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Elin Marie Nicolaisen

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Introduction

Two decades ago, fault zones did not get much attention in reservoir geological models. Today, this has changed due to petroleum exploration and production. Faults are complicated structures, and it is not easy to completely understand their impact in a petroleum- or water reservoir (Fossen and Gabrielsen, 2005). Faults, can in some occasions prevent fluid flow, and other times they can lead fluid flow. Faults can seal reservoirs, but they can also give better communication between reservoirs by leading stratigraphical isolated reservoirs in contact to each other (Fossen and Gabrielsen, 2005).

Seismic interpretation is the main method to map and understand the subsurface, trace faults and visualize reservoirs. During the last decade, major improvements of seismic interpretations techniques have been developed, mainly focused on fault delineation and seismic attributes to understand lateral continuity of horizons and facies properties of reservoirs. It has been previously demonstrated that changes in the physical properties of rocks along the fault zone affect the seismic response (Couples et al., 2007). This relation has been explored using synthetic seismic (Couples et al., 2007).

However, none or little effort has been done in the inverse direction, i.e. identify and define the internal properties of faults directly from seismic interpretation. Some key challenges for identification of fault zones from seismic data are:

1) fault zones are narrow zones and seismic observations are limited to a couple of seismic traces in either side of the fault zone;

2) seismic interpretation is dependant on seismic acquisition and processing which may affect the quality and final data available, not representing in the most extreme case the reality;

3) changes along the fault zone are dependant on the physical properties of the rock displaced, therefore a large variability of behaviour can be expected, i.e., brittle vs. ductile, compacted vs. uncompacted, overpressured etc.; and

4) few controls are available to quality check the seismic interpretation; in general, few wells are cored into fault zones and such observations tied via synthetic seismograms into the seismic.

In general faults and horizons are interpreted differently, but still faults are interpreted as surfaces and not volumes. In this thesis a qualitative standard seismic interpretation method will be used, but with an attempt to improve and evaluate the standard interpretation technique of faults. This means that faults are interpreted not only as surfaces, but also as volumes. At the same time, I will attempt to extract attributes of the fault zones, similar to how is done with seismic horizons. Hopefully, this method can develop into a new, more accurate interpretation technique of faults; not just as surfaces, but as volumes where petrophysical properties in the fault zone can be obtained from seismic. and ultimately patterns of connectivity identified for fluid flow in reservoir models.

The main goal is to recognize the consistence of seismic changes along and across the fault zone, i.e. patterns in and out of the fault zone that can lead to a detailed petrophysical analysis, that will be the input to reservoir models. In this study, a real data set was used, in contrast to previous studies (Couples et al., 2007). The data is 3D seismic survey covering an area of 6029 km^2, located in the Hammerfest basin. The dataset was provided by the Norwegian petroleum database, Petrobank. Seismic interpretation was carried out using OpenWorks® by Landmark, and the fault zone modelling using Petrel® by Schlumberger.

Theoretical Considerations

Fault zone

In the oil and gas industry faults are of great importance. The reason for this is that faults can act as seals but also as migration pathways. A fault can be defined as: *"a tabular volume of rock consisting of a central slip surface or core, formed by intense shearing, and a surrounding volume of rock that has been affected by more gentle brittle deformation spatially and genetically related to the fault (Fossen and Gabrielsen, 2005)".*

In seismic or geological profiles published on maps or cross-sections, faults are interpreted as a simple line, i.e. a fault is interpreted in the same manner as a surface/horizon. In real life, faults are more complex than these depictions.

A fault can be divided into a fault core, and a damage zone (Fossen and Gabrielsen, 2005). Figure 1 shows a normal fault zone. In this figure, the centre of the fault is an intensely deformed core, surrounded by a damage zone, which consists of small fractures. Often there also exist a drag zone where the layers are rotated towards the fault. Figure 2 shows an example of a fault from an outcrop in Western Sinai. Depending on the level of observation, the fault core can vary from a simple slip surface to a more complex zone with intense deformation (Figure 2 C). The fault core can be from a millimetre to a metre thick zone of cohesive or non cohesive breccias, non cohesive smeared out soft layers, lenses and membranes. A fault damage zone is the surrounding volume of brittle deformed wall-rock (Figure 2 B). The density of brittle deformation is higher than the background level. The brittle deformation can be deformation bands, shear fractures, tension, fractures and stylolites. The fault damage zone is located on both sides of the fault core, and also on both ends of the core (Figures 1 and 2). The drag zone can be identified as ductile or brittle deformation, depending on the scale of observation (Figure 1).

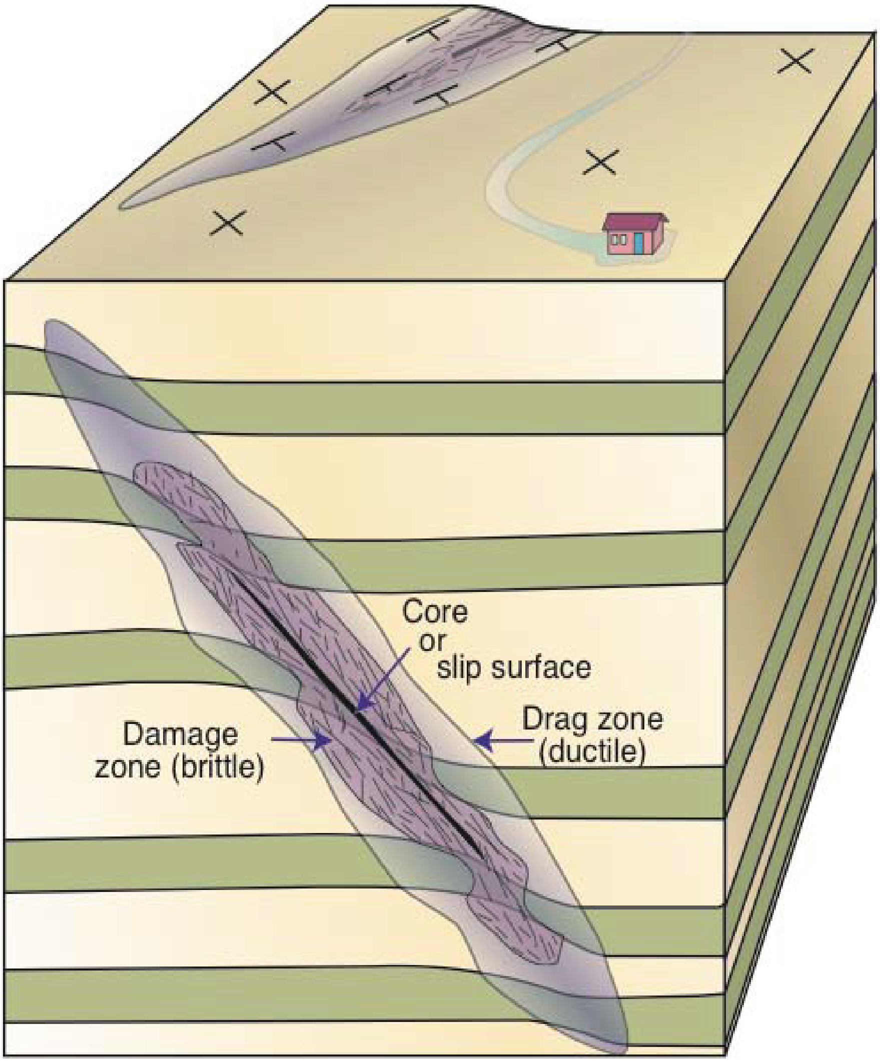
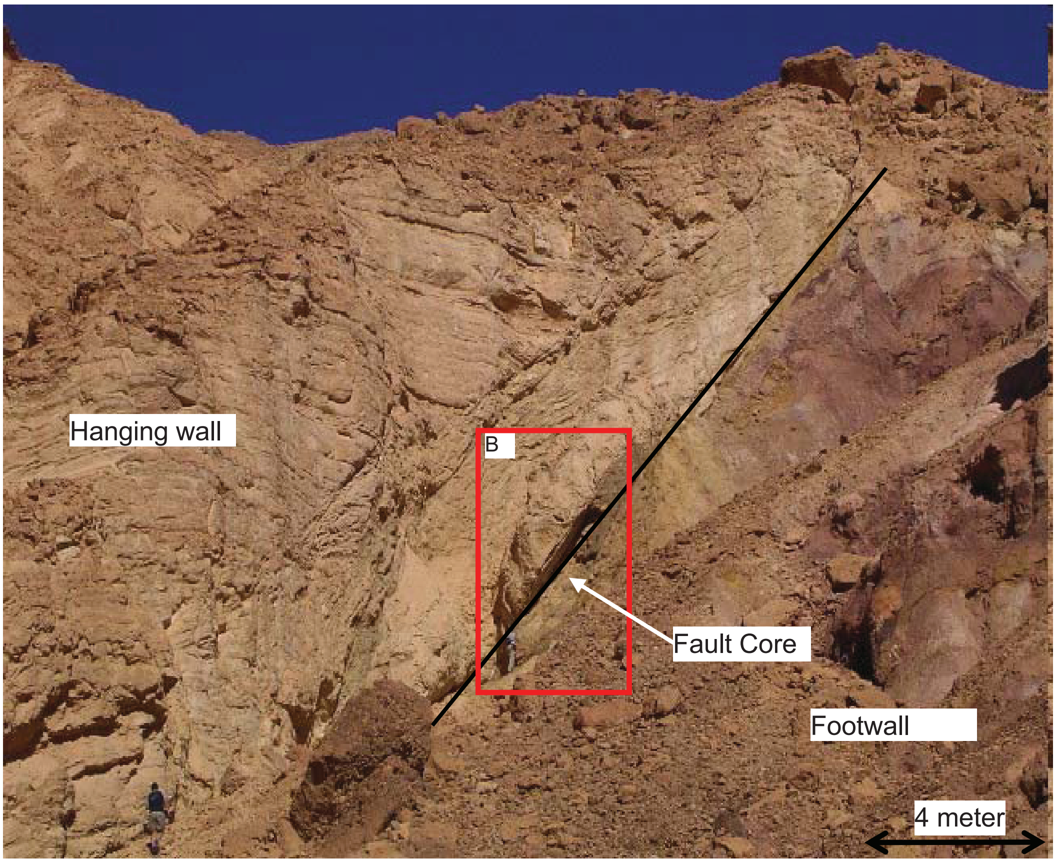
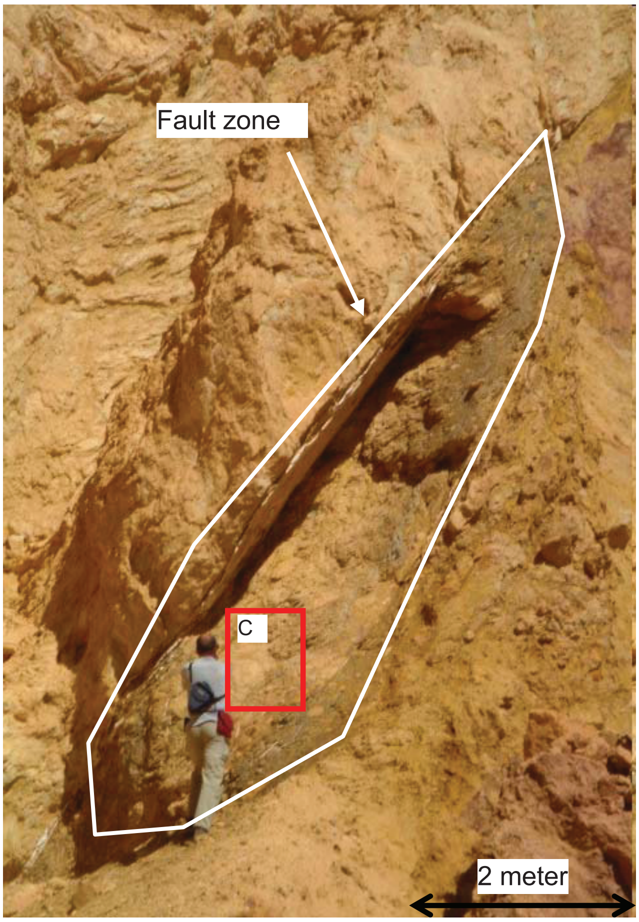


Figure 1: *Normal fault core. From Fossen & Gabrielsen, 2005.*

A





B

C

Figure 2: *Normal fault zone in Sinai (Thal fault). Eocene Tanka limestone in hanging wall and Paleozoic Nubian sandstone in footwall. A, B and C show different levels of observation of the fault zone. Pictures from Nestor Cardozo and Alvar Braathen.*

Fault facies

The fault zone consists of a varying number of discrete fault facies originating from the host rock and organized spatially according to strain distribution (Braathen et al., in press). In the same way as sedimentary facies, fault facies are linked to quantifiable observational data on dimensions, geometry, internal structures, petrophysical properties, and spatial distribution in the fault zone (Braathen et al., in press). Petrophysical properties can be porosity, permeability and water saturation.

Fault facies is a powerful tool for pattern recognition, description, modelling and forecasting property distribution in surface and subsurface fault zones. The main strength of the facies approach lies in its flexibility for subdividing bodies of rock into distinct classes or groups at any scale according to any set of properties or features, observed or interpreted (Braathen et al., in press). Tveranger et al. (2005) defines a fault facies as "*any feature or rock body that has properties derived from tectonic deformation*". This means that similar to sedimentary facies, "individual fault facies occur in certain combinations, or *associations*; in transitional sequences, or *successions*; and in larger scale associations with volumetric dimensions, the *architectural element*, which is controlled by the fault environment" (Tveranger et al., 2005).

A technique for using volumetric description of fault zones in industrial reservoir models has recently been developed by the Fault Facies project at the Centre for integrated Petroleum Research (CIPR), University of Bergen, Norway (Tveranger et al., 2005; Soleng et al., 2007; Cardozo et al., 2008; Fredman et al., 2008). The method describes tectonically deformed rock volumes in terms of facies (i.e. "fault facies"). The method uses standard stochastic modelling methods of data, derived from outcrop studies and structural modelling, to populate fault envelopes with volumetrically expressed fault facies and their petrophysical properties. Figure 3 is a synthetic model, where volumetric fault zone grids have been added to the reservoir model. Figure 3 A and 3 B display the standard way of including faults in a reservoir model.

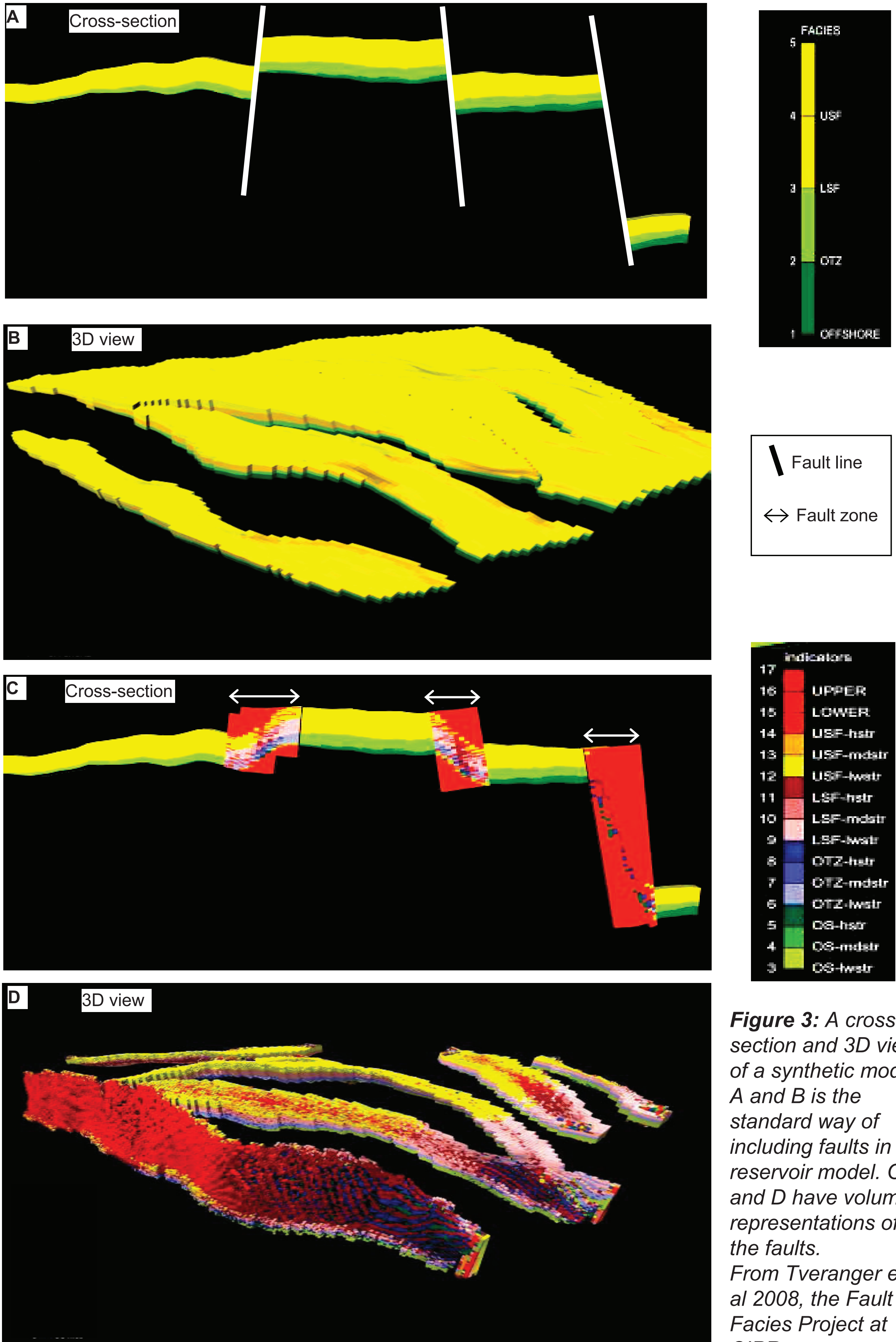


***Figure 3:** A cross section and 3D view of a synthetic model. A and B is the standard way of including faults in a reservoir model. C and D have volume representations of the faults. From Tveranger et al 2008, the Fault Facies Project at CIPR.*

Faults are lines or grid splits. Figure 3 C and 3 D shows the same reservoir model, but here the faults are represented as volumes. This method follows the concept of faults as volumes containing fault facies. By using fault facies as building blocks, it is possible to reach a more realistic fault zone structure. Based on this, it is possible to assign petrophysical properties to the fault zone, and to have a more realistic and accurate analysis of fluid flow in the reservoir. Still, few attempts have been done to extract the internal structure of fault zones from seismic.

Heave, Throw and Dip Slip

Faulted structures play a very significant role in the trapping of hydrocarbons (Tearpock and Bischke, 1991). Therefore it is important that anyone involved in the exploration of hydrocarbons uses correct and accurate subsurface mapping techniques for the interpretation of faults and integrated structural maps, often called fault surface maps. To construct a fault surface map the data required are obtained from well log correlation and seismic interpretation (Tearpock and Bischke, 1991).

The preparation of accurate fault surface maps requires three-dimensional thinking and a good understanding of the structural style of the area being mapped (Tearpock and Bischke, 1991). To understand the structural style of a fault, it is important to grasp the meaning of different fault slip components. In geology there are several fault slip components, but those that are mostly used in subsurface mapping in the petroleum industry are dip slip, heave, and throw (Figure 4).

