Effective Delivery of Reservoir Compliant Seismic Data Processing*

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Abstract

Modern seismic acquisitions deliver broadband seismic data containing 5 to 6 octaves of useable signal, starting just above 2 Hz. Modern surveys with long offsets also deliver high-quality pre-stack data, which in principle allow for the inversion of amplitude variation with angle (AVA) for reservoir quantities with much higher accuracy than just a decade ago. With these new acquisition types, data processing and imaging, and their quality controls prior to inversion, face new challenges. How can we image and monitor large amounts of data in an efficient manner, whilst ensuring signal preservation across all incidence angles and at all frequencies? How can this be done when no wells are available, or well segments are too short to quality control (QC) low frequencies? Addressing these challenges requires not only improved and updated processing algorithms but also better quality controls to ensure that data processing and imaging delivers pre-stack data over the full seismic bandwidth in a reservoir compliant manner. The key objective of this paper is to show how this can be done, to introduce new QC methods to that effect, and to use them to highlight improved processing and imaging algorithms.

Introduction

The goal of seismic processing and imaging is to remove as best as possible acquisition and wave propagation effects from the recorded seismic data so as to produce an image of the subsurface in terms of reflection coefficients. Ideally, the data are then ready for elastic inversion processes, which, via calibration at the wells, give us access to the reservoir parameters of interest. Seismic processing must ensure that data is reliably separated into signal and noise. Imaging must focus the primary signal energy in the right location in the subsurface with an accurate velocity model. This is only achievable with dedicated technologies as well as rigorous quality control (QC) of the seismic data. A QC approach benefits significantly from prior knowledge shared between the disciplines involved in processing, imaging and subsequent reservoir analysis. All available data, in addition to the seismic itself, should be used as much as possible to check for consistency.

To monitor the quality of the processing and the resulting seismic data we need to generate a set of qualitative and quantitative measures that are sensitive to the suitability of the data for subsequent reservoir property estimation (see for example Paternoster et al., 2013). Often, such QC is seen as part of a data conditioning program that starts once the data has been imaged, or even fully processed, in order to make the data more suitable for further reservoir analysis. However, given the complexity of the processing prior to migration, we start our QC much earlier in the processing sequence. As the inversion and amplitude versus angle (AVA) compliance of seismic data is measured on migrated gathers, a set of intermediate migrations are conducted, at key stages in the processing. QCs are generated and compared to the corresponding results from the previous QC set to check for signal preservation, wavelet stability in space, time and offset, geological consistency, coherence, and improvements in signal compliance with expected AVA behaviour. QC maps are generated in a geologically consistent manner by tracking horizons. Such maps can also be combined or used in supervised or unsupervised classification methods to reduce redundancy or to further isolate areas with particular noise issues. If wells are available, in addition to aiding the velocity model build, they can be used for well-ties, wavelet and AVA consistency analysis.

Broadly speaking, we can classify reservoir compliant QCs as either well driven or data driven. Lacombe et al. (2017) describe a QC flow with two main aspects. Firstly, integration of all available data, including wells, to QC their consistency with the seismic data. In many instances, we may not have access to log data, but we should ensure that any additional information, such as knowledge of the local geology, is used. Since well-log data provides spatially and temporally limited information the second part of the strategy is the creation of statistical volumetric QCs to monitor the data quality globally. These volumetric QCs are the main focus of this paper, and in particular, we will show how they can be used for pre-stack data QC across the full seismic bandwidth and from the start of data processing.

In both well-driven and data-driven approaches the quality of processed data can be assessed in the data-domain (the seismic wiggles) and/or in the model-domain. Examples of model domain parameters are intercepts and gradients from AVA fitting, or seismic impedances and velocities, from AVA inversion. These observations are complementary for several reasons. Firstly, the relationship between data and model parameters is often non-linear; secondly, the spectra of seismic reflectivity, and those of layer quantities such as impedance or interval velocity, are very different. Reflectivity and impedance spectra both have exponential trends, and the reflectivity spectrum is proportional to the impedance spectrum multiplied by πf (Lancaster and Connolly, 2007). Whereas reflectivity has a blue spectrum, impedance is dominated by the low frequencies, and its spectrum is red (Figure 1). Since we want to apply data interpretation in both domains, we need good signal to noise ratio at all recorded frequencies. In order to be less reliant on low frequency models, where the seismic bandwidth tails off, we particularly require good seismic S/N at the low frequencies.

To monitor the data over the complete bandwidth, we can either split the data into frequency bands or perform pre-stack inversions to layer quantities. This can be done via simple integration of the blue'd reflectivity, with coloured inversion (Lancaster and Whitcombe, 2000), or with more complex inversions. In the examples below, we use a deconvolutional Bayesian inversion, which is flexible and can be used in 3D, 4D or joint PP-PS processing projects. The three mentioned inversion methods have in common that they do not require an a-priori low-frequency model; they give us a relative inversion result within the bandwidth of the seismic data, which is ideal for the purposes of seismic data QC. We often prefer inversion QC to the simpler visualisation of the data in frequency bands, since this allows us to see directly the behaviour of the data with the spectrum representative of layer quantities, as required in reservoir analysis. Since the inversion products are dominated by the low frequencies, this domain is also ideal to QC the quality of the broadband seismic in this frequency range. Lastly, visualising the data in the impedance domain can have the added benefit of enabling a more direct conversation between geophysicist and reservoir engineer. If this can be done earlier in the seismic processing, it can only be a good thing.

