NTNU – Trondheim
Norwegian University of
Science and Technology

Integrated Reservoir Modelling of the Norne Field.

Volume Visualization/Seismic

Attribute,Structural and Property Modeling.

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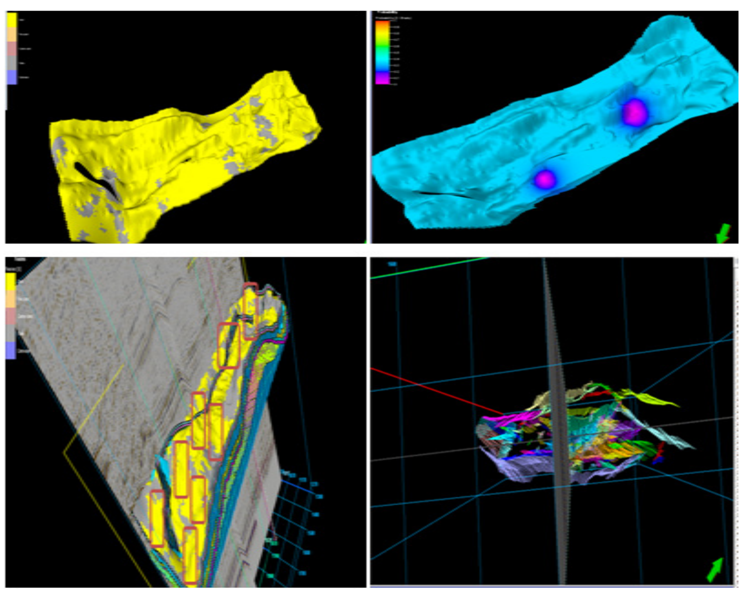

David Ahanor

June, 2012.

Preface and Acknowledgements

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Trondheim, June 2012

ABSTRACT

The purpose of this thesis project work is to build reservoir models (structural, facies and Petrophysical property models) of the different reservoir surfaces using integrated data sets (seismic, wells, fault sticks, eclipse models, horizon surfaces) of the Norne field which is located in blocks 6608/10 and 6508/1 in the southern part of the Nordland II area. Different visualizations techniques, volume rendering and seismic attributes were applied to aid the seismic interpretation and to provide detailed evaluation/integration of the data. 3D seismic interpretation for the whole seismic volume within the reservoir section was done manually with controlled input surfaces/reflectors of the Top horizons of the Not and Åre Formations. Fault and surfaces interpretation of the reservoir were generated as key inputs in the modeling process

The structural 3D grid skeleton and models were generated with critical inputs of the manually interpreted faults/horizons, using different qualitative/quantitative templates in Petrel. This was followed by well interpretation and upscaling to provide discrete facies which are needed in populating the structural models of each of the reservoir surfaces. A probabilistic facies model was done to capture the proportion of the spatial dimensions of each discrete facies in the model frame.

The initiation of this study involves quantitative data quality controls and management of inputs files into the Petrel window, qualitative control involves transferring geologic licenses/understanding to the various interpretations in the visualization schemes, seismic interpretation and reservoir modeling templates. The combination of different data type and idea (volumes, wells, top surfaces, and fault sticks) types means that the user must have a multivariate understanding (Geologic, Geophysical, Petrophysical, Geostastistic, Geo-Modeling and Reservoir Engineering) in other to integrate the data sets and deliver the models.

Eleven wells were used in reference to the Top surface of the Not, Åre Top surfaces and Statoil Reference report of the field, to deliver and control the seismic interpretation. A wedge shape structure was observed in the reservoir section. Typically, minor and major faults were interpreted as forming compartments in the reservoir, which were interpreted across the different lines. The structural framework in the field was largely defined by the Norne Horst and associated faults, with the erosional surface of the BCU with internal sub unconformities observed. The property facies model of the reservoir surfaces (Garn, Ile, Tofte, and TIlje) suggest that the Norne Horst and sub relief structures are mainly sand rich, which provides additional prospect indicators in exploring the field

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1. INTRODUCTION

The Norne Field is operated by Statoil and discovered in December 1991 and it is located 80km north of the Heidrun Field in blocks 6608/10 and 6508/1.Total hydrocarbon column (based on well 6608/10-2) is 135m which contains 110m oil and 25m gas (Statoil,2001).The hydrocarbons are found in the rocks of Lower and Middle Jurassic age.(statoil,2001); approximately 80% of oil is located in the Ile and Tofte Formations and gas in the Garn Formation (Statoil,2001).

This thesis work is directed to apply different techniques in creating geologic models and realization; the process is initiated from the scratch by visualizing the seismic volumes and applying different attribute functions to aid the seismic interpretation of horizons /faults in the reservoir sections to provide the necessary inputs for the different modeling templates. Key software used is Schlumberger's Petrel which is a window based software designed to visualize seismic attributes, interpret seismic and produce geologic models/interpretations of the seismic volumes.

Key inputs from the Norne field interpretation includes seismic SegY vintages (mid, far and near offsets), fault sticks, Production, Wells, Horizons and Eclipse Models. These data were inputted into the Petrel workstation for visualization, interpretation, evaluation and modeling. It is noteworthy that this work is directed to focus models in delivering geologic realization and interpretations.

Furthermore, key deliverables includes appropriate quality control and assurance of input data, seismic attribute /seismic interpretation of the volumes, generation of reservoir surfaces, structural 3D grids and modeling, Facies/ Petrophysical property modeling, Model up scaling and prospect evaluation. The Geologic models are also refined and tested based on a prior geologic controls and relevant reference information to cut out interpretation nuisances in other to deliver a functional based model where prospect evaluations could be inferred and/or provide necessary inputs for dynamic simulation based interpolations.

Multifaceted functions were applied starting with the visualization template which includes Opacity filters and amplitude extractions, Rendering, Cropping and amplitude clipping, slicing etc. Seismic interpretation with manual fault interpretation and horizon picking across lines with flattening techniques used to restore seismic surfaces in a bid to understand the prevailing geologic processes /controls. Automatic fault extraction (Ant Tracking) was deployed alongside seismic attribute volumes to generate fault surfaces as a basis to controlling the manually based fault interpretation/modelling. The high point of the structural modeling includes fault building, pillar gridding, Make horizon process and zone process.

The final process of the work flow is property modeling using upscaled well logs based interpretation of sand/shale lithofacies classes in populating the 3D structural grid. Different algorithm were used and described in the facies process with stochastic simulation was used as the main property algorithm. Petrophysical modeling was done on each of the interpreted reservoir surfaces in other to determine the reasonable confidence of the discrete facies models. Prospect evaluation and upscaling of the models were the latter work done in this work.

1.1 Location of study Area

The field is situated in the blocks 6608/10 and 6508/1 in the southern part of the Nordland II area. It is an oil field located about 80 km north of the Heidrun field in the Norwegian Sea. (Statoil, 2001).

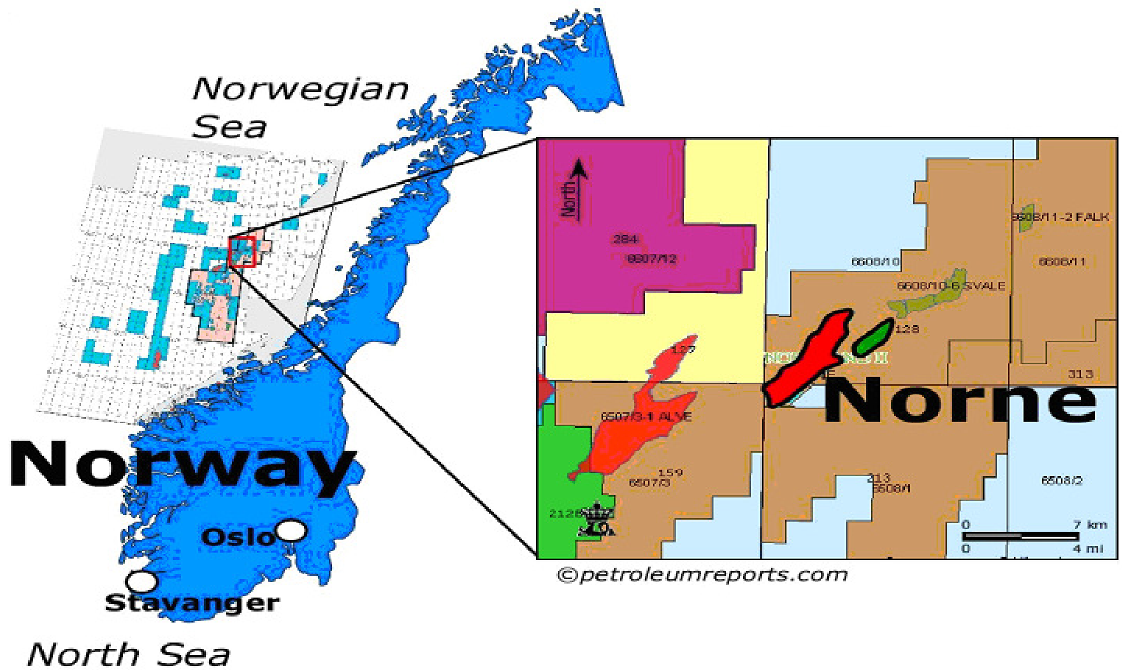


Figure 1: location of the study area in blocks 6608/10 and 6508/1.

1.2 Aims and Objectives

The main purpose of this work is first to have a clearer understanding of current visualization techniques and seismic attributes as applied in Petrel; applying these techniques in interpreting seismic volumes.Also, applying available geologic controls and understanding to provide key structural and stratigraphic interpretation in creating static reservoir models with facies/petrophysical properties from upscaled well logs.

Key outputs Include:

- Quality control and input results of each datasets.
- Volume rendering and different visualization outputs.

- Fault interpretation and fault sticks(applying manual and automatic fault interpretation techniques
- Modeling of faults and Interpretation
- Modeling of Horizons (Horizon operations, surface operation and surface attribute
- 3D structural grid skeleton/surfaces of the Garn, Ile, Tofte, Tilje formations
- Property modeling (facies modeling and techniques, facies log interpretation)
- Upscaling of well logs
- Data analysis of reservoir discrete properties
- Petrophysical modeling
- Prospect evaluation from structural/facies model.
- Upscaling/simulation grids of the Norne interpreted reservoir surfaces

2. OUTLINE OF GEOLOGIC HISTORY OF THE STUDY AREA

The Norne field is located in blocks 6608/10 and 6608/11 in the Norwegian Sea. The main structural features are defined by the Trøndelag Platforms, Nordland Ridge, and Donna terrace. It is separated from the North Sea province by the northeast- southwest trending More- Trøndelag Magnus- West Shetlands Spine Fault complex (Knott et al., 1993)

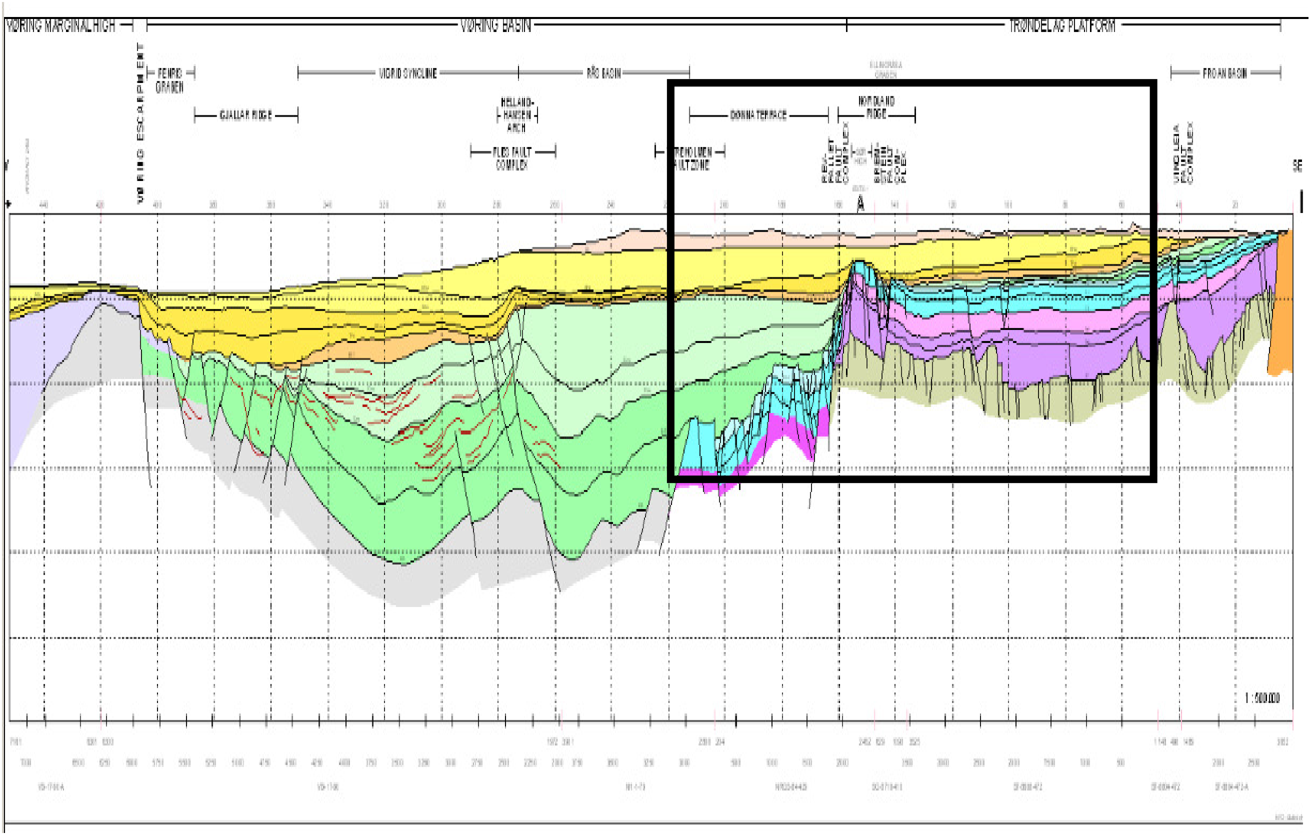


Figure 2:Regional profile across the Mid-Norwegian Margin, with the shaded boxed area showing the Donna terrace, Trondelag Platform and Nordland Ridge. Refer to figure 3, which gives the geologic ages and indicates the different colour schemes used in the profile.

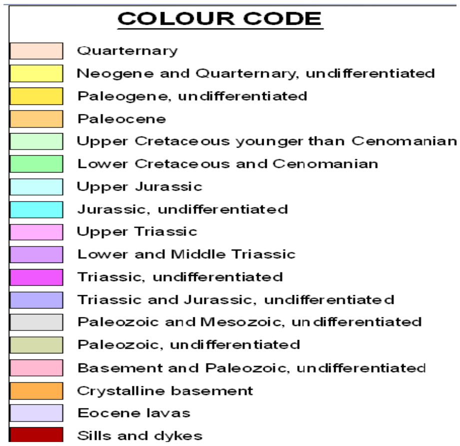


Figure 3: Colour code used to describe the geologic profile of the Norwegian Sea margin of figure2

The tectonic evolution of the Norwegian Sea is linked closely with the break-up of the North Atlantic and the Caledonian orogeny. The tectonic history of the area is divided into three periods:

1. The closure of the Iapetus Ocean during the Caledonian orogeny in late Devonian times. (Coward, 1993)

2. The continental separation between Eurasia and Greenland which comprised episodic extensional deformations until the Paleocene- Eocene boundary.

3. Active seafloor spreading between Eurasia and Greenland marking the Eocene to present time.

The geologic history of the basin prior to the early Tertiary continental break-up is much of interest to petroleum exploration with major rifting episodes in late Carboniferous and early Permian, late Jurassic and early Cretaceous, late Cretaceous to early Tertiary defined. Also, other extensional tectonic periods have been identified in the Triassic, early Cretaceous and post Cenomanian (Surlyk et al., 1994)

The late Carboniferous to Permian times the region suffered rifting reported in the mid- Permian (Surlyk et al., 1994) .The Triassic times saw the waning of tectonic activities and deposition of extensive braidplain /playa mudflat environments. In the early Jurassic, the formation of red to grey bed as a result of the Northward drift of Mid-Norway in the Triassic times; this culminated to the deposition of paralic coal bearing sediments of the Åre Formation. (Swiecicki et al., 1998)

The Mid Jurassic to Late Jurassic was marked with rifting (Swiecicki et al., 1998); with main rifting phase that formed the Halten Terrace and Nordland Ridge. This rifting phase continued until the early Cretaceous. The late Cretaceous – Early Tertiary rifting phase affected areas to the west of the Vøring Basin; and did not affect the Nordland Ridge area. In the Necomian phase, the basin margins developed further and the separation between the platform and the terraces became more accentuated (Price & Rattey, 1984)

In the mid Norway two major regression and transgression are identified. The Aalanian to early Bajocian, comprises of tidally influenced shallow marine and shore faced sandstones of the Ile Formation, which is succeeded by the transgressive shelfal mudstones of the lower Not formation. The Not and Garn Formations of deltaic and shore faced sandstones formed during the late Bajocian to Mid Callovian. (Swiecicki et al., 1998)

The Early Jurassic is marked with the deposition of the Tofte Formation sand; Fangst Group sediment were deposited, mostly as blanket sands during a quiet episode through the Aalenian, Bajocian and most of Bathonian times. (Price & Rattey, 1984)

The late Jurassic is marked by the deposition of Melke and Spekk Formations of mid Callovian to Kimmeridgian age; with observed syn rift growth (Swiecicki et al., 1998). The Cretaceous is marked by an early sequence of poorly stacked sandstones separated by marine shales; this sequence condences across Trøndelag Platform (Swiecicki et al., 1998).The late Cretaceous shows continuous onlap and overstep of the basin margins; most the pre- existing highs were submerged and a widespread, shale dominated succession predominate. In Mid Norway the change is characterized by the passage to Mid to Upper Lange Formation, the Upper Lange is absent over the Trøndelag Platform and Nordland Ridge (Swiecicki et al., 1998).

2.1 Norne stratigraphy and sedimentology

Hydrocarbons are located in the Lower to Middle Jurassic sandstones of the Garn, Ile, Tofte and Tilje formations (Figure 4). The reservoir sandstones are dominated by fine-grained and well to very well sorted sub-arkosic arenites. (Dalland et al., 1984) The sandstones are buried to depths of 2500-2700 m and are affected by diagenetic processes. Mechanical compaction is the most important process, which reduces reservoir quality. Still, most of the sandstones are good reservoir rocks. The porosity is in the range of 25-30 percent while permeability varies from 20 to 2500 mD. The source rocks are believed to be the Upper Jurassic Spekk Formation and Lower Jurassic coal bedded Åre Formation (Swiecicki et al., 1998).

The cap rock, which seals the reservoir and keeps the oil and gas in place, is the Upper Jurassic Melke Formation (Swiecicki et al., 1998). The Not Formation also behaves as a sealing layer, preventing communication between the Garn and Ile Formations, within the reservoir sequence (Verlo and Hetland, 2008).

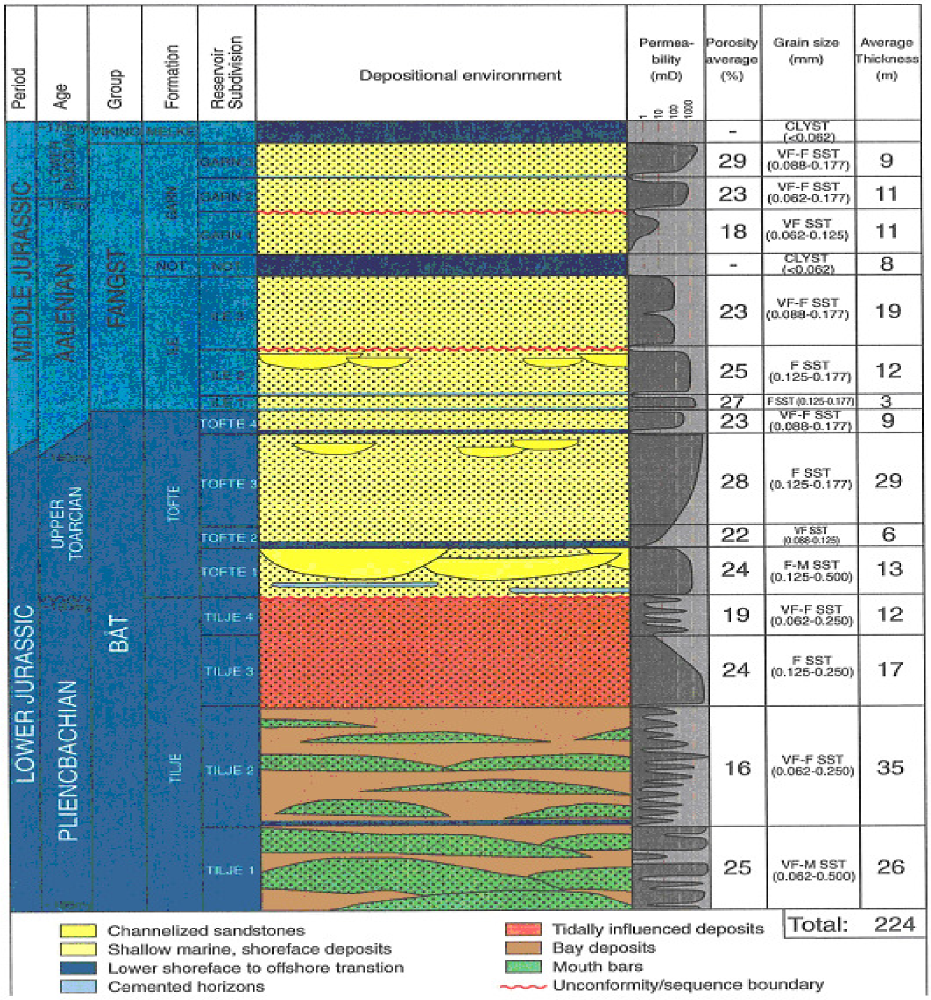


Figure 4: Stratigraphic sub-division of the Norne reservoir (Statoil, 2001).

