Seismic resolution and thin-bed reflectivity inversion

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Introduction

Ever since the seismic method was introduced, way back in the 1930s, enhancing the frequency bandwidth of surface seismic data has always been a quest for geophysicists. In fact, seismic resolution is the key to extraction of stratigraphic detail from seismic data and this has become more important over the last decade or so. Seismic resolution comprises two aspects – the vertical and horizontal resolution. The vertical resolution refers to the ability to distinguish two close seismic events corresponding to different depth levels, and the horizontal or spatial resolution is concerned with the ability to distinguish and recognize two laterally displaced features as two distinct adjacent events. While both aspects are important for interpreting small features on seismic data, here, we focus our attention to the vertical resolution, recognizing that migration procedures are usually put in place for collapsing the Fresnel zones that enhance spatial resolution.

Vertical resolution

If the average spectrum of a seismic wavelet is centered around 30Hz, which is usually the case, reservoirs having a thickness less than 25 m, may not have top and base reflectors resolved. This may suffice for structural objectives, but stratigraphic targets are usually set to look for reservoirs 10 m or less in thickness. Attempts to achieve such objectives often lead to frequency enhancement procedures to be followed on surface seismic data. Conventional wisdom usually follows the conclusions enunciated by Widess (1973) some three decades ago. Widess proposed $\lambda/8$ as the resolution limit, λ being the predominant wavelength in the data. In the presence of noise and the consequent broadening of the wavelet during its subsurface journey, this resolution is usually taken to be only $\lambda/4$, and geophysicists have been assuming this resolution limit as a gospel truth till now. So, wavelength is the yardstick for resolution, which in turn depends on velocity and frequency. Since there is nothing we can do for velocity, which shows a general increasing trend with depth, the key factor that determines resolution according to the Widess model is frequency. Thus, for getting greater reflection detail from seismic data, utmost care is exercised, first at the seismic data acquisition stage in terms of field parameters, seismic sources and improved recording adopted, and secondly, during processing where attempts are made to enhance the spectral bandwidth.

Revisiting the Widess model

Widess (1973) in his classic paper entitled 'How thin is a thin bed', published in 'Geophysics' in 1973, concluded that for thin beds (below 1/8th of a wavelength), the seismic character, peak/trough time and frequency do not change appreciably with thickness, and also that amplitude varies almost linearly (along the almost linear portion of a sinusoid) with thickness, which goes to zero at zero thickness. Below 1/8th of a wavelength, as the only characteristic of the seismic response that changes appreciably with thickness is amplitude, there is no way to separate reflection coefficient changes from thickness changes. Thus, 1/8th of a wavelength is considered by many to be the fundamental limit of vertical seismic resolution. The seismic response becomes virtually the derivative of the seismic wavelength below 1/8th wavelength, so there is no significant variation of peak frequency as zero thickness is approached. These conclusions were based on a simplified wedge model embedded in a homogeneous rock giving a pair of equal and opposite reflection coefficients corresponding to the top and base of the wedge. It is not difficult to infer that Widess's wedge model is not representative of most real situations and we shall see that such an analysis as applied to practical cases usually leads to incorrect amplitude tuning curves. Also, the theoretical limits of resolution are found to be far better than what Widess model suggests. For example, Figure 1 (Tirado, 2004) shows the peak frequency variation as a function of bed thickness for a realistic synthetic wedge model produced from a sonic log. As the bed thickness decreases, there is a gradual increase in the peak frequency, but below a certain thickness (at some fraction of the tuning thickness), the peak frequency rolls off and returns to the peak frequency of the wavelet (rather than that of the derivative of the wavelet) at

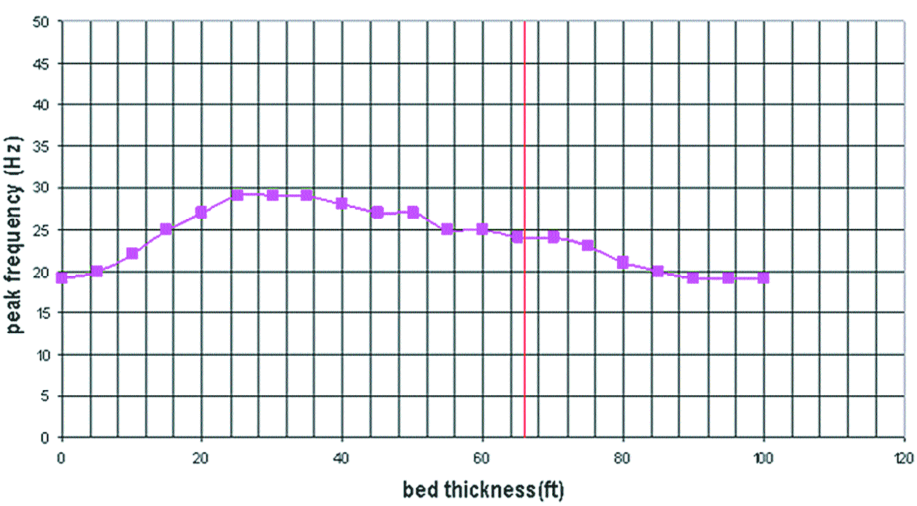

Figure 1. Shows the variation of peak frequency with bed thickness. There is a gradual increase in frequency as the thickness of the bed decreases and beyond some fraction of the tuning frequency it rolls off.

