

Simple net pay estimation from seismic: a modelling study

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Abstract

Amplitude scaling techniques are a simple way of removing the effect of tuning on seismic maps and predicting net pay thickness in low-impedance hydrocarbon-bearing sands. This modelling study addresses net pay prediction in layered sand/shale reservoirs using reflectivity and band-limited impedance approaches. It is demonstrated that net pay prediction using band-limited impedance is more accurate than reflectivity. These techniques, however, are only appropriate in specific geological circumstances. Prior to application, it is advisable to evaluate potential accuracy through modelling as well as to consider the benefit of amplitude-versus-offset projections.

Introduction

Seismically thin hydrocarbon accumulations within basin-fill sequences are commonly evident as bright spots, i.e., high amplitude composite seismic reflections arising, for example, from the top and base of a gas-bearing zone. Whilst the presence of hydrocarbons is an important factor affecting the amplitude of the bright spot, the overprint of thickness variations means that the amplitudes are not direct indicators of pay thickness and should not be relied upon in isolation as indications of where to drill. Thus the interpreter needs to take account of the thickness effects on amplitude, make a reasonably accurate estimation of the hydrocarbon volume in place, and determine appropriate 'sweet-spot' locations for drilling. The context of this paper is to discuss the problem with reference to amplitude scaling approaches that the interpreter may be able to apply relatively quickly. Note that, for the sake of simplicity, all the models presented contain zero-phase wavelets, and issues associated with uncertainty in the wavelet phase are not addressed.

Simple wedge model

The simple wedge model (Figure 1a) is a well known description of the interference effects related to the top and base of a low-impedance sandstone encased in shale. A zero-phase wavelet (Figure 1b) has been used in the creation of the reflection model. For this type of model Widess (1973) pointed out that, when the sand is very thin, estimating its thickness from the separation of trough and peak seismic loops will result in a significant overestimate. However, the thinning of the wedge does affect seismic amplitude.

The tuning curves in Figure 1c show how the trough-to-peak composite amplitude changes with actual sand thickness, in two-way time, and with apparent sand thickness defined as the trough-to-peak time separation. The amplitude plot-

ted is the composite amplitude, i.e., the combined absolute amplitude of the trough and the peak. It is evident that the character of the tuning curve is related to the shape of the wavelet, with the tuning curve for amplitude versus actual thickness (Figure 1c) having the shape of a wavelet half cycle (cf. Figure 1b). The amplitude tuning curve is a maximum at the sand thickness below which the peak and trough separation remains constant. This is commonly referred to as the 'tuning thickness'. Below the tuning thickness, the amplitude decreases in response to the thinning sand. A comparison of Figure 1c and d indicates that, for a limited range of thicknesses above tuning thickness, estimating sand thickness using trough-to-peak separation would result in a slight underestimate.

Given these interference effects, how can thickness be accurately determined from seismic data? In the case of isolated units of clean sand, the simple tuning curve from the wedge model could be used as a scalar to back out the thickness from the seismic amplitude and apparent thickness, provided that the wavelet is known. In practice, sands are rarely clean homogenous units. Sandstone reservoir net-to-gross (N:G) can vary with the presence of shale and possibly with the presence of other lithologies, but it can also be related to the presence of layering, i.e., interbeds of sand and shale. With simple net pay estimation as the focus, the following discussion will concentrate on the effects of sand/shale layering.

Net pay from reflectivity

Early modelling work on 'thin-bed' reservoirs (i.e., those below tuning thickness) comprising varying thicknesses of sand and shale was conducted, amongst others, by Meckel and Nath (1977) and Schramm et al. (1977). From simple reflection models they concluded that for thin zones the

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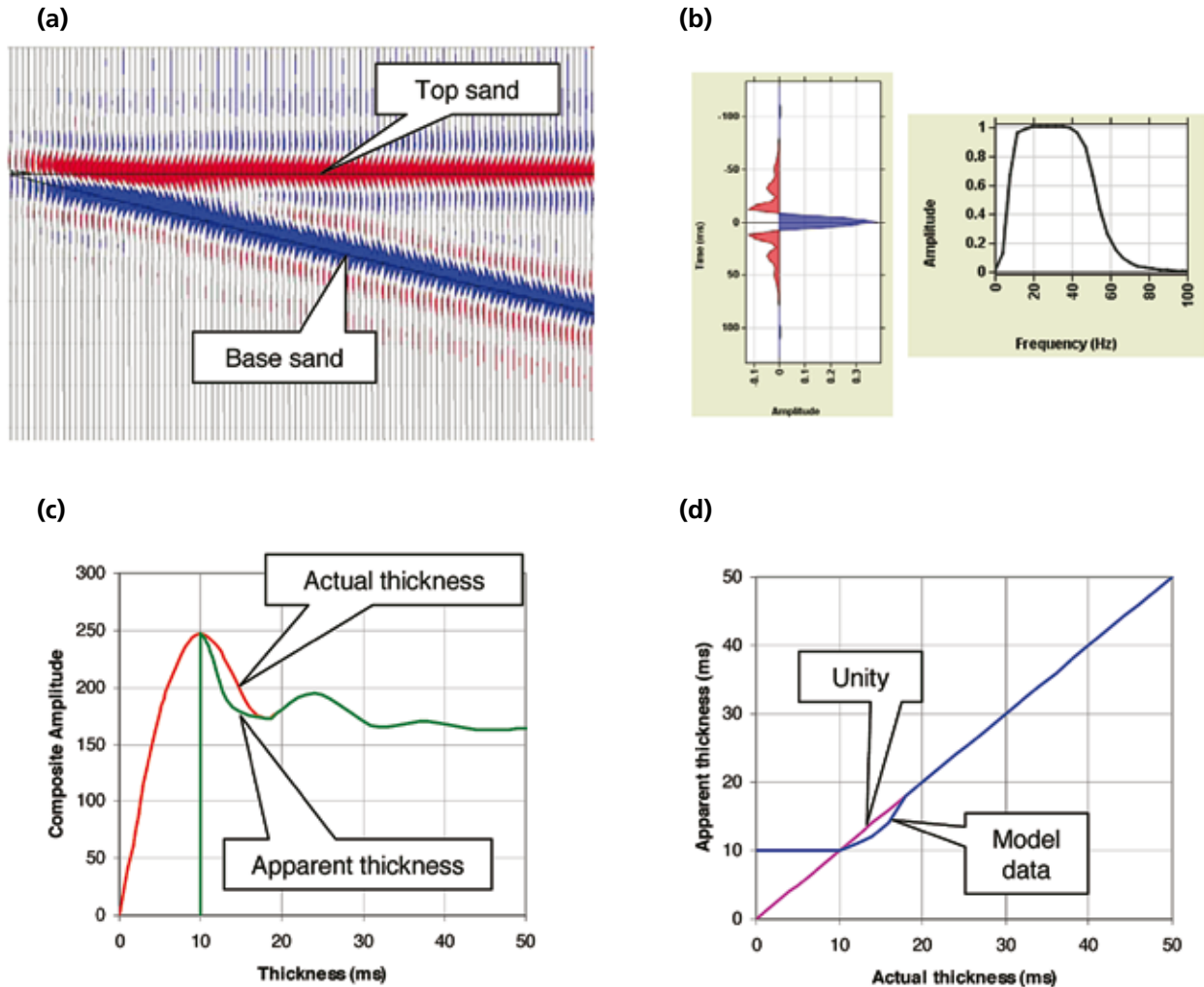


