Thin-bed reflectivity inversion and some applications

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Abstract
Thin-bed reflectivity inversion is a form of spectral inversion which produces sparse reflectivity estimates. It resolves thin layers below the tuning thickness under favourable circumstances when the assumptions are met in practice. The process differs from other inversions in that it is driven by geological rather than mathematical assumptions, and is based on aspects of the local frequency spectrum obtained by using spectral decomposition. Application of thin-bed reflectivity inversion to seismic data yields superior resolution which can help in various ways. The advantages include being able to pick up more reflection detail, to perform more accurate interpretation on seismic volumes obtained by convolving reflectivity volumes with wavelets of higher bandwidth than the input data, and to visualize subtle anomalies when some attributes are run on thin-bed reflectivity inversion output. Thin-bed reflectivity inversion is a useful process which should be utilized for extracting meaningful information from surface seismic data in the characterization of thin reservoirs.

Introduction
Enhancing the bandwidth of surface seismic data has always been a desirable goal for geoscientists. Conventional wisdom dictates that, in the presence of noise and consequent broadening of the seismic wavelet during its subsurface journey, the resolution limit is theoretically 1/8 and practically 1/4 of the dominant wavelength of the data. This limit follows from the Widess model, which assumes a pair of exactly equal and opposite reflection coefficients and is thus a special case with atypical resolution. Based on an analytical analysis of a realistic earth reflectivity model, it is found that the seismic amplitude and frequency vary continuously far below the conventional view of the limit of seismic resolution, and it is possible to infer thickness below the seismic sample rate under favourable circumstances if reasonable assumptions are made (Puryear and Castagna, 2008). This implies that frequencies beyond the original seismic data bandwidth can sometimes be recovered.

Method
Thin-bed spectral inversion is a novel way of removing the wavelet from seismic data and extracting reflectivity (Castagna et al., 2003; Portniaguine and Castagna, 2005; Chopra et al., 2006). It is based on the premise that the spacing between spectral peaks and notches for a windowed portion of a seismic trace is a function of layer thickness in the time domain (Partyka et al., 1999). In the special case of a seismic reflection response produced by a single layer and, in the absence of noise, it is possible to determine layer thickness uniquely with no resolution limit by inverting a relatively narrow band of frequencies (where the top and base reflection coefficients have unknown polarities and magnitudes) provided that the wavelet spectrum is known and there is an even component to the reflection response (Chopra et al., 2006). Under such circumstances, once layer thickness is found, both top and base reflection coefficients can also be determined.

In practice, thickness and reflection coefficients can be inverted for as far below the tuning thickness as noise will allow. The 1/8 wavelength Widess limit on resolution only applies if the reflection coefficients are exactly equal and opposite. When there are multiple layers contributing to the seismic waveform and noise, the inversion becomes non-unique, but if we make the reasonable assumption a priori that the reflection response is dominated by only a few layers, one can readily and robustly invert the superposition of sinusoidal layer responses in the frequency domain for an earth model that provides an alternative, and often better, image of the geology than the original seismic trace. If the seismic response results from many fine layers, and/or contains transitional interfaces, or if the seismic data are very noisy, the inverted reflectivity can be sparser than may be desired for interpretation purposes. If the even component of the signal is below the noise level, the resolution achievable falls back to the Widess limit. Our experience has shown that the simple assumption that each seismic reflection is dominated by only a few reflection coefficients, albeit not necessarily the sparsest number, often results in an inverted image that is far superior to the original seismic data for exploration and development purposes.

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Puryear and Castagna (2008) described the theory behind the method, demonstrated its utility by performing layer thickness determination on a real seismic survey without well calibration to achieve estimation accuracies of a few millseconds at time thicknesses approaching 1/16 wavelength, and showed how much more geologically reasonable inverted reflectivity images are from a stratigraphic point of view than are the seismic sections from which they are derived. Based on inverted seismic images, they proposed that wavelet side-lobe interference caused by lateral variations in rock properties introduces a false sense of bedding plane discontinuity on conventional seismic sections which can be mistaken for structural or stratigraphic complexity.

As described by Puryear and Castagna (2008), the inversion utilizes spectral decomposition to unravel the complex interference patterns created by thin-bed reflectivity. Spectral shape information as a function of record time, in the form of a time-frequency gather for each original seismic trace, drives an inversion based on the complex superposition of layer spectral responses to obtain the reflectivity. The inverted reflectivity generally has significantly greater vertical resolution than the original seismic data. This inversion process does not require stringent assumptions for its performance. It does not require any a priori or starting earth model, or any reflectivity spectrum assumptions beyond that implied by the assumption that the earth model is blocky, nor horizon constraints. Neither is a well constraint mandatory, though having one well control point can be helpful for wavelet extraction. For data with high signal-to-noise ratio (SNR), thicknesses far below tuning can sometimes be resolved. Appreciable noise in the data deteriorates the performance of the inversion outside the frequency band of the original seismic data, but the method still enhances high frequencies within the band without blowing up noise as conventional deconvolution would do. This occurs because rather than shaping the amplitude spectrum by spectral division, or its equivalent, which must blow up the noise at frequencies where there is weak signal, the reflectivity output from the inversion process is constrained to a large extent by those spectral bands in the original data where the SNR is high, and thus noise is attenuated at frequencies where the signal is originally weak.

