SUPERIMPOSED GEOLOGIC FEATURES IN SEISMIC INTERPRETATION

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ABSTRACT

In seismic interpretation, accurate identification of geological features builds a better understanding of subsurface geology, which turns a prospect into a success. Most often geological features are superimposed on a seismic map because of geophysical and analysis parameters, or geologic complexities. Additionally, the seismic data is always band-limited and it is often hampered by noise. If the geologic features (e.g. channels, faults, and other structural and/or stratigraphic features) are superimposed together with noise, interpretation and finding scientific explanations can become difficult. The issue is primarily in 3D analysis, which has its own merits but it adds misleading elements and pitfalls in interpretation. These problems can include limited observation, loss of evidences, and reservoir distribution. The first challenge in interpretation is to resolve the problem by distinguishing the features from one another (improving resolution and definition). In this paper, few examples are presented to demonstrate the issue. Solutions to the problem of superimposed features are sought by applying advanced seismic interpretation techniques. Several of the workflows are proposed here. To remove noise and improve the visibility of geologic features, a structurally oriented filter is applied. The resolution problem is improved by applying spectral enhancement and spectral decomposition, which have improved the efficiency of algorithms and seismic attributes. Apparent seismic attributes and spectrally enhanced seismic data are also considered as the optimal choices to improve the results. This paper attempts to present various workflows as solutions to the issues that would indirectly help the industry to manifest such problems in prospect identification.

INTRODUCTION

This paper is a short review on geologic features observable on seismic results that are interfering, cutting across, and overlying on each other. In this paper, these features are labeled as superimposed geological features i.e. geologic features that are observed on seismic data, which are intermingling and interfering on top of each other. The word “superimposed" is used in consideration of the law of super position, which states that the geologic features that are overlain on each other represent different stages of a geological record. Thus, “superimposition” could also be used in seismic interpretation, in reference to multi-depositional elements resting on top of each other.

There are two critical views of the present discussion: potential reasons for superimposed geological features and the solutions to improve the results. The purpose of writing this article is to elaborate these thoughts and to propose workflows to improve the results. Through numerous cases, it is observed that the superimposition of geological features results because of inherent limitations in seismic data analysis. Importantly, a seismic signal is band limited. Analysis parameters and laterally varying geology also play vital roles in the results. In other cases, it could also be the result of geologic complexities. In former case, it is considered that the data can be improved by applying various workflows as described in this paper. In the later case, geological principles may play an important role in improving the results. Although, it is impossible to alter geologic complexities, which are facts, the superimposition of geologic processes may give a completely different picture than it is normally expected.

To elaborate on the focus of this review, an example result is illustrated on a horizon map (Figure 1) of

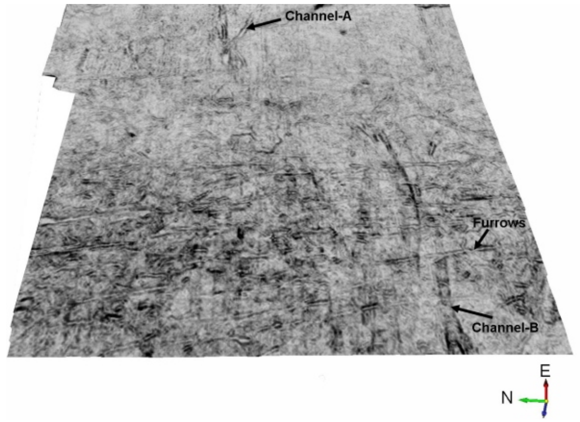

Fig. 1. A perspective view of an attribute (waveform similarity) map, which is extracted from a 3D seismic data of the Dutch sector, North Sea. The map shows several geologic features interfering, cross cutting and superimposing on each other. For scale, the average width of channel-B measures 400m.

Pliocene interval, Dutch sector, North Sea. The horizon map is prepared using a waveform similarity attribute (a 3D seismic attribute). The result of this attribute shows several geologic features (Figure 1). It gives a picture of different depositional elements: a channel system (EW elongated), and mega scale furrows. The channel-A, which is located on the eastern most side of the map (Figure 1), is not overlain by any other geologic feature at seismic scale. Contrary to channel-A, the southern most channel system (labeled as channel-B) is not clearly evident on this map and it is interfered by other geologic features that are orthogonal to channel-B (Figure 1). Moreover, the channel-B is not fully resolved on this map. It is observable in this example that some features are not distinguishable because they are overlain by other geologic features. Therefore, the major thing to mention is the need of solutions to distinguish the superimposed features before any interpretation is carried out from the results. It is suggested that in order to distinguish and resolve this issue, some modification and improvement in the results should be incorporated by applying various workflows addressed in this paper.