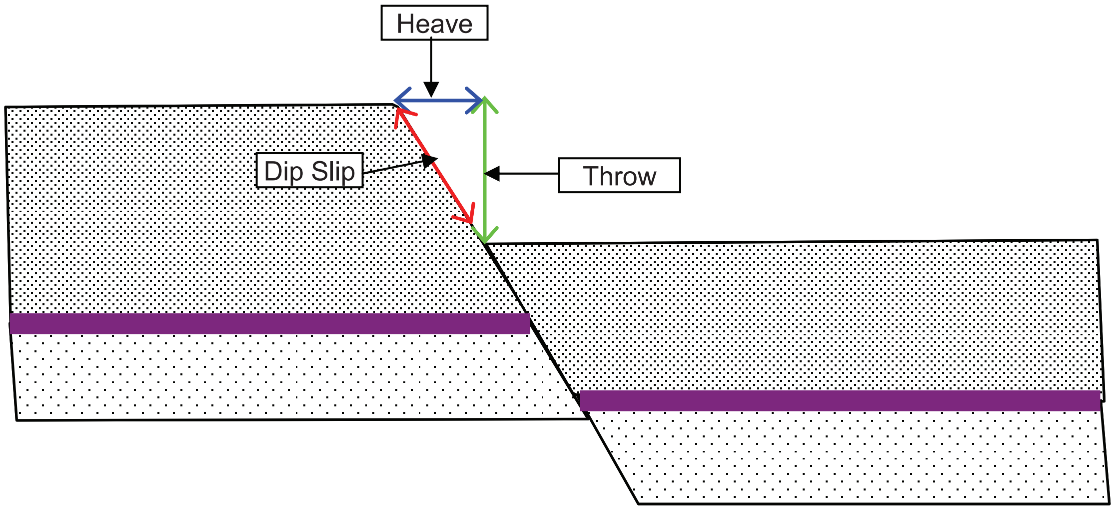


Figure 4: *Illustration of three different fault components. The cross section is perpendicular to the strike of the fault. From Fossen and Gabrielsen, 2005*

- Throw is the vertical component of dip slip. It is the difference in vertical depth between the fault intersection with a line or plane (such as a formation top) in one fault block and the fault intersection with the same line or plane in the opposing fault block, determined in a direction perpendicular to the strike of the fault (Figure 4) (Tearpock and Bischke, 1991).
- Heave is the horizontal component of dip slip. It is determined in a direction perpendicular to the strike of the fault (Figure 4) (Tearpock and Bischke, 1991).
- Dip Slip is the component of the fault parallel to the dip of the fault. Also known as normal displacement (Figure 4) (Licker et al., 2003).

Seismic attributes.

During the last years, the use of seismic attributes has increased (Brown, 2003).There are different horizon and formation attributes available, some of which are listed in Table 1. They are not independent of each other, but simply they are different ways of presenting and studying a limited amount of basic information. This basic information consists of time, amplitude, frequency and attenuation (Brown, 2003). These are the basis of the different attribute classifications.

Time-derived attributes provide structural information, and amplitude-derived attributes provide stratigraphic and reservoir information. Those derived from frequency are not totally understood yet, but there is optimism that they will provide additional useful stratigraphic and reservoir information (Brown, 2003). Attenuation is not used today but there is a possibility that in the future, it will yield information on permeability (Brown, 2003).

Reflection amplitude is measured at the crest of an identified reflection. When these are extracted over one horizon, it produces a display normally called a horizon slice. The composite amplitude is the absolute value summation of the amplitude of reflections identified at the top and base of a reservoir, or other, intervals. Acoustic impedance derived from amplitude by seismic inversion is another way of combining information from reservoir top and base (with thickness limitations).

Seismic Attributes

Time	Frequency
Velocity	Instantaneous frequency
Time	Spectral decomposition
Isochron	Wave shape
Residual	Loop area
Dip	Arc length
Azimuth	Average inst. freq.
Edge	RMS inst. freq.
Illumination	No. zero crossings
Inst. phase	Peak spectral freq.
Curvature	1st dominant freq.
Roughness	2nd dominant freq.
Coherence	
Continuity	
Chaotic bed indicator	

Amplitude	Attenuation
Far-near difference	Slope spectral freq.
Reflection amplitude	Slope inst. freq.
Composite amplitude	
Relative impedance	
Reflection strength	
Average absolute	
RMS amplitude	
Variance of amplitude	
Energy half-tine	
Slope refl. strength	
Ratio pos. to neg.	

Table 1: *A simplified overview of the seismic attributes, which are derived from or related to the basic information of time, amplitude, frequency and attenuation. Modified from Brown, 2003.*

In this study, RMS (root mean square) amplitude, instantaneous frequency, and chaos attributes are used in order to map fault zones and to establish continuity of fault properties. They have the following meaning:

- *RMS Amplitude*; "computes Root Mean Squares in instantaneous trace samples over a specified window" (Petrel-userguide, 1998-2008).
- *Instantaneous frequency*; "is the time derivative of phase, which is calculated from the temporal rate of change of the instantaneous phase. It is often used to estimate seismic attenuation. It helps to measure cyclicity of geological intervals and may be useful for cross-correlation across faults. It could also identify contacts between gas and water, or gas and oil. Instantaneous frequency tends to be unstable in the presence of noise and may sometimes be difficult to interpret" (Petrel-userguide, 1998-2008).
- *Chaos*; "the chaotic signal pattern contained within seismic data is a measure of the "lack organization" in the dip and azimuth estimation method. Chaos in the signal can be affected by gas migration paths, salt body intrusions, and for seismic classification in the chaotic texture. Chaos in the signal can be used to illuminate faults and discontinuities and for seismic classification of chaotic texture. Chaos can be related to local geological features as it will be affected by gas migration paths, salt body intrusions, reef textures, channel infill, etc" (Petrel-userguide, 1998-2008).

Subsurface fault identification and interpretation

Identifying faults is important in connection with hydrocarbon exploration and production (Fossen and Gabrielsen, 2005). Several methods can be used;

Seismic data.

The interpretation of seismic data is the most used method to identify and map faults in the subsurface. This method provides results within some tens of metres of resolution (Fossen and Gabrielsen, 2005). It requires that seismic reflections can be interpreted and correlated. Faults will appear where the reflections are discontinuous, and the correlation of the reflection from one side of the fault to the other, determines the apparent displacement of the fault. 3D-seismic data allow the interpretation to be done in difference directions. Figure 5 shows an example of a 3D-seismic cube taken from the seismic survey used in this study, where faults can be interpreted as discontinuities in the seismic reflection.

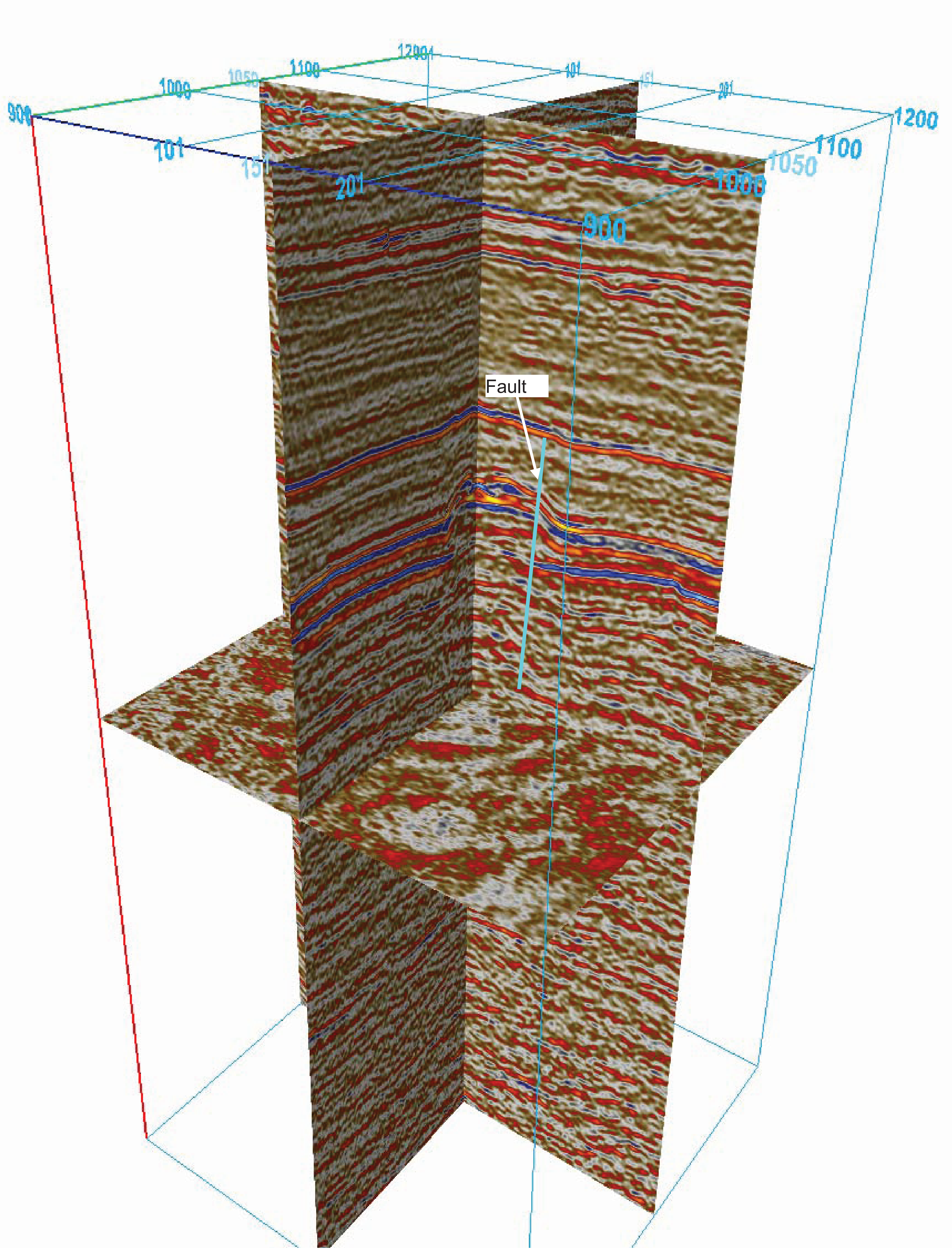


Figure 5: *3D-seismic data organized in a cube. This example is taken from the dataset used in this study.*

Well logs.

Faults can also be identified when a sedimentologist discovers a great change in a well, that can be difficult to explain by stratigraphical changes (Fossen and Gabrielsen, 2005). The standard well logs, such as gamma ray, density, neutron, and resistivity logs are then correlated in detail. Figure 6A shows an example of how the gamma, density, neutron and resistivity logs from two wells are correlated to identify a fault zone. This was done by correlating missing intervals (normal fault) or repeated intervals (reverse fault) in the different sections. A missing section corresponding to a fault with its damage zone is shown in figure 6B. It is possible to identify faults down to 5 metres, as long as the wells are tight together, characteristic logs are in the current stratigraphic area, and that these changes are small or regularly, and well understood (Fossen and Gabrielsen, 2005). By correlating an electric log from one well with other electric logs from surrounding wells, it is possible to determine a fault cut (Tearpock and Bischke, 1991). Fault cut is the vertical thickness (figure 4) of the stratigraphic section missing or repeated in a wellbore as a direct result of a normal or reverse fault cutting through the section.

Dipmeter data.

In addition to the standard well logs, the dipmeter tool can be used to identify faults and unconformities in the subsurface. An unconformity appears on an electric log as missing section (figure 6A). The dipmeter data can be used to differentiate between the structural dip, which is different above and below an angular unconformity. In general the dip below an unconformity is steeper (Tearpock and Bischke, 1991). Also, dip changes are related to faults, as the rocks are deformed in the fault zone, or by the drag of the fault in the adjacent areas.

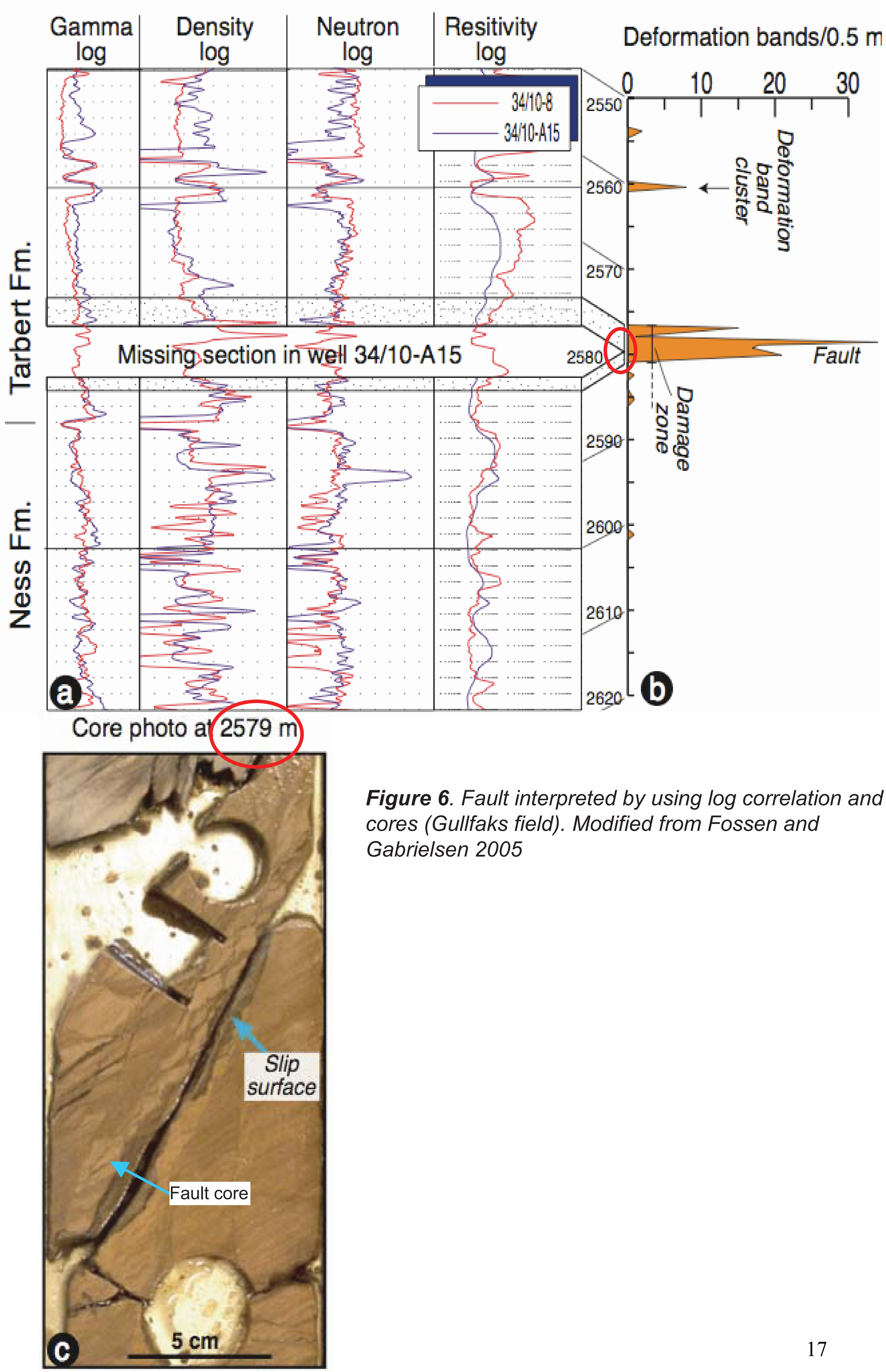


Figure 6. *Fault interpreted by using log correlation and cores (Gullfaks field). Modified from Fossen and Gabrielsen 2005*

Drill cores.

In exploration wells, drill cores are taken to get a sample from the subsurface. Rarely faults are represented in the drill core material, because drillers are reluctant to cut cores across faults because of the risk of jamming and potential pressure problems. Another issue is that some cored fault rocks may be so non-cohesive that they fall apart during collection (Fossen and Gabrielsen, 2005). Figure 6 C shows an example of a fault in a core, where it is possible to see fault core and slip surface.

For fault analysis this is very important information for the fault zone, e.g. how damaged is the rock in the fault zone and the dip of the fault plane, as well as continuity. The information provided from drill cores are of very high resolution because they provide detailed information. But, they are limited in extent (both horizontal and vertical).

Data and geologic setting

The main dataset is from the Askeladd field, which consists of a 3D seismic survey, covering an area of 6029 km^2. This 3D- seismic survey was shot by Geco for Statoil in 1983. This survey consist of lines oriented N-S, with a bin size of 25 x 25 m (Figure 8), and amount to 6029 km^2 of three-dimensional data (Grung Olsen and Hanssen, 1987). Also 3 wells were available. The wells are the following: 7120/8-1, 7120/8-2 and 7120/8-3 (Figure 8). All data was downloaded from the Norwegian petroleum database (Petrobank).

The Askeladd field is located on Tromsøflaket (figure 7A), which is approximately 100 km off the Norwegian coast and 200 km north-east of Tromsø (Grung Olsen and Hanssen, 1987). The Askeladd field is positioned in the western part of the Hammerfest Basin (figure 7B), close to the transition zone to the Tromsø Basin. The Hammerfest basin is an E-W trending basin between Loppa High to the north and the Tromsø-Finnmark Fault Complex to the south. The basin widens and dips westwards towards the Ringvassøy-Loppa Fault Complex (figure 7B). This fault complex is a network of N-S trending listric faults dipping towards the very deep Tromsø Basin (Grung Olsen and Hanssen, 1987).

Based on the 3D seismic survey and the information about Askeladd written by Grung Olsen and Hanssen (1987), a couple of continuous horizons were recognized. Figure 9 shows the key interpretation made by Grung-Olsen and Hansen. This shows that Base Cretaceous (BC) and Top Oxfordian Shale (TOS) could be good horizons to interpret. Figure 9 indicates that the horizons chosen could be shale or interbedded sandstone, siltstone and shale, based on the well logs from the area.

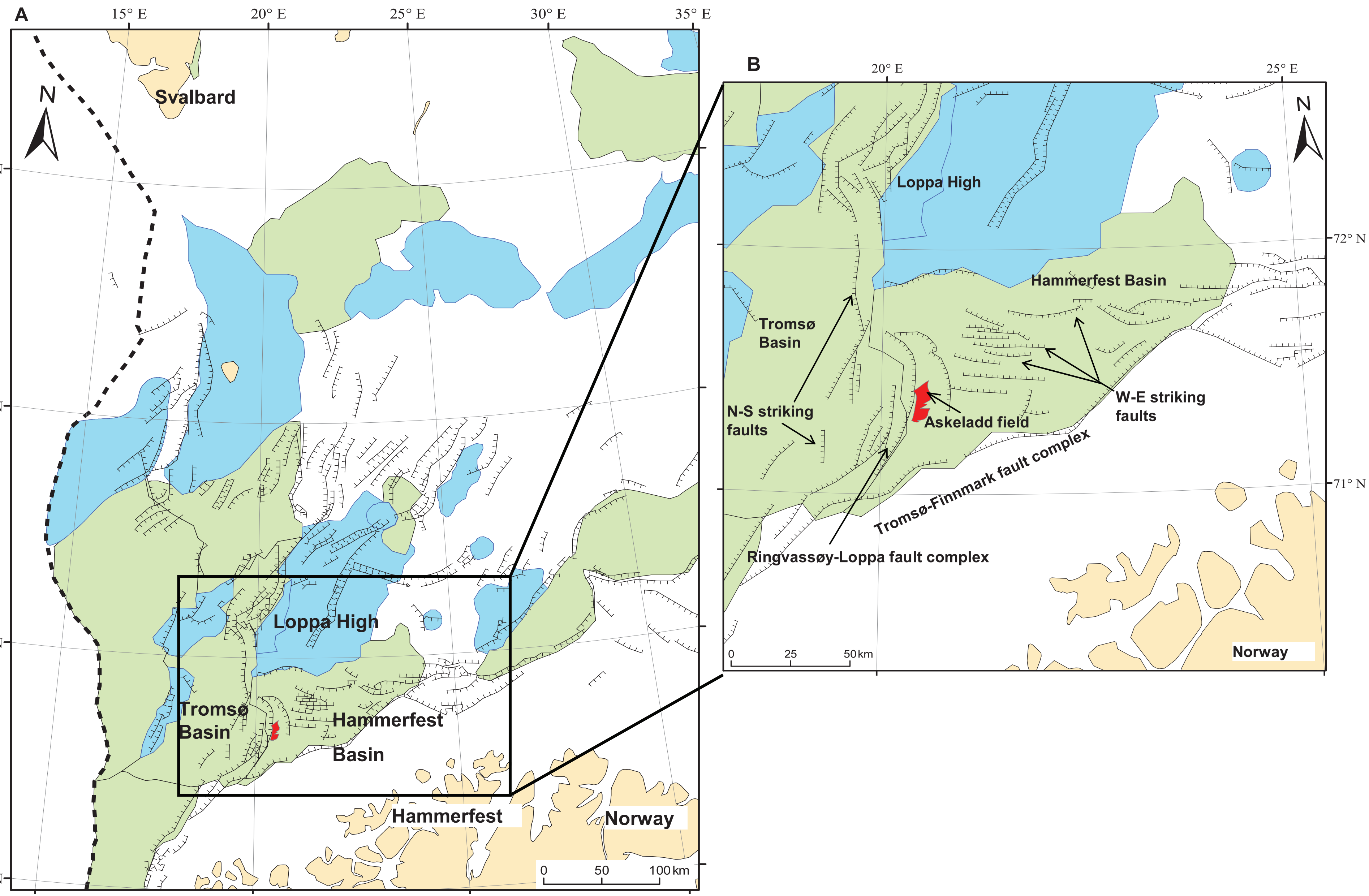


Figure 7 *: Map showing the location of Askeladd field. The main basins and fault complexes are marked in B.*