The entire reservoir thickness, from Top Åre to Top Garn Formations, varies over the Norne Field from 260m in the southern parts to 120 m in the northern parts [Statoil, 1994]. The reason for this difference is the increased erosion to the north, causing especially the Ile and Tilje Formations to decrease in thickness [Statoil, 1995]. This has been found from seismic mapping [Statoil, 1994].

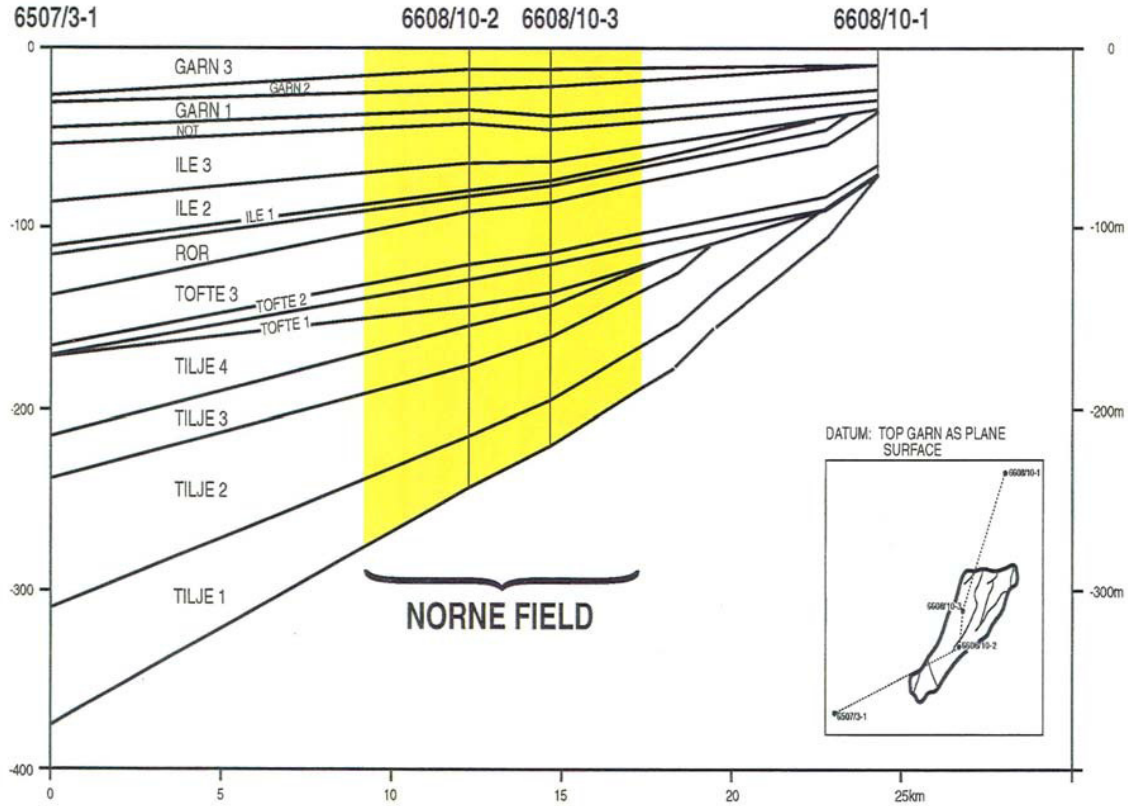


Figure 5:Cross-section through the reservoir zone [Statoil, 1994]

The Åre Formation has a heterolithic composition and represents the lowest formation within the Båt Group. It comprises mainly channel sandstones which are 2-10 m thick and interbedded with mudstones, shales and coals. The coals of the Åre formation are considered a source for gas generation in Mid Norway (Hvoslef et al.,1988); the interbedded fluvial distributary channel sandstones provide a reservoir horizon in the Heidrun Field (Whitley, 1992).The Åre Formation was deposited during Hettangian to Early Pliensbachian. Its thickness varies from 200 m in the southern Haltenbanken area, to a more than 800 m thick column discovered in well 6608/10-2 (Dalland et al., 1988). An increase in the sand/shale ratio eastwards is observed. The depositional environment was probably alluvial to delta plain setting, transported from a source area to the east (Hvoslef et al., 1988).

The Tilje Formation was deposited in a marginal marine, tidally influenced depositional environment (Dalland et al 1988). It is composed of sand with some clay and conglomerates. The source of the sediments was located west of the Norne Area (Swiecicki et al., 1998). The formation is thinning to the north due to decreased subsidence rate during the deposition, along with increased erosion to the north/northeast at the base of the overlying Tofte Formation (Dalland et al., 1988). An unconformity is found at the top of the Tilje Formation (Verlo and Hetland, 2008). This hiatus was most likely created due to uplift, followed by subaerial exposure and erosion. It was probably the result of an important tectonic event. The hiatus marks the transition from heterolithic sediments of the Åre and Tilje Formations into thicker marine sandstones of the overlying formations. The Tilje Formation is divided into four reservoir zones based on biostratigraphic events and similarities in log pattern. Tilje 1 is not cored in either of the wells 6608/10-2 or 6608/10-3 (Verlo and Hetland, 2008), but it is believed to consist of two sequences of sand that are coarsening upward and more massive sand at the top. Tilje 2 has a heterolithic composition consisting of sandstone layers of variable thicknesses, heavily bioturbated shales, laminated shales and conglomeratic beds.A varying depositional environment is characteristic for the Tilje 2. Tilje 3 consists of fine grained sand which has a low degree of bioturbation. (Dalland et al 1988) It is therefore possible to see mud drapes, cross-bedding and wave ripples in the deposits. Implications of the presence of fresh water are also found. Tilje 4 is a fine grained, bioturbated and muddy sandstone in the lower parts, while the upper parts have conglomeratic beds interbedded with thin sandstone and shale layers (Dalland et al., 1988)

The Tofte Formation was formally called the leka sandstone; it was deposited on top of the unconformity mentioned above during the Late Toarcian by marine foreshore to offshore deposition (Dalland et al 1988). The mean thickness of the Tofte Formation across the field is 50 m and was describe from type well 6508/12-1 to have a thickness of about 65m (Statoil). To the east of the Nordland Ridge the deposits are mostly shales, whilst sand was deposited to the west. In addition, there is proof of minor erosion at the top of the ridge. It is therefore assumed that the Nordland Ridge was a barrier for sand transportation to the east (Verlo and Hetland, 2008).

The Tofte Formation is divided into three reservoir zones. Tofte 1 consists of medium to coarse grained sandstones with steep dipping lamina (Dalland et al., 1988). The lower part is more bioturbated and is finer grained. The cross beds suggest that the source area for sediments was to the north or northeast of the field. (Dalland et al., 1988). Another important issue related to Tofte 1 is the limited distribution in the east-west or northeast-southwest direction. Tofte 2 is an extensively bioturbated, muddy and fine grained sandstone unit. Floating clasts can be found in the lowermost part of the section, which is coarsening upward. Tofte 3 consists of very fine to fine grained sandstone where almost none of the depositional structures are visible because of bioturbation. (Dalland et al., 1988) Some low angle cross-bedded layers occur in the upper part. There is a coarser grained bed representing a sequence boundary at the top of the unit, this represents the Upper Toarcian-Aalenian boundary (Dalland et al., 1988).

The Ror Formation is time equivalent with the Tofte Formation and is a very fine grained/shaly unit of lower shoreface deposits. In addition to the sand content, glauconite, phosphate nodules and calcareous shells can be found in the extensively bioturbated sandstone deposition. The Ror Formation is only 8.5 m thick at the Norne Field but was described in type well 6407/2-1 (Saga Petroleum) with a thickness of 104m. At the top of the formation calcareous shells have been dissolved and cemented, which creates a calcareous cemented unit (Dalland et al., 1988).

The Ile Formation was deposited during the Aalenian to early Bajocian, comprises the easterly progradational, tidally influenced, shallow marine and shoreface sandstones (Dalland et al 1988), and its thickness varies from 32-40 m. This formation is divided into three reservoir zones; Ile 1, Ile 2 and Ile 3. The separation between Ile 1 and Ile 2 is the same as the boundary between the Ror and Ile 1 Formations, a cemented calcareous layer.(Swiecicki et al 1998). These layers are probably the result of minor flooding events in a generally regressive period. Both the calcareous layers are correlative in the wells 6608/10-2 and 6608/10-3, and are assumed to be continuous throughout the Norne Field. Ile 2 and Ile 3 are separated by a sequence boundary, which is an indicator of the change from regressive to transgressive environments (Swiecicki et al., 1998).

The reservoir quality of the Ile Formation is generally good, especially in the regressive deposits, whereas the reservoir properties are decreasing toward the top of the formation. Ile 1 and Ile 2 both consist of fine to very fine grained sand which is coarsening to the north. Bioturbation, glauconites and plenty of calcareous shell fragments give clues as to the type of depositional environment. Despite bioturbation some lamination and ripples can be seen, but the quantity is not sufficient to determine the transport direction (Verlo and Hetland, 2008). The coarser grained sequence boundary that was mentioned above is at the top of Ile 1. Ile 3 lies above the sequence boundary and is an extensively bioturbated, with upward fining fine to very fine grained sandstone. This zone also contains phosphorite nodules, glauconites and clay clasts; which provide evidence of periods of starvation during the transgression (Dalland et al., 1988).

The Not Formation was also deposited during Aalenian time. It is divided into three sequences: the upper Not Formation, which consists of shallow marine mudstones, the middle Not Formation of shoreface sandstones, and the Lower Not formation of shelfal mudstones (Dalland et al., 1988). It is about 7.5 m thick, of dark grey to black claystone with siltstone lamina. The depositional environment was quiet marine, probably below wavebase. However, palynological findings indicate that there was freshwater influencing the environment (Swiecicki et al., 1998). This is explainable if one assumes that the water column in the basin was stratified, hence preventing the water from mixing before it reached far into the basin. The Not Formation has a coarsening upward trend which continues into the Garn Formation (Dalland et al., 1988). Therefore, it can be found a layer of very fine grained, bioturbated sandstone in the upper part of the formation (Verlo and Hetland, 2008). The upward coarsening indicates deposition during a regression.

The Garn Formation was deposited during the Late Aalenian and the Early Bajocian, and is 35 m thick shoreface sandstone (Swiecicki et al., 1998).Reservoir quality is increasing upward within the formation, from good in the lower parts to very good in the upper parts. This formation is also divided into three reservoir zones based on differing properties and deposits (Dalland et al., 1988). Garn 1 is a sandstone unit which is coarsening upward, from very fine to fine grained sand. The lower part is muddy and bioturbated, as it is the continuance of the Not Formation, while the upper part has an increased sand content. This part of the formation has bedding, ripple lamination and thin layers of coarser grained sandstone. At the top of Garn 1 a coarse to very coarse grained, garnet rich bed is found. (Dalland et al., 1988).This bed is interpreted to be a beach deposit from the maximum regression period; it is a sequence boundary that is correlateable in the Norne wells. Garn 2 is a transgressive deposit consisting of fine grained sandstones, where some layers are bioturbated while others are laminated. At the top, a calcareous cemented sandstone unit is found. It represents a starvation in the supply also called maximum flooding surface. This layer is expected to be continuous throughout the field and can be a local barrier to vertical fluid flow (Verlo and Hetland, 2008). The lower part of Garn 3 is not cored in any of the wells. The upper part of this zone is made up of low angled cross bedded and fine grained sandstone. A coarse grained bed is located in the top of Garn 3. This is an erosional surface from maximum regression. The Garn Formation is much thinner in well 6608/10-1 and most of Garn 2 and the entire Garn 3 are missing in this well. This is due to tectonic uplift in the north during the deposition (Dalland et al., 1988). The Garn Formation south of the Norne field is thicker due to higher subsidence rates, which give more accommodation space. At the top of Garn 3, sandstone and mudstone sediments with floating clasts are found. This is a result of ravinement and reworking during a transgressive period (Verlo and Hetland, 2008).

The Melke Formation was deposited during the Late Bajocian to the Early Bathonian times; in offshore transitional to lower shoreface environment (Dalland et al., 1988).The thickness of the formation varies from 212 m to 160 m of claystones and siltstone lamination composition, in the wells 6608/10-2 and 6608/10-3. (Verlo and Hetland, 2008).

The offshore transitional environment deposits are not uncommon in the Norne field, while the lower shoreface environment dominates in the north. This indicates that the land was located north of the Norne Field, which also is the source area for sediments. Three coarsening upward units are recognised in the lower parts of the Melke Formation. Each of these ends with muddy, very fine grained sandstone. The Melke sandstones in well 6608/10-1 was earlier correlated to the Garn Formation on the Norne Field, but by considering biostratigraphical evidence, it is clear that the Melke Formation is younger than the Garn Formation. The Melke Formation acts as a seal in the field. This is because it is not well enough developed to provide reservoir rock properties. Within the Tofte, Ile- and Garn Formations there exist three calcareous cemented layers, as mentioned above. They are all interpreted to be continuous over the entire Norne Field. (Verlo and Hetland, 2008).

Reservoir communications

The cemented layers, together with the shaly Not Formation, are believed to act as stratigraphic barriers to vertical fluid flow within the reservoir. The sealing qualities of the Not Formation have been verified through Formation Multi Tester (FMT) data from wells drilled since production started (Statoil, 2004). The thickness of the Not Formation across the field is between 7 and 10 m, while the thickness of the calcareous layers varies in the range of 0.5-3 m. Other layers which are believed to restrict the vertical fluid flow are Tilje 4, base Tofte 2 and base Tofte 4 (Verlo and Hetland, 2008).

Vertical and lateral flow in the Norne Field is affected by both faults and stratigraphic barriers. Although these barriers are not expected to be important in a field-wide scale, it is important to consider the effect they have on the fluid flow to enhance the drainage strategy. Faults, especially major faults, can be discovered by studying the seismic data. Each subarea of the fault planes has been assigned transmissibility multipliers. To describe the faults in the reservoir simulation model, the fault planes are divided into sections which follow the reservoir zonation. These are functions of fault rock permeability, fault zone width, the matrix permeability and the dimensions of grid blocks in the simulation model (Verlo and Hetland, 2008).

3. Visualization Techniques /Applications to Norne Full Field data

3.1 Data Inputs/ Co-ordinate systems

The inputting of data into the Petrel workflow forms a critical process, the integration of different data types from seismic Seg Y files, Horizon, fluid contacts, Well log Las and Ascii files, fault files, Eclipse models into the Petrel ware means that the user has to be aware of the nature of the data, the different processes or method of importation of the different data sets and the general knowledge of making file adjustments. The integration of the Norne field data with the importation into Petrel was done with identifying critical steps with unique methods of importation of the different data sets. Further consideration was given also in quality control and quality assessment of the data sets before and after importation into Petrel.

3.1.1 Seismic Importation

The Norne full field seismic SegY was imputed with preset header parameters which has defined inline and crossline ranges, the header file was checked against the inline and corresponding crossline range of the chosen seismic volume. Different seismic vintages and processed data was provided for different years as seen in Figure 6, which ranged from Near, Mid and Full stacked data. The most recent of the vintages from Norne4d-2004 to 2006 was chosen for corresponding visualization, interpretation and modeling, since they represent reprocessed data of earlier vintages of 2001 which offers better processed quality.

The cross line number 193 and inline number 189 were read off from the SEGY header from first file (Figure7), trace header field was the line detection method applied which gave a stricter frame to choose specific crossline to inline ranges, other line detection method available was the EBCDIC and /or binary header and the X; Y coordinate gap.

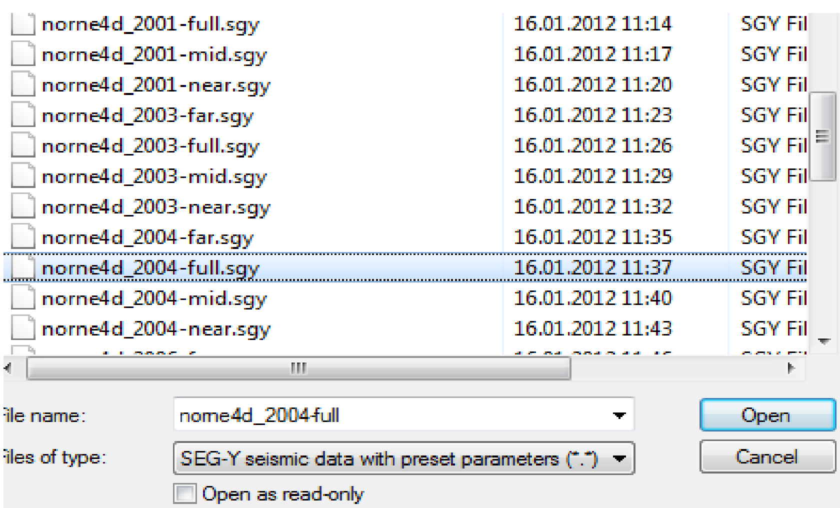


Figure 6: Seg Y Importation with preset parameters.

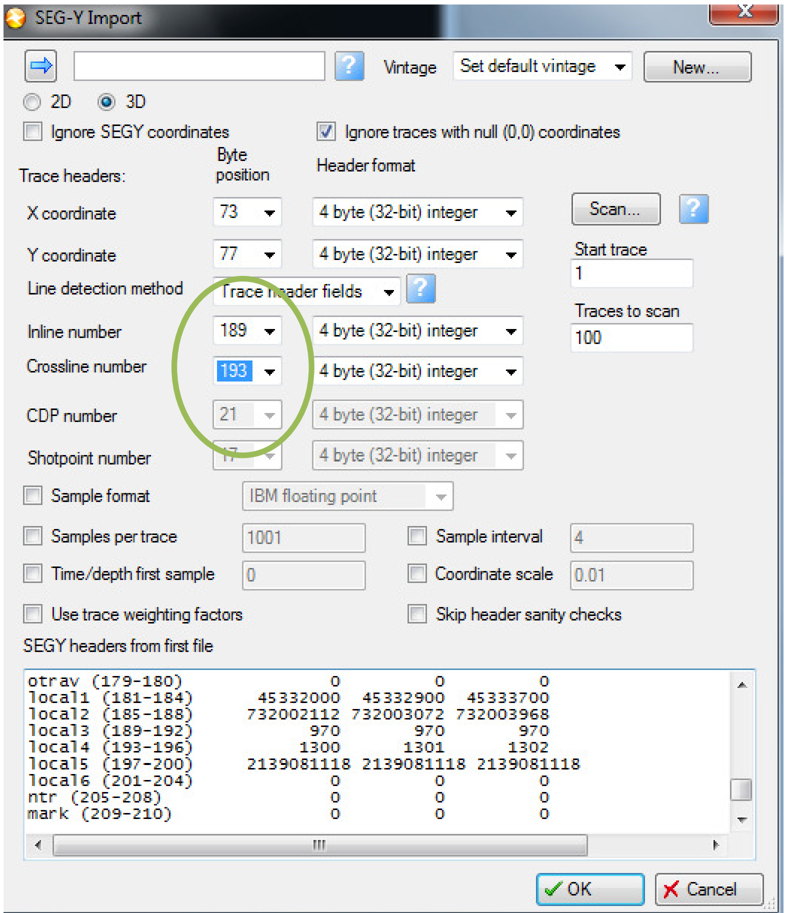


Figure 7: Trace Header file with inline and crossline number as seen in the green circled area

The next process was to reference the location of the seismic volume to the geographical co-ordinate coordinate system and define the imported seismic volume in space. In Petrel **the Universal Transverse Mercator** (**UTM**) coordinate system was applied which is a method using grid to specify locations on the surface of the Earth and a practical application of a 2-dimensional Cartesian coordinate system. The E segment seismic volume reference coordinate system of ED50-UTM32, in reference to Europe -between 6°E and 12°E - Denmark; Germany offshore; Italy; Netherlands offshore; Norway; Svalbard; was also applied to the full field volume sets and data (Figure 8).

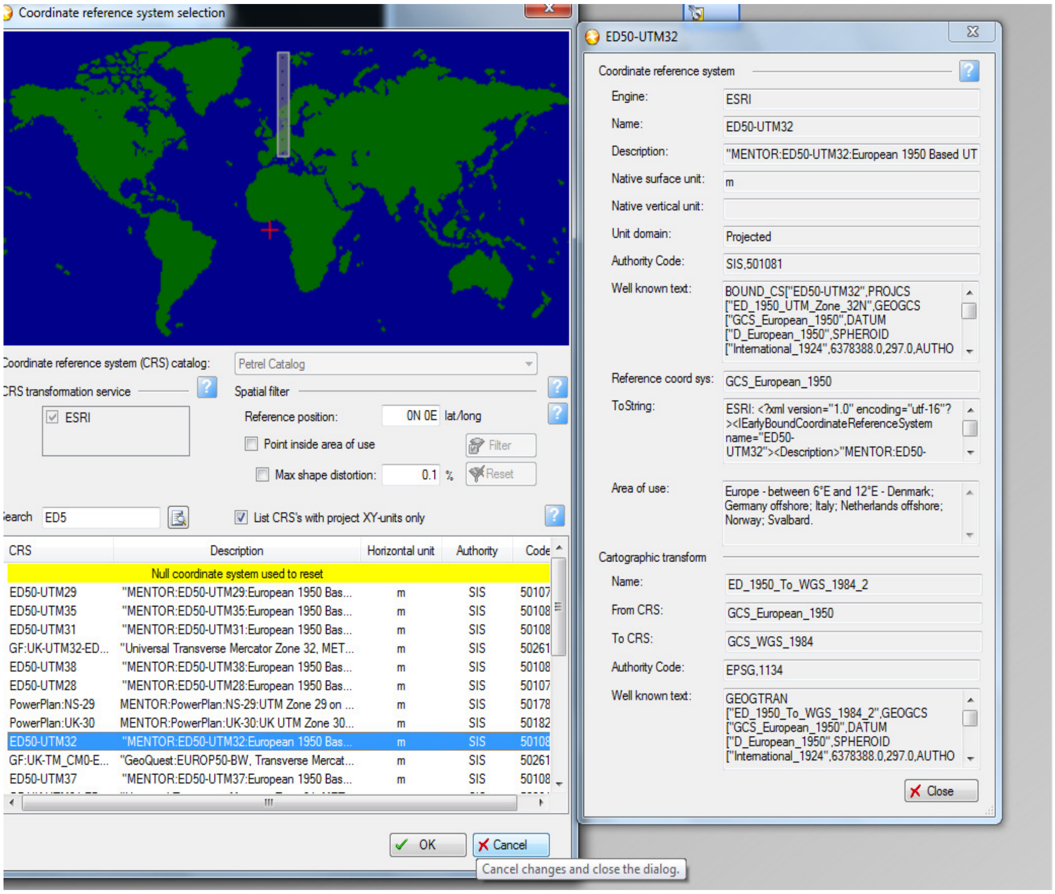


Figure 8: UTM coordinate system applied in referencing the seismic volumes or inputs.

