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Application of Advanced Seismic Attributes for Fault Network Characterization in Geothermal Exploration

Isaac Gonzalez

Heathen International Energy, Delft University of Technology CiTG.

inheath@msn.com

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ABSTRACT

The prospects of geothermal exploitation in the Netherlands (NL) are on an upward trend following resolutions by the Dutch government to gradually phase out dependence on energy from the Groningen gas field. The Master Plan for Geothermal Energy in the NL lays foundations to increase geothermal production from the current 830000 Megawatt Hour (MWh) to a planned 55555555 MWh by 2050. Estimates of the technical potential in the NL is around 277777777 MWh. This "New Energy" is expected to be tapped by greenhouse horticultural and district heating. The seven strata in the NL that are potentially suitable for geothermal exploitation are the Rotliegend, the Triassic, the Jurassic-Chalk, the Upper Carboniferous, the Chalk, the Tertiary and Zechstein plays. The ultra-deep geothermal energy (UDG) potential is most promising in the three Dinantian sub-plays, namely, Friesland, Midden-Nederland and Rijnmond. Around 80 % of the demand for heat in the NL is in areas where there is little subsurface knowledge. Hence de-risking geology during the exploration phase of geothermal plays is crucial. The Dutch government has set a positive example by mandating the release of 3D seismic datasets to the public domain within a stipulated time by operators. Synergies between the oil and gas industry and the geothermal sector is encouraged with respect to industry best practices in subsurface modelling. In this contribution, we highlight the utility of efficient workflows for fault mapping based on 3D seismic data for geothermal developments. Geothermal systems are dominantly fracture-controlled i.e. structural settings and resultant fault architecture can dominate flow and thermal response of fluids and hence determine the ultimate productivity of a planned development. Fault step over regions, fault intersections and fault tips are often favorable targets for geothermal drilling. On the other hand, faults may also act as flow barriers due to sealed and non-conducting fault cores, fault-controlled hydrothermal developments, therefore, require a systematic structural analysis to understand natural permeability patterns. Conventional fault characterization workflows based on reflection seismic involve a great deal of manual effort in tracing faults. We present an automated workflow to characterize fault planes from 3D reflection seismic. The methodology involves a novel workflow of advanced seismic attributes i.e. dip steered and filters followed by harmonic signal processing-based edge detection and finally automated fault plane rendering. Our technique is able to extract fault planes and calculate fault intersection and terminations delivering and revealing rapid 3D fault network patterns in an automated manner with. We are able to create rapid fault geometry realizations that can subsequently be used as an input for numerical simulations of fluid, heat transport, or coupled processes such as pore pressure changes related or due to induced seismicity along faults. We showcase our methodology to a case study from a seismic dataset from the F10 Block, Dutch offshore. The example that is presented encompasses complex faulting over the characteristic group dominated by carbonates. The methodology enables to determine a robust fracture characterization that may be applied to any 3D reflection seismic dataset.

1. INTRODUCTION

The impact that faults and fractures have in resource extraction in geothermal, petroleum and mining industries is unquestionable and of great importance. The correct delineation of faults and fractures can constrain the viability of the projects developed in the mentioned industries. Depending on the type of operations, fault and fracture networks can generate benefits for the projects developed in these industries or act in detriment of them (Opperman, 2012a). In the Petroleum industry a correct characterization can provide positive effects, for example in naturally fractured reservoirs like the ones found in the Mexico, faults and fractures can become conduits for the hydrocarbon production. Also, correct characterization of the fault and fracture network can be included in production and optimization operations enhancing the project economic benefits and viability (Verduzco, 2010). As well a good characterization of the fault and fracture network can deliver optimization plans for drilling operations (Petukhov, 2015). With the advantages that computer machine has brought, new methodologies have evolved in the last decade, allowing geoscientist to better manipulate seismic data, to develop fault extraction methods and to apply advanced seismic attributes in order to extract more valuable information from such datasets (Opperman, 2012a). The aim of the study is the application of the methodology developed by (Jaglan Hardeep, 2016) and (Qayyum, 2015) to generate seismic attributes for an improved fault and fracture characterization with the latest seismic attributes techniques. This methodology allows to generate fault and fractures measurements based on the seismic information, rather than just creating a measurement of faults and fractures based only on manual fault and fracture interpretation. On the other hand, a poor understanding of the characteristics of the faults and fractures can evolve into catastrophic problems in drilling and production operations (Opperman, 2012b). The aim of the study is the application of the methodology developed by (Jaglan Hardeep, 2016) and (Qayyum, 2015) to generate seismic attributes for an improved fault and fracture characterization with the latest seismic attributes techniques. The results presented are faults manually interpreted from the Chalk and North Sea Group on a seismic volume enhanced for fault and fractures characterization. The comparison of enhanced seismic volume and original seismic here presented allowed a better geological interpretation.