Figure 1 Simple wedge model: (a) 2D reflectivity display; (b) typical processed seismic wavelet (SEG positive standard polarity – downward increase in impedance is positive number = peak, with trough coloured red and peak coloured blue); (c) crossplot of thickness versus composite amplitude; and (d) actual thickness versus apparent thickness.

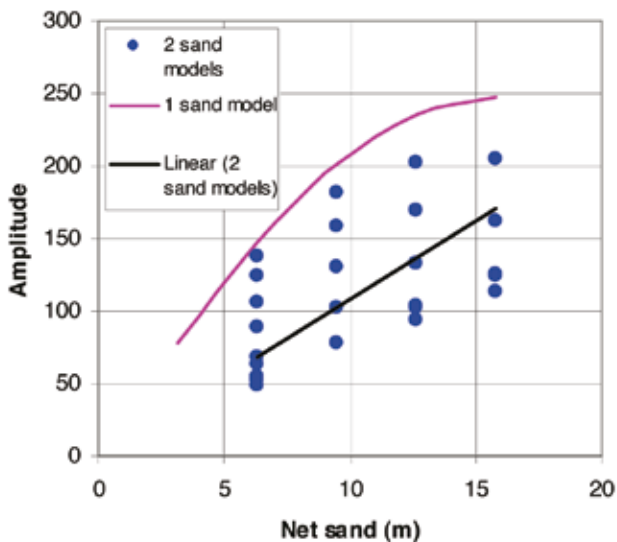


Figure 2 Results for five-layer reflection model with two sand layers. Points shown are for models where the gross thickness is less than the tuning thickness.

composite amplitude is roughly linear with changing net thickness of sand. To illustrate this, and to investigate whether the relationship is dependent on the layering, numerous reflection models have been created using five layers (two sand layers of equal thickness and three shale layers) together with the wavelet shown in Figure 1 and a primaries-only convolutional model. The thicknesses of the sands have been varied between 6 m and 32 m and the middle shale unit varied from 2 m to 16 m. Thin-bed responses from these models are shown in Figure 2. Whilst there is a first order trend of net sand with amplitude, there is a large scatter dependent on the nature of the layering. If the amplitude was used to predict net sand (i.e., using the linear trend marked on the plot) the points above the line would be overestimated, by up to 100%, whereas below the line they would be underestimated, by up to 30%. In a given geological scenario it is unlikely that there will be this much variation in the layering, but the potential inaccuracies of the technique are highlighted.

Brown et al. (1984, 1986) introduced a technique which addresses both thin and thick beds (i.e., thicker than tuning thickness). It is based on the similarity of the data cloud outline on the crossplot of composite amplitude versus seismic thickness and the simple single-layer tuning curve derived knowing the wavelet in the data (Figure 3). Implicit in the method is the positioning of the tuning curve to represent the reflectivity of clean sand (i.e., N:G =1) together with the assumption that for any given apparent thickness the ratio of the composite amplitude to the tuning curve amplitude is a measure of the N:G. The tuning curve is positioned on the plot either to encompass the majority of points or to ‘calibrate’ to wells. The blue line in Figure 3 defines a ‘no-tuning’ baseline with constant amplitude above tuning thickness and tending to zero below it. Thus to remove the effect of tuning on a seismic amplitude map a scalar is applied, defined by the no-tuning baseline divided by the tuning curve. Net sand or net pay can be calculated by multiplying the ‘corrected’ amplitude map by the apparent thickness. In practice, this technique becomes error-prone with increasing thickness above tuning, as the seismic amplitude becomes increasingly biased to the rock property contrasts at the top of the wedge and less dependent on the properties of the gross interval.

The method of Brown et al. (1984, 1986) has been investigated using the model dataset described earlier. The results for both thin and thick beds are shown in Figure 4, together with the clean sand tuning curve. It is evident that, in the presence of layering, the simple tuning curve may not represent an upper bound. For example, a second maximum is evident, related to the presence of two sands close to tuning thickness which are separated by a thin shale. Figure 5 illustrates the predicted versus actual values of N:G using the approach of Brown et al. (1984, 1986). (Note that the data points above the tuning curve in Figure 5 would give N:G values greater than 1 and have therefore been reduced to conform to the tuning curve before net calculation). The technique performs reasonably well except for the data associated with the second maximum, where the predictions are overestimated by 25-100%.

