Visualization, interpretation, and cognitive cybernetics

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Abstract

Interpretation of 3D seismic data involves the analysis and integration of many forms and derivatives of the original reflectivity data. This can lead to the generation of an overwhelming amount of data that can be difficult to use effectively when relying on conventional interpretation techniques. Our natural cognitive processes have evolved so that we can absorb and understand large amounts of complex data extremely quickly and effectively. However, these cognitive processes are heavily influenced by context and color perception. Seismic interpretation can benefit greatly through better exploiting the positive aspects of visual cognition and through techniques designed to minimize the pitfalls inherent in the cognitive process. The interpretation of data also requires the ability to combine data analysis with knowledge and expertise that is held by the interpreter. It is this combination of visual perception techniques to see the information, combined with interpreter guidance to understand what is seen, that makes interpretation of seismic data effective. Geological Expression workflows that are data driven and interpreter guided enable us to see and effectively interpret the geology that is present in the seismic data. In effect this gives us a Cognitive Interpretation of the data.

Introduction

Seismic interpreters face an enormous challenge to convert an ever-increasing amount of data into improved exploration success and better recovery. Seismic data contain vast amounts of information, and interpreters need to analyze several attributes of the data simultaneously to understand the behavior of geologic systems. A high level of cognition is required to collate the different types of information into a single, comprehensive interpretation in which heterogeneous information is progressively transformed into coherent models.

It is now common to have a whole suite of seismic volumes covering the same area, all of which tell different parts of the story. The driver behind this proliferation is the desire to obtain a more refined understanding of the subsurface. As a result, we are pushing the limits of what seismic imaging technology can do particularly in areas in which the seismic imaging problem itself is more difficult. A second issue is that, no matter how good the data, they are still incomplete and ambiguous representations of the subsurface and hence the need for seismic interpreters who understand geology and geophysics. This means we are often drowning in seismic data, while struggling to solve what are very complex problems, often with very tight deadlines. Trying to work through enormous amounts of data very quickly with inadequate tools leads to cognitive overload and much of the available information being disregarded.

At first sight, the solution to this problem may be expected to lie in automation of the interpretation process, and a lot of progress has been made in the development of powerful computational techniques for analyzing objectively the information content of seismic data. However, application of such techniques on their own "does not an interpretation make." Interpretation is the process of explaining the meaning of something, which is one task that humans are still far more effective and efficient at than computers. However, if we can bring the power of computational-based approaches and the human visual cognitive process together more effectively, we can make a step change in the efficiency with which we can interpret seismic data.

Human visual cognition

Human visual cognition is a big subject in its own right, and one in which there are many unknowns and plenty of controversies. Two of the key strengths of visual cognition that we instinctively harness in seismic interpretation are context and association. These are at the heart of how we understand and interact with the world around us. To make more effective use of visual cognition in seismic interpretation, we need to understand the strengths and weaknesses of the human visual system, and how these can influence what we see and the decisions we make.

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Context and association

A critical aspect of human visual cognition is that it is very good at constructing unified entities from incomplete and ambiguous data. It is an inherently multiscale process that simultaneously comprehends local inferences within a whole-scene context and links at conscious and unconscious levels with world knowledge and heuristics that make these inferences effective. Context and association are critical to how we understand the world based on visual stimuli. We can illustrate these properties of the human visual system by some simple examples (Figure 1). What most of us recognize when we first see Figure 1a is just a few black shapes on a white background. However, if we give ourselves a bit more context (Figure 1b), we can infer that we are looking at a panda holding its cub. We see this despite there being no panda-shaped objects in the image at all; we are associating very disparate shapes into an object that we recognize as a panda because of their spatial relationship. Once we know that we are looking at the panda, if we take the additional context away, we will still recognize this image as showing part of a panda because the association remains. In addition to this, we can start to draw in the missing outline of the panda cub (Figure 1c). How we position this outline is driven more by what we think a panda cub looks like than the information in the image. There is certainly no boundary in the image for us to track. This is central to how we interpret seismic data. The fact that we see geologic structures in seismic data is as much because the knowledge base that is stored in our minds as it is to the information that is contained in the data themselves.