3.2 Well Importation

The integration of well data with seismic interpretation and property modeling in this workflow means that the well importation process should appropriately be defined as allowed in the Petrel workflow. The well Logs LAS (*.las) was the file type in Petrel that was used in opening up the log files. The following wells (11) that were imported with Las files includes well 6608/10-E-2H,6608/10-E-3H,6608/10-F-1H, 6608/10-E-2H, 6608/10B-3H, 6608/10-B4H, 6608/10-C-3H, 6608/10-D-1H, 6608/10-D-3H and 6608/10-F-4H.(Figure 9)

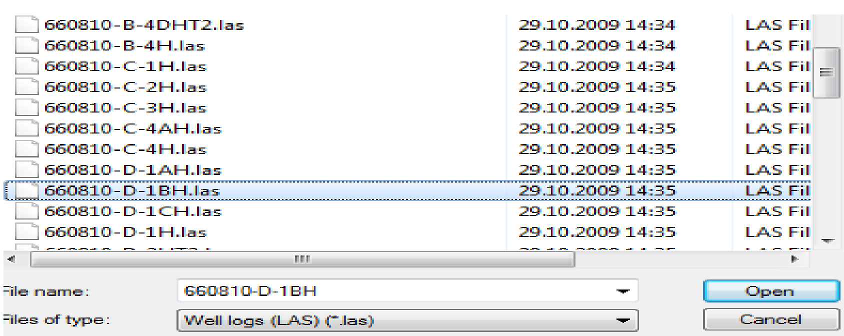


Figure 9: Well logs files been opened with well logs Las file.

The global well log template in Petrel allows the imported well to follow the universal log properties and Log profiles which mean that the log would have standard log scales, automatic log properties and all the log types. To have a firm grip of this process, the user has to define or uncheck the imported logs and determine what type of log to use is adequate to suite the purpose of the work. For example in this workflow, facies analysis with static model of the Field would mean that gamma ray log and/or the neutron density logs would be needed to characterize the type of reservoir as either shale, sand, etc.

The type of logs to use in making the interpretation has to be verified against their standard unit. The advantage of this process is that on the well log interpretation window the interpretation worksheet would not be too crowded with different logs in carrying out the interpretation of the wells and also for correlation purposes (Figure 10).

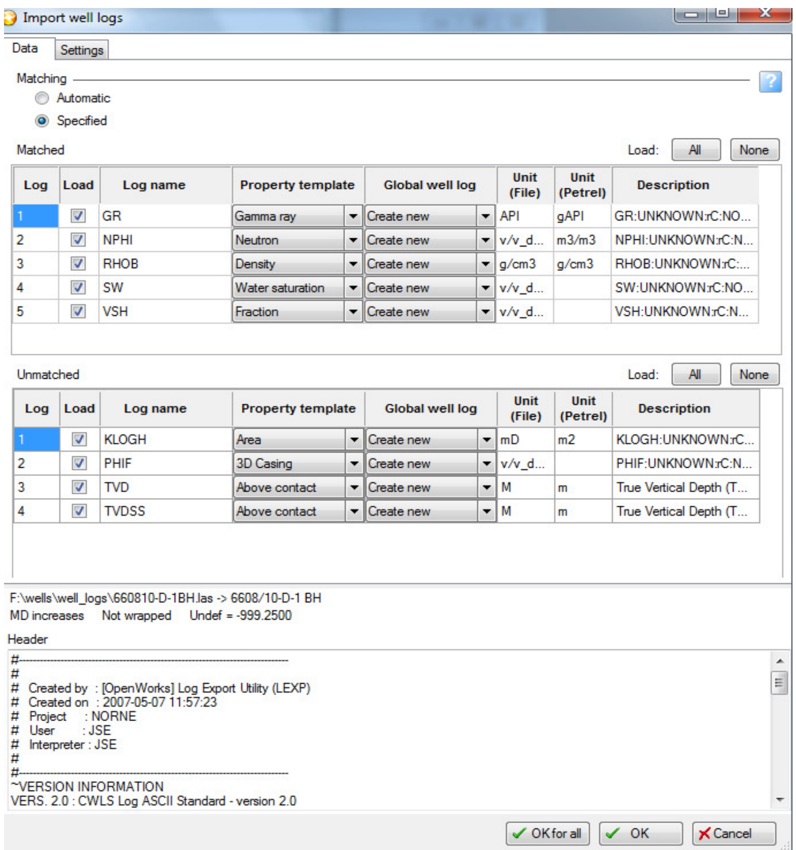


Figure 10: Imported well logs with specification on the required log types needed for interpretation.

The last importation process is to choose a reference coordinate in space where the well can be referenced. The well and seismic are inputted with same UTM coordinate of ED50-UTM32, the challenge with choosing the wrong co- ordinate would mean that the data would be out of position which would lead to spurious interpretation.

3.3 Fault Sticks importation

The importation of fault sticks which forms a critical part of the structural frame of the modeling is also a unique process. To carry out this process, the user has to read the data report and have a thorough understanding of what type of software/files the fault sticks were initially interpreted. In the Norne data report the sticks were generated with Seisworks interpretation frame, in Petrel the Norne generated fault stick folder (Kseim_r06_faults_depth) was opened using the file type Seisworks fault sticks (ASCII)(**) (Figure 11).

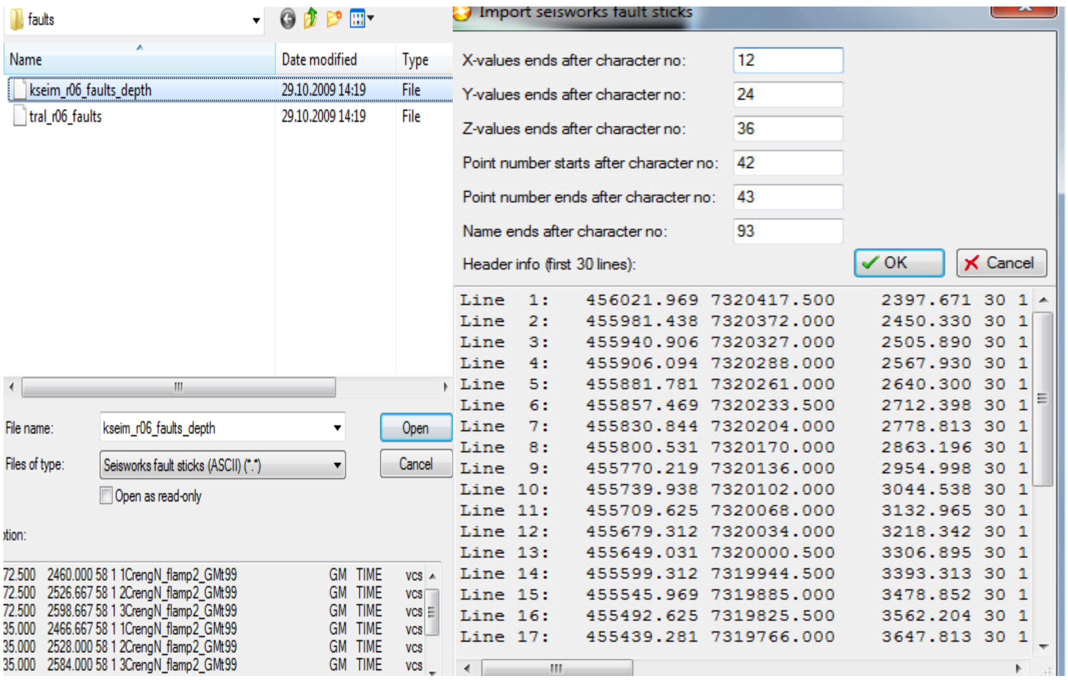


Figure 11: Fault importation folder with fault header information.

The fault file is read into the software with knowledge of the X, Y and Z values of the fault which is used to determine the spatial position of the fault within the seismic volume. The position of these sticks in 3dimension is necessary to determine the vintage seismic under which the sticks were created and at the same time it allows the user to quality check the interpretation of these imported fault sticks. The last process is to reference the fault sticks to the geographical position or UTM coordinate system, the seismic UTM coordinate of ED50-UTM32 was used in the referencing.

3.4 Horizon importation

Oil water contacts and two horizon tops of the Not Formation and Åre Formation were inputted into the Petrel workflow. The file type that was applied in Petrel in importing the tops was the General Line /Point Ascii. The second step is to determine the number of header lines to skip before reading in the actual points and also it is important to have an apriori clue of the X, Y and Z column references. To solve this challenge reading the data help guide or attachment which clarifies different columns information as to measured depth, TVD depths, TD, X, Y, and Z values (Figure12).

A critical challenge that is encountered in this process is when the files have to be adjusted in terms of column references before importation into Petrel, since some of the files are not in sync with the Petrel template. The easy way is to open the file in Text-pad document which preserves the actual dimension of the document in comparison to Notepad, which is copied into an Excel spread sheet. The columns and rolls are managed in Excel and correspondingly adjusted to fit the Petrel setup frame (Figure 13).

The last process is also to reference the horizon or fluid contacts data to the seismic UTM coordinates.

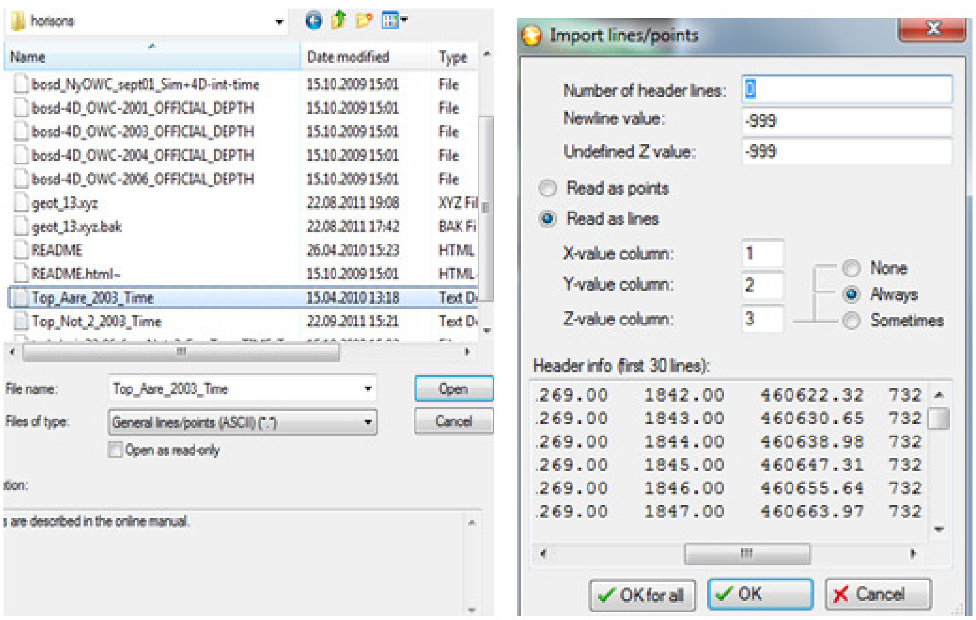


Figure 12: Imported horizon folders with the General line Ascii with header information.

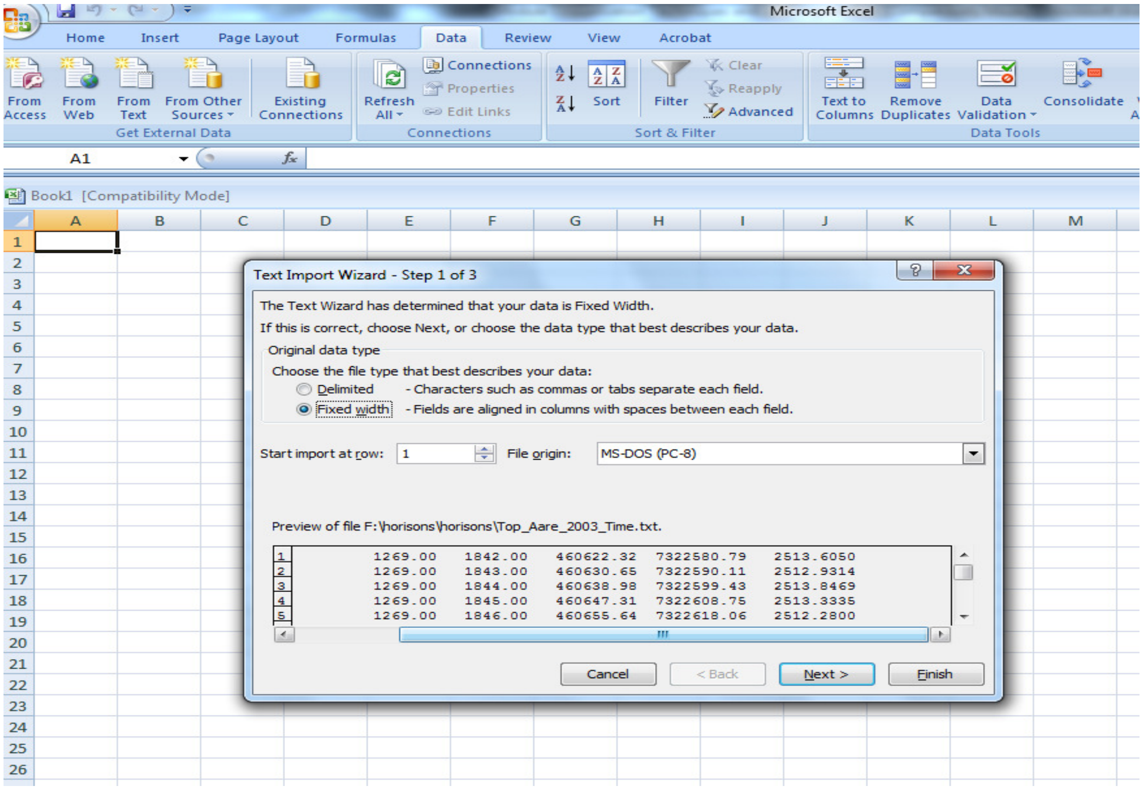


Figure 13: Excel spread sheet with imported Top of Åre Formation with Text pad documents for column readjustment.

3.5 Eclipse well data Importation

The end use of geologic static models is mainly to carry out dynamic simulation of the models, up scaling layer properties to field dimension. To import Eclipse models of the Norne field, the Model pane is first opened as compared to other data types where the input pane is first activated in the petrel workflow tree. The file type known as the Eclipse/Front Sim data and results (*,*) was used in opening the Norne Grid file (Figure 14).

The simulation files of both the static folder and dynamic folder are imbedded in the RESULT frame in Petrel, the Grid dimensions are localized or rather found in the model pane of the Petrel workflow. These different setups are activated for the different purposes for which the files are needed.

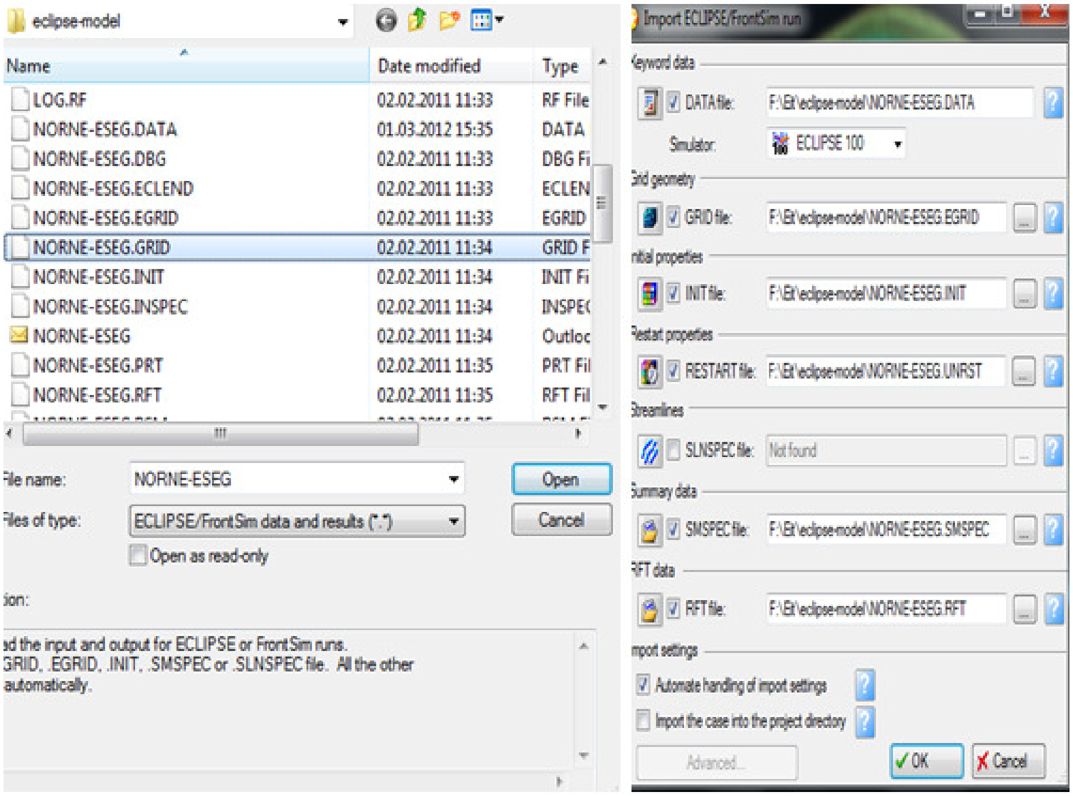


Figure 14: Importation of Eclipse model into Petrel

3.6 Seismic Visualization Techniques

3.6.1 Volume Visualization/Volume wall display

The process of volume visualization shows how the whole volume is viewed in 3D space in relation to local features or structures, other imported data and attributes displays. Previous work on the E segment of the Norne highlighted 3 volume techniques of Normal wall displays, transparent and inside display. With the importation of full field vintage seismic, the structural dimension of geologic features has increased as compared to just the E-segment. Also, other imported data sets have to be critically framed into the whole new process of the volume visualization and overall seismic interpretation.

The first application of these techniques was a **combination** display where the full field seismic volume was displayed transparently while the Norne E segment volume had a normal volume wall. This was done to give a reference dimension of the E-segment to the overall full field seismic (Figure 15).

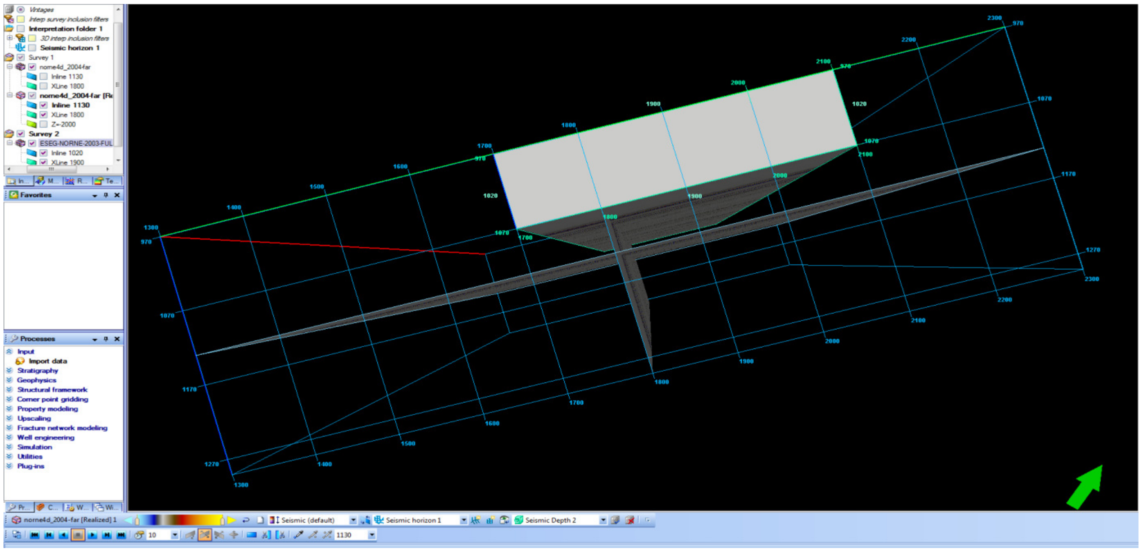


Figure 15: Full field seismic display of the Norne with embedded Normal wall display of the Norne E-segment volume.