The output of the inversion process can be viewed as spectrally broadened seismic data, retrieved in the form of broadband reflectivity data that can be filtered back to

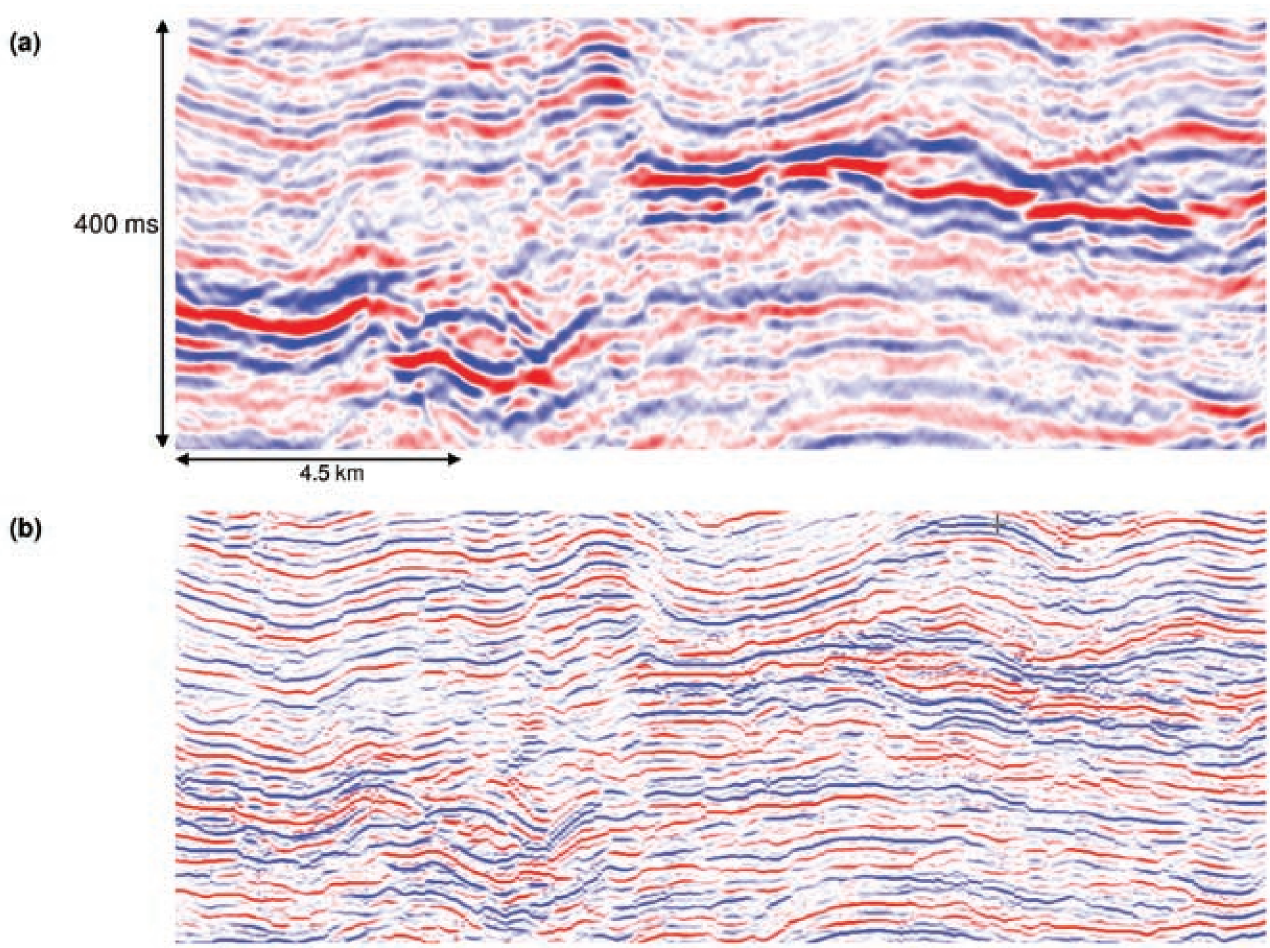

Figure 1 Segment of a seismic section (a) before and (b) after thin-bed reflectivity inversion.

any bandwidth that filter panel tests indicate adds useful information for interpretation purposes.

Examples

Figure 1 shows a comparison of a segment of a seismic section from Alberta in the foothills of the Rocky Mountains, and its equivalent reflectivity section. After reflectivity inversion, notice how much reflection detail one gets to see, not only in terms of extra reflection cycles, but also in the fault detail.

Figure 2 shows another comparison of a segment of a seismic section from Alberta and its high resolution reflectivity inversion. The objective here is a pinch-out at the indicated level in the highlighted area, which appears as a continuous reflection on the seismic section. The reflectivity section shows the pinch-out clearly. Similarly, notice the resolved reflections on the reflectivity in the lower highlighted zones. Horizon interpretation carried out on the input seismic when overlaid on the reflectivity section shows how irregular the horizon tracking is. Horizons tracked on reflectivity volumes are usually seen to be smoother.