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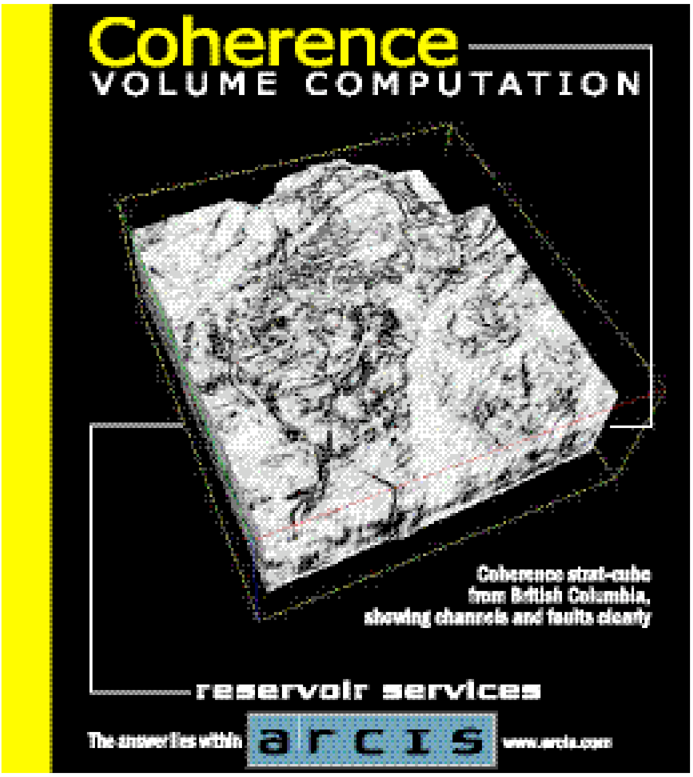


zero thickness; a conclusion contrary to what Widess predicted for a simple thin layer. The above observation suggests a relook at the applicability of Widess to real situations.

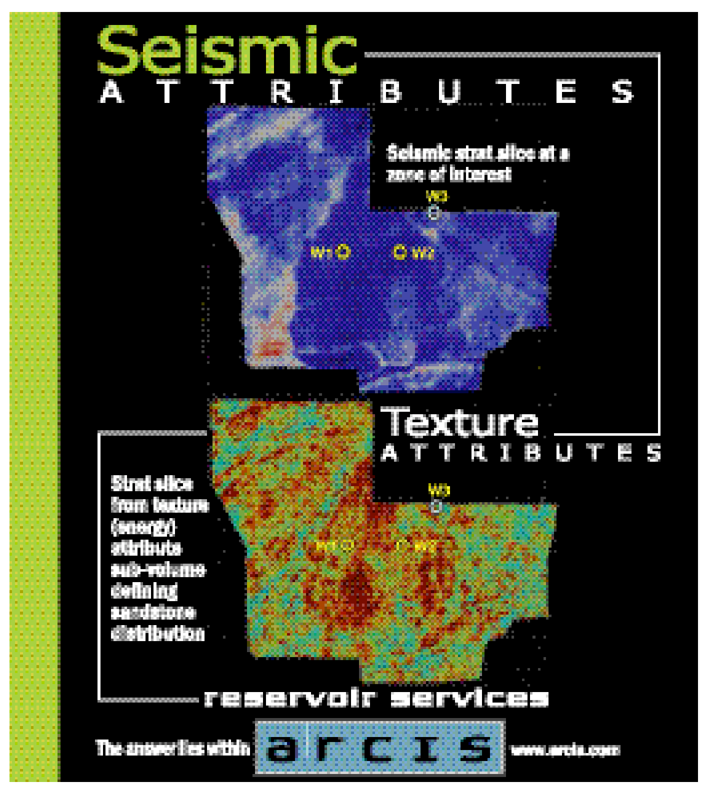
Tirado (2004) has studied this problem, following the work of Chung and Lawton (1995). A practical situation may be represented by a 2-point reflectivity sequence shown in Figure 2. This may be shown to be the sum of a pair of sequences, an odd part consisting of a pair of equal and opposite reflection coefficients (like in the Widess model), and an even part made up of two reflection coefficients of the same polarity. Modeling analysis on these two components shows that for the odd component the amplitude first increases (tuning) and then decreases as the thickness gradually reduces. For the even part this variation is just the opposite (see also Kallweit and Wood, 1992). So, most real situations would require both these contributions, depending on the magnitude of the reflection coefficients in the two additive components. It is possible that the contribution from the odd component is more than the even component, or vice-versa and this would be dictated by the situation at hand. In the case of bright spots, the contribution from the even part may be relatively weak and so noise, rather than the dominant frequency will control the fundamental limit of resolution.

Based on such an analytical modeling analysis, Figure 3 and 4 shows the peak amplitude and peak frequency variation respectively with thickness for a situation where the odd part is significantly stronger than the even part. Notice that the total peak frequency (sum of the contributions from the odd and even components) shows a variation as depicted in Figure 1. When the reflection coefficients at the top and the base of a thin bed are not exactly equal and opposite, a more general behaviour is observed, where the peak frequency decreases as thickness decreases below about half of the tuning frequency. Exactly at what thickness this rollover occurs depends on the relative magnitudes of even and odd reflection coefficients. Contrary to the Widess model, below this rollover, there is a strong dependence of peak frequency on thickness. This suggests that the seismic response is more sensitive to thin beds than generally thought previously. From this analysis we conclude that the Widess model for a thin bed is a very special case of a more accurate combination of reflection coefficients and that the behavior predicted by Widess becomes more atypical as thickness approaches zero. Also, 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. This implies that frequency beyond the seismic data bandwidth can be recovered.

