VIP methodology is explained and its impact on the migration artefacts and inverted impedance is shown with synthetic and real data examples.

Method of preconditioning

Dip-dependent wavelet distortion in migrated images leads to richer apparent low-frequencies on the seismic image. Neglecting this effect causes leakage of dipping noise and migration artefacts from higher frequency bands to the lower frequencies. This especially affects the impedance inversion process as it will significantly amplify the lower frequencies.

We represent a 3D migrated image in depth domain with $s(x, y, z)$ where x, y, and z are three cartesian coordinate axes, with z pointing vertically downward. The corresponding image in the wavenumber domains is $S(k_x, k_y, k_z)$ where k_x, k_y and k_z are wavenumber components. Using integration as a proxy for impedance inversion, the correct way to obtain band-limited impedance (*IMP*) from a migrated image is to run the inversion with respect to the total-wavenumber $k = \sqrt{k_x^2 + k_y^2 + k_z^2}$ axis:

$$IMP(k_x, k_y, k_z) = \left(\frac{1}{ik}\right) S(k_x, k_y, k_z), \quad (1)$$

where $i = \sqrt{-1}$. This is equal to integrating the image along the wavelet and normal to the dip of the event. We then back off the integration through differentiation but this time in the vertical direction i.e. with respect to k_z axis:

$$\bar{s}(x, y, z) = \mathcal{F}^{-1}\{ik_z\, IMP(k_x, k_y, k_z)\}, \quad (2)$$

where $\mathcal{F}^{-1}$ indicates the inverse Fourier transform. The preconditioned data $\bar{s}$ are now ready for post-processing and inversion with the conventional tools that assume the wavelet is aligned vertically.

Inversion in the vertical direction will negate the earlier applied differentiation with respect to the k_z axis. This process is fully reversible by swapping the arguments for differentiation and integration. The total computational cost of VIP is a forward and reverse 3D Fourier transform, which makes it highly attractive. The preconditioning may be applied to the full-stack image or to each offset, angle or sub-stack image independently to prepare data for inversion.

As described above VIP is conducted in the depth domain. In the case of time-migration it is recommended to stretch the image back to depth using the migration velocity model, apply the correction and stretch back to time. It is also possible to apply VIP in the time domain by using an approximate velocity (v) to calculate the total wavenumber $k = \sqrt{k_x^2 + k_y^2 + (w\ /\ v)^2}$, where w is angular temporal frequency. The approximate velocity v can either be the representative average velocity of the target formation or the minimum expected acoustic velocity within the migration aperture. The downside of using a constant velocity is that the areas of the image with higher velocity will be under-corrected and the areas with lower velocity will be over-corrected. It is worth mentioning that the pre-conditioned data will have weaker amplitudes for dipping events which will be corrected after inversion. Note that the proposed approach is limited to correcting for dip-dependency of the wavelet and illumination and velocity related variations of the wavelet are not addressed here.

Synthetic example

Here we demonstrate the performance of the proposed VIP preconditioning on a synthetic dataset from the BP2007 model. The data are imaged with Kirchhoff pre-stack depth migration using a smoothed version of the correct velocity model. Figure 1 shows the inverted relative impedances obtained from the migrated stacks stretched to time. The limitations in source and receiver sampling as well as limitations of Kirchhoff imaging in handling complex ray-paths have led to migration artefacts particularly around the salt structures (Figure 1a).

