Oops: An Introduction to Seismic Wavefield Visualization

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Summary

Despite all of the processes that we apply to our data, both processing and interpretation are ultimately visual sciences and our ability to make informed decisions rests heavily upon the effectiveness of the display at communicating coherent seismic information. Conventional seismic displays, however, cannot be considered as true seismic displays; they are seismic amplitude displays. A seismic wavefield is not defined by amplitude alone. It is continuous in both time and space and the amplitudes we record only represent one small part of the total wavefield.

To fully visualize a seismic wavefield we must also visualize the connections between the amplitudes. It is my assertion that those connections contain far more information than the amplitudes alone and that by ignoring them we discard entire levels-of-detail of significant coherent information.

A single unmigrated seismic section is examined using both conventional seismic amplitude displays and various seismic wavefield displays with the intent of proving that conventional seismic amplitude displays are incapable of imaging what should be visually dominating coherent features. An argument is made that we should adopt seismic wavefield displays for both processing and interpretation and that we should begin investigation of the features that they reveal.

Introduction

Mindset: *In decision theory and general systems theory, a mindset is a set of assumptions, methods or notations held by one or more people or groups of people which is so established that it creates a powerful incentive within these people or groups to continue to adopt or accept prior behaviors, choices, or tools.*

Oops: *"The view beyond a mindset."*

A seismic section contains an almost limitless amount of information all of which must be communicated to the viewer visually. An interpreter's ability to make informed decisions rests heavily upon the display's ability to communicate that information in a compact and meaningful way. Since the advent of digital signal processing in the late 60's, we have made great strides in improving seismic resolution and yet, for the past 30 years, our ability to communicate that resolution to the interpreter has remained static.

Today, almost all seismic data is still viewed using the same combination of wiggle trace displays, chromatic variable density displays and achromatic grey scale displays as it was over a generation ago. These displays are so entrenched in our working lives that the view of seismic data they present has become a mindset. That mindset entrenches in us an outdated notion that what we are working with and have worked with since the dawn of the digital era is seismic data. Nothing could be farther from the truth.

Conventional seismic displays, despite their venerable familiarity, cannot be considered as true seismic displays; they are seismic amplitude displays and the distinction is important. A seismic wavefield is not defined by amplitude alone. It is continuous in both time and space and the amplitudes we record only represent one small part of the total wavefield. What are missing, what we do not record, are the connections between the amplitudes. It is those connections that define the wavefield and it is the information contained within them that, because of technological limitations, we have never investigated.

Fortunately, the advent of gpu technology places those technological limitations firmly behind us. By using a model of how the amplitudes connect, we can now visualize the full seismic wavefield, move beyond our mindset and investigate if there is anything in the connections that was not in the amplitudes.

Questions

The concept of visual resolution is not new. There are three seismic amplitude displays: the wiggle trace display, the chromatic variable density display and the achromatic grey scale display. We already know that no single display or even combination of displays can image all of the myriad signals contained within a seismic section or record. The visual resolution of each display is different and we accept that when we use one of them to view seismic data, there is always information left behind.

Both processing and interpretation, however, are predicated upon the assumption that a signal resolved in the data is perceptible in the display and that the theoretical limits of resolution, as determined by the processes applied to the data, and the working limits of resolution, as determined by the display, are virtually the same.

> *But what would it mean if they weren't?*
>
> *What would it mean if the visual resolution of the displays that we have used, almost unchanged, since the dawn of the digital era, were orders of magnitude less than the theoretical resolution of the data?*
>
> *More to the point, how would you know?*
>
> *And, even more to the point, what word would you use, when you realized it!*

Where are the Diffractions?

The purpose of this talk is to challenge the viewer's mindset about what seismic data is and what signals are contained within it. Obviously, proving that every seismic record or section contains levels-of-detail of previously unperceived signals is beyond the scope of a single presentation. This talk will focus only upon establishing the possibility that this hypothesis is true. To that end, I will use the images in this talk to examine a single question:

"Is it possible that conventional seismic amplitude displays filter out entire levels of detail of relevant information?"

Along the way, I will also introduce some of the psychophysical aspects of vision that are central to this research and show how, inadvertently, we have already brought them into play.

The images in this section are all of a single, unmigrated seismic section. The section is highly faulted and contains numerous major and minor faults all of which should cast off diffraction hyperbolae. Those diffractions should be the most dominant features of the data but we rarely notice them in practice.

So have they been filtered out by the processing or by the display? I will begin to answer that question by taking a new look at a venerable old display and explaining why, despite its obvious limitations, it is still the display that many interpreters turn to first.

Seismic Amplitude Displays

Wiggle Trace Displays

In this section, I will examine the visual resolution of various types of seismic displays. I have chosen to begin with seismic's oldest display because many geophysicists, myself included, learned about seismic by studying wiggles. And we still find them fascinating although the reason why has always been a mystery. There is an answer and it has implications for the future but to find it we have to look deep into our visual system.

Figure 1 is graphical representation of a hypercolumn, one of the first processing stages of our visual system and it earned its discoverer (Hubel, 1968) a Nobel Prize. Hypercolumns are the base layer of our visual perception and they are nothing more or less than sophisticated edge detectors. They feed into the higher layers of the visual cortex where they are processed for many things but mainly for pattern recognition. This explains why wiggle traces are so fascinating and so essential to an interpretation. In combination with the most fundamental level of our visual processing system, they form the world's best seismic pattern recognition engine. No other display or process comes close.