It is also presented that there could be a pitfall in interpretation if the above-mentioned problem is encountered. A common pitfall in interpreting such features is an inappropriate prediction of timing of geological events due to imprecise analysis. In other cases, one may miss a part of a depositional element if it is not resolved on seismic data. Similar cases are addressed if geologic complexities are encountered e.g. structural elements interfering with the stratigraphic features, such that both are inherently aligned parallel to each other. Such examples are quoted in the text and are explained by considering the critical factors controlling the superimposition of geologic features.

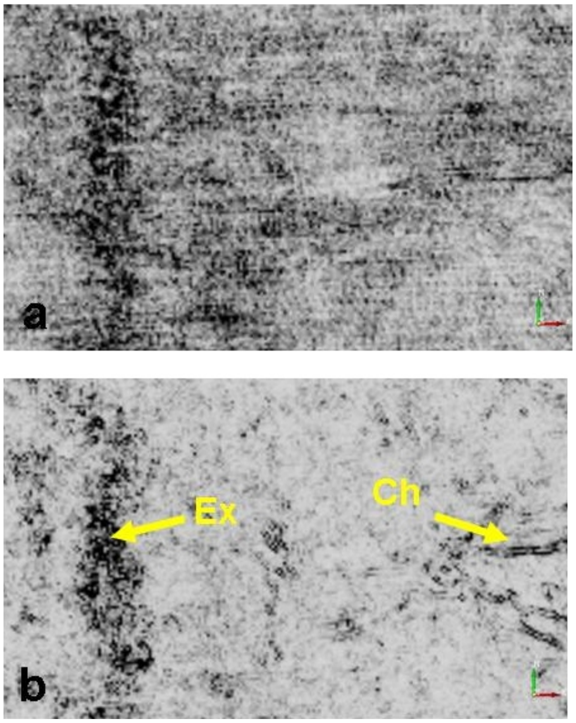

Fig. 2. A conventional time slice of similarity attribute is shown, which is extracted from a good quality PSTM stack (a). The data is further processed after the stack by applying a structural oriented post-stack filter (b). After a post-stack filtering, the noise has been filtered. The label 'Ch' refers to channel and 'Ex' refers to gas expulsion feature

Thus, this paper considers the problem by revisiting some potential triggers for superimposition and the solution to the problem is addressed in the later part of the discussion. Moreover, some conclusive points are also addressed after discussing merits and pitfalls of superimposed geologic features.

POTENTIAL TRIGGERS

As described in the previous section, there are several causes that may lead to produce the superimposed geologic features in the results derived from seismic data. Some of the key and known reasons are addressed in this section. These are considered as critical factors controlling the precision of the results.

Noise or Signal

Noise hinders a seismic signal and thus hides geologic information. Additionally, a seismic signal is inherently altered by the earth's intrinsic properties and it is exposed to considerable filtering from other sources (acquisition, and processing). Thereafter, the final signal is even more limited and complex than expected. In a general statement, the final signal is a composite response of several processes. From such a composite signal there is something that is mostly left behind (i.e. randomness) even after careful seismic processing [1, 2]. An example of a random behavior of noise is presented in Figure 2a. The results are extracted from the shallow section (Pleistocene interval) of a 3D seismic data of Dutch sector, North Sea. The data quality is good and processed up to standards to reveal stratigraphic information. Nonetheless, when an attribute is extracted from the data along a time slice, noisy results are produced. It is clear from the result that the interpretation is difficult because the data contains noise and thus hiding the geologic information.

The technology is still overcoming this issue by improving acquisition systems and processing algorithms [1, 5]. If one considers a signal to have a geometrical shape and the noise to have a random behavior, one can improve the result. Such a consideration is known as structurally oriented filtering. The dip-steered median filter (structurally oriented filter) is applied to the same data set and the same attribute is extracted. The filtered output is illustrated in Figure 2b. Note that after a careful post-stack filtering the data quality has been improved thus it is improving the efficiency of the seismic attribute. The final result (Figure 2b) reveals hidden geologic features (channels and pockmarks/gas expulsion) that are not visible on the non-filtered data (Figure 2a). It is often thought that filtering seismic data, after a final seismic stack is produced, changes the shapes of geologic features. However, this is not true and it is contrary to the results presented in Figure 2. This exercise clearly shows that objective driven filtering with the appropriate filtering parameters improves the signal to noise ratio. Such filters are helpful to resolve the hidden geologic features, which may help an interpreter to understand the subsurface preserved geology.