2. METHODOLOGY

For the present study the methodology followed is described in figure 1 and provides an ideal workflow for the application of the seismic attributes to achieve the fault and fracture characterization (Jaglan Hardeep, 2016). The methodology encompasses two main aspects: i) the conditioning of seismic data enclosed in the proposed domain to obtain the dip and azimuth of the overall structure, remove noise and acquisition footprints, pitfalls that seismic surveys inherently contain. ii) calculate the seismic attributes in order to generate the most deal framework for the fault and fracture characterization.

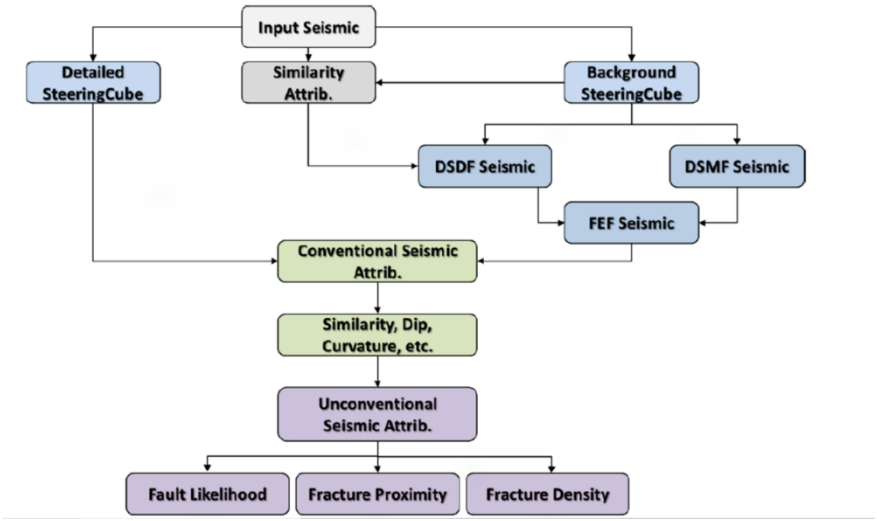


Figure 1: Flowchart for application of the conventional and unconventional seismic attributes (modified from Jaglan and Hardeep, 2016).

2.1 Conditioning the seismic data

The conventional seismic data usually contains noise and pitfalls due to acquisition or incorrect processing. Another reason is that geological features can be affected by acoustic disturbances that can veil their proper visualization. A systematic method that allows filtering the seismic data and removing the random noise from it is applied. This method improves and enhance the lateral continuity of seismic events and allows a sharper delineation of faults and fractures. Further explanation of the steps followed to enhance the seismic is found in the following chapters.

2.1.1 Extracting dip and azimuth

The dip computation marks the framework to further filter the post- stack seismic and to generate geometrical seismic attributes. The dip of the seismic is characteristic that allows to guide the analysis of further attributes like similarity, hence the importance of this calculated volume that is named as a Steering Cube. The dip of the seismic volume can be calculated trough three methods i) Amplitude based ii) Phased based iii) Amplitude-frequency based (Marfurt, 2007). In this project OpendTect is used and calculates the dip trough the Phased- based method using of BG fast algorithm. Different steering cubes can be created depending on their objective that is pursued, this are Background steering cube and Detailed Steering Cube (Qayyum, 2015).

2.1.2 Background steering cube

This strongly filtered cube is used for further analysis of faults and fractures hence the structural geology. The Background Steering cube allows to determine the overall trend of the large-scale dip trends in the seismic reflection data. This is a strongly filtered cube that allows to determine the trend of the large dip and is used for the further analysis of structural geology oriented processing (Qayyum, 2015).The Background steering cube which contains information regarding the primary geological structure, is used to accentuate the overall features of that geological structure and to calculate the multi-trace attributes such as similarity. The cube also used form evaluation mainly to accentuate the overall geologic structure as well to calculate the multi-trace attributes like similarity. This cube is used for the evaluation of Dip Steered Median Filter and Dip steered diffusion filter. Inputs that eventually are used for the creation of the Fault Enhancement Filter.