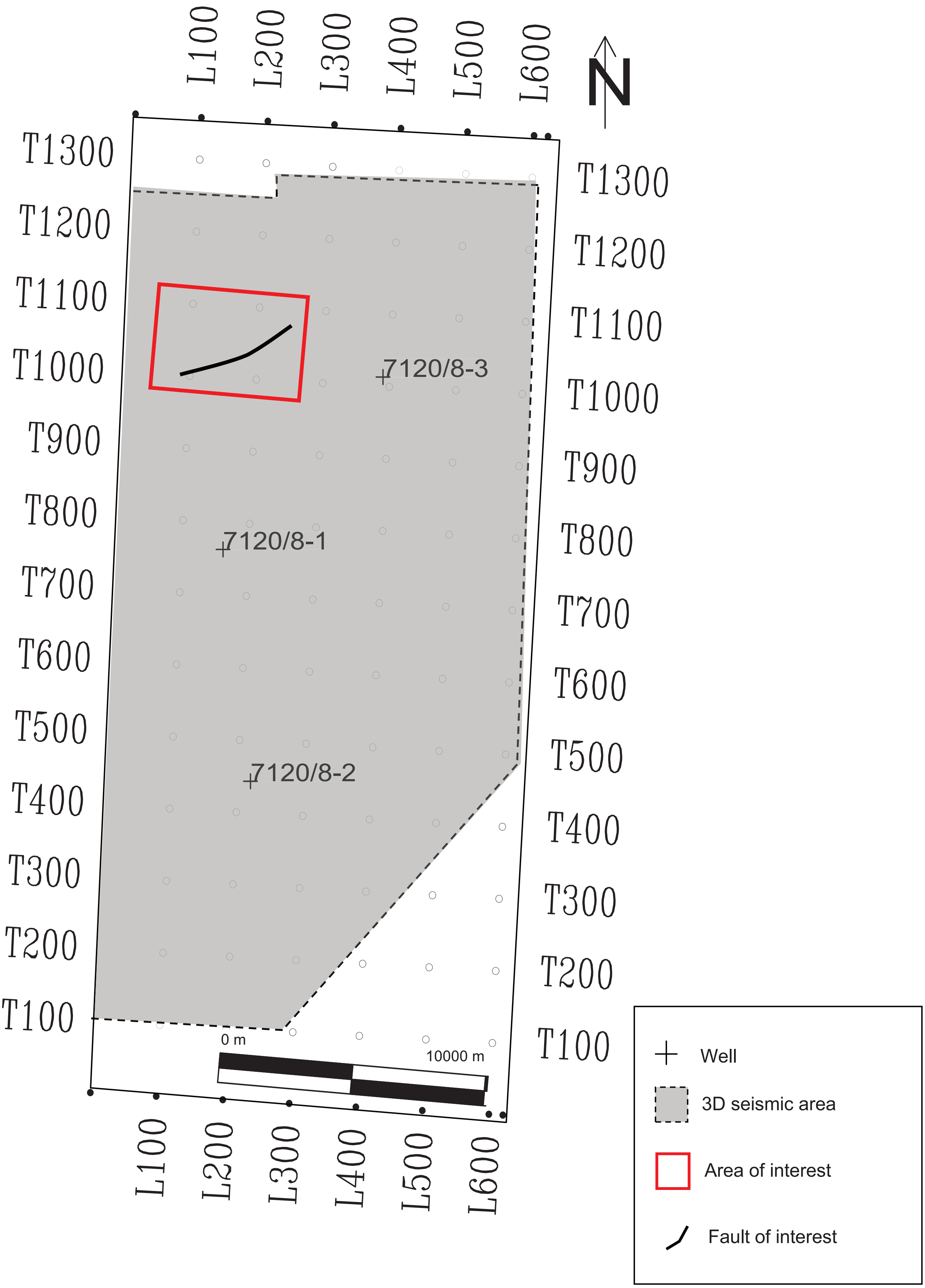


Figure 8: *Seismic shot points with the three wells drilled in the area. Area of interest (red polygon) and fault of interest (black segment) are also shown.*

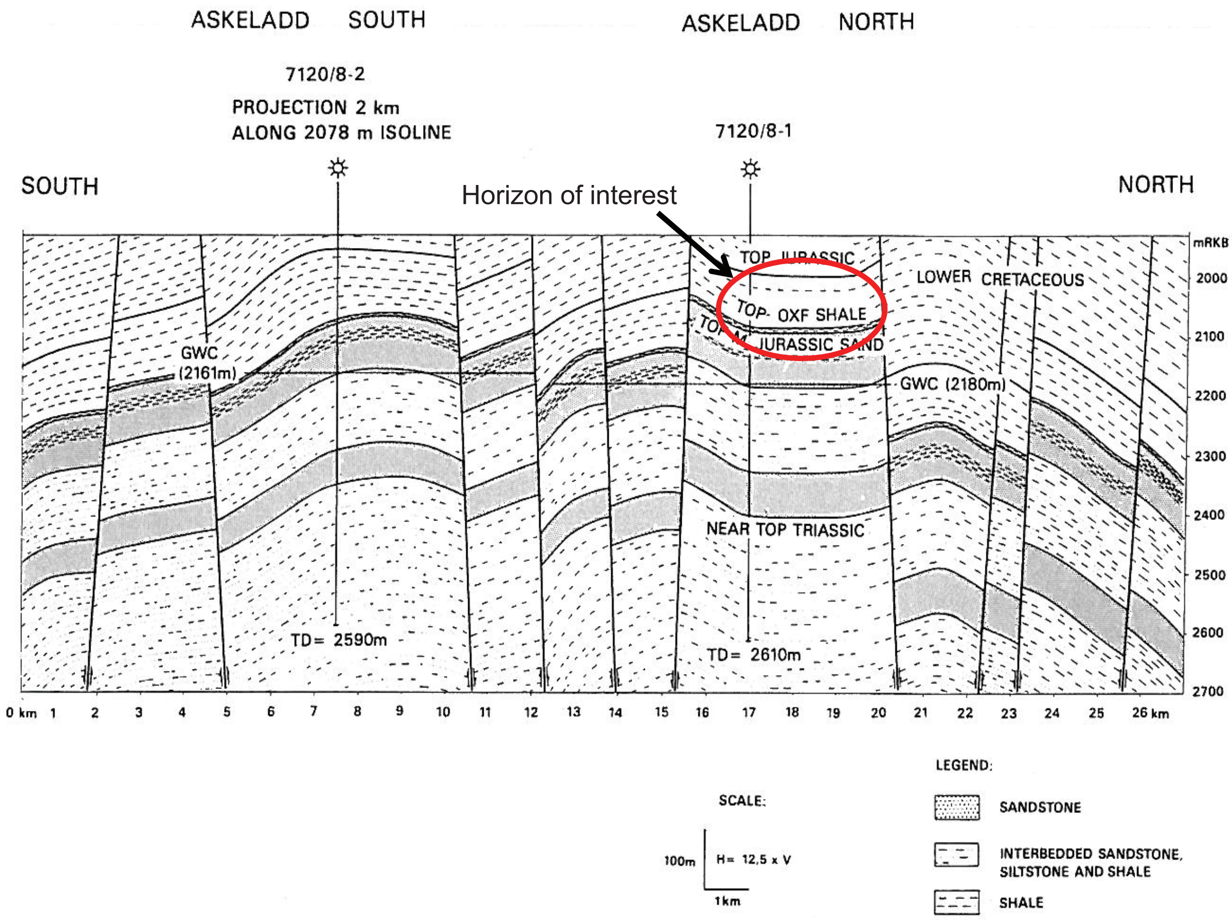


Figure 9: *Structural cross-section across the reservoir. Taken from Grung-Olsen and Hanssen, 1987.*

Askeladd is delineated by a major N-S fault in the west, which reflects the eastern most progradation of this major fault system. This fault system consists of several normal faults, with very continuous reflectors, that are easy to interpret in the seismic data.

For this thesis, it is important to have access to faults that are easy to interpret. Because it is important in this thesis to be able to follow the fault throughout the seismic survey. Simultaneously, it is essential that the faults are simple to visualize, what they are in this particular field. This visualization is important when it comes to the fault volume analysis.

Since the goal is to improve the seismic interpretation technique, the rest of the experiment is carried out in a smaller interval; 5.60 km x 3.75 km, marked with a red square in Figure 8.

Methodology and observations

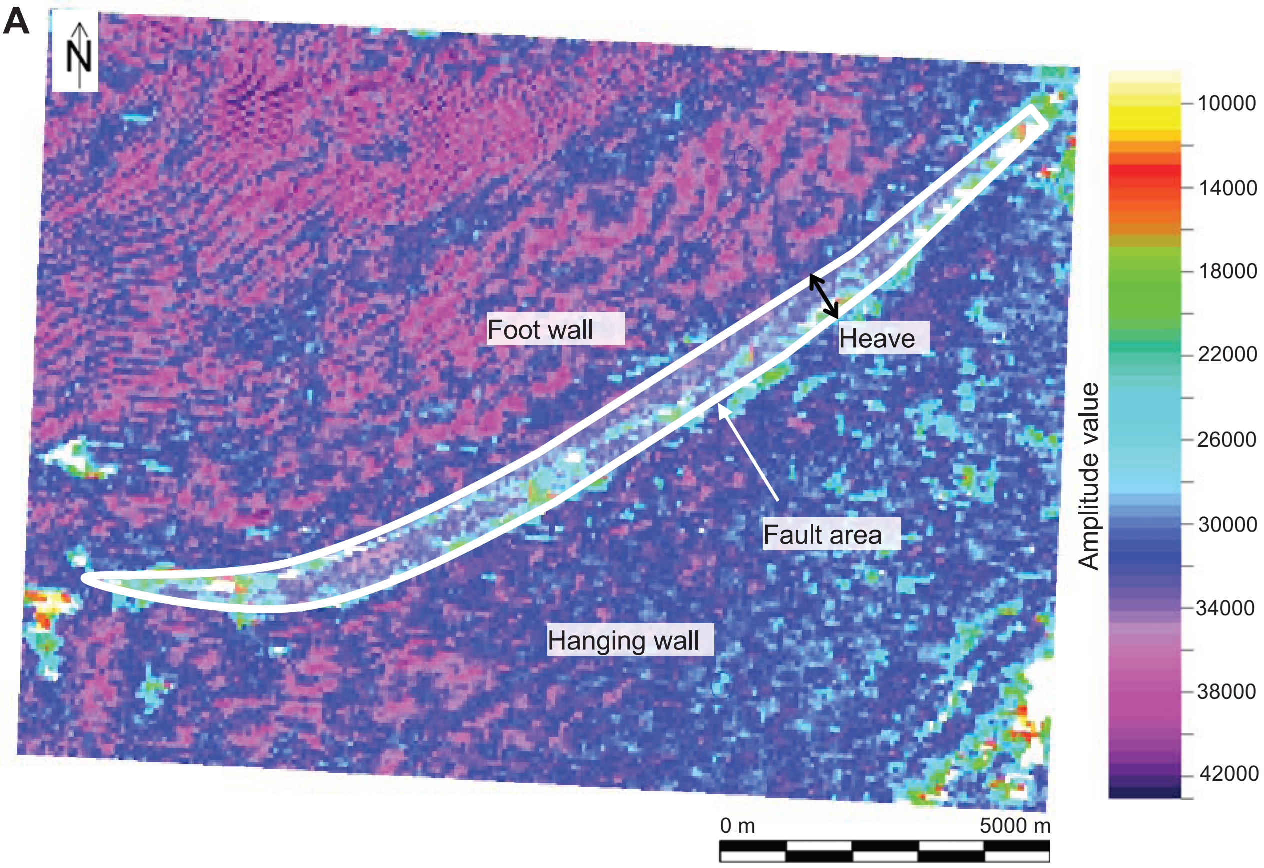
The main objective of this thesis is to develop a methodology that, improves the standard seismic interpretation techniques, to extract attributes of fault zones from seismic, and shows the importance of characterizing fault zones from the seismic. Therefore, this section is divided into two parts; A) deals with the feasibility analysis to evaluate if its possible to characterize fault zones from seismic, and B) is about fault volume analysis.

A) Feasibility analysis.

Standard interpretation.

The interpretation of the horizons was carried out in intervals of every 20^{th} line and trace, using Landmark OpenWorks® software from Landmark Graphics Corporation (LGC). Then an interpretation tool was used to create maps of the continuity and amplitude for each seismic reflector interpreted.

The area of 3D seismic is shown in figure 9. The horizons were interpreted in the area marked by the red square on the figure (5.60 km x 3.75 km). A small area is chosen since it is the fault zone that is of interest for this thesis. The fault interpretation was carried out in this study area in the same interval as the horizons. The amplitude map for each horizon (Base Cretaceous and Top Oxfordian Shale) is shown in Figures 10A and 10B. These maps show that there is a change in the amplitude values in the fault area (Figure 10). This information together with the information provided from Figure 8A, supports the choice of the fault to work further on with. Amplitude maps and time slices were used as tools for interpreting the fault.



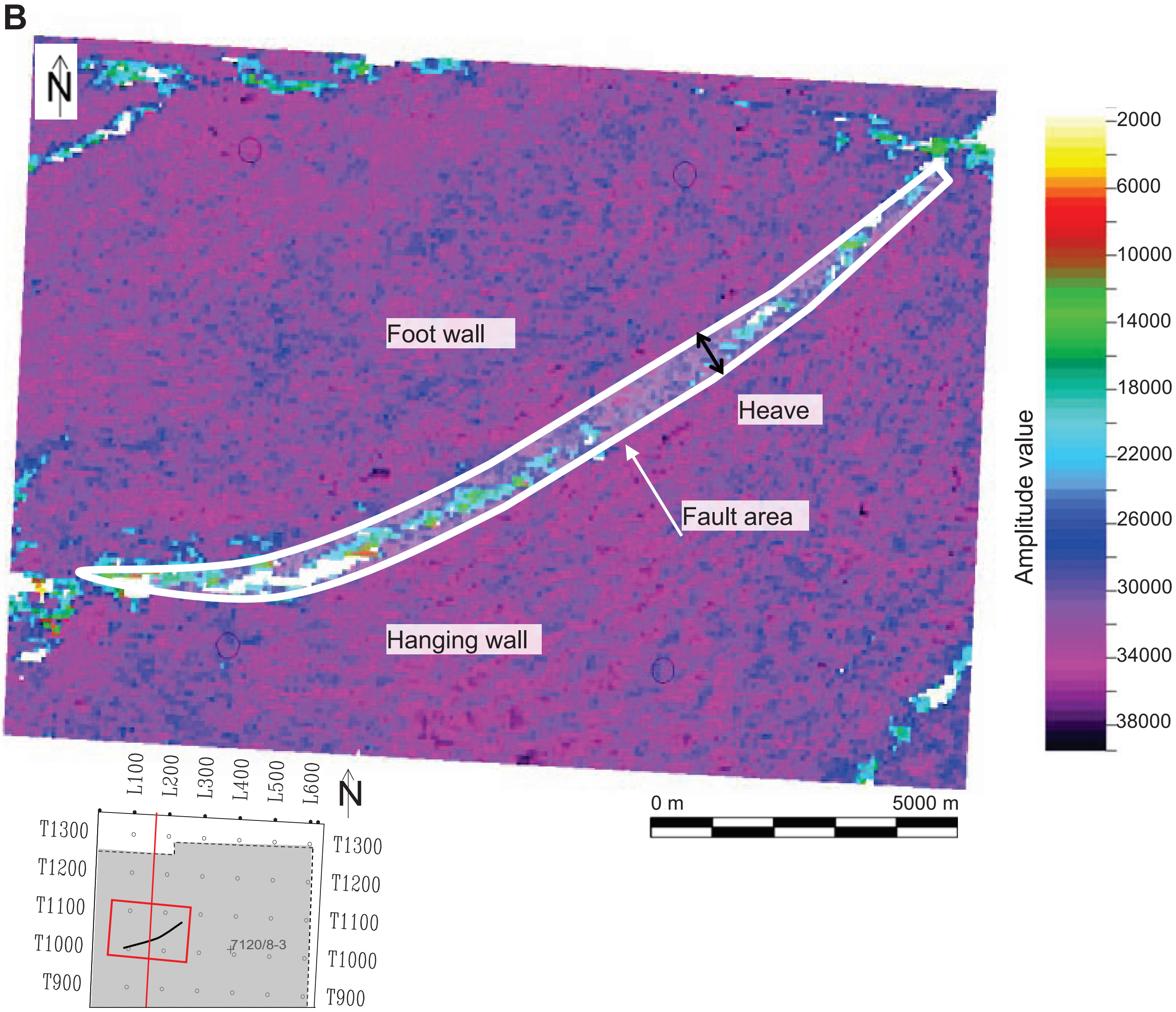


Figure 10: *Amplitude maps are calculated in the red square shown in the inset. A) amplitude map of Base Cretaceous and B) Top Oxfordian Shale*

An example of interpretation is shown in Figure 11, where the fault is interpreted in the standard way, as a surfaces. The fault is a normal fault. It shows an area of deformation with 100 milliseconds of displacement (throw).

Based on the seismic interpretation (Figure 11), it is easy to see that the interpretation is not trivial to perform. The reflections in the horizons are sometimes of good quality, and other times almost disappear. This lead to some guessing while interpreting horizons. When it comes to interpreting the fault (figure 11B), it is more difficult. It is hard to decide where the core of the fault is, and in this case also where the fault boundaries start and end. On the seismic, the interpretation is done by studying the seismic carefully, and only visual inspection and experience can tell where the fault is. Due to different resolution the fault will most likely be interpreted different throughout the seismic cube.

The available tools like amplitude maps, time slices etc. can provide some help while interpreting. Specially when interpreting faults vertically. But it is still not enough to give a better understanding on how the seismic reflectors behave in different areas. Together with faults, fluid flow and salt domes will also influence the seismic behaviour.

