Visualization techniques for enhancing stratigraphic inferences from 3D seismic data volumes

Tracy J. Stark,* Stark Reality, describes some techniques that he has been developing to visualize bed thickness as a function of relative geologic time using spectral decomposition, ColorStacks, Age volumes, and Seismic-Wheeler volumes.

Data visualization techniques allow interpreters to integrate more types of data and extract more usable and pertinent information in significantly less time. It often requires, as in this case, the application of special hardware, software, and display solutions, coupled with experience and proper training. It is helping the interpreters meet the 'I want it all, I want it now, and I want it right!' roar of their boss or investors.

The ultimate goal is to recognize and convey the maximum amount of geologic information in a minimum amount of time. We want to clearly see what had previously been unseen. This paper makes a few assumptions. First, it assumes that you, the interpreter, would like to see how bed thickness varies, not just as a function of inline, crossline, and travel time, but also as a function of relative geologic time. In other words, along a continuous set of seismic horizons. Second, spectral decomposition, to first order, provides information containing relative bed thickness. Third, the Age volume contains adequate information to convert seismic travel time to relative geologic time. And fourth, it assumes you are not colour blind.

Spectral decomposition, ColorStacks, Age volumes and Seismic-Wheeler volumes have all been described independently in the literature (references later). This is the first time they have all been brought together. Briefly: A ColorStack is where you 'stack' data using additive colour instead of additive numbers. With a trained eye, you can see both the forest and the trees using a ColorStack. An Age volume is a seismic volume that contains an estimate of geologic age instead of band-limited reflectivity. A Seismic-Wheeler volume is a three-dimensional Wheeler diagram (or chronostratigraphic chart) showing the spatial seismic response (or lack thereof during hiatuses) as a function of relative geologic time.

For those wanting the bottom line now, jump to Figure 12. It contains colour-coded thicknesses for just a few of a continuous set of relative geologic age horizons: reds represent thicker beds, blues represent thinner beds, while solid grey represents a hiatus (either erosional or non-deposition).

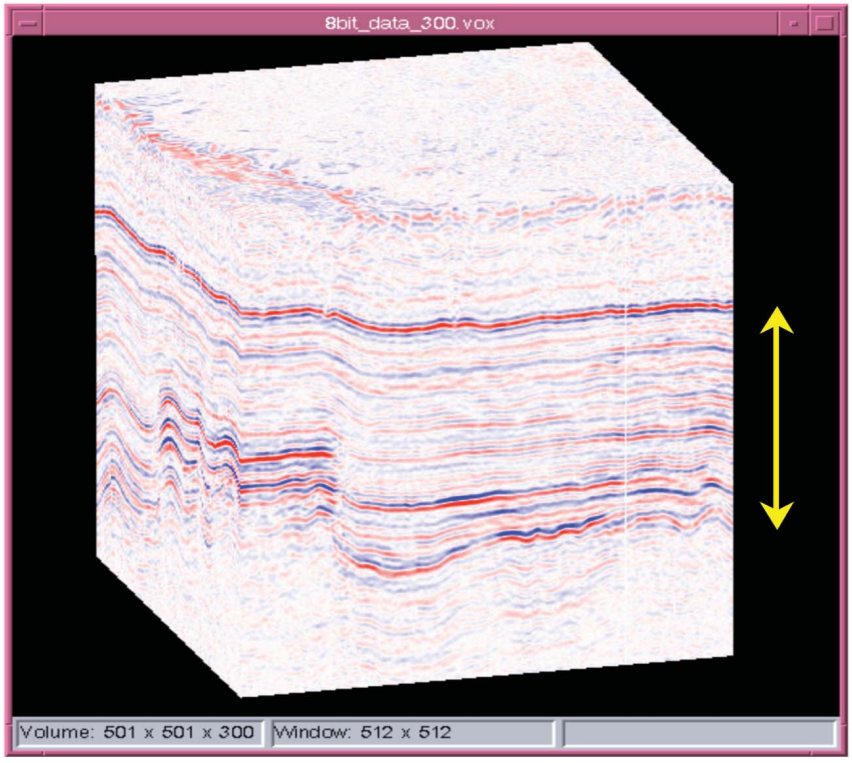


Figure 1 *Portion of a 3D seismic volume containing 501 inlines by 501 crosslines and 1200 ms. Yellow line represents interval over which Age volume is available.*

Example data set

Figure 1 contains the data volume used to illustrate the various visualization techniques discussed in this paper. It is a subset of a much larger 3D land survey. The data in Figure 1 contains 501 inlines and 501 crosslines, covering about 100 km². The vertical time axis spans 1.2 seconds consisting of 300 samples space 4 ms apart. Note that this sub-volume does not start at t=0.

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The seismic amplitude value at each data point in a seismic volume (if properly processed) represents the band-limited reflectivity. The term 'band-limited' implies that each value is some type of average over a small sub-volume of the subsurface. In general the higher the frequencies, the smaller the sub-volume averaged. The yellow vertical line in Figure 1 represents the stratigraphic interval over which the high resolution Age Volume (Figure 5) was generated.

Spectral decomposition

Recently much attention has been given to spectral decomposition. It has been used for both thickness estimation (Partyka et al., 1999) and direct hydrocarbon indications (Castagna et al., 2003). The SEG Spring 2005 Distinguished Lecture by Greg Partyka on 'Spectral Decomposition' was presented some 28 times worldwide. *The Leading Edge* in February 2006 contained a special section on 'Attenuation and Spectral Decomposition', and in the last *First Break* Castagna and Sun (2006) compared spectral decomposition methods and discussed their matching pursuit decomposition method (EPD).

There are a variety of different procedures to perform spectral decomposition, and a variety of ways to show and interpret the results. The methods of viewing the spectral decomposition results shown here are largely independent of how the results were generated. The key in using the results of spectral decomposition is to put them in a context that allows you to readily make geologic inferences. You want to be able to clearly see what had previously been unseen.

Wulf Massell of Fusion Petroleum Technologies ran its EPD spectral decomposition routine, ExSpect, on the data shown in Figure 1. This spectral decomposition produced 100 SEGY data volumes, each the same size as the original seismic volume. These volumes, numbered 1 to 100, contain the high resolution spatial and temporal distribution of the instantaneous spectral amplitudes associated with wavelets from 1 to 100 Hz.

How do you utilize or visualize this much data? At the 2005 SEG convention in Houston, Stark Reality demonstrated (on the exhibit floor) a software/hardware solution that sequentially volume rendered 50 of these cubes (~72 Mb/cube) at about 15 frames per second. The user could interactively change the orientation, colour table, opacity function, lighting, clip-planes, etc, as the volumes changed from low to high frequencies. In this demonstration, the complex nature of the spatial frequency variations was readily apparent in a few seconds. However, making quick geologic inferences was not as easy as you would like. It was an interesting demonstration of the speed and capabilities of the volume rendering board, but if left you with more questions than it answered.