Related to this is our ability to almost instantaneously identify and classify objects that we see in an image with a very high degree of reliability without the need to have seen exactly the same object previously. For example, in Figure 2, we immediately recognize all these images as being pictures of houses despite their obvious qualitative (and quantitative) differences, for example, in shape, color, and composition. We do this subconsciously through processes that are poorly understood but which rely very heavily on past experience so that we are supplementing the image information with knowledge from other sources to make

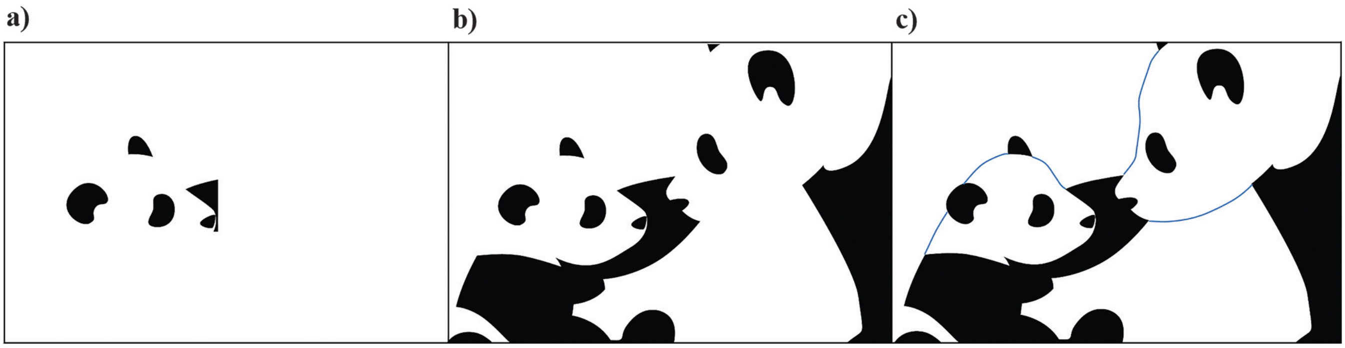

Figure 1. The effect of context in the human visual system. (a) On first sight, a partial view of the image is perceived as random black shapes, (b) when the full image is seen, the context of those initial black shapes becomes apparent and the meaning of the image is understood, even though it is comprised of disparate shapes, and (c) once the meaning of the shapes is understood, it is possible to draw in the missing sections of the image.

Figure 2. These buildings are all immediately recognizable as houses, even though there are obvious differences in shape, color, and composition. This is because of our cognitive ability to relate what we see with past experience and knowledge.

inferences. This means that how we understand images is as much dependent on our experience and knowledge as it is on the image data itself. Again this is at the heart of how we interpret seismic data.

The dependence on knowledge and experience can be illustrated by looking at a more technical example (Figure 3). Whether or not we see these as an image of a piece of rock and a wild landscape or two images of different types and scales of geologic faulting is dependent on whether or not we have a knowledge of geology. At the present time, we are quite some way off in being able to match this human facility computationally. The less complete and more abstract the representation of the object, the greater the level of expertise required to correctly infer what we are looking at. Seismic data are a very abstract representation of geology; it therefore follows that if we can convert seismic data into a set of less abstract representations, then we should be able to improve the reliability of our interpretations and confidence in them and also the efficiency of the interpretation process.

Figure 3. A nongeologist is likely to see an image of a rock and a landscape. A geologist is likely to see two examples of faulting. Our knowledge and experience guides how we interpret an image.

Color perception

However, the visual cognitive system is far from foolproof as the ease with which optical illusions can be generated testifies. The eye's varying sensitivity to color greatly impacts on how we interpret information presented in the form of an image. For example, Figure 4 shows a circle in which the intensity increases as you get closer to the center. When this is displayed using a grayscale color bar, it looks like the intensity varies smoothly, which it does. However, when we use a spectrum-type of color bar, we see a set of rings of varying width and what look like almost step changes in intensity among these rings (Froner et al., 2013). This is because the sensitivity of the human eye is not constant across the color range. This phenomenon is known as *false contouring*, and it can have a significant impact on how we assign structure to an image and how we assess the size of objects with diffuse boundaries.