The application of the Inside/transparency wall display means you could see the internal relationship of features in the seismic to other imported data such as well , imported fault sticks, eclipse models etc.One critical application of this technique in the Norne data was to unravel fault geometries , depths and interpretation with Time slice display.The time slices were chosen at specific depths with distinct fault planes, making a timeslice movie display where the slices are taken at different time depths as a movie display to provide a dynamic interpretation of the fault planes.(Figure 16)

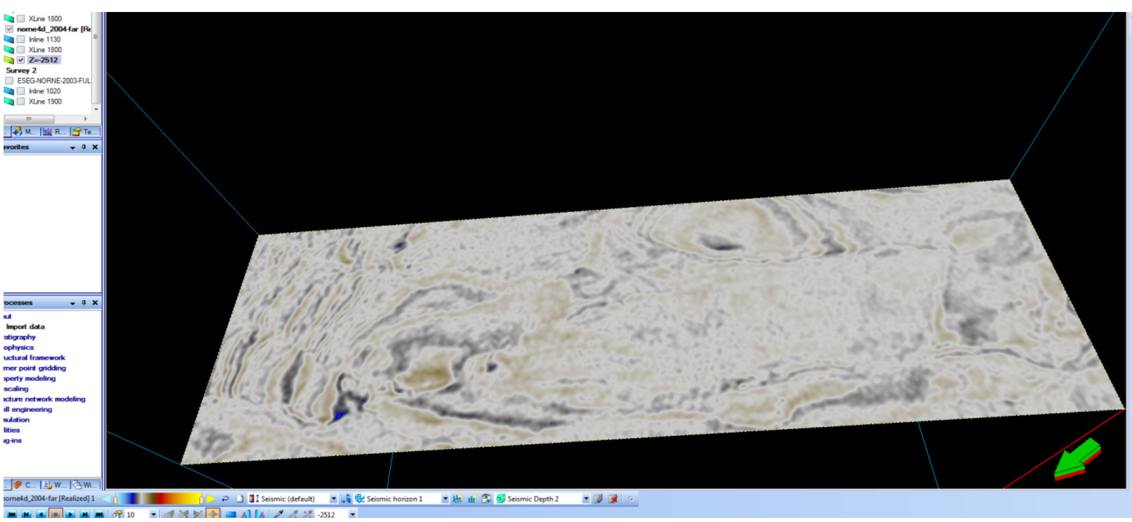


Figure 16: Time slice section which are dynamically moved as movies for fault interpretation

The inside /transparent display also made it possible to view the seismic volumes with the internal well geometries and spatial position of the wells, this gave information of the well target depths indicating which wells are shallower or deeper when compare to the reservoir depths/level to determine the suitability of the wells for correlation purposes.The inside wall display of the well to the seismic clearly shows the spatial coordination of the well in relation to the specific target zone and it also provides better understanding of the fault sticks interpretation since you have the opportunity to see the seismic features relation to the imported fault sticks (Figure 17 and 18).

Furthermore , this application can also be applied for sub volumes or cropped sections of the vintage survey where specific depths of interest especially within the reservoir section are illuminated for quicker visualization and also interpretation.This display offers the chance to see the volume internal property relationship also with dynamic data files of the eclipse model, where you could visualize fluid simulation to the seismic volumes itself (Figure 19).

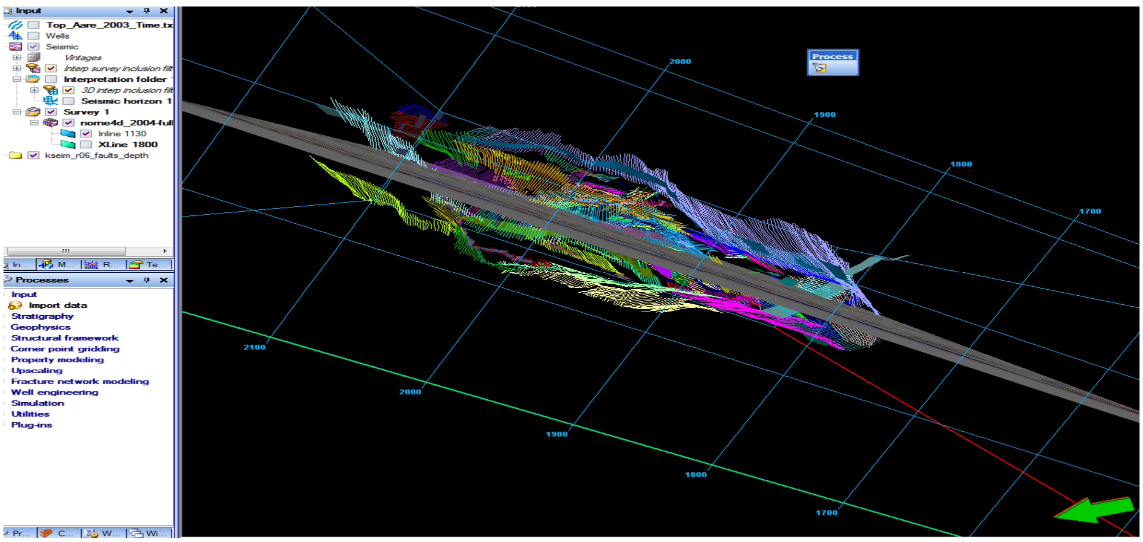


Figure 17: Fault stick display with transparent section of the Norne full field.

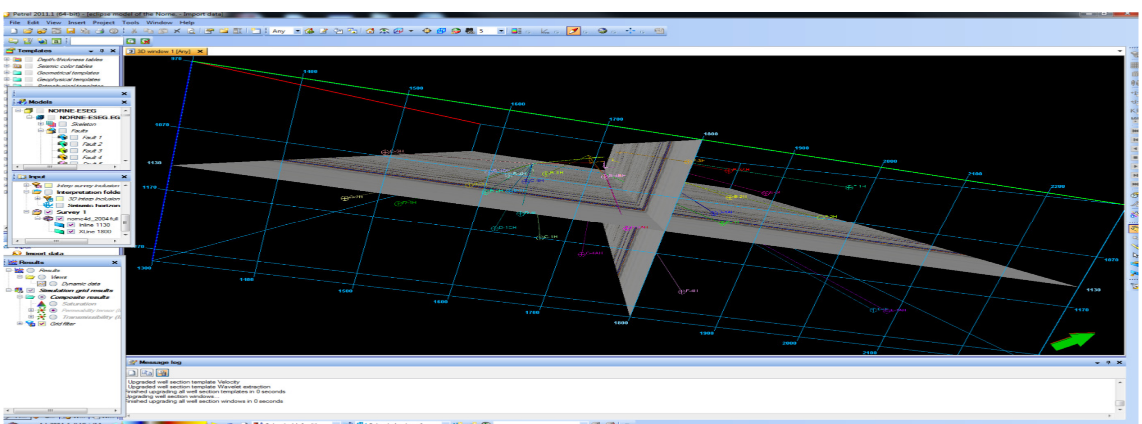


Figure 18: Transparent inside wall display of seismic sections with well path visualized.

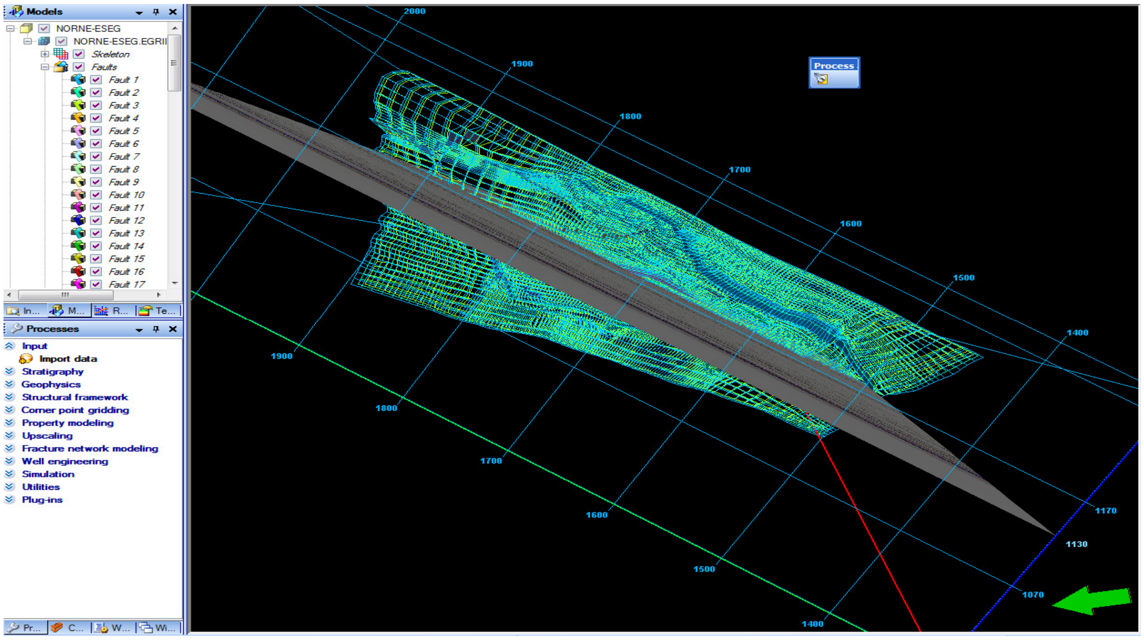


Figure 19: Transparent seismic section with Model.

The application of the **Normal display**, which provides solid 3D cube view of the seismic volume, provides little internal attribute function of the volume but it shows on the outward frame the general trend of features in a 3D view. In the full field vintage application it gives a snapshot of interesting features , for examples you could easily see overburden fault structures, large fault planes in the reservoir section, the horst and graben structures , Base Cretaceous Unconformity (BCU), etc (Figure20/21).

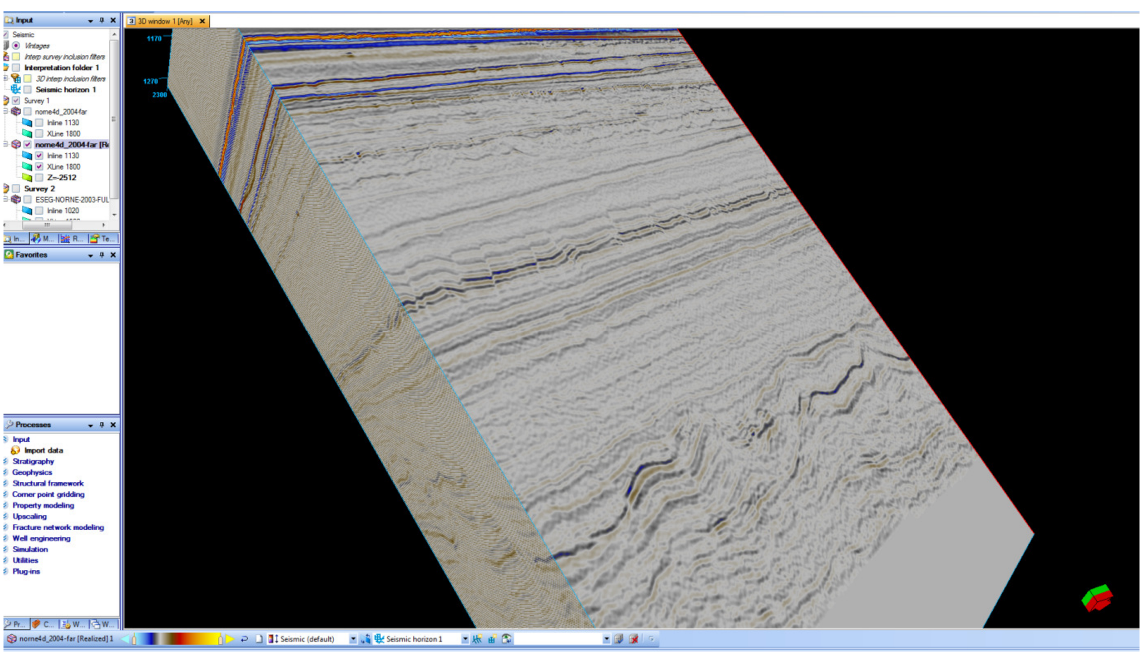


Figure 20: Normal display of the Norne with 3D field wide structures observed

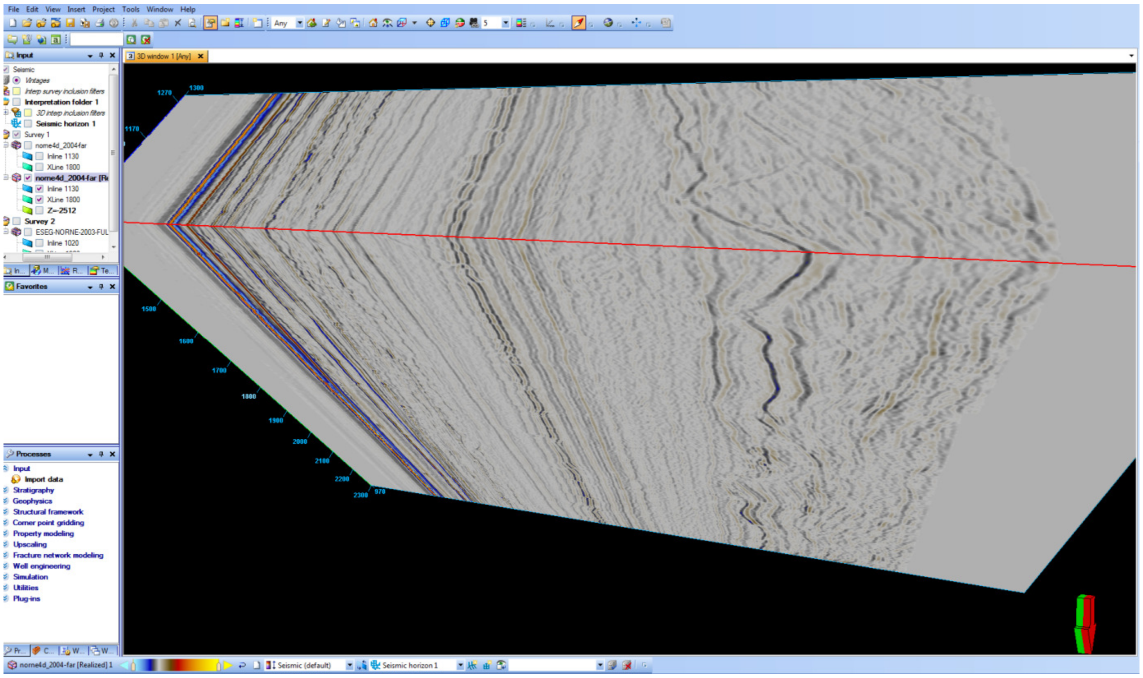


Figure 21: Rotated Normal display of the Norne back view

3.6.2 Colour and Opacity Filters

The application of colour scales in visualizing seismic property ranging from amplitude spectrums, frequency distribution, with different attribute displays and property descriptions requires the manipulation or toggling of the colour scales to capture different property contrast. The minimum and maximum amplitudes are easily displayed for seismic interpretation and continuity of reflectors with appropriate color scales. This property was also applied to discriminate different Interpreted seismic horizons. In visualizing the Norne full field volume , the Petrel software allows flexibility in deciding the colour range to visualize within chosen specific volume of interest, cropped sections and realized volumes; this application was further applied in the other property modeling where properties within the models were define with specific colour scales (Figure 22).

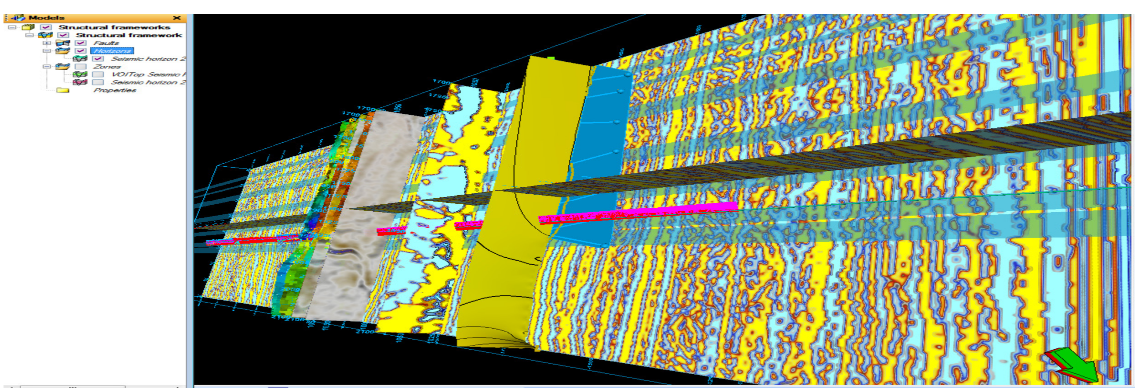


Figure 22: Colour display of realized section

The Opacity filters were used to visualize specific lines in the seismic which were unclear or rather difficult to interpret in the full volume. The BCU surface in some of the lines were rather difficult to capture but with the application of this technique made it easier to screen out the position of that surface. Also different attribute functions and display were done with opacity contrast, it captures to what extent you the seismic attribute function could have singled out or aid in interpreting a geologic property of interest.

3.6.3 Cropping

The application of cropped volumes which is simply the process of isolating a section of the entire seismic volumes for specific purposes, which could be cropped seismic interpretation sections, visualization of specific target zones, anttrack analysis of subcrop volumes, realization of sections for appropriate opacity filter and colour scaling .etc. The process of using a cropped section is that it allows the extra advantage of speed in carrying out interpretation and also helps or serve as a 'guinea pig' where you could tweak properties of the subvolume and see the effect before making general applications to the entire volume.

In the Norne full field , subcrop sections where taken in the target zones of the reservoir at specific depths interval of (-2400 to -3400) with inline range of (1000 to 2300) and crossline range of (1300 to 2300)(Figure 23).This were typically applied in carrying out further visualization and ant track process of fault extraction. The use of the cropped sections also makes the process of realization and rendering much easier and quicker, with little CPU processing time of each subvolume.

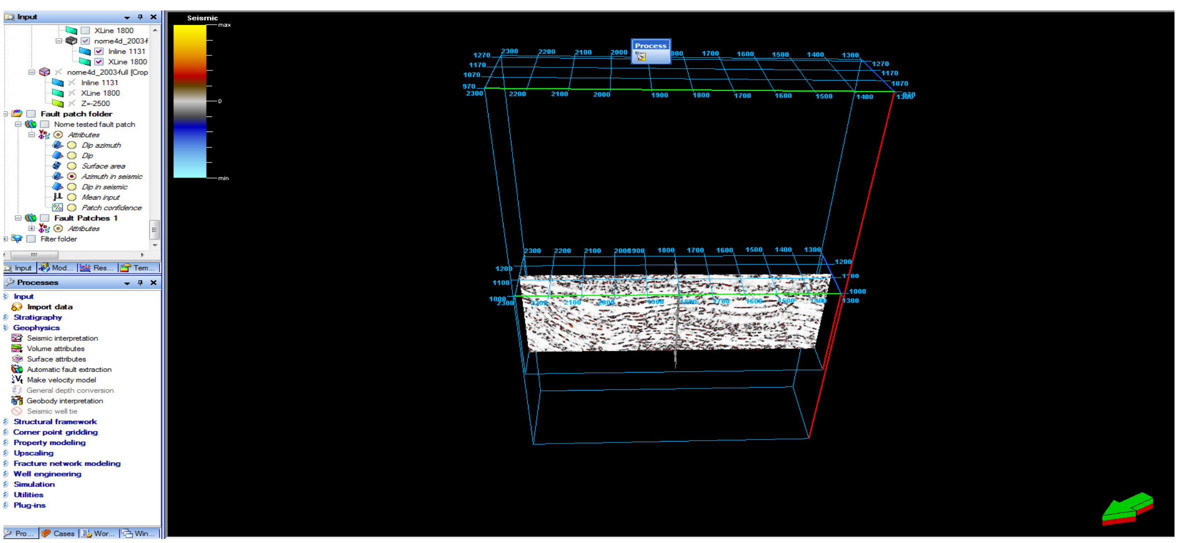


Figure 23: Cropped reservoir section realized for anttrack process and visualization.

3.7 Volume Realization

This technique was adopted in the visualization of the entire E- segment of the Norne, and was adopted in the visualization of full field seismic vintage. It involves the creation of exact physical copies of the original vintage seismic which forms the basis under which other techniques were done or interpreted to make final comparison to the original volume.

This process of realization has different impact in creating seismic attribute volumes form structural to stratigraphic attributes of the pristine seismic volume .It also enables the capacity to make Ant track volumes of the Norne volumes which were compared to the vintage in terms of structural analysis of the fault. The realization of time slice displays with each time slice been compared to the vintage, with typical differences in colour and opacity as key elements use to observe property changes (Figure 24).

In the Norne field the Full stacked 3D data of 2004 using the effect of Opacity filters on the realized whole volume, you can easily view the continuity of reflectors (Figure 25).The key difference in this application is that the difference in the virtual volume from the background vintage seismic is a function of inherent features in the seismic and the imposed realization technique. This concept was extended to specific interesting Zones of interest (ZOI) of particular inlines and crosslines where different attribute volumes were realised. The flexibility in creating copies using timeslices proves very effective in detecting structures like faults; in the Norne seismic volume this slices were made in the reservoir section to determine the extent of fault planes across the reservoir sections.

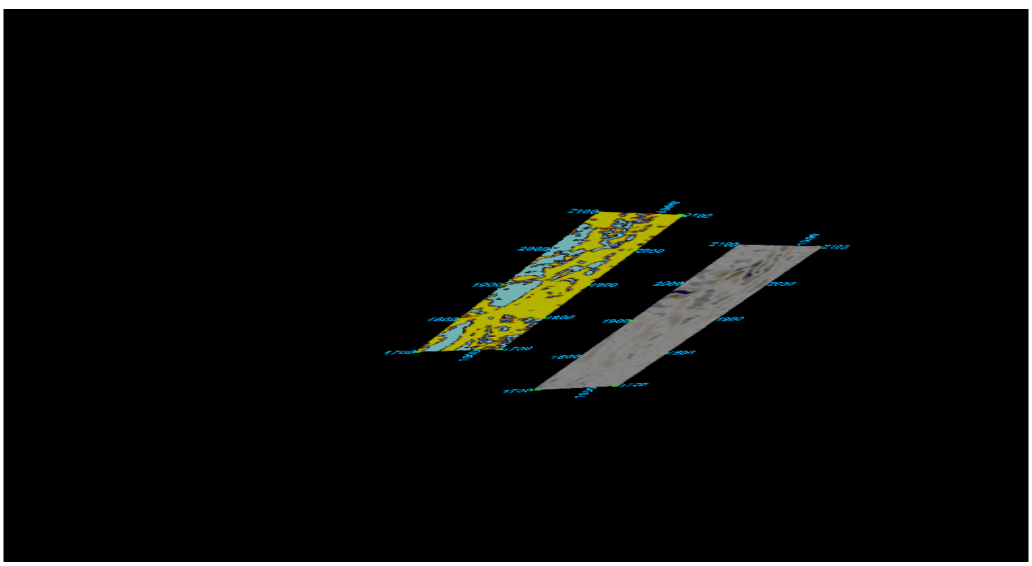


Figure 24: Realized Time slice.