Seismic Resolution and Beyond

Seismic resolution is an unavoidable problem, which has disturbed seismic interpreters since the start of seismic exploration. Now-a-days technology has improved so that a bed of 5-8m thickness is often resolvable on the seismic data.

In common industry practice, the bedding interfaces are identified by preparing a synthetic seismogram. The method is quite fundamental to identify the resolvable beds on the seismic. After identification, the bedding interfaces are interpreted as surfaces in 3D. The seismic attribute analysis is then done on the surfaces by extracting attributes along them. An example of this practice is presented in Figure. 1, which is a volumetric analysis along a horizon map.

To elaborate the resolution and volumetric analysis more, a band limited seismic signal is illustrated in Figure 3. The seismic signal is presented together with a layered geologic column, and a gamma ray log. It is observable in Figure 3, when the trace is compared with the lithological column (e.g. between A and B in Figure 3), that there are several interference patterns: constructive and destructive interferences [2]. Such patterns often create limited results if a seismic waveform (e.g. AB) is compared in 3D. The idea of superimposed geologic features in seismic interpretation is therefore considered beyond the seismic resolution (i.e. the output is resolvable on the results but geological features are interfering with each other). Any geologic object that falls below seismic resolution is considered to be unresolved or not observable in the results. The issue is treated mainly as a volumetric analysis of the subsurface, where a sub-volume of a layered earth is correlated in time and space using a seismic waveform (or a trace segment). Therefore, the concern is to improve the results beyond the seismic resolution while studying the subsurface using volumetric analysis.

It is pointed out that the resolution limit controls the results if a geologic feature falls below the limit and beyond that addressed triggers and other factors are introduced. Hence, seismic resolution enhancement will be addressed while discussing the spectral enhancement workflows.

Multiple Algorithms

To date, several industry standard workflows have been introduced that were built with some modification of the original algorithms. Many of these algorithms (e.g. attributes) show similarities and a relationship with each other when they are cross plotted [3]. However, similar attributes serve the same purpose in a general sense. For instance, there are several industry standard post stack filters available [1] that improve a seismic reflector's continuity by suppressing noise. In some cases one algorithm works better than the other. Similarly, too many seismic attributes [3] have been introduced to the industry. Some out of other attributes have similarities in defining a geologic object e.g. coherency and similarity [1]. It is observed that an algorithm design could also cause differences in the results. Some algorithms require a small time gate (vertical evaluation scale) and the others operate well on a larger time gate thus the two algorithms are indirectly sampling different geologic columns. Considerations for selecting the proper algorithm or seismic attribute are addressed in the following section.