A possible doubt that could crop up in an interpreter's mind is whether the extra level of reflection detail is genuine. Since the proof of the pudding is in the eating, it is advisable to correlate the input seismic as well as the derived reflectivity convolved with a known bandpass wavelet, with the synthetic seismograms available in the area. We show such a correlation in Figure 3.

In Figure 3a, the synthetic seismogram generated by filtering the reflectivity obtained from sonic and density logs with a zero-phase bandpass filter having amplitude response 10-15-70-80 Hz is correlated with the input seismic data. Data from this well were used for quality control purposes,

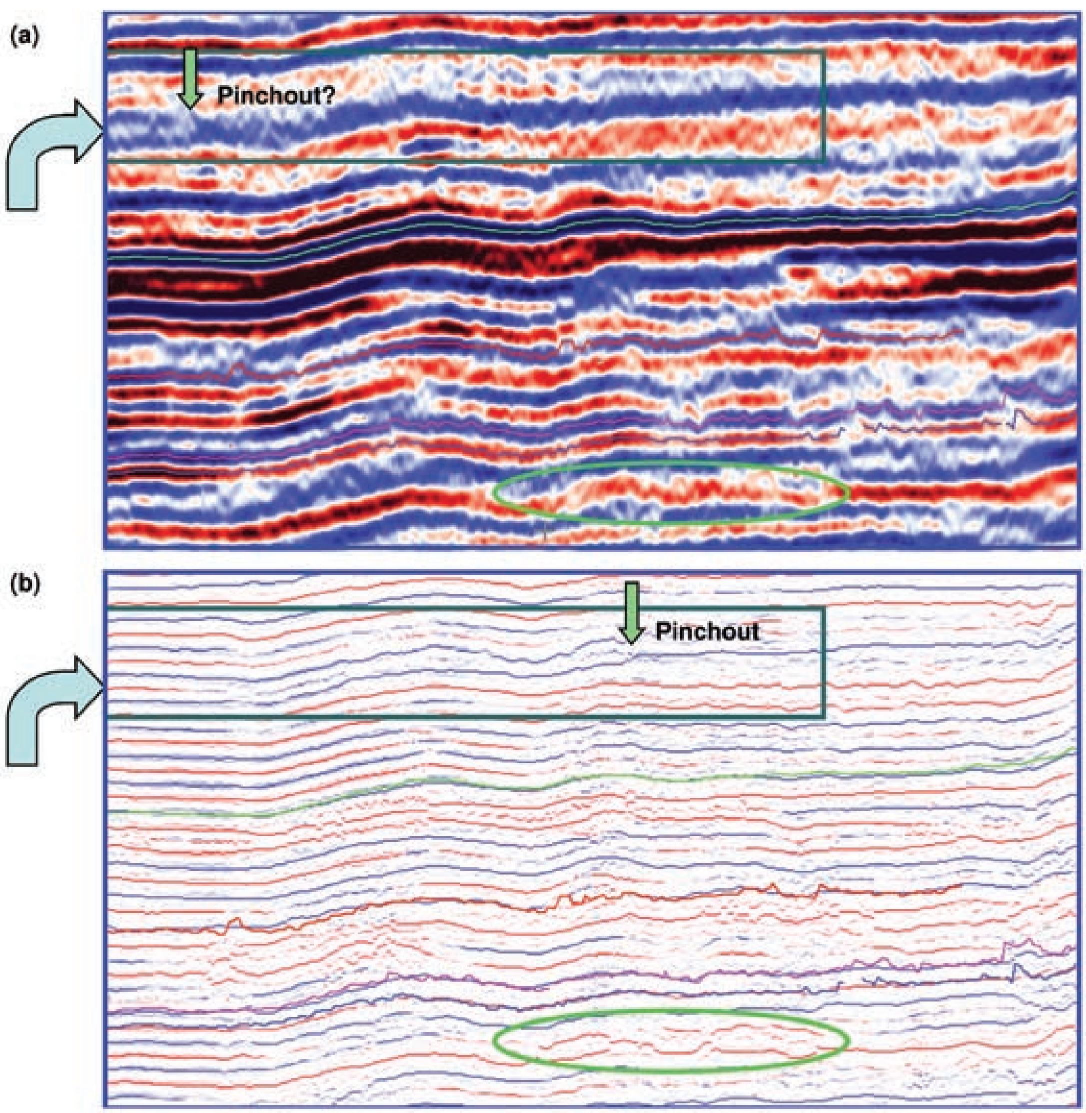

Figure 2 *Comparison of (a) the band-limited seismic section with (b) the derived thin-bed reflectivity. From Chopra et al. (2006), courtesy CSEG.*

though not used in the inversion process itself. The inversion quality control steps involve, amongst other proprietary things, a check on the stability of the time-variant set of extracted wavelets. Besides the visual examination of these extracted wavelets, the check is made by generating and comparing the synthetic seismograms obtained from (1) the reflectivity derived from the well logs and the extracted wavelets, and (2) the inverted trace reflectivity at the position of the well and the extracted wavelets. Should this match not be as expected, the requisite parameterization is varied until a suitable match is obtained. In Figure 3b, the reflectivity from the sonic and density logs is filtered with a zero-phase band-pass filter having amplitude response 10-15-120-130 Hz, and compared with the seismic traces obtained by passing the thin-bed reflectivity derived from the input seismic through the same filter. Notice that the extra reflection cycles seen in the seismic correlate with the corresponding cycles on the synthetic seismogram, lending confidence in trusting the extracted reflection detail. Also, note that the correlation coefficient between the synthetic and the seismic data increases after frequency enhancement.