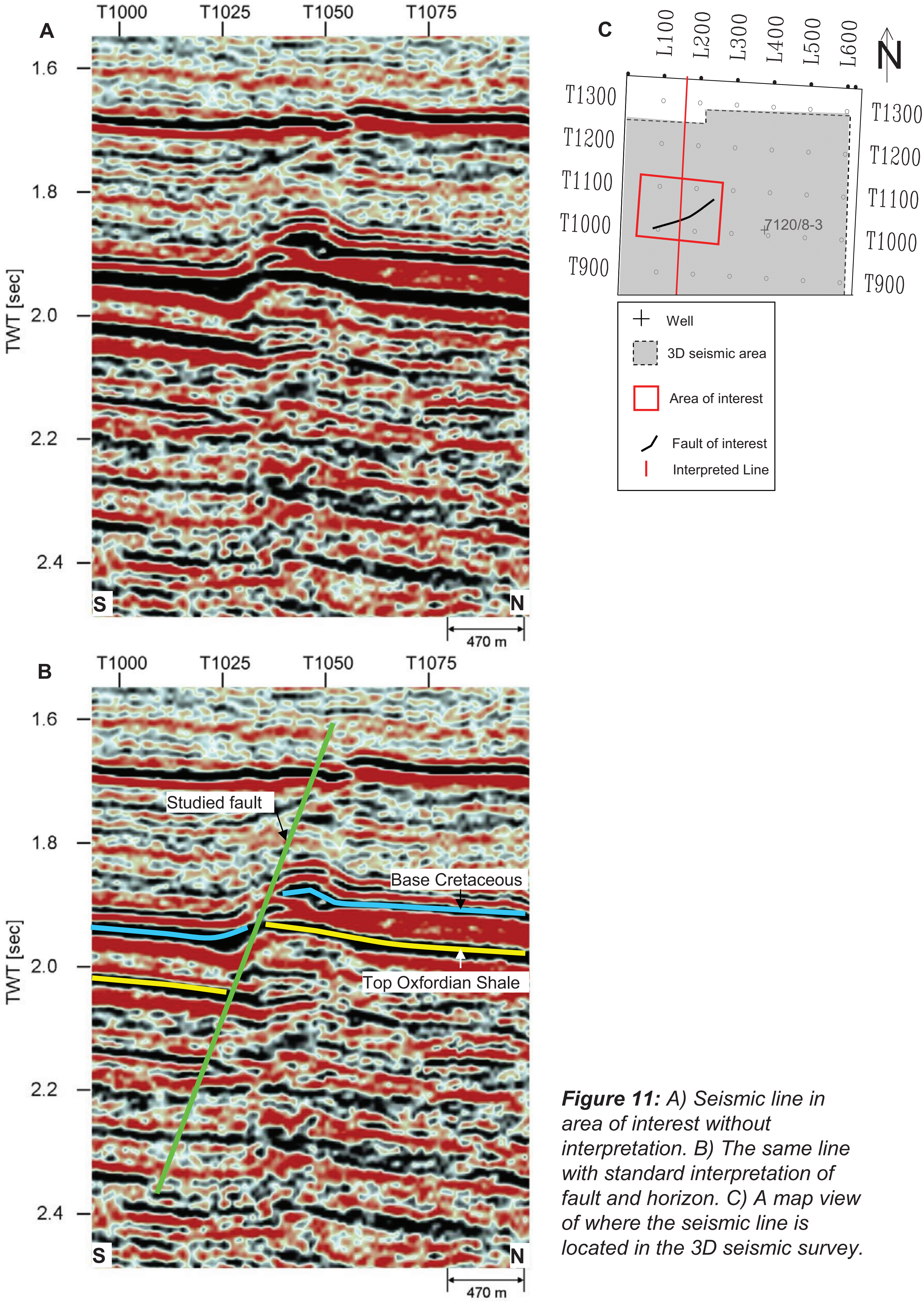


Figure 11: *A) Seismic line in area of interest without interpretation. B) The same line with standard interpretation of fault and horizon. C) A map view of where the seismic line is located in the 3D seismic survey.*

Amplitude Analysis.

Amplitude values were extracted based on the interpretation of the horizons. The amplitude values were then plotted against the number of traces in the specific line, perpendicular to the fault strike. Figure 12 shows an example of the amplitude variations across the fault, for the Base Cretaceous horizon. In particular major changes are across the fault zone. In each side of the fault an amplitude maximum is observed, followed by a drop in value (in this case from ~30000 to ~15000)

By comparing the amplitude changes to the seismic interpretation (Figure 13), it is clear that the largest deviation from the amplitude values, matches the same area of the interpreted fault. To be able to get a better understanding on how the amplitude graph matches the seismic interpretation, the amplitude values (Figure 12B) were filtered to provide a smoother curve (Figure 13B), outside the faulted area so that we can focus in the fault zone. The filtering process was carried out using the average value on both sides of the major anomaly on the amplitudes. Then original values were replaced by the average value. In this way the curve got smoother, and the smaller anomalies got erased (Figure 13B). The amplitude smoothing helped eliminating the noise on both the footwall and hanging wall, and show focus in the fault zone, which from now is defined as a zone and not a surface. Appendix 1 shows the table from the amplitude values together with the average values.

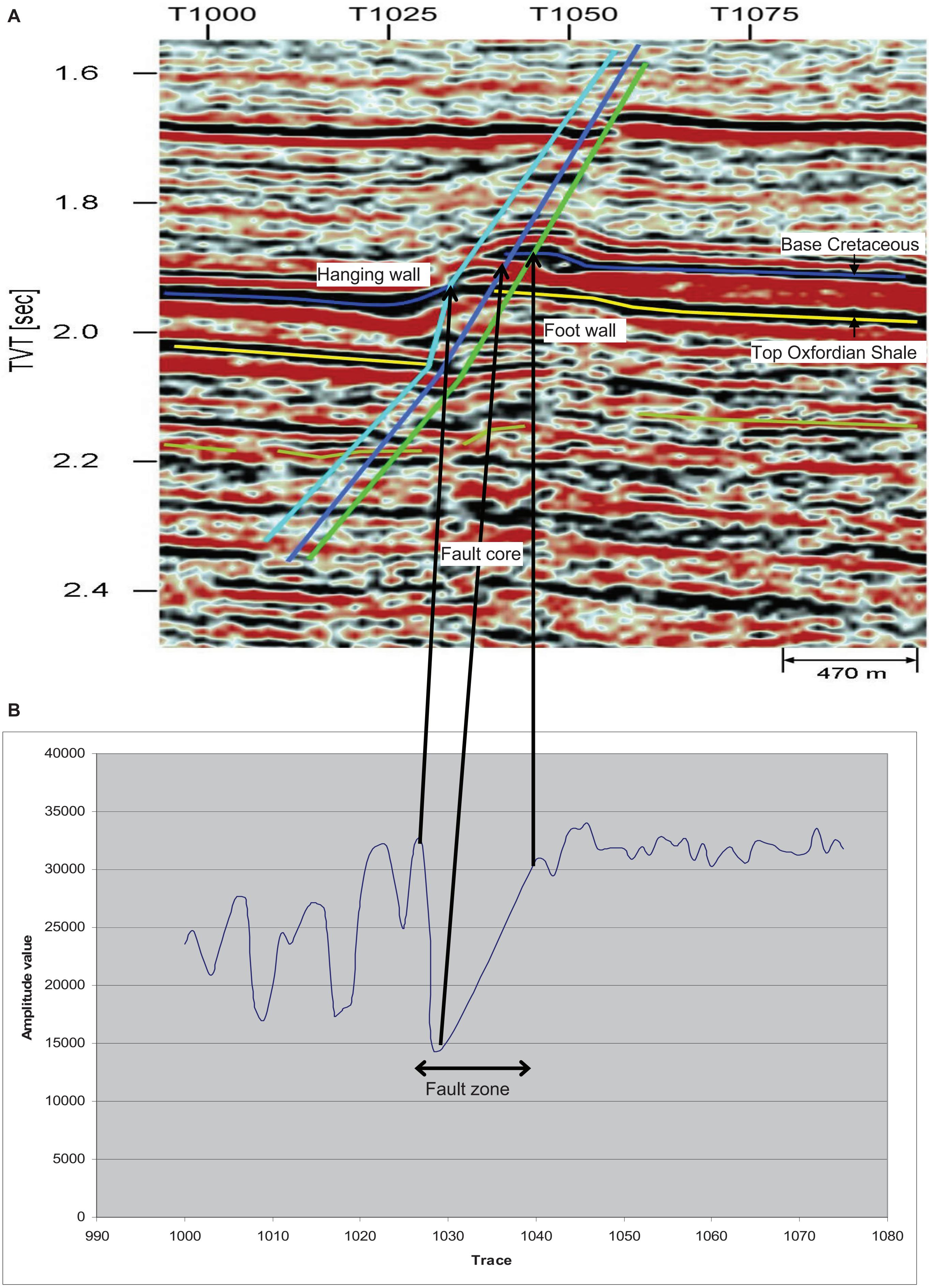


Figure 12: *A) Seismic with fault interpretation. B) Amplitude value versus trace graph for the Base Cretaceous horizon. The graph was created from the amplitude values extracted from the seismic.*

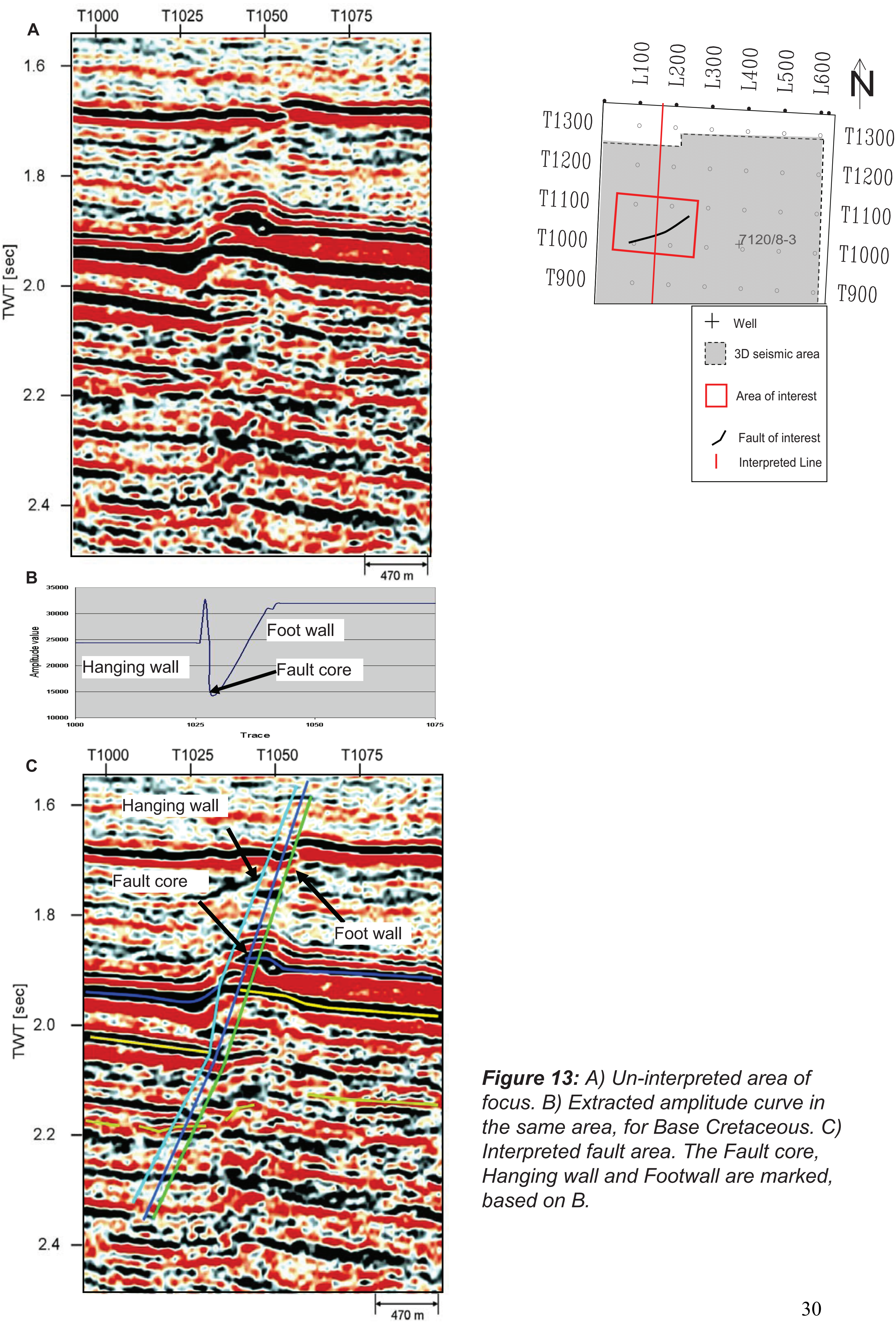


Figure 13: *A) Un-interpreted area of focus. B) Extracted amplitude curve in the same area, for Base Cretaceous. C) Interpreted fault area. The Fault core, Hanging wall and Footwall are marked, based on B.*

Figure 12 shows amplitude values extracted versus the traces. It has some small changes more or less over the hole area, but in one place it changes rapidly. Whether or not all changes in the curve indicate faults at the seismic and sub seismic resolution, is hard to tell exactly. At least the main change in the graph is reflecting the interpretation of the fault of interest. Because the fault is reflected on the amplitude, it is possible to delineate the fault zone. Based on this assumption the fault boundaries can be assumed to be at the beginning and the end of the amplitude anomalies, maximum anomaly could indicate the fault core.

After studying the amplitude values from several lines, the same trend was observed. In some lines the indications on the main fault was more clear than in other lines. The reason for this could be that the seismic resolution changed from line to line, or the interpretation might not be exactly where it should be. Overall, the similar trend is there, and it support the assumption that the amplitude values can indicate where the fault zone is.

Interpretation of fault boundaries.

Based on observations of both amplitude values extraction and heave, throw and dip slip extraction, it is possible to interpret the fault boundaries. Figure 13 shows a close up of the seismic in the fault area. This clearly shows that the fault is not only a single line. Since the fault consist of a fault core with a fault boundary at each side of the core, the following nomenclature will be used from now on. This is a normal fault where the Hanging wall (HW) is on the left hand side of the fault core (FC), and the Footwall (FW) is on the right hand side. The boundary between HW and FC is the Hanging wall boundary fault (HBF), while the boundary between FW and FC is the Footwall boundary fault (FBF).

As mentioned in the section about amplitude analysis, the interpretation of the fault boundaries could be accomplished by the amplitude values. Since the original graph created from the extracted amplitude values has background noise relative to the main fault, it is filtered. After filtering, it is easier to see where the large peak started and ended (figure 13 B). These changes were, as mentioned, addressed to HBF and FBF. The anomalies in the amplitude value graph has its own location according to a trace. The same trace was localized in the seismic line, to be able to interpret both HBF and FBF (Figure 13C). Relayed on this observation, it is reasonable to say that it is possible to use the amplitude values to determine where the fault zone starts and ends.

Heave, Throw and Dip Slip.

Heave, Throw and Dip Slip are essential features when it comes to fault characterization, and therefore, it is important to extract these values as well as the amplitude values. Heave gives an idea about the horizontal component of the fault dip slip, throw plays the same for the vertical component of the fault dip slip. These values got extracted, using 3DMove® from Midland Valley Exploration Ltd. Figure 14 shows a comparison of the heave, throw and dip curve together with the amplitude value graphs.

Figure 14 shows the Heave, Throw and Dip Slip graph together with the amplitude value analysis. The heave, throw and dip slip is calculated along the fault. As seen in the Figure 14, the amount of heave, throw and dip slip varies along the fault. The fault shape is elliptical along strike (Figure 10); It is thin close to the fault tip and thick at the centre of the fault. Fault displacement is elliptical along strike; it is small close to the fault tips, and large at the centre of the fault.

Those amplitude value graphs in Figure 14 are perpendicular to the fault. There should therefore be a certain connection between these and the changes in heave, throw and dip slip, because of e.g. loss of similarity or that different horizons are in contact. This corresponds to the observations here; that larger amplitude changes seem to correspond with larger throw, dip slip and heave changes.

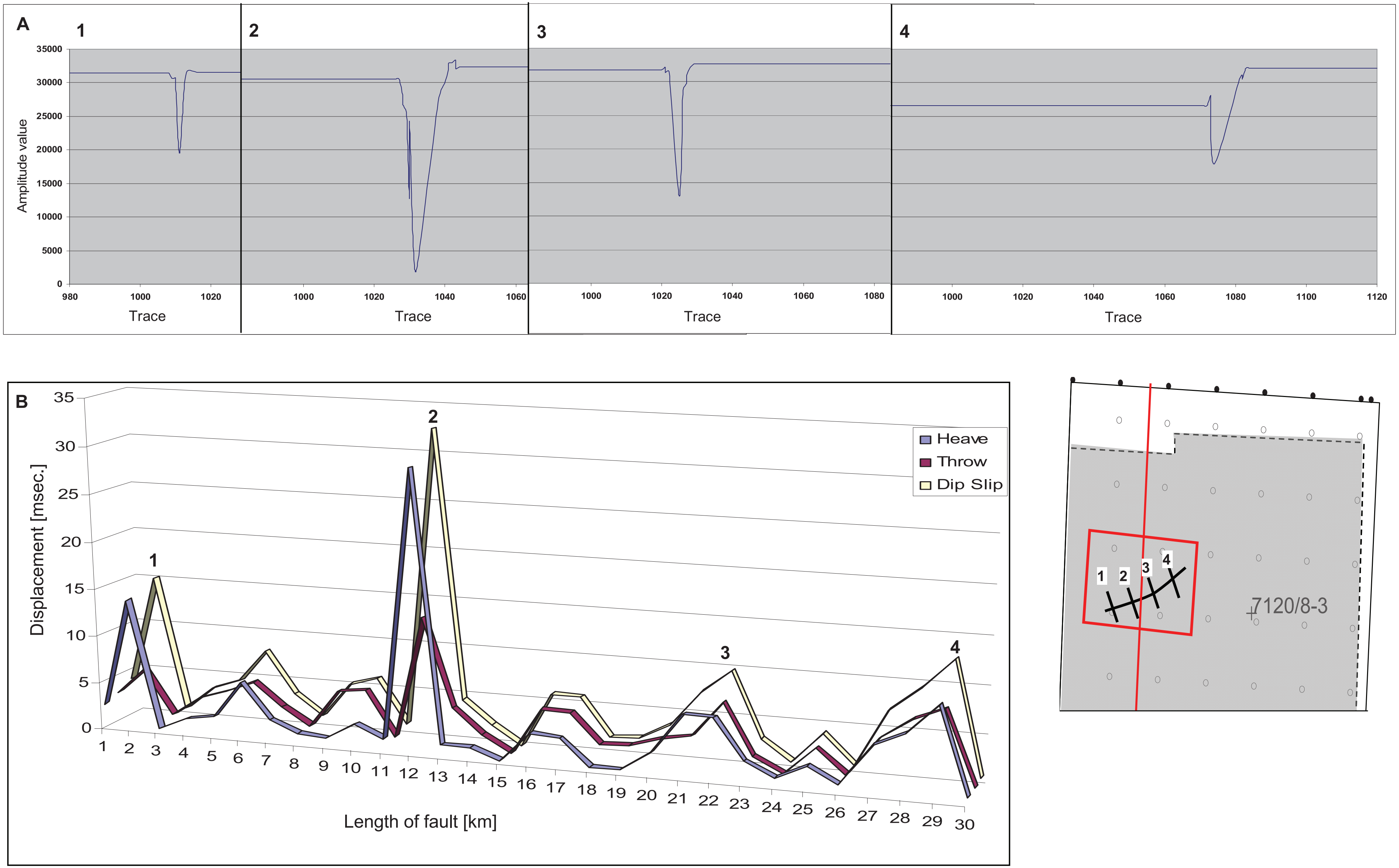


Figure 14: *A) Amplitude value curves perpendicular to the fault. B) Heave, Throw and Dip Slip calculated along the fault. This figure shows that there is a connection between the peaks in the amplitude value and the Heave, Throw and Dip Slip.*

B) Fault Volume Analysis.

Given that it was possible to identify the fault zone and that changes in amplitude are found, I proceed to characterize the volume using seismic data and reservoir modelling tools. The standard interpretations from the previous section is imported to Petrel® software from Schlumberger. The standard interpretation consists of the two horizons, Base Cretaceous and Top Oxfordian Shale, and the three fault boundaries: Fault Core (FC), Hangingwall boundary fault (HBF) and Footwall boundary fault (FBF).

Gridding.

The gridding process has to be performed so that a volume can be added to the fault area. The grid size can be either small or large, and it is normal to differentiate between geological grid and simulation grid. A geological grid often has several million cells (Petrel-userguide, 1998-2008). This type of grid is important when it comes to volume calculations and to preserve the heterogeneity of the reservoir. A simulation grid has less cells than the geological grid. The flow simulation process runs quicker when the grid does not have too many cells. This is important to take into account, especially since the simulations has to be performed quick and easy to fulfil the companies demand. The reduction in number of cells in the grid will often lead to a homogenization of property values within the grid. The challenge is then to find a grid size that does not lose too much valuable information, but that can run quickly.

In this trial three different grid sizes are used; the finest grid is 20 x 20 (rows and columns), the middle one is 40 x 40, while the coarsest is 60 x 60. The vertical resolution is 5 layers. This is the same for all the three grid sizes. Figure 15 shows a comparison of how the different grid size look like. The 20 x 20 grid size (figure 15A) is a detailed grid size compared to the 60 x 60 grid size (figure 15C).

