Understanding Thin Beds Using 3D Seismic Analysis Workflows

Henning, Alison*
ffA
800 West Sam Houston Parkway
Building 12, 3rd Floor
Houston, Texas 77024 USA
*now at Rice University
Department of Earth Science
6100 Main Street, MS-126
Houston, Texas 77005 USA

Paton, Gaynor
ffA
The Excel Centre, Suite e3
Aberdeen Science & Energy Park
Exploration Drive, Bridge of Don
Aberdeen, UK

Abstract

Seismic analysis workflows can help improve vertical resolution and identify thin beds on seismic reflection data. Thin beds are events that fall below the level of seismic resolution and occur in all geologic settings. Thin bed analysis can help define pinch outs, internal bedding geometries, and other subtle stratigraphic features that are not initially visible on seismic data. We present workflows that include noise cancellation and spectral enhancement, as well as terrace, doublet, bed form, and instantaneous frequency attributes to enhance the vertical resolution of 3D seismic data. Geobodies are then extracted from these attributes to produce a three-dimensional view of data zones having shared characteristics. Examples from several 3D data sets from different geologic settings illustrate the wide applicability of these workflows.

Introduction

Seismic attribute analysis is playing an increasingly important role in interpretation of 3D seismic data for oil and gas exploration. Data conditioning techniques such as structurally oriented noise filtering can enhance attribute performance by reducing coherent and random noise to reveal subtle geologic features. There are numerous workflows available to enhance resolution of small scale geologic features, which can be used for thin bed identification and analysis. Three-dimensional geobodies can be extracted from single or multi-attribute volumes to map the vertical and lateral extents of thin beds and other geological features.

High frequency reflections are attenuated by the earth, so their influence in reflectivity data is reduced with depth, resulting in poor definition of thin beds. It can therefore be particularly challenging to identify subtle stratigraphic features at great depth. Selectively enhancing the existing high frequency responses, in combination with noise attenuation filters to prevent enhancement of noise, results in improved vertical resolution of the data and thus better imaging of thin beds.

Frequency and wavelet geometry analysis can also be effective tools for delineating thin beds. Several new attributes are described here, including the terrace, bed form, and doublet attributes. The terrace attribute is a wavelet blocking attribute that assigns the maximum amplitude to segments of a seismic trace between points of inflection. This results in the separation of wavelet doublets, allowing interpretation of previously unresolved events. The bed form attribute extracts lineaments along peaks and troughs based on phase, rather than amplitude, revealing stratal relationships more clearly. When calculated from spectrally enhanced (and noise attenuated) data, the terrace and bed form attributes can reveal subtle stratigraphic details, such as clinoforms and pinch outs. Negative instantaneous frequency, especially combined with the bed form attribute, can also provide information on thin beds and help push the limit of seismic resolution. The doublet attribute is effective at highlighting the location of doublets and provides a useful attribute from which to extract geobodies of poorly resolved events.

Methods

Data conditioning

Data conditioning such as poststack noise reduction can significantly improve attribute performance. Structurally-oriented noise filtering can be designed to suppress coherent noise, random noise, or a combination of both. Coherent noise includes processing artifacts as well as acquisition footprint. Steering volumes are used to distinguish noise from dominant structural dip, so noise can be suppressed while preserving signal. The results increase confidence in the geologic significance of attribute based workflows.

A structurally-oriented finite mean hybrid filter was applied to a 3D data set from northwest Australia (Fig. 1). The filter removes coherent noise in the image while at the same time preserving subtle details like edges, corners, and sharp dips in the structure.

Spectral enhancement improves vertical seismic resolution by boosting the high frequency content of the data (Knapp, 1990; Countiss, 2002). The wavelength (λ) of the data controls the vertical resolution. The definition of a thin bed is originally defined as λ/8 for noiseless data, but for practical purposes it is commonly taken to be λ/4 (Widess, 1973; Chopra *et al.*, 2006; Chopra and Marfurt 2007; Zeng, 2009). Wavelength equals velocity divided by frequency (λ=v/f); seismic analysis cannot alter the velocities, but can increase the frequencies.

