Visualizing Geological Structure with Subtractive Color Blending

Purves, Steve
Newcastle Technopole
Kings Manor
Newcastle upon Tyne
United Kingdom

Basford, Helen
Northpoint
Suite e3
Aberdeen Science and Energy Park
Exploration Drive
Aberdeen
United Kingdom

Abstract

3D seismic attributes enable seismic interpreters to gain a more complete understanding of subsurface geology resulting in more complete and detailed interpretations. Building a thorough understanding of 3D structural variations and fault networks often requires working with multiple seismic attributes due to the fact that different attributes convey different information and that the seismic signature of faults changes through the data set.

Color blending techniques have proven effective in intuitively allowing interpretation of information in multiple seismic attributes simultaneously. One of the most successful techniques uses an RGB (Red, Green, and Blue) color model to present data in a manner which is in tune with the way people perceive color. These types of blend are highly effective at visualizing data such as results of poststack frequency decomposition or offset-stack volumes.

We present an alternate color-blending model based on combining attributes using the subtractive primary colors cyan, magenta, and yellow (CMY). When used with structural attributes, the subtractive model produces displays that are predominately light, and structural variations and faults are associated with darker shades of varying hues and black, and the model is aligned with the way we are accustomed to visualize fault and structural attributes, making these displays very intuitive.

In this paper we provide a number of examples of how these blends can be used to show how fault character changes laterally through a fault network and relate

individual faults to surrounding damage, drag zones, and areas of high fault density.

Introduction

Interpretation of multiple attributes using color models

Volumetric seismic attributes are commonly used to highlight properties and structures within 3D seismic data that are often not readily visible and can be difficult to interpret directly from a seismic section. Attribute measurements that are made on 3D seismic data can convey a significant amount of additional geometrical and structural information relating to features, such as faults and subtle structural trends within a data set, than can be interpreted directly from the seismic section itself. How successfully this information is conveyed is highly dependent on the parameters of the visualization system, and by far the most significant parameter is the color mapping scheme used to display that attribute itself. Whether color mapping is achieved using a simple gray scale intensity or RGB color blending has a significant impact on the information within the attribute that is visualized.

In this paper we examine a cyan, magenta, and yellow (CMY) color model, demonstrate that this model is appropriate for visualization of structural deformation and faulting, and examine how our perception of color can be used positively to influence our interpretation of data presented via such models.

Interpreting in color with modern workstations

Interpretation of 3D seismic data on modern computer workstations allows for rich and colorful visualization techniques to be applied. However, the impact of coloring of the data often is not considered in as much depth as perhaps it should be, as the impact is often significant and can be in cases as negative as it is beneficial. When working with color visualization, there are numerous factors that affect how a piece of data is displayed. These factors include the properties of the color mapping scheme, the display hardware, the physical properties of the display, the color calibration parameters (where color calibration is made), and the perceptive abilities of the interpreters themselves including color selectivity, sensitivity of the eye, and the entire visual system.

Instead, here we examine some properties and principles of the two different color spaces that have proven to create highly detailed, informative color multiattribute blends for visualization that provide significant value to the seismic interpreter: the red, green, blue (RGB) model and the cyan, magenta, yellow (CMY) model.

Color blending with three channel color models

In order to simultaneously interpret the information in multiple seismic attribute volumes it is necessary to co-visualize this data in some way. A mode of co-visualization that has proved very successful with certain classes for 3D seismic attribute is color blending based on an RGB color model (Henderson *et al.* 2008; Guo *et al.* 2008).

RGB color blending

The RGB color blending model (Fig. 1A) is an additive color model that incorporates information from each of three primary color channels (red, green, and Blue), which are mixed additively in the same way as projected light, so as to produce a final color. With the wide range of seismic attributes with which we have experimented, we find RGB tends to produce darker blends that increase in intensity and saturation as attribute values increase and shift in hue as the relative strength of attributes change. When applied to 3D seismic attribute analysis, the color of a given voxel within a 3D-blended volume is determined by this mixture of RGB intensities, enabling the eye to extract a wealth of subtle variation and information from within the blended data that is often not readily visible on any of the three attributes in isolation.

The reason that RGB color blending is such a compelling way to construct colored displays is to some degree due to the way it is in tune with people's color perception. Although RGB blending does tend to excel in creating certain intuitive displays of certain classes of seismic attributes, it proves less effective with others. In our experience, RGB blends have proven most effective when data have a reasonable level of correlation present between the different attributes used. These tend to produce displays that are more colorful, hence utilizing more of the dynamic range of the color model and interpreters perceptual capabilities.

Examples of effective attributes are band-limited reflection strength resulting from spectral decomposition (Leppard *et al.*, 2009; Henderson *et al.*, 2007) or offset stack volumes such as near-, mid- and far-stacks. In these blends objects of interest are represented and visible as bright, colored entities while low energy events such as faults appear as dark structures (Fig. 2) the variation in color enables an interpreter to rapidly understand the variation in the underlying attribute volumes and in many cases to map out and extract the detailed structures that are visible using a variety of semi-automated and automated techniques (McArdle *et al.*, 2010).

CMY color blending

The motivation behind creation of different color blending scheme for seismic attributes was to provide a means to blend usefully and so co-visualize a wider range of attributes that would cover some attributes that do not render effectively in an RGB model. We find that CMY model (Fig. 1B) that mixes these primary colors on a computer display gives a behavior similar to the subtractive model used in printing and graphics reproduction.[1]

The CMY model itself is constructed from inversion of the axes of the RGB color model as follows; the CMY and RGB color models are therefore complementary:

$$C = 1.0 - R, \quad (1)$$

$$M = 1.0 - G, \quad (2)$$

and

$$Y = 1.0 - B. \quad (3)$$

where all monochrome intensity values have been normalized to fall within the range (0.0 – 1.0).