In order to use the ColorStack technique (described next), the 100 data volumes were reduced down to three (Figure 2). These three volumes represent the low, mid, and high frequencies. The low, mid, and high frequency cubes contain the sum of the instan-

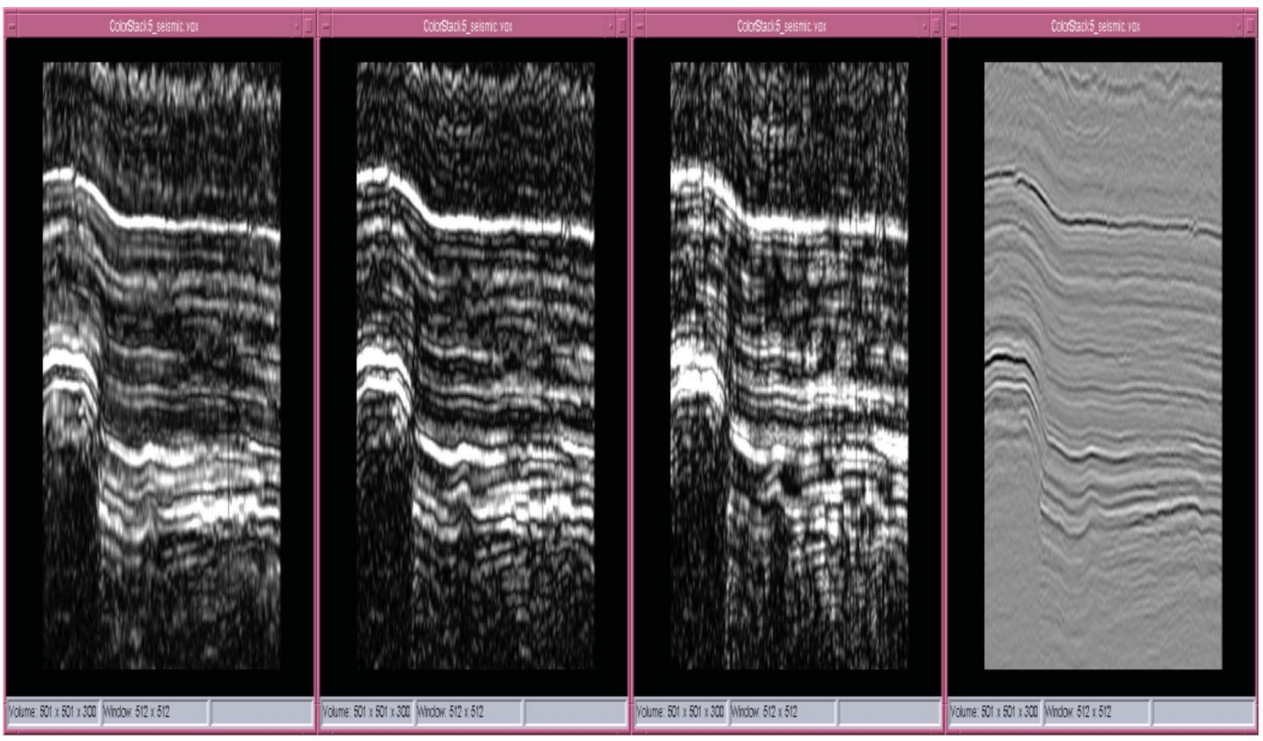


Figure 2 *Low, mid, and high frequency spectral amplitudes (from left to right) displayed using the same gain. These spectral amplitudes are the results of summing the 1 to 27 Hz, 28 to 42 Hz and 43 to 100 Hz output from the Fusion EPD method. The input seismic section is on the far right. This figure indicates that an event's frequency varies laterally.*

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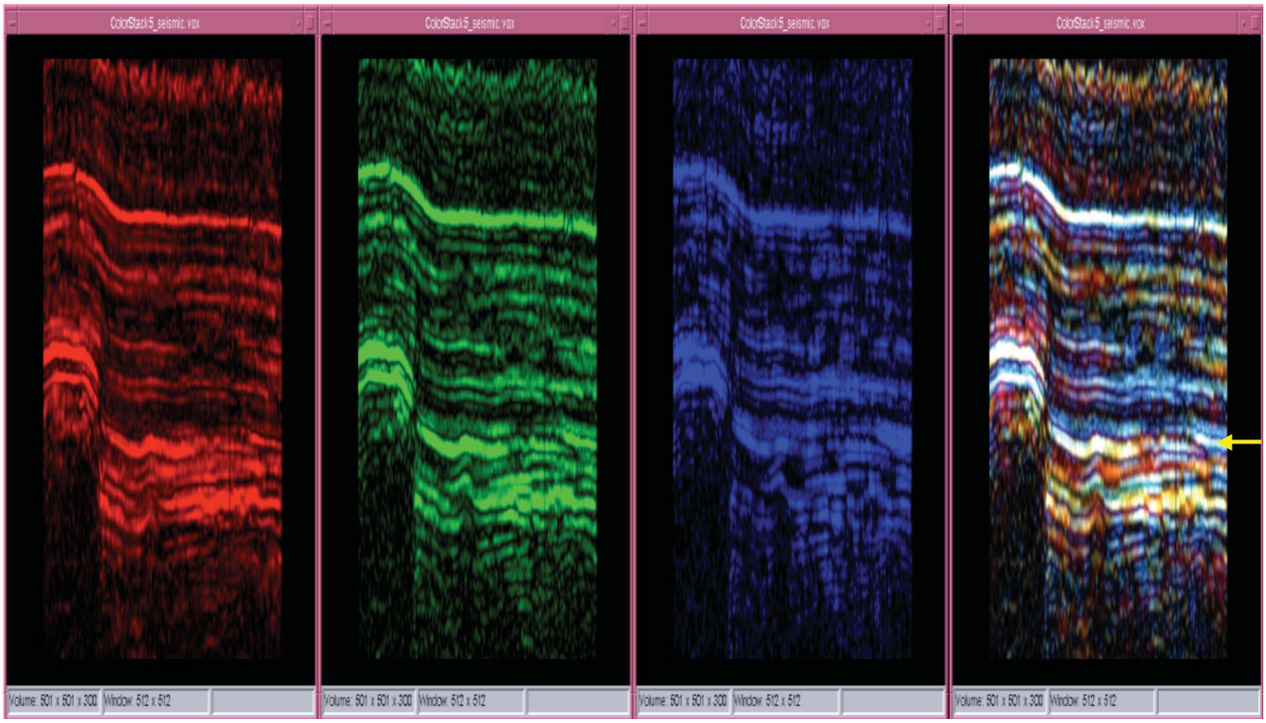


Figure 3 *ColorStack generation using the three spectral decomposition bands. The left three images are the same as the left three images of Figure 2, but using a gradational colour scale. The right most image is the colour composite, or ColorStack, of the three images to its left. The colour variations in the ColorStack are geologically significant.*

taneous spectral amplitudes from the 1 to 27 Hz cubes, 28 to 42 Hz cubes, and 43 to 100 Hz cubes respectively. These frequency divisions 'clipped' about the same number of points in each volume when they were converted to 8-bits using a single scale value. Summing the cubes in this manner has reduced the frequency resolution of the original spectral decomposition. However, it probably has not adversely affected either the temporal or spatial resolution of the results.