Spectral inversion

Expectedly, seismic sections should bear a striking resemblance to geological cross-sections. If this happens, interpretation becomes straight-forward. When this does not happen, seismic interpreters resort to the art of geological interpretation of the seismic data based on their knowledge of the basic principles of geology and geophysics and their experience. In the practical scenario a certain amount of imagination is relied on when the bandwidth of the data is not supportive of the interpretation. Thin-bed reflectivity inversion helps the seismic interpreters by narrowing the gap between the two extremes mentioned above.

Portniaguine and Castagna (2005) discuss a post stack spectral inversion method that resolves thin layers below the tuning thickness. This method is driven by geological rather than mathematical assumptions and keys on aspects of local frequency spectrum obtained by using spectral decomposition (Castagna et al, 2003, Portniaguine and Castagna, 2004). This spectral or thin-bed inversion outputs a reflectivity series and its apparent resolution is far superior to the input seismic. This aspect makes the method ideal



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for detailed delineation and characterization of thin reservoirs. Applications of this method (commercially known as ThinMAN™) in deconvolving the complex seismic interference patterns from seismic data are changing the conventional mind set of interpreters and yield interpretable stratigraphic patterns with remarkable detail. This is a novel way of extracting reflection detail and removing the seismic wavelet without blowing up noise at high frequencies, with corresponding improvement in seismic resolution. It is well known in seismic inversion theory that a *priori* information can produce inversions that are higher frequency than the input data. The quality and meaningfulness of this "restored bandwidth" depends on the validity of the assumptions made. The simple assumption that geology preferentially occurs in layers of a limited variety of shapes is a useful constraint that can be used to drive spectral inversion (see Partyka, 2005).

This inversion process does not require stringent assumptions for its performance. It does not require any *a priori* model, any reflectivity assumptions, any horizon constraints and neither is a well constraint mandatory, though having at least one well control point is helpful. Starting with the band-limited seismic data, the method yields a high reflectivity section/volume (depending on whether it is 2-D or 3-D data).

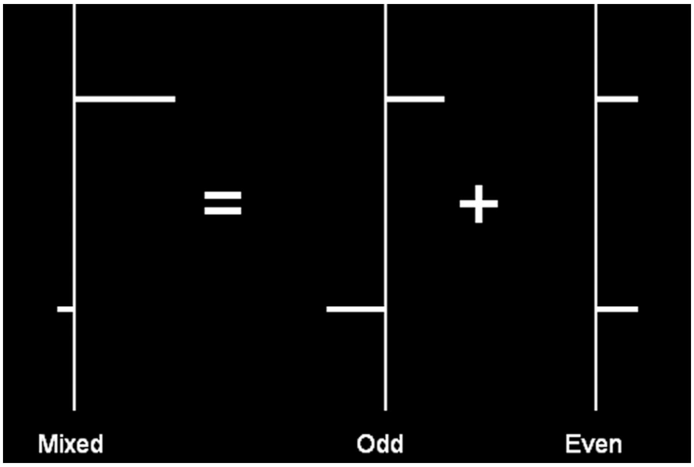

Figure 2. A practical thin bed subsurface situation represented with a two point reflection coefficient series corresponding to the top and bottom of a layer. This two point series can be written as a sum of a two-point series with equal and opposite reflection coefficients (odd) and a another two-point series which has reflections coefficients of the same sign (even).

While the finer details of the algorithm employed are proprietary, the method essentially consists of following steps:

1. making accurate estimation of a time and space varying set of wavelets from the data. For this purpose having some well control is desireable. In the absence of any well control, a statistical method of wavelet estimation is adopted.
2. the wavelets estimated in step 1 are removed from the data using seismic inversion with spectral constraints that have their roots in spectral decomposition procedures.

It is important to note that no starting earth model or interpretation is used in the inversion procedure. The trace-by-trace procedure requires no starting model and has no lateral continuity constraints.

An extensive suite of quality control steps are included in the processing procedure that ensures the most optimum performance of the thin-bed inversion. Of course the quality of the final result is dependent on the contribution of the even part, the knowledge of the wavelet and also the wavelet characteristics (bandwidth).

Another aspect that needs to be mentioned is about an important attribute of the reflection process that the seismic interpreter looks for (in addition to four other attributes, namely, reflection polarity, strength, continuity and relationship to other reflections). While thin-bed reflectivity serves to provide four of these characteristics clearly, the reflection character can be studied by convolving the reflectivity with a wavelet of a known frequency bandpass. This will not only provide an opportunity to study reflection character associated with a feature(s) of interest, it will also serve to get a confirmation on its close match with the original data.