The advantage of this technique apart from the ability to reveal and interpret features, it makes it easier to render volumes and enhance other interpretation techniques to be performed in the Volume. The reservoir sections and key horizons which formed the basis of interpretation and models; were screened out as (ZOI), where each modeling process and iteration where compared using the realized volume

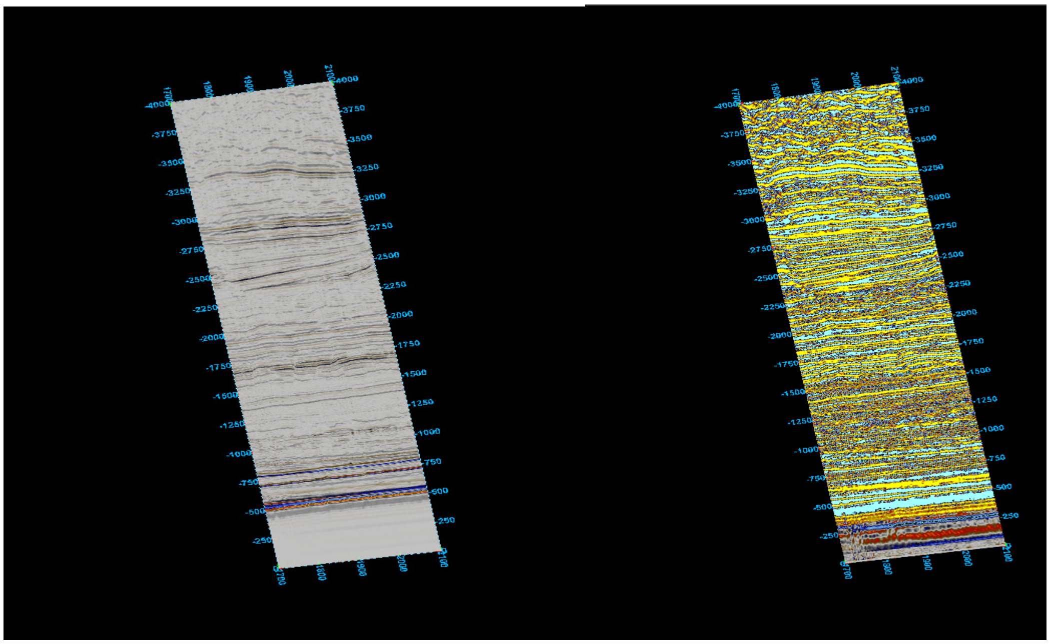


Figure 25: Continuity of reflectors with observed opacity and colour changes

3.8 Volume Rendering

The use of volume rendering is simply the 3D visualization in space of the sum total of all visualization techniques. This was done by extracting the full field seismic volume of the Norne, with the display of sub volumes or cropped sections, wells, fault sticks , horizons, geo models etc with chosen color scales, different volume walls and opacity filters. The gains of rendering the Norne sections are that it provides at a glance the relation of interpreted seismic horizon to the seismic volume in the display window, and also it tells of the models in relation to wells/faults .It provides a holistic view simultaneously of all the data and of their relationship to interpreted geologic structures. One key difference between display function and rendering is that rendering provides a dynamic property change in relative position of features in 3d view.

This process of rendering is a back and forth process, which tells of how much progress of the seismic interpretation in the 3D volume display. It also provides a reconnaissance of the interesting geologic elements or structures for complete interpretation. The reservoir section in the Norne were isolated with the inputted tops of the Åre and Not formations and fluid contacts been rendered to provide adequate guides for seismic interpretation of the other horizons / reflectors of interest. Furthermore, it found other applications in the modeled fault patches on how they are displayed with the geologic static model (Figure 26). This creates an allowance for making adequate corrections and provides quality assurance of interpretations of faults.

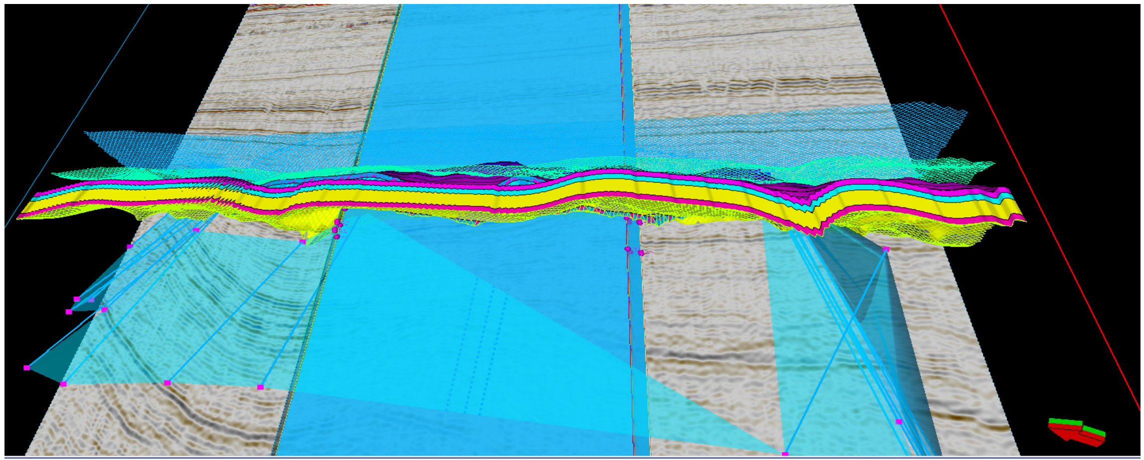


Figure 26: Rendered static models with triangulated fault surfaces

3.8.1 Key results from whole Volume Visualization/ Rendering

The contributions of the whole volume visualizations to creating static models of the Norne field; it provides a clear spatial overview of the total data in a single frame from the seismic, wells, fault sticks, horizons etc. This process tells of the spatial position of the wells relative to the specific target depths or segments, which mainly is the reservoir section of the field. From the inputted Norne well data you could clearly differentiate deeper and shallower wells in each segments of the seismic volume and also observe how deviated the wells are. Deeper wells E-4H, E4AH, F1H, D4H, E1H,E3AH,E2H,B2H, B4H,B1H etc were identified and shallower wells like C2H,D1H,D4H,C4H etc were screened out as not suitable for correlation purposes and much vertical wells was rather preferred in the processing of modeling and petro physical interpretations (Figure 27).

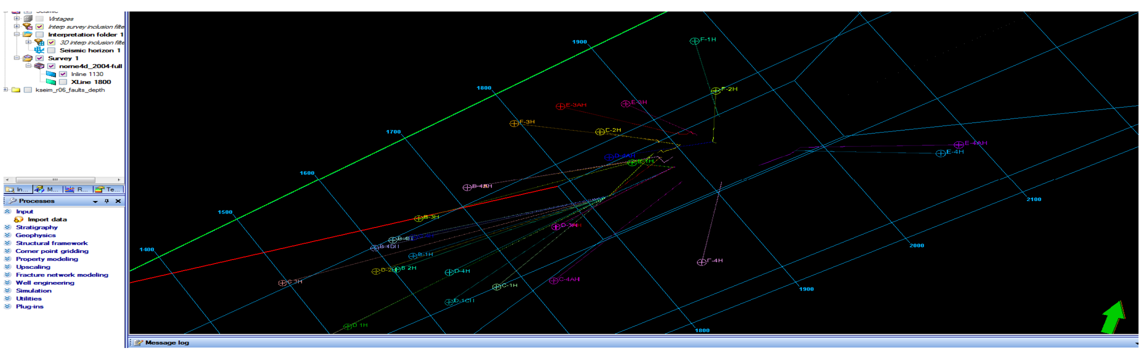


Figure 27: Well path and deviation observed from visualization with seismic volume.

Furthermore, it helped to manage interpretation of fault structures with inputted fault sticks, you could visualize through the seismic volume of the fault geometries/trends, and make personal interpretation more accurate in interpreting the seismic volume. It also provides a glance of specific zones where you could isolate or crop out for specific seismic interpretation and also for structural analysis like anttrack process, attribute analysis etc.

Also, it provides an overview of geologic structures in 3D view with different displays, in the Norne field you could decipher overburden polygonal fault structures to large scale planar fault in the reservoir sections, capturing horizons and strong reflectors, horst and graben features etc. This provides a concrete interpretation mindset that is unlimited to the seismic interpretation window.

Again the display of timeslices as movies with the concept of inside transparent display in interpreting fault structures is a major plus in the visualization, which extends a dynamic interpretation of structures as against a static picture of timeslice interpretation you get from class room work. The time slice movie display moves across inlines / crosslines to specific target depths.

4. Volume Attributes/Seismic Attributes

The concept of attribute is to provide a dynamic or static quantitative characteristic of a seismic volume to characterize subsurface reservoirs or zones of the seismic volume of interest. Critical parameter for attribute analysis could be structure related (Horizon depth, reservoir thickness, faults etc), petrophysical properties, internal architecture (measure of heterogeneity) and hydrocarbon properties (Cosentino, 2001).

The application of an attribute function to the seismic volume provides the basis of creating a volume attribute. The sensitivity of the attribute to observe geologic features and horizon reflectors with sharper fault planes is the intended goal of applying attribute function to the Norne seismic volume. The intention of its application is to see how much it could help to illuminate the seismic sections for proper geologic interpretations and model building.

4.1 Brief Introduction/ Science of Seismic Attributes

Liner et al (2004) divided attributes into geometric, kinematic, dynamic or statistical features derived from seismic data. They include reflector amplitude, reflector time and azimuth, complex amplitude and frequencies, generalized Hilbert attributes, spectral decomposition etc. The Hilbert transform formed the base to making complex trace analysis/attributes, with a seismic amplitude trace been as the real part of a complex analytical signal with imaginary components of the signal used in computed corresponding Hilbert transform (Figure 28).

The Envelope is taken as the square root of the sum of the squares of the imaginary and real components of the seismic trace .This further leads to classifying the attribute into envelope with the instantaneous envelope which is sensitive to reflection strength/ acoustic impedance contrast which is sensitive to lithology. The second is the phase attribute which is sensitive to tracking reflector continuity, detecting unconformities; fault analysis. The last is the Instantaneous frequency which is applied to discriminating attenuation and thin beds.

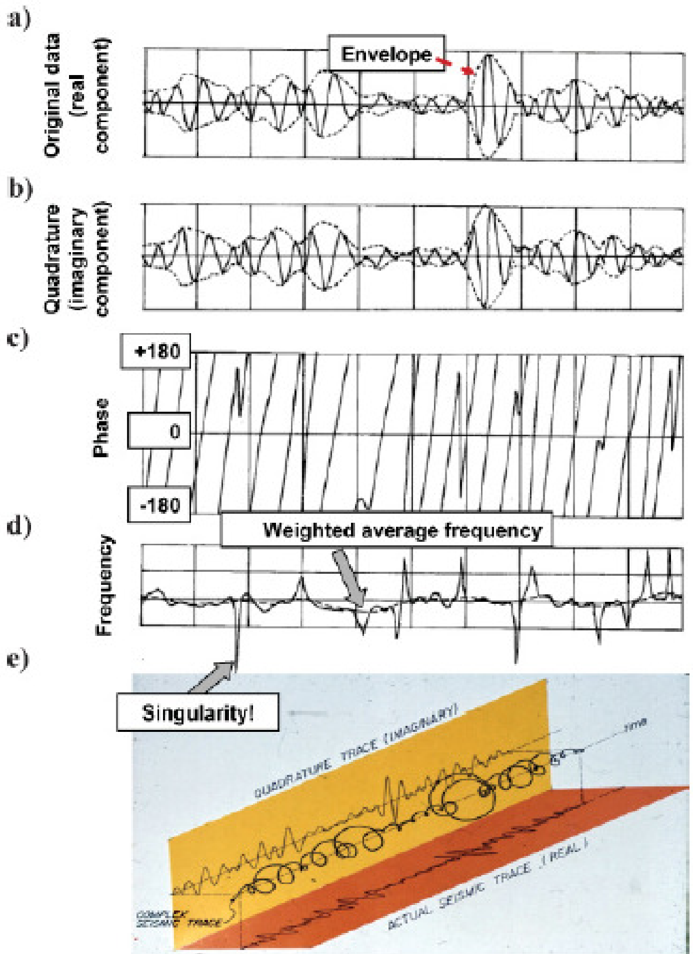


Figure 28: Imaginary and real seismic traces as a computation for complex attribute diagram after Taner et al (1979).

Furthermore attributes were classified by Taner et al. (1994) as they were divided into geometrical and physical. The geometric attributes are made to enhance the visibility of geometric features of seismic volumes in respect to reflector continuity, dip, and azimuth. Physical attribute deals with physical parameters which relates to lithologies such as frequency, phase and amplitude. For the purpose of this work it is important to mention Horizon/interval based attributes (Dalley et al., 1989; Sonneland et al., 1989) which were introduced based on the fact that interpreted seismic horizons exhibited poor reflection strengths making interpretation difficult to achieve with poor lateral continuity of reflectors.This was purely the case observed in the Norne field where it was challenging to follow the continuity of the BCU surface, fault terminations and other interpreted horizons.

Vail et al. (1977), with Taner and Sheriff (1977) had linked seismic stratigraphy as a measure of depositional process to seismic attributes. There are several schemes or classifications given by different authors on attributes, the application of these functions as a tool to provide better illumination of geologic structures as an aid to seismic interpretation is the germane of this application to Norne seismic data, which according to Dalley et al. (1989) could help deliver horizon interpretations and capture interval properties.

4.2 Petrel Attribute Application to Norne field

The primary goal of using seismic attribute to the Norne field is to spot geologic and stratigraphic features as an aid to performing good seismic interpretation of the whole volume. Six attribute categories forms the total attribute volume in Petrel, which includes Signal Processing, Complex attribute, Structural Methods, Stratigraphic Methods, Basic attributes, Amplitude versus offset (AVO) and depth conversion (Figure 29).The long list of attributes combining all the categories means that its application has to be managed to produce the desired effect so as not to disabuse their application.

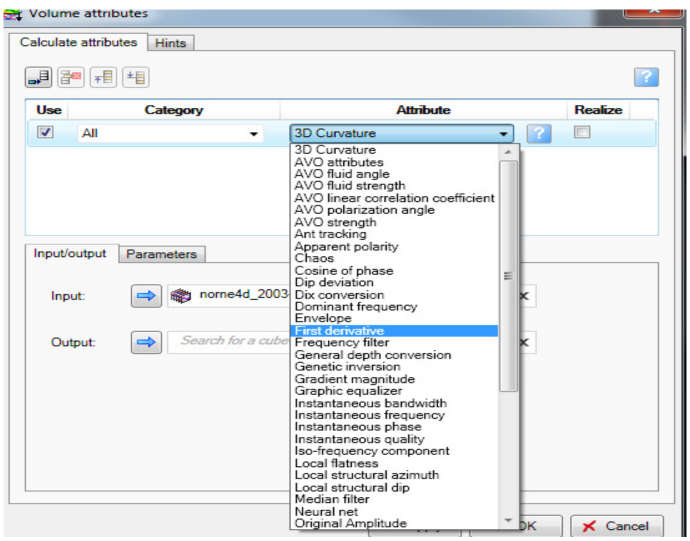


Figure 29: Different attribute with specific class and categories.

In the Norne field data (4D 3D near stack) with reference inline 1130; different attributes functions were applied. The process of applying this techniques starts by first creating physical copies or realizing the seismic reference line; this provides the opportunity to compare and contrast the impact of the attribute application to the seismic line. Also, creating a virtual copy of the seismic line from the realized copy means you could run several types of attributes on the virtual copy and erase their impact if does not provide the relevant results. After realizing the seismic lines of interest simply chose the icon **VOLUME ATTRIBUTES** which takes the user to the attribute categories and function template. (Figure30)

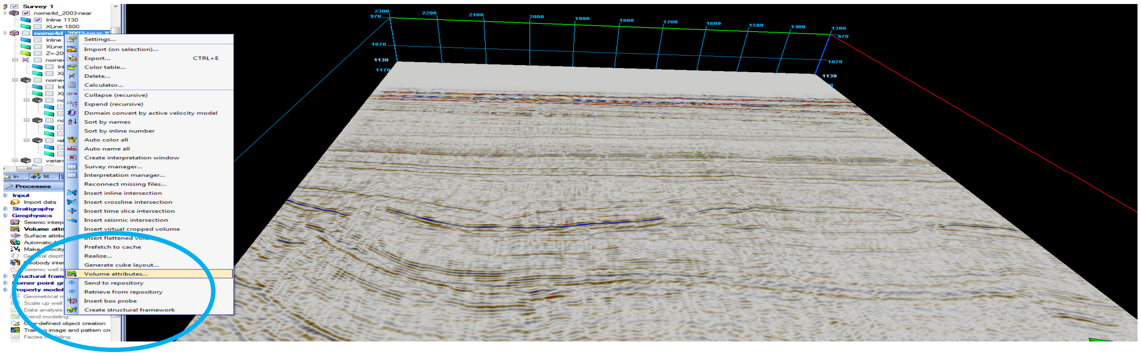
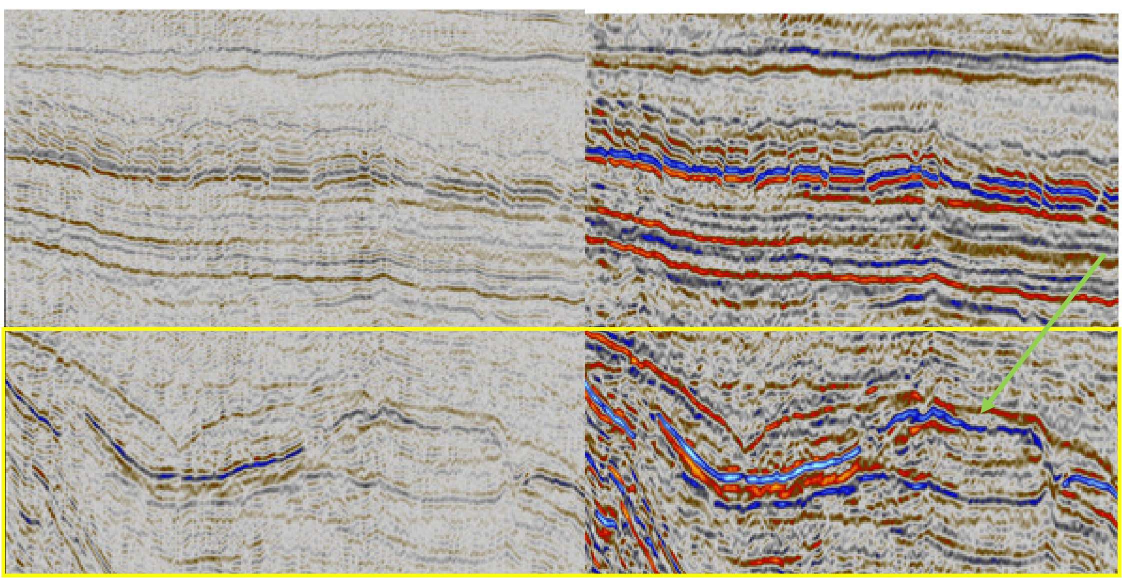


Figure 30: Seismic line 1130 used as reference inline for the attribute with volume attribute tab circled

4.2.1 Applied Attributes - Structural Smoothing

This attribute was applied in the smoothing of local features or which improves the lateral continuity of seismic horizons by smoothing the input signal (Randen, 2002).It works by isolating local structures with principal component dip and azimuth computations before running a Gaussian smoothing function. Apart from the fact that it delivers better horizon interpretation and continuity, it helps to isolate flat events like flat spot if it is properly guided with appropriate Dip guiding.



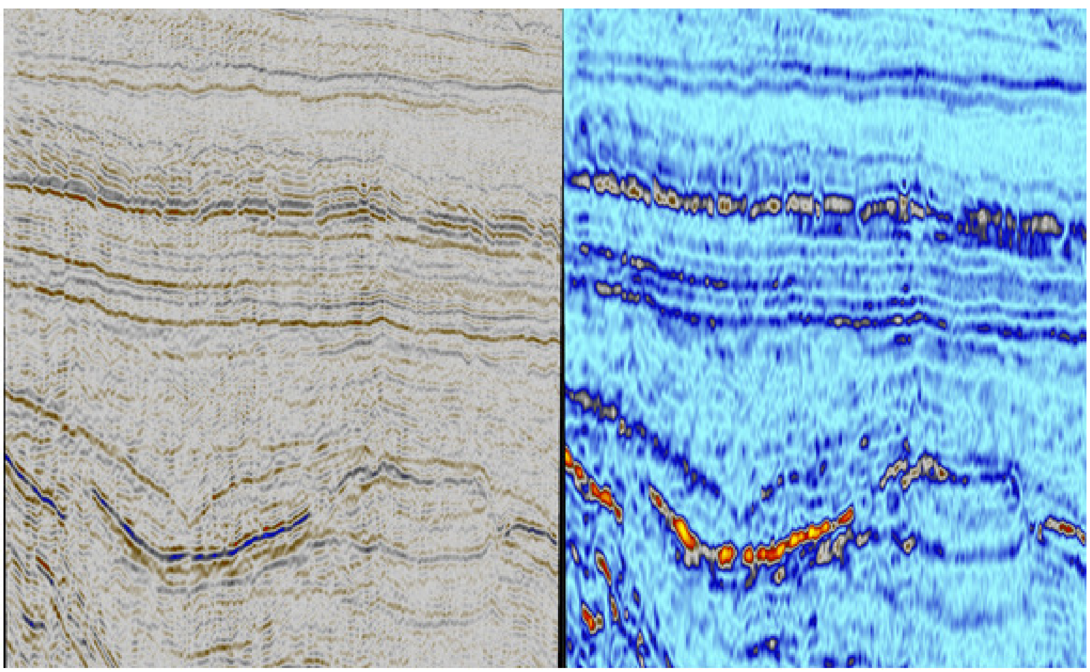
(a) (b)

Figure 31: Plate (a) unsmoothed realized copy; plate (b) smoothened version with horst structures well defined, fault surface clearly defined within the reservoir section, Base Cretaceous Unconformity clearly seen with green arrow and the overburden planar faults sets well defined in the yellow boxed area.