Figure 2 summarizes the spectral decomposition results. It contains four vertically-squeezed grey-scale displays of the same seismic line. Going from left to right these are: the summed spectral decomposition results for the low, mid, and high frequency bands, with the original seismic data on the far right. It is apparent from this figure that even with this course frequency decomposition most reflections exhibit some form of lateral frequency variation. However, this method of display does not lend itself to 'clearly see what had previously been unseen'.

ColorStack

Greg Onstott developed a seismic ColorStack technique as part of his University of Texas at Austin Master's thesis (Onstott et al., 1984). He got the idea from displays of multi-band satellite imagery. Historically it could only be done on a single line with a high-resolution color monitor. Recently, Stark (2005c) demonstrated how the ColorStack technique could be used to analyze 3D AVO volumes, particularly identifying class 2 flat spots.

In this paper the ColorStack technique is used to study the frequency variation of the seismic data, much in the way colour is used for multi-band satellite imagery. (Other authors, such as Bahorich et al., 2002, have used similar displays for spectral decomposition data.) The ColorStacks are generated such that red events are cause by strong low frequency contributions, green events by strong mid frequency contributions, and blue by strong high frequency contributions. White or grey events have equal contributions from all frequency bands. The low and high frequencies are interpreted as roughly corresponding to thick and thin beds respectively. In Figure 3 the individual spectral decomposition lines of Figure 2 are shown with gradational red, green, and blue colour scales. On the right, instead of the original seismic data, there is now a ColorStack of the images to its left.

The right hand panel in Figure 3 is indeed colourful. But is it providing significant, easy to understand geological insight? Are the colour variations due to noise or are they geologically significant? Geologically significant is the correct answer. Figure 4 helps in understanding why the answer is 'geologically significant'. It is a comparison of a standard time slice using a red-white-blue colour scale and its corresponding ColorStack time slice derived from the low, mid, and high spectral decomposition frequency bands. (This slice was taken from the level indicated by the yellow arrow in Figure 3.) Notice the spectacular difference between these two time slices.

On the ColorStack display three arrows have been added to denote 'channel-like' features. The green arrow points

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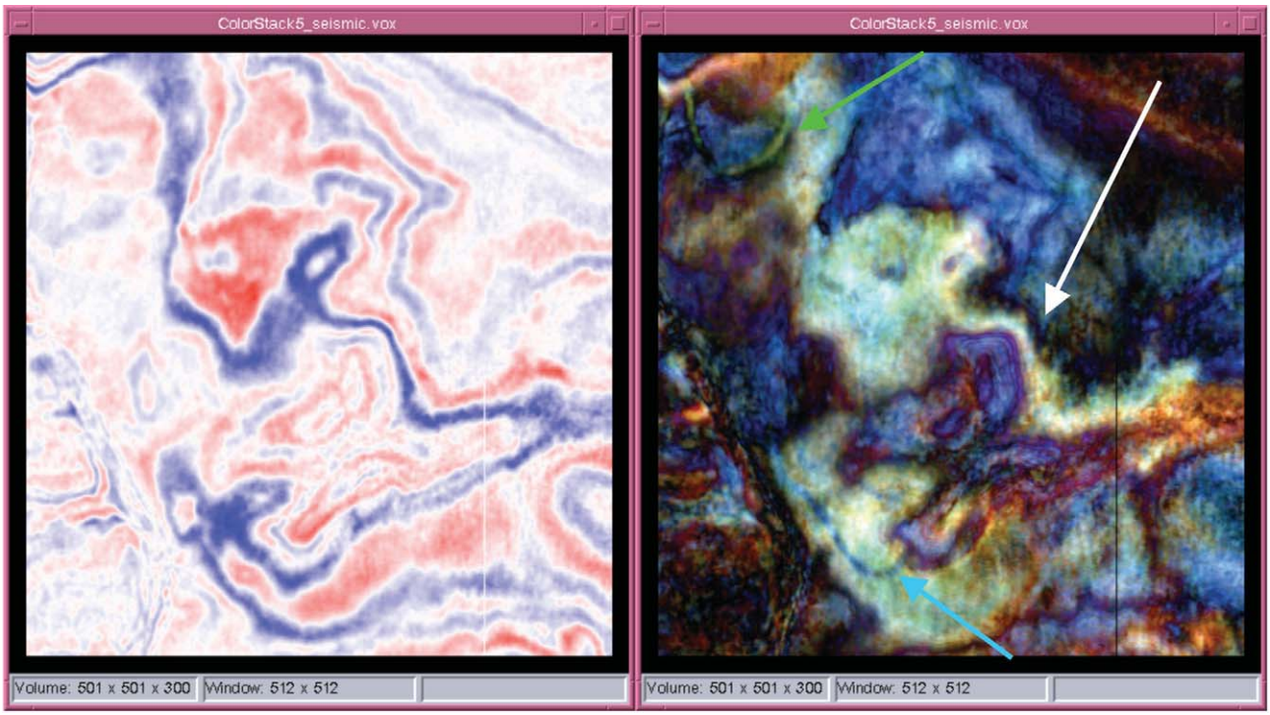


Figure 4 *Comparison of a standard time slice (left) and a ColorStack time slice (right). The green and cyan features, denoted with arrows, are local channels, while the white event is a steeply dipping reflector. The colours indicate that the green channel is composed of thicker units than the cyan channel. These two channels are very hard to identify in the corresponding standard time slice display.*

to a green (dominated by the mid frequencies) event in the upper left. This event is not visible on the current time slice, but if the slices are panned up and down it can be found. The white arrow in the middle points to a white event that is part of a locally steeply dipping horizon. It is not a channel at all. This event is visible in the standard time slice. The cyan arrow points to another meander loop that is only barely visible in the time slice. Again, panning through the time slices, portions, but not all, of this channel can be discovered. The blue colour implies the bedding inside of this channel is thinner than in the green channel.

This display is beginning to meet the objective of seeing the unseen and quickly making geological inferences, but it also indicates that we are not getting the whole picture. It is much better than the conventional time slice display, but we can only see portions of individual channels and there is a chance of confusing dipping events with wide channels. We want to see the entire preserved channel complex and not be tricked by horizon geometry. So this brings us to our next topic, the Age volume.