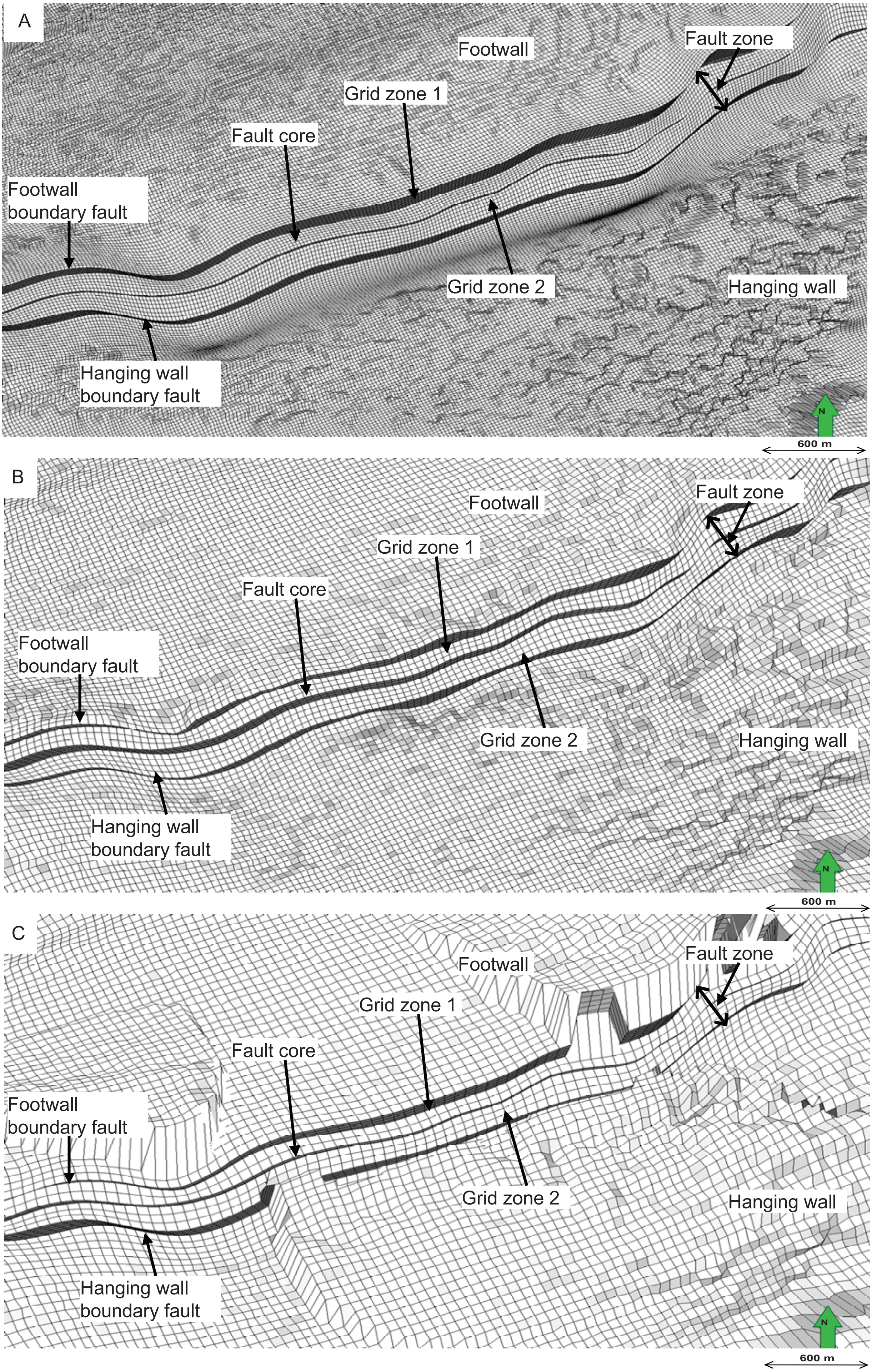


Figure 15: *The different grid sizes tested. A) is 20x20, B) is 40x40 and C) is 60x60 rows and columns. The vertical resolution is 5 layers.*

The gridding is created considering the fault zone. The fault zone in this gridding process consists of three fault lines. Here the HBF, FBF and FC (from the amplitude analysis) creates one fault line each. This is the reason why the gridding process divided the fault into two grid zones (Figure 15). This means that the area around the fault needs to be changed a little to get smoother grids around the fault. The smallest, 20 x 20 grid (figure 15A), gives detailed information and follows the fault better than the larger grid sizes. The 40 x 40 grid (figure 15B) still follows the fault structure pretty well, while the 60 x 60 grid (figure 15C) creates some artificial grid cells, specially close to the fault zone.

It is most time consuming to run simulations with 20 x 20 grids, but this is at the same time the cell size that provides most detailed information. When the attributes is added to the 3D grid (Figure 16), it is easier to see how the different grid size affect the 3D grid. The smallest grid, 20 x 20 (figure 16A) provides a more detailed picture on how the attributes change along the cells, when small changes are visible. With a 40 x 40 grid (figure 16B), it is still possible to track the main changes, but some of the small and nice features disappear. The 60 x 60 grid (figure 16C) provides a dull picture, and it is hard to track the continuity of attribute changes inside this grid, in the fault zone. Based on this observation the rest of the discussion is made with the 20 x 20 grid.

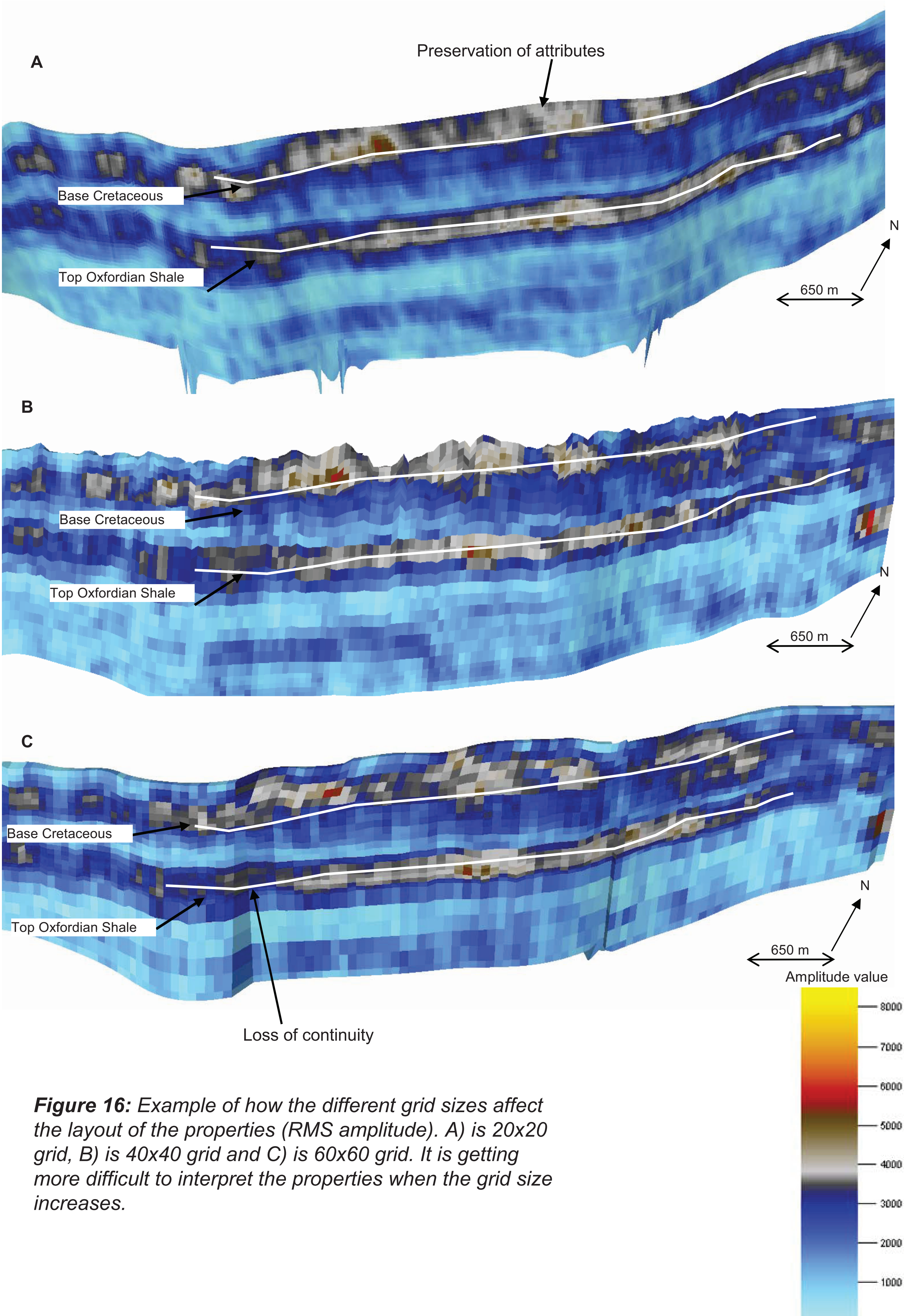


Figure 16: *Example of how the different grid sizes affect the layout of the properties (RMS amplitude). A) is 20x20 grid, B) is 40x40 grid and C) is 60x60 grid. It is getting more difficult to interpret the properties when the grid size increases.*

Seismic attributes.

By sampling a seismic volume (raw seismic or attributes), seismic properties can be created into the 3D grid in time or depth according to the seismic domain (Petrel-userguide, 1998-2008). In this thesis, analysis is performed in time.

The different attributes within Petrel are many. All these attributes have not been used in this work, but a couple of attributes are chosen in order to provide a feed back if it is possible to analyze the fault zone. The following attributes were created into the 20 x 20 grid; RMS Amplitude, Instantaneous frequency and Chaos.

The 3D grid with properties is shown in Figure 17. Figure 17 A is shown with gridlines and 17 B is shown without gridlines. In order to better show the attributes the gridlines will be removed during the rest of the analysis. By adding different seismic attributes to the 3D grid, it is assumed that it is possible to analyze what occurs inside the fault zone. In the traditional way, where the fault is interpreted similar to a surface, it is not practicable to add volume to the fault. Here the fault boundaries are located as well, and it is possible to compare the changes in properties on the different side of the fault zone.

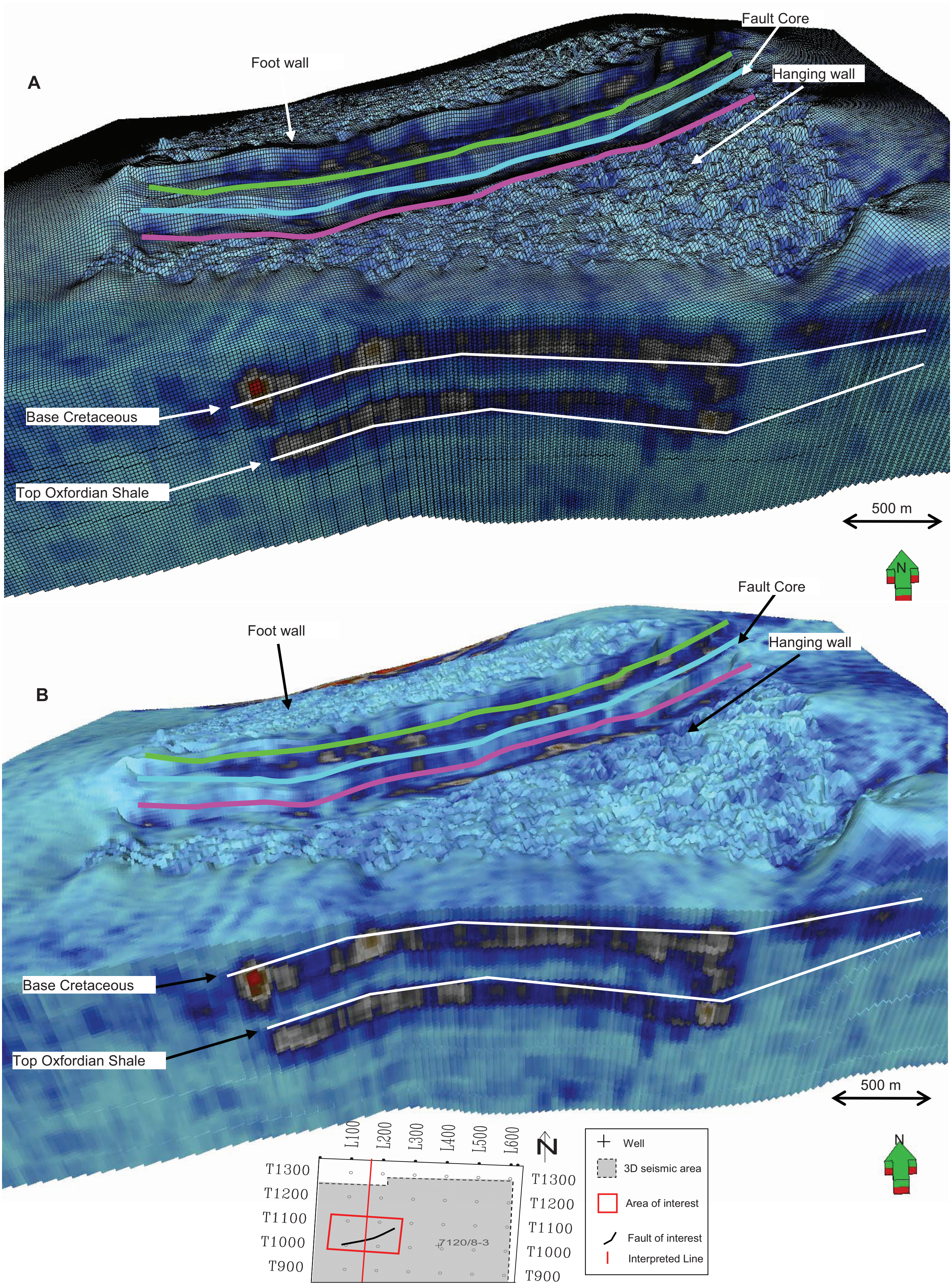


Figure 17: *3D grid cube with RMS amplitude attributes. A) With grid lines, B) Without grid lines. The gridding used here was 20x20. A and B A also show where the interpreted fault and horizons are located.*

Continuity of properties.

The seismic attributes extracted from the 3D grid can be studied in more detail. Since I am interested in the fault zone, sections parallel and perpendicular to the fault where created. Figure 18 shows the location of the locations of the grid sections that were analyzed for continuity of seismic attributes across the fault zone (both parallel and perpendicular to the fault zone).

In Figure 19 A-F the RMS amplitude is followed from the footwall to the hanging wall, through the fault (parallel to the fault). The horizons, Base Cretaceous and Top Oxfordian Shale are also shown in the same figure. By studying how the properties are changing from the undeformed zone in the footwall (Figure 19A) to the undeformed zone in the hanging wall (Figure 19F) different changes are observed:

- The horizons are represented by the darkest colour (greyish to yellowish, value 3000 - 5000 in the seismic colour scale) reflector. In the undeformed zone in the footwall (Figure 19A), the horizon reflectors are quite continuous. Moving closer to the fault zone (Figure 19 B) the continuity of the reflector proceed quite well for Base Cretaceous, while it starts to disappear for Top Oxfordian Shale. At the footwall boundary fault (Figure 19C) both reflectors fade away. Inside the fault core (Figure 19D), the reflectors from the chosen horizons are totally missing. At the hanging wall boundary fault (Figure 19E), Top Oxfordian Shale reflector is almost coming back in the similar strength, as before hitting the fault zone. Base Cretaceous starts to come back. In the virgin zone at the hanging wall (Figure 19F), the reflectors of the horizons are almost similar to the undeformed zone in the footwall.

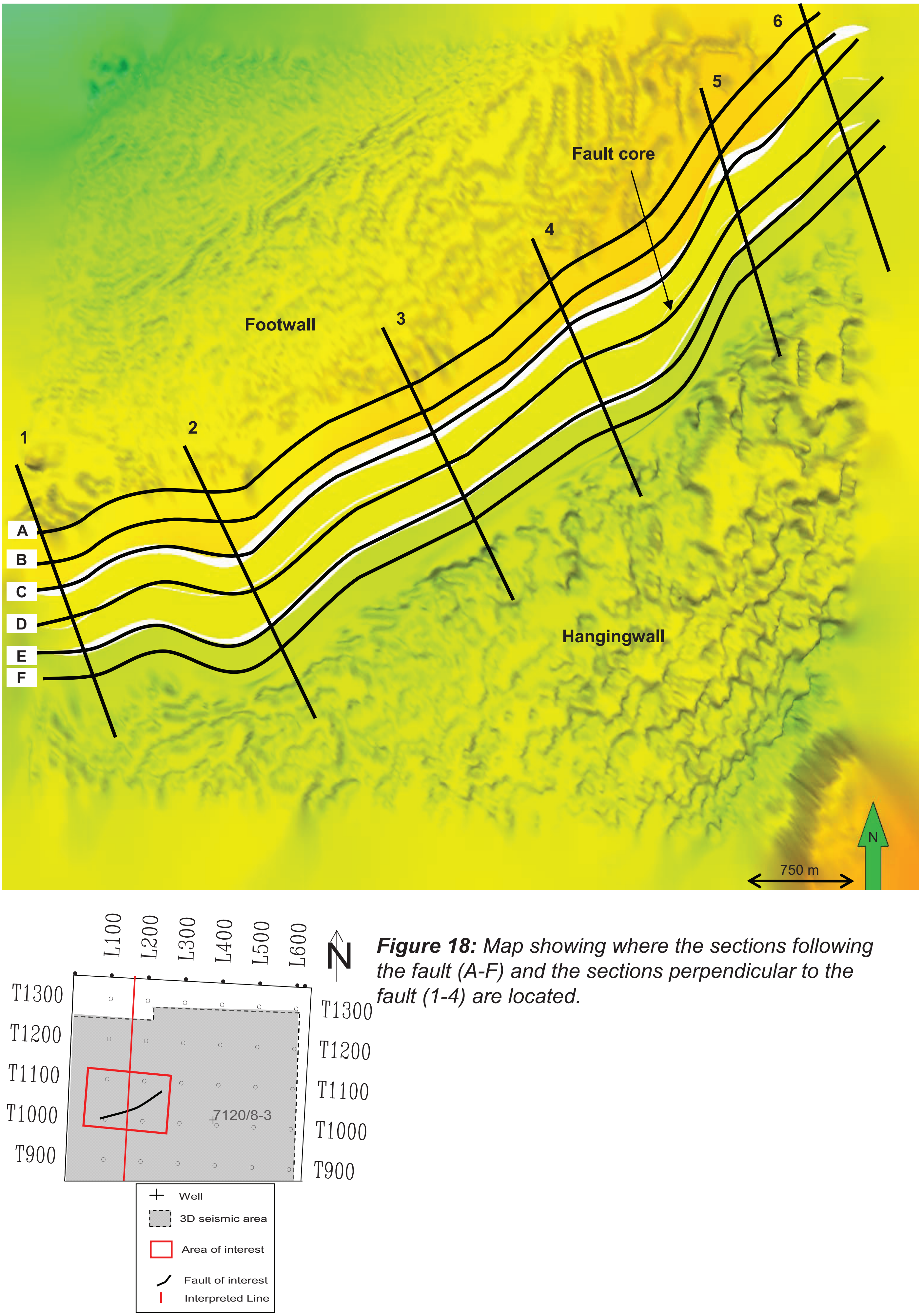


Figure 18: *Map showing where the sections following the fault (A-F) and the sections perpendicular to the fault (1-4) are located.*