2.1.3 Detailed steering cube

A less filtered cube is defined as Detailed Steering cube and allows to further calculate more localized characteristics for local dips of seismic reflectors. This cube preserves the small variations on the seismic reflection and contains the information of the faults or flexures from the subtlest geological features (Qayyum, 2015). It is used to maintain the detailed features for example in the curvature attribute in order to accentuate the flexures on the horizons.

2.2 Structural geology oriented filters

This method creates an enhanced volume that allows the interpretation of faults and fractures by smoothing the seismic reflections, enhancing the edges of the seismic reflector and preserving the characteristics of the structure. (Jaglan Hardeep, 2016). The enhancement of the signal quality is achieved by suppressing the random noise that is contained in the signal it is performed by processing and conditioning the seismic data in a routine way. The method proposes three steps i) create an improve in the lateral continuity of the seismic reflectors, achieved with the Dip Steered Median Filter, ii) improving the position of the fault, using the dip

steered Diffusion Filter and last, iii) merge previous two steps in order to create a logical statement to produce a Fault enhanced seismic data (Qayyum, 2015).

2.2.1 Dip Steered Median Filter

This filter is applied using the background steering cube which contains the large-scale dip trends (Marfurt, 2007). The statistical filter smooths the seismic volume, preserving and improving the lateral continuity of seismic reflector and removing the background noise by using the median statistics of the seismic amplitudes and following the seismic dips (Qayyum, 2015). This filter can smooth too much the discontinuous features like faults and fractures, this is dependent on the size of the fault zone. If the fault zone is smaller than the mean is smoothed out, the Dip Steered Diffusion Filter is applied. This Filter is mostly used to remove the noise for the seismic data.

2.2.2 Dip Steered Diffusion Filter

This is defined in the routine as the intermediate step that takes the advantage of the diffuse character of the signal close to a fault. The Dip Steered Diffusion Filter utilizes the diffuse characteristic near a fault and evaluates the seismic data in a dip steered circle. It replaces the diffused seismic traces near a fault and with the better-quality seismic traces, resulting in sharper faults (Jaglan Hardeep, 2016). The Dip Steered Diffusion filter is mainly used to make sharper faults by enhances the diffusion in the proximity of the fault. This filter is the input for the calculation of the Fault Enhancement filter.

2.2.3 Fault Enhancement Filter

The final stage of the method to obtain structural oriented filters is achieved by combining previous two logical filters. The Dip Steering Median Filter (DSMF) and Dip Steered Diffusion Filter (DSDF) which are systematically applied in conjunction to obtain a geometrical seismic attribute named Fault Enhancement Filter and calculate with this the similarity. The Fault Enhancement Filter attribute uses a defined threshold value in order to systematically apply previous filters DSMF and DSDF. As Fault Enhancement Filter is computed analyzes the similarity attribute if it is above the threshold proposed it applies the DSMF meaning that the lateral correlation exists (Qayyum, 2015). If the similarity is computed and is below the threshold value, it uses the DSDF to enhance the faults that can be present.

2.3 Seismic attributes

This is second part of the methodology, where the creation of the geometrical attributes takes place on the targeted horizons. The method relies on applying the geometrical attributes systematically to the images of complex geological features encountered in the area of interest. The attributes allow us to extract the most detailed geological features. The attributes are applied in a sequential order, to enhance the characterization of faults and fractures of the Chalk, and North Sea Group targets. The geometrical attributes applied are categorized as 1) conventional attributes and 2) unconventional attributes. Conventional attributes have been standard methods of great use in the industry and because of their common use, are termed this way. The term unconventional attributes refer to the fact that they are new techniques applied in the industry to obtain more information from the seismic data. With OpendTect the attributes are evaluated with specific entry parameters to test their result, the parameters used to calculate the attributes are varied in order to obtain the best results. This means are calculated either in one specific inline or crossline and only when the result satisfies and honors the geological features, attributes are computed as volumes to build and to gain information of the whole seismic volume.

2.3.1 Conventional attributes

Conventional attributes are commonly used to enhance the seismic data for further characterization of geological features. The geometrical seismic attributes used in this study follow the overall trend of the geological features that are encountered in the subsurface.