Age volume

Figure 5 contains a high resolution Age volume generated over a 200-sample subset of the data shown in Figure 1. It is limited to the stratigraphic interval denoted with the yellow line in Figure 1. The age volume has the same spatial dimensions and coordinates as the seismic data volume, but instead of seismic amplitude, each sample contains an estimate of relative geologic time (age). The rainbow colour scale at the bottom of Figure 5 represents increasing relative age going from left to right. Note that the colour within each hue becomes progressively darker with increasing relative geologic time. High-resolution age values were not generated for events at the top and base of this cube and therefore the top and base are denoted with single ages, and therefore single colours. Just like the seismic amplitude volume, the Age volume contains significantly more resolution than can be represented by an 8-bit color scale.

The relative geologic time or Age volume was first introduced to the industry by Stark (2002). Methods to generate and display the Age volumes were further discussed in Stark (2003 & 2004b). For those wanting details of the generation, display, and uses of the Age volume they can look at the three US patents concerning the Age volume (Stark 2004a, 2005a, & 2005b).

According to Stark (2004b), 'The phrase relative geologic time should be interpreted as: "If relative geologic time A is greater than relative geologic time B, then the rocks of relative geologic time A were deposited before rocks of relative geologic time B." Thus, using this volume, we can tell if a data sample A is younger or older or the same age as data sample B, but we cannot say how much older or younger A is than B until a calibration step is performed.'

Any horizontal slice taken from the Age volume in Figure 5 will contain a geologic map corresponding to

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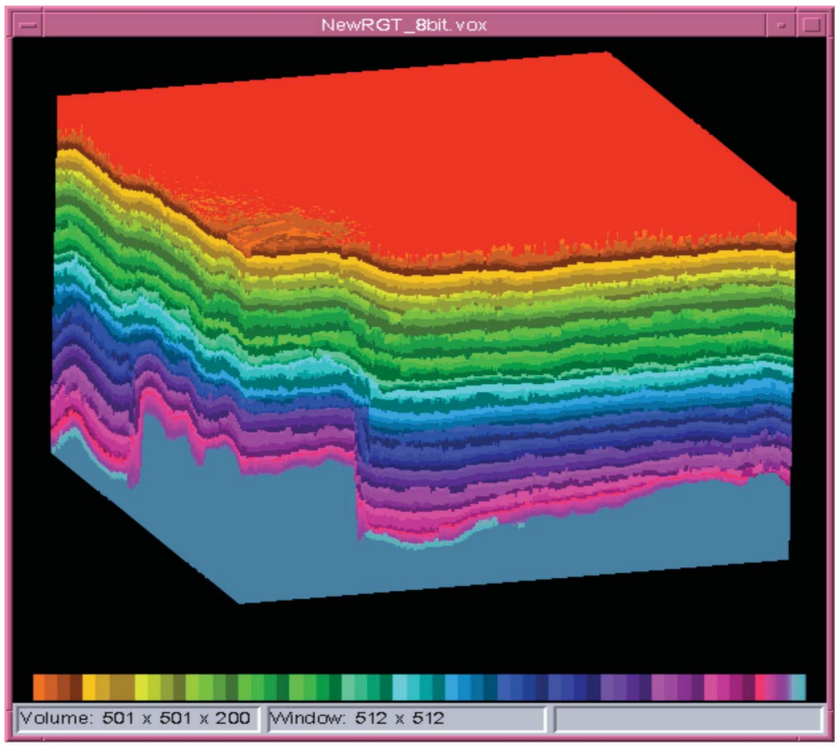


Figure 5 *Age volume corresponding to stratigraphic interval noted in Figure 1. Constant colours represent constant relative geologic time. Colour bar at bottom shows ages increasing from left to right.*

that time (depth). Similarly, any vertical cross section through an Age volume, such as a face on the cube, represents a geologic cross-section. Further, a constant colour represents essentially a constant age. Therefore, samples in Figure 5 that have the same colour will belong to the same horizon: this can be exploited using a variety of data processing and visualization techniques, some of which will be described below.

Unwrapping instantaneous phase

The high resolution Age volume shown in Figure 5 was generated by unwrapping (in three dimensions) the instantaneous phase of the data shown in Figure 1. This technique of generating an Age Volume will be reviewed briefly. More details can be found in Stark (2003 & 2004b).

In Figure 6 a single trace, taken from the middle of a 2D synthetic line (inset), is used to illustrate unwrapping instantaneous phase to generate an Age volume. Starting on the left, the seismic trace is converted to instantaneous phase such that the instantaneous phase generally increases with travel time. Next a cycle trace is generated (cyan line) that steps an integer multiple of 2π every time there is a significant change in the instantaneous phase values. The size of the integer multiple depends upon the surrounding data. The cycle number and the instantaneous phase are added together to generate the unwrapped instantaneous phase (red line). The location and size of the cycle steps are modified such that 1) the resultant unwrapped phase always increases with travel time and 2) large spatial gradients in the unwrapped phase are concentrated along faults and unconformities. These conditions basically require the unwrapped phase, which is (non-linearly) proportional to geologic time, to honour the law of superposition. Note that the large step size in the middle of the figure is required to compensate for the angular unconformity.

Age volume histogram

The histogram of the Age volume contains a significant amount of geologic information as Figure 7 illustrates. In this figure relative geologic age increases from left to right. The dark blue represents the number of voxels containing a particular relative geologic age value; the taller the blue curve, the more voxels of that age. Therefore, in essence, this figure is showing us the volume of rock preserved for each relative geologic age. The peaks represent laterally extensive, or thick age units,

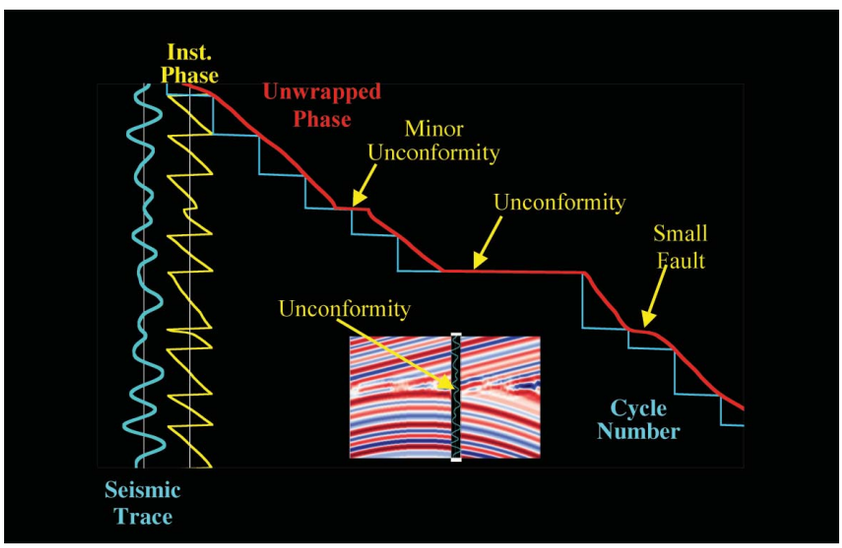


Figure 6 *Example of unwrapping the Instantaneous phase of a single synthetic trace in the context of a 2D line containing unconformities and a fault.*