High vertical resolution and accurate localization are associated with a high mean frequency and a large frequency bandwidth (Knapp, 1990). The goal of the spectral enhancement process is to maximize the mean frequency and bandwidth of the data by producing a "white" spectrum, in which all frequencies contribute equally to the power in the signal. Frequency decomposition of the seismic data is used to extract multiple band limited sections across the full range of the spectrum. Selective weightings are applied to each frequency band to enhance the contribution of the higher frequencies that contain the thin bed information.

Enhancement of high frequencies can often lead to an increase in noise content, and therefore most frequency enhancement techniques are only successful on data sets having high signal-to-noise ratios (*e.g.*, Countiss, 2002). We utilize an approach that selectively enhances the existing high frequency signal by applying frequency-dependent, structurally-oriented noise filters in order to enhance signal and reduce noise.

A 3D seismic data set over the Eagle Ford play in south Texas shows a peak frequency of about 13 Hz at the Eagle Ford horizon (Fig. 2). Structurally-oriented noise filtering followed by spectral enhancement increases the vertical resolution of the data between the Buda and Austin Chalk reflectors, where the Eagle Ford reservoir is located (Fig. 3).

Teapot Dome is located in Wyoming, USA, and the field consists mainly of interbedded sands and shales. Over 1300 wells have been drilled into this field, so a close tie between seismic and well data is desirable. The increase in vertical resolution achieved through spectral enhancement improves the correlation between seismic data and well log data (Fig. 4).

The individual sub-bands obtained through frequency decomposition may also be used to identify thin beds (Partyka *et al.*, 1999). The Stratton gas field in south Texas, USA, presents an example of challenges in thin bed identification. The field produces from a series of channel fill deposits, which are thin and discontinuous and difficult to resolve on 3D seismic data (Hardage *et al.*, 1994). After frequency decomposition, these channels are easier to interpret on high frequency magnitude response volumes (Fig. 5).

The terrace attribute uses a wavelet blocking algorithm that measures wavelet characteristics along each trace. The terrace algorithm analyzes local reflector waveforms on a trace by trace basis. Within each trace, the data values at each point are replaced by a square terraced form, the location of these terraces being defined either by zero crossings or points of inflection (Fig. 6).

Each terrace is then assigned a value based on amplitude, thickness, arc length, or event labeling. The terrace amplitude attribute is most closely related to the original seismic wave and translates the seismic waveform into a square waveform in which the amplitude of peaks and troughs are determined by the maximum amplitude of peaks and troughs within that terrace.

The terrace thickness method measures (in voxels) the thickness of the peak and trough of the squared wavelet over each terrace.

The terrace arc length measures the distance along the curve of the half-wavelet between two events. This is also commonly known as “graph length.” It provides information on both the wavelet amplitude and the wavelet thickness. The arc length attribute sums piece-wise arc lengths over the duration of each event defined by inflection or zero crossings. As with thickness terracing, trough events are terraced with negative values, and linear interpolation is applied to determine the exact arc length section to be added to each event where a sign change in the event delineation function occurs.

Finally, the terrace event labeling option counts the number of events defined by either zero crossing or curvature from the base of the trace up. There will be more 'events' where there are thin beds compared to where there are thicker beds.

Further options exist to allow for a wider range of results from these three terrace types. Example uses of terracing include:

- to highlight changes in lithology, stratigraphy and pore fill,
- to make the zero crossing more stable for use with auto-tracking,
- to show on time/depth slices the most appropriate adjacent peak / trough value, and
- to allow thin beds to be extracted as geobodies without bleeding into neighbouring reflectors

Figure 7 illustrates the subtle stratigraphy that can be revealed using the terrace thickness attribute. Figure 8 shows an example from Teapot Dome in Wyoming, USA. The sequence consists mainly of interbedded sandstones and shales. The terrace attribute is used to extend the presence of a reflector beyond an apparent pinch out on the original data.