On the basis of these types of results, Neff (1990a, 1990b, 1993) considered the amplitude scaling method of Brown et al. (1984, 1986) to be an oversimplification. He highlighted the fact that the relationships between trough-to-peak amplitudes, isochrones, and reservoir parameters may not only be complex but also may vary significantly between different geological scenarios. Forward modelling, informed by a local understanding of the key petrophysical and rock physics variables, is the key to transforming seismic isochron/amplitude data to relevant reservoir property predictions. He subsequently proposed a graphical transform technique in which extensive forward modelling results are used to establish a calibration template for prediction of reservoir parameters. Recently, Fervari and Luoni (2006) have also used this type of technique. The natural progression of these ideas is the use of forward modelling for inversion (e.g., Burge and Neff, 1998; Spikes et al., 2008).

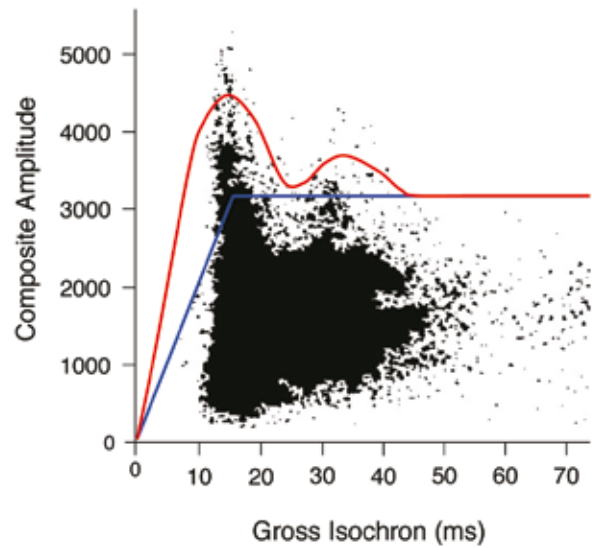


Figure 3 Seismic crossplot example of thickness versus composite amplitude with simple tuning curve (red) and baseline (blue). Redrawn from Brown et al. (1986).

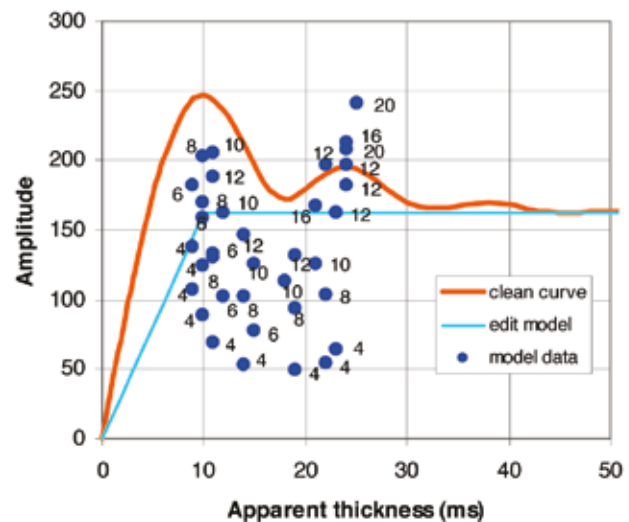


Figure 4 Results for five-layer reflection model with two sand layers. Gross thickness ranges from below to above tuning thickness. Annotation numbers are actual pay thicknesses in milliseconds.

Net pay from band-limited impedance

Of course, sophisticated solutions to the net pay problem are appropriate when reliable well data are available. The question arises as to how to handle exploration situations with little or no well control. Recently, Connolly (2005, 2007) presented a map-based amplitude scaling technique based on band-limited impedance through coloured inversion (Lancaster and Whitcombe, 2000). Thus, it is based on an interval attribute rather than an amplitude measurement from two reflecting boundaries.

The coloured inversion of the wedge model in Figure 1 is shown in Figure 6. An acoustic impedance model has been convolved with a wavelet consistent with the spectral characteristics typical of coloured inversion operators. Connolly’s

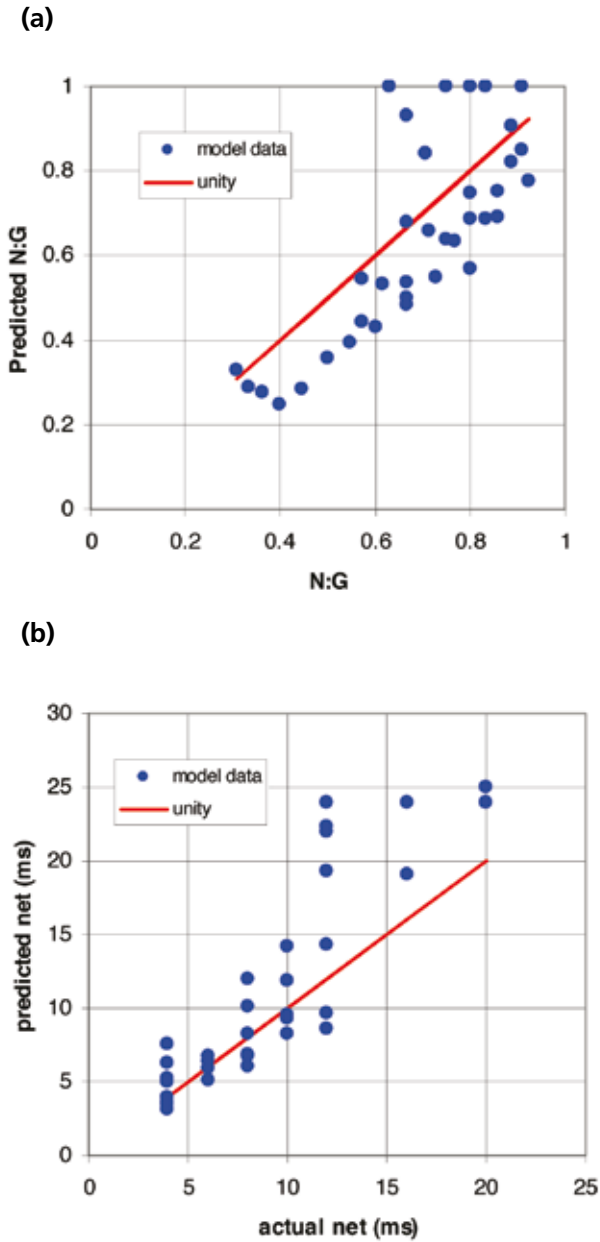


Figure 5 Prediction technique of Brown et al. (1986) applied to five-layer reflection model data: (a) N:G; and (b) net pay thickness (ms).