Figure 1 shows a 3D representation of the two color models. In the RGB case, the origin is black diagonally opposite white at the highest intensity along the line O-O,' representing the gray scale intensity line through the RGB model. This is the same in the CMY model case except that the direction of intensity variation is reversed and the color at the origin of the model is white. As the origin of the color space will be mapped to attribute values, blends produced by using the CMY model will be predominantly white, increasing in saturation as amplitude within each attribute channel increases. As with the RGB model, variation in hue represents changes in the relative amplitude of the different attributes, while black indicates a strong uniform response in all three.

Using CMY color blends effectively

Our work in applying CMY blends to 3D seismic attribute to-date has shown these to be very effective in co-visualizing geological faults and structural trends by using a selection of volumetric structural attributes. As

1. We note that one of the formally used models in the printing domain is CMYK, where the 'K' represents black (or no light); however, we have omitted this, as for our purposes the near-black achieved by mixing CMY is sufficient.

our case study within this paper shows, the results of CMY blending are predominantly light blends that can be flexibly constructed to provide a much more complete view of faulting and fault networks than can be achieved with numerical combination of single fault and coherency-like attributes alone. A further significant advantage is that changes in hue can be used to visually track changes in fault character or to map out structural deformation and damage in the vicinity of fault such as the presence of damage zones and the change from brittle to ductile deformation.

However, the reasons as to why the CMY blends are so much better at visualizing structural data over RGB blends, and vice versa why RGB blends are so much better at representing spectral decomposition output is not clear. From our experience working with these blends we would postulate that the CMY blends better lend themselves to visualization of the sparser structural and fault attribute data than RGB, and that we are biased toward the use of lighter colored blends for fault and structural information as it is how seismic attributes such as dip magnitude and coherency have historically been displayed and interpreted. Additionally it is apparent that certain color channels are more suited to display of certain attributes depending on their dynamic range and the scarcity of their anomalously high (non-zero) values, as we demonstrate in our examples. Whether we can describe the psychology of color perception or not, the CMY blending model is able to convey new levels of information and insight on the geological structure within a 3D data set to the interpreter.

Application

Case study: Mid-Norwegian North Sea

The following case studies demonstrate the application of the CMY blending technique discussed above when investigation faulting in the Norwegian North Sea. The Norwegian North Sea is characterized by fault systems of multiple scales. Tectonically formed large-scale fault zones, small-scale fracture lineaments with associated damage zones, and polygonal fault networks are all present.

The seismic expression of faults in this area is also widely variable, not only from fault to fault but in many cases along the length of a single fault. Figure 3 shows a representative vertical seismic section through a highly faulted zone in the Norwegian North Sea. In this small section we see that the seismic character of the faults present includes:

- sharp break in the reflector, clear offset, and lateral phase change indicating a narrow fault zone (rectangle A),
- High dip and associated flexure of reflectors (rectangle B), and
- More subtle amplitude changes (rectangle C).

In order to image such a wide range of seismic characters, different edge-detection attributes are required. Three such attributes are:

- Volumetric dip magnitude,
- Structurally oriented semblance, and
- An attribute formed from the two smallest eigenvalues, $\lambda_1 + \lambda_2$ of the gradient structure tensor.

Volumetric dip magnitude is a measure if the inclination of the reflector from a horizontal reference plane calculated using the eigenvectors of the gradient structure tensor (GST) computed with a local 3D window about each sample. Dip magnitude can be used to identify faults that give rise to locally high dip. Structurally oriented semblance is a measure of coherence calculated along the dip and azimuth of a postulated local reflector. The structurally oriented semblance attribute identifies faults that are expressed with a clear offset in the data, which in turn introduces a lateral change in phase and amplitude change across the fault. The structurally oriented nature of its calculation ensures that high responses are not seen along zero crossings in steeply dipping areas. The "tensor" attribute is the sum of the two smaller eigenvalues of the GST. Since $\lambda_1 + \lambda_2$ are a measure of the nonplanar energy of the data, the tensor attribute is good at identifying faults across which there is a large amplitude contrast. Such amplitude contrasts across faults are seen where there is either significant throw and different lithologies have been juxtaposed against one another, or no throw but an amplitude dimming along a reflector. The tensor attribute is therefore good at identifying both large and small scale faults.

Figure 4 shows a time slice through the three different (above mentioned) edge-detection attributes. In these displays, the higher the response (or closer to black) the higher the likelihood of there being an edge (or fault) in the data at that point. The three slices all show high responses, but the amount of detail, the location, magnitude, and width of each response is different. The dip magnitude volume (Fig. 4A) shows a large amount of variation of dip throughout the volume: sharp, high dip lineations, and broader linear zones of mid-high dip that represent faults and non fault-related structural dip variations. The structurally oriented semblance volume (Fig. 4B) has a much higher contrast between edge and non-edge areas than the dip magnitude volume and shows only sharp responses that represent continuous faults, discontinuous fault segments, and stratigraphic edges. The tensor attribute volume (Fig. 4C) shows broader, more continuous fault lineation's than either the dip magnitude or structure-oriented semblance, contains less clutter, but also fewer of the small-scale fault segments and stratigraphic terminations.