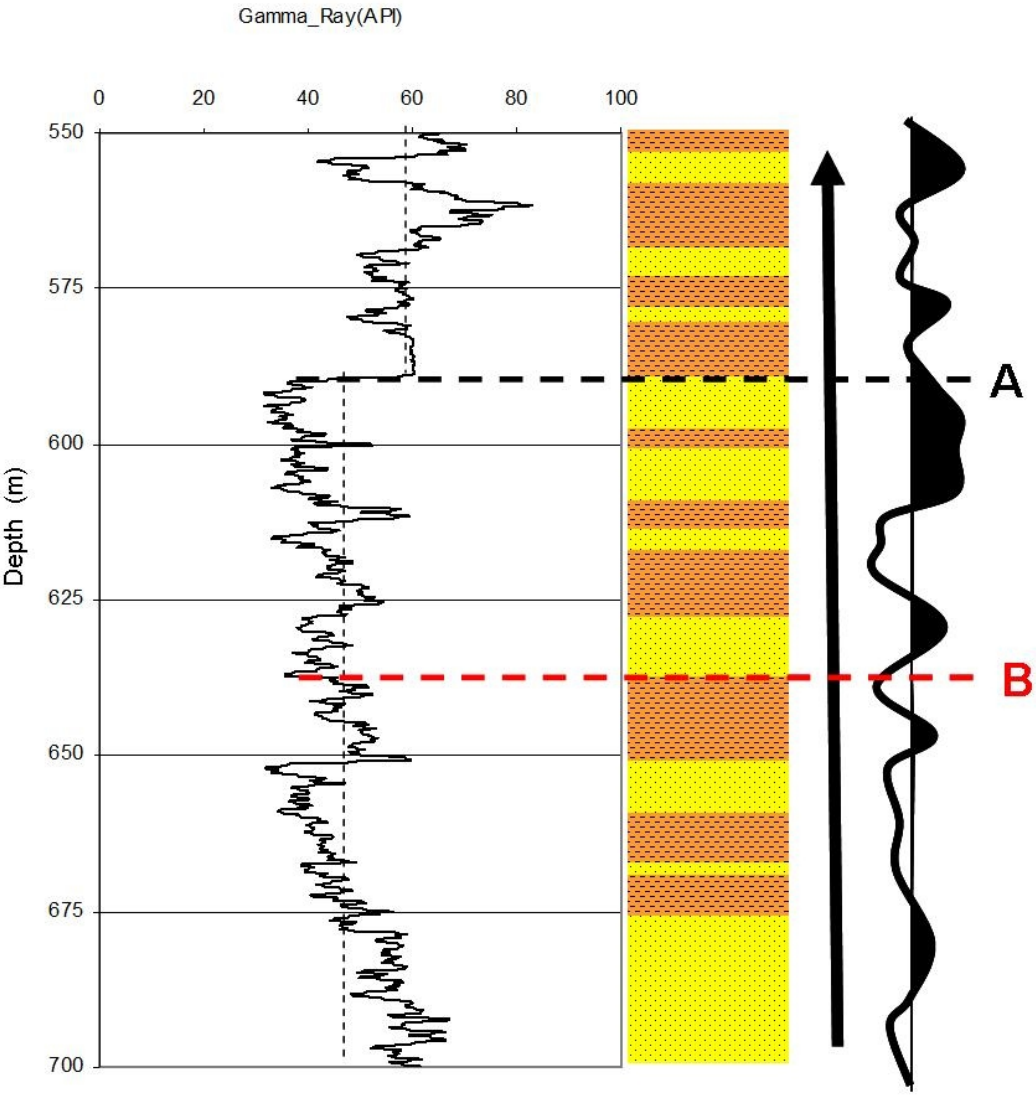

Fig. 3. A typical GR log with a lithology column and a conventional seismic trace. The markers A and B mark a geologic interval to be compared in 3D (e.g. volumetric attributes), which inherently considers superimposed geology. The arrow marks the superimposed layers with older layers at the base.

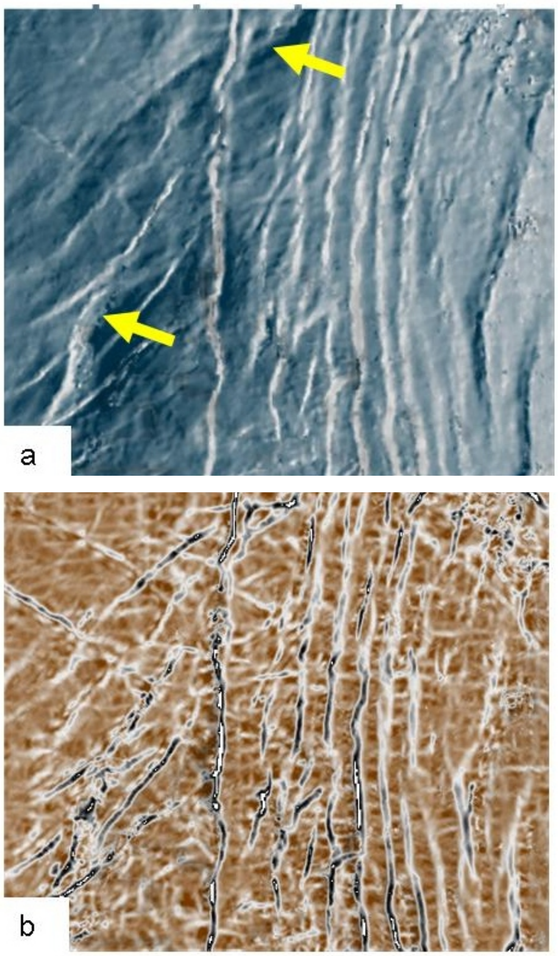

Fig. 4. Top section (a) is a horizon map of seismic dip extracted along the Upper Cretaceous Interval of North Sea (Dutch sector). The lower section (b) is a most negative curvature map of the same horizon. The yellow coloured arrow marks stratigraphic features which are not visually identifiable on curvature map.

Choice of Seismic Attribute

As discussed above, the choice of proper seismic attribute is very valuable in generating optimal results. There are several attributes developed that serves different purposes [1]. However, the current issue is mainly experienced in 3D (e.g. volumetric and geometric seismic attributes). The choice of the most appropriate seismic attribute can make a huge difference in interpretation. For instance, consider two geometrical seismic attribute results (Figure 4): reflector's dip and volumetric curvature [4]. Both attributes are extracted along a horizon, which shows a complex geologic picture. The dip attribute (Figure 4a) shows a result in which structural features (lineaments) can be visually separated from stratigraphic features (wavy trends indicated by arrows). Compared to the dip attribute (Figure 4a), the volumetric curvature (Figure 4b) shows stratigraphic features, but it is difficult to visualize them. Therefore, considering this practical example it is obvious that volumetric curvature is good for structural interpretation while the dip attribute is better to interpret structure and/or stratigraphy. Thus, this leaves no doubt that the choice of attribute impacts the interpretations.