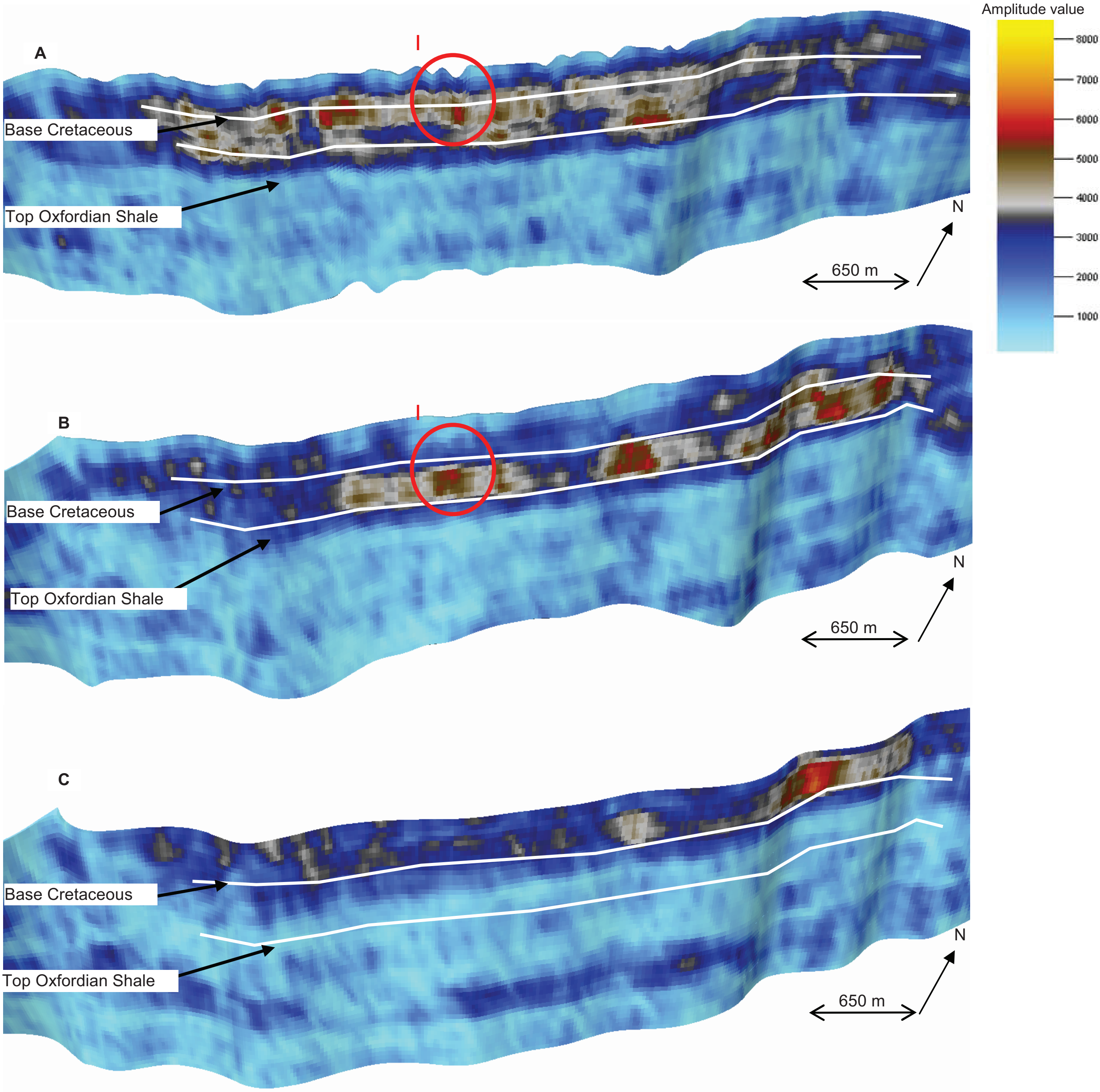


Figure 19: *Sections along the fault showing how the RMS amplitude changes from along the fault. A: Footwall in virgin zone. B: Still in footwall, getting towards the fault. C: Footwall boundary fault.*

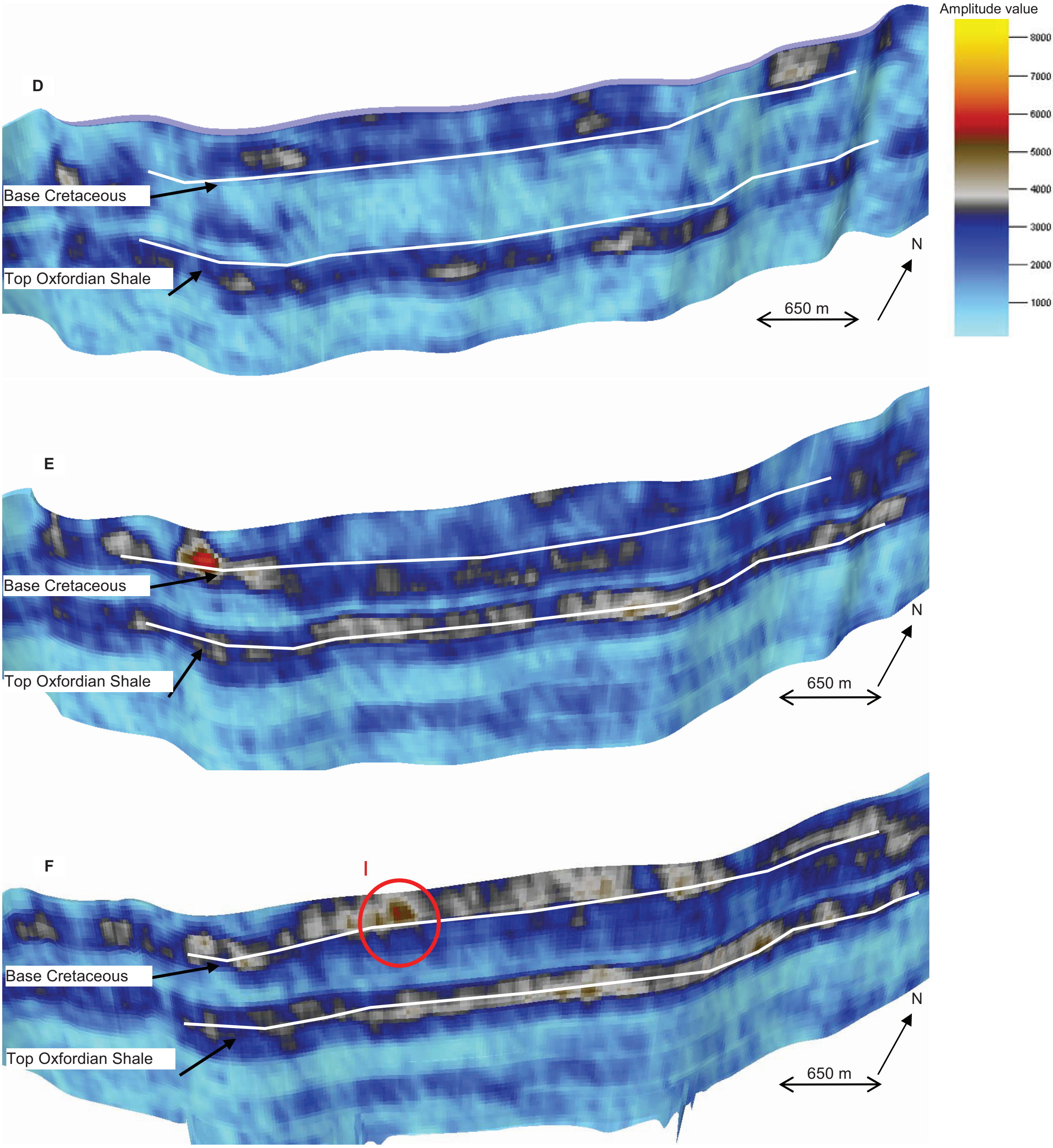


Figure 19 (continuation): *D: Fault core. E: Hangingwall boundary fault. F: Hangingwall in virgin zone. Red circle marked with I indicates that it is possible to track a certain property from footwall to hanging wall via the fault core. This property disappears inside the fault zone (C, D and E).*

- The red circle in Figure 19A, Figure19B and Figure 19F indicates that a specific property appears in the undeformed zone. Seismic properties change in most of the fault zone but in some areas. In the areas where it changes the most it suggest that petrophysical properties are lost, where in few areas continuity is observed suggesting that petrophysical properties are continuous.

In Figure 20 A-F the RMS amplitude is followed perpendicular to the fault. The horizons, Base Cretaceous and Top Oxfordian Shale, and FBF, HBF and FC are also shown in the same figure. By studying the RMS amplitude, Figure 20 A-F shows that the reflectors from the horizons fades away inside the fault zone in some areas, while it is possible to track the horizon reflector in other areas. This might indicate that the fault can provide fluid flow in some areas, while it act as a seal in other areas.

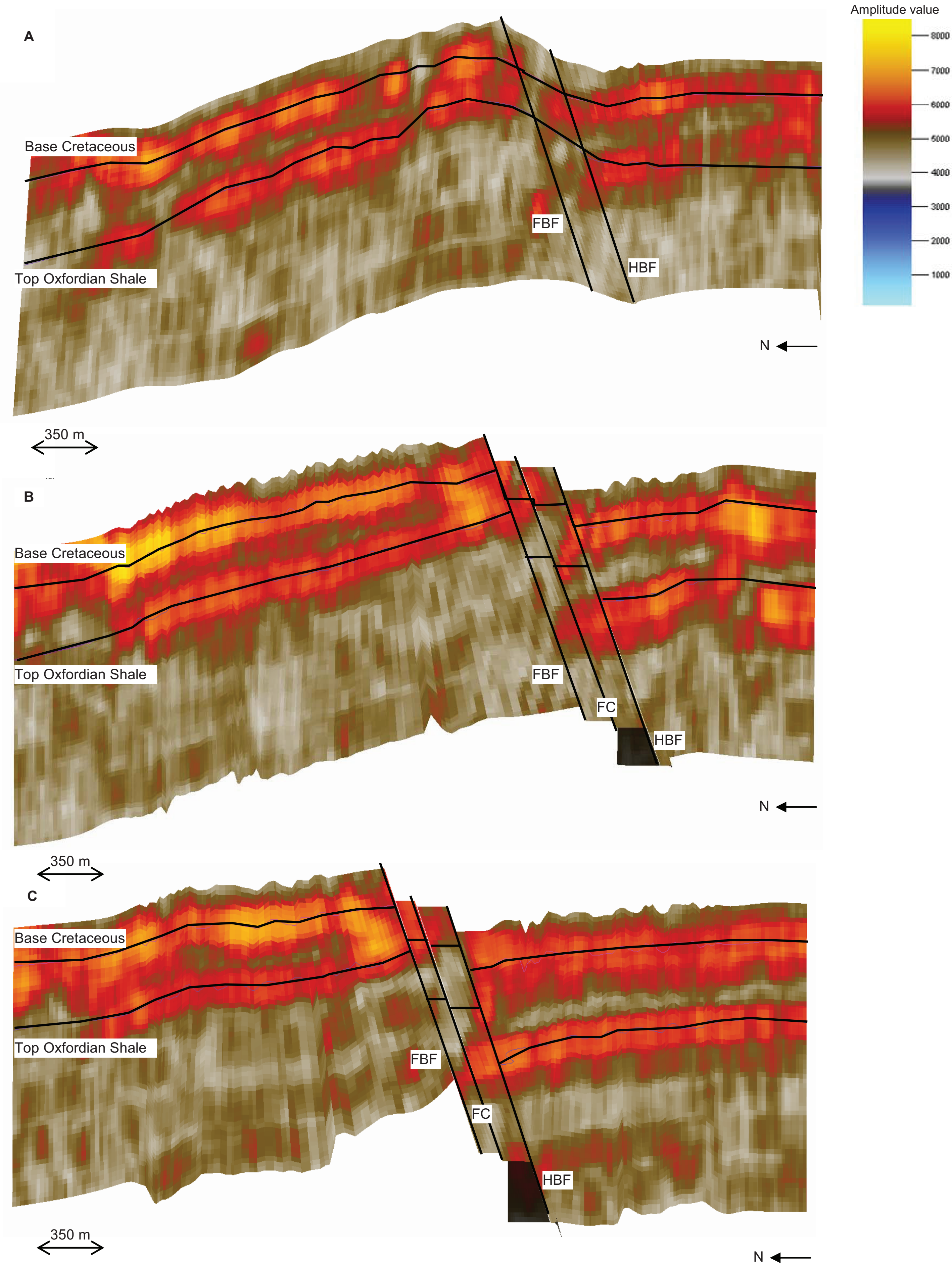


Figure 20: *Sections perpendicular to the fault showing how the RMS amplitude changes* from the footwall to the hanging wall.

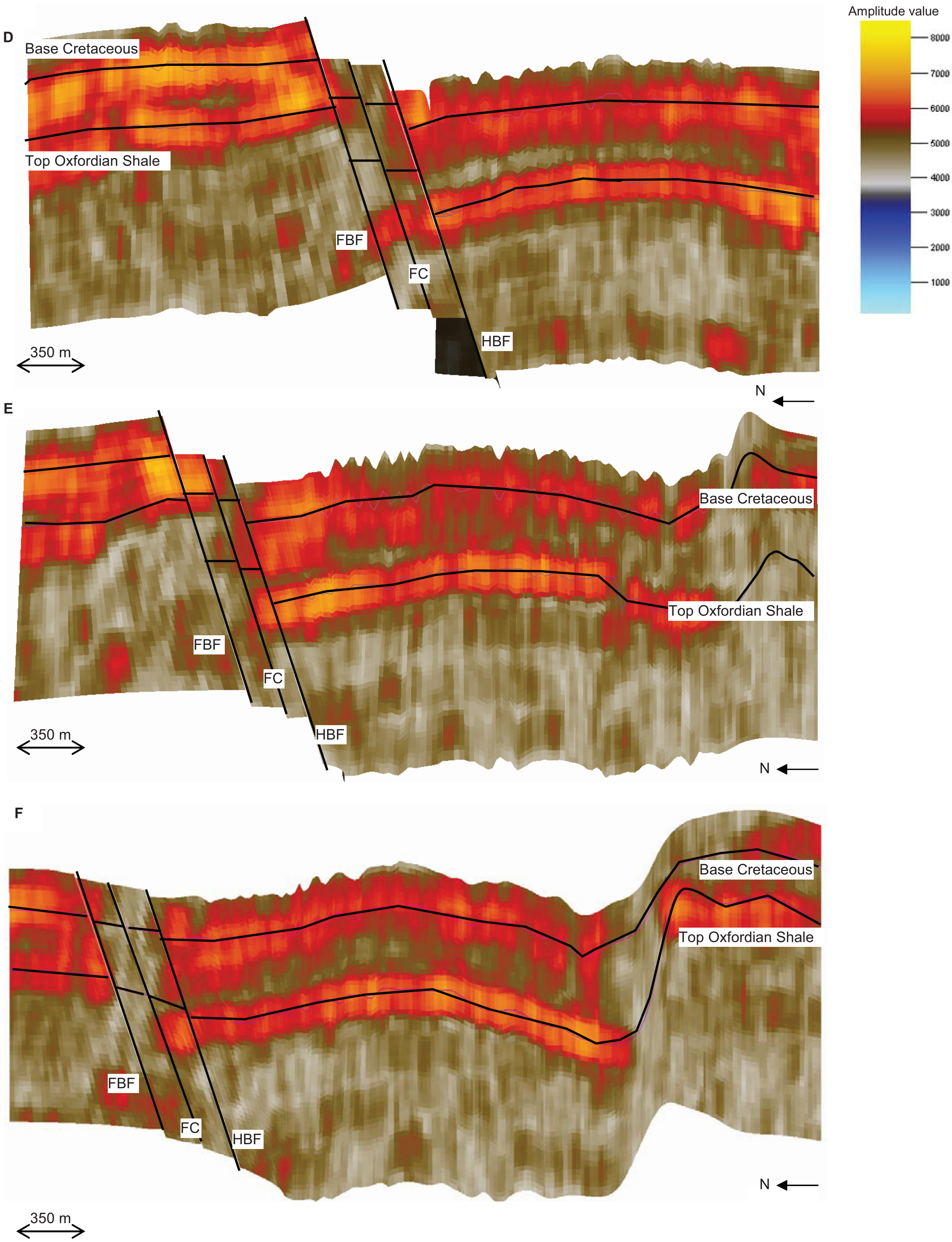


***Figure 20 (continuation):** sections perpendicular to the fault showing how the RMS amplitude changes* from the footwall to the hanging wall.

In Figure 21 A-F the instantaneous frequency is followed from the footwall to the hanging wall, through the fault (parallel to the fault). The horizons, Base Cretaceous and Top Oxfordian Shale are also shown in the same figure. By studying how the properties are changing from the undeformed zone in the footwall (Figure 21A) to the undeformed zone in the hanging wall (Figure 21F) different changes are observed:

- The horizons are represented by yellow with orange spots reflectors. In the same way as in RMS amplitude, the horizon reflectors are quite continuous in the undeformed zones. While they becomes mixed up with something else in the fault zone. This can indicate that other features affect the instantaneous frequency inside the fault zone.
- The red circle in 21A, 21B, 21E and 21F indicates that it is possible to track a feature, and to follow it along the horizon through a fault zone. Also here the seismic properties change in most of the fault zone but in some areas. In the areas where it changes the most it suggest that petrophysical properties are lost, where in few areas continuity is observed suggesting that petrophysical properties are continuous.

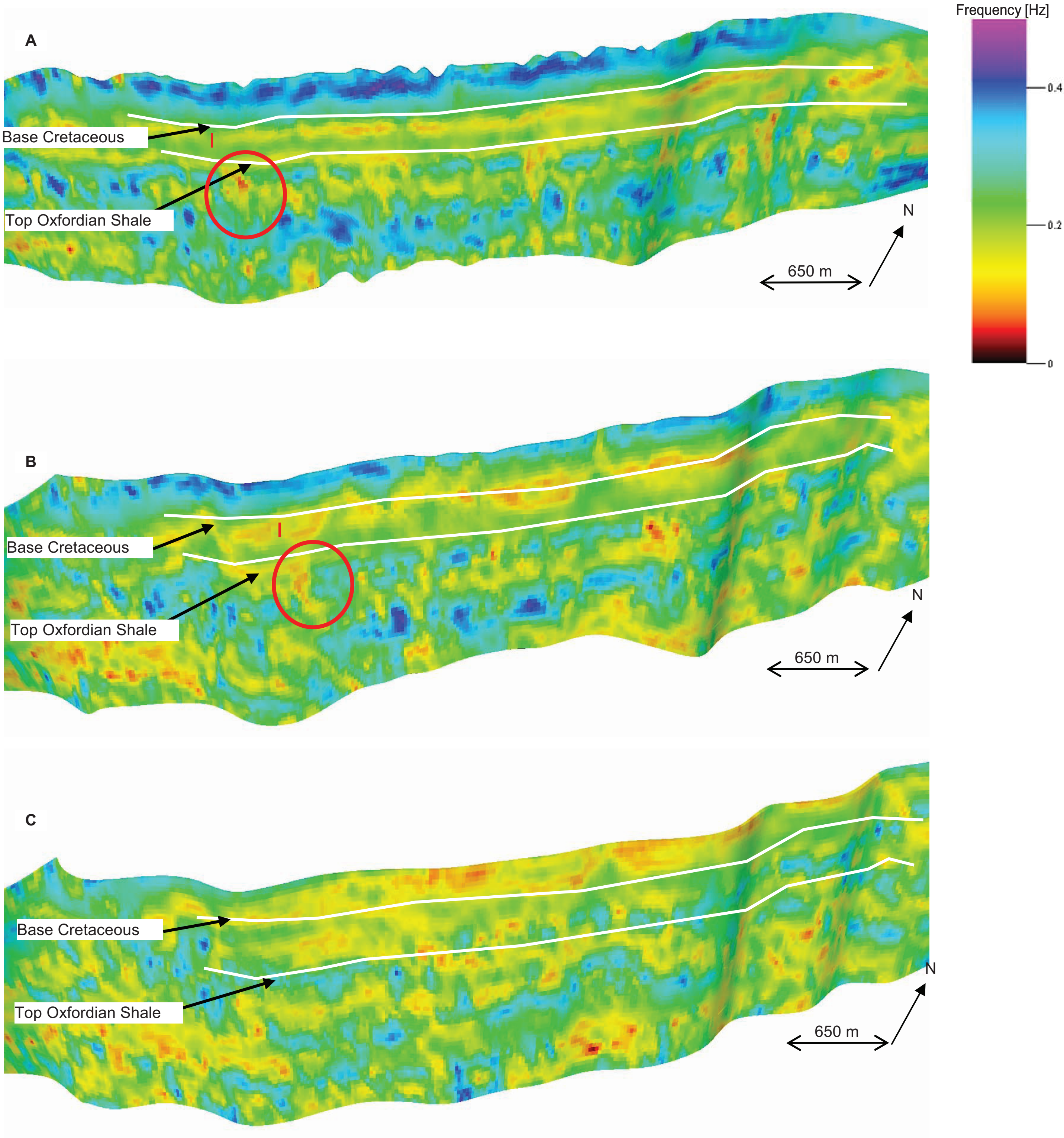


Figure 21: *Sections along the fault showing how the instantaneous frequency changes along the fault. A: Footwall in virgin zone. B: Still in footwall, getting towards the fault. C: Footwall boundary fault.*