In conventional imaging and extraction techniques, the volume that the interpreter considers to be the best of these three options would be selected and utilized for fault imaging. However, by color blending using the CMY color blending scheme we can visualize all three attributes simultaneously and gain a much more complete understanding of the fault networks present. The different colors of the faults seen in Figure 5 indicate which attribute or combination of attributes is identified in a given segment of the fault. By understanding the physical meaning of the component attributes, an experienced interpreter can also identify the fault's seismic character. In this manner, cyan represents edges detected predominantly by the dip magnitude attribute; magenta represents edges detected predominantly by the structurally oriented semblance attribute; and yellow represents edges detected predominantly by the tensor attribute. Blue represents edges detected by the dip magnitude and structurally oriented semblance attributes; red represents edges detected by the structurally oriented semblance and tensor attributes; and green represents edges detected by the tensor and dip magnitude attributes. Finally, black represents edges detected by all three attributes.

The color variation along a single fault such as the east-west trending fault in zone Y (Fig. 5) shows that different segments have been identified by different attributes and no single attribute would have been sufficient to show all of the details. In the central part of this fault there is a sharp black lineation signifying a strong response from all attributes and a fault that is characterized by a high dip, amplitude contrast, phase change, and clear offset. East of the fault, the expression widens and is dominated by small sections of cyan, blue, and magenta, signifying small fault segments having a high dip and clear offset. Figure 6 shows the same area deeper in the seismic section where the changes in character along the fault are even more pronounced. To the west, the fault has a clear sharp response and is interpreted as a clean fault with minimum disturbance associated to surrounding reflectors. To the east the fault widens into a fault zone comprising multiple small-scale fault segments. This has been interpreted as a broad seismic scale fault damage zone in which there is increased potential for fault and fracture influence on fluid movement.

Area X in Figure 5 is characterized by blue and pink nonlinear edges. The blue and pink colors indicate these features are identified by the dip magnitude and structurally oriented semblance attributes and not by the tensor attribute. This appearance implies that the edges in Area X are characterized by clear breaks having no significant amplitude contrast. The lack of a tensor attribute response suggests these edges are not related to large faults having substantial throw. The sharp nature and dark color of the response from the dip magnitude attribute means that the dip is very high over a very narrow zone, which is characteristic of clear breaks in the reflectivity rather than regional structural trends. Additionally the structurally-oriented semblance, which is very good at delineating stratigraphic edges, has a high response. This evidence all suggests that these detected edges have very limited vertical extent and as such are related to either very small scale faulting or stratigraphic edges. The geometry of the edges in this area is also highly nonlinear and sinuous. The geometrical expression can therefore be incorporated into the interpretation such that the combination of attribute response and edge geometry suggests that these edges are related to depositional and stratigraphic features rather than to faults.

Using CMY blends as a measure of confidence

A second example of illustrating the value of CMY blending the same three attributes is shown in Figures 7 and 8. In this example from deeper in the same seismic volume, two families of faults can easily be seen, one trending approximately north-south and the other trending approximately northeast–southwest.

Figure 7 shows the dip magnitude, structurally oriented semblance and tensor attributes and has three areas of interest highlighted (N, M, O). Area N contains strong and equal responses from all three attributes for the dominant northeast-southwest trending fault. Area M shows weak northeast-southwest trending responses from the structurally oriented semblance and tensor attributes, while the dip-magnitude attribute shows both northeast-southwest and north-south trending lineations running parallel to the known fault trends of the region. The vertical responses seen in area O also vary between the three attributes: the dip magnitude and structurally oriented semblance attributes show small near-vertical segments of limited connectivity and the tensor attribute shows a broader fault response having good vertical connectivity. By generating a CMY color blend (Fig. 8), the contribution and interaction between all three of these attributes can be seen. In this example, cyan represents the response from the structurally oriented semblance attribute, magenta represents the response from the tensor attribute, and yellow represents the response from the dip-magnitude attribute. Green represents areas where there is an equal response from the structurally-oriented semblance and dip magnitude attributes and black represents an equal and strong response from all three attributes.

The transition from clear black faults to the west into dominantly yellow faults in the east shows that the character of the faults is changing. To the west, the strong response from all attributes suggests there is a high confidence in the faults and they are characterized with clear offset, phase and amplitude contrast. The yellow response of the faults to the east shows that they are only expressed via a zone of high to medium dip. The fact that their trend runs in line with the other faults suggests they were formed as part of the same compressional and faulting episode, suggesting that they may be slicing through a different lithology. The combination of the three attributes also provides a much better vertical continuity for the faults in area O than any of the individual attributes could.

The importance of color association and further work

The examples in Figure 5 and Figure 8 have been created by blending together the same three attributes, but in each case they have been associated with different colors in the CMY blending scheme. The following example demonstrates how the way in which attributes are assigned to the three different color channels will influence the resultant colors of any faults or structural trends that are highlighted in the blend. Figure 9 shows three CMY color blends of the same attributes for a small time slice section through a heavily faulted region of the Norwegian North Sea data set. Table 1 describes how the attributes (dip magnitude, structurally oriented semblance, and tensor) have been assigned to the cyan, magenta, and yellow channels.

In each case, the dominant background color in the blend (Figs. 9 A-C) is that associated with the attribute that has the lowest contrast. In the case of the three attributes selected here, the dip-magnitude attribute has the lowest contrast. This is due of the fact that there are very few areas of low dip in this section and so the difference in dip response between edge and no edge is quite low. It is interesting to note that while all faults and structural trends can be seen in all three blends, the subtle details of the variation in dip magnitude can be seen better when it is associated with either of the two darker colors (cyan or magenta). Linking the results we see here with theory about color perception is an area we propose to investigate further in order to make recommendations for preferred attribute color combinations.