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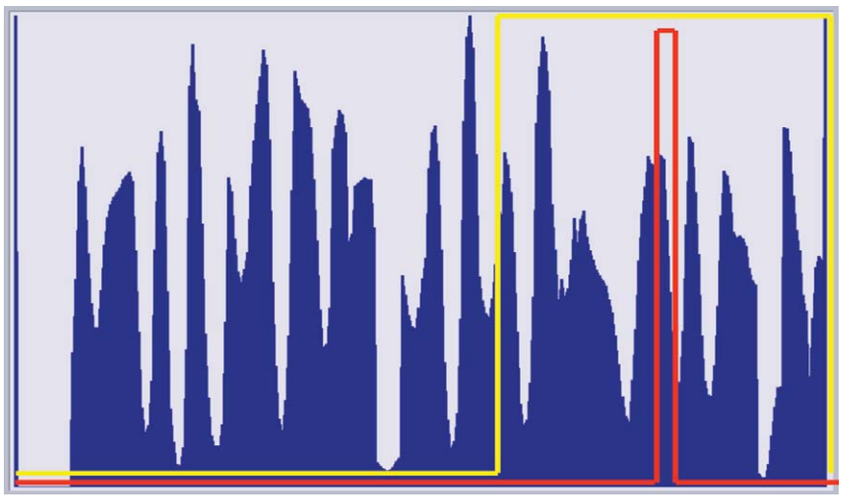


Figure 7 *Age volume histogram, age increases to the right. Blue peaks represent either thick or laterally extensive horizons while the notches represent hiatuses. Note both high and low frequency trends in this histogram.*

while the notches represent either very thin units, or times of either erosion or non-deposition. (Note that the figure has been scaled such that the large number of voxels associated with the undetermined young and old ages at the top and bottom of the cube do not bias the display.)

Seismic stratigraphers might want to rotate the figure clockwise 90 degrees, so that increasing age points down. Note that the blue peaks follow a low frequency trend of peaks and troughs. In this orientation, the histogram looks somewhat like one of Vail's sea level charts (Vail, 1977). Even though this data is from a mid-continent region presumably unaffected by global seal level changes, this observation led to the generation of the Seismic-Wheeler volumes discussed a little later. The yellow curve in Figure 7 represents the opacity curve used to generate Figure 9, while the red curve represents the opacity curve used to generation Figure 10. These figures will be discussed next.

Visualization methods

Four visualization methods in which the Age volume and spectral decomposition ColorStack volume are used in concert to 'make the unseen seen' are presented next. These methods are: horizon extraction, horizon sculpting, formation sculpting, and the Seismic-Wheeler volume. The Seismic-Wheeler volume will be presented in the next section.

Horizon extraction. As noted in the discussion of Figure 4, we prefer to look at the ColorStack of the spectral decomposition along a horizon in order to see the entire preserved channel system. Given any position in the seismic volume, such as a point on one of the channels, the relative age of that position can be determined from the corresponding location within the Age volume. Every trace in the Age volume can then be scanned to extract the arrival time that corresponds to the desired age. This surface can then be used to extract the seismic amplitude,

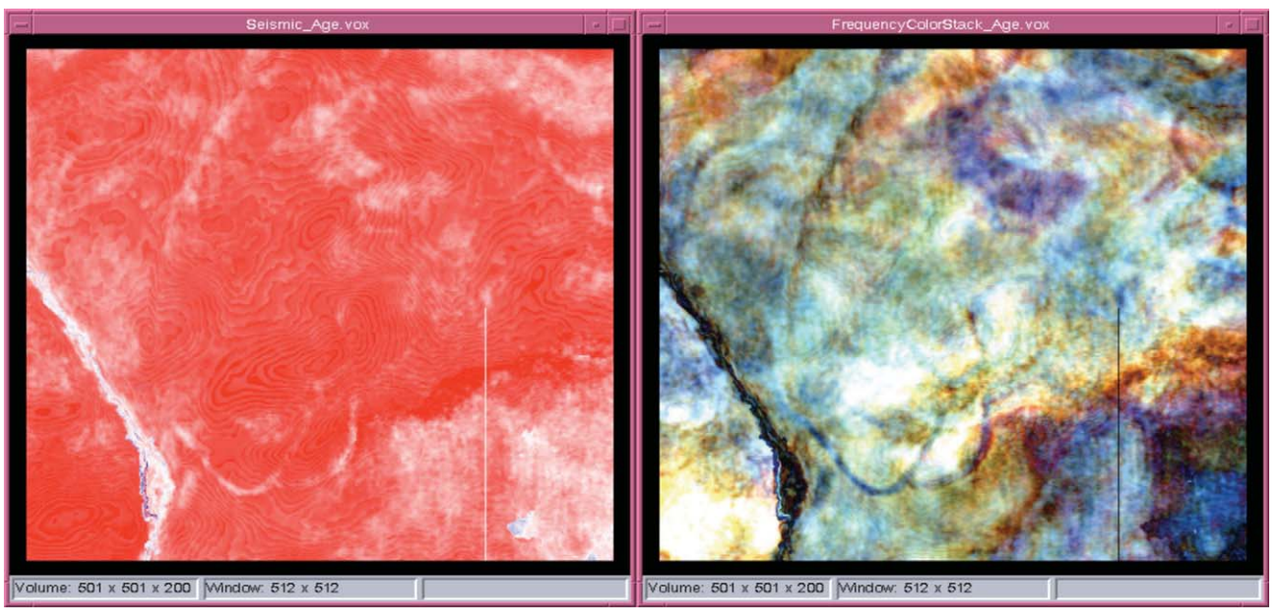


Figure 8 *Horizon extraction results. The left hand side of this figure contains a typical stratal slice. The right hand side contains the same slice but in a spectral decomposition ColorStack format. Most of the channels are easier to see in the ColorStack stratal slice. The colours in the ColorStack stratal slice are related to the local bed thickness. Note there are a variety of spatial thickness variations that should have geological significance.*