The doublet attribute is derived from a combination of terrace attributes. The terrace arc length is computed for both zero crossing and inflection point options, then differenced and smoothed. This yields an attribute that highlights areas of the seismic trace that display a change in inflection without a zero crossing (a doublet). This workflow automatically extracts locations of doublets from the seismic volume; no prior interpretation is required.

The Boonsville Field in north Texas, USA, produces from thin sandstone reservoirs in the Fort Worth Basin (Hardage *et al.*, 1994, 1996). Depositional features are often at or below tuning thickness, so the 3D data contain numerous doublets. The automatic doublet extraction process identifies these features and can be used to infer the presence of thin beds (Fig. 9).

Negative instantaneous frequency

Instantaneous frequency is a commonly used seismic attribute. Recently, the value of negative frequency spikes in identifying thin beds has been recognized (Zeng, 2010). The negative values can be used to highlight thin beds. Figure 10 shows an example from Teapot Dome, where the negative instantaneous frequencies correlate with doublets on the reflectivity data.

Bed form

The bed form attribute extracts lineaments along the minimum and maximum phase of the data and is therefore independent of amplitude and frequency. It skeletonizes the wavelet, making the shapes and geometries of the reflectors more visible. It does not explicitly identify thin beds but often reveals subtle stratigraphic relationships.

The bed form attribute can be combined with the negative instantaneous frequency to reveal even more subtle stratigraphy (Fig. 11). This workflow is amplitude independent and is therefore good at highlighting low amplitude thin beds which are easy to overlook in the seismic data.

Geobody extraction

Stratigraphic features or elements which have a characteristic attribute, or attributes, can be highlighted and extracted as 3D geobodies. The key to successful imaging of these elements is the choice of attribute. In some cases, a simple trace attribute is sufficient to extract the feature. In other cases, a composite attribute or multi-attribute volume is required.

The Eagle Ford play in south Texas contains numerous doublets, which can be used to infer the thinning of beds to the level of seismic resolution. Mapping thickness variations, which can range from 40-400 ft, are a crucial part of understanding the play (Donovan and Staerker, 2010; Treadgold *et al.*, 2011). Automatic doublet extraction highlights these areas, and when viewed in conjunction with other attributes produces a more complete geologic picture (Fig. 12). First, the doublet attribute is created from the data to extract doublet responses. This doublet volume is then sculpted over the reservoir interval and extracted as a 3D geobody. The geobody is displayed by a horizon slice through the combined dip/azimuth structural attribute volume and a vertical slice through the seismic amplitude volume to show that thin beds appear to surround a structural high (Fig. 12). The combined dip/azimuth attribute combines dip and azimuth information such that colors represent changes in azimuth and saturation represents magnitude of dip. This display is useful for identifying structural features, such as ridges and faults. In this case, it is used to view the relationship between the location of doublets, regional faults, and a structural high.

2D Examples

While most of the workflows and examples presented here focus on 3D data, the same methods can be applied to 2D data as well. Frontier exploration projects are often initially based on 2D data, and interpretation of these data can help determine where to acquire 3D data.

Figure 13 shows a portion of a 2D line from the Chukchi Sea off Alaska. Spectral enhancement, combined with structurally-oriented noise filtering, reveals thin bedding and stratigraphic relationships between reflectors. In the case of 2D data, the structurally oriented nature of the noise attenuation filters is limited to the two dimensions available in the data, so the filters are oriented along the apparent (visible) structure in the data.

Discussion and Conclusions

Data conditioning is crucial to obtaining optimal results from attribute-based seismic analysis workflows. Structurally-oriented noise filtering removes coherent and random noise and produces results having greater geological significance.

There are multiple workflows available for identifying thin beds on seismic data. Spectral enhancement improves the vertical resolution of the data, which allows for more accurate interpretation of thin beds on seismic reflectivity data. Frequency decomposition produces sub-bands that can also be used to interpret thin beds. Wavelet blocking and automatic doublet extraction is a fast and efficient method for extracting the locations of possible thin beds, without any prior interpretation required.