Once the thin-bed reflectivity is derived from the input seismic volume using for example, a wavelet derived from an existing well, an interpreter would like to ascertain the associated uncertainty of the inversion process by using a blind well test. This is a good way to test the accuracy of the inversion process. Our experience with such exercises suggests that thin-bed spectral

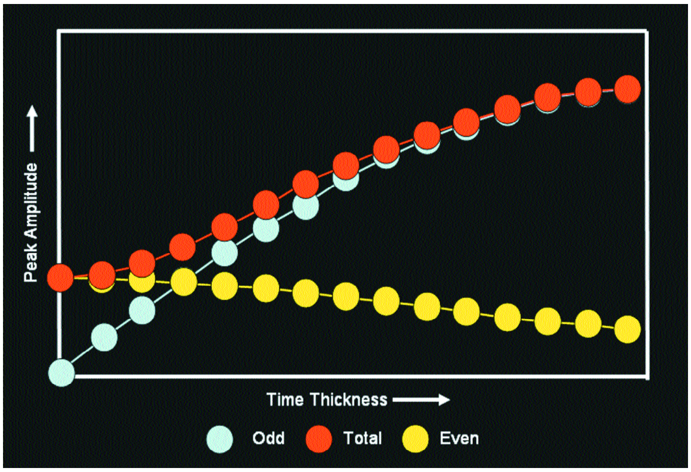

Figure 3. Peak amplitude variation as a function of time thickness of the beds showing the contributions from the odd and the even components shown in Figure 2 as well as their sum.

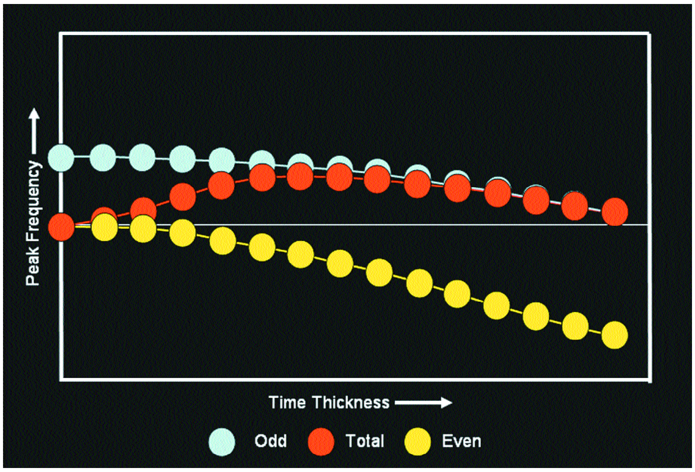

Figure 4. Peak frequency variation as a function of time thickness of the beds showing the contributions from the odd and the even components shown in Figure 2 as well as their sum.

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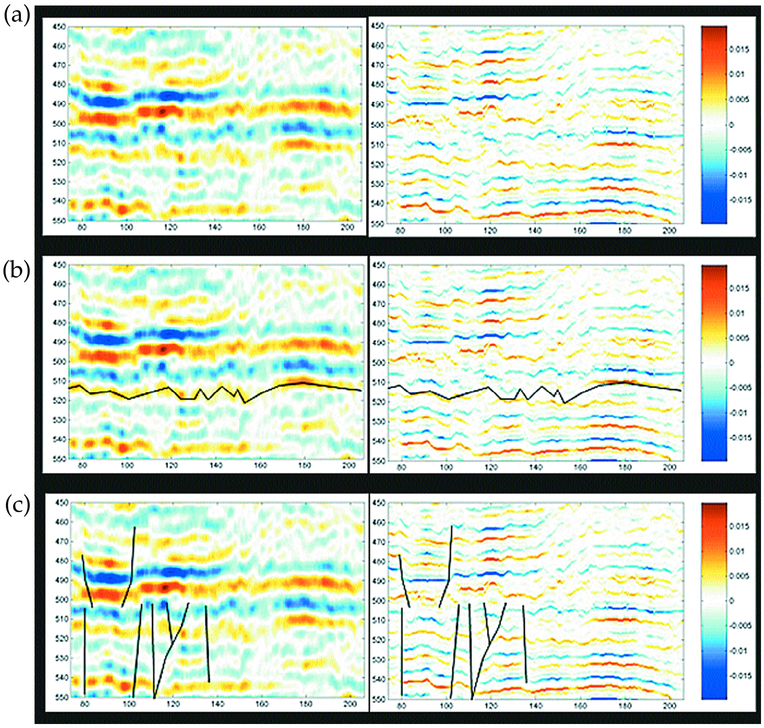

Figure 5. Comparison of the band-limited seismic segment (left) with its derived thin-bed reflectivity (right). Notice how continuous the reflections look in the lower half of the reflectivity. The interpretation carried out on the band-limited seismic and overlaid on the reflectivity section shows how erroneous it is. Similarly the fault interpretation carried out on the reflectivity section and overlaid on the conventional section shows the accuracy that we are losing in conventional interpretation.