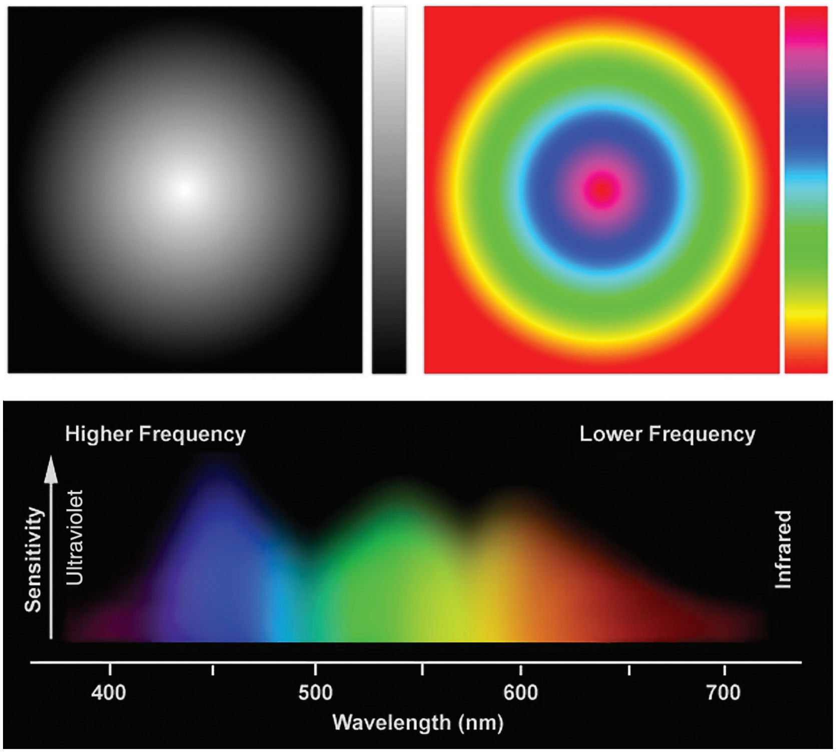

Figure 4. False contouring is apparent when using a spectrum color bar because of the eye's varying sensitivity to different wavelengths of light.

Another issue with the human visual system is that it is based on a relative assessment of the visual stimuli so that what we see depends on an object's context (as mentioned earlier). This means that visual comparisons are often unreliable. In Figure 5, most people would say

Figure 5. Simultaneous contrast makes us perceive the inner square as a different shade of gray in each of the three boxes, whereas they are in fact an identical shade of gray.

that the inner square is a lighter shade of gray as you go from left to right, whereas in fact it is exactly the same gray level in all three images. This is a phenomenon known as *simultaneous contrast*.

What are we interpreting?

As we know, humans are very good at perceiving patterns and making connections between multiple pieces of information when that information is presented in the form of an image. However, the way that our visual system reacts to color and the amount that this varies from observer to observer hamper our ability to make reliable measurements from image data.

This can be illustrated with a simple example (Figure 6). What we have here is an amplitude extraction, which was interpreted as showing a spit system intersected by a channel. To the human observer with experience of working with this type of data, these features are obvious and we can quite easily draw a polygon to delimit the extent of the features that we can see.

With something that is as clear an amplitude anomaly as the spit in Figure 6, you would have thought that it would not matter how we display the image. For example, as shown here, the features are obvious no matter whether we use a spectrum, grayscale, or hot metal color bar. Therefore, in this case, feature recognition is not the main challenge. However, when it comes to defining the extent of this feature, it is far from easy. Just setting an image threshold does not work because the spit and channel have identical amplitude values, so we are left with manual interpretation.

However, doing this manually is not only tedious, but also, the result we get is very much dependent on who does the delineation and what color bar they chose as shown by the chart in Figure 6c. Eight interpreters measured the area of the spit system six times with each of the four different color bars. The results showed a systematic tendency for all interpreters to produce a tighter contour when the image was displayed with a grayscale colorbar compared with a spectrum color map and overall the largest area delineated was more than twice that of the smallest (Henderson et al., 2012).

Explicit encoding

The power of seismic attributes comes in large part from the fact that they allow us to focus on just one aspect of the seismic signal thereby getting rid of a lot of the clutter that hampers us seeing what is really in the data. However, we have already seen that the human visual system needs context to understand what it is seeing. Context comes from seeing different types or pieces of information simultaneously. Therefore, rather than looking at one attribute, we should be looking at two or three attributes at the same time. The most efficient way of doing this from a cognition perspective is a technique known as *explicit encoding*.