The bed form attribute is an amplitude-independent attribute that can highlight small scale stratigraphic features. Bed form in conjunction with negative instantaneous frequency can highlight thin beds. This workflow is especially useful in areas where amplitude is not preserved, such as some subsalt data sets.

Finally, the workflows presented in this paper can be applied to both 2D and 3D data.

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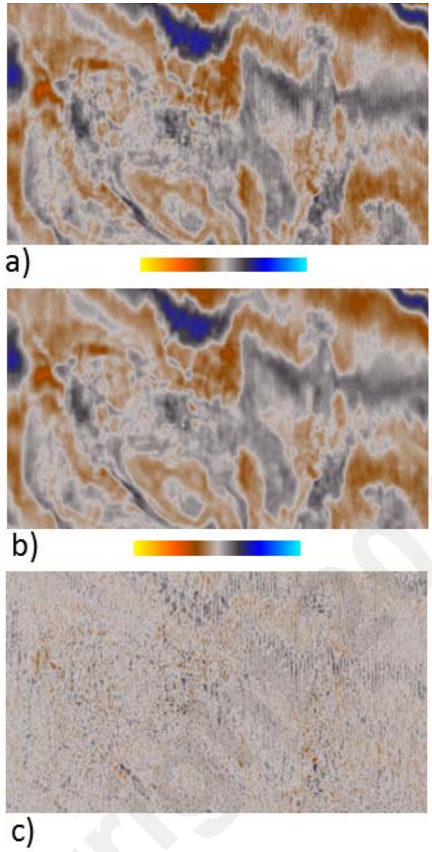

Figure 1. Time slice through seismic data. (A) Before and (B) after structurally oriented noise attenuation. (C) The difference volume showing the coherent north-south noise that has been attenuated in the data. ***Data courtesy of Geoscience Australia.***

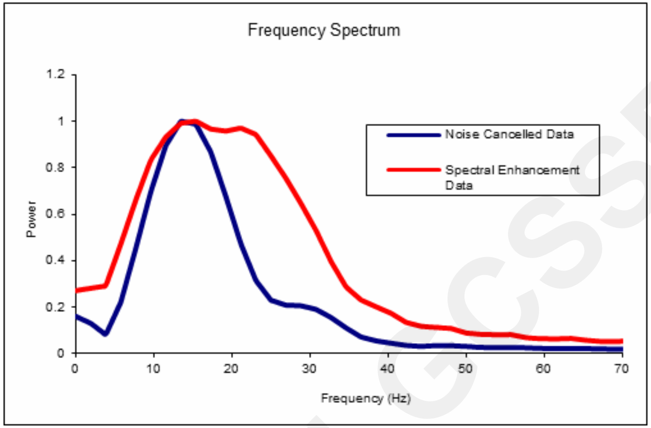

Figure 2. The effect of spectral enhancement on the frequency spectrum of the noise cancelled seismic data. The dominant frequency remains the same and the mean frequency increases.

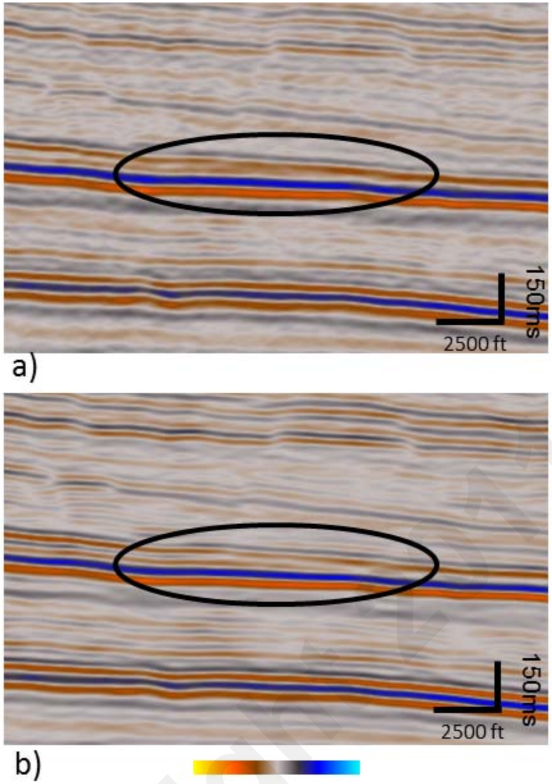

Figure 3. Seismic line from 3D data over the Eagle Ford play (A) before data conditioning and (B) after structurally oriented noise filtering and spectral enhancement. *Data courtesy of Seitel.*