2.3.2 Similarity

It analyzes the correlation of two trace-segments, it is a form of coherence defined by the distance in hyperspace between the vector of the segments (de Groot, 2003), which is normalized to the sum of the length of the vectors. Similarity of the traces is estimated trough the reflection, computing the Euclidean distance between the amplitude vectors of the trace of the waveform (Tingdahl, 2005). It is namely a form of coherency that searches the correlation of the waveforms along a reflection (de Groot, 2003). This similarity attribute is calculated since faults and fractures can be described as discontinuous reflection patterns that provide low response to similarity. For the purpose of evaluation of similarity equation 1 is described after (Tingdahl, 2005) to evaluate the dip steered similarity. This attribute allowed to discern faults and fractures as they are sensitive to the lateral position of the trace segment. The similarity is applied using the Fault Enhancement filter as an input, as well an evaluation of the similarity without steering is calculated in order to demonstrate the improvement that steering can generate.

2.3.3 Curvature

The different types of curvatures were created with the Background Steering Cube as an input, as this volume contains the dip of the volume in the inline and crossline direction of the overall Geological features. The curvature is an effective method to describe how much a surface of interest deviates from being a straight line (Roberts, 2001). The method of curvature attribute utilizes this concept to evaluate and to provide insight of discontinuous variations of geometrical deformation from being a straight line (Marfurt, 2007).A group of curvatures is used in order to evaluate geological features as anticlines or the upthrow part of the fault, for the latter the most positive curvature was used. A second method evaluates the most negative curvature providing idea of geological features like anticlines or the downthrown part of the fault.

2.3.4 Unconventional attributes

These are defined as unconventional attributes due to the fact that they are of recent application in seismic interpretation for fault and fractures. OpendTect has developed three new attributes that are created using the filters DSDF, DSMF, FEF described in the previous chapters.

2.3.5 Thinned fault likelihood

The thinned fault likelihood attribute is calculated with the Fault Enhancement Filter as an input which contains the information of the dip in a volume. It searches for the orientation of the minimum semblance along the tridimensional volumes. It is defined as a power (for instance n=8) of semblance (1- Semblance^n) (Qayyum, 2015).The values of this attribute range between 1 and 0 (Jaglan Hardeep, 2016) showing the probability of the anomaly to be present. This attribute can generate faults and fractures that have non-geological dips and strikes due to its sensibility and due to the characteristic that these geological features represent the most likely, discontinuity possible (Hale, 2013).

2.3.6 Fracture density

The fault density attribute is computed using the thinned fault likelihood volume and it allows to evaluate the area were fractures concentrate by calculating the ratio of several traces that are distinguished to be fractures in a defined area (Qayyum, 2015). This attribute allows to highlight the location of fractured areas in respect of a radius provided. (Jaglan Hardeep, 2016).

2.3.7 Fracture proximity

The method to evaluate this attribute is using the Thinned Fault Likelihood volume as an input volume. This unconventional attribute allows to characterize the fracture connectivity (Qayyum, 2015). Utilizes the position of the trace that is identified as a fracture and evaluates the distance laterally. This attribute is determined by a threshold value, revealing the closeness of a particular sample from a fracture, as well the closeness between fractures. This attribute is used to visualize the connectivity of the fractured network (Jaglan Hardeep, 2016).

4. RESULTS

The methodology proposed by (Jaglan Hardeep, 2016) is used to condition the seismic data, and to provide a suitable framework for the handling and application of seismic attributes. The method to obtain information on dip and to generate a volume that steers the attributes enhances the best framework for the manual interpretation of faults and fractures. This method allows to determine the scale, orientation and characteristics of fractures. The procedure shows faulted and fractured zones that could not be recognized in the original seismic volume. In this section the results are presented along with the most representative geometrical attributes calculated in each targeted horizon. The results are shown in an enhanced seismic volume where the manual interpretation is improved.