Once the data are modelled, such as with an AVA fit or inversion, the decomposition of the data into signal (the modelling result) and noise (the modelling residual) is further analysed. A basic signal indicator is the data similarity across the pre-stack offsets (Sablon et al., 2016). In addition, we monitor the adherence of the data to the AVA model equations, by mapping the similarity between the data and the modelled data (Coleou et al., 2013, Rivet et al., 2016). Lastly, noise is captured by mapping the modelling residuals, which are a measure of the misfit between the data and the models. These are examples of QCs which can be monitored at each processing step, starting as early as possible. Repeating the QCs within specific frequency bands, such as below 10 Hz, is also advisable. Tracking the QCs as processing progresses can highlight areas with specific signal processing issues that can then be further targeted for additional QC, and improved processing.

We demonstrate the application of the quality monitoring procedures we have outlined on datasets from the North Sea and offshore Western Australia, representing two different geological scenarios with associated processing challenges. We focus on pre-migration processing steps such as demultiple and improved imaging algorithms. We show that through meticulous quality control of processing stages both in data and reservoir parameter domains, the processing parameters can be tuned, and the reservoir compliance of the data improved. In particular, high data quality from both a low-frequency and an AVA standpoint can be ensured. We discuss the limitations of the monitoring process and identify potential areas for further improvements.

First Case Study: Improved Demultiple QC During Early Processing

Removing multiples from seismic data is often one of the most critical stages of data processing, as a large proportion of the energy of the recorded data can be discarded at the end of this process. Hence, it is essential to ensure only noise is removed and primary signal is preserved. Often several realisations of multiples are generated using complementary methods (e.g. SRME, high resolution Radon) which are adaptively removed from the data to separate the primary signal from the multiples.

The quality of demultiple sequence is traditionally assessed by looking at the auto-correlations of the data before and after the process and by mapping the energy removed. Well-tie analysis i.e. comparison of well synthetics (acoustic or elastic) with seismic is highly advisable, but is of course limited to the well locations. Sablon et al. (2016) proposed a QC approach based on event continuity in the pre-stack data domain to reduce the risk of subjective decisions for the optimal demultiple sequence. Each trace in the gathers is correlated over sliding time-windows to a partial angle-stack and the maximum value of the cross-correlation is visualised. This QC can be displayed as a correlation gather or the QC gather can be stacked to give an average of the pre-stack quality. A case study showed that a detailed analysis of correlation values on a gather-by-gather and also on a volumetric basis can identify primary damage, hence allowing the selection of the most appropriate demultiple processing parameters with minimum primary damage. The authors also showed that the key to improve the low frequency signal preservation is an improved demultiple process, wherein the data are decomposed into a primary model with good AVA preservation in particular at the low frequencies, and the multiple model.

Beyond correlation-based measures, which are most sensitive to the dominant seismic frequencies, a dedicated QC is required to assess the impact of demultiple on the lower frequencies. In the following example, we employ the following attributes: (1) correlation between near and far angle-stacks in the full-bandwidth and in the low-frequency range; (2) the inverted relative Vp/Vs ratio.

Figure 2 and Figure 3 show an example of using the seismic and inversion domains to assess the performance of two different demultiple sequences on a deep-water dataset from offshore Western Australia (see Sablon et al., 2016). Two alternative demultiple flows A and B were applied and QC was carried out to identify the most suitable flow. Figure 2 shows the low-pass filtered mid and far stacks after migration from demultiple flows A and B. The correlations between mid and far stacks for the full-bandwidth and for the low frequencies are also shown at the top of the image. Whilst at full bandwidth, the correlation QC yields acceptable values, restricting the data to 4-8 Hz shows areas of distinctly low similarity. This data mismatch is confirmed by visual inspection of the 4-8 Hz band-passed seismic. Part of the mismatch may be due to wavelet differences, such as those due to stretch, however the dip in correlation is local, indicating that this is not the likely issue here. To see the impact of the lack of pre-stack continuity at the low frequencies we performed an elastic inversion (Figure 3). This also allows us to model the data with different wavelets as a function of angle. The right hand side of Figure 3 shows the results for demultiple B. The low frequency mismatch across angles results in a lack of lateral continuity in the inverted relative Vp/Vs. Even worse, the well log (not used in the inversion) shows that the deeper reservoir 2 response has been lost. By contrast, demultiple flow A (shown on the left) gives a laterally more consistent Vp/Vs, in good agreement with the well and the reservoir 2 can be identified. This is also reflected in a good correlation between the mid and far stacks both for the full bandwidth and the low frequency data (not shown here). In Figure 4, we take a closer look at the inversion in terms of the model correlation with the data, and the model residuals. We compare data and model traces at near, mid, and far angles in an overlay display, with the residuals in a yellow colour. Only the result for the low frequency range of the data and the model is shown. Similar to what we found in Figure 3, the full bandwidth inversion residuals do not discriminate well between the two demultiple flows (not shown). However, as Figure 3 shows, the mismatch between the angle ranges for demultiple flow B, is reflected by larger inversion residuals for the low frequencies, compared to demultiple A. This validates the use of inversion residuals (at the low frequencies) as a QC in the absence of log data. Demultiple A, the superior of the two algorithms, is a demultiple flow specifically tailored to preserve amplitudes across the larger bandwidth of broadband seismic (Sablon et al., 2016).

Second Case Study: Verifying AVA Compliance of Improved Imaging Algorithms

The role of seismic migration is to position the recorded reflection data at the correct subsurface location. The accuracy of the position of the imaged reflection energy depends on the accuracy of migration algorithm and the migration velocity model which converts recorded travel-time to depth. Huang et al. (2014) list other potential issues in creating a reliable and geologically meaningful image: (a) under-sampled and irregular acquisition geometry; (b) areas of poor resolution resulting from limited recording aperture; (c) ringing artefacts caused by ripples in the source wavelet, and (d) weak amplitudes resulting from geometrical spreading, attenuation and defocusing. An effective processing sequence and imaging algorithm should be able to account for these effects. Clearly, we also need reliable QC tools to monitor the efficacy of imaging algorithms.