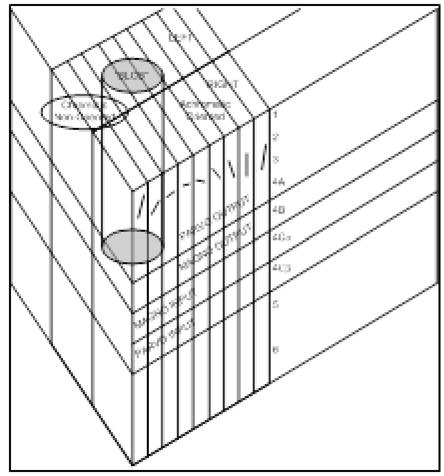

Figure 1: "Representation of a hypercolumn in visual area V1 of the primate brain.

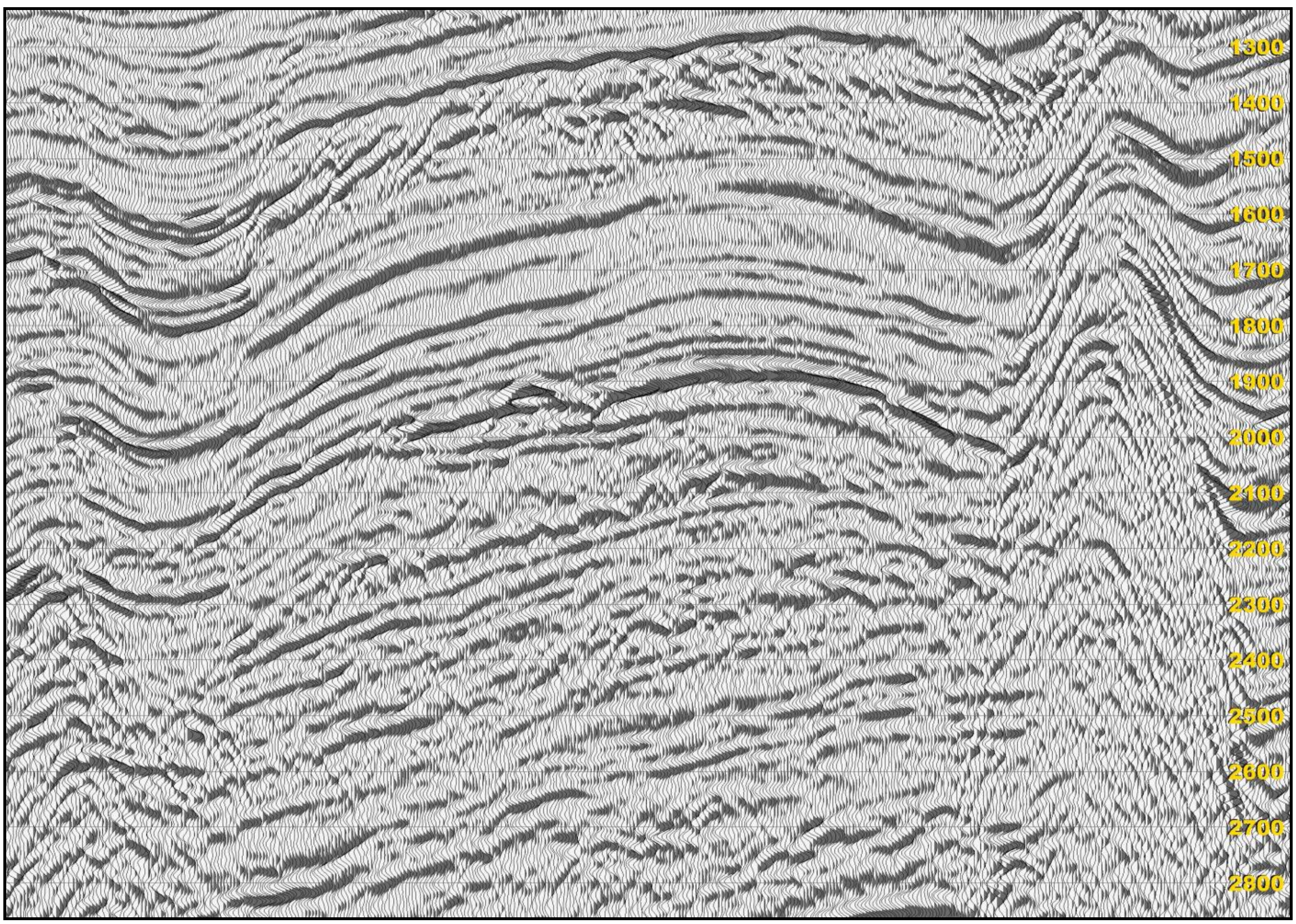

Figure 2: Wiggle trace display of an unmigrated section (data courtesy unnamed source). Note the complex faulting and the salt intrusion on the right. Despite the many obvious and significant terminations in this data,

there are few visible diffractions. Are the diffractions absent from the data itself or are they simply not visible in the display?

Unfortunately, patterns are only a part of the information contained within a typical seismic section. In general, wiggle trace displays have the lowest visual resolution of any of the conventional displays. Consider Figure 2. Viewing it, any season geophysicist would be able to tell you that the presence of subtle diffraction hyperbolae on the display proves that the data is unmigrated. But they could only comment in a general sense and in exploration, we live with the details. The details in this case are first the number of diffractions that given the level of both major and minor faulting, should be visible and second, the amplitude, frequency and phase characteristics of each of them. Of that information, this display is virtually silent.

This is the conundrum of wiggle trace displays. Their low visual resolution makes them unsuitable as a general purpose display but because of their particular nature, they are essential for examining waveforms and character changes.

Achromatic Grey Scale Display

Chromatic variable density displays and grey scale displays are virtually the same. Both produce an image by referencing seismic amplitudes to values in a palette, the only difference being that grey scale displays use a purely achromatic palette. While this may not seem significant, because of this one simple difference, our visual system processes each display separately and for entirely different purposes.

When we view a scene, we are only conscious of a single image. This is remarkable because that image never exists anywhere in the brain. Our visual system, as illustrated by Figure 3, instead first produces a single achromatic neural channel, which it uses to form the base of our perceptions and then it forms two chromatic neural channels, which it uses to modify those base perceptions.