Figure 3c shows the correlation of a blind well test. It is blind in the sense that while the well log curves in Figure 3a and b were used for the inversion quality control pur-

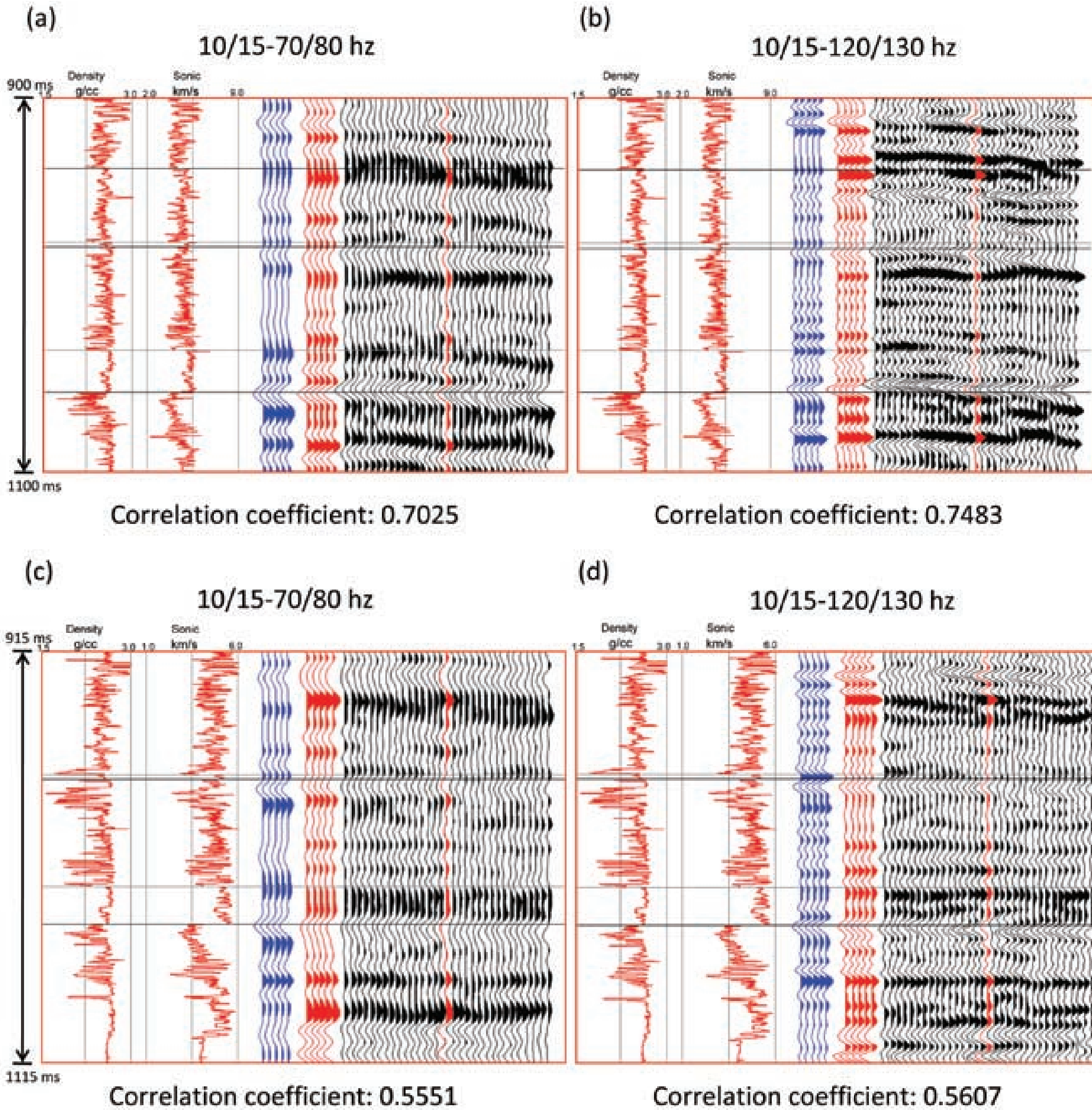

***Figure 3** Correlation of well log curves and synthetic seismograms with (a) a representative seismic section, and (b) the equivalent seismic section with enhanced resolution. (c) and (d) show a similar correlation for a blind well. Synthetic seismograms are shown in blue and traces from the surface seismic data at the well locations are shown in red.*