As an example, the recently developed least-squares migration is examined. The goal of least-squares migration is to account for illumination issue as well as migration artefacts such as those mentioned above. Single-iteration LS-migration, introduced by Guitton (2004) and further developed by Khalil et al. (2016), has shown promising results. Wu et al. (2017) extended the single-iteration LS-migration to the visco-acoustic case (incorporating Q effects) and Casasanta et al. (2017) describe its AVO fidelity.

Figure 5 shows an example of applying single-iteration LS-Kirchhoff migration including Q-compensation to a North Sea dataset compared to conventional Kirchhoff migration. Although visual inspection of the migrated images shows significant improvement in signal-to-noise, migration artefacts and illumination, further quantitative measures are required to ensure meaningful improvement is achieved and AVA compliance is improved.

To this end, we performed an elastic inversion on three partial-angle stacks of each dataset. Figure 6 shows the inverted P-impedances and Vp/Vs ratios for both migrations. As with the seismic, improved geological and lateral consistency can also be seen in the impedance domain. The dashed box on the P-impedance image highlights an area of interest where at the deeper part hydrocarbon anomalies are expected. The cross-plot of P- and S-impedances (shown as insets) show higher correlation of the inverted attributes after LS-Kirchhoff migration. A potential hydrocarbon anomaly, indicated with a black arrow on the lower cross-plot, is better separated from the background trend. This quantitative QC, even in the absence of log data, provides greater confidence in proceeding with LS-Kirchhoff migration.

Discussion: Broadband Processing Challenges and Pre-Stack Signal QC

The goal of seismic data processing and imaging is reliable full-bandwidth angle-dependent reflectivity. Some, if not all, of the challenges in achieving this are:

1. Limitations of the seismic acquisition systems (bandwidth and spatial sampling).
2. Ghosts in marine data, and the near surface in land environments.
3. Relatively less effective demultiple for the lower frequencies than the dominant frequencies.
4. The need for a high-resolution velocity model for pre-stack depth imaging.
5. Honouring full propagation effects in the imaging.

These challenges need to be addressed through improved acquisition, processing, imaging, and quality control. Our two case studies addressed improved full-bandwidth demultiple and optimized imaging with least-squares migration. We showed several QCs that can be used to determine optimal processing parameters.

To Summarize Important Aspects of the QC Methods Presented Above

Firstly, pre-stack QC must start early in the processing, not after the final imaging of the data. This requires us to perform intermediate migrations. With modern computer power, this is not an issue, even for massive datasets. Data quality, and also the quality of the migration velocity can be poor at this stage of the data analysis. In this case, QCs must be robust enough to allow for a meaningful comparison between alternative processing parameters and from one step of the processing to the next. AVA fitting can be made robust to outliers (and even residual multiple) with the use of techniques such as M-norms (Walden, 1991). In addition to this, gathers can be quite effectively flattened “on-the-fly”. AVA analysis can be run on macro-bins, that collect surrounding gathers, and this can also be done by taking into account the dip in the data. Whilst the AVA fit may still be unreliable early in the processing, we should monitor the relative changes with processing parameters at each step.

Secondly, we showed that QC using the complete bandwidth of the recorded data could fail to find processing issues, in particular at the low frequency part of the spectrum. We showed that converting the data to impedance and Vp/Vs, with fairly simple methods, is an effective way to QC the data at the low frequencies because they play a major role in the impedance inversion. The added benefit is of course that this visualizes the data in a manner more amenable to reservoir geophysics.

Third and last, we showed that many of our pre-stack QCs follow a common principle: the data are decomposed into signal and noise, where the signal is a projection of the data onto a given model, such as an AVA equation. The similarity and the dissimilarity of the data and the modelled signal then constitute our measure of data quality. By consistently monitoring these attributes throughout the processing, ideally using horizon guided QC maps, we can identify those areas of the data where signal is potentially damaged, and where we then need to focus our processing efforts.

These QC methods are complementary to QCs using around available well-log data as well as other data quality measures (see for example Paternoster et al., 2013). They address the new challenges posed by modern broadband seismic acquisition methods.

With the improved demultiple and imaging algorithms, we showed the power of these three ideas, particularly, when used in combination. The above methods have been clearly shown to aid in the determination of better signal preserving processing parameters. Ideally, as in our first example, reliable well log data is available to provide a localized cross-check of our processing parameters and our QC observations.

There are of course aspects of signal preservation we have not addressed. Most, if not all, of our processing algorithms are attempts to separate signal and noise, generally with statistical methods. Our goal in AVA fitting or inversion is no different, but now we use physically motivated models. Ideally, processing would incorporate AVA compliance into the algorithms directly. But this is particularly difficult when processing un-migrated data. However, if we begin to take pre-stack and AVA QC more seriously, as shown here, this will continue to lead to better algorithms.

We close the discussion with an example that shows the impact of improved acquisition bandwidth and imaging on inversion through a North Sea example where two acquisitions are available: one is broadband and another is conventional. Both datasets have gone through similar broadband processing (both have been de-ghosted). The goal is to evaluate the quality of the conventional data de-ghosting and to determine the value of the low frequencies (JafarGandomi et al., 2015). Despite similarities of the images (Figure 7a: broadband and Figure 7b: conventional), the inverted impedances show the impact of a dedicated broadband acquisition. A closer look at the impedances (Figure 7c and Figure 7d) reveals sharper layer boundaries, greater continuity and better match with the well-log for the broadband acquisition. We have also compared the difference between the seismic data and its corresponding model from the inversion. Figure 7e and Figure 7f show the frequency-dependent normalized root-mean-square (NRMS), which quantifies the inversion residuals, along the selected line. In general, we can see lower residuals (i.e. small NRMS) for the broadband data and particularly in the lower-frequency range. Broadband data show valuable information in the data down to 2.5 Hz, while the informative bandwidth of conventional data stops at around 5 Hz.