Explicit encoding computes the relationships between objects and provides a visual representation of the relationship, not just the data themselves (Gleicher et al., 2011). The type of explicit encoding that is being used most commonly in seismic analysis is color blending. By color blending three attributes using a red-green-blue (RGB) color scheme, we are conveying orders of magnitude more information to the observer than a single attribute display, but cognitively this has no impact on the time we need to absorb and process the information that is being presented to us (Figure 7). This type of explicit encoding requires much more sophisticated display systems than those commonly used in seismic interpretation.

The problem with 256 colors

Many seismic interpretation packages still rely on simple 8-bit color bars comprising 256 colors. This is

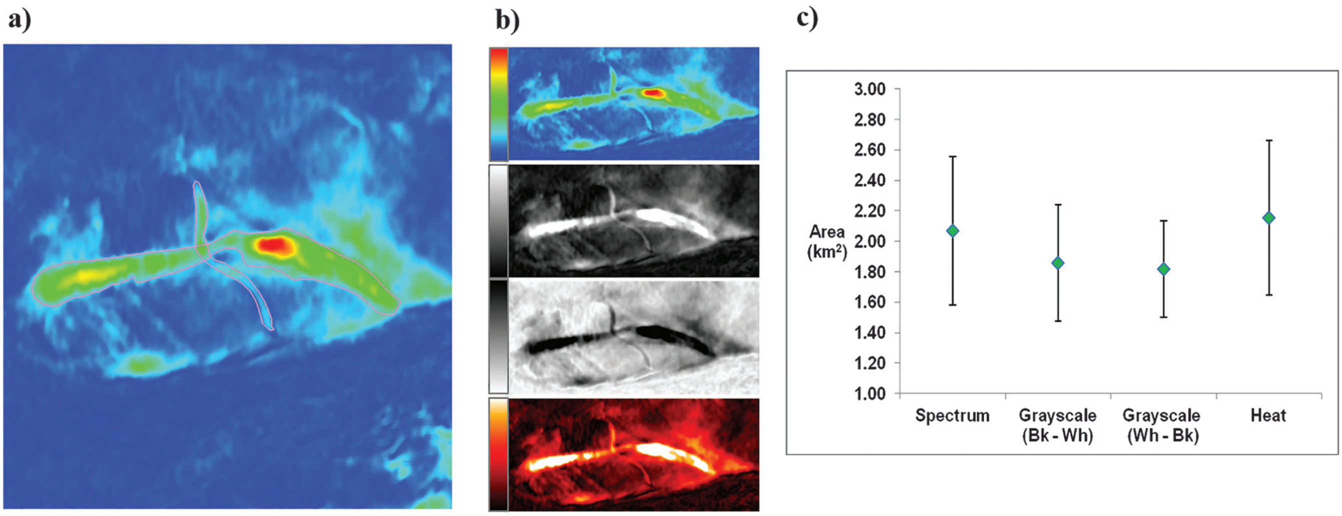

Figure 6. The effect of color on interpretation of a spit and channel system. (a) Envelope attribute showing a spit with intersecting channel, (b) the same data with four different color bars, and (c) the size of the interpreted spit varies depending on the color bar used (Henderson et al., 2012). Data courtesy of Lundin Norge AS.

hugely limiting even when trying to represent the information in standard reflectivity data, which is generally stored in at least 16-bit if not 32-bit precision, and it is certainly inadequate for explicit encoding of seismic attributes.

Explicit encoding has been around for many years, and it is responsible for producing some of the astonishing images that we are used to seeing from astronomy and medical imaging. It is not new in seismic interpretation (Henderson et al., 2007), with many examples of RGB blending of seismic attributes being presented in the past 10 years. However, one of the things that has hampered the uptake of this type of technology in seismic interpretation is the lack of tools for doing anything with these images. If we are to more fully harness the power of visual cognition in our interpretation systems, we need to go further than looking at color-blended images, we need to extract the information from them and use that information, in conjunction with our understanding of geologic systems, to build our earth models.

Cognitive cybernetics

Cybernetics is the continual process of feedback loops that close the gap between the current situation and the desired situation. They are present in electronics, robotics, computer programming, and importantly, human physiology is almost entirely controlled by cybernetic processes. *Cognitive cybernetics* is a more refined definition, referring to the neuronal feedback systems that govern how we learn, how we behave, and how we make decisions. Understanding these cognitive processes helps us to understand how we perceive the world around us and what influences our decisions.