Conclusions

The CMY color blending method presented here is a successful and important method of visualizing multiple fault attributes in order to gain a complete understanding of the faults and structural trends present with seismic data. The simultaneous visualization of three edge attributes that represent three different types of seismic character and fault expression using CMY blending can enable a more complete fault model to be interpreted. Visualizing the change in seismic character laterally along a fault zone can quickly show how the fault character changes, for example form a sharp fault zone to a broader zone where a clear fault break is not seen but the structural trend continues. This is often the case towards the tip of a fault or in the region between two small faults that are growing together and can thus influence the interpretation of the lateral extent of the fault in question. Being able to compare three different edge attributes can also ensure all possible faults are identified and not missed due to poor attribute selection while giving the interpreter a good understanding of the confidence of the faults they are mapping. If three independent attributes delineate the same fault, the response will be black, and there is a very high confidence associated with it.

Acknowledgments

Data courtesy of Statoil.

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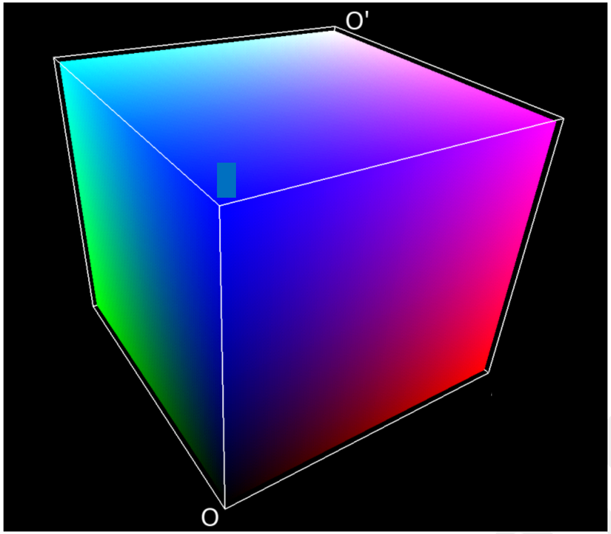
Table 1. Assignment of edge attributes to the cyan, magenta and yellow channels in Figure 9.

Figure	Cyan	Magenta	Yellow
9A	Dip magnitude	Structurally oriented semblance	GST λ1+ λ2
9B	Structurally oriented semblance	GST λ1+ λ2	Dip magnitude
9C	GST λ1+ λ2	Dip magnitude	Structurally oriented semblance



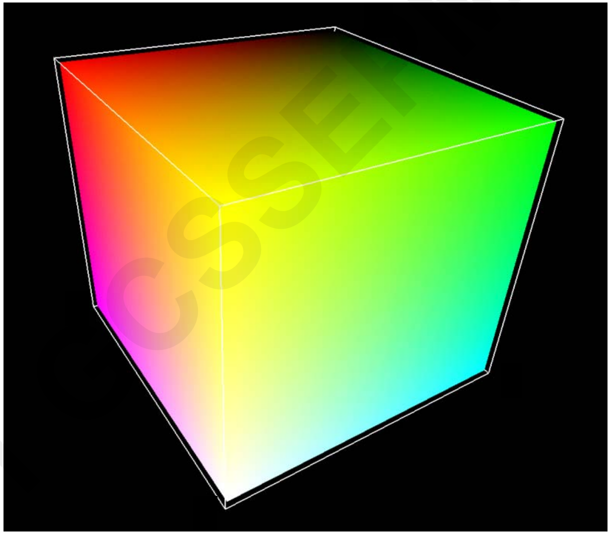


Figure 1. 3D representation of the color models. (A) The RGB color model shows the origin O as black and the three primary colors (red, green, and blue) are represented on the axes O-R, O-G, and O-B respectively. (B) The CMY model shows the origin O as white and the three subtractive primaries (cyan, magenta, and yellow) are represented on the axes O-C, O-M, and O-Y respectively. We note that both the RGB and CMY models represent essentially reversed versions of the same color space.