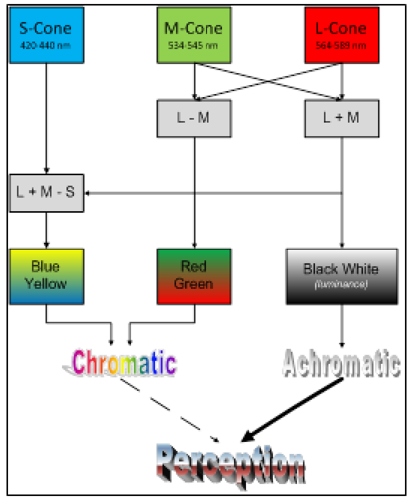

Figure 3: The Hering Theory of Opponent Color Vision.

Neither grey scale displays nor variable density displays supply our visual system with all of the information it needs to turn an image into visual perceptions. We process grey scale displays to produce our perception of form, which is why they often appear to be virtually three dimensional but they lack details. We process variable density displays to fill in the details.

But details of what?

There are two problems with the grey scale display shown in Figure 4. First, the image is unnatural because it linearly maps amplitude to intensity. Our achromatic channel may have evolved to process patterns of light and dark but it expects those patterns to be of reflectance. Reflectance maps the slope to intensity and as I will show later, it looks very different and contains far more information. Second, there are no details. We can identify more diffractions than we did on the wiggle trace display but they are featureless. Almost all of the amplitude, frequency and phase information is lost and it always will be. This display simply lacks the visual information to provide such intricate detail.

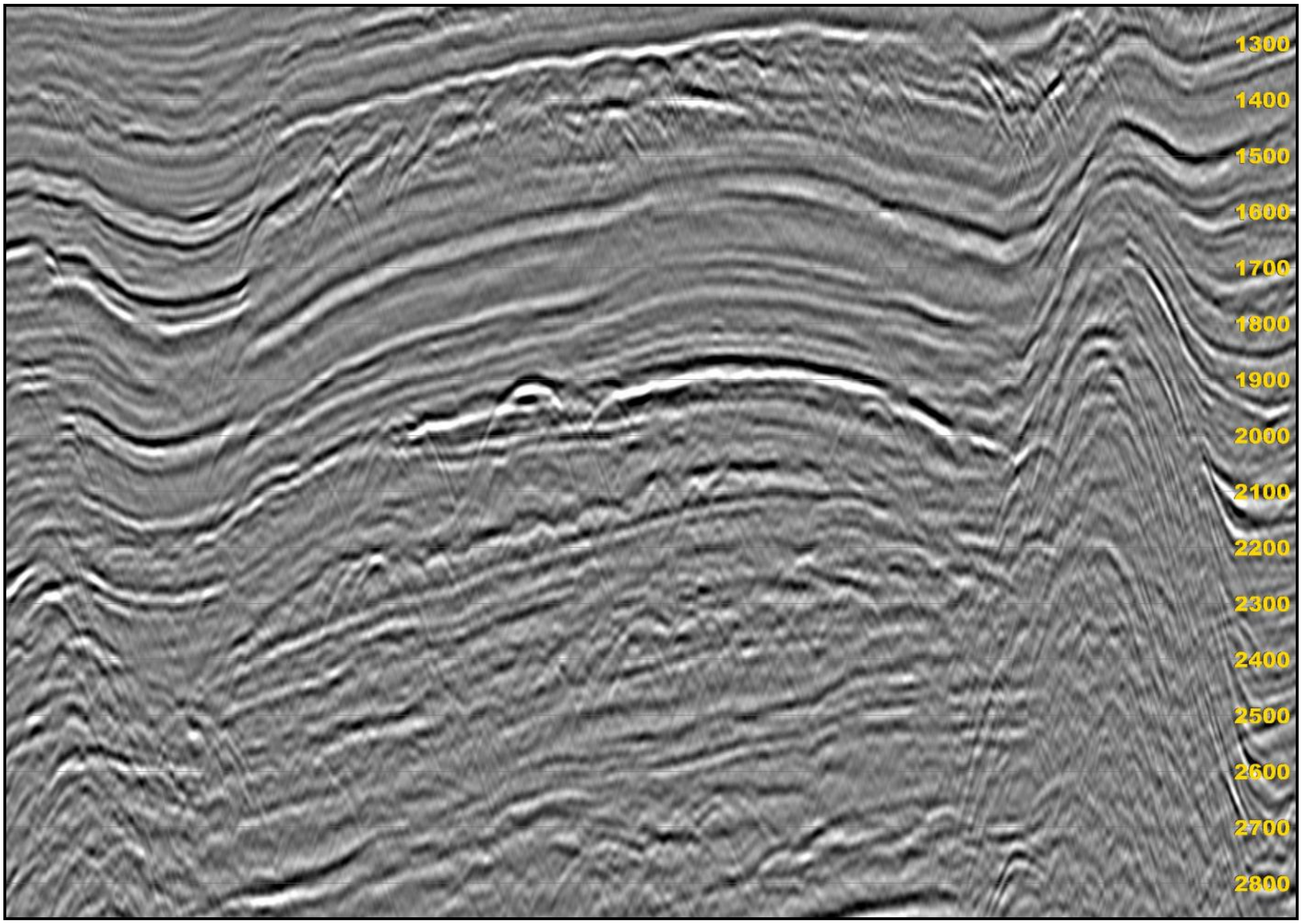

Figure 4: Grey scale display of the data shown on the previous page. Grey scale displays are purely achromatic and linearly map seismic amplitude to intensity. Unfortunately, whereas a computer monitor or printer may produce 16 million colors, only 255 of them are grey. As a result, the display while proving that the diffractions exist can provide very few details about them.