Our understanding of what is in the seismic data (our mental model) begins with an initial "guess," and the mind continuously adjusts its hypotheses as new information is discerned through more in-depth interpretation of the data available. With each hypothesis, the mind refines its conceptual geologic model that it compares to information that is extracted from the available data. Misfits between the conceptual model and the observed data lead to the formation of a new hypothesis, which is then further refined as new information or new data becomes available. This cognitive circularity is the cybernetic process.

These fundamental aspects of cybernetics need to be considered during the software development process if we are to produce interpretation software that enables interpreters to work in a cognitively intuitive manner and not become overloaded by the vast amounts of data that can be created.

Cybernetic software design

The key to successful cybernetic interpretation software is interactivity. We need to see different attributes and parameters quickly and to combine images quickly and easily. It is important to remember that understanding is most effectively generated by looking at the relationship between different pieces of information rather than considering separate pieces of information in isolation. Therefore, the ability to easily compare and combine different pieces of information to create the full picture is a very important aspect of software design.

There are three main data-comparison techniques that enable the relationship between different data to be investigated (Gleicher et al., 2011):

1) *Juxtaposition* is looking at different pieces of information (or different realizations of the same information), which are visually adjacent to each other. It relies on short term memory to identify changes, and to be effective, the images must be within the space of an eye span. Juxtaposition is helpful for showing the differences between images because it keeps the different sources of information separate, but the human visual system is not particularly good at seeing the spatial relationship between objects presented in adjacent images of the same scene.
2) *Superposition* addresses this issue and refers to situations in which two images are overlain using opacity to display both images in a colocated position. This enables the relationship between the data in the two images to be seen by the interpreter.
3) *Explicit encoding* is the third and perhaps most powerful technique. In this case, the relationship between different images is analyzed to produce a wholly new compound image. When we have three images that we want to compare, then this can be

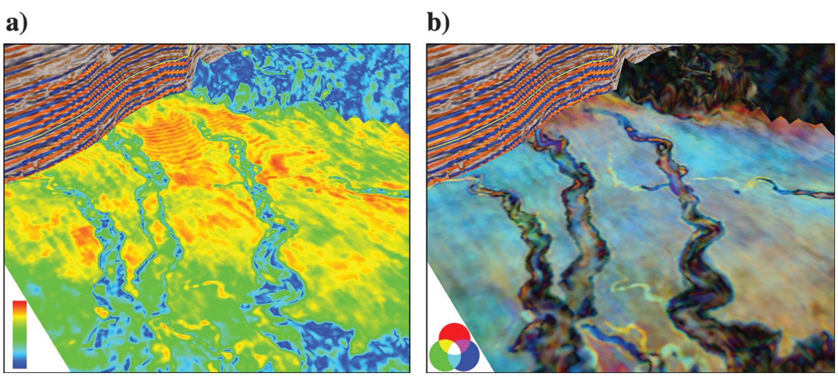

Figure 7. Explicit encoding in the form of RGB color blends reveals more information than one attribute alone. (a) Envelope attribute of turbidite channel systems and (b) RGB blend of three frequency magnitude responses reveals the channels and their depositional geometries with more detail and clarity.

performed very quickly and easily using color blending.

Example-driven frameworks (Figure 8) enable us to see different attributes and parameter sets simultaneously. We can then go through the cybernetic process in a matter of seconds, visually comparing the options in front of us, initially using juxtaposition and superposition to help us simultaneously optimize our attribute parameters and enhance our understanding of the geology. Taking this further, we then use explicit encoding to objectively visualize the relationship between three of the attributes.

Using the three data comparison techniques within one framework maximizes our cognitive function by presenting the data in a form that makes cognitive cybernetics very quick and easy. It allows the brain to function at full speed, and in so doing, it builds up our understanding of the geology in an incredibly fast but iterative manner. For example, in Figure 8, we can see three different fault attributes that are responding to different characteristics in the seismic data: amplitude change, phase breaks, and flexures. If a fault is being picked up as a flexure with no phase break or amplitude change, this suggests it could be a low-throw fault (or the fault tip), or it could be indicative of more ductile rock. Likewise, areas that display a strong amplitude change across the fault indicate juxtaposition of different lithologies.