Algorithm Parameters

Each algorithm and seismic attribute could have its own parameter selection relative to the objective. Most of the algorithms and attributes operate on a constant parameter selection relative to a calculation level of interest (e.g. horizons). However, geology is not constant and it changes laterally and vertically. Consider a simple example from Figure 1, which is an attribute extracted along a horizon interpretation. Multi-depositional elements are observable on it since the attribute parameter (time gate) is selected relative to the horizon interpretation. The parameters are later on optimized after considering seismic frequencies and the vertical time window. The result is explained in the later part of discussion (see *spectral enhancement*). Therefore, the selections of appropriate parameters that shall neither over-rule the algorithm limitation nor the objectives would be suggested. It may be noted that most of the algorithms are defined by considering constant time window. However as stated previously: the geology is not homogeneous and it is always laterally varying in thickness. One has to compensate for this using a constant time window by adding a degree of uncertainty in the results.

Geologic Complexities

The example illustrated in Figure 1 is quite simple to understand, because it considers only a stratigraphic issue. However, in practice subsurface geology could be complex if severe tectonic and structural complexities are encountered. To elaborate this point, an example of structural and stratigraphic complexities is illustrated in Figure 5. It is a horizon slice of a similarity attribute highlighting several stratigraphic features (A1, A2, B1, B2), which are disturbed by structural features (fault lineament). In this example, several geologic processes are superimposed on each other to create this geological complexity. Often the features are resolved (A1) but sometimes the features are not clearly evident (B2). A1 is a clearly resolved feature compared to the others and it is underlain by A2 (channel system of small width). The feature B1 represents channels superimposing on each other but structural complexities are not evident. Contrary to B1, there are similar channel systems overlain on each other (in B2) but the structural features (i.e. faults) disturbing them together with noise.

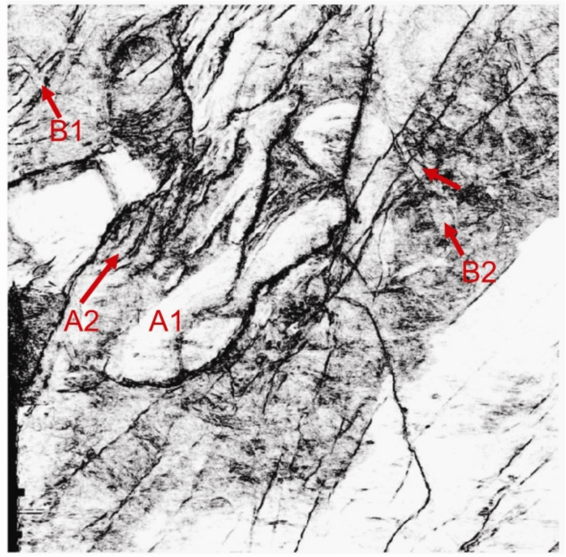

Fig. 5. Horizons slice presenting structural and stratigraphic complexities. The stratigraphic feature separated by fault lineament is labeled as `A`; while the superimposed features within structural complexities are labeled as `B`.

Superimposition of several geologic processes brings a complex picture of the subsurface. Variable sedimentary processes may operate one after another and the different structural elements may also operate in later stages. Nevertheless, the features that are resolved in seismic data, as presented in Figure 5, may help to understand the geology. Nonetheless, the features that are not imaged (not resolved) on the data, may still keep the truth buried. Therefore, geologic complexities are considered yet another cause of this problem and it could adequately be solved by considering the principles of geology.

WORKFLOWS

Several industry standard workflows are briefly explained in this section. The suggested workflows are quite useful and are presented here as they significantly minimize most of the issues of superimposition of features that are due to data limitations.

Dip-steered Median Filter

First and of foremost importance, the noise should be suppressed from the data in order to see the preserved geologic complexities. As discussed earlier, it is optimal to apply a post stack structurally oriented filter. Such a filter not only improves signal to noise ratio but it also improves geology. One well-known filter, such as has been described, is designed by dGB Earth Sciences B.V [5]. This is a special structurally oriented post stack filter. The filter uses median statistics by following a seismic reflector's dip, which assumes that the geology is smooth within a certain filtering range. The filter is very powerful if applied with care because it is preferably edge preserving and improves the continuity of a seismic reflector. Therefore, the efficiency of seismic attributes is significantly improved. A practical example of this filter is illustrated in Figure 2.