Conclusions

Acquisition, processing, and data QC must work together at all times, in order to deliver full-bandwidth pre-stack data that can be inverted for reservoir parameters. Algorithms and methods need to be adapted for the full bandwidth of the seismic data. For data QC, this means starting well before the final migration. Impedance domain quantities from pre-stack inversions are well suited to assess the impact of processing at the low-frequencies and the suitability of the data for AVA. New algorithms, such as those shown for demultiple and least squares migration, when combined with new QCs, increase the likelihood of good quality full-bandwidth pre-stack data.

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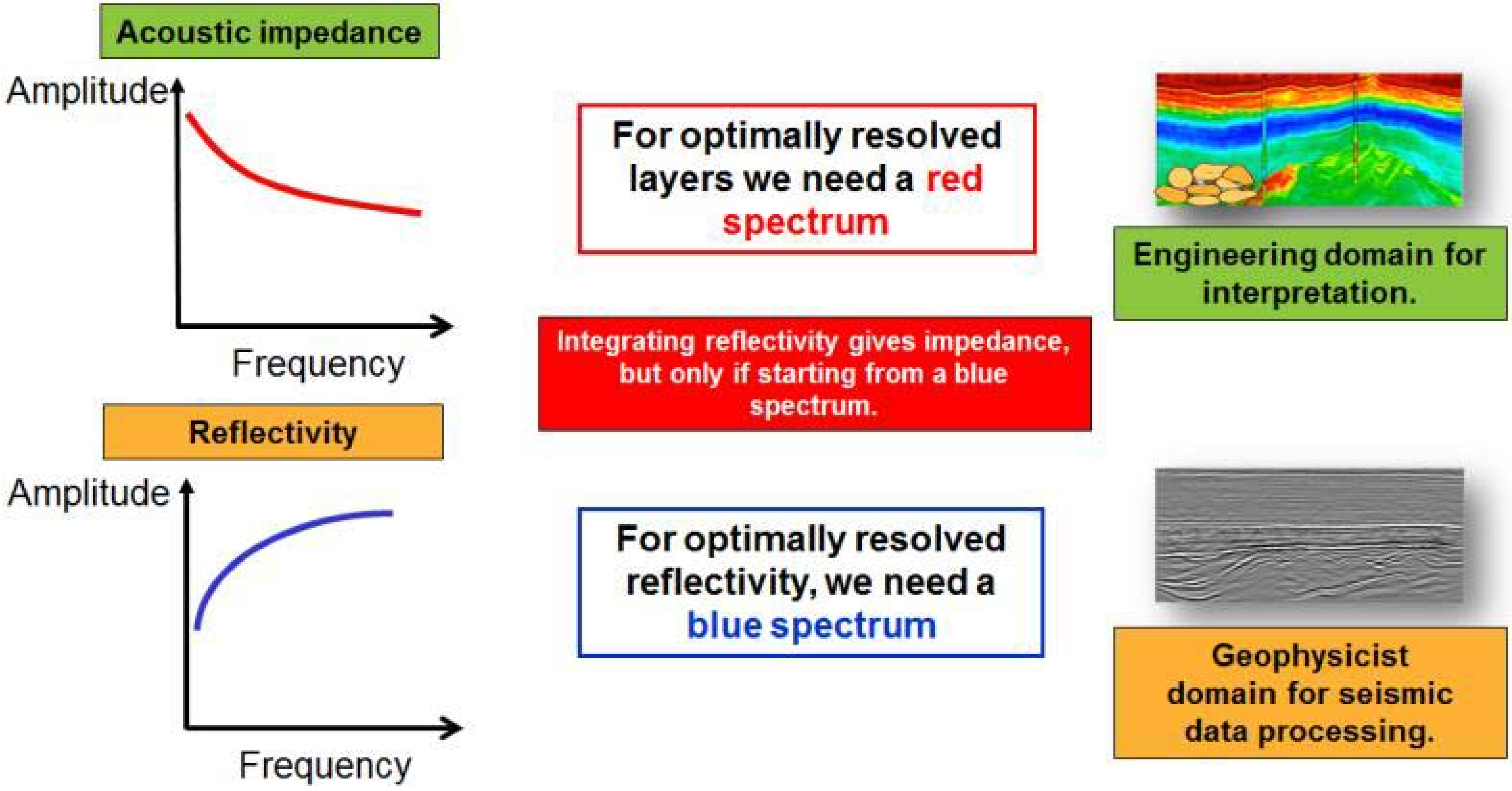

Figure 1. The spectra of reflectivity and impedance are very different. Layer quantities such as impedance are low frequency heavy. Since we need to interpret the seismic data, and the impedance, we need good signal to noise at all frequencies.