The impact of this attribute which is a classic example of geometric/horizon based attribute function cannot be denied, it has deliver a much robust overview of reflectors, especially the base cretaceous unconformity, fault surfaces within the reservoir section and also in the overburden section (Figure 31) .It also shows horst and graben like features within parts of the reservoir sections. The advantage of this attribute is that it could be snapped into the main interpretation window which could aid in delivering a much better interpretation of these features in terms of horizons and faults. It also serves as a stepping process in the creation of ant track volumes and other attribute functions.

4.2.2 Sweetness Attribute

This attribute combines the instantaneous frequency and envelop which are example of complex attributes. Mathematically, it is defined as Envelope/SQRT (instantaneous frequency).Its application is in the identification of features within areas of stronger energy changes in the seismic volume. This was applied to the Norne data in understanding major energy reflectors with a given package (Figure 32). Areas of same package with almost same reflection strength are characterized by light green colour shades, while areas of main energy reflections have much darker green patches It shows packages within the reservoir sections. Its application has been recorded to identify channel structures and other geologic events.

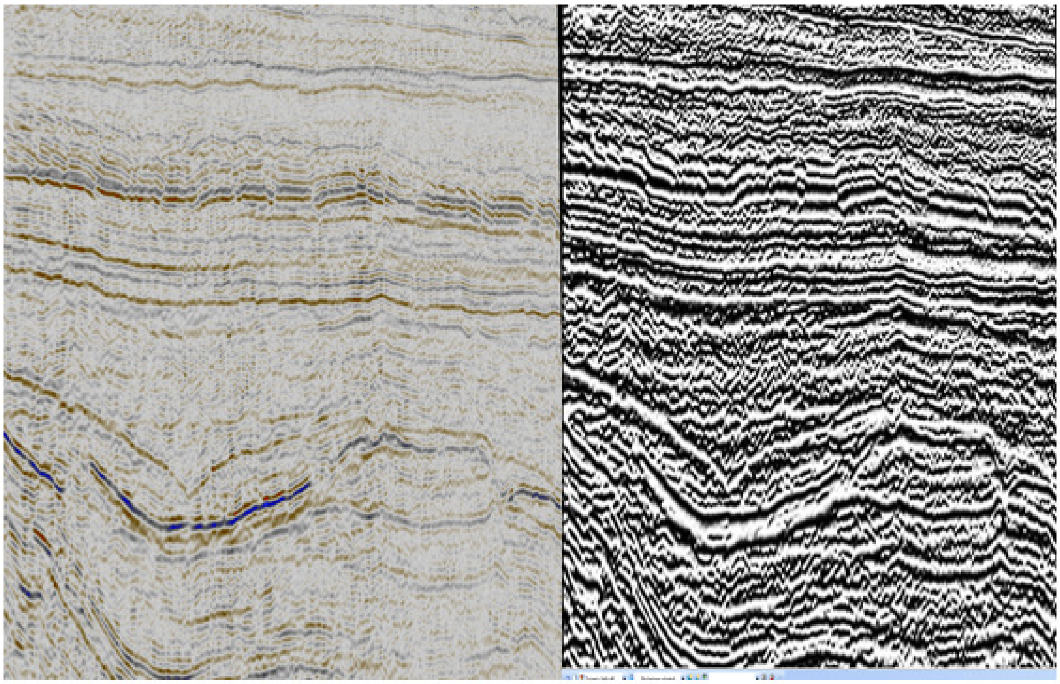


(a) (b)

Figure 32: Sweetness attribute used to understand major energy changes within the volume. Plate (a) the normal seismic section without attribute function; plate (b) the seismic section with applied sweet attribute

4.2.3 Cosine of Phase Attribute

This attribute finds its application in delineating structural events or to enhance their interpretations. It is also called Normalized Amplitude because it helps to guide interpretations in areas of poorly defined amplitudes. In applying it to the Norne volume (Figure 33) you could resolve the fault structures and capture the continuity of horizons for better interpretation. Interpreting the BCU surface was much easier since reflection terminations can easily be identified.



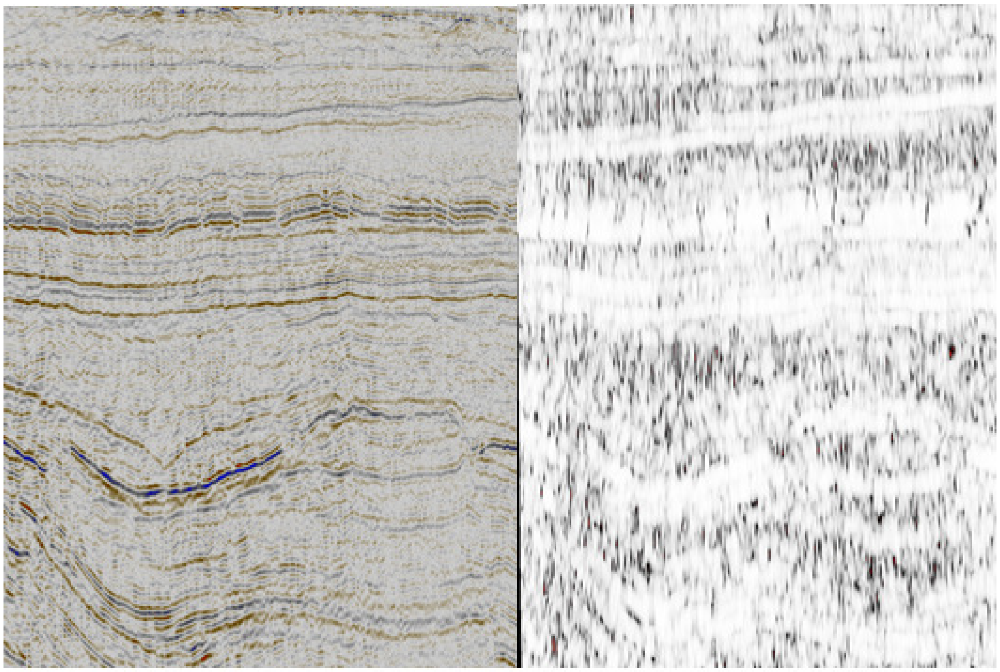
(a) (b)

Figure 33: Cosine of phase amplitude as applied in the Norne field .plate (a) the normal seismic volume without attribute (b) the cosine of phase attribute section illuminating structural features such as faults and horizon interpretation.

4.2.4 Variance/ Chaos Attribute

The chaos attribute tends to measure the lack of organization in dips and azimuth estimations; it helps to understand the level of chaotic texture you could attribute to seismic volume. It is practically used as main input volume in carrying out ant track process as was adopted in the Norne field with automatic fault extraction.

The variance which produces almost same function with the chaos attribute is used basically to estimate local variance in signals. Both attributes can be used in delineating edges or discontinuities in horizontal continuity of reflectors which forms a basis to detect faults for automatic extraction. It is acclaimed to isolate local geologic or depositional events or structures like reef, salt body intrusions gas migrations channel infill etc. (Figure 34).

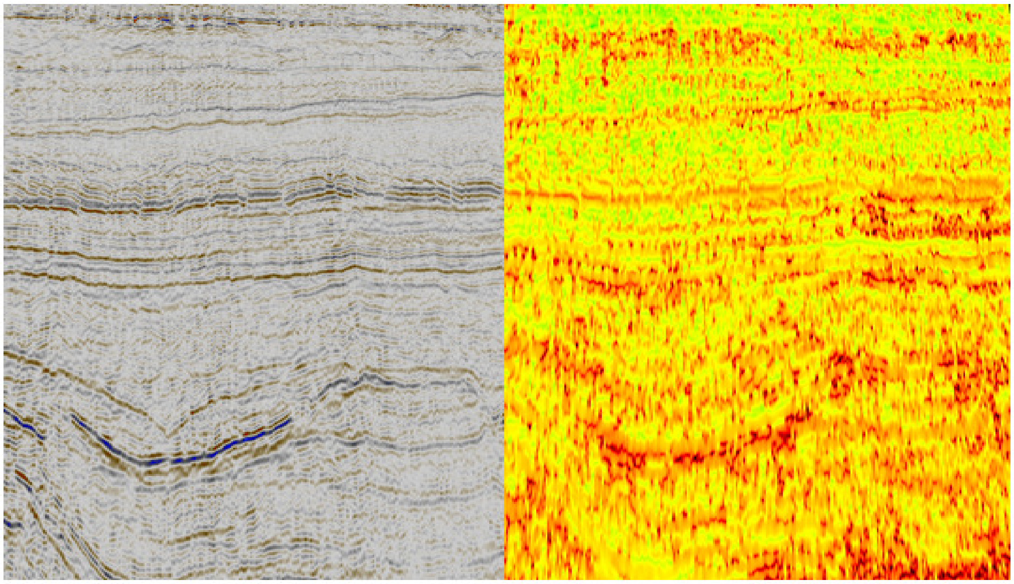


(a) (b)

Figure 34: Chaos/variance attribute volumes of the Norne .plate (a) Vintage seismic view without attribute (b) chaos attribute seismic volume used in ant tracking for automatic fault extraction .

4.2.5 Instantaneous Frequency

It is one of the complex attribute which is a time derivative of instantaneous phase often used to determine bed attenuation, correlation of faults and fluid contacts. Its application to the Norne did not suggest much information to horizon clarity when compared with other attribute functions as sweetness and structural smoothing which is the main focus of this work. However despite the challenge in attributing any added contribution from the use of this particular attribute, it showed that the semblance of frequency events across geologic features of faults, reflectors with distinct red colored patches (Figure 35).



(a) (b)

Figure 35: Instantaneous frequency attribute as applied to the Norne seismic data

4.2.6 Discussion on the attribute application to the Norne

The use of attribute function to the Norne seismic data has achieved amongst other things better illumination of structures in picking out horizons in the seismic interpretation window, with lateral continuity and well defined edges using the structural smoothing and sweetness attribute. Fault patches and fault interpretation were delivered with manual interpretation and automatic fault extraction with the variance/ chaos attribute function.

In this workflow, other attribute functions were tested such as the Dominant frequency, Envelope, Instantaneous phase, Reflection Intensity, Local Flatness, etc. The results of these other attribute had little value to the intended purpose of delivering better seismic interpretation, illuminating features and geologic structures. The purpose of use of an attribute must be clearly defined, even when an attribute is not sensitive to geometric properties it could have better value in other properties of intent. In this work, I have combined the cosine of phase attribute and structural smoothing to deliver horizon interpretation of the Base Cretaceous Unconformity, reservoir Top of the Ile, Tofte, Tilje and Garn Formations. Also in the reservoir section, fault planes were manually interpreted and using the variance attribute automatic fault patches was interpreted.

The ease of using a virtual copy of the Norne seismic sections to test the attribute functions without making much references in realizing several copies, which takes a lot of CPU time ; means that it offers an efficient process to test the efficacy of the attributes to the volume and fine-tuning interpretation.

5. 3D SEISMIC INTERPRETATION

Following the process of volume visualization and attribute displays, manual interpretation of faults and horizon was performed in the reservoir section .The seismic interpretation was set for interpretation for 25 in-lines and every 10 traces with the intention to produce a dense spatial interpretation, for better horizon /surface evaluation needed for modeling the reservoir surfaces. The inputted seismic was zero-phased (Stat oil, 2003), with interpreted inline range from (970 to 1300) and cross lines ranged from (1700 to 2300) (Figure 36).

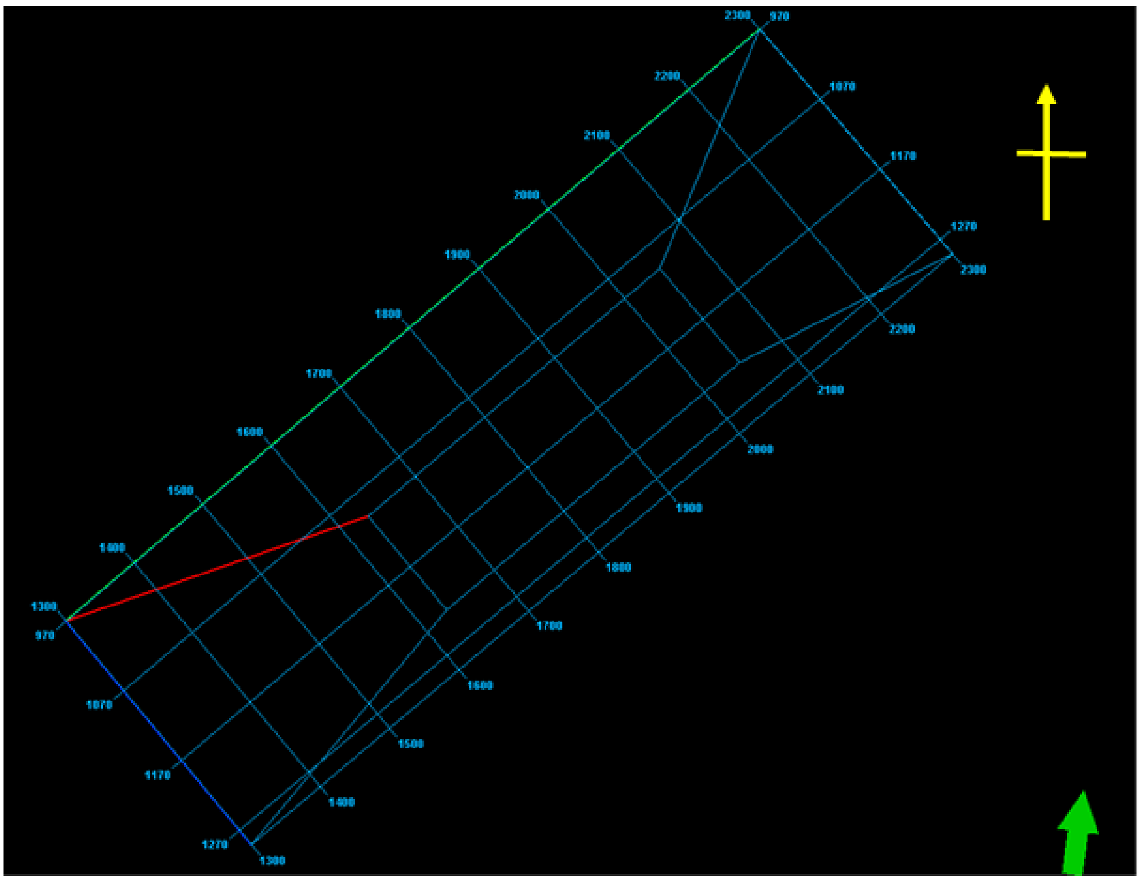


Figure 36: Base area overview of the seismic volume, capturing the inline and cross line. The survey is pointing in the direction of North as indicated by the yellow notation in the top right corner of the figure.

Typical reflectors that were considered for interpretation was the Base Cretaceous Unconformity(BCU), Top Garn formation, Top Ile formation, Top Tofte formation, Top Tilje Formation. The Top Not and Åre Formation were inputted into the interpretation based on Statoil field interpretations which were also used as reference guides in interpreting the other horizons. The reference interpretation zone of the reservoir section in the seismic volume was taken at (2400 to 2700m) from the reference report given by Statoil (Figure 37).

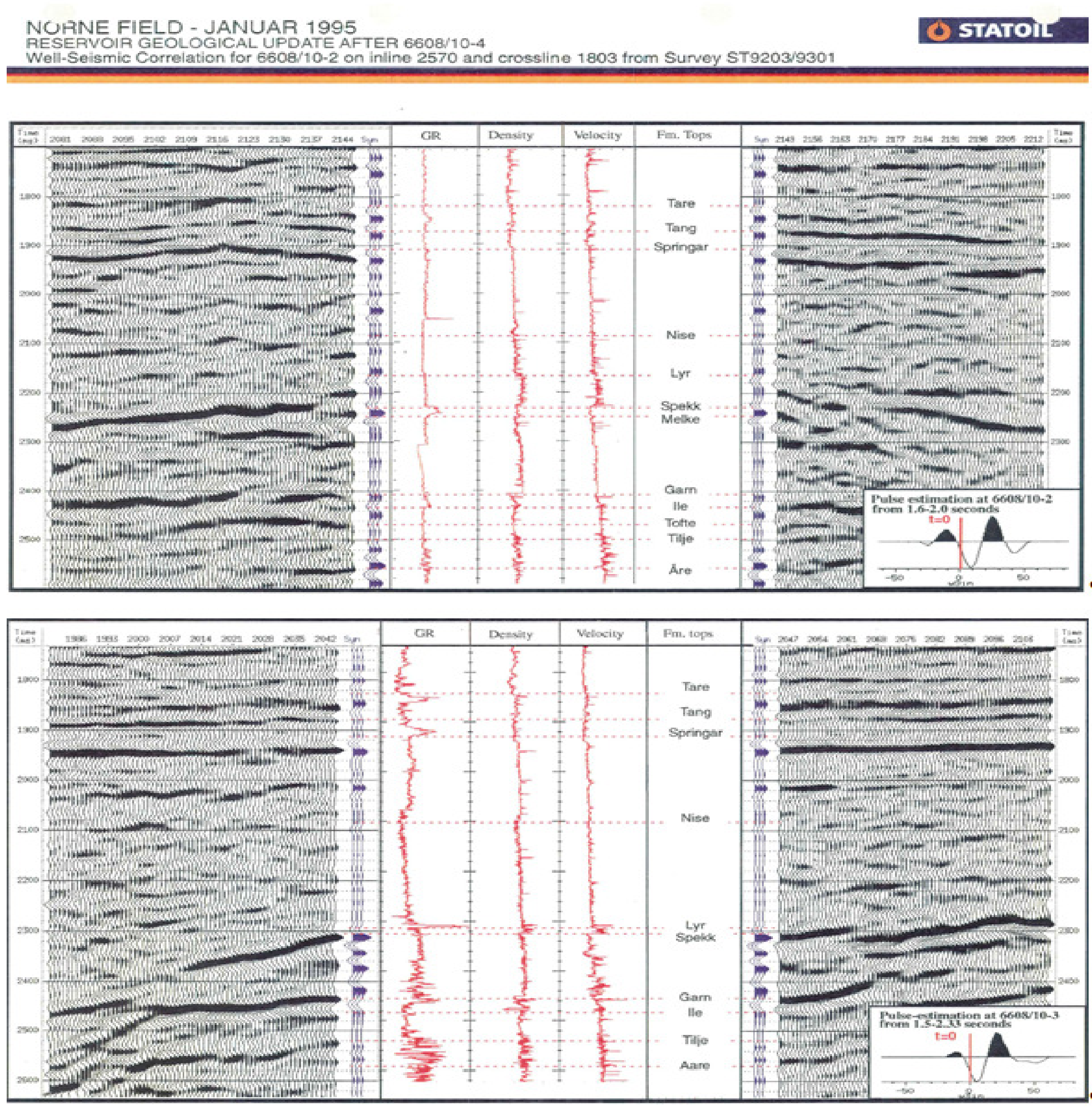


Figure 37: Statoil reference depths of formation tops used in guiding interpretation

5.1 Base *Cretaceous* Unconformity

This was interpreted with a strong peak reflection over the entire volume and it form typical crested wrapping over the horst structure and within sections of graben fill deposits. It was interpreted on a seismic depth window of 2300 to 2400m as Horizon 1.Typically it is marked with top lap terminations and / or erosional truncation of some horizon within the northern western section of the lines where the horst structures are typically prominent. In the southern sections of the volume, interpreted inlines and crossline captures the BCU to have a concordant to parallel relationship with other interpreted horizon (Figure 38/41).

Furthermore, it was noticed that the reflection strength of the BCU was much weakened in the crested part of the horst structures when compared to the graben like structures or ‘depression fills ‘in the volume. According to Statoil report of 2001, this was probably attributed to the erosion of the Spekk Fm which has removed the strong impedance contrast between the lower Cretaceous and Spekk Fm.

Also the large planar reservoir sectional fault were observed to have been outlasted by the BCU surface , it was observed however that some of the faults (horst and graben associated fault) were found as been reactivated within parts of the graben fills making displacement of the BCU surface and parts of the graben fill deposits. This might mean that the erosional event and deposits in the fill is syn tectonic to last phase fault reactivation due to late phase rifting episodes.