Spectral Enhancement

A seismic waveform is a band-limited signal that can be improved by collecting and adding some information from a well data. In other words, adding high frequency information collected from well data to seismic data. Seismic spectral blueing (SSB); developed by ARKCLS, is designed for such purpose, which provides a globally optimized operator such that the seismic data to be consistent with observed earth's reflectivity [6]. In general, the seismic spectrum is re-shaped to match the observed behavior of the reflectivity data obtained from wells. In Figure 6, two amplitude spectra are presented (before and after spectral enhancement) to show the improvement in frequencies (resolution) after spectral enhancement. To show the results, SSB is applied to a 3D seismic data (Figure 7). By comparing the results before and after SSB, it is quite evident that the vertical resolution of the original data is improved. Such an improved version of the seismic data could be valuable in dealing with the addressed problem. Because, a multi-trace attribute will correlate resolved geologic succession trace by trace and thus improving the efficiency of an attribute.

Bandwidth enhancement (BE) is an alternate way of spectral enhancement. In BE, it is considered that a seismic wavelet contains information of a reflector beyond the dominant frequency of the seismic wavelet [7]. The BE technology is developed by GeoTrace using continuous wavelet transformation (CWT).

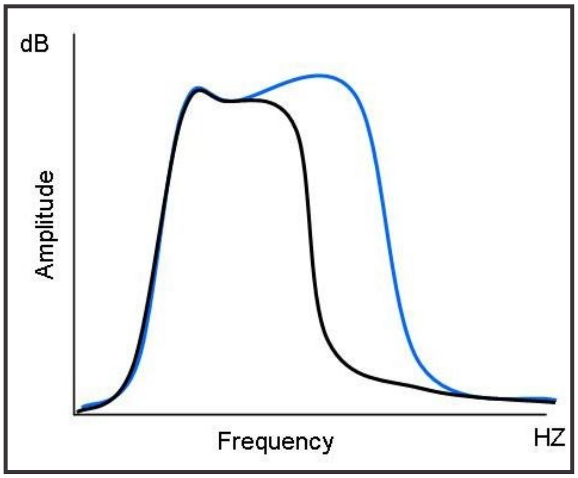

Fig. 6. Conceptual amplitude spectra: before (black) and after (blue) spectral enhancement. The blue spectrum shows a bandwidth extension to the seismic spectrum (black).

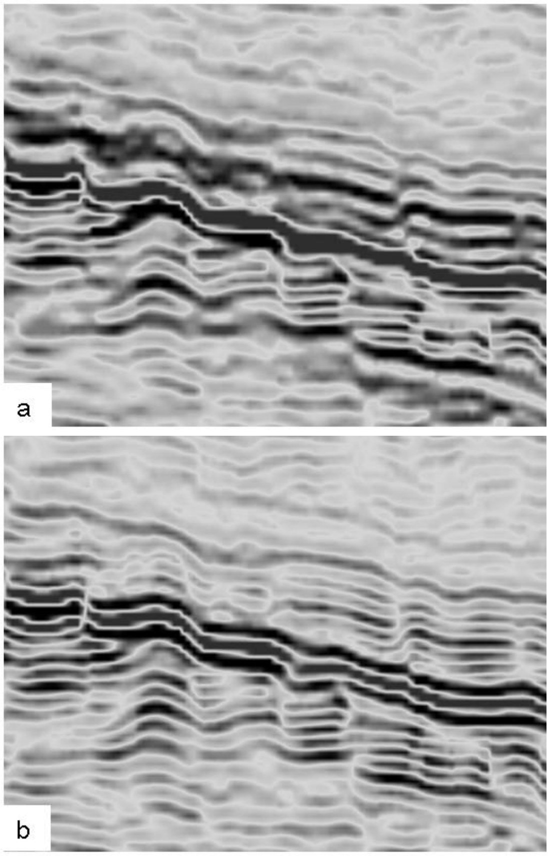

Fig. 7. Seismic spectral blueing is applied to improve the resolution of seismic events by adding frequency information from a well data. The original section (a) shows poorly resolved seismic events whereas after SSB (b) the resolution of the seismic data is improved.