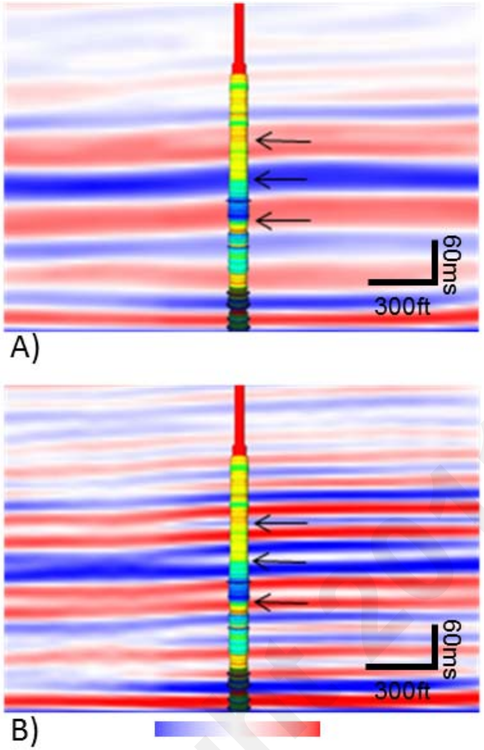

Figure 4. The noise cancelled seismic data (A) before and (B) after application of the spectral enhancement workflow. The log data shows the gamma ray response with red indicating low gamma ray and blue indicating high gamma ray. The black arrow indicate areas where reflectors are only visible after the spectral enhancement workflow and which correspond to a change in the gamma ray response. ***Data courtesy of RMOTC.***

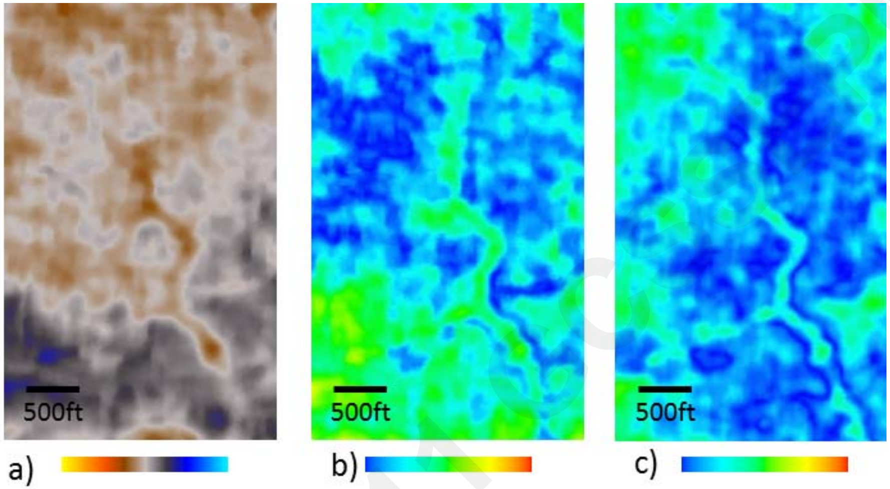

Figure 5. The 30-Hz magnitude response volume (C) shows the detail of a branching channel more clearly than on the noise cancelled seismic data (A), or the full frequency envelope response (B). ***Data courtesy of BEG*****.**

