Predicting stratigraphy with spectral decomposition

Matt Hall and Eric Trouillot, Landmark Graphics, Calgary, Canada

2004 CSEG National Convention

Introduction

Interpretation of subsurface geology is greatly enhanced by 3-D seismic data, and this accounts for its ubiquity in today's search for hydrocarbons. Seismic interpretation has two fundamental disciplines at its core: seismic geomorphology and seismic stratigraphy. Plan views allow the explorationist to apply principles of geomorphology, based on analogies with modern sedimentary systems, to interpret depositional environments and even predict facies distributions. On the other hand, section views require stratigraphic interpretation and help determine stratal architecture and the temporal development of the depositional system. Both approaches give insight into the geological processes that formed the hydrocarbon play (eg Posamentier 2003). This paper explores a technique to take this insight to deeper levels.

Spectral decomposition unravels the seismic signal into its constituent frequencies. This allows the interpreter to see amplitude and phase tuned to specific wavelengths, just as a radio can pick out a single station, or a prism a single colour. Since the stratigraphy resonates at wavelengths dependent on the bedding thickness, the interpreter can not only image subtle thickness variations and discontinuities, but also accurately predict bedding thickness quantitatively (eg Partyka 1999). In addition, since the high-frequency response of a reflector can be attenuated by the presence of compressible fluids, spectral decomposition can also assist in the direct detection of hydrocarbons (eg Castagna et al. 2003). These approaches, applied alone to a seismic dataset, can be very enlightening but the results can also be somewhat cryptic. Seismic modelling gives the interpreter critical insight into tuned attribute maps, and also allows him or her to predict what a particular bed geometry or thickness trend will look like. Volume visualization and interpretation can enhance the interpretation further still, significantly reducing exploration risk. This paper shows how ordinary interpretation tools give the explorationist the ability to quickly and easily predict and interpret this powerful attribute.

To illustrate this work in progress, we present examples from the Williston Basin and the Western Canadian Sedimentary Basin. In each dataset, three horizons were interpreted with sparse seed lines and an autopicking tool; in each case, all three horizons were finished in under an hour. The horizons were interpolated and smoothed and are used for building a velocity model for depth conversions, and for guiding the attribute extraction algorithms along structure. The idea is to use the minimum amount of time on interpreting horizons, and the maximum amount of time on exploring the more subtle aspects of the data.

Modelling the frequency response

Seismic volumes are complex images of reflections, noise, interference, and tuning effects. It can be difficult to know what to expect a given sandbody or stratigraphic geometry to look like in the seismic, or what a particular seismic reflection pattern represents. Whilst it is tempting–and commonplace–to take the seismic at face value and simply interpret it *de facto*, it often pays to be more rigorous. Seismic modelling can give the interpreter insight into the seismic image, and allow him or her to iterate through many scenarios in order to match a known response, or predict a given geometry. Interpretation can then be made with much more confidence in areas where there is little or no well control. A basic workflow for seismic modelling to illuminate stratigraphic relationships is shown in Figures 1 and 2. Other workflows can help with interpreting lithology variations and fluid content within the reservoir interval.

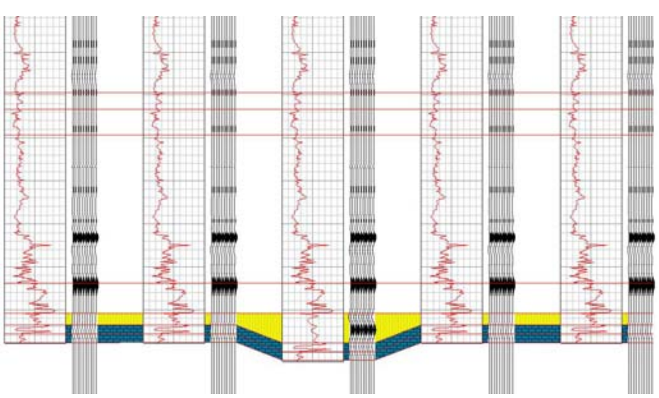

Figure 1. *Resolving the issue of exactly where a sandbody is in the seismic can often be resolved with synthetics. Sometimes, however, even this approach leaves some uncertainty, especailly between the wells. Here we have taken a single well and repeated it in a cross section, displaying the sonic curve and the synthetic for each well. In the centre well we have added about 20 metres of sand thickness. We can now convolve this geological model with a seismic wavelet to generate an interpolated seismic trace model to compare with the real seismic (see Figure 2). Predicting the response at a particular frequency is simply a matter of varying the freuqncy of the wavelet used.*