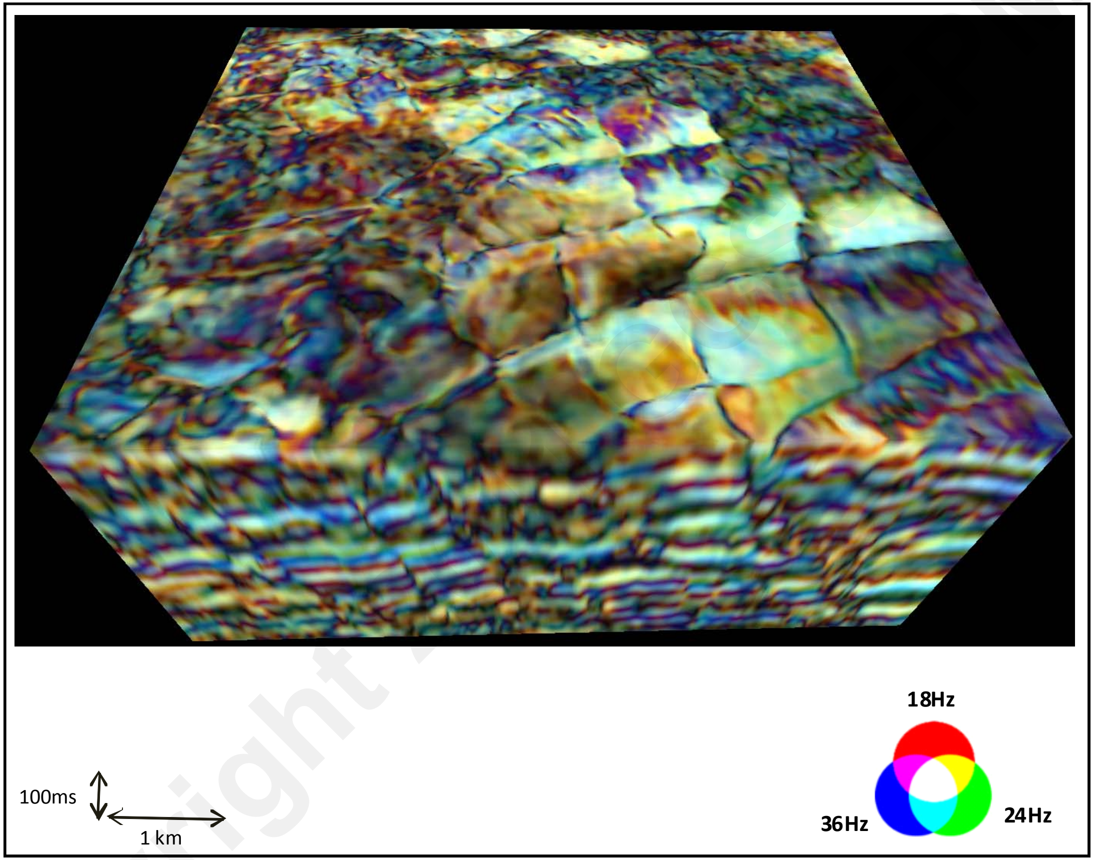


Figure 2. Volume RGB Blend of 18 Hz, 24 Hz and 36 Hz magnitude responses. Red represents areas where the 18 Hz component is dominant, green represents areas where the 24 Hz component is dominant, and blue represents areas where the 36 Hz component is dominant. Faults are clearly seen as dark to black lineament, resulting from a low response from all three magnitudes.

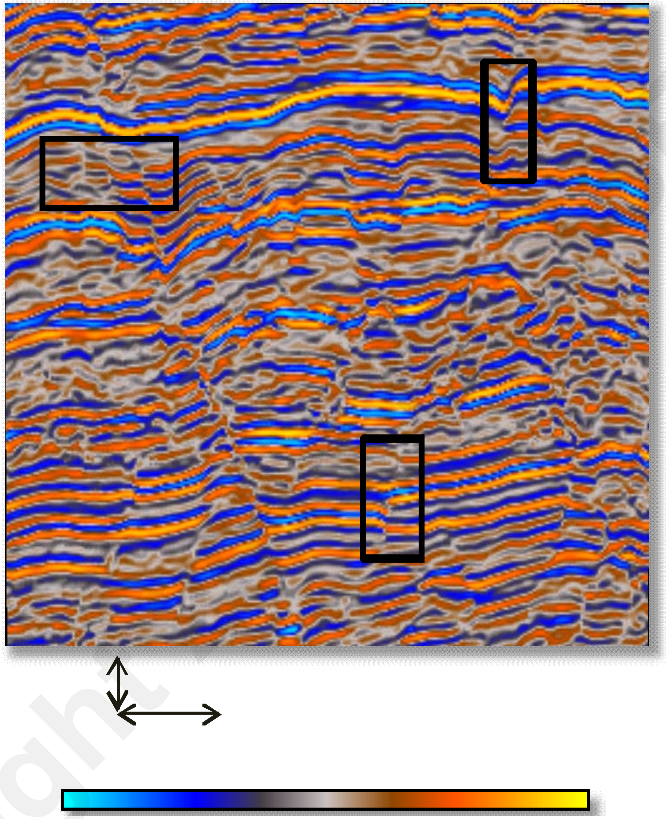


Figure 3. Vertical seismic section. Zones A to C show faults of different seismic character.