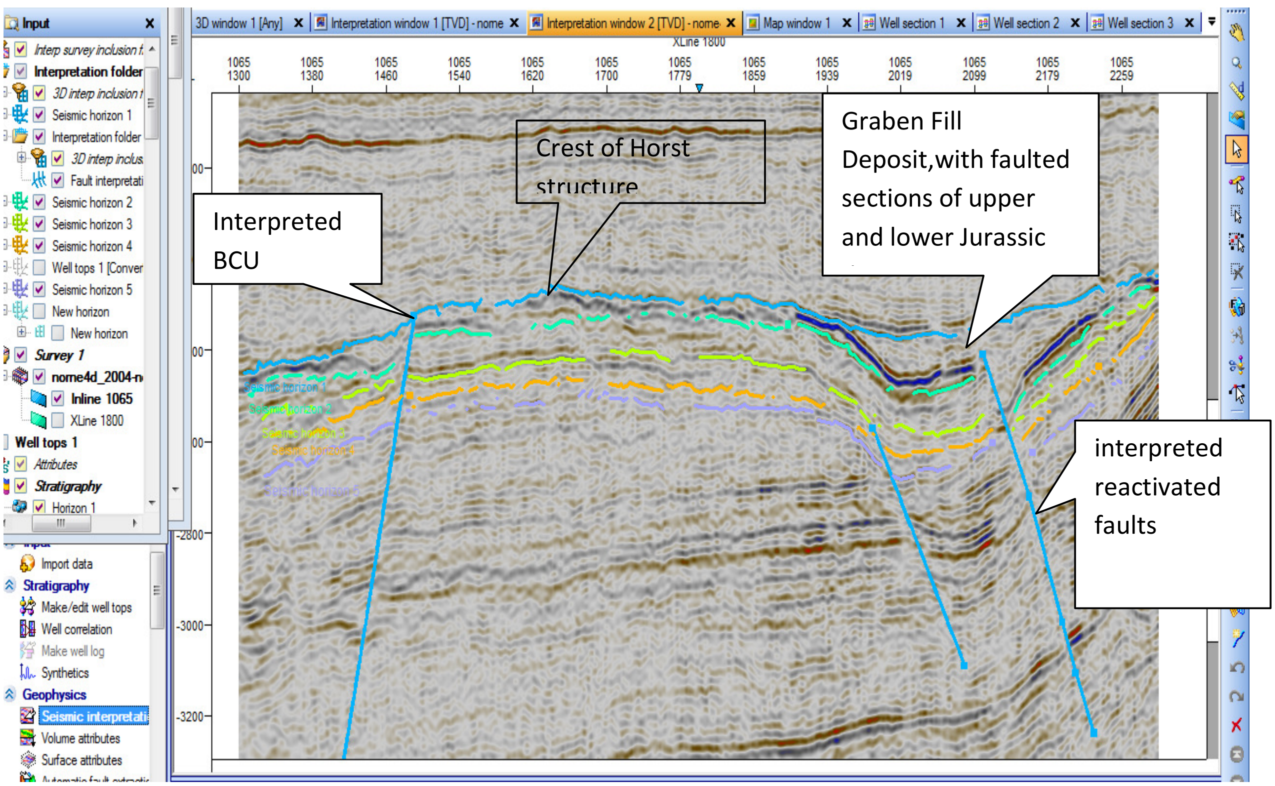


Figure 38: Seismic inline 1065 showing the interpreted BCU, main horst structure and graben fills.

5.2 Formation Tops/ Interpretation (Garn, Ile, Tofte, Tilje)

The Top Garn Formation was interpreted as horizon 2 in the seismic interpretation window. Its interpretation was guided using the reference Statoil report (2003), inputted OWC contact surfaces, and Top of Not formation. The Top Garn Formation was interpreted with the seismic depth window of between 2400 to 2500 m. It was interpreted to form typical wedge shape structures in parts of the Horst structures and truncated in some parts by the BCU. This truncation of the Garn by the BCU has a major control on its thickness profile across several interpreted lines (Figure 39).

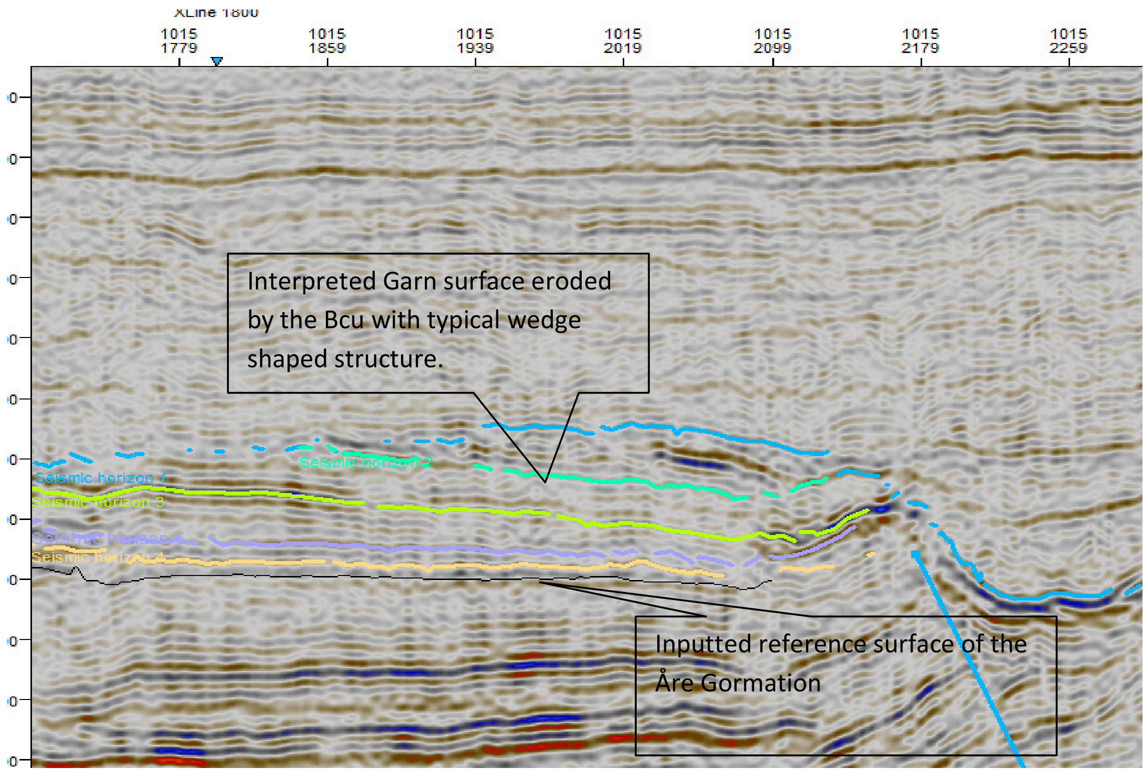


Figure 39: Seismic inline 1015 showing the interpreted Garn surface with typical wedge structure that tapers towards the eastern section of the seismic profile accompanied with erosional truncation of the surface by the BCU.

The Top Ile formation was interpreted at (2450 to 2550m) its surface is conformable with the interpreted Garn surface .It is also truncated in some parts by the BCU surface with typical wedge structures with seismic sections in the north western part showing much thickness when compared to the south eastern sections. The Tofte and Tilje formations was interpreted as horizons 4 and 5 with the bottom Åre formation surface inputted to mark off their interpretation and also the conformable profile of these horizons makes it easy to trace it laterally across the seismic profiles.

The Norne horst structure forms a prominent event with positive relief features and typical planar fault at its flank which sets limits or bounds its margin. The crest has been eroded with erosion features as seen with the BCU surface. Fill deposit probably from the eroded horst form parts of the graben or depression structures adjacent the prominent horst margins (Figure 40/43). It was observed that as the seismic crosslines and inlines were interpreted away from the northern western section, the horst/graben structure became less prominent, and the BCU had a concordant relationship with other horizons (Figure 41). It probably might mean that the level of erosion was much higher in that section due to regional uplift during rifting (Figure 40/41).

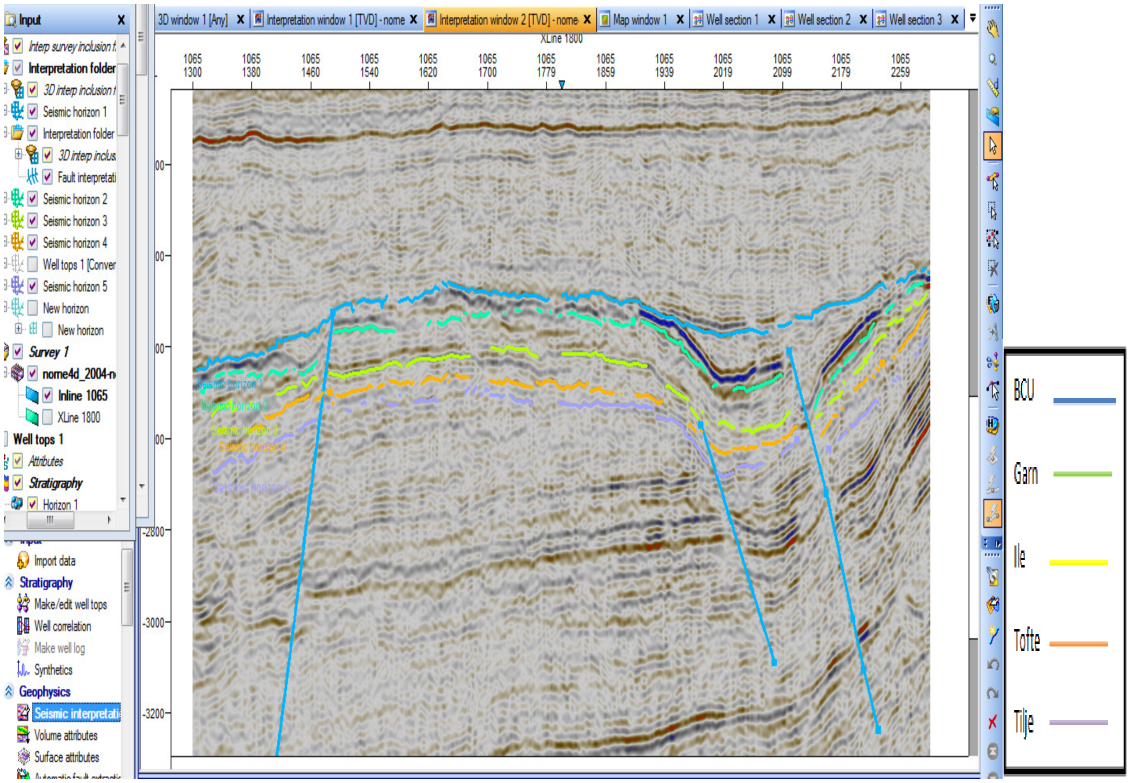


Figure 40: inline 1065 showing the prominent horst structure and adjacent graben fills, with color bar showing the interpreted horizons

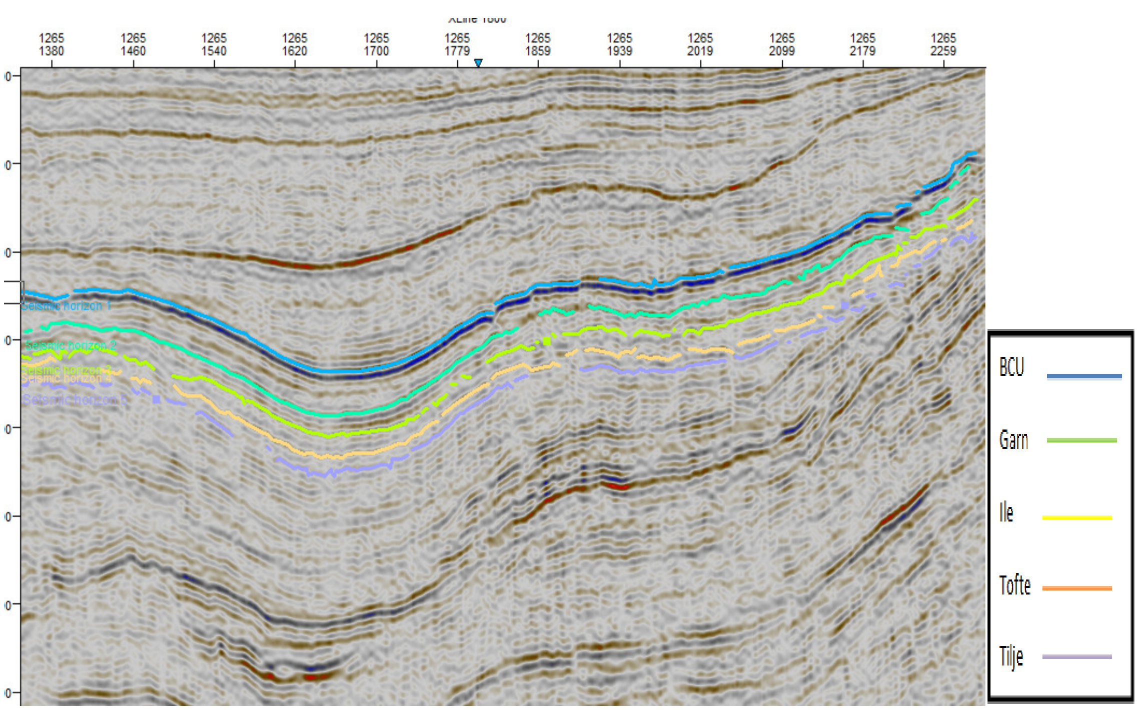


Figure 41: The BCU making a concordant relationship with the other interpreted reflectors in inline 1265. The color bar showing the interpreted horizons

Furthermore the thickness of the reservoir section was approximately 200m judging from well sections with the inputted Top Not and Åre formation. From the interpreted seismic it was evident that the thickness of the horizons was tapering in the direction of the east with wedge shaped structures observed within parts of the Horst (Figure 39). Internal discontinuous reflectors were observed with parts of the reservoir section with subtle unconformities and terminations interpreted.

Fault interpretation was manually done for all the interpreted lines and stored on the fault interpretation folder for static modeling .Large scale planar faults were interpreted within some of the sections as the interpreted horizons were displaced and terminated on the fault surfaces (Figure 42). The fault positions seem to be controlled by the main horst structure which bounds the structure, other minor fault sets were interpreted aside from the large faults. The inputted fault stick data were used to control the interpretation so as to deliver better fault patches in carrying out the modeling process.

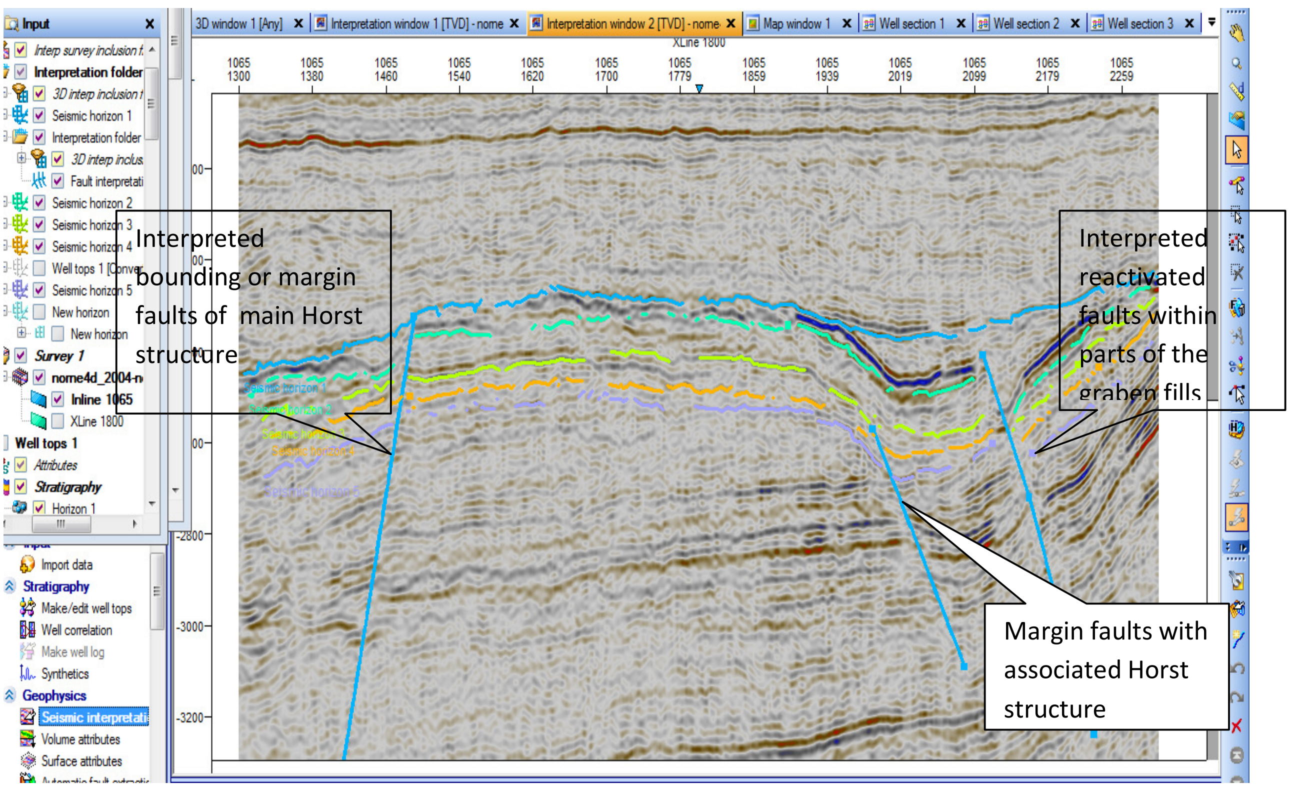


Figure 42: Inline 1065 showing interpreted horst and graben structures with interpreted faults.

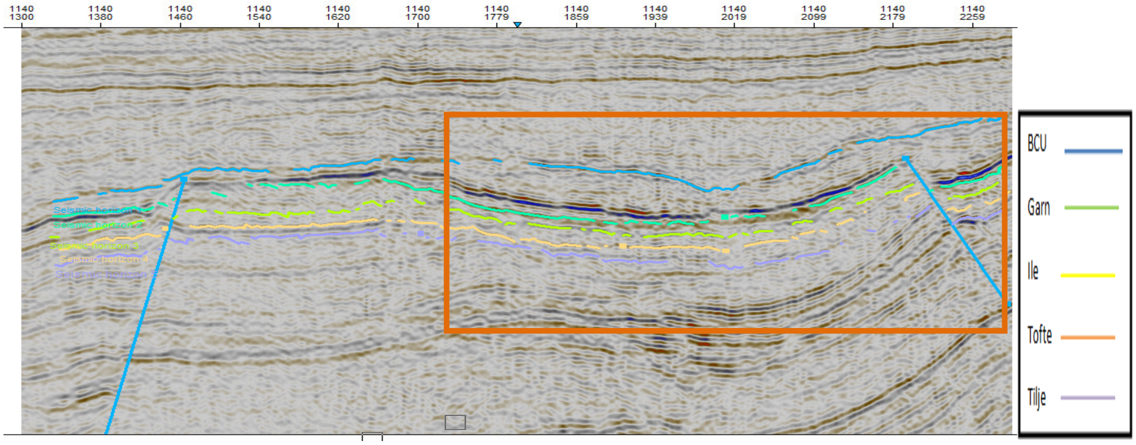


Figure 43: The pink boxed section shows in inline 1140 of the south eastern section of the volume showing a much larger extension of the graben fills.

Horizon flattening technique was applied to restore the structure (horizon surfaces and faults) before deformation. This technique served as a good control to understand to what extent the structure has been deformed and the events of deformation. Restoring the BCU surface to a flatten depth you could approximate the amount of the eroded sections of the Norne Horst which is greater than about 100m from section line of 1090 inline (Figure 44). Furthermore, you could tell that the erosional event supplies fill deposit for the graben looking that the axis of the graben to the flattened position of the BCU. Also, you could tell that the positive relief of the horst structure is fault assisted looking at the flattened sections which captures the displacement of the horst as seen with the horizon prior to the latter event of erosion.

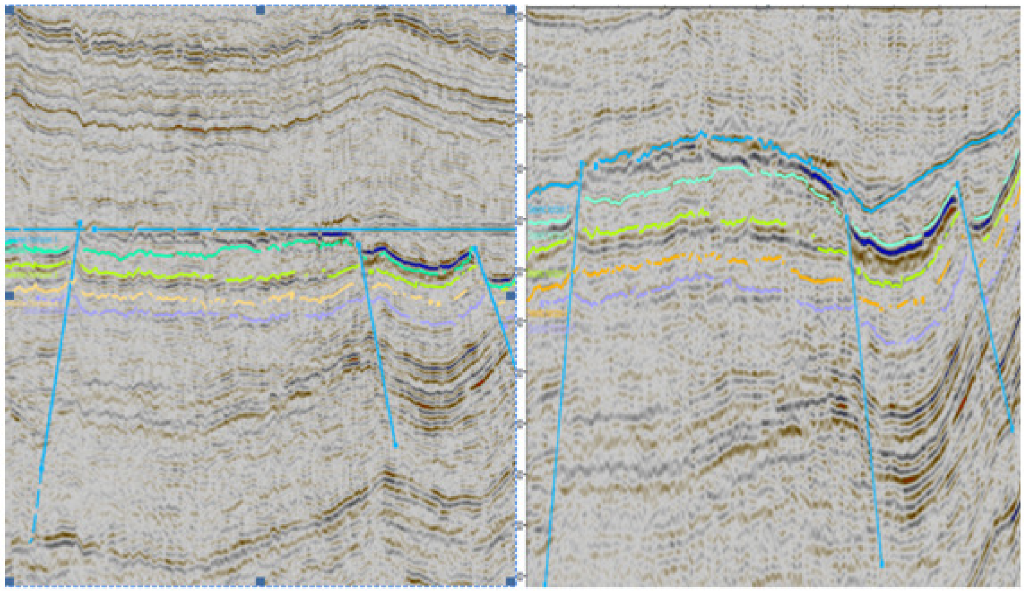


Figure 44: Seismic section 1090 inline (a) shows the flattened section (b) shows the unflattened interpretation

5.3 Depth Conversion and controls on the interpretation.

The purpose of the seismic interpretation is to generate the reservoir surface which would be applied in creating the seismic models from generated interpretation. The application of geologic license with guided knowledge of seismic interpretation is applied in interpreting the whole sections. However, the inputted seismic was in the time domain, depth conversion using an average velocity of about 2055m/s (Statoil, 2003) was estimated from the Top Not and Base Åre formation which was used to make adjusted to well marker horizons and the interpreted seismic horizons.