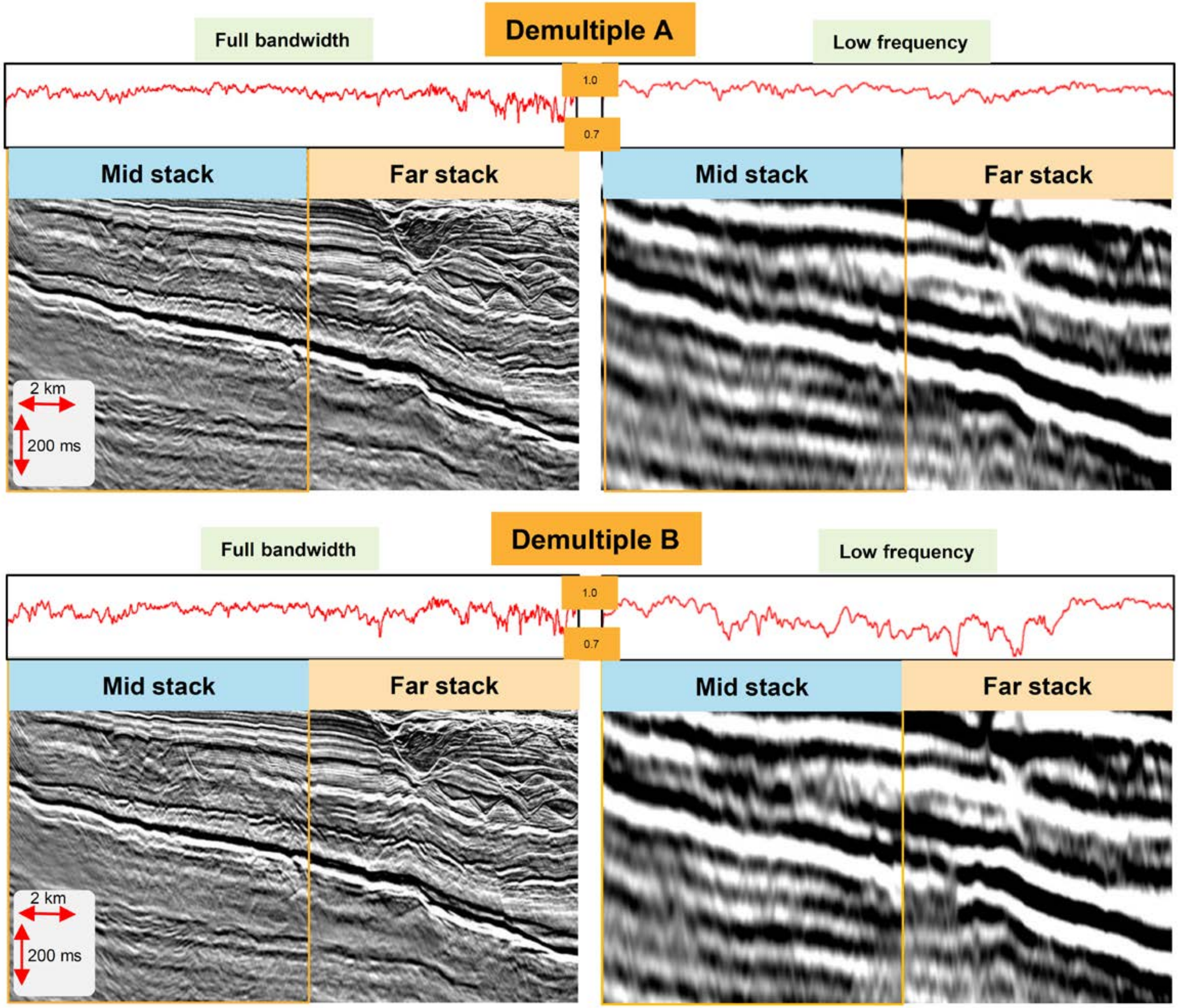

Figure 2. Composite full-bandwidth and low-pass filtered mid and far stack data and their correlation from demultiple flows A and B. We can see the mismatch of the angle stacks at the low frequencies, i.e. for demultiple B, which the correlation has picked up, but only if the low frequencies are QC'd on their own.