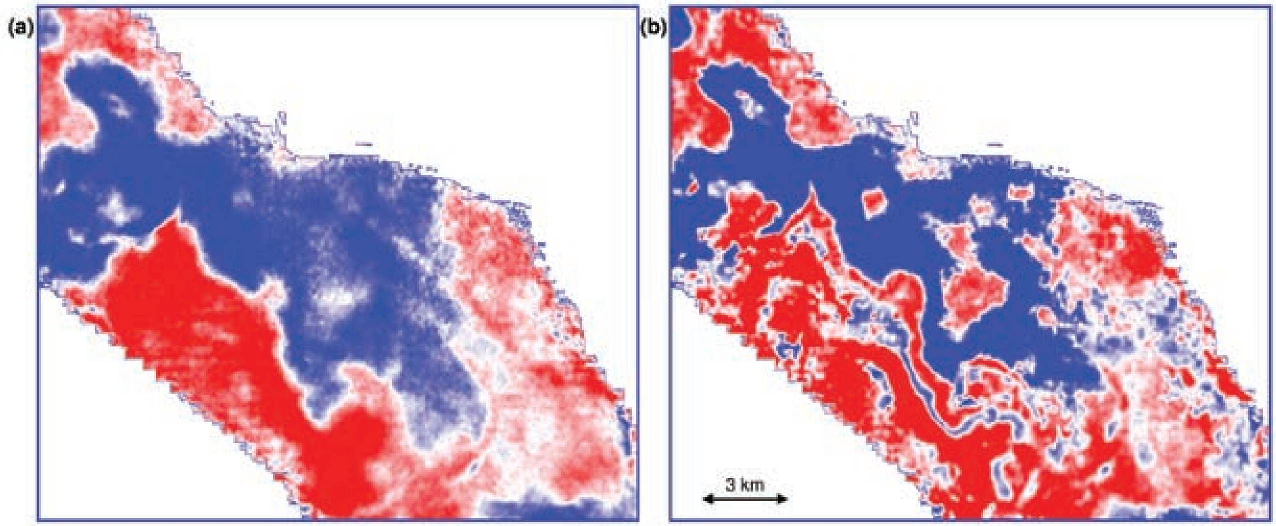

Figure 4 *Time slices at 1672 ms through (a) the input seismic data volume, and (b) the frequency-enhanced seismic volume, obtained by convolving the derived thin-bed reflectivity volume with a bandpass wavelet with higher bandwidth.*

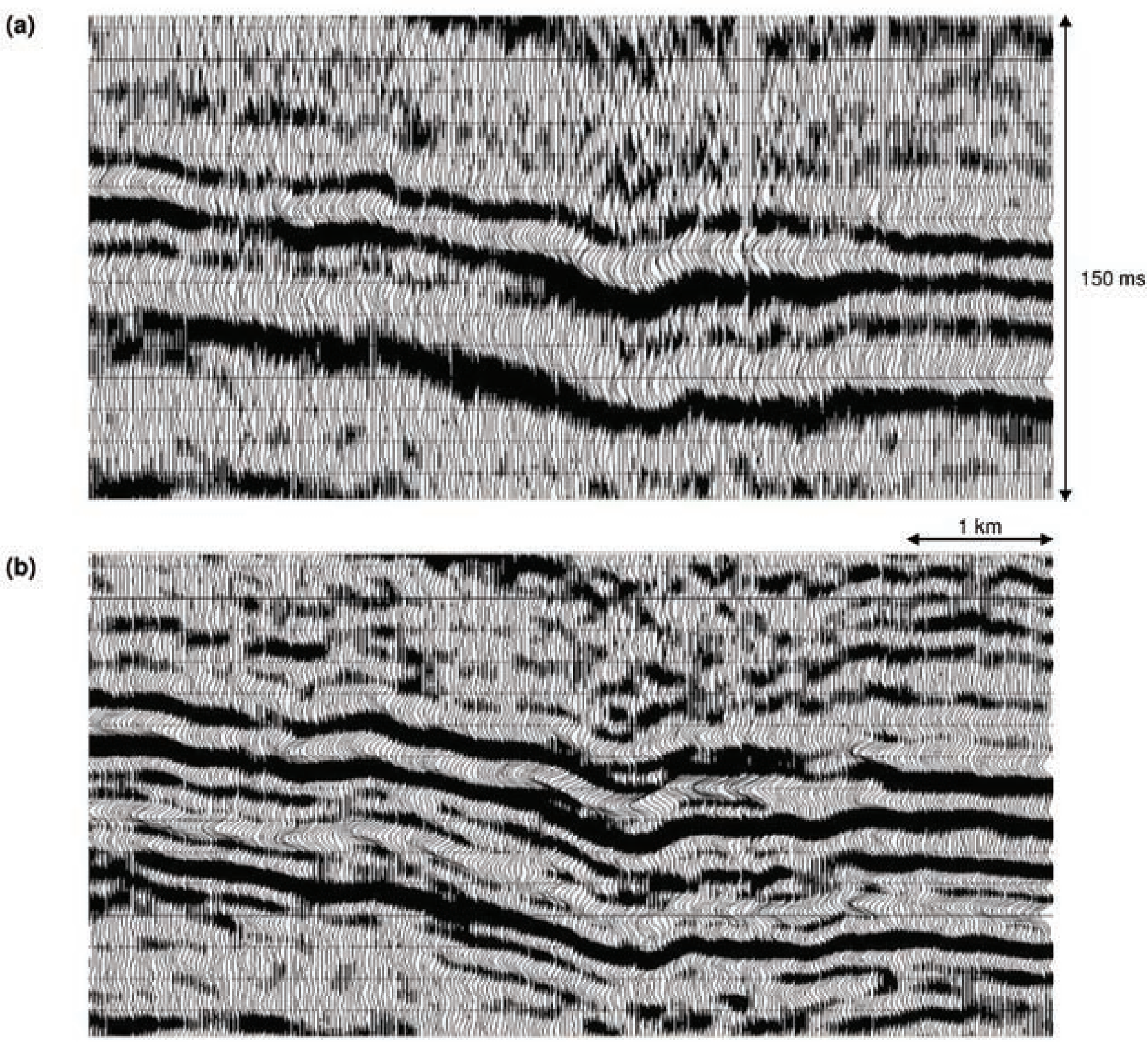

Figure 5 *Segment of a seismic section from (a) the input seismic data and (b) the reflectivity volume convolved with a bandpass wavelet with a high end of 120 Hz.*