(2007) method utilizes the apparent thickness and average band-limited impedance measured between zero-crossing picks. Figure 7a shows the band-limited impedance tuning curve for the simple wedge model.

To describe the essence of Connolly's (2007) technique, the starting point is the net pay formula:

$$\text{Net pay thickness} = \text{N:G} \times \text{Gross thickness.} \quad (1)$$

To apply this to the wedge model data, Connolly introduces the concept of Seismic N:G, where

$$\text{Seismic N:G} = \text{Net pay thickness} \div \text{Apparent thickness.} \quad (2)$$

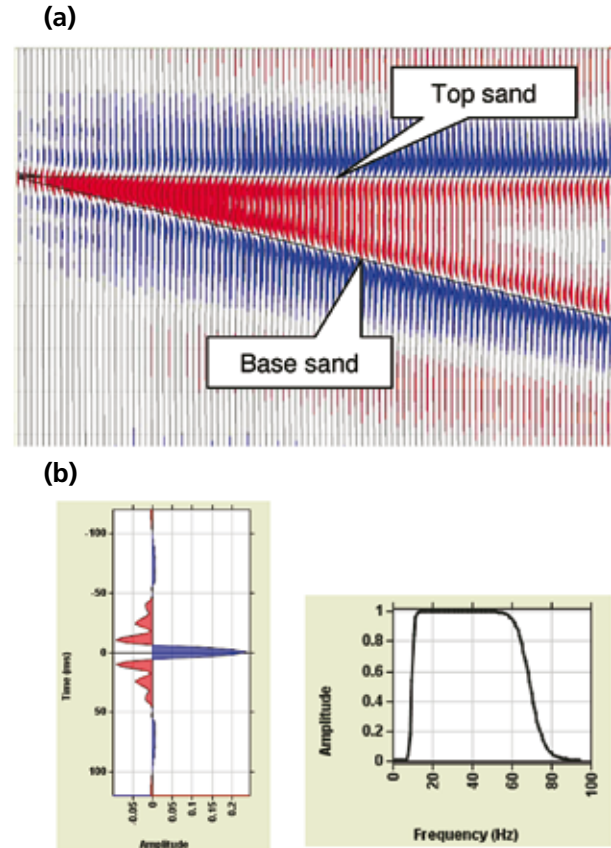


Figure 6 Coloured inversion for the simple wedge model: (a) band-limited impedance; and (b) trapezoidal wavelet typical of coloured inversion spectral shaping.

Thus, the modification of the net pay formula in Equation (1) becomes:

$$\text{Net pay thickness} = \text{Seismic N:G} \times \text{Apparent thickness.} \quad (3)$$

Figure 7b illustrates the Seismic N:G of the wedge model. For Equation (3) to be applied to seismic data, Seismic N:G needs to be related to the band-limited impedance. After investigating a number of interval attributes, Connolly et al. (2002) and Connolly (2005) determined that Seismic N:G varies more or less linearly with average band-limited impedance (ABLI) for a given apparent thickness. Thus the net pay equation becomes:

$$\text{Net pay thickness} = \text{Scalar} \times \text{ABLI} \times \text{apparent thickness,} \quad (4)$$

where

$$\text{Scalar} = \text{Seismic N:G} \div \text{ABLI.} \quad (5)$$

The scalar varies with apparent thickness (Figure 7c) and is related to the wavelet implicit in the band-limited impedance, i.e., the time integral of the operator applied to the seismic data. In practice, Equation (4) can be used to predict net pay thickness from seismic map data once the scalar