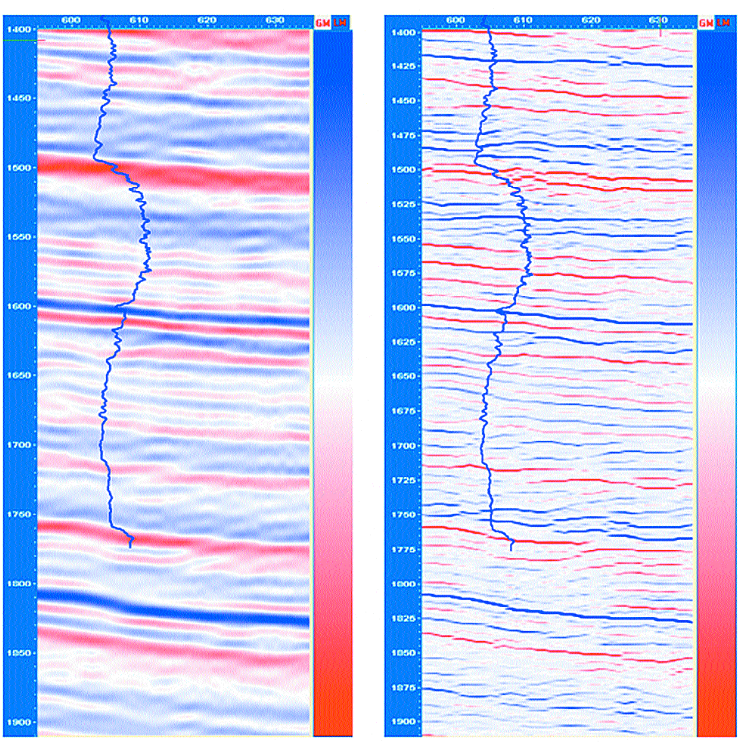

Figure 6. shows a comparison of the conventional seismic section (left) with its derived thin-bed reflectivity (right). Notice how well the overlaid sonic log ties with the reflectivity.

inversion will tie favourably with the other wells on the 3D volume (not used in the wavelet extraction process). Needless to mention, this conclusion is valid for seismic volumes that do not have a significant lateral variation in the seismic wavelets determined at the control point. Should significant lateral wavelet variations occur in locations without wells, poor inversions may result. These are generally recognizeable by experienced analysts and the process can be fine tuned by laterally varying the wavelet so as to avoid inversion artifacts that are clearly non-geological in nature.

The inversion results are amplitude preserving in the sense that the original seismic data is readily re-obtained simply by reapplying the wavelet(s).

Applications to real data

Figure 5, from a North Texas 3D dataset, shows an at-a-glance comparison of a segment of a seismic section with its high resolution reflectivity inversion. Notice how the individual reflection sequences in the lower half of the reflectivity section in Figure 5(a) show a greater continuity and resolution detail in the highlighted zone. Any interpretation carried out on the high-resolution reflectivity section is bound to be more accurate. Also, notice how the horizon tracking on seismic in Figure 5(b)(left), when overlaid on the reflectivity section in Figure 5(b)(right), appears to be erroneous (offtrack and cycle jumps). Similarly, the fault interpretation carried out on the high-resolution section when overlaid on the original band-limited seismic section indicates inaccuracies in its interpretation on conventional seismic. (Figure 5(c)).

Figure 6 shows a comparison of a segment of a section from Alberta and its correlation with a sonic log curve (which has a 5-point smoother on), before and after reflectivity inversion. After reflectivity inversion, notice how much reflection detail one gets to see in terms of not only extra reflection cycles, but also the fault detail. The correlation with the sonic log curve shows how religiously the kinks on the curve follow the reflection detail on the reflectivity section.

Figure 7 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 seismic when overlaid on the reflectivity section shows how irregular the horizon tracking is.

Similarly, Figure 8 shows another comparison between the original band-limited seismic section and its reflectivity inversion. The display contrast on the reflectivity section has been enhanced purposely to bring out the reflection detail on the display, though in practice, it is usually set so that the reflection coefficients look proportional to the reflection strength seen on the band-limited seismic section. Such an

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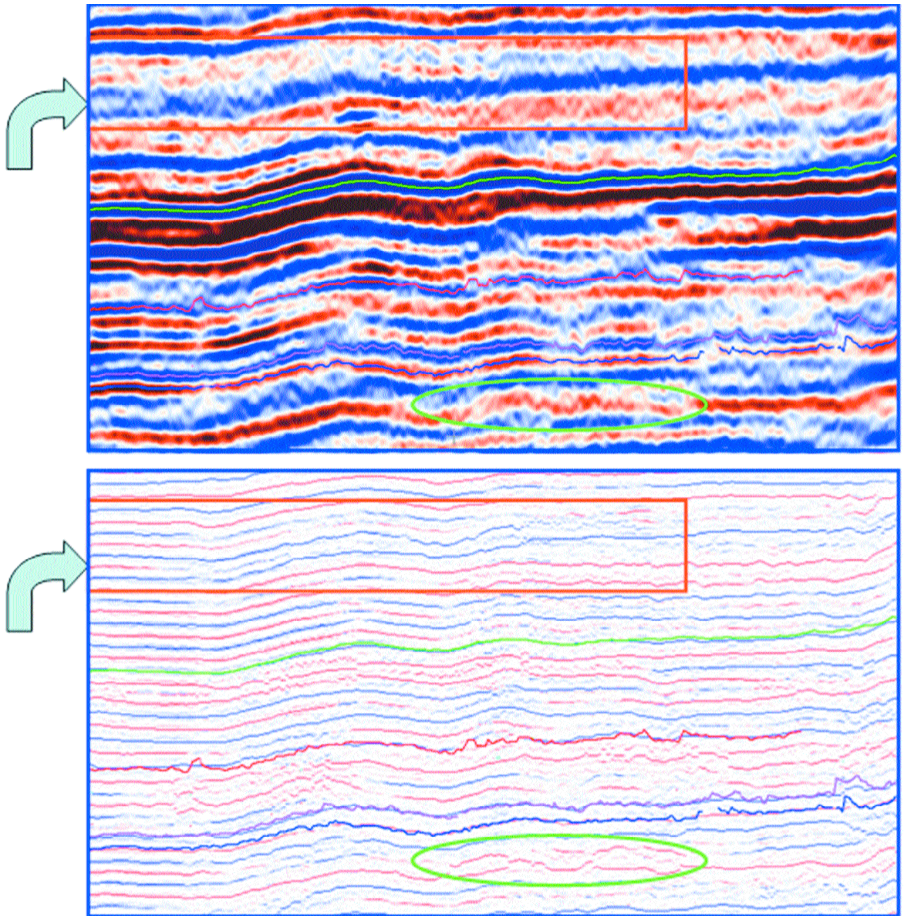