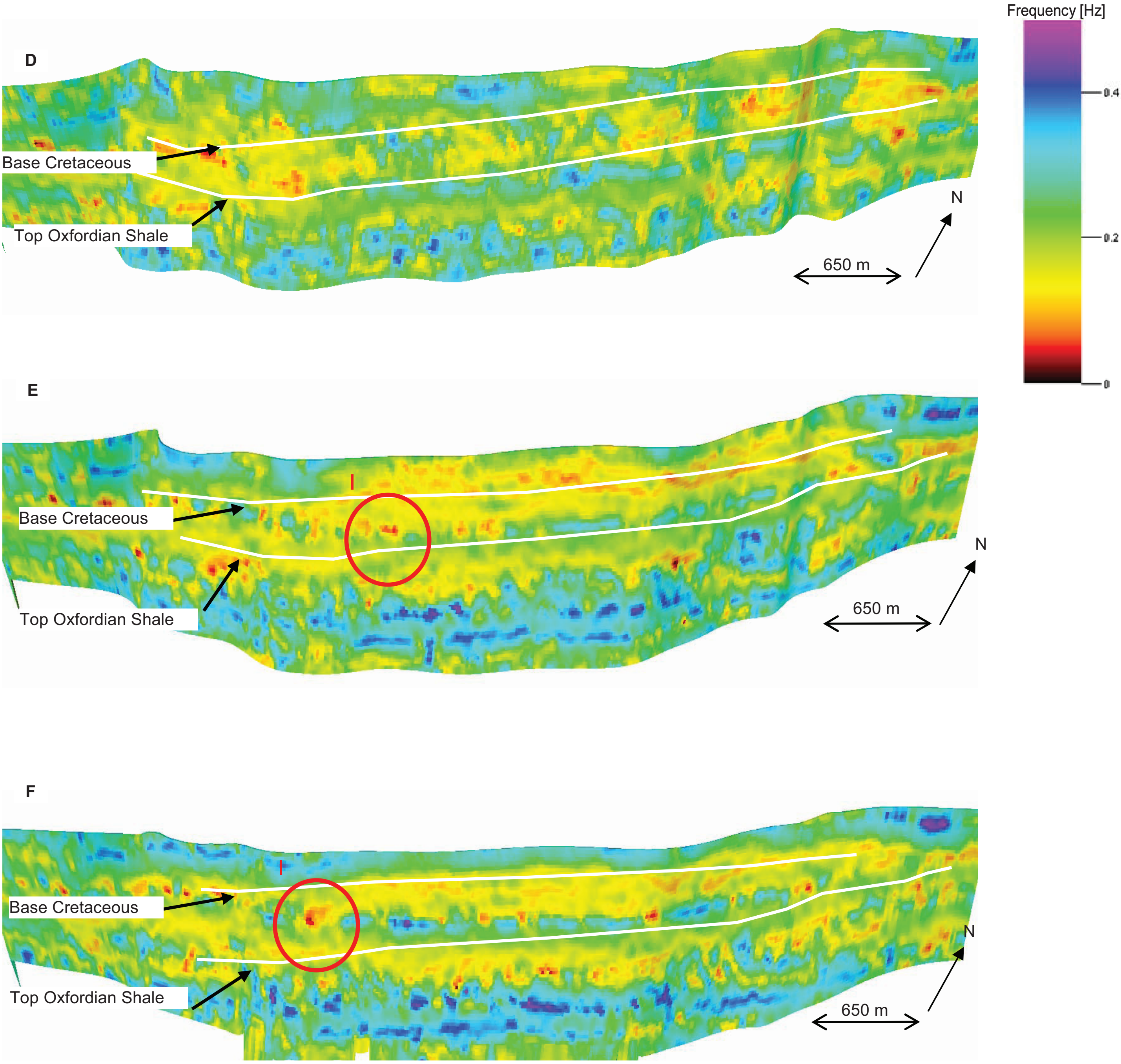


Figure 20 (continuation): *D: Fault core. E: Hangingwall boundary fault. F: Hangingwall in virgin zone. Red circle marked with I indicates that it is possible to track a certain property from footwall to hanging wall via the fault core. This property disappears inside the fault zone (C and D).*

In Figure 22 A-F the instantaneous frequency is followed perpendicular to the fault. The horizons, Base Cretaceous and Top Oxfordian Shale, and FBF, HBF and FC are also shown in the same figure. By studying the instantaneous frequency, Figure 22 A-F shows that the reflectors from the horizons fades away inside the fault zone in some areas, while it is possible to track the horizon reflector in other areas. This might indicate that the fault can provide fluid flow in some areas, while it act as a seal in other areas.

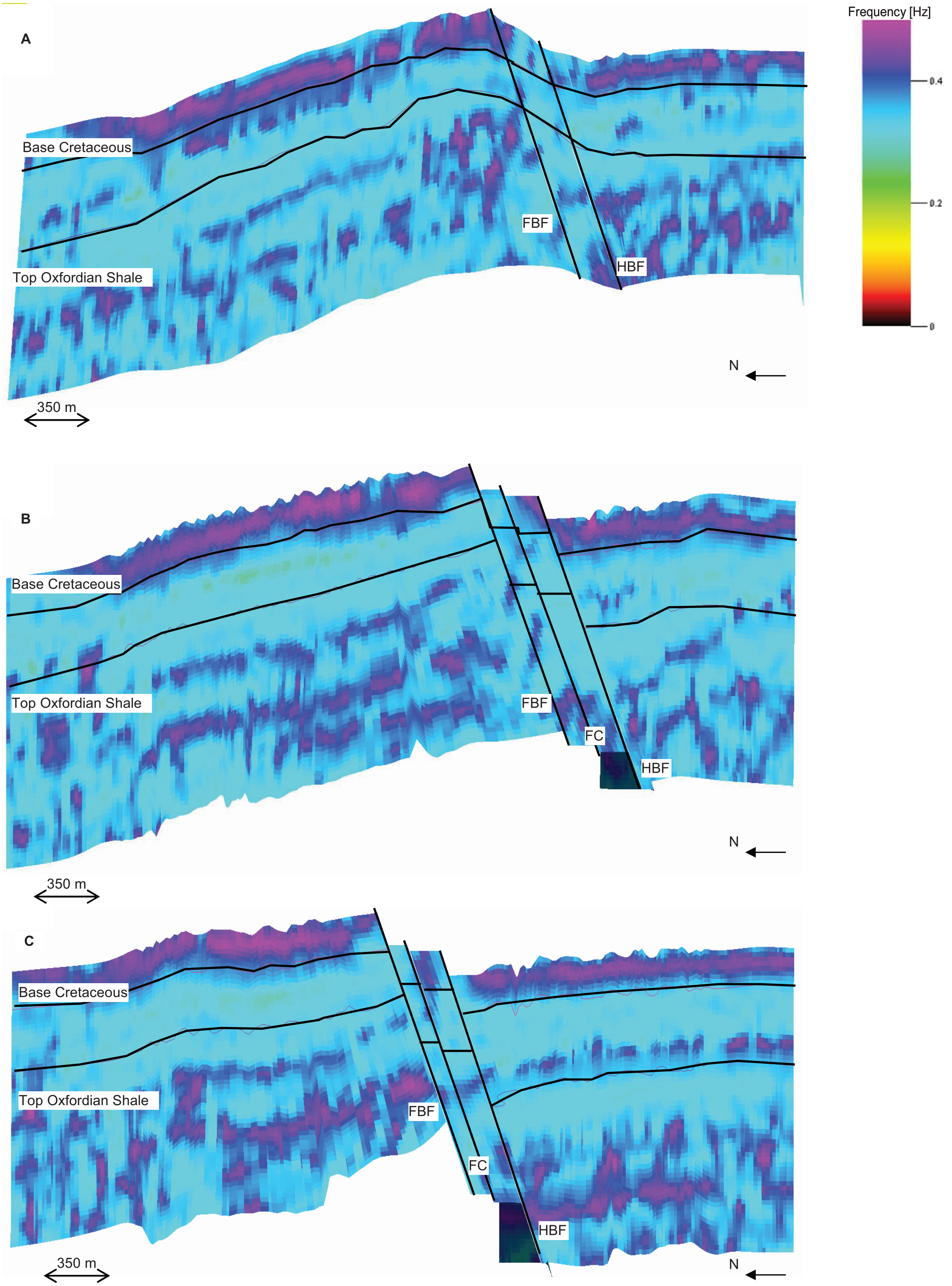


Figure 22: *Sections perpendicular to the fault showing how the instantaneous frequency changes* from the footwall to the hanging wall.

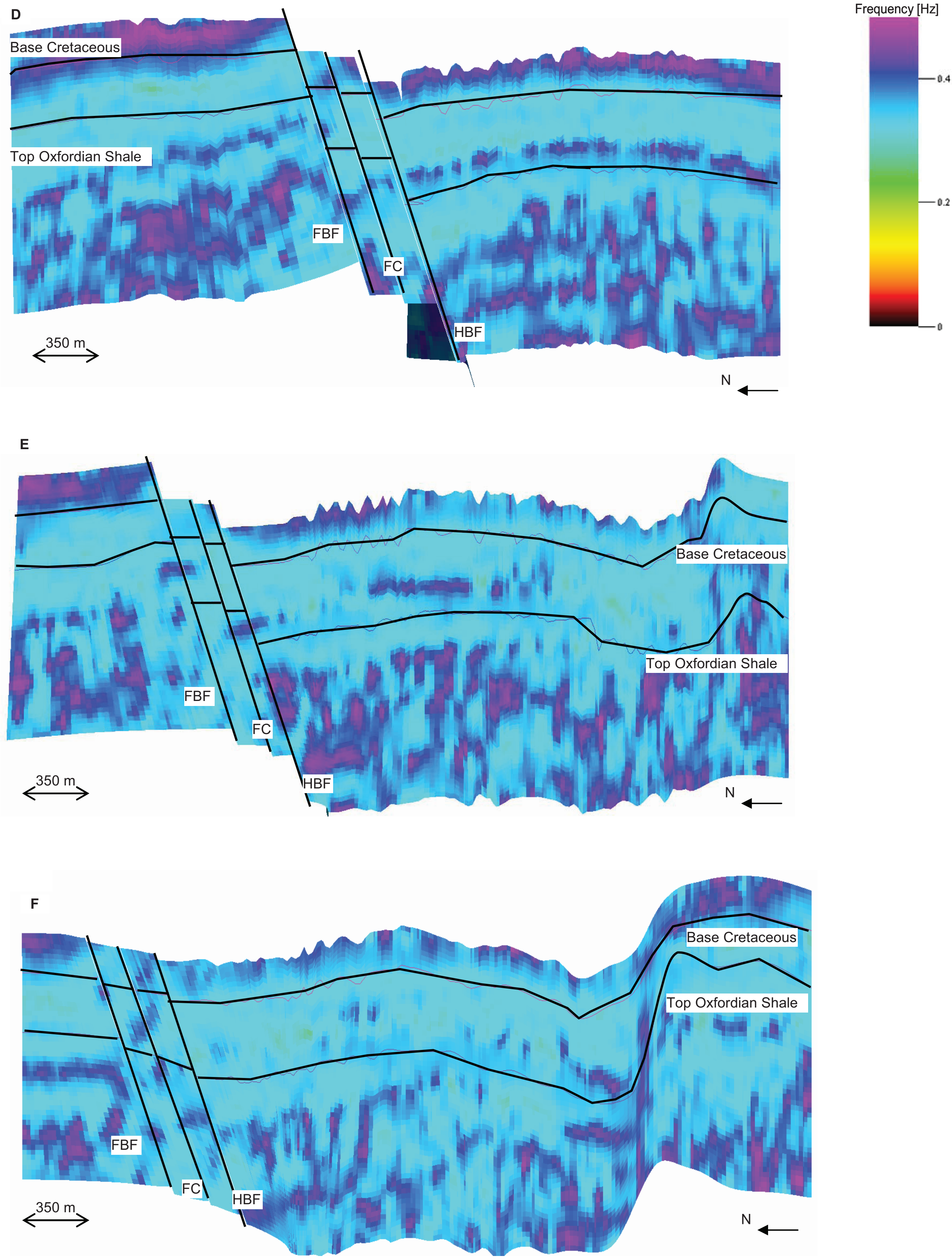


Figure 22 (continuation): *sections perpendicular to the fault showing how the instantaneous frequency changes* from the footwall to the hanging wall.

In Figure 23 A-F the chaos is followed from the footwall to the hanging wall, through the fault. The horizons, Base Cretaceous and Top Oxfordian Shale is also shown in the same figure. Buy studying how the properties are changing from the virgin zone in the footwall (figure 23 A) to the virgin zone in the hanging wall (figure 23 F) the following is observed:

- The horizons are here represented by orange reflectors. These shows that the horizons are continuous in the undeformed zones, while they gets affected by the fault zone. Inside the fault zone the reflectors gets divided, and becomes more chaotic. This indicates that the deformation caused by the fault also affects the seismic properties.
- There is not possible to track a special feature here, as we did with RMS amplitude and instantaneous frequency.

When it comes to follow the properties perpendicular to the fault (figure 23, 24 and 25) the reflectors from the horizons fades away inside the fault zone in some areas, while it is possible to track the horizon reflector in other areas. This might indicate that the fault can provide fluid flow in some areas, while it act as a seal in other areas.

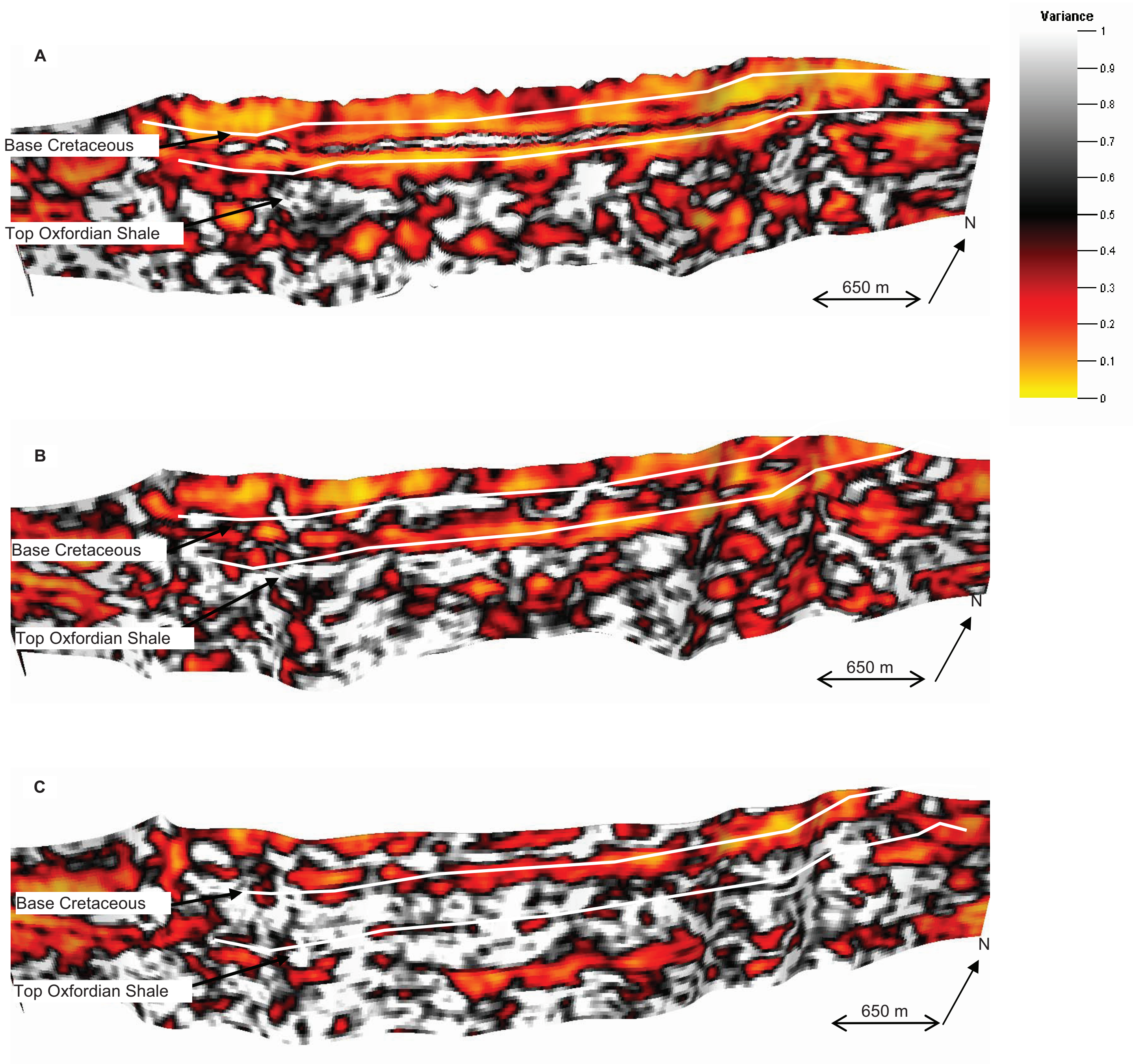


Figure 23: *Sections along the fault showing how the chaos changes from one side of the fault to another. A: Footwall in virgin zone. B: Still in footwall, getting towards the fault. C: Footwall boundary fault*

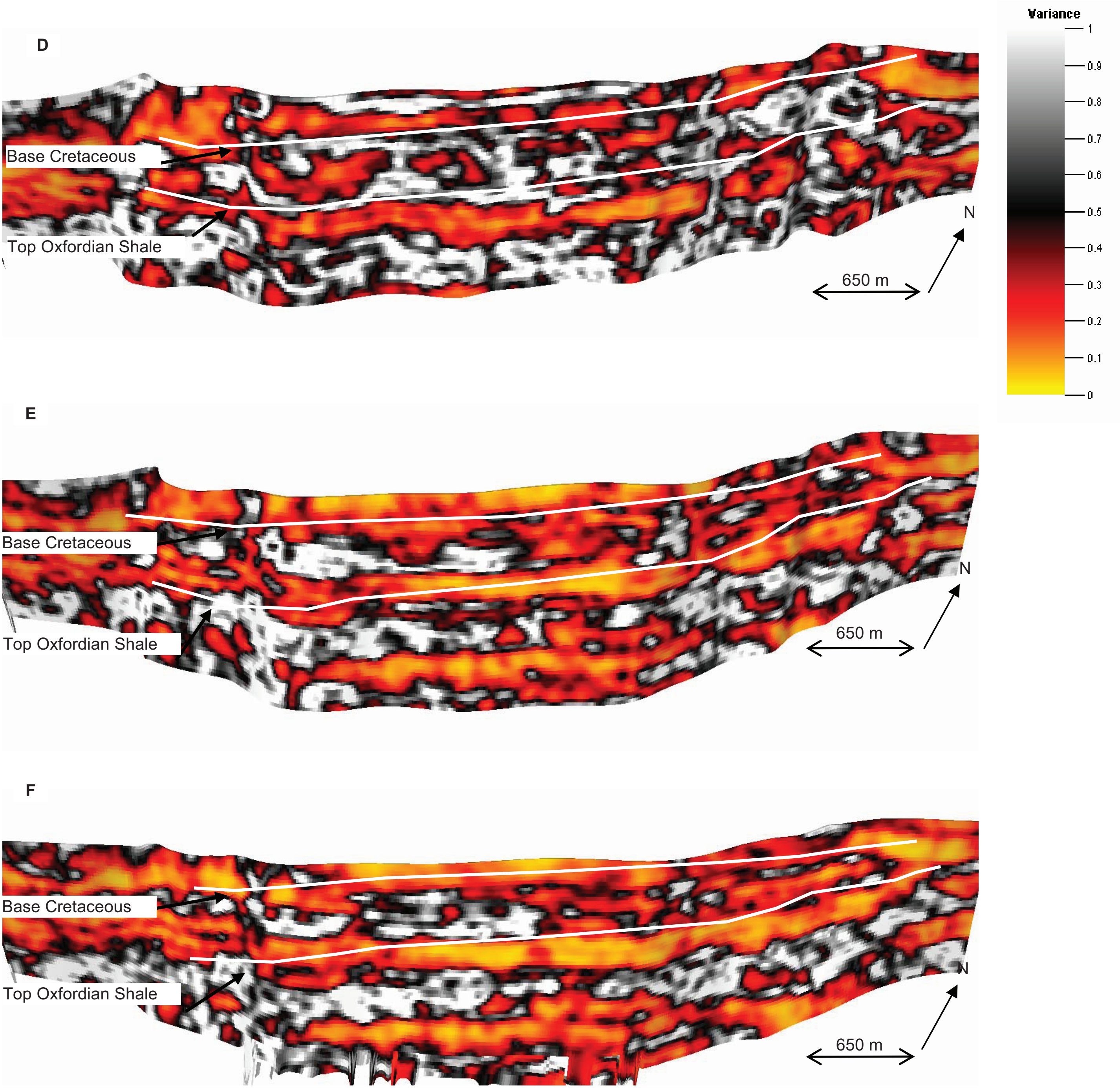


Figure 23 (continuation): *D: Fault core. E: Hangingwall boundary fault. F: Hangingwall in virgin zone.*

In Figure 24 A-F the chaos is followed perpendicular to the fault. The horizons, Base Cretaceous and Top Oxfordian Shale, and FBF, HBF and FC are also shown in the same figure. By studying the chaos, Figure 22 A-F shows that the reflectors from the horizons fades away inside the fault zone in some areas, while it is possible to track the horizon reflector in other areas. This might indicate that the fault can provide fluid flow in some areas, while it act as a seal in other areas.