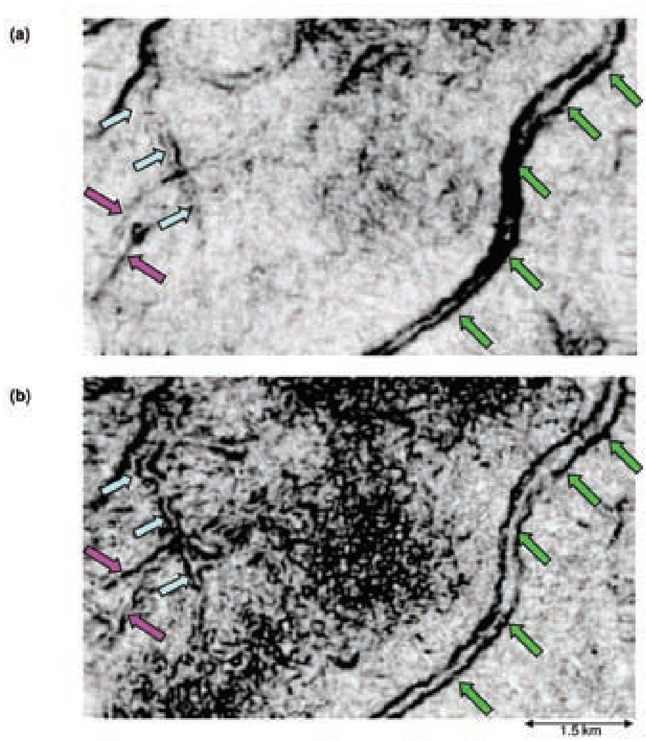

Figure 6 Time slices at 1110 ms through (a) a coherence volume derived from the input seismic volume and (b) the corresponding coherence volume generated from the frequency enhanced volume.

pose mentioned above, in this case the well logs were not used for any such thing. This well is located a few kilometres away from the one shown in Figure 3a and b. Again, notice that the extra cycles on the frequency-enhanced seismic correlate with their equivalent counterparts on the synthetic, and that the correlation coefficient is marginally higher after frequency enhancement.

Another common way of making a comparison between the input seismic data and its frequency enhanced version is through time or horizon slices. Figure 4 shows such a time slice comparison. Notice the blue and red blobs in the input in Figure 4 are seen in more detailed reflection patterns in Figure 4b. Thus the frequency enhanced version of the input seismic allows easy interpretation of subtle stratigraphic features, as illustrated here.

In addition to reflection polarity, strength, continuity, and relationship to other reflections, an important attribute of the reflection process that a seismic interpreter looks for is reflection character. Thin-bed reflectivity serves to provide the four aforementioned characteristics clearly, and the reflection character can be studied by convolving the reflectivity with a wavelet of a known frequency bandpass. This not only provides an opportunity to study reflection character associated with features of interest, but also serves to confirm its close match with the original data. Figure 5a shows a segment of a seismic section from the input seismic