Figure 7. Shows a comparison of the band-limited seismic section (above) with the derived thin-bed reflectivity (below). The feature of interest is a pinch out on the reflection indicated with the arrows on the left. While this reflection is seen as single and continuous across the section, the reflectivity indicates the pinch out clearly in the middle of the section. Also notice the resolution of the feature in the lower highlighted zone.

Seismic input　　　　Thin-bed reflectivity

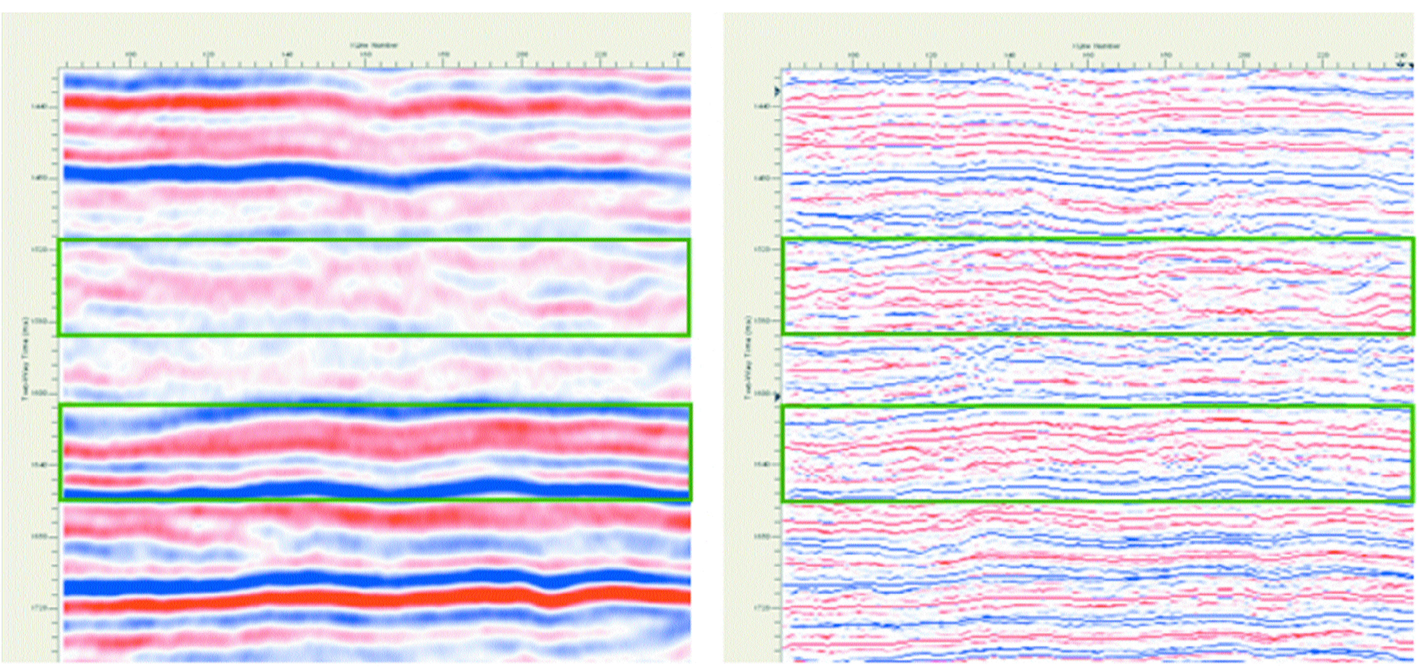

Figure 8. shows a comparison of the band-limited seismic section with the derived reflectivity section. The display contrast for the reflectivity has been enhanced purposely to bring out the resolution detail that can be seen.