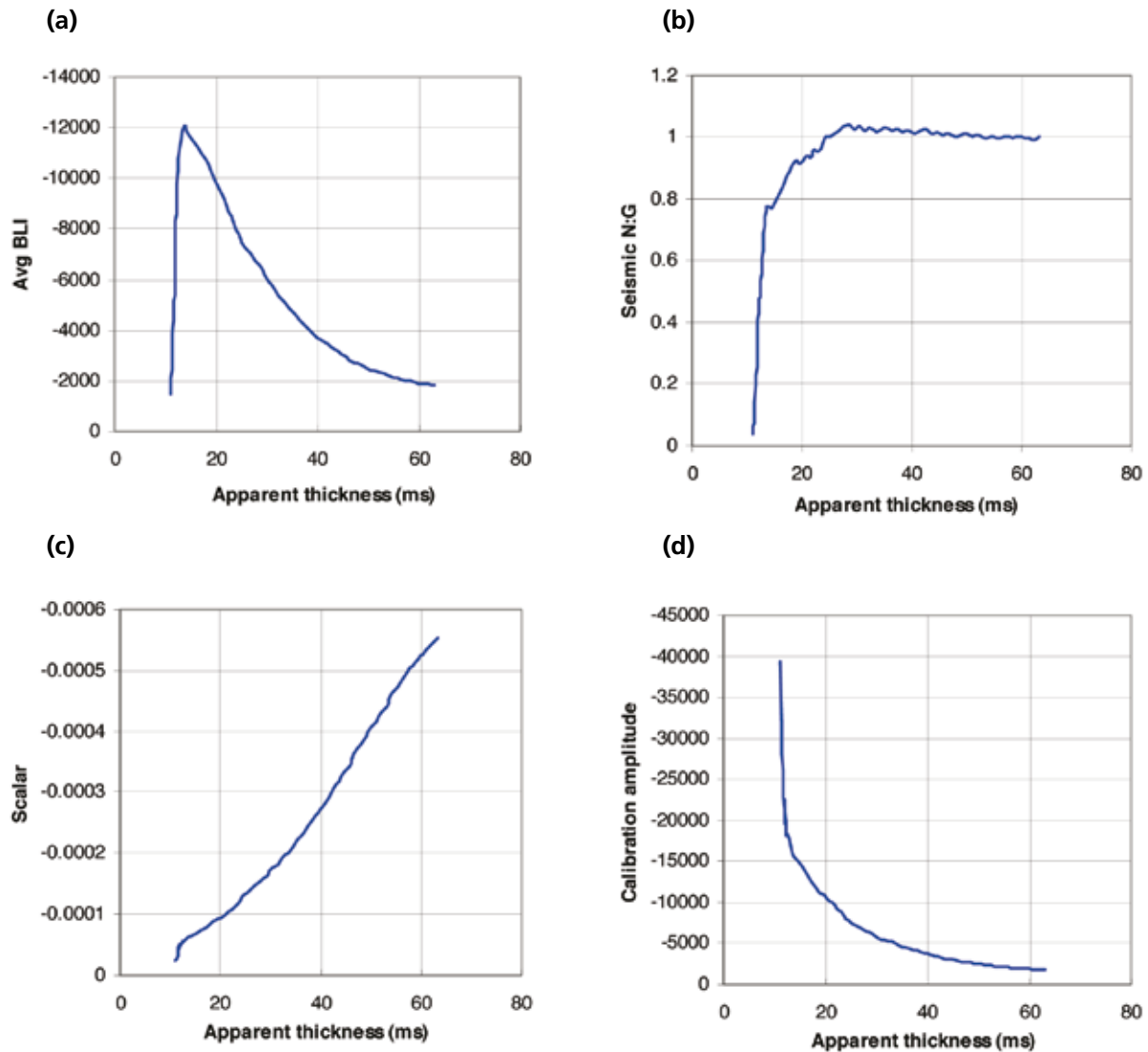


Figure 7 Coloured inversion for the simple wedge model – crossplots versus apparent thickness of (a) average band-limited impedance; (b) seismic N:G; (c) scalar; and (d) calibration amplitude.

function has been calibrated to well data. Calibration is done by interactively scaling the amplitudes of the wedge model tuning curve so that the predicted net pay thickness matches the net pay thickness in the wells.

Another way of thinking about the scalar is to consider its inverse, the ‘calibration amplitude’ such that

$$ABLI \div \text{calibration amplitude} = \text{Seismic N:G.} \tag{6}$$

The calibration amplitude curve can be plotted (Figure 7d) and this plot can help us to appreciate the nature of the scaling issue in predicting net pay.

To illustrate how the net pay prediction technique works, a model was generated using data based on a real field example (Figure 8), including both thin and thick layering situations. The model comprises gas sands and shale, in which the acoustic properties are held constant between the wells, and there

are no hydrocarbon contacts. Contact effects on net pay prediction are addressed later in the paper. For each of the model wells, apparent thickness and average band-limited impedance were calculated. The function Scalar in Equation (4) for net pay prediction was then calibrated as described above. The model results (Figure 9) show a good level of accuracy, with a standard deviation of 1.48 ms, essentially illustrating the validity of Connolly’s (2007) net pay approach.

In order to compare this result with the reflectivity approach, the model dataset was convolved with a low frequency wavelet such that all model well thicknesses were below tuning thickness. Figure 10a illustrates that the composite amplitude is roughly linear with actual net pay thickness. Linearly transforming the composite amplitude to predict net pay thickness (Figure 10b) gives a result which is inferior to the band-limited approach, with a standard deviation of 2.72 ms.

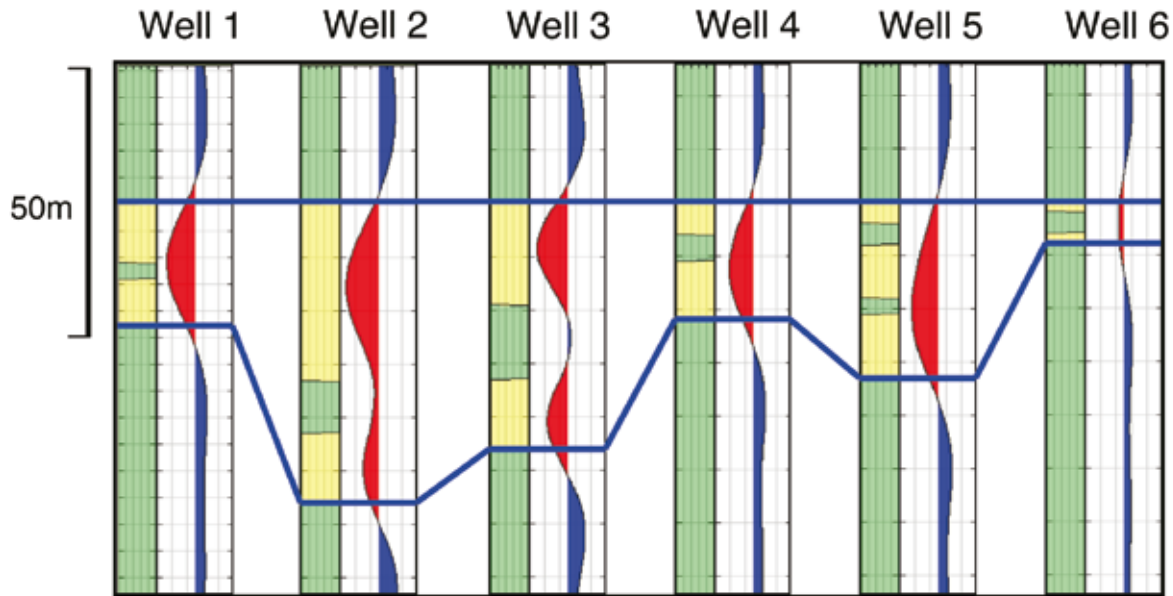


Figure 8 Model well dataset. Yellow = sand, green=shale. All sands and shales have constant properties. The synthetic trace is band-limited impedance using the wavelet shown in Figure 6b.