Chromatic Variable Density Display

A common misconception is that humans, along with our old-world primate relatives, can see color. Our retina does contain three cone pigments but those cones do not produce color coded signals. In fact, surprisingly, there are no hue specific signals anywhere in our visual processing system. As a result, we do not see color; we perceive color and that perception is only formed by contrast.

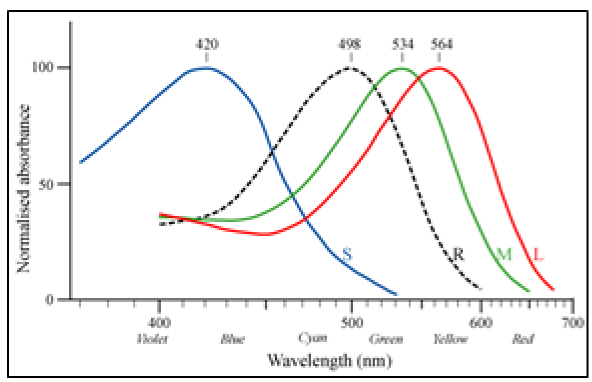

Figure 5: Absorption spectra of the three catarrhine cone pigments plus the rod spectrum (broken line).

We also do not perceive color very well. Mammals were nocturnal for most of their history and we lost two of the original four pigment genes. It appears that old-world primates have three but in reality, two of them, the M and L cones, are slightly mutated copies of the same gene. This mutation improves our ability to discriminate colors in the red-green area of the spectrum but in general, our ability to discern hue throughout the entire spectrum is less than that of birds, fishes, reptiles and nearly all of our early Devonian ancestors.

What this means in practical terms is that we are not color obsessed creatures. Color lets us discriminate ripe fruit and young leaves but beyond that, from an evolutionary perspective, it is of little interest to us. That is why variable density displays are so inefficient.

Consider Figure 6. The color palette is tuned so that high amplitudes are represented in yellow, a color that attracts our attention, whereas other amplitudes are either green or blue, colors that are of little interest to us. The image conveys so little information, especially about the diffractions, that even an experienced interpreter might look at it several times before realizing that it is unmigrated. It is not a matter of losing details of the diffractions, visually, they simply do not exist. And on this form of display, they never will.

This is not a palette issue! Interpreters often have their own preferred palette and research is ongoing to find the best way to map amplitude to color. In my opinion, these efforts are bound to fail. We will never produce a palette that communicates the full spectrum of seismic information because we simply lack the color discrimination ability to see all of the nuances of seismic amplitudes.