Another workflow is to decompose the seismic data at individual frequency responses as the frequency attribute is reciprocal to temporal thickness. This technique is widely known as spectral decomposition [8]. In the present workflow the spectrally decomposed amplitude slices are colour blended (Figure 8) by optimizing the algorithm parameters (time gate). It is a colour blended amplitude response at three discrete frequencies. The channel-A is not evident because it doesn't fit within the defined time gate of the spectral decomposition. The results reveal the significant parts of channel-B (distributary channel system) that are not clearly visible in Figure 1. Therefore, the results are giving more insights to the depositional history of the region with less interference of other geologic features.

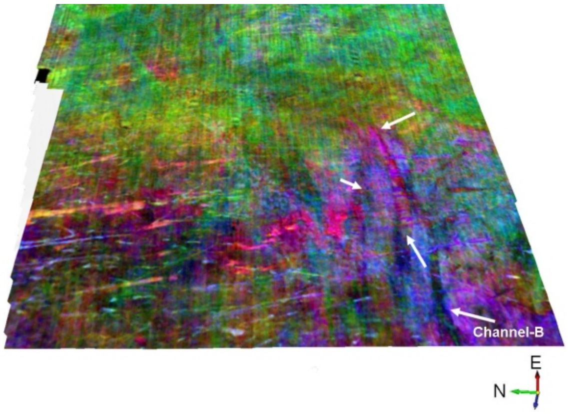

Fig. 8. A colour blended horizon map (Fig. 1) of spectrally decomposed amplitudes at discrete frequencies. The map is prepared after colour blending three amplitude maps that are extracted at three discrete frequencies (low, dominant and high). The result is a blended amplitude response of low (red), dominant (green), and high (blue) frequencies, respectively. White arrows mark the distributary channel system compared to Fig. 1. It also illustrates low degree of superimposition i.e. there are less geologic features overlain on each other.

Apparent Seismic Attributes

Consider that structural features are interfering with the stratigraphic features and both have different geographic orientations, one may think about polarization of seismic attributes. The polarization here relates to recalculation of a seismic attribute at various azimuths. This could easily be done using the following trigonometric relationship:

$$\text{Output} = A \times \cos(\text{Azimuth}) + B \times \sin(\text{Azimuth})$$

Where,
A = Input attribute in inline directions
B = Input attribute in crossline directions
Azimuth is measured from geographic north

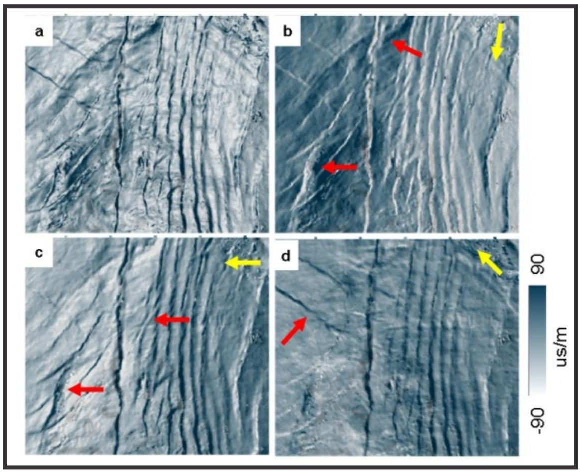

Fig. 9. Apparent seismic dip maps of a horizon slice (see also Fig. 4). (a) A seismic dip attribute map (dark coloured areas are of higher dip values). This attribute contains dip information at all azimuths. The same data is improved by re-calculating the seismic apparent dip attribute at different angles as pointed by yellow coloured arrow (b, c, and d). The red arrow (b) marks a stratigraphic feature that is not evident in other views.

The above equation projects two similar attributes, which are measured on orthogonal planes to a plane defined by a user-defined azimuth. To elaborate the workflow further, several apparent dip attribute maps were generated from the seismic dip that is measured in inline/crossline directions (Figure 9). The actual dip map does show all geologic features (structural and stratigraphic) all together i.e. superimposing on each other. The seismic dip map is then improved by rotating the dip measurements to user-defined azimuths. Such an optimization has revealed the stratigraphic features (red arrows on Figure 9) that are not clearly evident on conventional dip map(s). Moreover, the structural features are also independently depicted on Figure 9d. Therefore, such a workflow is very useful in interpreting superimposed geologic features. Such an application can preserve the geologic features at a known azimuth, thus highlighting only the features of interest. It is suggested that the azimuth selection should be perpendicular to the geologic feature to be highlighted.