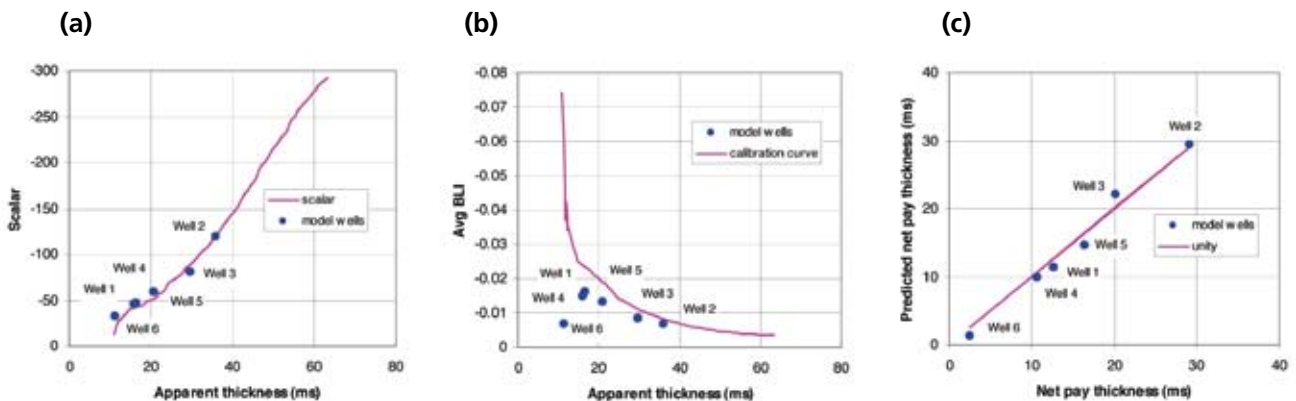


Figure 9 Net pay thickness prediction using Connolly's (2007) technique for the model well dataset: (a) calibrated scalar; (b) calibration amplitude; and (c) actual versus predicted net pay thickness (ms).

In practice, if there are wells available to generate the coloured inversion operator but there are no pay values to guide the fitting, the calibration curve would be positioned by eye above the data points on the crossplot of average band-limited impedance versus seismic thickness. Connolly et al. (2002) refer to this procedure as 'self calibration'. If the curve is positioned close to the main cluster of data points, it is likely that net pay will be over-predicted, because thick clean sandstones are relatively rare. However, the relative sense of predicted net pay variation would be correct.

An interesting simplification of Connolly's (2007) technique is to assume that the scalar is linear. A linear scalar describes a calibration amplitude curve which is defined by:

$$\text{Calibration amplitude} = \text{constant} \div \text{apparent thickness.} \quad (7)$$

Substituting Equations (6) and (7) into Equation (4) gives:

$$\text{Net pay} = (\text{ABLI} \times \text{apparent thickness}^2) \div \text{constant.} \quad (8)$$

Figure 11 illustrates that the simplification works quite well with the model dataset for apparent thicknesses of less than 30 ms. However, at greater thicknesses (e.g., at well 2), the linear scalar assumption progressively underestimates net pay. The simplification may be useful in areas where there are no wells or where the seismic data have relatively low bandwidth because lowering bandwidth tends to make the scalar more linear.

The successful implementation of Connolly's (2007) technique will in practice depend on a number of geological and data factors, the prime requirements being:

- 1) There is bipolar geology in which sands have one impedance and shales have another.
- 2) The sands have lower impedance than the shales.
- 3) There is no interference between the reservoir and events above or below.

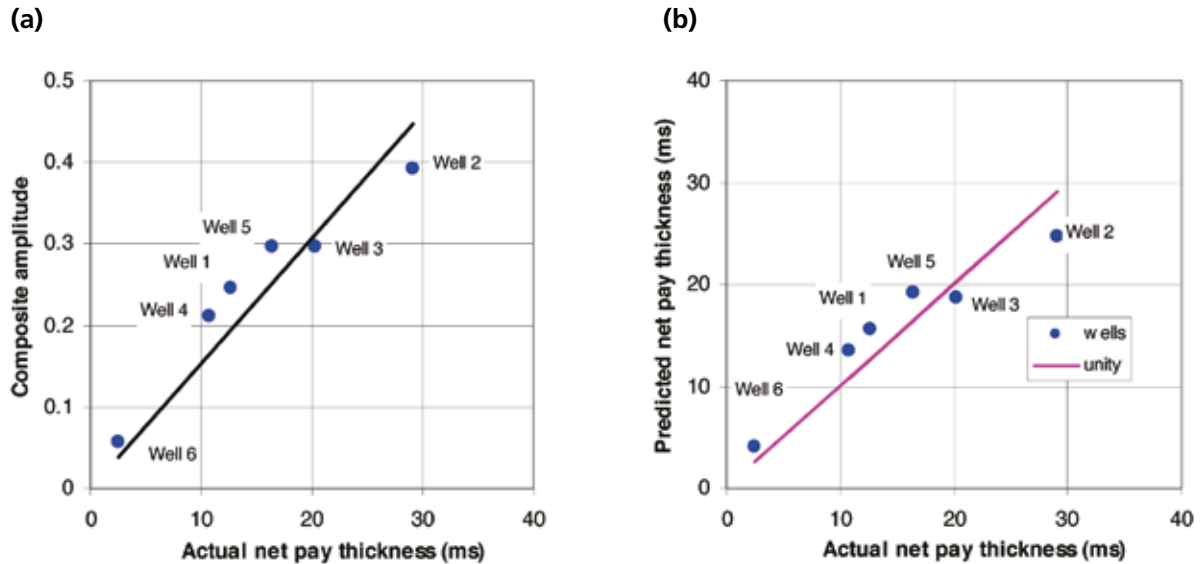


Figure 10 Net pay prediction using low frequency reflectivity for the model well dataset: (a) relationship between amplitude and net pay (ms); and (b) actual net pay thickness (ms) versus net pay thickness (ms) predicted from linear amplitude scalar.