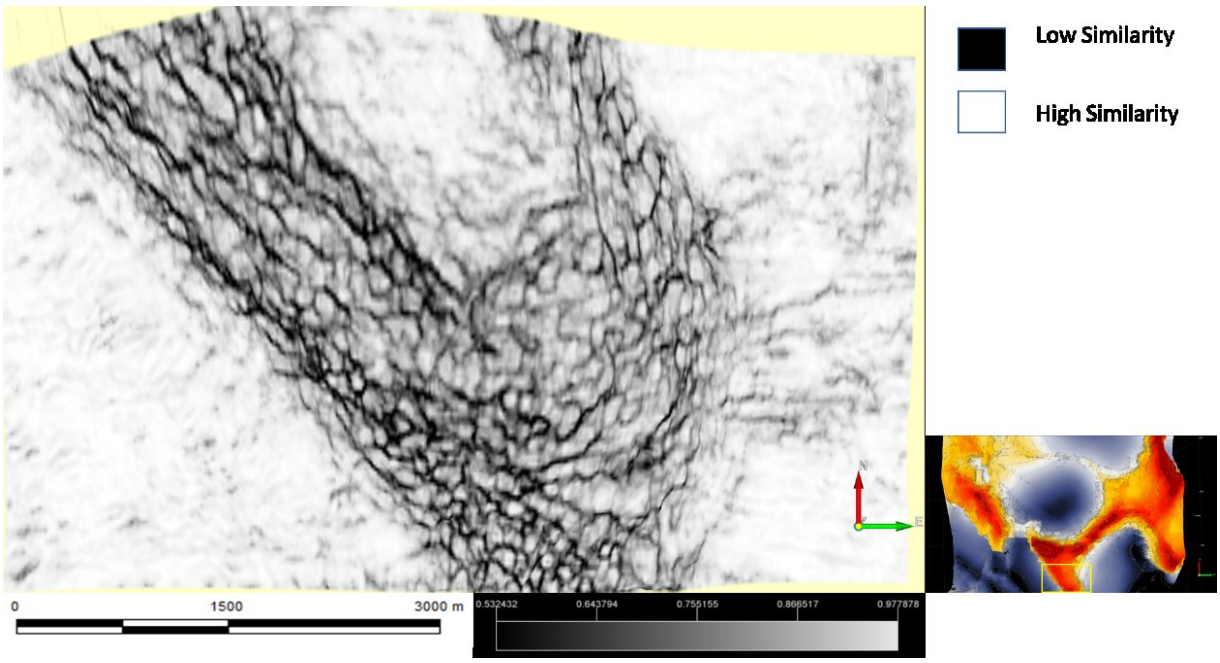


Figure 2: Similarity created with the Fault Enhancement Filter of the Chalk horizon. Bottom right figure shows the location of the study area in Block F10. The figure shows better delineated faults and fractures. In dark the faults and fractures enhanced for manual interpretation. In white high similarity showing less faults and fractures.