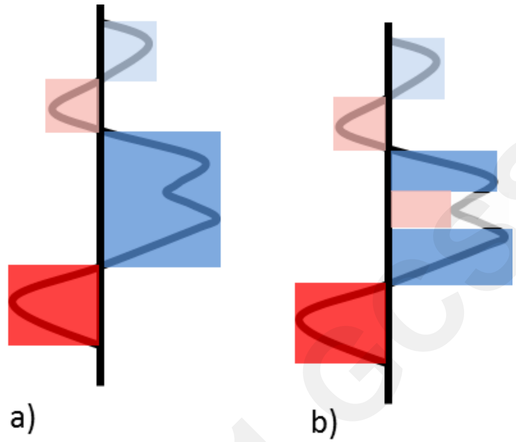

Figure 6. The terrace attribute blocks the wavelet between zero crossings (A), or inflection points (B). When inflection points are used, thin beds which cause doublets in the data are identified as discrete events.

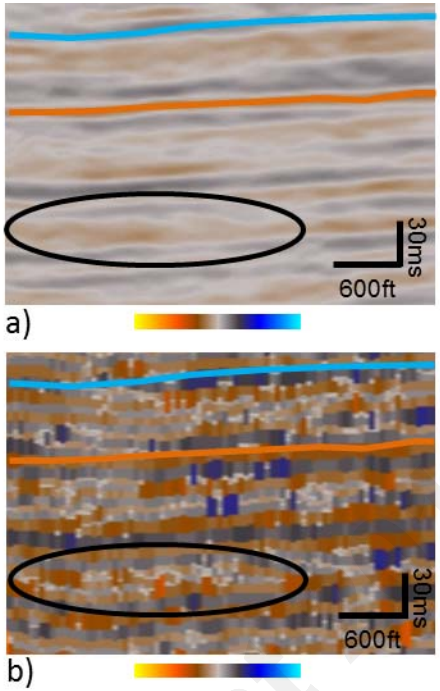

Figure 7. (A) Noise cancelled seismic data and (B) terrace thickness attribute using inflection point delineation. The black circle highlights clinoforms which are now visible in the terrace thickness volume, and in the upper section between the blue and orange horizons thin beds and pinch-outs become visible. ***Data courtesy of RMOTC.***

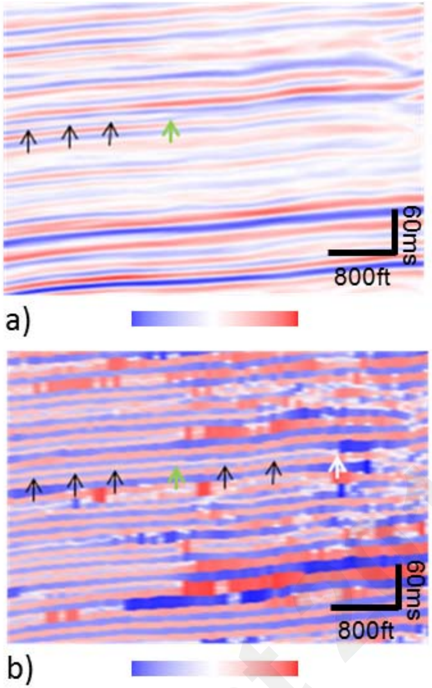

Figure 8. (A) Noise cancelled seismic data and (B) terrace thickness attribute using inflection point delineation. The black arrows highlight a peak event (red) which pinches out in the noise cancelled data at the location of the green arrow. In the terrace thickness volume, the same peak is a continuous event much further along the section until the position of the white arrow.

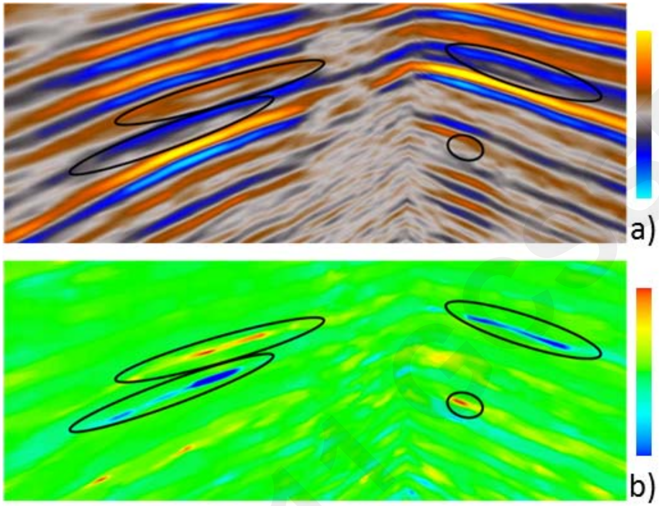

Figure 9. (A) Noise cancelled seismic data and (B) doublet attribute. The black ovals indicate high responses in the doublet attribute and the corresponding doublet expression within the seismic data.