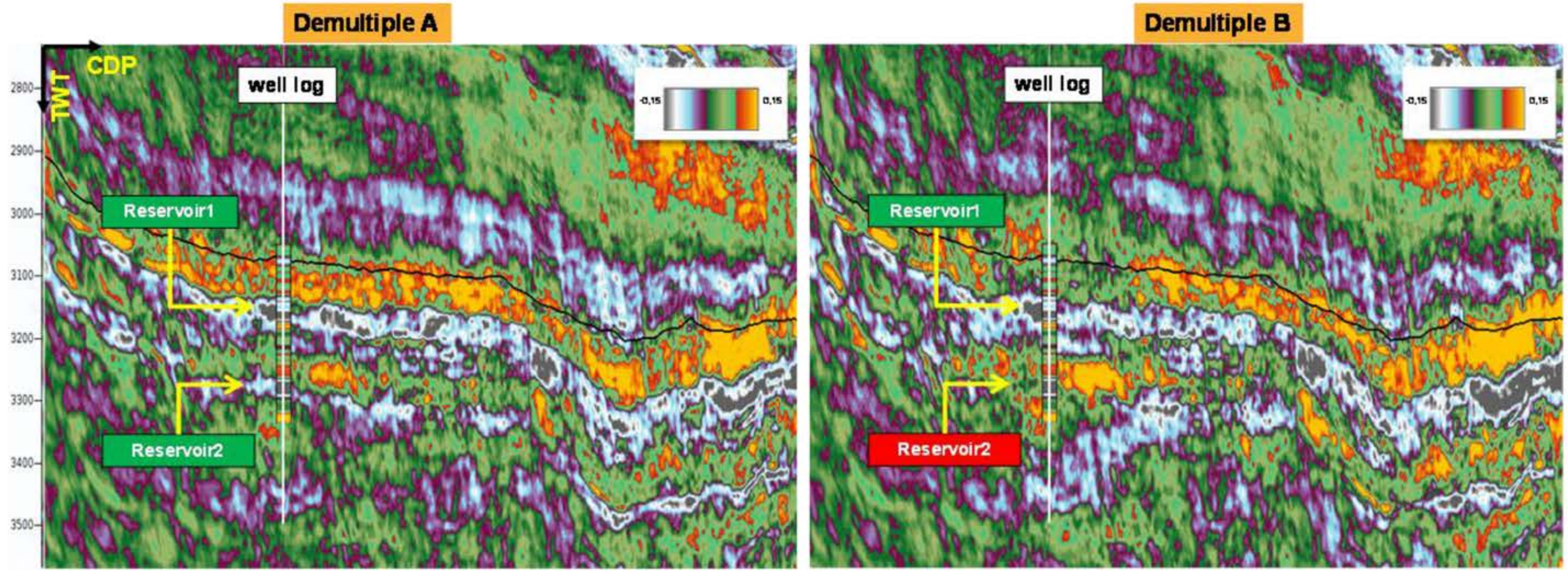

Figure 3. Relative Vp/Vs attribute from pre-stack inversion with the embedded well log value for demultiple flow A (left) and B (right). See text for discussion.

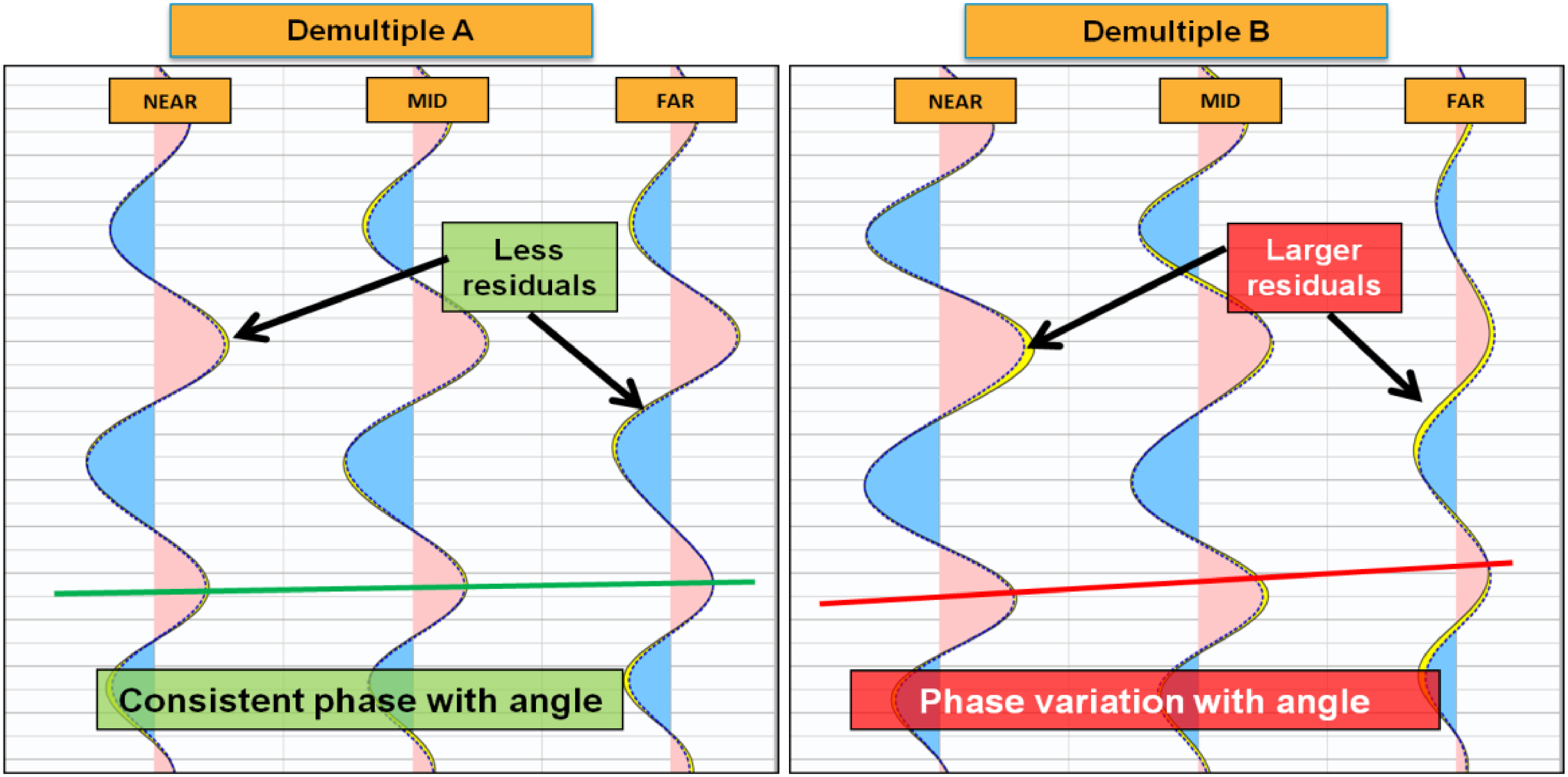

Figure 4. Inversion residuals in reflectivity domain at three angle ranges at the low frequencies. Demultiple flow B is less AVA compliant, as seen in larger inversion residuals (in yellow) as well as in the phase variation which is also inconsistent with the model.