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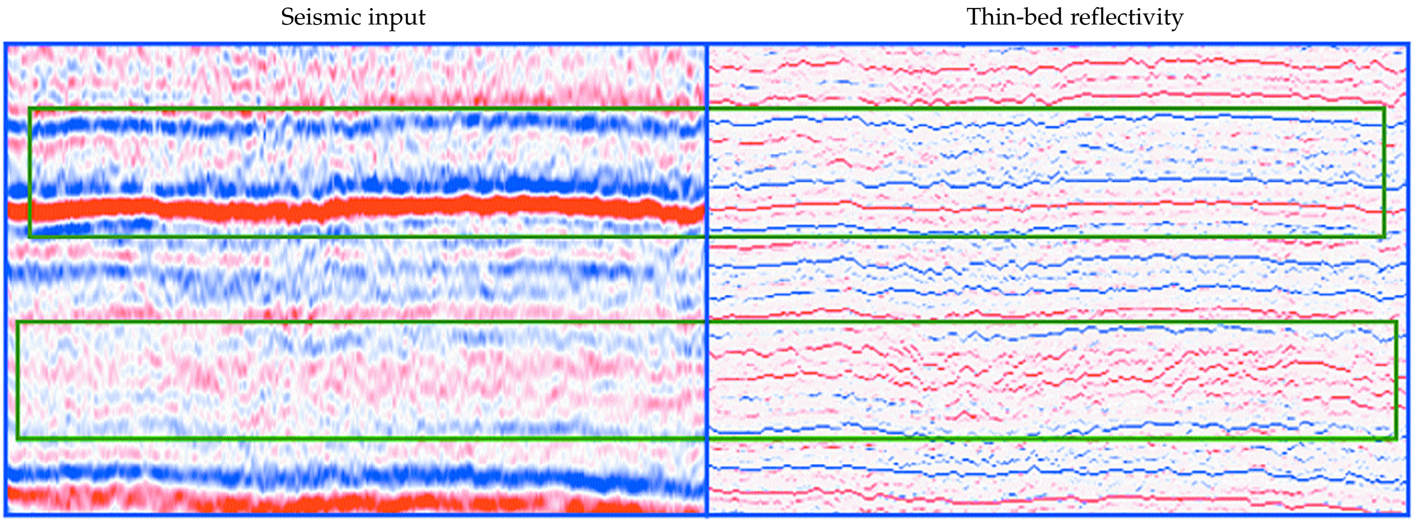

Figure 9. Shows a comparison on a noisy seismic section (left) and its derived reflectivity section (right). The thin-bed inversion process is robust enough to handle moderate levels of noise. However, for higher noise levels the performance of the inversion can deteriorate.

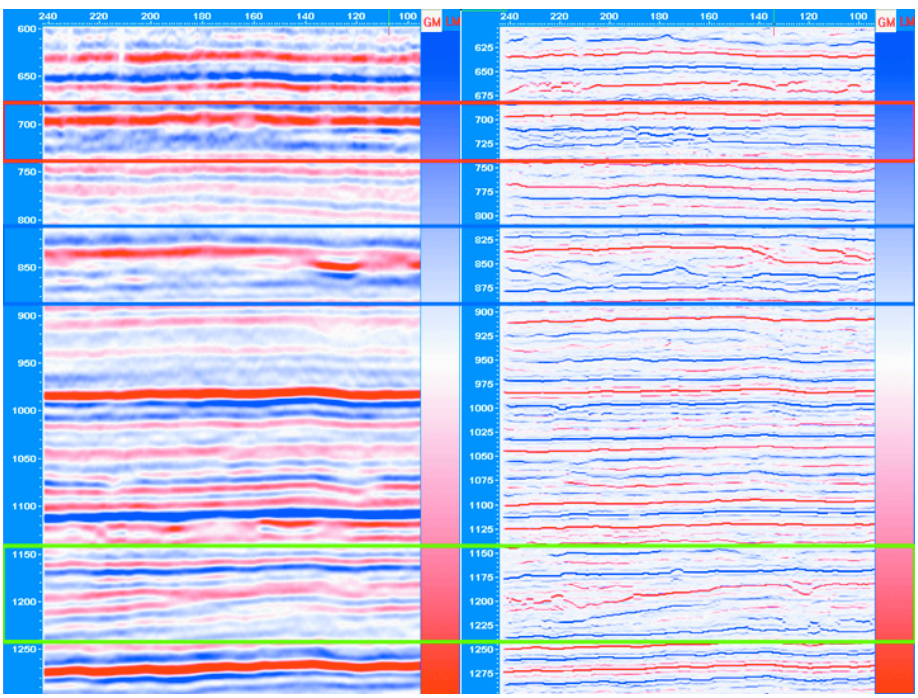

Figure 10. Shows a comparison of the conventional seismic section (left) with its derived thin-bed reflectivity (right). Notice the resolution detail in the highlighted zones.

abundance of reflection detail can be beneficial to the seismic interpretation in many ways – from showing an accurate correlation with log curves, getting reflection detail that throws light on the subsurface geologic model for the area, to helping make an accurate seismic interpretation on the workstation.

The quality of the final reflectivity section has a strong bearing on the quality of data going into the inversion process. Though usually the final data volumes being interpreted on the workstation (for 3-D seismic data) are the input to the inversion process, it is important that the data be free of any coherent noise patterns. Figure 9 shows a seismic section infested with vertically inclined noise patterns. While the reflectivity section depicts the main reflection trains extracted clearly from the welter of noise, some of the weaker ones do show up as choppy (in the highlighted area). In contrast to this, in Figure 7 the reflections look nice and continuous and so the reflection coefficients, even the weaker ones also appear to be continuous and focused. It is therefore imperative to ensure the quality of the data going into the inversion process, for optimum reflectivity results.

Figure 10 again shows another comparison where the thin-bed reflectivity section shows a lot more promising detail than is obvious on the seismic section.