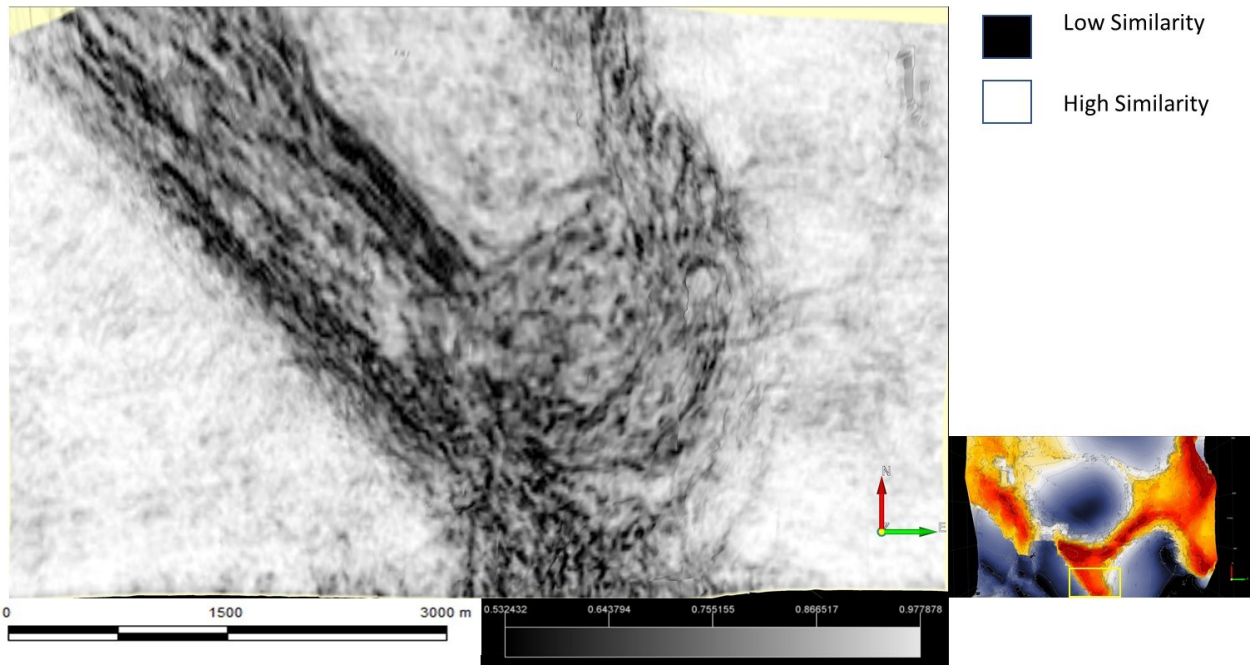


Figure 3: Similarity created with original seismic on Chalk horizon. Bottom right figure shows the location of the study area in Block F10. The figure shows delineations that do not allow the improved manual interpretation. In dark the faults and fractures for manual interpretation. In white high similarity showing less faults and fractures.

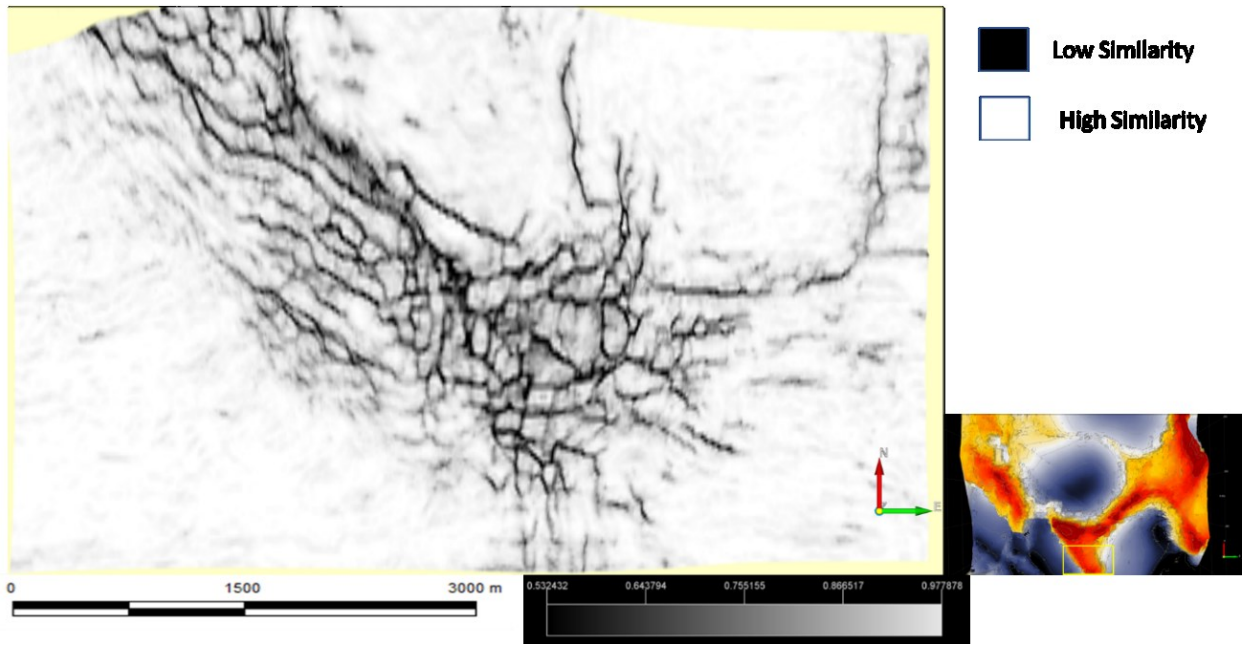


Figure 4: Similarity created with the Fault Enhancement Filter of the North Sea Group horizon. Bottom right figure shows the location of the study area in Block F10. The figure shows better delineated faults and fractures. In dark the faults and fractures enhanced for manual interpretation. In white high similarity showing less faults and fractures.