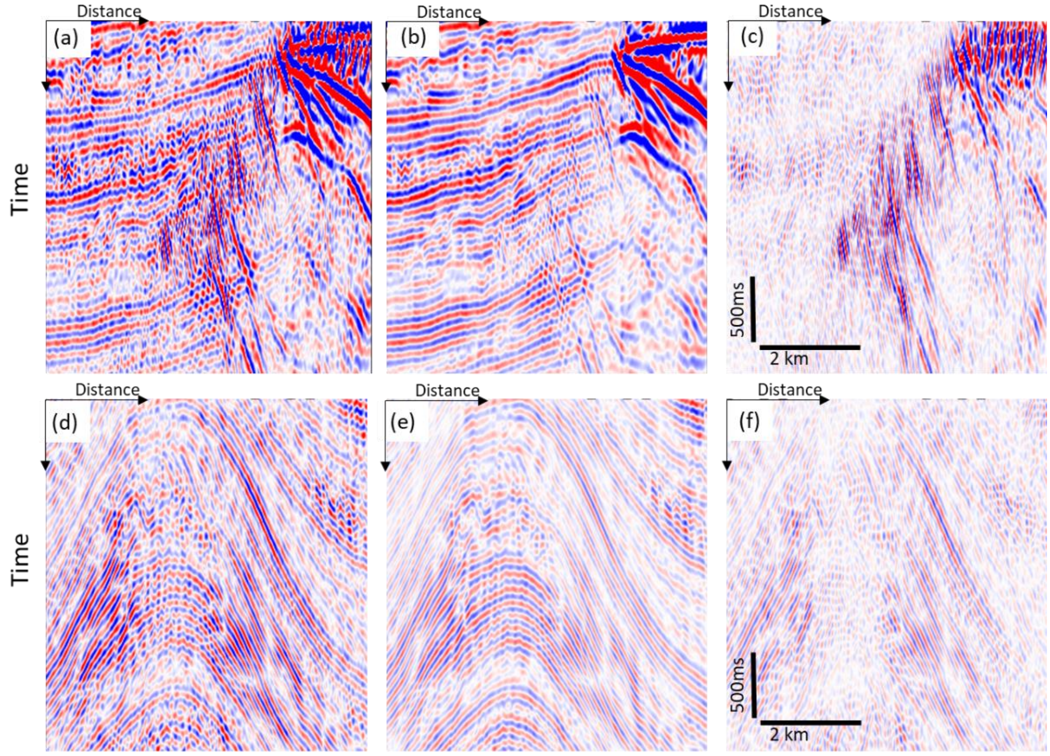

Figure 1 *(a-c) Inverted relative impedance for the synthetic BP2007 model (a) without and (b) with VIP and (c) their difference. Images d-f are from different parts of the BP2007 model.*

Figure 1b shows that cross-cutting migration artefacts are significantly damped in the inverted relative-impedances after VIP, which enhances interpretability and continuity of the geological events. Figures 1d-1f depict another part of the synthetic model. The anomalously amplified impedances on the flanks of the dome structure (Figure 1d) are corrected on the VIP result (Figure 1e). The higher uniformity in the variation of amplitudes at the top and along the flanks of the dome structure is expected based on the known synthetic model. The difference images (Figures 1c and 1f) show the impact of VIP on damping migration smiles and correcting the amplitude of dipping events.

Real data example

We apply the VIP approach to a sub-cube of the fast-track processed and time-migrated data from a 3D marine seismic survey. The data are migrated on a 25 m by 25 m grid. Figures 2a-2c show common-inline full-stack pre-stack time-migrated images before and after VIP preconditioning as well as the difference between the two, respectively.

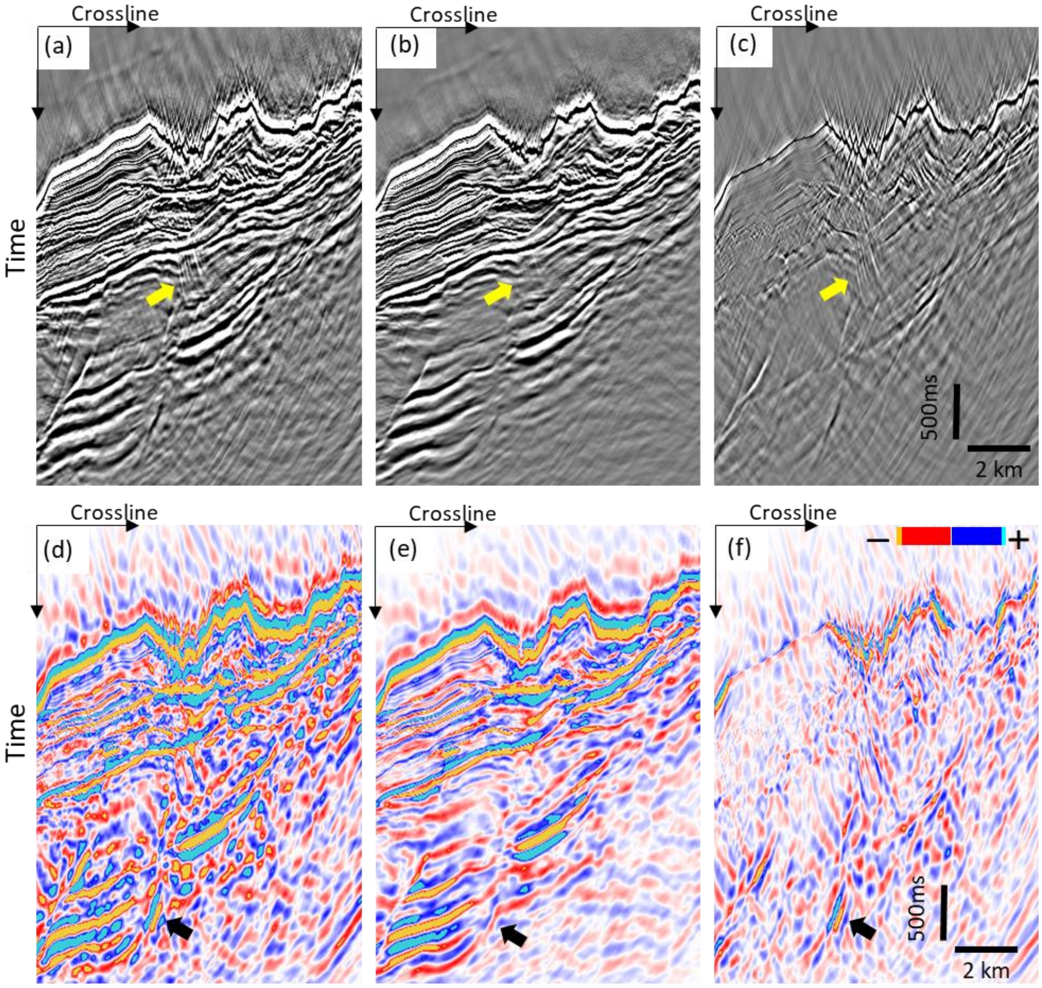

Figure 2 *Migrated image (a) before and (b) after VIP preconditioning and (c) the difference. (d-f) depict corresponding inverted relative impedances.*