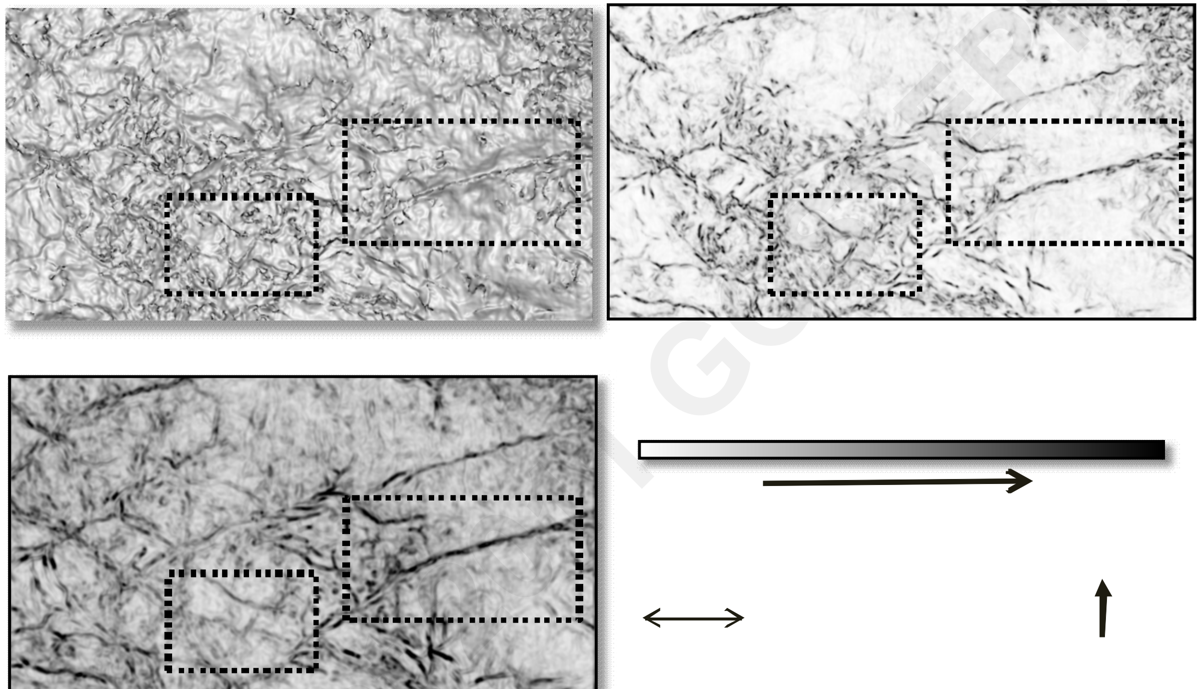


Figure 4. Three fault attributes shown on a time slice at t=3000 ms. (A) Dip magnitude, (B) Structurally oriented semblance, and (C) an attribute constructed from the eigenvalues of the gradient structure tensor (which we will simply call the "tensor" attribute).

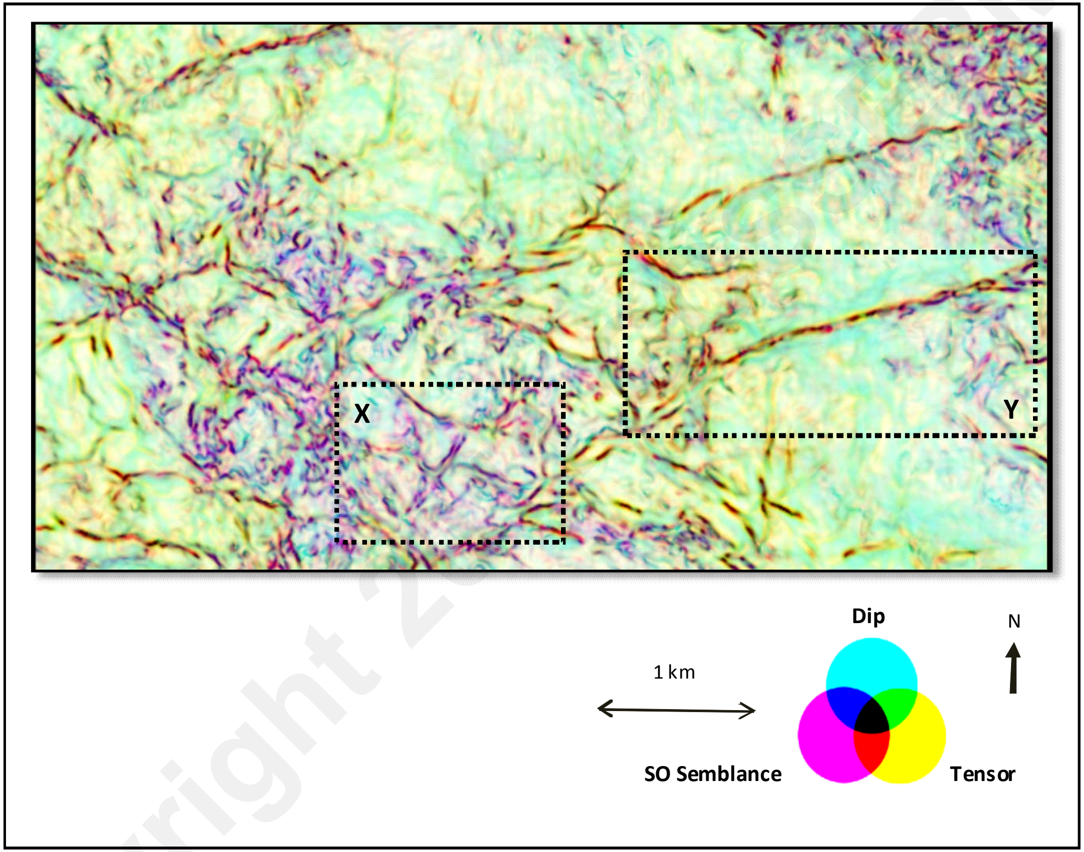


Figure 5. The three fault attributes shown in this figure plotted in CMY space forming a blended, multiattribute image of dip magnitude plotted against the cyan axis, structurally oriented semblance plotted against the magenta axis, and tensor plotted against the yellow axis.