How do we interpret it? The Geological Expression workflow

The power of explicit encoding using color blending is now well recognized, and even an untrained interpreter will quite quickly start to see features and geometries that represent discrete geological elements. However, it is also important to have the ability to extract those geological elements (faults, channels, or other features) from the blends and create interpreted surfaces. We discussed earlier how doing this manually through an interpreter digitizing the boundary of an object leads to a highly uncertain result and at the same time involves a highly tedious and labor-intensive process. Fortunately, this can also be performed in a cybernetic manner so that we can use the data to constrain the delineation process and make it much faster while allowing the interpreter to guide what is produced so that the end result respects the data and the interpreter's view of what is geologically reasonable. This cybernetic approach to data analysis supports a full seismic analysis and interpretation workflow starting at noise cancellation and data conditioning, through attribute selection and optimization, geobody, or surface delineation to facies definition, and it provides what is, in effect, a 3D model created directly from the seismic data at the original seismic resolution. This cybernetic process, using a data-driven but interpreter-guided approach to the identification and extraction of geological features, is what we term a *Geological Expression workflow*.

A portion of this workflow, geobody detection, circles back to our example of an interpreter digitizing the boundary of an object. Segmentation in multiattribute space is challenging because of the variable nature of the signal in the image. Drawing data clusters on the feature of interest samples the data and creates a multidimensional pdf, which is used for the data-driven component (Figure 9). The path that is drawn also acts as an initial model and the growth of the geobody extends from this path, enabling interpreter guidance. The geobody grows based on the analysis of the multidimensional feature space representing the attributes from which the composite display is formed and a set of forces that constrain the way in which the surface can deform (Henderson, 2012). This creates a direct link between the input data and the geometry of the object that is delineated (Paton et al., 2011). The geobody is represented by a triangulated mesh that can also be adjusted manually, allowing the interpreter to reposition its surface so that it can be forced to take a more geologically reasonable position in areas of data ambi-

a) b)

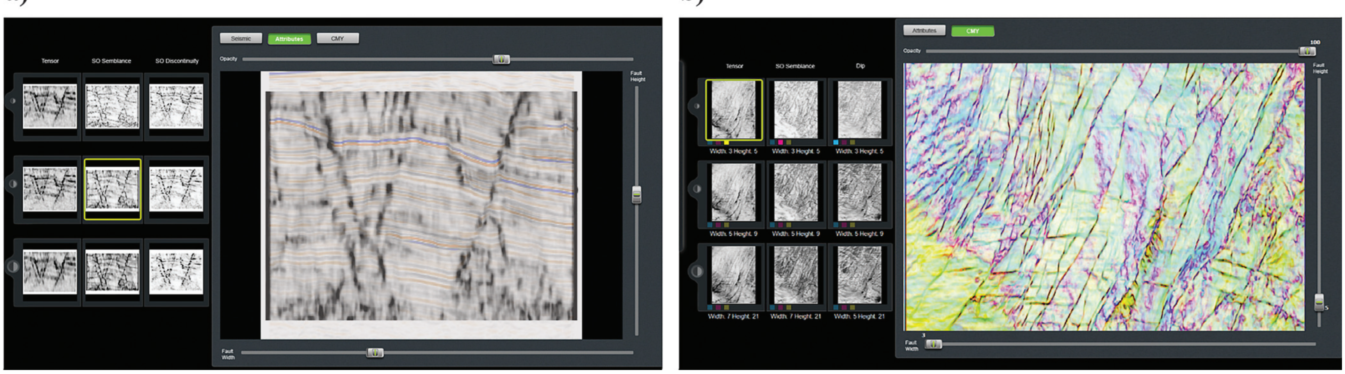

Figure 8. Example-driven frameworks enable comparison of different attributes and parameters using juxtaposition, superposition, and explicit encoding. (a) Juxtaposition of different attributes and parameters with superposition of the attribute and reflectivity data and (b) juxtaposition of different attributes and parameters with explicit encoding of three of those attributes. Data are courtesy of Geoscience Australia.

guity or bridge gaps when the seismic signature of the object of interest blends too closely into the surrounding matrix (in much the same way as we drew lines on the panda image in Figure 1 to create a more realistic representation).

A similar approach can be taken to define seismic facies based on multiattribute classification. Again, the key to the cybernetic approach is image superposition and explicit encoding combined with a high degree of interactivity. The interpreter is able to view an RGB blend and define or alter the definition of facies classes based on their interpretation of the blend. The results update in real time showing the impact of any decisions taken on the final facies classification. An example of how effective the cybernetic Geological Expression workflow can be seen in Figure 10 (from Henderson et al., 2012), in which the interpretation of a submarine fan system is achieved using Geological Expression workflows. The Adaptive Geobodies and Interactive Facies Classification is used to interpret the different facies visible in the RGB blend (Figure 10). Both techniques delineate facies boundaries and describe the morphology of the facies at a level of detail that would not be possible to achieve with manual interpretation techniques.