Migration smiles are particularly strong around the deep canyon at the seabed and deeper around the faulted area. The difference image (Figure 2c) indicates that the dipping events including smiles and faults have been attenuated in the preconditioned data. As discussed, the impact of preconditioning is more pronounced after inversion. Figures 2d-2f show relative impedances before and after preconditioning as well as their difference, respectively. Damping of dipping events on the VIP image leads to more accurate and cleaner relative impedance images. For example, the anomalous high impedance event along the fault (highlighted by back arrow) is now weaker on the VIP image.

Figure 3 shows a comparison of applying VIP in the time and depth domains. Applying a constant velocity (in this case 2500 m/s) for time-domain application works well only locally where the subsurface velocity is close to the applied velocity and over- or under-corrects where the subsurface velocity is lower or higher, respectively. Corresponding frequency-wavenumber spectra are shown in the lower row in Figure 3. Depth domain application (right panels in Figure 3) indicate smaller difference in general and the difference is only dip-dependent and independent of subsurface velocity.

Conclusions

We have developed an efficient vertical image projection approach that preconditions migrated data for inversion through correcting for the dip-dependency of the wavelet. It alleviates the limitation of existing inversion approaches that are based on the 1D vertical convolutional assumption in dealing with dipping events. The proposed approach leads to more accurate impedances along steeply dipping reflectors and significantly reduces the leakage of noise and migration smiles into lower frequencies due to inversion. The preferred domain for applying VIP is depth and time-migrated data can also be stretched to depth before preconditioning.

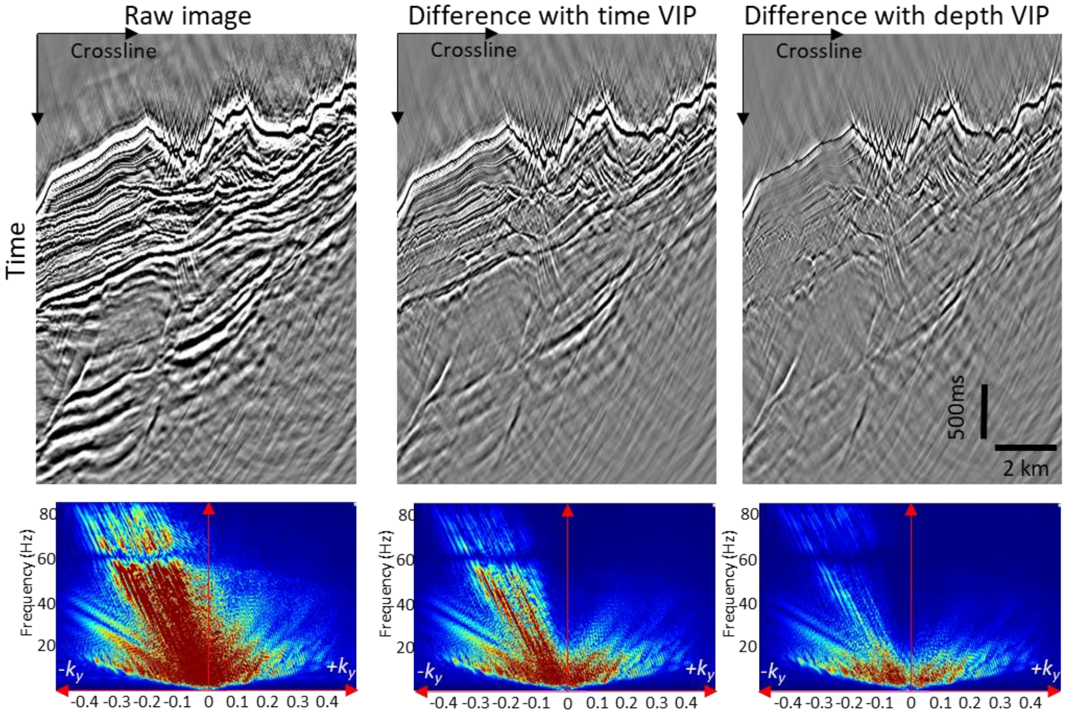

Figure 3 *Raw migrated image and its difference with VIP images corrected in time domain (middle) and depth domain (right). Corresponding f-k spectra shown in the lower row. The values on the horizontal axis of the spectra are normalised by the trace spacing (25 m).*

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