MERITS AND PITFALLS IN INTERPRETATION

A good quality seismic data often shows evidence of paleoclimates or stratigraphy. These are effectively interpreted by observing the geologic elements and scanning through the data. This is achieved through volumetric analysis of the data (e.g. 3D seismic attributes). Considering it a merit of seismic analysis; whether superimposed features appear or not, it gives a perspective of a depositional system. However, that is not the ultimate goal of oil and gas exploration. The goal is always to get more details because the reservoir scale is always relatively orders of magnitude lower in scale (i.e. a few meters to hundreds of meters in thickness). Within this merit there are pitfalls if superimposed depositional elements are observed. Figure 1. shows some of the elements that give a clue of a type of depositional environment that an interpreter is dealing with. Observing on the eastern most side of the channel-B, along its depositional profile, it appears that some of the evidence is not resolved; for instance, the initiation of the channel system. Here an interpreter may think about many possible interpretations. For instance, the channel is straight and it is not an extension of another channel, or the channel is a tidal enhanced entrench and the extension of that part is not resolved and so on. However, a different interpretation perspective is achieved in Figure 8. Three parts of distributary channels are observable in Figure. 8 compared to Figure 1. The pitfalls in interpreting distribution, morphology and origin of geologic objects, are thus minimized by understanding the problems in the results: choice of attribute, parameters, and spectral enhancement. Following the triggers of superimposition, a clearer picture is observed and consequently the pitfalls in seismic interpretation are minimized. After minimizing the pitfalls, one can think of the merits and benefits that are noticeable after adopting the appropriate workflow.

DISCUSSION

The focal point of seismic interpretation is always to collect geologic information from the data so that hydrocarbon exploration is eventually successful. To get a better geologic picture of subsurface, seismic data is analyzed in a sub-volume domain. Analysis of the data in a sub-volume domain restricts an interpreter according to the algorithm design, which results into a final geologic picture of the subsurface. As pointed out in the previous section, the analysis parameters are mostly constant relative to any analysis level (e.g. horizon). This generates the results, which often interfere with each other. Sometimes it is simple to improve the results by applying the mentioned workflows and by considering general principles of geology (Figure 1), but in other cases (Figure 5) it becomes more difficult when the geologic complexities are introduced. However, if it is the later, it is mostly about the geologic complexities: one geologic process is superimposing on other.

Therefore, the issue can be broadly summarized into two segments. First is the seismic data that shows a limited geologic record. Second are the geologic processes that are operating on each other to make a final geologic record. When these segments (seismic and complex geology) are interpreted together to find the evidences of geologic events, one should revisit the triggers/causes of superimposition with caution. If the features are superimposed on each other, the evidences may be partially lost on the results but they are often present in a geologic record. Defining a geologic history from such results could be meaningless, if there is a room of improvement as highlighted in the previous section. It is addressed that the reason for a loss of evidence could be one or more triggers of the problems. Broadly speaking, careful selection of parameters, choice of attribute/algorithm, correct workflows, improvement in the resolution (if possible) are all concerned causes that creates the superimposed geologic features.

On the other hand a geologic record itself is an assemblage of complex processes operating on each other. One geologic process exceeding in pace and operating on another geologic process are often observable in a basin. Often these are operating at local scale, and in other case these may operate on a regional scale. The resultant depositional system is thus a complex assemblage. Tectonic, climate, basin geometry, and several other sedimentary processes are also superimposed on each other to make a final depositional system. Therefore, the principle is valid on various scales but when the seismic data is used to adopt the same principles, the limitations may also arise. Some of those are broadly considered in this review.

Therefore, it is very important to find a solution to the problem instead of labeling and interpreting the results. The article directly and indirectly provides the comprehensive explanation to the causes and solutions to the problem by incorporating the common industry practices. It is also considered that the suggested workflows are applicable in case of geologic complexities.

CONCLUDING REMARKS

From the above discussion and the results, it is concluded that the superimposing, interfering and overlying geologic features can be introduced from several reasons. There is no single or unique reason that may result into the addressed problem(s). The discussed potential triggers are of vital importance and can be improved significantly by adopting appropriate techniques. Our analysis shows that if such a situation occurs, the results can be improved by applying suggested workflows. Nevertheless, such features can give a completely different perspective if the results are analyzed through traditional practices. A completely distinct perspective is observed after using the advance workflows addressed in this review.

The issue of superimposed geologic features was addressed with several examples to deliver a message to the people who are dealing with seismic data. It is suggested that direct application of geologic principles should be avoided because this leads to a hypothetical conclusion and interpretation from the observations that are carried out from the seismic data. Nonetheless, the pitfalls can also be manifested by following the right workflow. The workflows are applicable in most circumstances. After the improvements from implementation of such workflows, more convincing evidence could be found that may lead to a more robust conclusion.

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