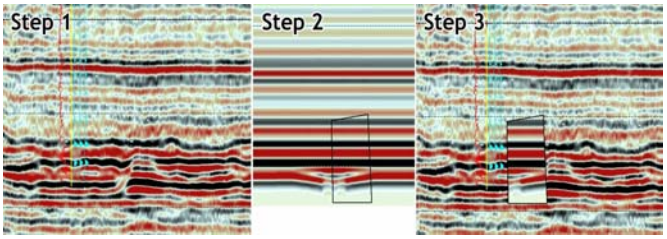

Figure 2. The centre image is the seismic trace model generated from the cross section in Figure 1, using a Ricker wavelet with a peak frequency of 33 Hz and a very narrow bandwidth. The sand wedge the model has created is clearly visible at the centre well. By cropping a part of this model, capturing the sand wedge, and overlaying it on the actual seismic in the zone of interest (step 3), one can match the strong upper reflectors from the model with the strong reflectors on the seismic in the top part of the reservoir. The sand wedge clearly matches the discontinuous seismic reflections, suggesting that the model closely represents the actual geology.

Spectral decomposition of seismic data

Ordinary 3-D seismic data typically has a 60–80 Hz bandwidth, so it contains energy reflected from the subsurface at a wide range of frequencies, all of which are compounded in a typical seismic volume. In certain circumstances, especially subtle stratigraphic plays and areas of low-amplitude faulting, it may be helpful to see the amplitude or phase of reflections at particular frequencies. These tuned amplitudes are directly related to the physical spacing of the acoustic impedance contrasts in the image—often the bedding thicknesses or fault widths (eg Partyka et al., 1999). There are also examples of mapping the attenuation of high-frequency signal by hydrocarbons, allowing their direct detection (eg Castagna et al., 2003). Spectral decomposition analysis allows the explorationist to quantify amplitude variation with frequency, and thereby gain insight into the distribution of stratigraphic entities, faults and fractures, and/or hydrocarbons.

There are three key spectral decomposition workflows. The first is to process a discrete window around a very smooth seismic horizon interpretation, transforming the amplitude or phase data into the frequency domain (in other words, a new volume results, with frequency represented by the z-direction; a typical volume might contain 100 slices, representing amplitude or phase at 1–100 Hz). Such a volume is called a 'tuning cube'. The resulting images (Figure 3) provide a rich and attractive snapshot of subtle reservoir characteristics. While these images alone can be compelling, they can also be difficult to interpret, especially quantitatively. The modelling workflow described above allows the explorationist to interpret the results with more confidence, and even to make quanititative predictions about the reservoir. In particular, fluid substitution modelling can help establish the expected spectral signature, if any, of pay versus wet sands, or gas versus oil.

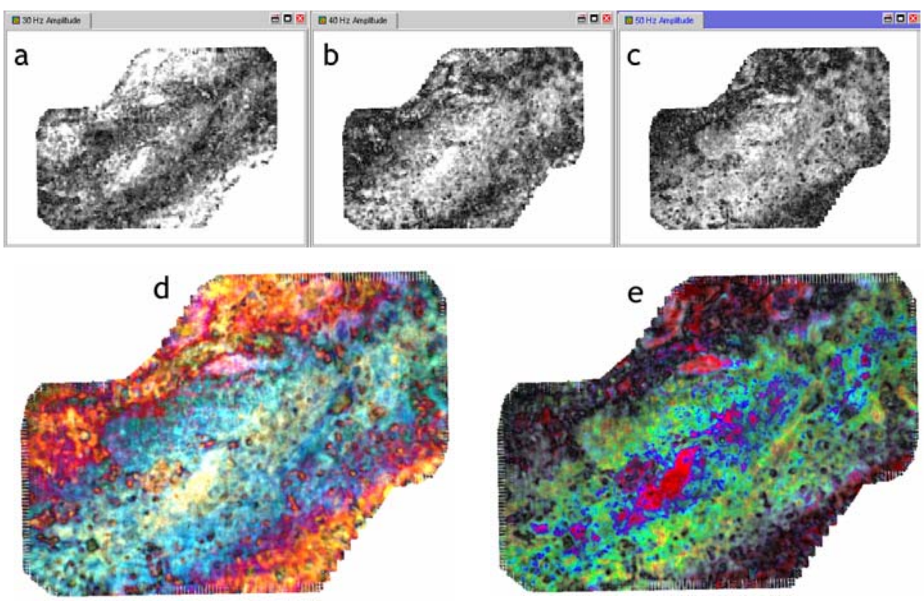

Figure 3. Spectral decomposition analysis. (a)–(c) show amplitude at 30 Hz, 40 Hz and 50 Hz respectively. A bright response is represented by white. (d) is a red-green-blue (RGB) blended image comprising of the individual images above displayed in red, green and blue respectively. The colours are additively combined to produce the full-spectrum image shown. For example, yellow hues indicate that the red (30 Hz) map and the green (40 Hz) map have coincident high amplitude responses in that area. (e) is a hue-saturation-brightness (HSB) blended image. The same three amplitude slices are represented by hue (colour), saturation (colour intensity), and brightness (or colour value) respectively. The images are then combined to give the final map; a bright, saturated red colour indicates that all three frequencies are 'bright' in that area.