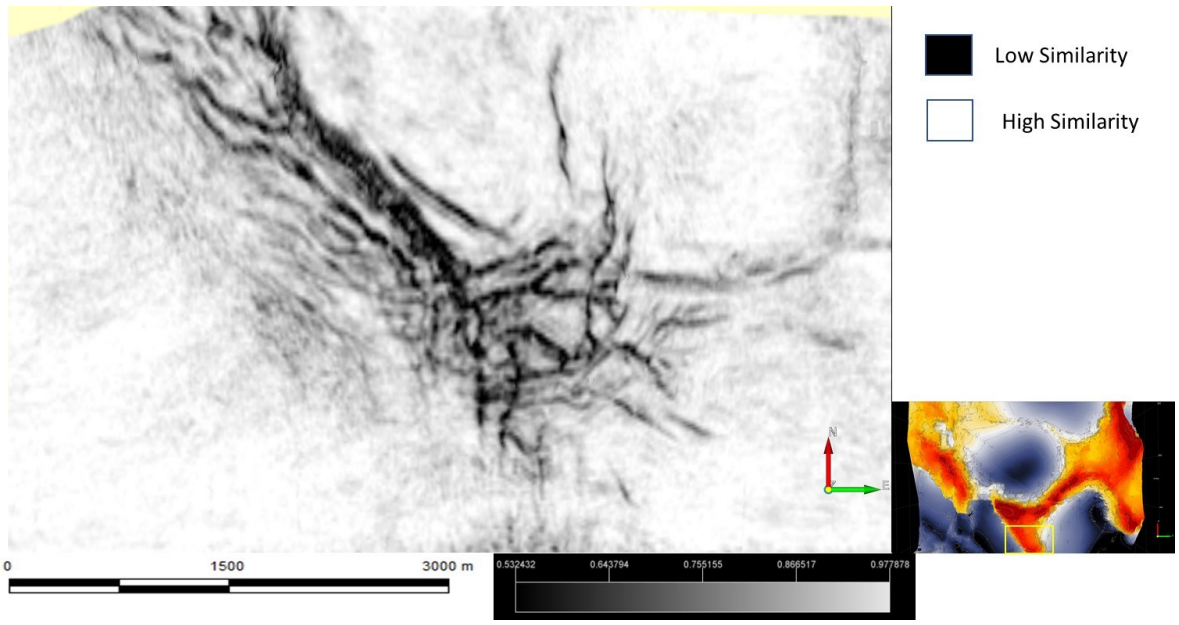


Figure 5: Similarity created with original seismic on the North Sea Group horizon. Bottom right figure shows the location of the study area in Block F10. The figure shows delineations that do not allow the improved manual interpretation. In dark the faults and fractures manual interpretation. In white high similarity showing less faults and fractures.

5. CONCLUSION

The application of geometrical attributes has delivered an enhanced framework for the accurate fault and fracture interpretation over specific horizons belonging to the Jurassic and the Cretaceous, located in the F10 block offshore the Netherlands. The attributes that delivered the most optimal and realistic representation of faults and fractures were the Similarity evaluated with the Fault Enhancement Filter, the different curvatures like Most Positive Curvature, Maximum Curvature, Most Negative Curvature and the newly developed Thinned fault likelihood. Using the software OpendTect created by dGB Earth Sciences and following the methodology proposed by (Jaglan Hardeep, 2016) an improved the interpretation of the structural features in the seismic survey was done introducing the structural dip data to the generation of the geometrical attributes. The creation of seismic volume determined a Steering Cube that contained and respected the information on the structural dip. This volume improved the delineations and visualizations of faults by removing the noise from the seismic reflectors. Two Steering cubes were developed. One is the Background Steering Cube which is a heavily smoothed volume that honors the overall trend determined as structural dip. The other is the Detailed Steering Cube that is moderately filtered and proved to define local dip trends. The application of the Structural oriented filters Dip Steered Median Filter enhances the seismic amplitude and the Dip Steered Diffusion Filter enhances the diffusion in the proximity of the fault. A final filter is generated to delineate faults and fractures, determined as Fault Enhancement Filter. This filter was used to generate a new similarity attribute that demonstrated better fault and fracture delineation and better visualization than without application of the Steering cube and filters generating more confidence when interpreting the faults and fractures. The generation of curvature attributes using the Detailed Steering Cube allowed to visualize structural features like the upthrown or downthrown side of the fault, this curvature attributes works as reference for determining faults and fractures that would not be visible with other attributes. The creation of the Thinned Fault Likelihood that is an automated fault extraction method based on the semblance of the seismic data, proved to be a great contribution for the analysis of the faults and fractures. This attribute created a new measurement based on the evaluation of the semblance that was scanned along the dips and strikes allowing to use it as a confirmation of the faults and fractures in the seismic data. Further unconventional attributes were calculated with this thinned fault likelihood filter as an input, these unconventional attributes are fault density and fault proximity.

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