- 4) The zero-crossing picks are clear. Calculation of the average band-limited impedance is highly sensitive to picking accuracy (P. Connolly, pers. comm.)
- 5) There is a single hydrocarbon phase.
- 6) The thickness of the reservoir is no greater than a half cycle of the lowest frequency component, e.g., 60 ms at 8 Hz low cut frequency (Connolly, 2007).
- 7) The relationship between N:G and bandlimited impedance is straightforward.

Errors may result when the fluid or lithology elements deviate from these assumptions. Connolly and Kemper (2007) have presented a workflow to estimate the net pay uncertainty owing to geological variation. Of course, the lateral and vertical fidelity of seismic amplitude will also be a critical issue in the accuracy of the technique.

Amplitude-versus-offset effects

Another issue that the interpreter needs to consider in net pay prediction of thin-bed responses is amplitude-versus-offset (AVO). Figure 12a shows that the AVO style for the model dataset is Class IV (Castagna and Swan, 1997). Both shale/brine sand and shale/gas sand interfaces have negative reflection coefficients reducing in magnitude with increasing angle. A problem for net pay estimation using conventional stacks with this type of reflectivity is that pay will be predicted from the negative amplitudes in the brine zone. In order to address this problem and to define the edge of the field use can be made of AVO techniques.

By using two-term AVO projections it is possible to generate pseudo-seismic sections that reduce the reflectivity of the wet sands, whilst maintaining the negative reflectivity of the gas sands, i.e., ‘tune’ the seismic image to maximize fluid content information (Whitcombe et

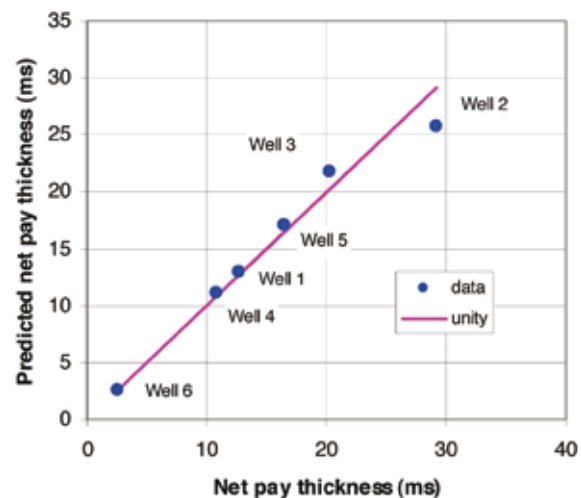


Figure 11 Net pay thickness prediction using Connolly's (2007) technique for the model well dataset with a linear scalar.

al., 2002). To visualize the idea of projections in AVO discrimination, the data are plotted on the AVO crossplot of intercept, R_0 , versus gradient, G (Figure 12b), so that each response on the AVO plot (Figure 12a) now becomes a single point. By drawing a line through the origin to the brine point in Figure 12b and measuring the angle with the vertical, the fluid projection angle, χ , is calculated to be 45°. The reflectivity projection can be calculated using

$$R_c = R_0 \cos \chi + G \sin \chi, \tag{9}$$

a modified form of Shuey's (1985) equation (Whitcombe et al., 2002). To create a 2D model with band-limited impedance at the fluid angle, use is made of the extended elastic impedance (EEI) concept (Whitcombe et al., 2002), where

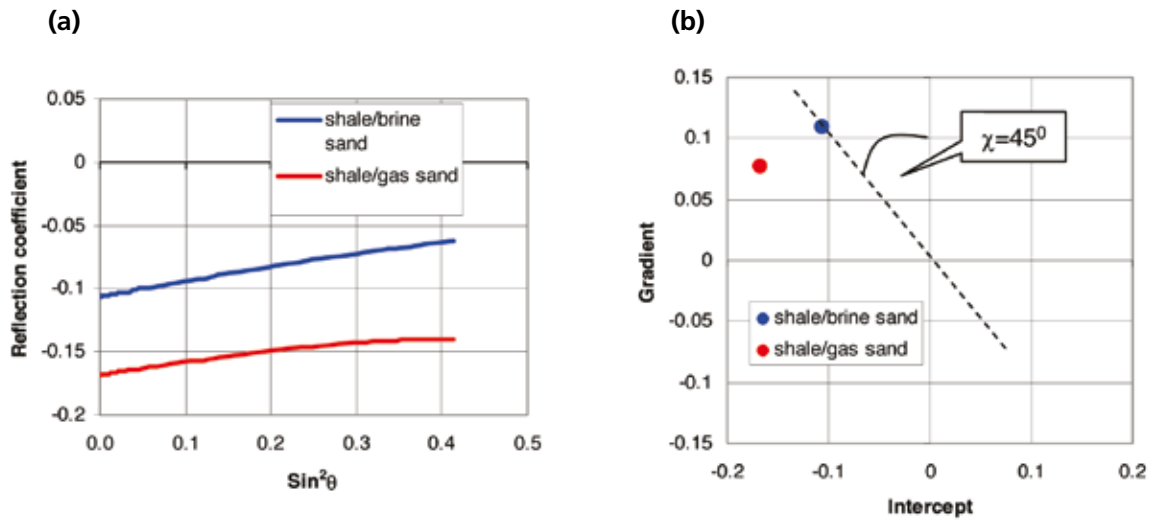


Figure 12 First order AVO response for the model well dataset: (a) AVO plot; and (b) AVO crossplot.