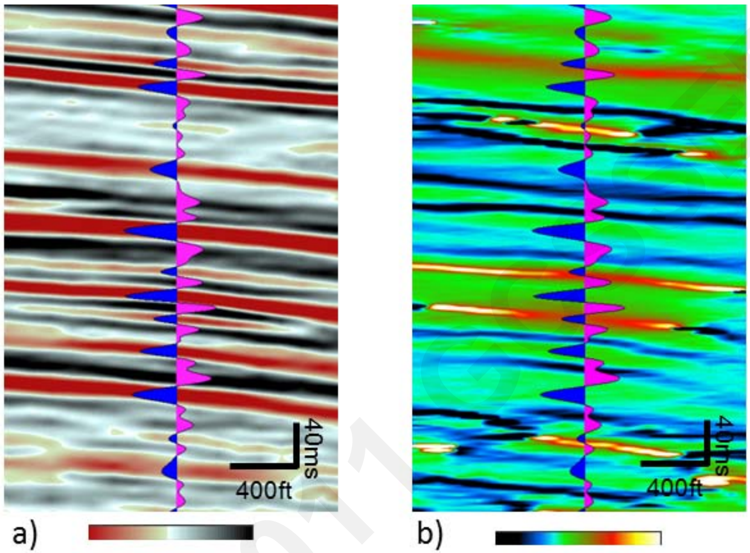

Figure 10. (A) Noise cancelled seismic data and (B) instantaneous frequency attribute. The black lineaments in the instantaneous frequency attribute represent negative frequency spikes which correspond to doublets in the trace. High frequency events are seen as red or white lineaments and often extend into black lineaments when a thin bed becomes unresolved.

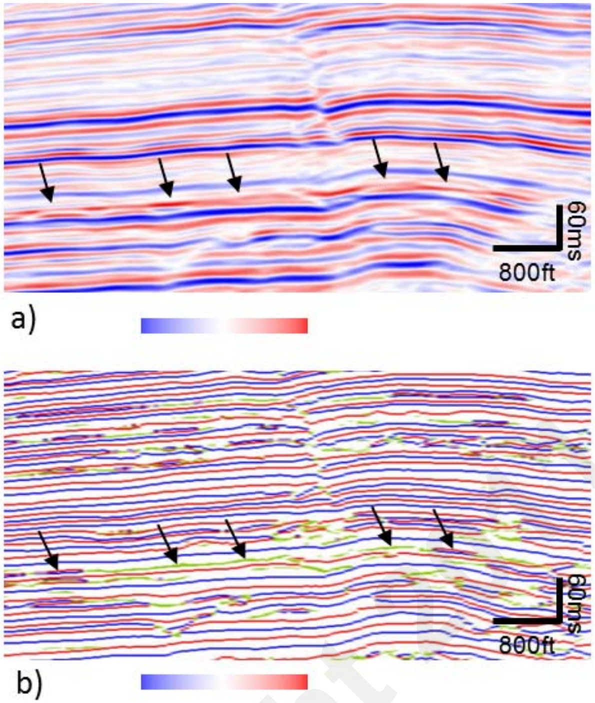

Figure 11. (A) Noise cancelled seismic data and (B) bed form attribute. The wavelet is skeletonised so that the red lines represent the peaks and the blues lines represent the troughs. The green lines are the negative frequency events and represent poorly resolved reflectors. The black arrows indicate a poorly resolved reflector whose expression comes and goes across the section in the noise cancelled data, but can be seen as a continuous event in the bed form attribute. *Data courtesy of RMOTC.*