The second workflow leaves the data in the time domain, processing the data with a series of time windows (a 'running window'). Typically, a flattened seismic volume is used, with the same guiding horizon as a datum. The result is a flattened volume which is tuned to a specific frequency (as established in the tuning cube workflow). Using a flattened volume gives insight into the geological evolution of the interval, and animating through a tuned volume shows the same reservoir subtleties revealed in the first workflow, but now with the added dimension of geological time. As before, modelling the frequency-dependent reponses of different thicknesses, geometries and fluids significantly enhances the interpretation.

The third workflow gives a valuable quantitative estimation of bedding thickness in the analysis window, without the need for accurate seismic interpretation or phase concerns. The thickness estimation map is easily derived from the first spectral peak frequency attribute (the frequency of the first peak in the amplitude spectrum for each trace; see Partyka et al. 1999). A simple horizon calculation transforms the first spectral peak frequency attribute into an isochron or isochore map. Since this is an independent measure of bedding thickness, this workflow is an important risk reduction tool. The approach is especially powerful when coupled with synthetic modelling and/or crossplotting the predicted thicknesses with actual vertical thicknesses as measured in offset wells.

These workflows, well-proven by several years of application in the industry, can give valuable insight into the internal organization of the reservoir interval. We have found the images and animations particularly effective communication tools, particularly in plays with strong stratigraphic components such as channel sands and deep marine gravity deposits.

Volume spectral analysis

While this paper is focused on two dimensional views of the seismic data, volume visualization and interpretation is now well-established as an interpretation discipline. A 3-D seismic volume has not been truly interpreted until it has been volume interpreted (Figure 4). Two aspects of volume interpretation make it an important tool for spectral decomposition analysis: multiple volume visualization and surface visualization. These techniques enable a more intuitive and thorough interpretation process, especially if undertaken in collaboration with others.

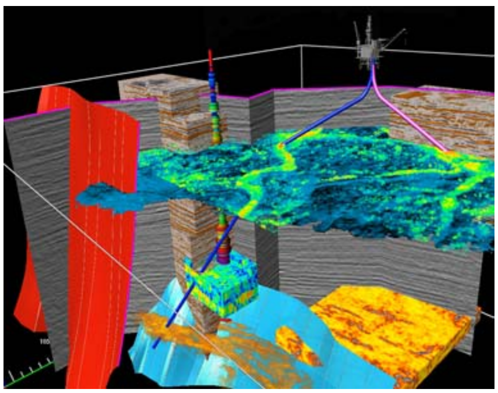

Figure 4. *Volume visualization and interpretation give new insight into the spatial arrangement of stratigraphic features and broaden the interpreter's perspective. This makes it possible to interpret seismic or plan well trajectories interactively and dynamically, with input from the geophysicist, geologist and engineer, each of whom can see their own data in the same space. This allows them to significantly reduce risk and make complex decisions with much more confidence. Images like the one shown are replacing the venerable contour map as the fundamental decision tool. See Meyer et al. (2001) for more examples. [Data courtesy of Seitel Inc.]*

The ability to see and interpret on multiple seismic volumes simultaneously is key for spectral decomposition analysis, since it allows the interpreter to quickly and easily compare responses at a range of frequencies, or to see a single frequency at a range of times. It is also easy to correlate seismic attributes to responses in well logs, since all the data is present in the 3-D space.

Surface visualization is an important tool for seismic geomorphological studies (for example, see Posamentier 2003). Viewing angle, lighting direction, colour, texture, and vertical exaggeration can be instantly adjusted to bring out the particular features of a seismic horizon. Attributes, such as tuned amplitude or phase, can be overlain on structural surfaces and visual correlations instantly made. In our experience, the explorationist can learn more in minutes of playing in 3-D than in days of looking at maps.

Conclusion

Spectral decomposition analysis is an important reservoir imaging tool. Very little data preparation or effort are required to get results which significantly enhance the explorationist's understanding of the reservoir. Seismic modelling and volume interpretation techniques do not take much more time, but can take the interpretation to a new level. In particular, a high-resolution picture of the reservoir can be built with greater confidence and a better understanding of risk than is otherwise possible.

References

Castagna, J, S Sun & R Siegfried (2003). Instantaneous spectral analysis: Detection of low-frequency shadows associated with hydrocarbons. *The Leading Edge*, February 2003.

Meyer, D, et al. (2000). Use of seismic attributes in 3-D geovolume interpretation. *The Leading Edge*, December 2001.

Partyka, G, J Gridley & J Lopez (1999). Interpretational applications of spectral decomposition in reservoir characterization. *The Leading Edge*, March 1999.

Posamentier, H (2003). Integration of seismic geomorphology and seismic stratigraphy: principles and applications. CSEG/CSPG Annual Convention Abstracts Volume, June 2003.