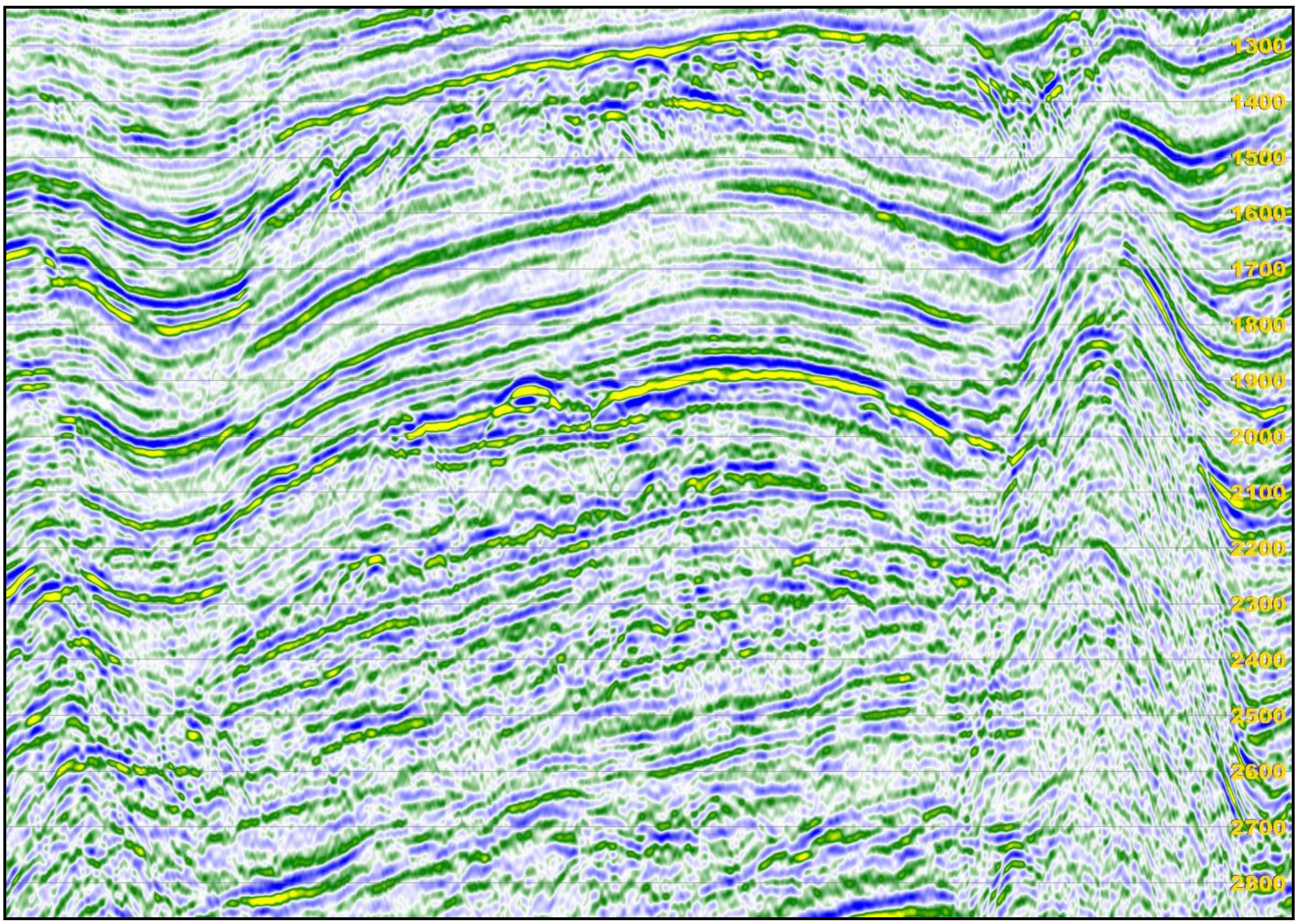

Figure 6: Variable density display of the data shown on the previous page. Blue represents negative amplitudes, white represents zero amplitude and positive amplitudes grade from white to green to yellow. Despite our best effort at translating seismic information to color, there are fewer diffraction hyperbolae visible on this display than there are on the previous wiggle trace display.

Seismic Wavefield Displays

Reflectance Display

Despite our familiarity with conventional displays, seismic data does not naturally form an image, chromatic or achromatic, and the seismic wavefield does not naturally segment into individual traces. The seismic wavefield naturally forms a three dimensional surface, one in which the amplitude of a sample provides the topography.

Seismic data often contains myriad overlapping and often contradictory signals and consequently, the seismic surface is never unique and representing it is a non-trivial exercise. In representing it, the most important element is reflectance, also known as shaded relief, which is simply a picture of how a surface reflects diffuse light of a given orientation.

Like a grey scale display, reflectance, as shown in Figure 7, is purely achromatic and therefore processed by our primary neural channel. In contrast, however, reflectance maps the slope of the surface to intensity rather than the amplitude. Consequently, the resultant image is more natural and our visual system is able to interpret it correctly. Comparing grey scale as shown in Figure 4 and reflectance as shown in Figure 7, it is clear that mapping the slope rather than the amplitude provides significant improvements in our ability to both identify diffractions and to follow them as their amplitude drops far below those of the reflectors they cross.

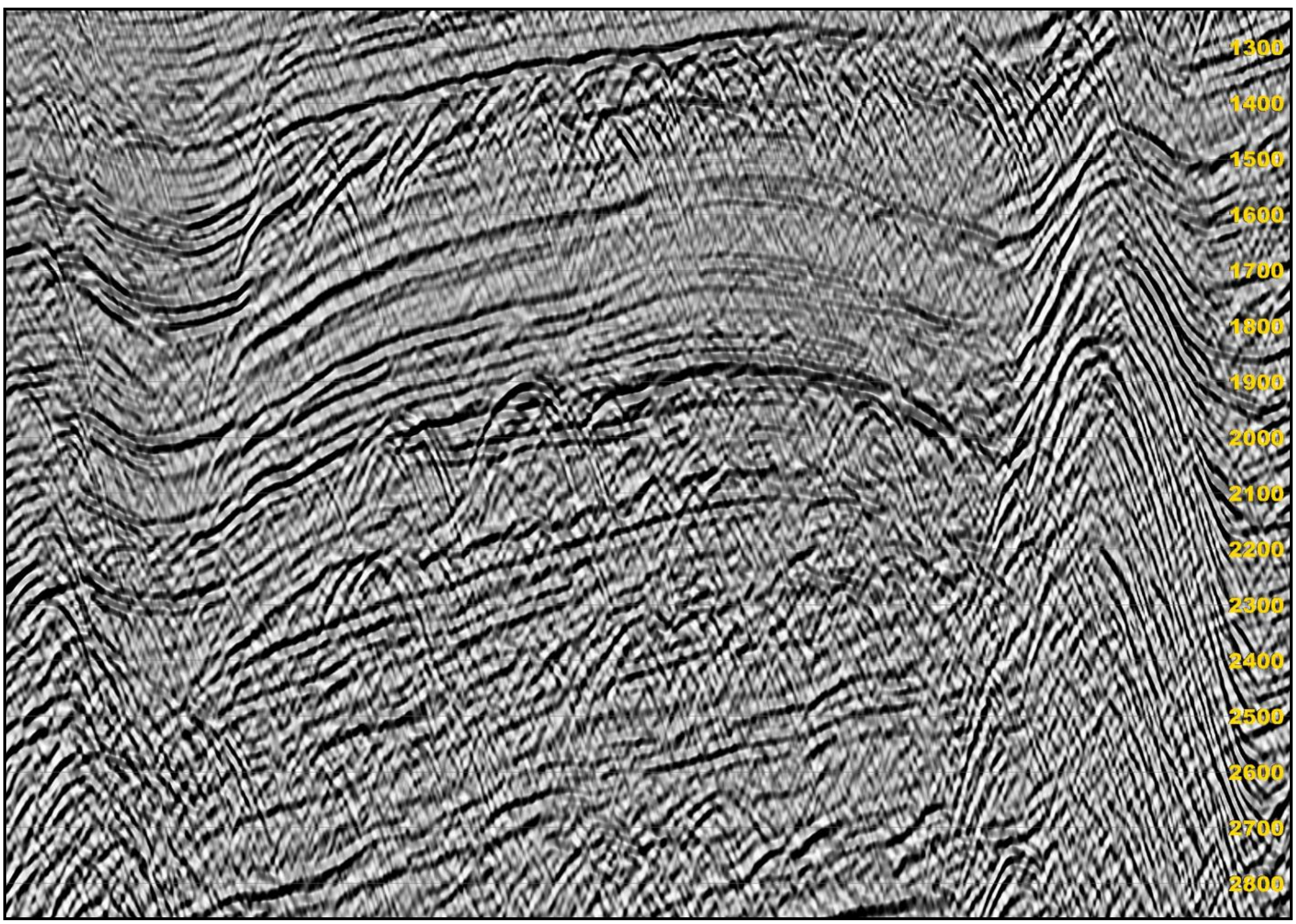

Figure 7: Reflectance display of our test data set. Reflectance is a picture of how a surface would reflect light of a given orientation (in this case from the upper left). Because it is a more natural presentation, our visual system is better able to interpret it and form the correct perceptions of the surface.