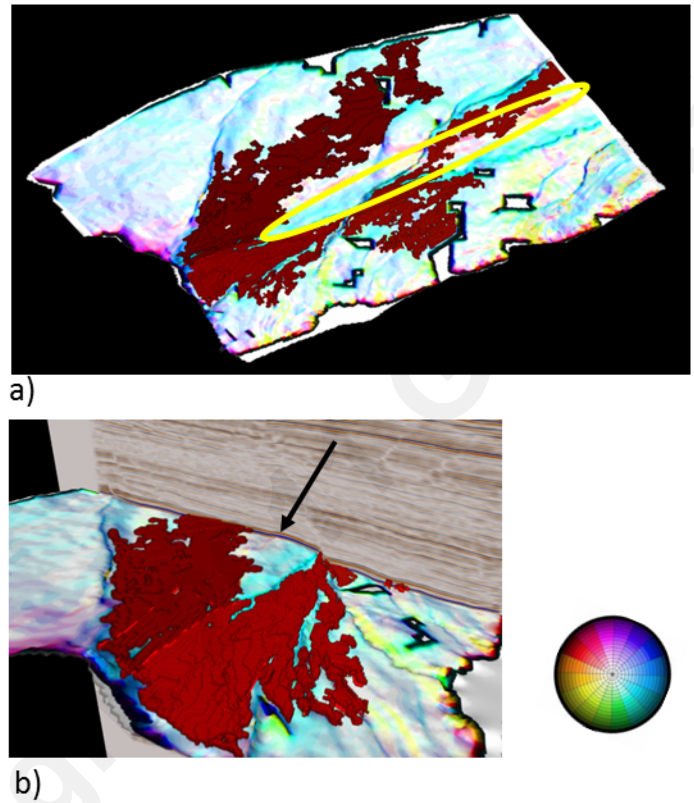

Figure 12. (A) Geobody (red) derived from the doublet attribute with a DipAzi combined attribute draped on the Austin Chalk horizon, just below the Eagle Ford. The yellow oval highlights an area where the absence of the geobody correlates with a structural high. (B) The same geobody with the noise cancelled seismic, the black arrow indicates the structural high where the Eagle Ford layer appears to be thinning onto the high. *Data courtesy of Seitel.*

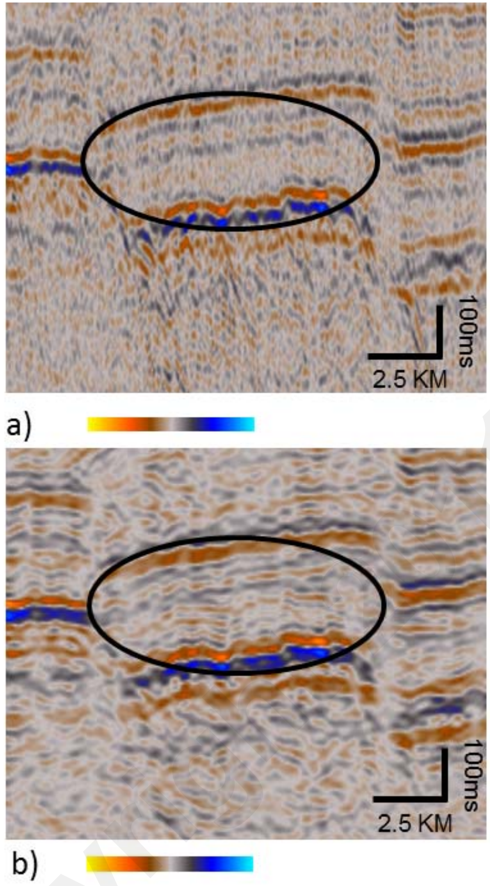

Figure 13. (A) Original 2D seismic data before and (B) after structurally oriented noise filtering and spectral enhancement. Note the improvement in image quality within the black circle. *Data courtesy of the US Geological Survey.*