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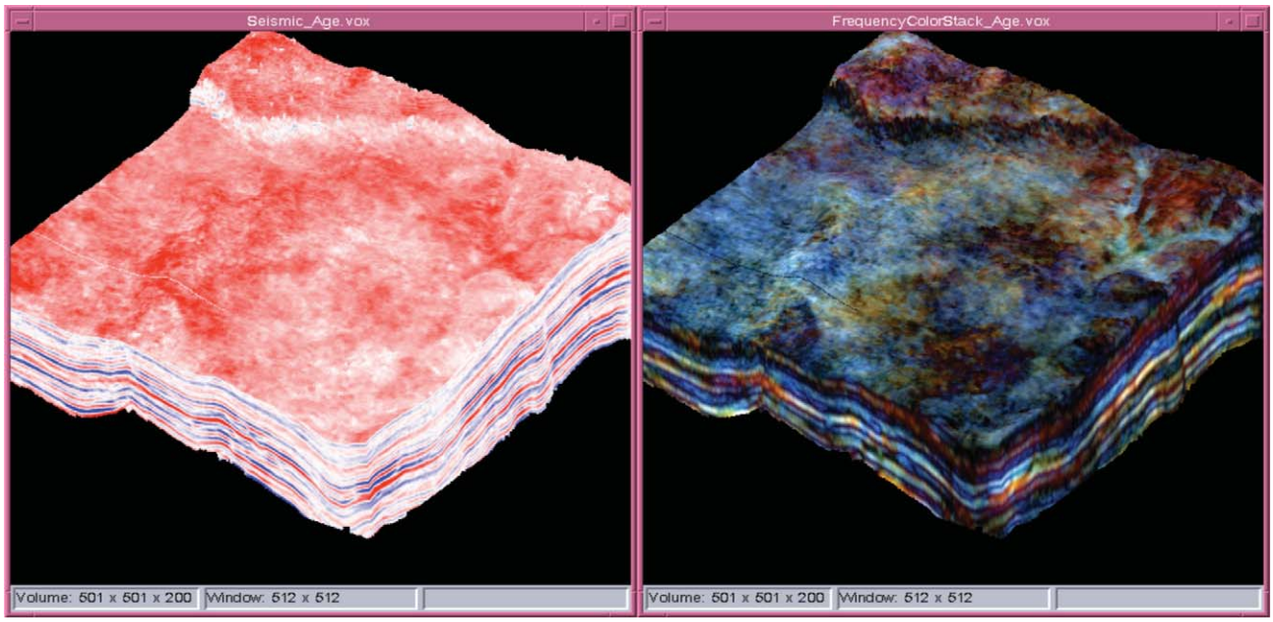


Figure 9 *Horizon sculpting results using the yellow opacity curve shown in Figure 7. Standard seismic amplitude is on the left, while a spectral decomposition ColorStack is on the right. Note the blue incised channel is easier to see in the ColorStack display. This is at a stratigraphically higher level and viewed from the northeast towards the southwest relative to the data shown in Figure 8.*

ColorStack amplitude, or some other attribute and display the result in a map view. Doing so results in Figure 8.

In Figure 8 we see a stark difference between the standard seismic amplitude (left) and the ColorStack display (right). The left hand display is typically called a horizon amplitude slice, or a stratal slice, and is similar to the types of displays generated by Zeng et al.(2001). This standard amplitude display does a poor job of displaying all of the channels cutting through this level (which is only partly due to its high amplitude and partial colour display clip.) However, in the ColorStack portion (right side) of this display a variety of channel geometries are easy to see. Besides the two blue channel loops preserved at the bottom of the image, there is also a bluish-purple region in the upper centre of the slice. This colour implies a mix of thin and thick beds. It only shows up as a dim spot on the standard amplitude section.

Horizon sculpting. Figure 9 depicts a second way in which the Age volume can be used to better understand the geological complexities of the ColorStack volume (Stark, 2004c). To generate the right hand side of this figure the low, mid, and high spectral decomposition volumes were combined with the Age volume to create a voxel volume containing four, 8-bit fields. This volume was then utilized by a special hardware and software combination that takes optimal advantage of this type of volume. This program uses the spectral decomposition volumes to determine the colour of the rendered voxels while using the Age volume to determine the opacity. In this figure, only the data samples that are older than a relative geologic age of interest are displayed; all those younger than the age of interest have been rendered transparent (using the yellow opacity curve shown in Figure 7). A similar volume, but with only two, 8-bit fields, is constructed using the standard seismic data and the Age volume to generate the left hand side of Figure 9.

We are at a stratigraphically higher level in this display than what we saw in Figure 8. This type of display allows the interpreter to see the stratal slices in their current structural position. Towards the right hand side of the figure there is a blue (thin bed) channel system cutting through a red (thick bed) background. We also note a variety of thickness variations across this horizon, with the thicker areas appearing to generally be concentrated on the structural highs. None of this information is available from the standard amplitude display seen to the left.

Although not shown here, the display orientation as well as the step in the opacity function can be moved interactively, and the volume re-rendered at about 15 or more frames per second to allow the interpreter to study the thickness changes as a function of relative geologic time.

Formation sculpting. Figure 10 represents a third way of using the Age volume. In this display the same multi-field voxel volumes employed to create Figure 9 are used. However, only the seismic data found within a limited relative geologic age range are visible, as depicted by the red opacity curve of Figure 7. All other ages are made transparent. The opacity of the visible data could also be modified to show a selected range of amplitudes if desired. This might be the largest positive or negative values in the original seismic data,

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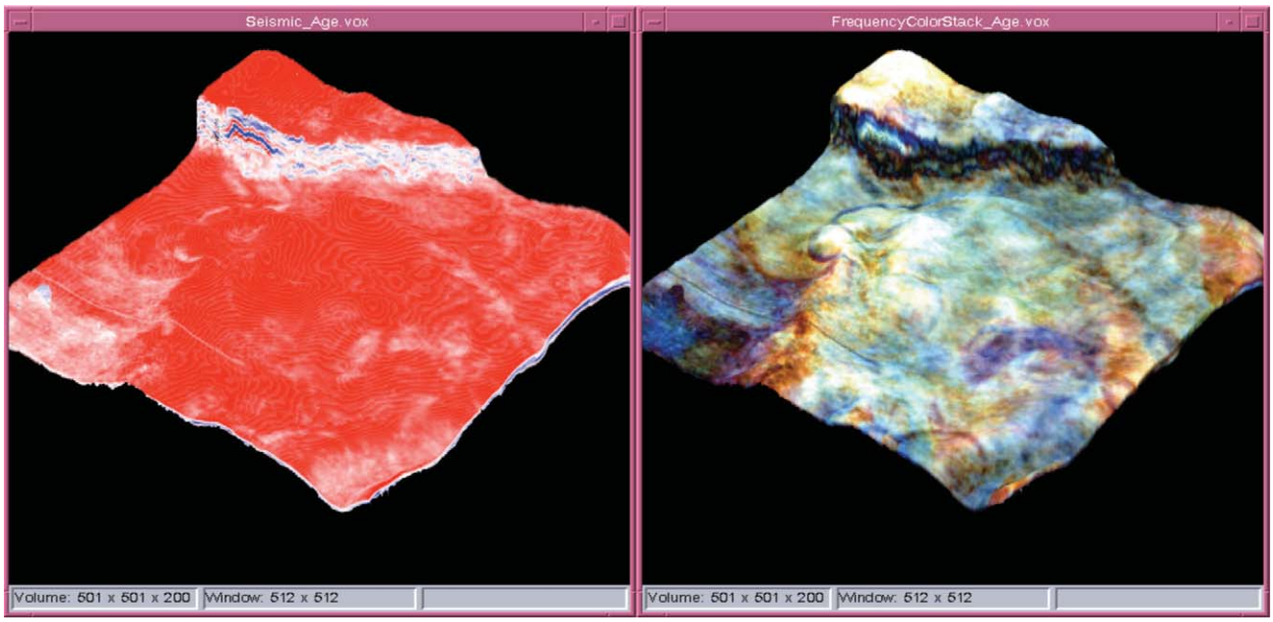