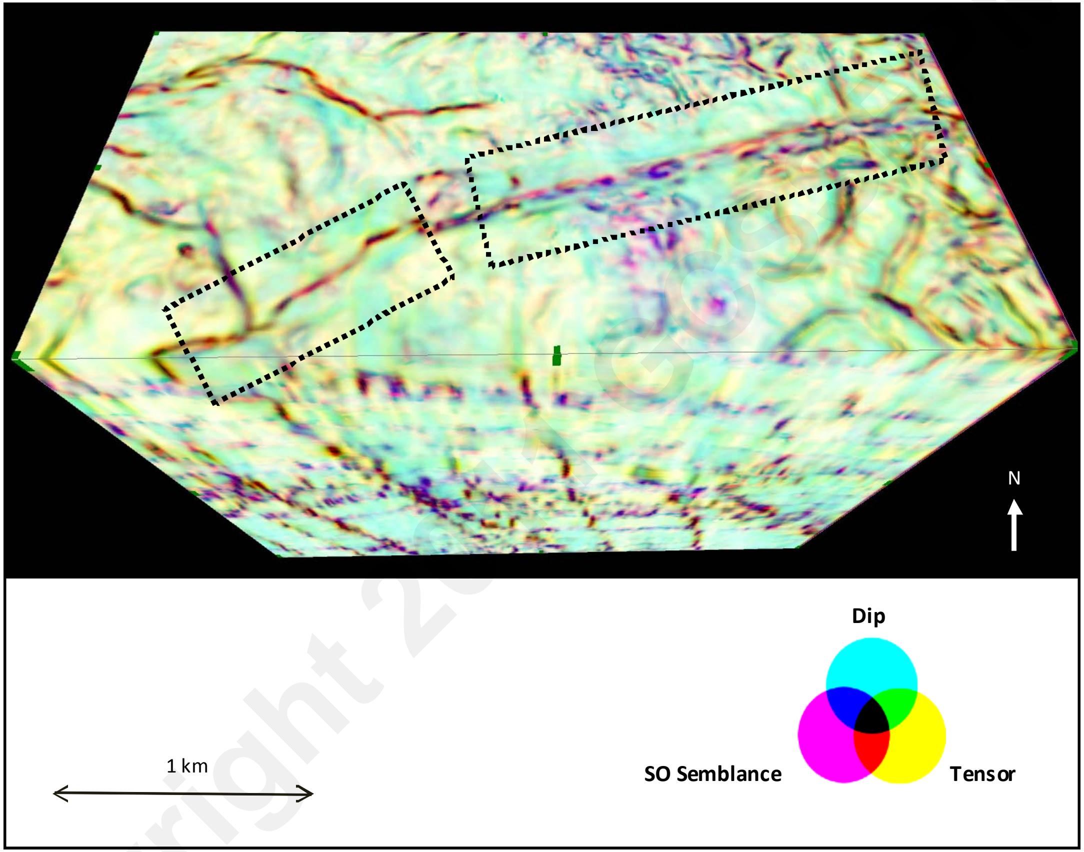


Figure 6. Volume CMY blend of dip magnitude, structurally oriented semblance and tensor for the area Y indicated by rectangle in Figure 5.

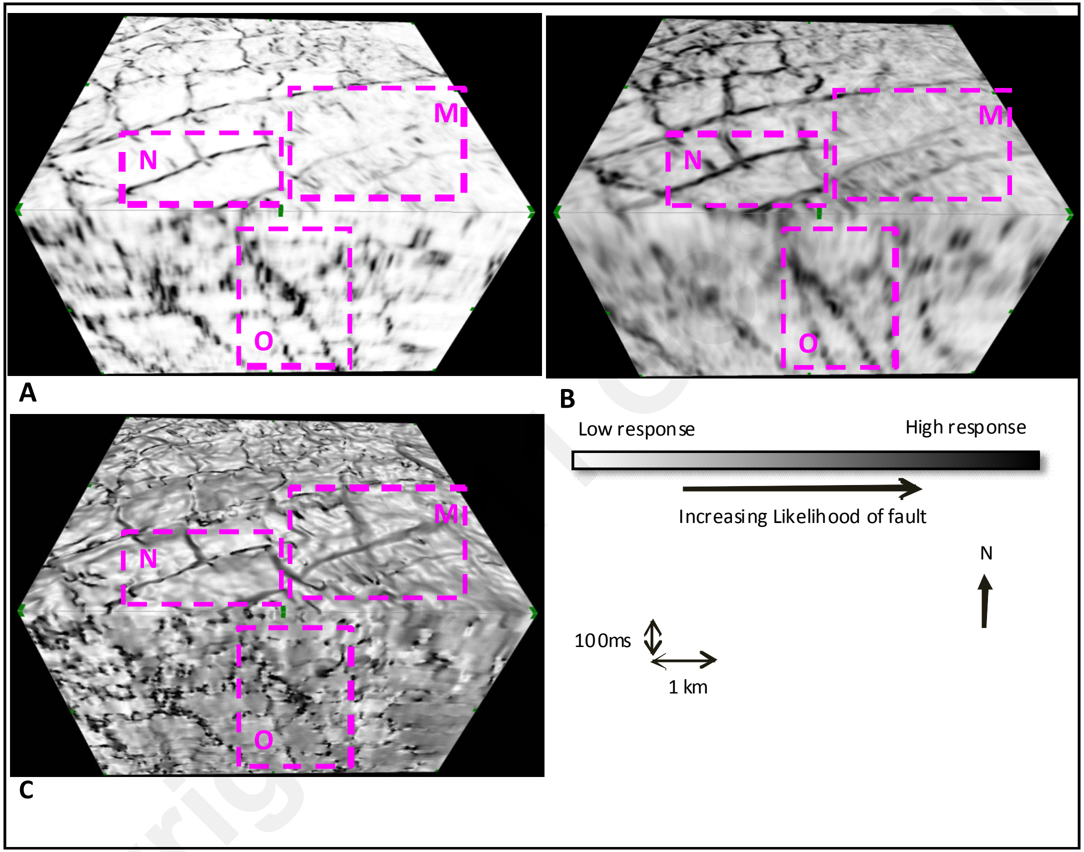


Figure 7. Three fault attributes: (A) structurally oriented semblance, (B) tensor, and (C) dip magnitude.