Chromatic Reflectance Display

Reflectance is achromatic and while it provides a better perception of the shape of the seismic surface and the intricate diffraction hyperbolae than a grey scale display, it only provides half the information that we need to fully visualize a surface. The other half comes from the color, which is contributed here by the variable density display shown in Figure 6.

Figure 8 uses a process called bump mapping to combine the reflectance and variable density displays into a single image. When we look at it, we are only aware of one image but behind the scenes our visual system extracts the chromatic and achromatic information into separate channels. As a result, this image produces the same perception of the wavefield as did the reflectance display but now modified by information supplied by the color.

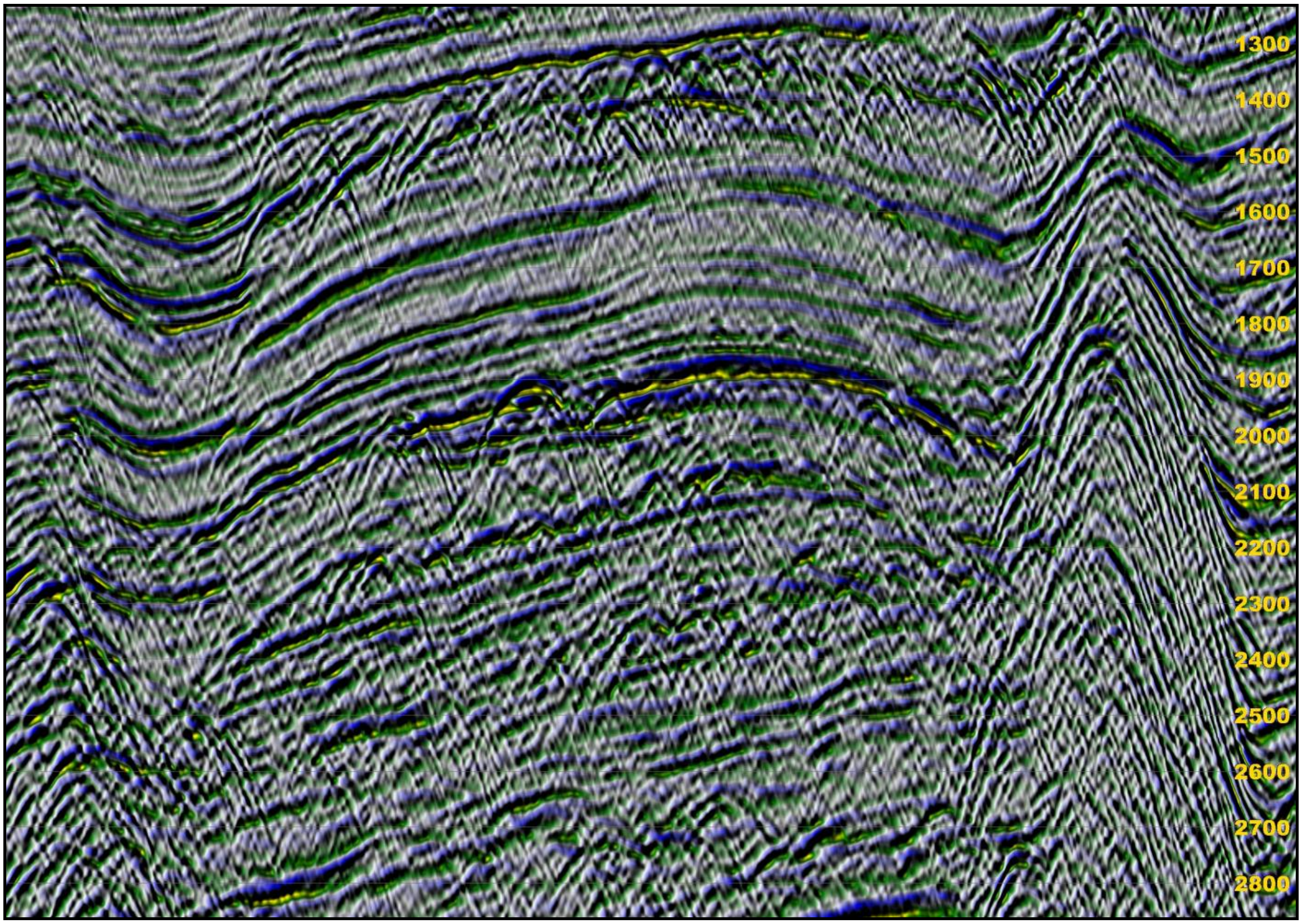

Figure 8: Chromatic reflectance display that combines the chromatic variable density image of this data with the corresponding achromatic reflectance image. Our visual system processes chromatic and achromatic information separately in parallel neural circuits. Consequently, this image provides the same achromatic perception as does the reflectance image but modifies it with the amplitude information from the variable density image.

One of the more useful features of this type of display is that it frees us to use color for more appropriate purposes. In the past, we used color to represent the full spectrum of seismic information with very poor results. A chromatic reflectance image, however, communicates most of its information about a surface via its reflectance component. Color is only used to segregate the image and provide highlights. As a result, we do not need to do as much with the palette and we can concentrate on developing color schemes that best highlight specific features.

Given their compactness and ability to reveal subtle seismic features, chromatic reflectance displays should, in my opinion, become the default seismic display and should replace both grey scale and variable density displays. Wiggle trace displays, however, remain the best way of examining waveform and character and for that reason both displays are needed in the future.