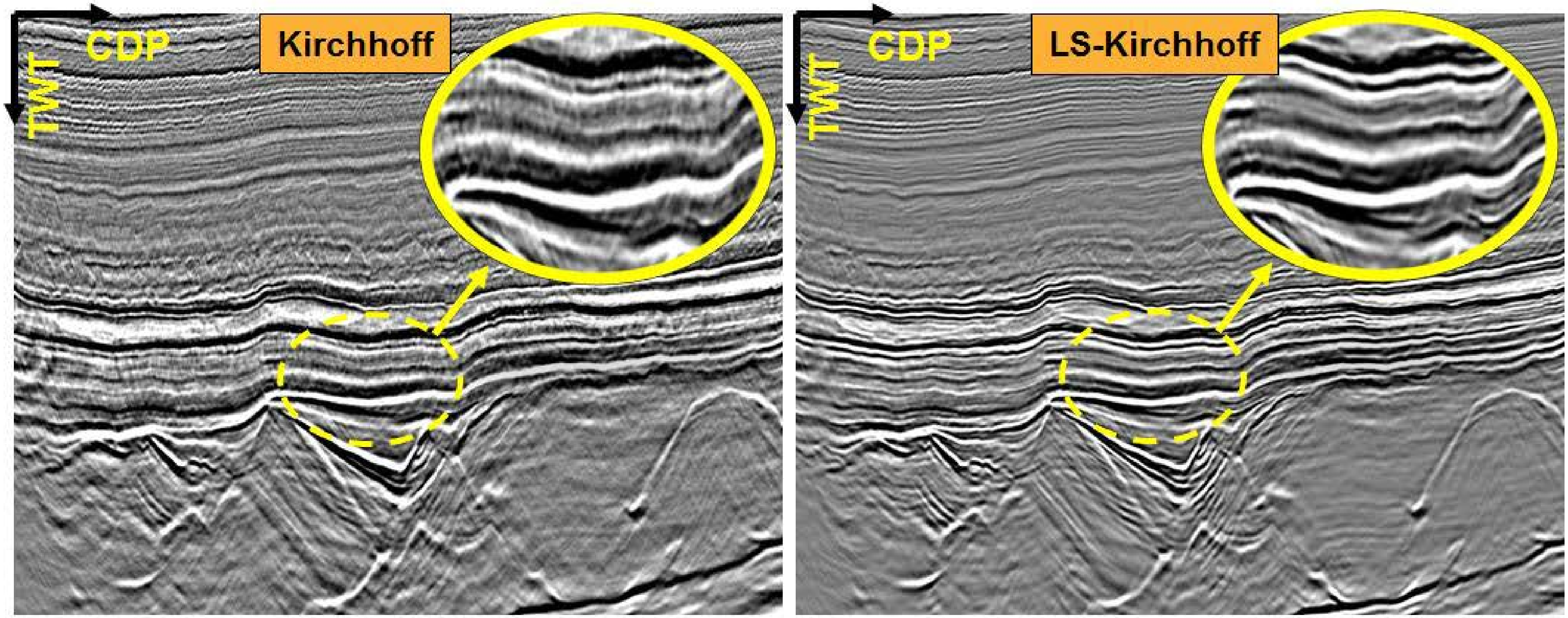

Figure 5. Near angle stacks using Kirchhoff depth migration without (left) and with least-squares migration.