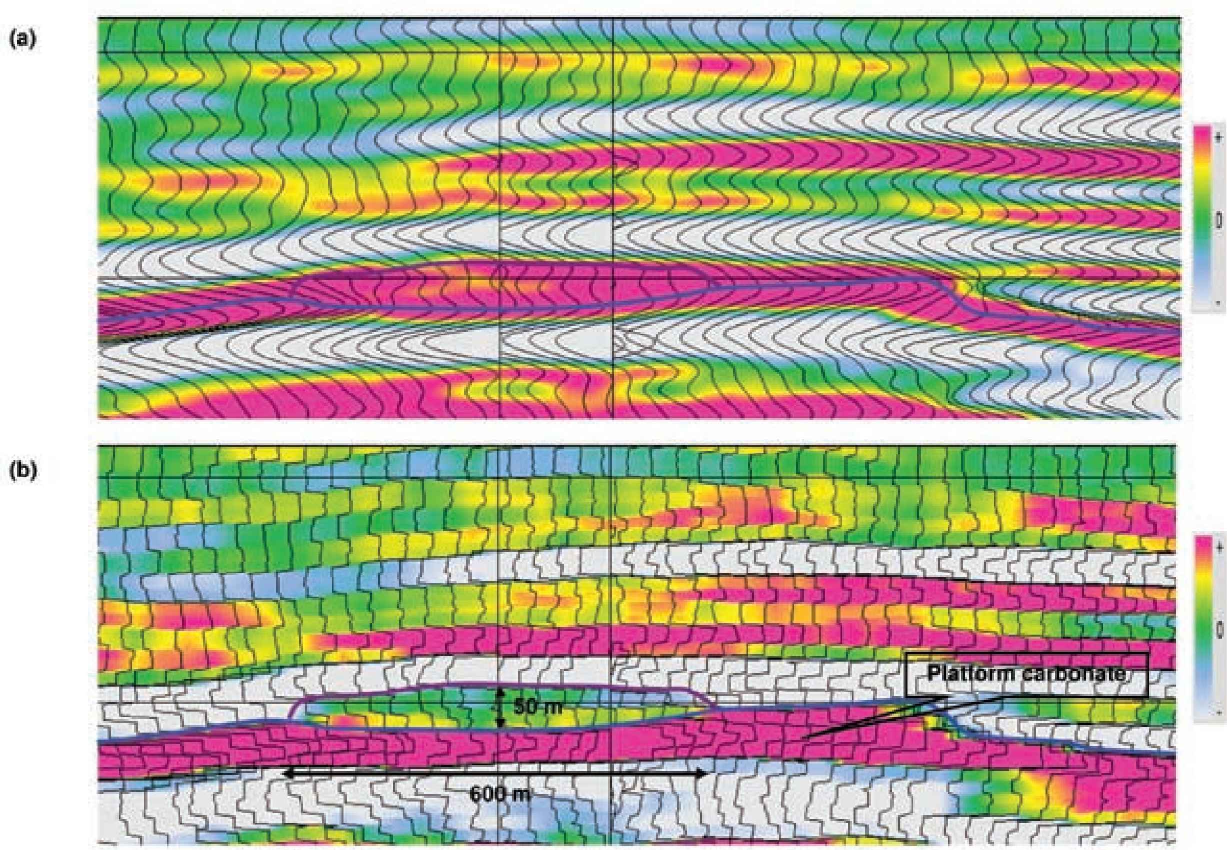

Figure 7(a) Segment of seismic section from the PSTM data volume shows the weak signature of a gas-producing reef, between the blue horizon and the dark purple horizon picked above it. (b) Equivalent section from relative acoustic impedance run on the thin-bed reflectivity derived from the input seismic data.

data and the equivalent segment from the reflectivity volume convolved with a bandpass wavelet with a high end of 120 Hz (Figure 5b). Notice the higher resolution that has been achieved as well as the fact that lateral changes in wavelet character can now be studied.

Some applications

Attributes run on frequency enhanced seismic data yield more accurate results and so more meaningful interpretation (Chopra and Marfurt, 2008). Whether it is the mapping of channels, faults/fractures, or subtle onlaps and offlaps, such an exercise always proves useful.

In Figure 6 we show a comparison of coherence time slices at 1110 ms in a seismic volume from northeast Central Alberta. On Figure 6a, the main channel to the right, running NE-SW, is seen clearly but not resolved well in terms of its edges (green arrows). Similarly, the thin channel to the left (blue arrows) as well as the lineaments (purple arrows) are not defined so well. By comparison, in Figure 6b we see them all resolved crisply with ocused edges.

Lancaster and Whitcombe (2000) introduced seismic coloured inversion as a quick way of inverting seismic data into relative acoustic impedance. Instead of correlating the tops and bottoms of formation boundaries with the well logs, relative acoustic impedance allows us to interpret reflection isochron units as individual formation thicknesses which can be clearly correlated with logs. Even though the impedance values are not absolute, coloured (or relative) inversion is a useful attribute.

In Figure 7 we illustrate the usefulness of a thin-bed reflectivity application in the identification of a 50 m carbonate reef which could not be distinguished from the base platform carbonate. As indicated in Figure 7a, the limited frequency bandwidth of the prestack time migrated (PSTM) seismic data does not distinguish between the two. Thin-bed reflectivity was derived from the PSTM data and put through the coloured inversion process. The equivalent impedance section is shown in Figure 7b. Notice the clarity with which the reef is seen sitting on top of the base carbonate platform. Its areal extent as interpreted here is 600 m across, and the two wells penetrating this gas-producing reef are indicated with the vertical black solid lines.

Finally, we discuss a recent application of thin-bed reflectivity inversion to a dataset from the North Sea, where a good workflow including LMR inversion and neural network analysis was established. LMR stands for lambda (λ, representing incompressibility), mu (μ, representing rigidity), and rho (ρ, representing density), the Greek letters commonly used as symbols for two elastic