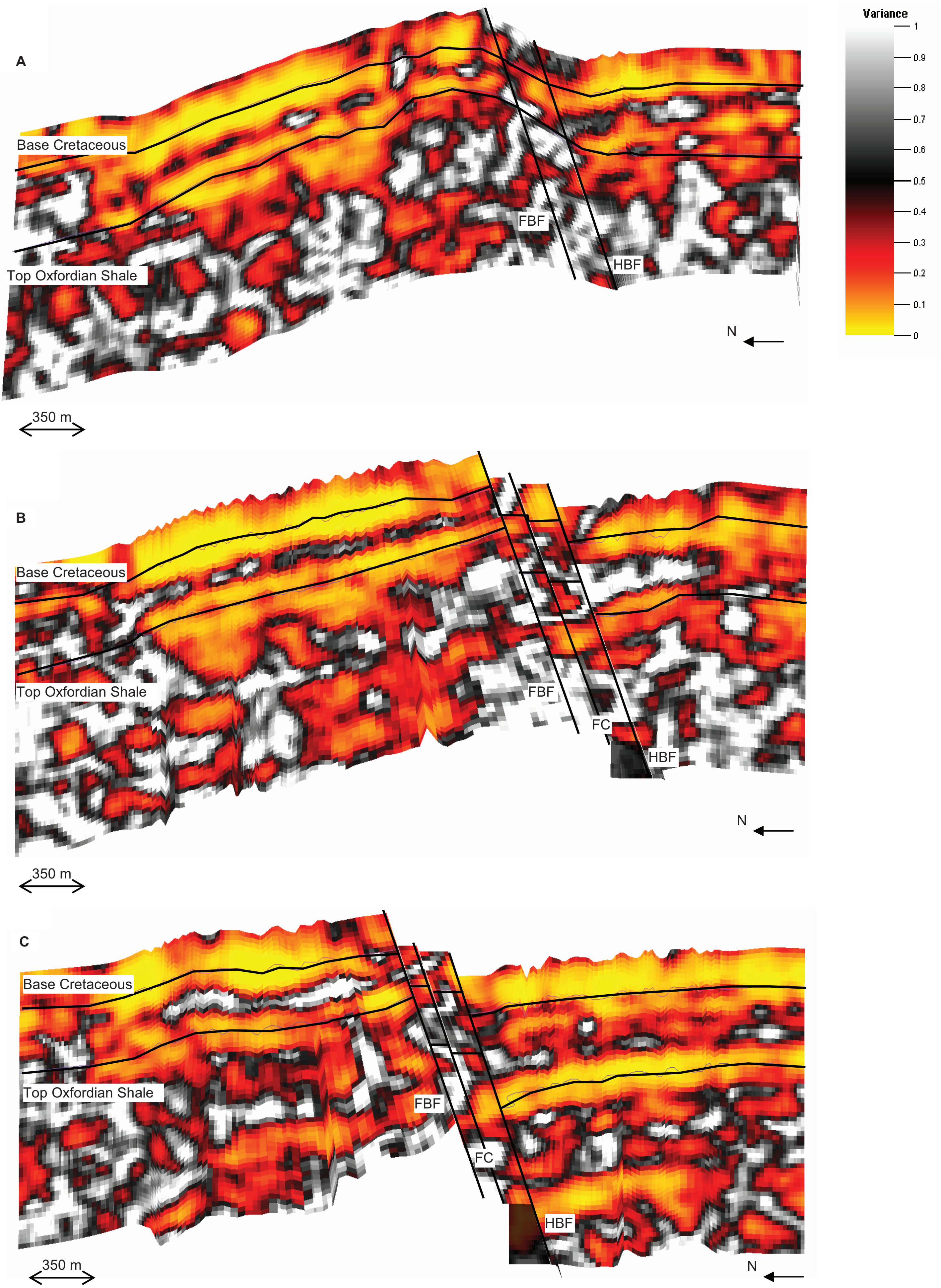


Figure 24: *Sections perpendicular to the fault showing how the chaos changes* from the footwall to the hanging wall.

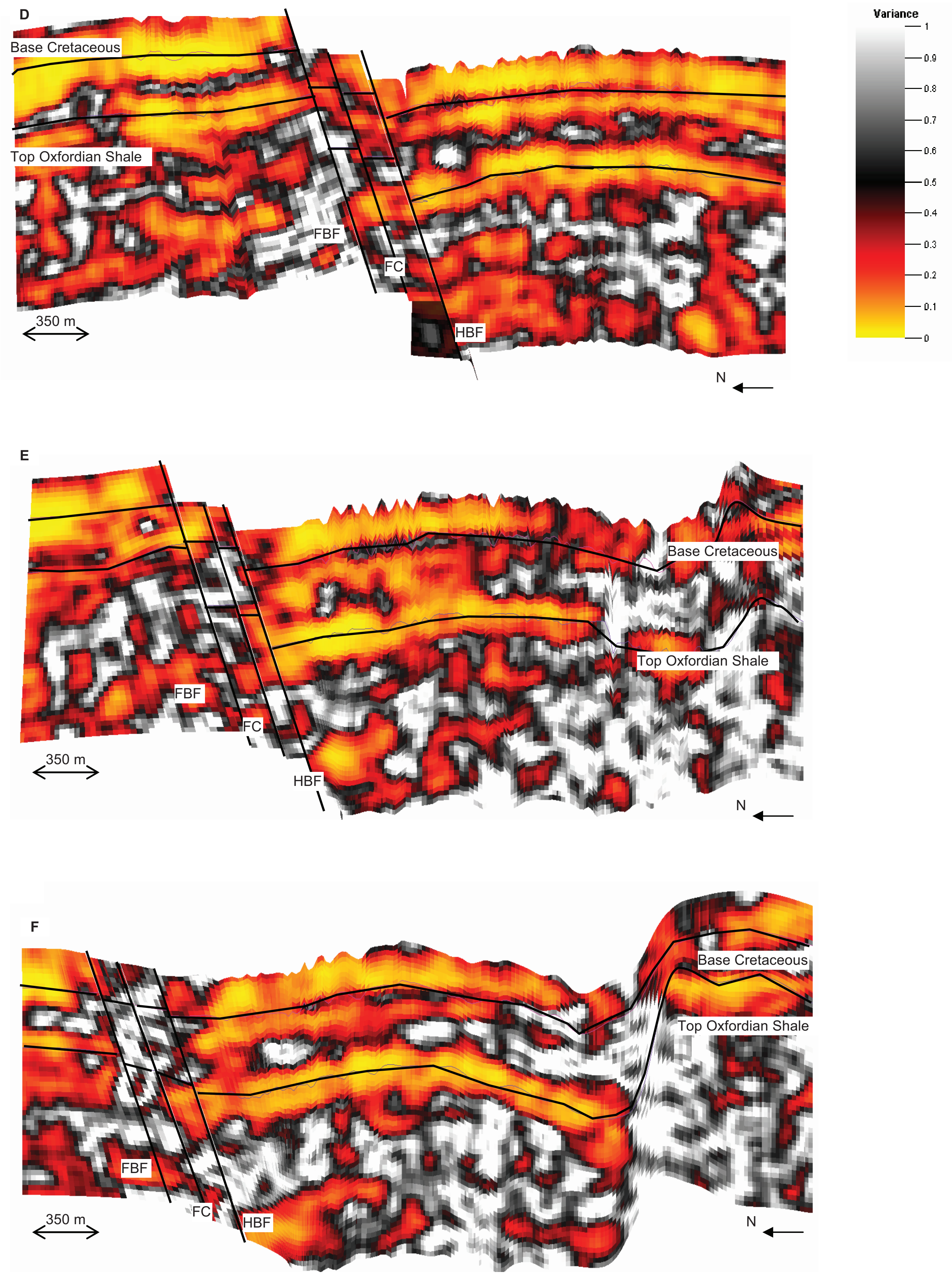


Figure 24 (continuation): *Sections perpendicular to the fault showing how the chaos changes* from the footwall to the hanging wall.

Discussion

Interpreting the fault is not an easy job, since the resolution of the seismic reflectors changes both laterally and vertically. In addition, the continuity of the horizons differs, which makes it even more difficult to localize the fault. At the end, the fault is not just a simple line, it consists of fault boundaries around a fault core.

By extracting the amplitude values from an interpreted horizon, it is possible to identify that the amplitude values changes in the fault zones (Figure 12). This information provided the fault boundaries from seismic data. Based on this two new fault lines were interpreted parallel to the fault core (Figure 13).

Heave, throw and dip slip were also calculated along the fault, based on the interpretation. Uncertainty tied to the interpretation will create a small value reliability of the heave, throw and dip slip values. However, the values show that there are larger changes along the fault in some places, compared to others. When combining the heave, throw and dip slip curves with the amplitude values perpendicular to the fault, the data shows that the larger the throw becomes, the more the amplitude values changes (figure 14). These observations support the suggestion, that using amplitude values while interpreting a fault, is a good solution.

After interpreting three fault lines on the seismic, it became possible to give the model a volume. This was done by creating a 3D grid based on the interpretation and the seismic.

The main goal was to recognize the consistence of seismic changes along or across the fault zone, patterns in and out of the fault zone that could lead to a posterior detailed petrophysical analysis.

By tracking the properties along the fault, it was possible to follow certain changes in the seismic from the hanging wall towards the footwall. In this case, the property was shown best in the undeformed zone, at both sides of the fault zone. A next step for further research is to link the seismic properties to petrophysical properties.

By tracking the properties perpendicular to the fault, only the continuity of the horizon was visible. Based on the observation it was possible to see in which area of the fault the horizons were more continuous. In some areas, it was possible to follow the reflector from the horizon through the fault zone. This could indicate the continuity of the horizon, which suggest connectivity, and if the petrophysical properties are consistent, fluid flow pathways can be interpreted. In the areas, were the horizon fades away, it is reasonable to assume sealing of the fault. Or the displacement of the fault is too large. As seen in Figure 14 (B1 and B2) the throw is large, which indicates a large displacement along the fault, specially in these two areas.

Conclusions and Recommendations

The main objectives of this thesis were to investigate a more accurate interpretation technique of faults; not just as surfaces, but as volumes where petrophysical properties in the fault zone could be obtained from seismic. In addition, the recognition of the consistence of seismic changes along or across the fault zone, and patterns in and out of the fault zone that could lead to a posterior detailed petrophysical analysis.

By extracting amplitude values in the horizons, it was possible to track the hanging wall boundary fault as well as the footwall boundary fault. This provides a better interpretation in the seismic, since the amplitude values show where the boundaries should be, compared to the fault core. Since the interpretation based on amplitude value was carried out manually, it might be a good idea to improve software, so that it could perform automatically interpretation of faults based on the amplitude values.

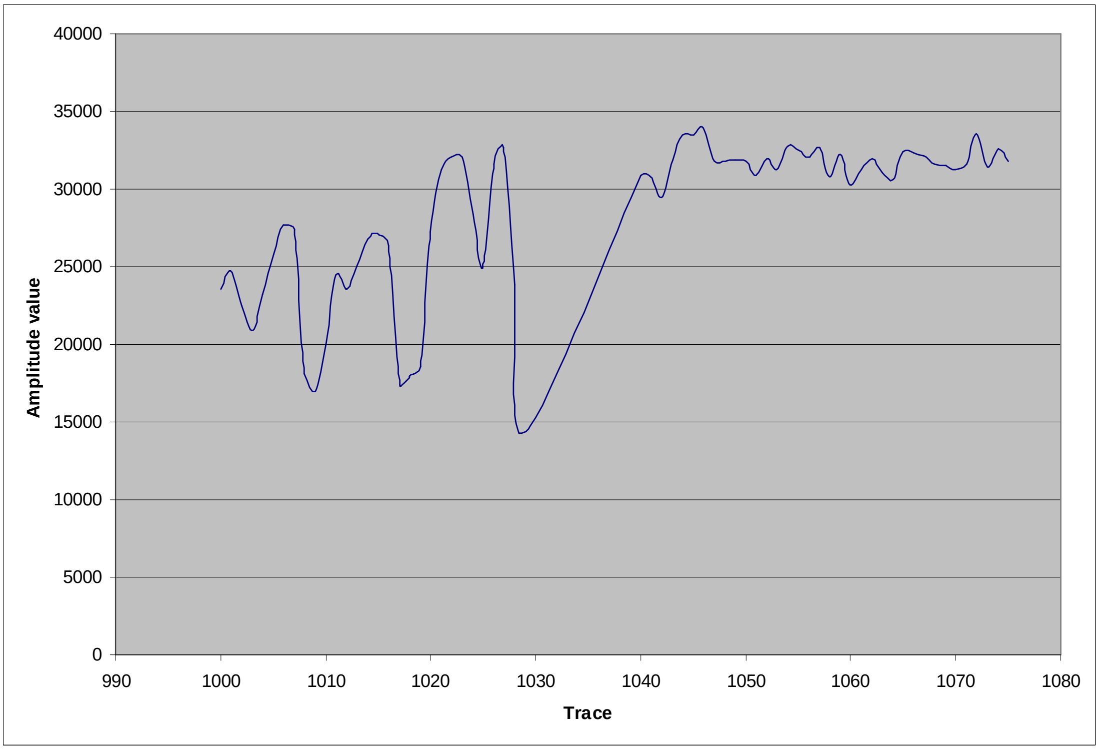
The interpreted fault boundaries were further used to create the edges of a 3D cube of the fault. Based on this, a 3D grid was created and properties were extracted into the 3D grid. The observations showed that it was possible to recognize the consistence of seismic changes both along and across the fault zone.

For future studies, deeper investigation, when it comes to the petrophysical properties inside the fault zone, should be performed. A closer look on what actually happens with the properties inside the fault, would help the understanding of fault zone influence on both reservoir conditions and fluid flow. Also lithology control and deformation level should be investigated in future studies.

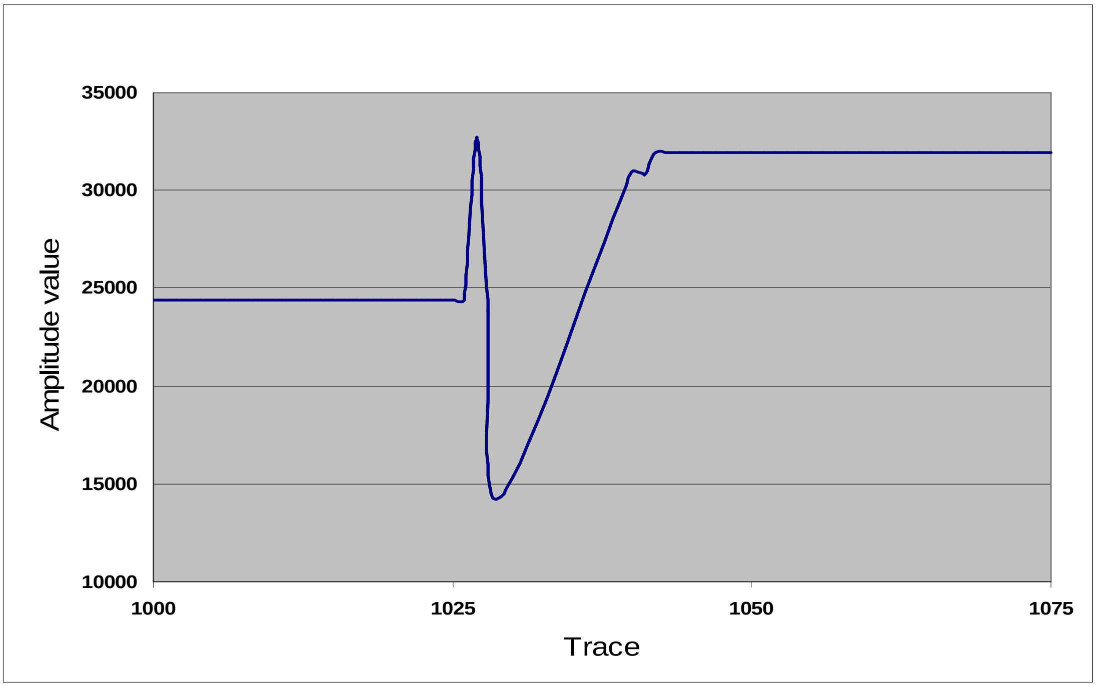
Appendix 1

Filtering of amplitude values.

Based on the originally extracted amplitude values along the seismic line the following graph was created:



This graph shows that there is a larger change in amplitude value around trace 1030. This is the same area as the fault is interpreted to be, based on standard interpretation techniques. To easier track which trace the fault boundary stars and ends on, the original values before and after the fault zone got changed to the average value on each side. Then the following graph was created:



Based on this filtered amplitude value graph the hanging wall boundary fault and the footwall boundary fault got interpreted on the seismic.

Table of amplitude values and the new average value:

	Line	Trace	Amp. value	New value	Line	Trace	Amp. value	New value
	160	1000	23574	24649	160	1042	29461	31885
	160	1001	24695	24649	160	1043	31875	31885
	160	1002	22485	24649	160	1044	33514	31885
	160	1003	20855	24649	160	1045	33490	31885
	160	1004	23223	24649	160	1046	33907	31885
	160	1005	25799	24649	160	1047	31774	31885
	160	1006	27645	24649	160	1048	31753	31885
	160	1007	27393	24649	160	1049	31839	31885
	160	1008	18101	24649	160	1050	31829	31885
	160	1009	16930	24649	160	1051	30867	31885
	160	1010	20047	24649	160	1052	31942	31885
	160	1011	24437	24649	160	1053	31281	31885
	160	1012	23565	24649	160	1054	32746	31885
	160	1013	24961	24649	160	1055	32519	31885
	160	1014	26792	24649	160	1056	32065	31885
	160	1015	27150	24649	160	1057	32706	31885
	160	1016	26355	24649	160	1058	30831	31885
	160	1017	17376	24649	160	1059	32244	31885
	160	1018	17985	24649	160	1060	30234	31885
	160	1019	18587	24649	160	1061	31258	31885
	160	1020	27273	24649	160	1062	31924	31885
	160	1021	31224	24649	160	1063	31077	31885
	160	1022	32013	24649	160	1064	30649	31885
	160	1023	32024	24649	160	1065	32410	31885
	160	1024	28383	24649	160	1066	32287	31885
	160	1025	25004	24649	160	1067	32138	31885
	160	1026	31651	24649	160	1068	31620	31885
Sum			665527		160	1069	31534	31885
Average			24649		160	1070	31277	31885
					160	1071	31599	31885
					160	1072	33608	31885
Fault zone	160	1027	32707		160	1073	31442	31885
Fault zone	160	1028	23824		160	1074	32612	31885
Fault core	160	1029	14357		160	1075	31768	31885
Fault zone	160	1040	30919	Sum			1084080	
Fault zone	160	1041	30807	Average			31885	

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