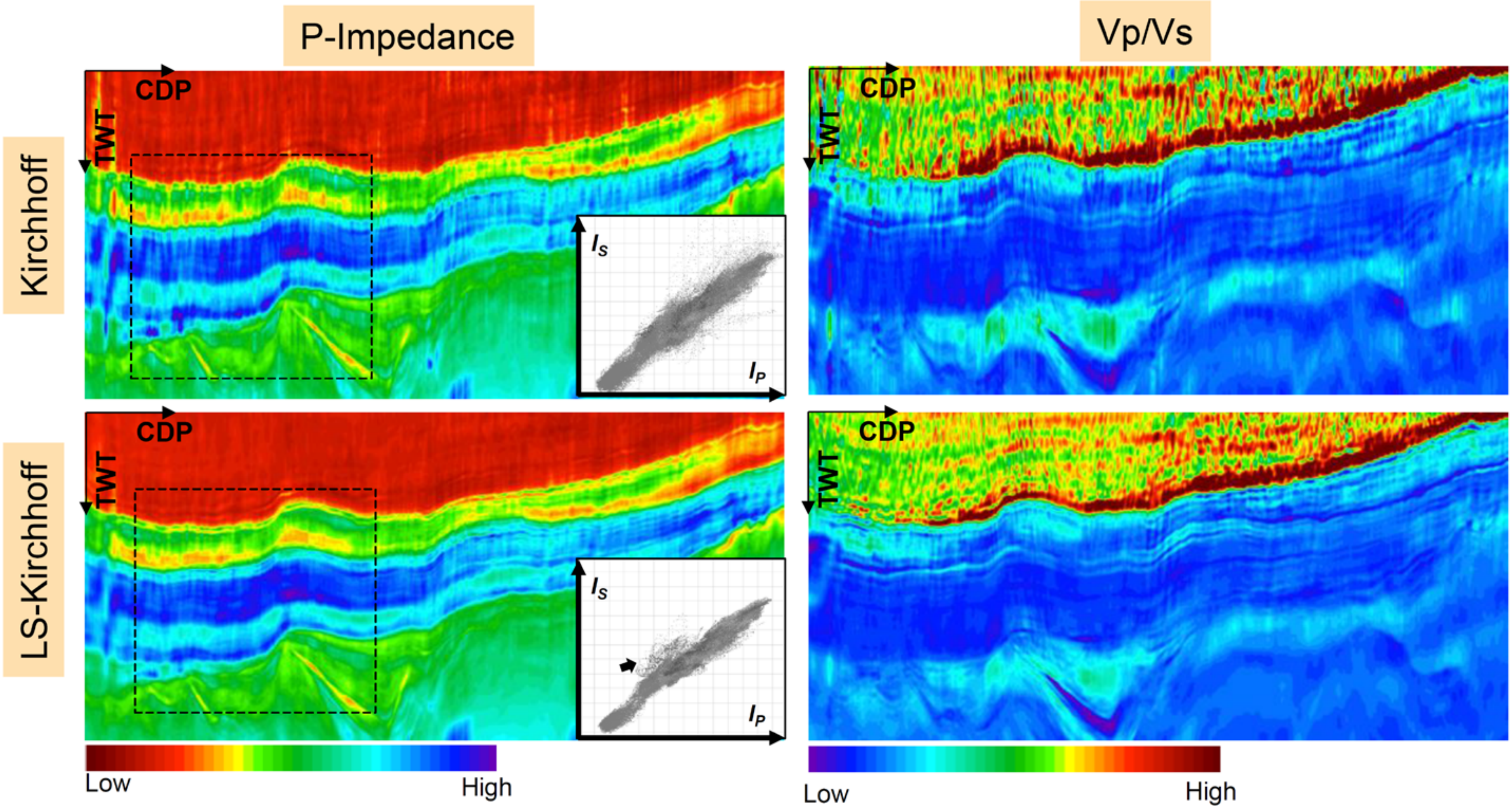

Figure 6. Inverted impedance and Vp/Vs ratio for conventional Kirchhoff and LS-Kirchhoff migrations. The potential hydrocarbon anomaly (indicated with a black arrow on the Ip-Is cross-plot for the LS-Kirchhoff results) is more visible after least squares migration.

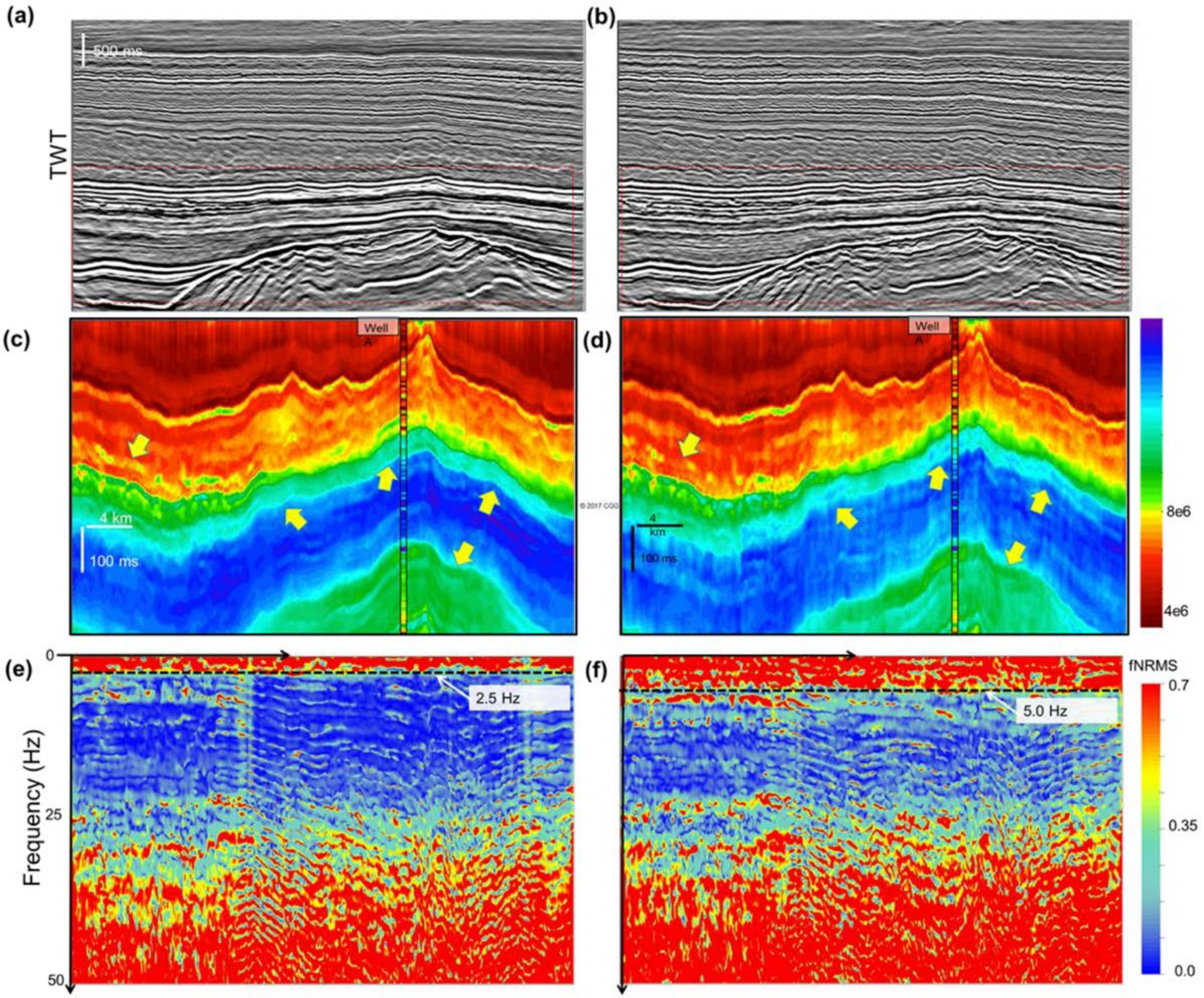

Figure 7. Impact of acquisition on seismic bandwidth. Left column: broadband acquisition, right column: conventional acquisition. Top row: full-stack data, middle row: inverted P-impedance and bottom row: frequency-dependent NRMS difference between data and corresponding inversion model.