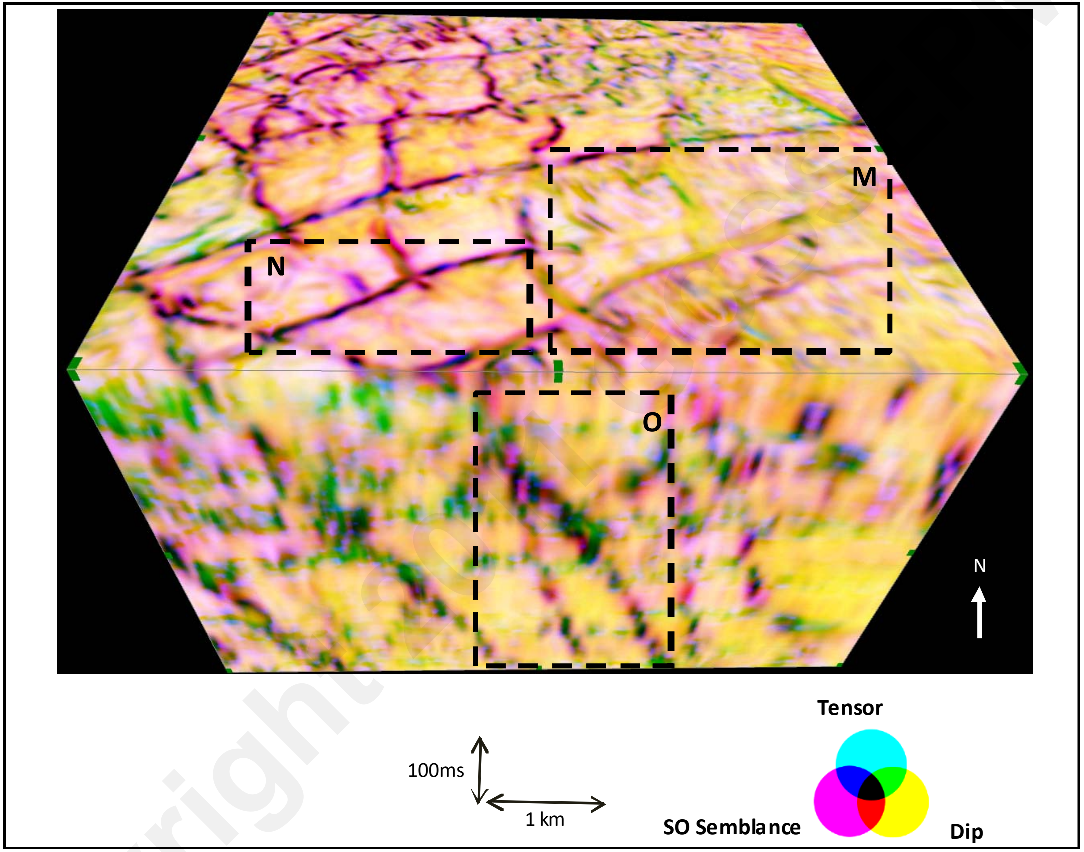


Figure 8. Volume CMY blend of structurally oriented semblance, tensor, and dip magnitude.

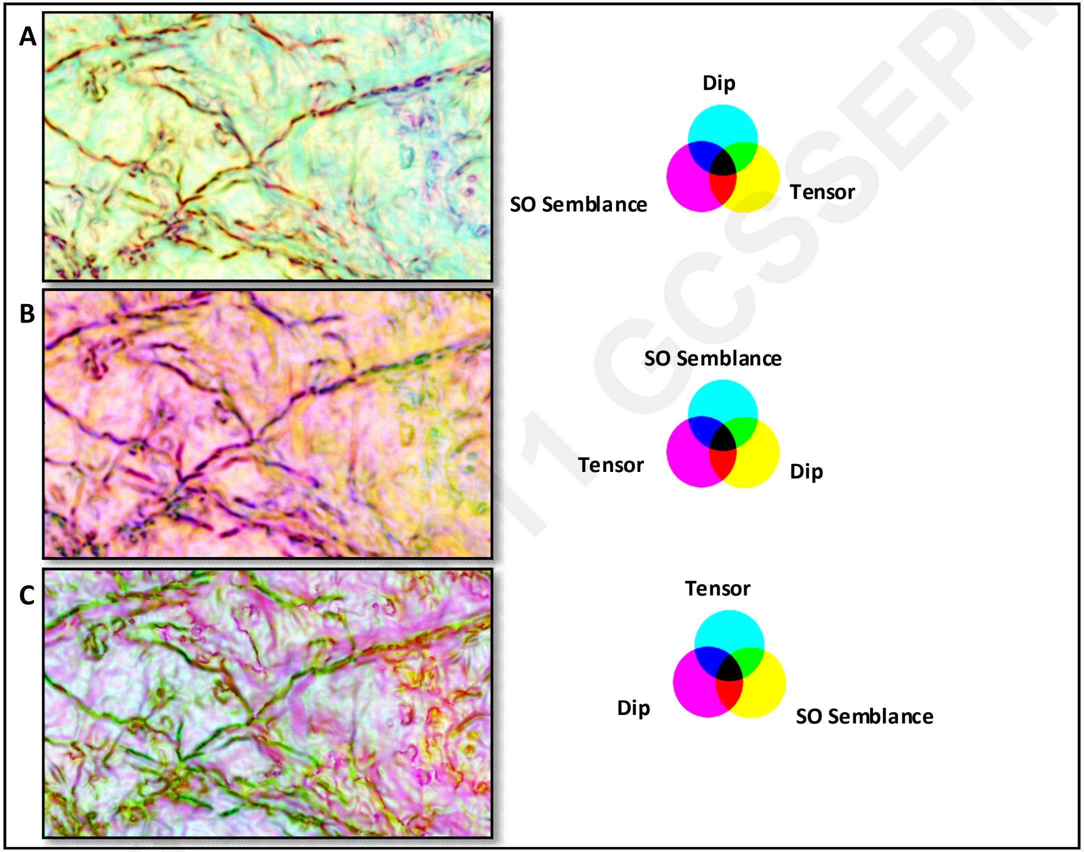


Figure 9. Volume CMY blend of structurally oriented semblance, tensor, and dip attributes associated with different color channels.