Seismic Wavefield Display

Reflection seismology in exploration geophysics is almost a century old. The technology to display it correctly, however, has only been around for a few years. A seismic wavefield has always formed a three-dimensional surface but without modern teraflop gpu’s, displaying it in 3D was impossible. Technological limitations forced us to use amplitude displays that are a poor approximation to the surface. Those limitations are now gone and we are left with a question: “What would seismic data look like if it were invented today?”

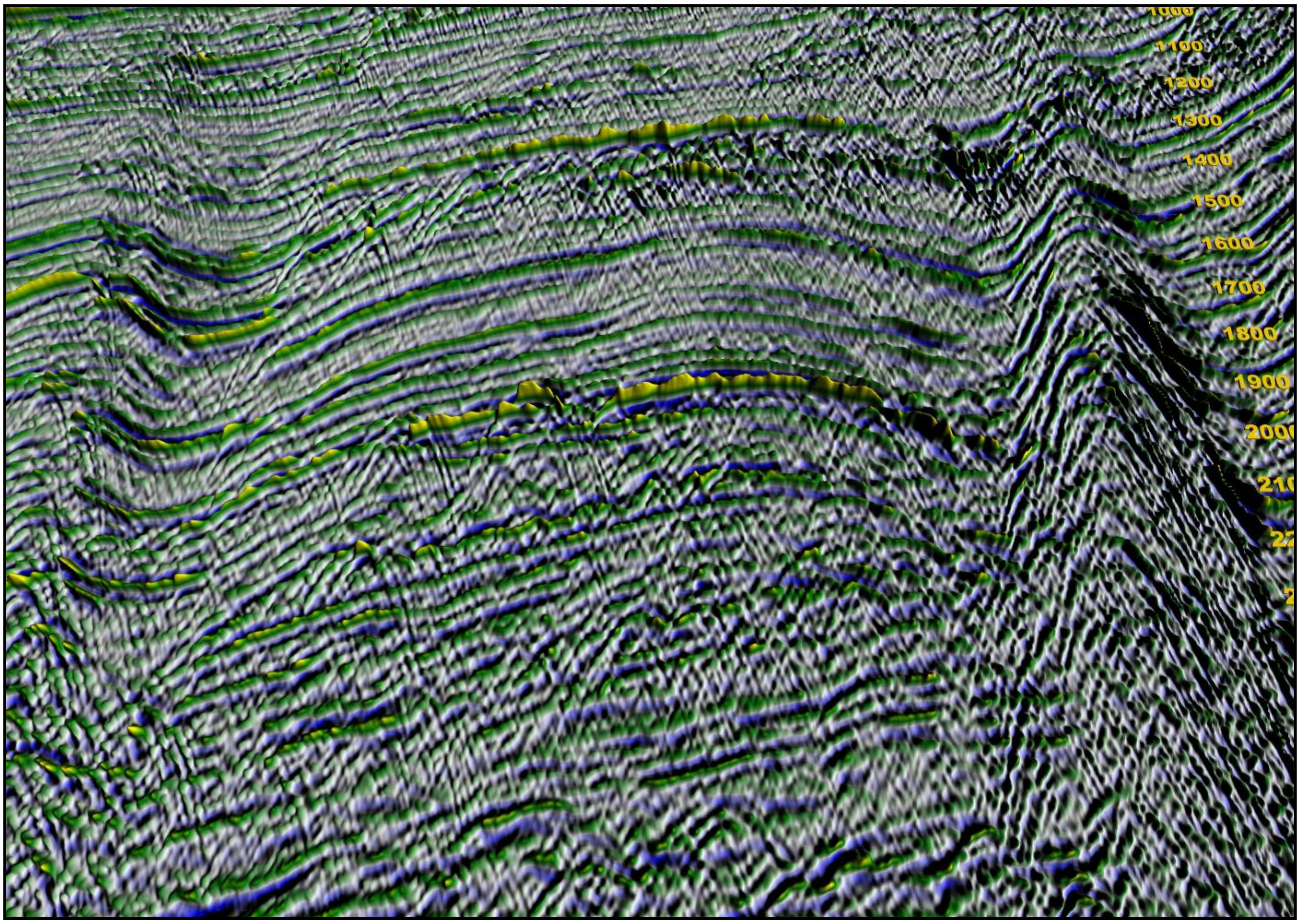

Figure 9: A seismic wavefield display physically (but non-uniquely) connects both adjacent samples and adjacent traces. Because of its three-dimensional nature, this type of display provides far more amplitude information than any other display, conventional or otherwise. As is clear from this image, however, the surface is not unique since any seismic section or record is actually a collage of overlapping and often contradictory signals

In my estimation, if, with all of our modern graphics technology, we invented seismic today it would like the seismic wavefield display shown in Figure 9. This is what a seismic wavefield looks like and all previous displays, including chromatic reflectance displays, are just approximations to it.

Even today, given the number of samples in a typical seismic section, producing and rendering a wavefield display is not a trivial exercise. Fortunately, chromatic reflectance displays provide much of the same information and they are easier to produce and work with. Amplitudes, however, are still a major issue. To fully appreciate the intricate and detailed nature of seismic amplitudes we have to look at a record or section in its true form, as a wavefield display.

Rethinking Resolution

When we think about resolution we typically think about it in terms of either spatial or temporal resolution, both properties of the seismic wavelet. When we apply deconvolution, spectral balancing, filtering or migration, we are working to improve one or both of those principal forms. One of the purposes of this talk has been to establish the possibility that we are working blind.

Consider, in detail, the wavefield display shown in Figure 10. When you first viewed the conventional amplitude displays of this data did you perceive or even suspect that the seismic under examination contained this level of detailed and intricate information? This is what a seismic wavefield actually looks like and this is how much information it actually contains.