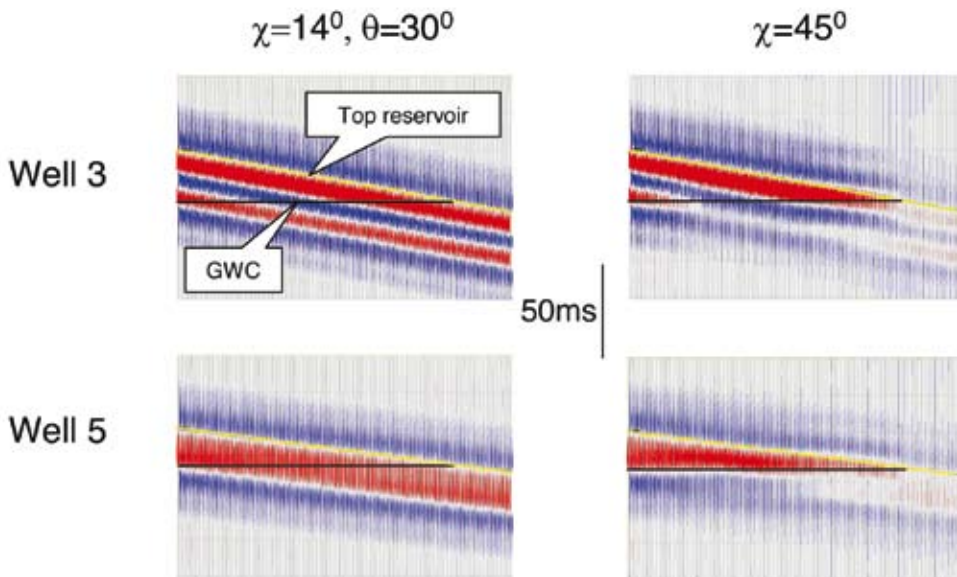


Figure 13 2D models based on model wells 3 and 5 for the model well dataset, illustrating the use of two-term AVO in defining optimum fluid band-limited impedance signature.

EEI is the impedance derivative of the projected reflectivity. The extended elastic impedance is then convolved with the wavelet in Figure 6b to generate the band-limited impedance model.

Hydrocarbon wedge models using two of the model wells are shown in Figure 13: well 3 with layering above seismic resolution, and well 5 with layering below seismic resolution. Two sections are shown for each model to illustrate the effect of the projection in comparison to conventional stack seismic sections. The first section is for typical far-offset seismic data where the effective angle of incidence, θ , is 30° . Given that $\chi = \sin^2 \theta$ (Whitcombe et al., 2002), this is equivalent to a projection at $\chi = 14^\circ$. The other section is calculated at the fluid projection angle, $\chi = 45^\circ$. On the far-offset model, the contact effect is indistinct whereas the fluid projection shows distinct termination of band-limited impedance at the gas-water contact.

Whilst the use of AVO in this way can help in defining the edge of the field and optimize the net pay estimation, it should be noted that the seismic angle at which the optimum fluid response is evident is usually less than that derived from logs. This is due principally to the effects of random noise (Simm et al., 2000). In practice, the fluid angle projection is arrived at by trial and error (Connolly et al., 2002).

Figure 14 illustrates the sensitivity of the net pay prediction in the model to the presence of contacts. For each model well, multiple band-limited impedance traces have been generated simulating increasing thicknesses of pay. Using picks at the top and base of the reservoir unit (Figure 14a), net pay has been predicted using the calibrated scalar shown in Figure 9. It is evident that the presence of contacts may introduce errors into the net pay prediction (Figure 14b).

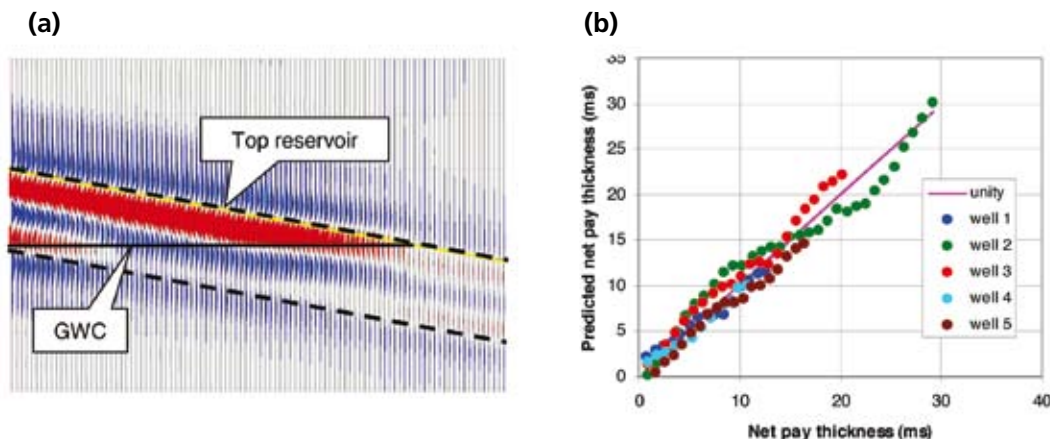


Figure 14 Effect of contact presence on net pay thickness prediction for the model well dataset: (a) 2D model example showing contact effect and model picks (dashed lines); and (b) net pay thickness prediction using 2D model traces from each model well.

Depending on the nature of the layering and the pay thickness, net pay thickness may be under or overestimated with percentage errors increasing with decreasing thickness. At around 10 ms net pay thickness, the modelled error is about $\pm 30\%$ whereas at 20 ms it is $\pm 15\%$.

Conclusions

This modelling study has demonstrated that in terms of simple amplitude-scaling techniques for net pay estimation from seismic, the band-limited impedance technique of Connolly (2007) is a significant improvement on the reflectivity based techniques of Brown et al. (1984,1986) and others. Interpreters need to be mindful that these techniques are only applicable to simple geological environments and should, if possible, evaluate their potential accuracy through forward modelling prior to application.

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