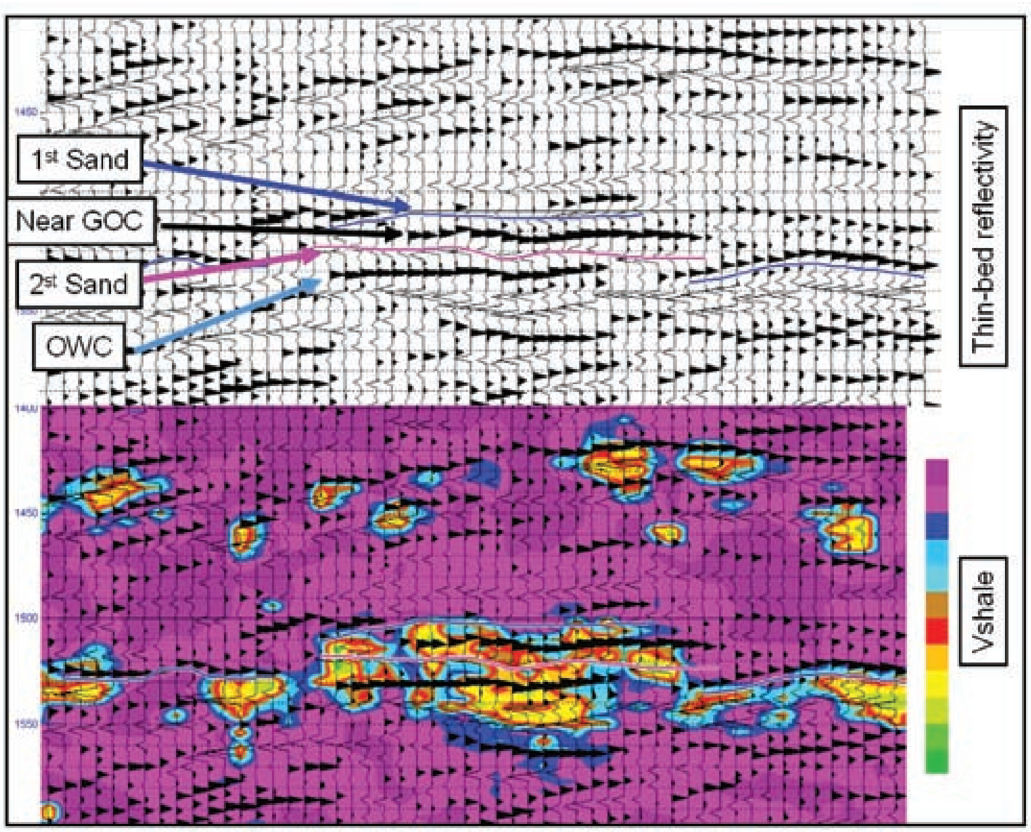

Figure 8(a) The thin-bed reflectivity section derived from the input seismic data was used to pick the individual sand intervals in the zone of interest. (b) The neural network solution in terms of the shale volume derived from the frequency-enhanced data displays one sand-body only. Image courtesy of Rainer Tonn, Oilexco, Calgary.

constants and density. When doing LMR inversion, the P-wave and S-wave reflectivities are first estimated from the prestack seismic data by solving Fatti's simplification of the Zoeppritz equations (Fatti et al., 1994). Then the P and S reflectivities are inverted to the respective impedances and finally transformed into Lambda×Rho and Mu×Rho attributes. Prospective zones are then recognized on these attribute volumes.

In spite of the LMR inversion, hydrocarbon identification remained a challenge prior to reflectivity inversion. In particular, the difference in the oil-water contact (OWC) on the east and west flanks of the field was puzzling. To find a solution to this problem, higher resolution seismic data were needed. The thin-bed reflectivity inversion process provided a means to refine the interpretation, and allowed the identification of individual connected or disconnected sand layers, indicated in Figure 8a. The high resolution thin-bed reflectivities enabled the interpreter to map the OWC, which is expressed as a flat spot. Furthermore, it was found that the thin-bed reflectivity data set could be tied to key stratigraphic intervals. However, the neural network solution in terms of the shale volume displays one sand body only (Figure 8b). The combined interpretation of the shale volume and the reflectivity volume made the correlation from one channel to the next easier for the interpreter (Tonn and Waters, 2007). At the end of the workflow, the interpreter was able to create a reliable map of the sand and additional upside potential was established.

Conclusions and discussion

The thin-bed spectral inversion method described here is a novel way of removing the wavelet from the seismic data and extracting reflectivity. For data with high SN ratio, and some asymmetry in the local impedance structure, thicknesses far below tuning can be resolved. Appreciable noise in the data deteriorates the performance of the inversion outside the frequency band of the original seismic data, but the method still enhances high frequencies within the band without blowing up noise as conventional deconvolution would do. Nevertheless, the highly resolved seismic data retrieved in the form of reflectivity data are very useful for making accurate interpretations and prove to be advantageous in many ways, as has been demonstrated here with several examples.

Anyone with schooling in signal processing knows you cannot produce valid signal by digital filtering at frequencies where the signal is absent. All an inverse filter can do is blow up noise where there is no or little signal. On the other hand, inverted seismic data commonly have frequencies outside the band of the original data. All sparse reflectivity inversions have frequency content that exceeds the original seismic bandwidth. We know that frequencies outside the original bandwidth of the data are within the null space of the inversion. The inversion process can put anything there, and the original seismic data will be recovered when the output sparse spike series is convolved with the original seismic wavelet used in the inversion. So the issue is not whether you can output high frequencies that are not contained in the inversion. The issue is 'how valid are they?' The answer depends entirely on the assumptions that are made and the a priori information used to recover those frequencies, how well matched those assumptions are to reality, and how useful the results are. In our case, we only utilize the mild assumption that the earth is blocky, with a small number of reflections contributing to any given seismic reflection response. If there is an even component to these reflections, we utilize it to push resolution beyond the classical Widess limit. Clearly, there will be some cases where a blocky earth model is not appropriate, and the method will fail to some extent. Our conviction is that, more often than not, our assumption is a sufficiently reasonable representation of the earth and, data quality permitting, the inversion will produce useful results.

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