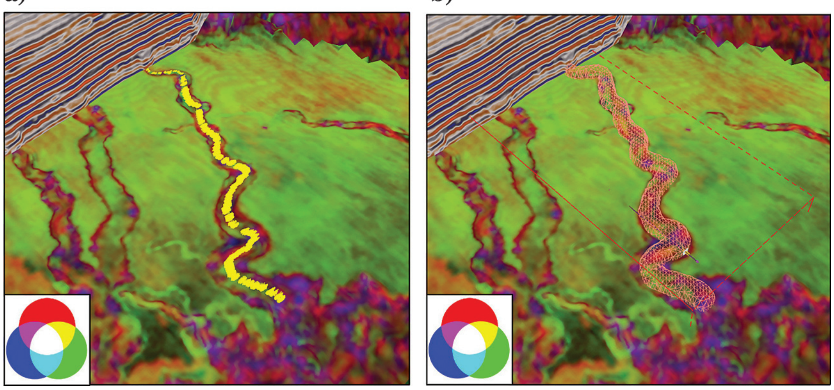

Figure 9. Adaptive geobody extraction using multiattribute data. (a) Data clusters that sample the data values and act as a guiding path for the geobody extraction and (b) the geobody surface is editable after the data-tracking process.

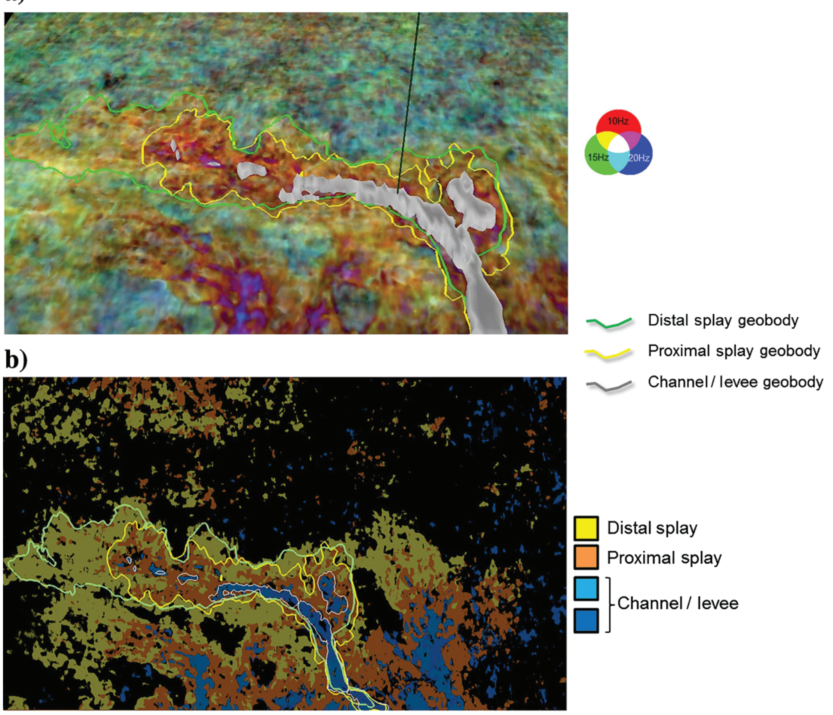

Figure 10. Geological Expression interpretation of a submarine fan system. Outline of the Adaptive Geobodies above (a) the input RGB blend, and (b) the Interactive Facies Classification result (from Henderson et al., 2012).

Conclusions

Integrating cognitive cybernetics into our approach to interpretation of seismic data helps us to work in a way that is in tune with our natural methods of thinking and understanding. Software interactivity and example-driven frameworks are at the heart of cybernetic software design because they allow us to compare data, choose options, and make informed decisions in a rapid but effective manner. This in turn minimizes the stress induced by cognitive overload, and it enables interpreters to complete comprehensive seismic analysis and interpretation workflows without additional time pressures caused by sequential attribute processing. This is the ethos behind a Cognitive Interpretation.

Acknowledgments

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