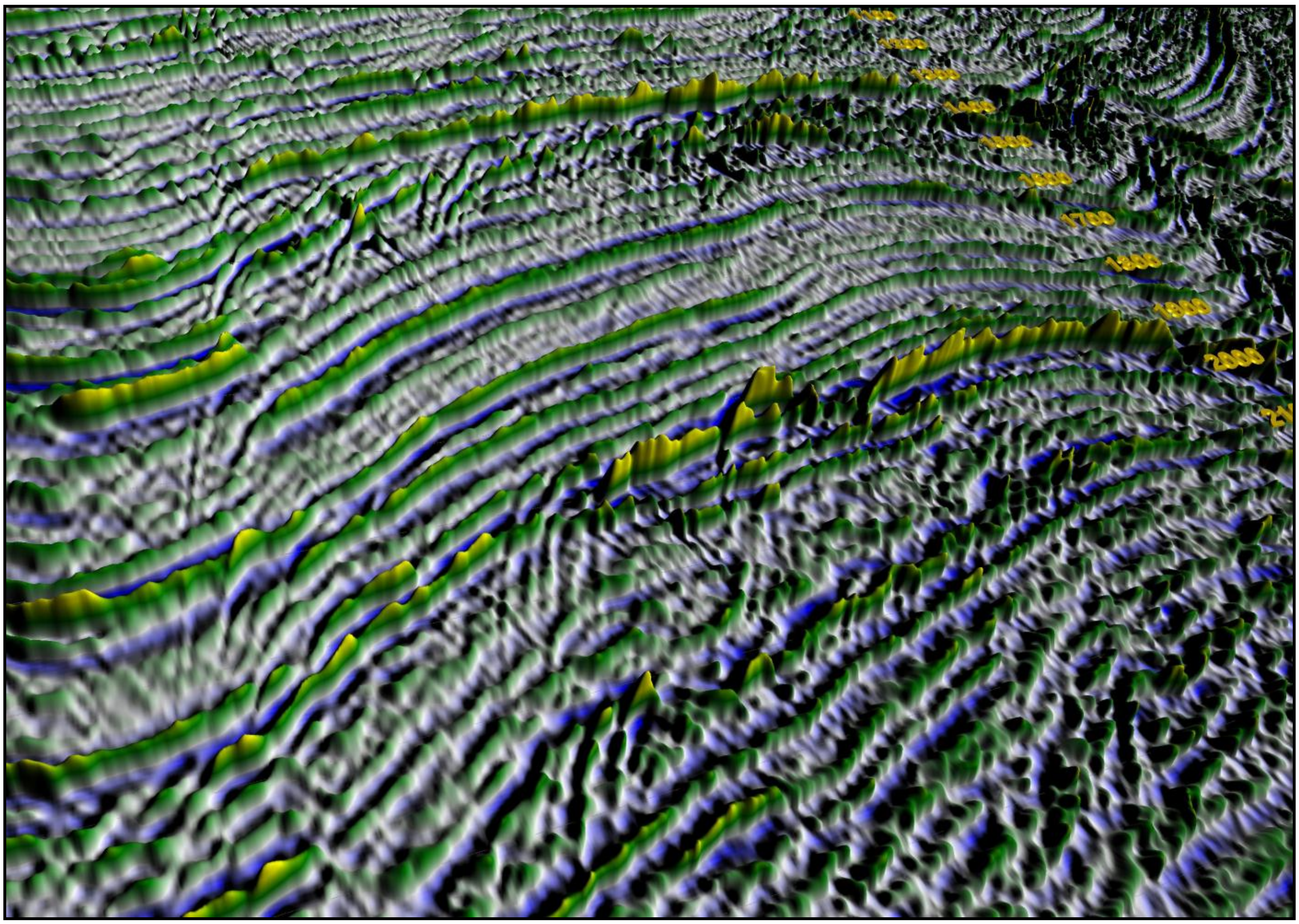

Figure 10: A seismic section is a complex mosaic of overlapping and often contradictory signals some of which are geologically based and some of which are noise. It is not the job of the display to discriminate between the two; that is the job of processing. The display must present all of the information contained within the data clearly, compactly and dispassionately.

We do not, of course, interpret unmigrated data but this has been more than just a theoretical exercise. I used diffractions to illustrate the point that conventional amplitude displays do not just filter out subtle information. The diffraction hyperbolae in this example are hardly subtle; they have strong amplitudes; they dominate the section and yet we can barely see them at all on seismic amplitude displays. Depending upon the display, you might even miss them entirely.

We may not be all that interested in diffractions but if we were, we would have to accept that the difference between the theoretical and working limits of resolution on the displays we have used all our careers, is far greater than we realised and far greater than we can accept.

You can argue that we do not need to see diffractions but can you argue that we should accept a situation where we cannot see things as dominant as diffractions?

One of the questions that I posed at the beginning of this section was: "What would it mean if the theoretical and working limits of were not even close?" What it would mean, in my opinion, is that the entire seismic method would be thrown into question.

Conclusions

The purpose of this talk has been to introduce the viewer to the concept of wavefield as opposed to amplitude visualization and to establish the possibility that by restricting ourselves to the latter, we have inadvertently filtered out many of the signals we have worked so hard to produce.

I began the presentation with a question:

> "Is it possible that conventional displays filter out entire levels of detail of relevant information?"

Comparing any of the reflectance or wavefield displays to any of the conventional amplitude displays shown earlier, the answer, I believe, has to be "yes". As inconvenient as they may be, we cannot simply ignore the implications of that answer.

A good mindset may be a terrible thing to waste but in my opinion, if we are to make further progress in our pursuit of resolution, we must move beyond our well established visual mindset and investigate those seismic signals that are contained in the wavefield but not in the amplitudes.

References

Hubel, D. H. (1968). Receptive fields and functional architecture of monkey striate cortex. J. Physiol. (Lond.), 195: 215-243.