Interpretation of seismic data is usually carried out on vertical profiles (inlines and crosslines) in preference to time or horizon slices. Correlation of top and base of thin layers with their respective changes on log curves could be time consuming and laborious, especially if there is an abundance of thin layers to be correlated. A way out of this problem is to integrate the thin-bed inverted reflectivity to produce a band-limited impedance estimate (coloured inversion) that is unbiased by existing well information. Such displays are useful for correlating the different horizon intervals corresponding to subsurface rock intervals with the individual litho-units interpreted on log curves. Time or horizon slices from impedance volumes serve as useful displays for stratigraphic differentiation of different strata. Figure 11 shows equivalent strat-slices from (a) the seismic volume, (b) thin-bed reflectivity volume and (c) coloured inversion (impedance) volume. Noticeably, the very fine detail on thin-bed reflectivity strat-slice does not appear to help infer geology from it. The thin-bed impedance strat-slice shows the features with much better clarity in their definition and so prove advantageous.

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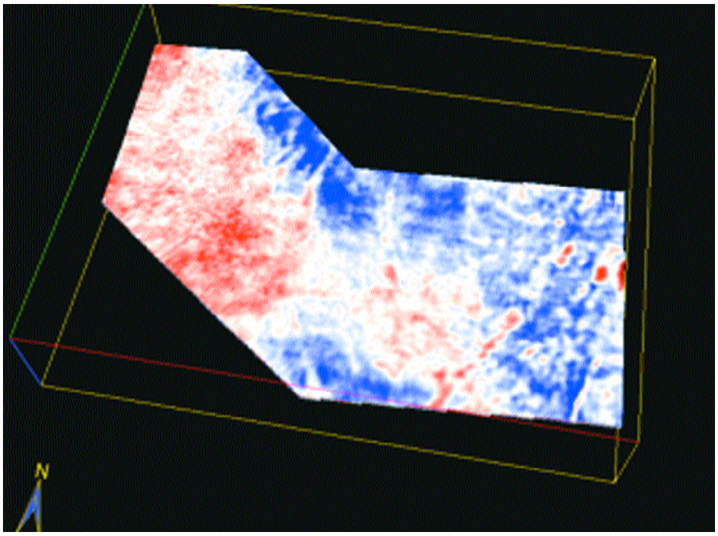
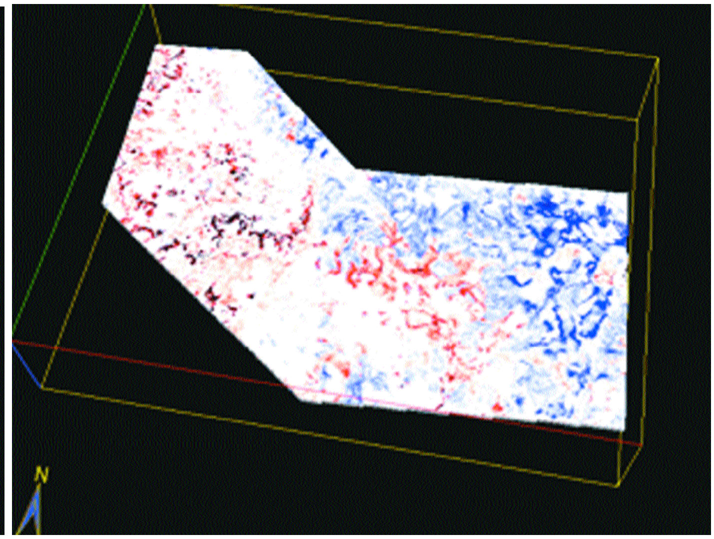
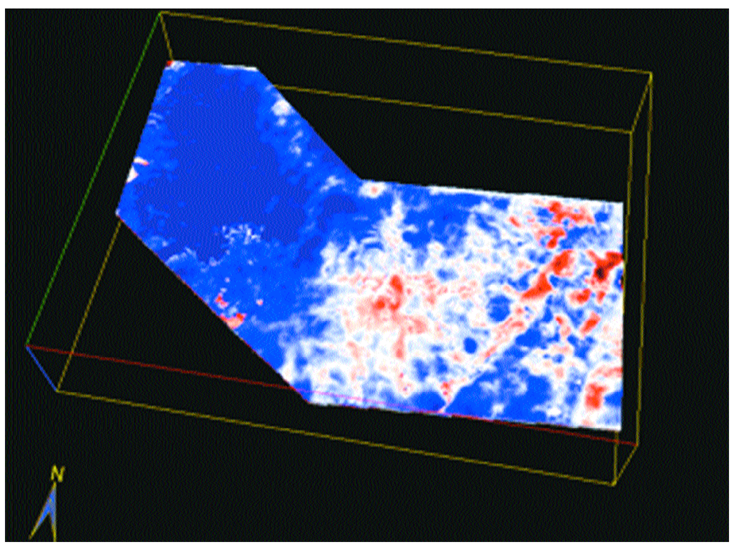


Seismic



Thin-bed reflectivity

Figure 11. Strat-slices from the band-limited seismic, thin-bed reflectivity and colored inversion run on thin-bed reflectivity. Features can be seen with a better definition and clarity on such slices.



Coloured inversion on thin-bed reflectivity

Conclusions

The thin-bed spectral inversion method discussed here is a novel way of removing the wavelet from the seismic data and extracting reflectivity. For data with high signal-to-noise ratio, 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 is very useful for making accurate interpretations and proves to be advantageous in many ways. *R*

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