Figure 10 *Formation sculpting results using the red opacity curve shown in Figure 7. Standard seismic amplitude is on the left, while a spectral decomposition ColorStack is on the right. This display corresponds to the stratal slices of Figure 8, but the data are now displayed in their current structural position. Modification of the opacity curve allows an interpreter to interactively change the age of the sculpted formation.*

or one of the spectral bands in the ColorStack display. Again, these colour lookup changes, as well as the age range of interest (opacity range) can be change interactively. Once the desired geologic time slab is found, the volume can be interactively rotated, translated, and zoomed to find the proper viewing location.

Seismic-Wheeler volume

The above figures are a drastic improvement over standard seismic amplitude displays, but there is still one thing missing from all of the displays – the locations of missing time. Where are the hiatuses? The Age volume histogram (Figure 7) indicates that hiatuses are contained within the Age volume, but the displays so far have done a great job of hiding then. Dennis Cooke and Jim Benson of Santos, upon seeing the Age volume results applied to standard seismic data, challenged me to find a way to combine the seismic volume and Age volume to build a Seismic-Wheeler volume similar to the Wheeler diagram shown in Figure 11 - Wheeler (1958), Vail et al. (1977). According to Jim, the locations of the hiatuses, as shown in Figure 11 are 'invaluable' to a stratigrapher.

As a result of their challenge, Stark (2005d) presented the industry's first Seismic-Wheeler volume at the 2005 SEG convention in Houston. This paper takes that work one step further and compares the Seismic-Wheeler volume with a ColorStack-Wheeler volume. The results for several different ages are shown in Figure 12. It contains pairs of Seismic-Wheeler and ColorStack-Wheeler volumes trimmed at the same constant relative age slice. The vertical axis in each of these cubes is relative geologic time. Any cross section through these volumes corresponds to the lower portion of Figure 11, but using a non-linear age scale. The seismic amplitudes are on the left of each pair and are displayed using a standard red-white-blue color scale. The ColorStack version is on the

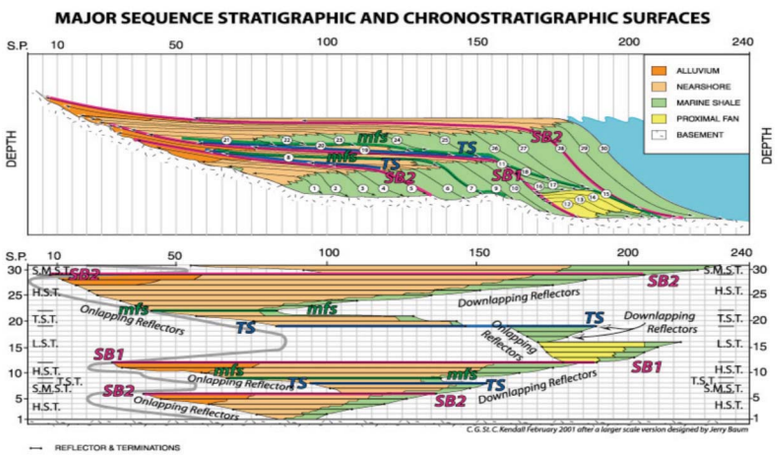


Figure 11 *Stylized stratigraphic section and corresponding Wheeler diagram (Chronostratigraphic Chart). This figure is Baum's stratigraphic+chrono chart solution taken from http://strata.geol.sc.edu/ss-chrono.html, 2005.*

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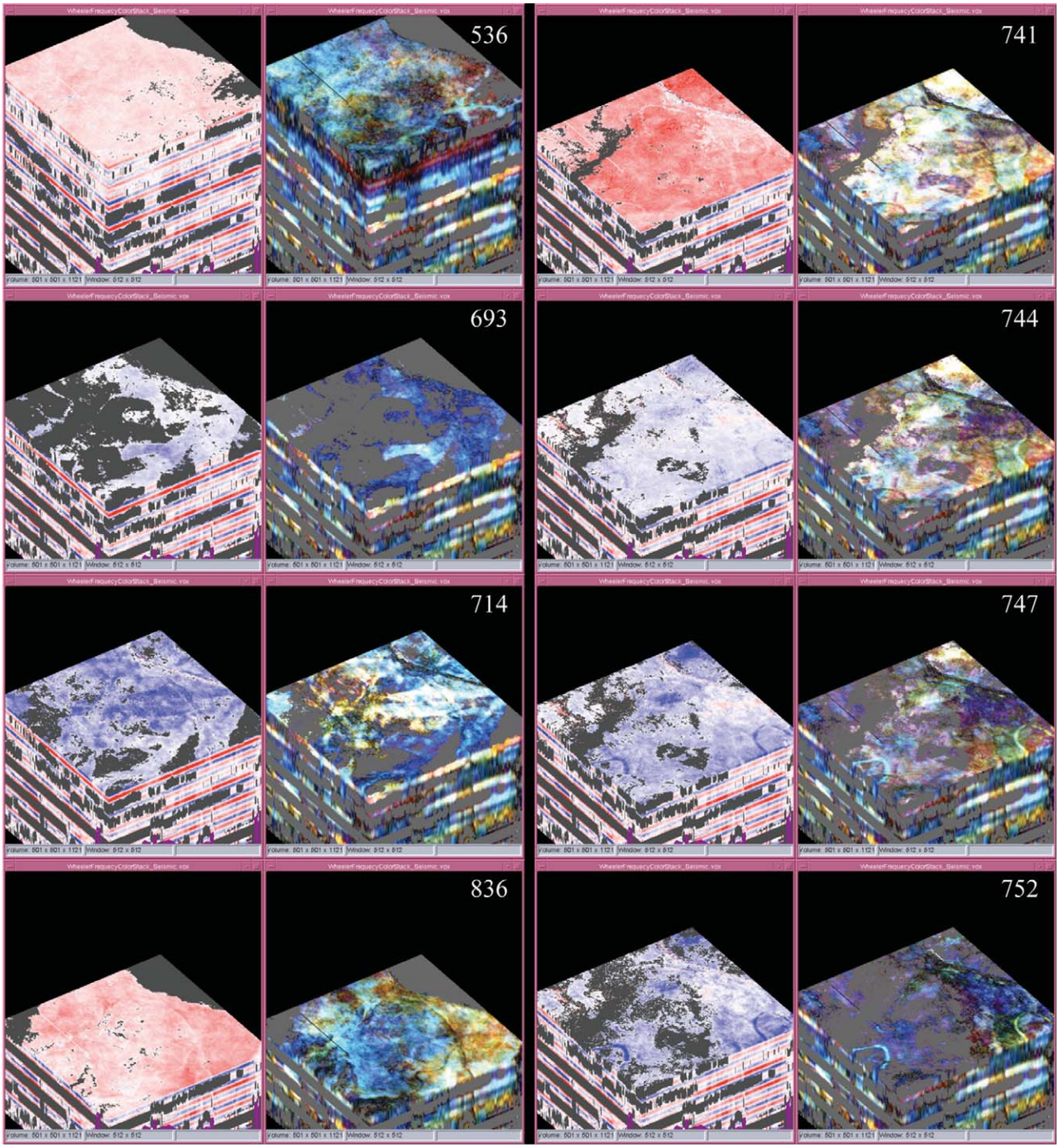


Figure 12 *Eight pairs, in two columns, of Seismic-Wheeler (left) and ColorStack-Wheeler (right) volumes. The top stratal slice of these pairs is incremented by a half to several cycles in the left hand column, while it is only incremented by a fraction of a cycle in the right hand column. The white numbers represent the relative geologic time of the top stratal slice. There are 32 relative age slices per cycle in this set of volumes. The grey colour in these volumes represents hiatus locations. The spectral decomposition ColorStack slices show significantly more stratigraphic detail than the standard amplitude slices. The colour variations in the ColorStack are assumed to be related to bedding thickness variations.*

right and is built as described above. In both displays grey is used to denote the hiatuses. The seismic constant age slice is similar to the stratal slices described by Zeng et al. (2001). However, the slices in Figure 12 contain hiatus locations, which are not present in the stratal slices generated by Zeng or others.

There are a total of eight pairs organized into two columns. In the column on the left, the age slices vary by over a half to many cycles. In the col-

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umn of the right, the four age slices are all from less than a half a seismic cycle. The white numbers in the upper right of each ColorStack-Wheeler volume represent the relative geologic time of the corresponding Wheeler volume pair. In this volume there are 32 relative age steps per cycle. The first thing to notice in studying these figures is the change in the shape of the hiatus area on the top stratal slice as a function of relative geologic time. It is not surprising to see the shape change when comparing two ages that are a cycle or two apart, as they are in the left hand column. However, the right hand column, where the ages are only a fraction of a cycle apart, there are also dramatic changes in the hiatus locations. This indicates the stratigraphic resolution contained in the Age volume.

The second thing to notice is that, within one pair of Wheeler volumes, the ColorStack colours typically exhibit significantly more lateral colour variations than seen in the corresponding seismic amplitudes. This indicates the power of the spectral decomposition and ColorStack technique. And finally, note the amount of colour, and therefore implied thickness variations in each ColorStack stratal slice. Particularly note the change from one stratal slice to the next in the right hand column. This indicates the vertical resolution of the spectral decomposition routine. Given that the decomposed spectra were summed into just three volumes for display purposes, how much more resolution would be available if the number of spectral stacks were increased?

Summary

This paper demonstrated several unique ways to view seismic volumes. The primary application was to investigate relative thickness variations as a function of relative geologic age and as implied by spectral decomposition. The spectral decomposition ColorStacks when combined with the Age volume allow previously unseen stratigraphic complexities to jump out of the images. These techniques allow an interpreter to quickly gain insight into the geological complexities of their data volume in a manner not previously possible.

The summing or grouping of the spectral decomposition results to generate the ColorStack displays clearly provides benefit. However, this spectral stacking is more likely to reduce the quality of the original decomposition than provide a 'square root of n' reduction in noise. Ways to display an increased number of 'spectral stacks' needs to be investigated. Ultimately, the Age volume needs to be combined with the individual spectral volumes to allow the frequency volume animations (briefly mentioned above) to be constrained by relative geologic time.

At this point the colour of the ColorStack is a qualitative indication of bedding thickness. Detailed modelling needs to be done in order to allow for a quantitative calculation. Further, the sensitivity of the ColorStack results to the particular spectral decomposition method is not known – this could be a topic of a future paper. For this type of 3-component spectral decomposition, the temporal resolution of the decomposition method is most likely more important than the frequency resolution.

The quality of the resultant Seismic-Wheeler and ColorStack-Wheeler volumes, as well as the sculpting displays, depends upon the quality of the input Age volume. Currently the generation of a high quality, high resolution Age volume is time consuming. A lower resolution Age volume can be generated much faster – but it will not allow the same amount of insights into the volume, and could cause the interpreter to get tricked by 'residual structure'. The high resolution Age volume is key to obtaining the hiatuses locations such as those indicated in Figure 7 and shown in Figure 12.

Figure 12 in particular illustrates the vast amount and detail of geologic information that can be gleamed from post-stacked seismic data. Look again at the right hand side of Figure 12 and note the amount of colour changes within this half cycle. It is a great example of Milo Backus's advice to 'interpret everything as signal until proven otherwise'.

In a printed paper it is not practical to illustrate the use of motion and interaction with a few static figures. The dynamic nature of the displays, particularly if they can be displayed in stereo, allows the interpreter significantly more insight into the data than a few static images. To help alleviate this problem, a QuickTime movie of the Wheeler volumes shown in Figure 12 was generated to illustrate the detail available as a function of relative time. This movie increments through all of the stratal slices instead of just showing the few slices selected for Figure 12. Those interested can contact the author at tstark3@verizon.net for a copy of the movie.

Note that as the volume size increases, so will the usefulness of the Seismic-Wheeler and ColorStack-Wheeler volumes for delineating sand delivery timing and play fairways. Although there is still a lot of work yet to be done, and a lot of questions to still be answered, the work presented here is clearly meeting our goals. Displays such as these both clearly help the interpreter to recognize and convey a large amount of geologic information in a small amount of time and allow you to clearly see what had previously been unseen.

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