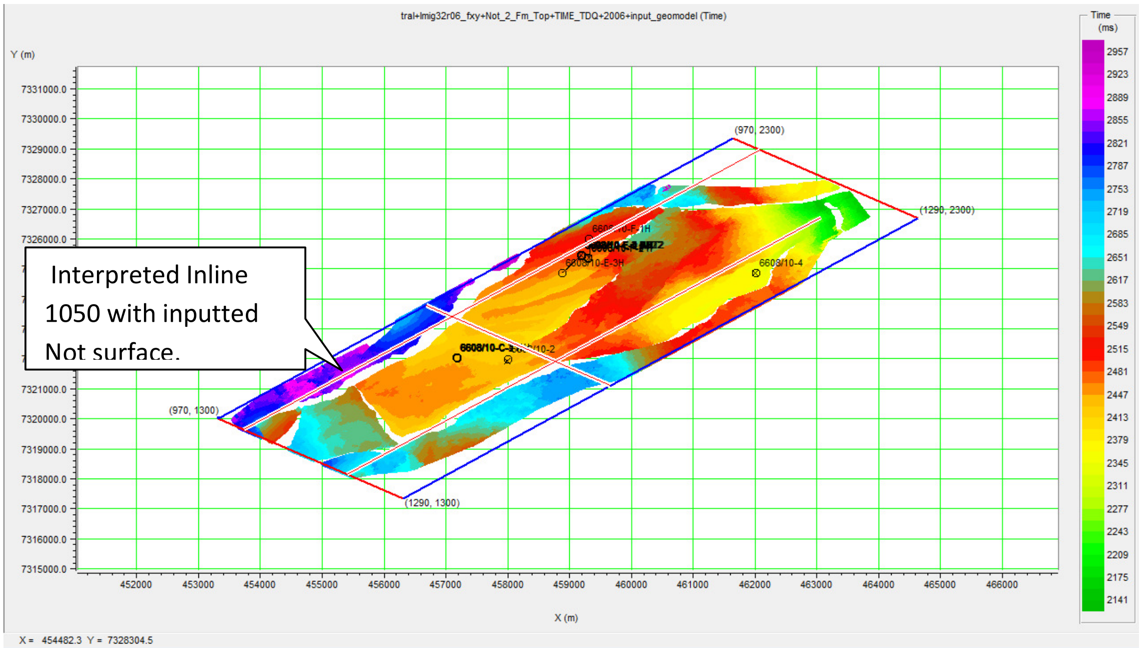


Figure 45: Inputted Not surface with interpreted seismic inline 1015

To tie in the well data to the 3D display also proved challenging with lack of checkshot data (available data sets at the time of study work and license limits available in Petrel software). To pass this hurdle, the inputted Top of Not and Åre formation were used with the inputted OWC (fluid contacts) to make appropriate interpretations of the horizons and determine their relative positions of the other interpreted formation tops (Figure 45 and 46) .This was also combined with the reference Statoil report of Figure 37. This makes these interpretations relative since checkshots and Reservoir tops of the Garn, Ile, Tofte, Tilje were missing in the available data sets. Finally, the process of making the models means that proper guides or checks must be maintained to sustain the interpretation quality.

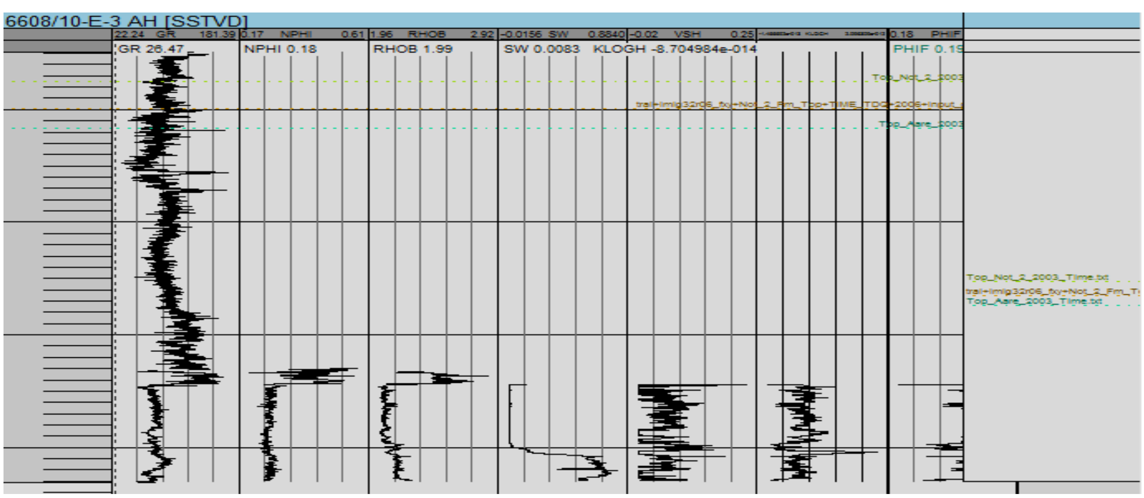


Figure 46: Inputted Top of Not and Åre formation which were used as guides to the interpretation

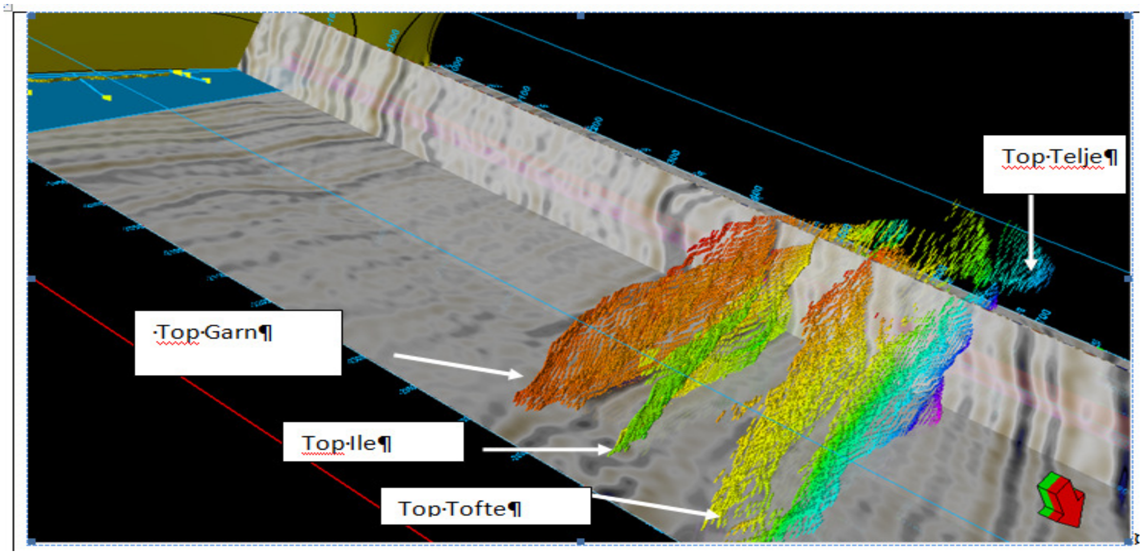
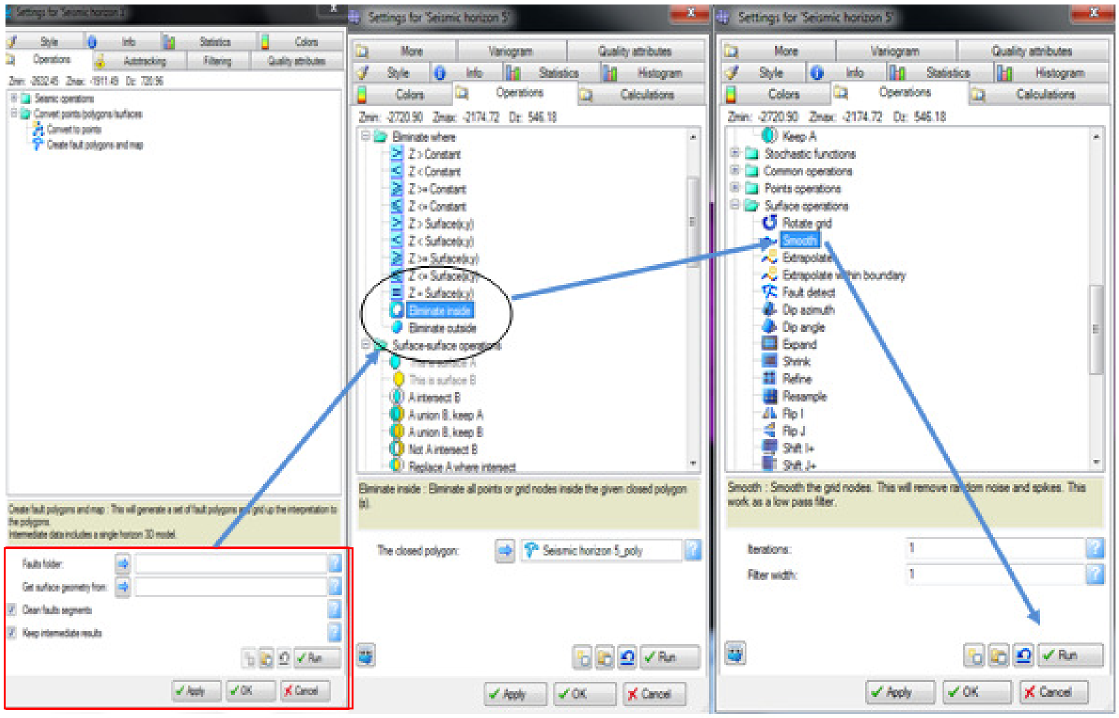


Figure 47: Visualized Fluid contacts used as controls to interpret the Garn,Ile,Tilje and Tofte formations

6. Horizon Operations / Surface Attributes

The seismic interpreted horizons of the Top Garn, Ile, Tofte, Tilje formations were converted to surfaces which carry their respective interpreted fault polygons. This process of creating the respective surfaces, takes into consideration that the fault interpretation from the seismic should make accurate intersection with the horizon data. The importance of this process is that the static models are based on the horizon surfaces which are typical inputs in the MAKE HORIZON process in the modeling work flow.

This process of making surfaces with polygons starts with opening the Settings tab for the given seismic interpreted horizon in the operations template. Use the Icon called Convert points and/polygons/surfaces folder to create the fault polygon and maps. Since the fault was interpreted with just one folder in the seismic interpretation, the fault folder was used to provide the needed inputs for making the polygons.



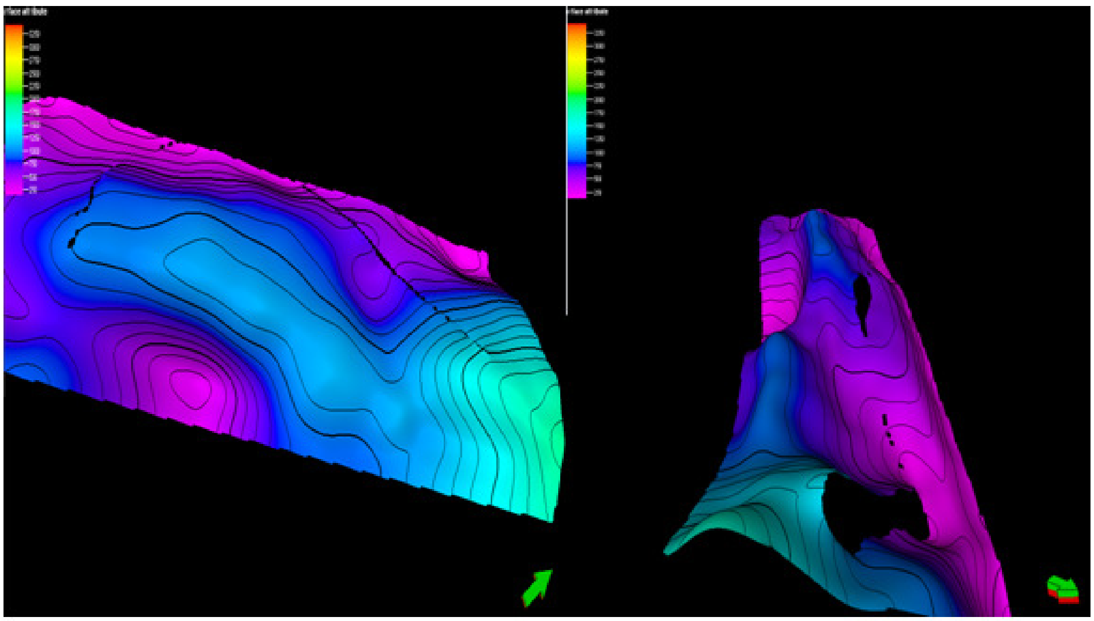
(a) (b) (c)

Figure 48:(a) Using the create fault polygon and map function in the operation tab to create seismic horizon surfaces and polygons. The red boxed area shows the key inputs needed from fault and surfaces. (b) Inside elimination of the fault polygon. (c) Smoothing operation for the surface.

The respective interpreted seismic horizons were imported into the workflow domain called GET SURFACE GEOMETRY FROM as seen in Figure 48(a); the fault interpretation folder 1 was used as key inputs for the fault polygons .This process was iteratively done for all the interpreted seismic horizons which represented the surfaces of the BCU, and Top Garn, Ile, Tofte, and Tilje formations. The Not and Åre formation tops were inputted directly into the modeling frame since they were already interpreted horizons. The next process in the workflow is to use the created seismic horizon polygon surfaces as input for the ELIMINATE INSIDE function (see Figure 48(b)). This function eliminates the inside area of the surfaces bounded by the fault polygon which makes it easier to see the dimensions of the faults in respect to the surfaces.

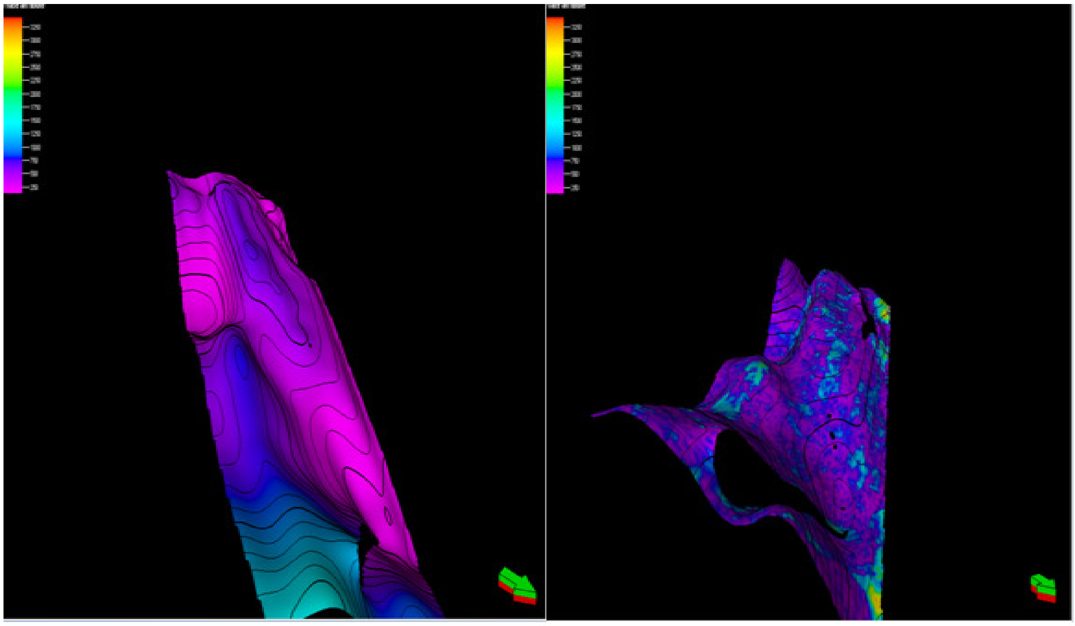
Finally, this process ends by applying the Smooth function which is run at different iteration level with a user defined filter to smooth the surfaces in order to deliver a geologic reasonable surface. This application of the smooth function to the formation surfaces of the Norne reservoir tops is critical to eliminate false positive relief closures, ‘bulls eye’ effects and contouring problems. The importance of this technique (Smooth function) is to determine the quality of the inputted surfaces to the model creation and also to deliver prospective drillable locations. The quality control on this process given the absence of established well positions is to use the seismic to surface tie options (Figure 52) with the inside wall visualization techniques which provide a clear control on polygons and structure reliefs. This technique is adequate to farming in new drillable locations in a virgin exploration area where you could determine the seismic positions to structural reliefs and closures.

In the Norne field data the interpreted horst associated faults typically form the main polygons with the dimensions of the polygons capturing the displacement of the fault to the corresponding surfaces. The BCU surface shows little faulting surfaces due the absence of fault displacement in the horizon; since the BCU postdated the rifting episodes (Figure 49a). Furthermore, the horst positive relief features were preserved on the surfaces and as well as the graben fill deposits (Figure 49,50,51).



(a) (b)

Figure 49: Generated surfaces of the BCU (a) and the Top Garn formation (b) with the blue zone capturing the areas of positive structural relief of the horst and the pink capturing areas of the graben fills. Fault polygons mainly within part of the graben fill areas.



(a) (b)

Figure 50: Generated surfaces of the Top Ile (a) and the Top Tofte (b) with the blue zone capturing the areas of positive structural relief of the horst and the pink capturing areas of the graben fills. Fault polygons mainly within part of the graben fill areas

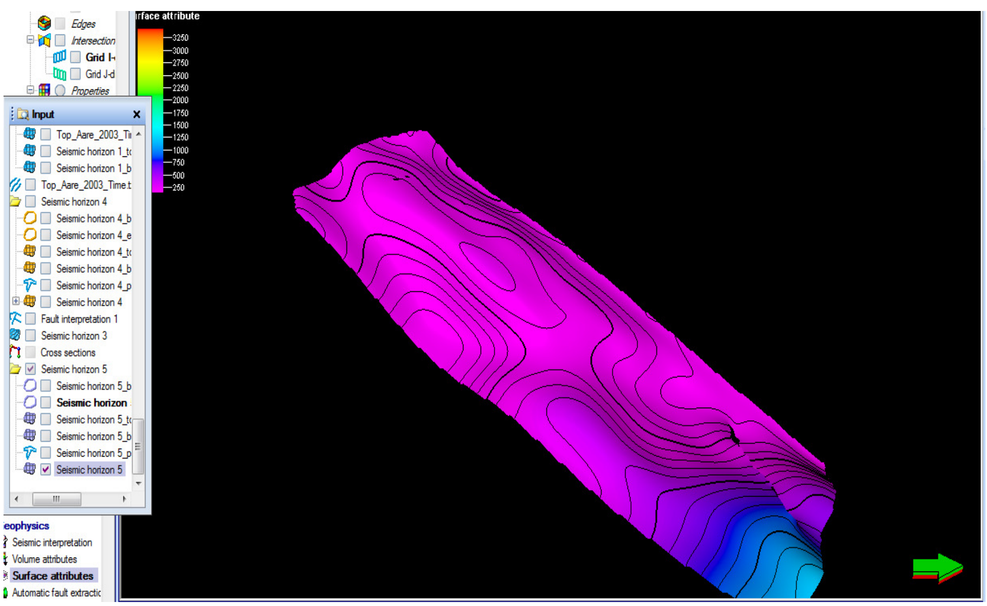


Figure 51: Generated surfaces of the Top Ile (a) and the Top Tofte (b) with the blue zone capturing the areas of positive structural relief of the horst and the pink capturing areas of the graben fills. Fault polygons mainly within part of the graben fill areas

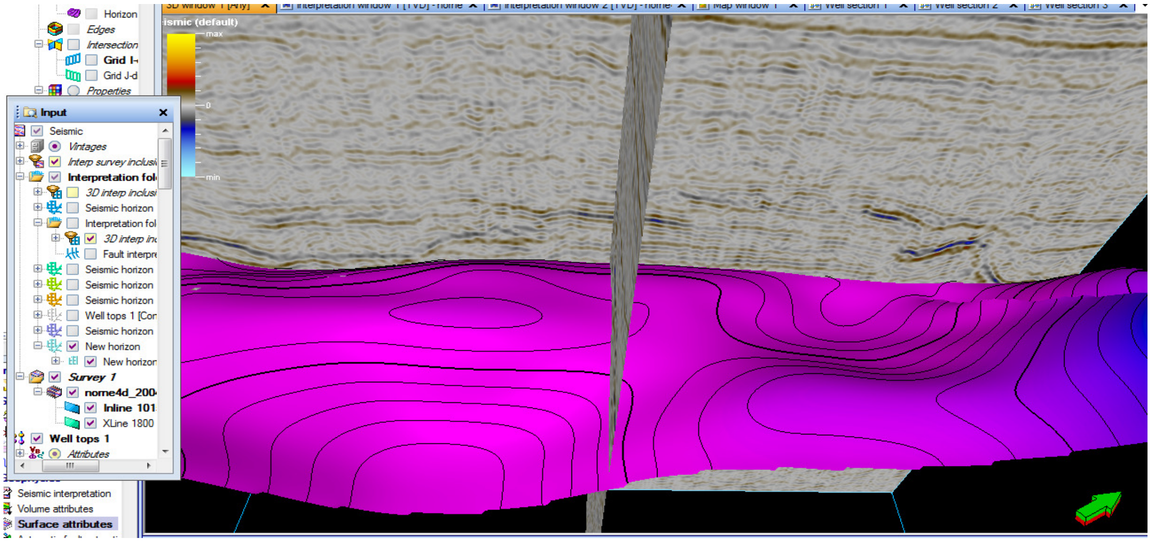


Figure 52: **The seismic to surface tie interpretation using the inside wall visualization technique.**

6.1 Surface Attributes

Generated surfaces are not just static products from seismic horizon interpretation; the application of surface attribute is a simple method of extracting the different seismic properties to the corresponding surfaces. This method is a comparable application to the initial seismic volume attributes which was applied to the Seg y 3D cube of the Norne seismic data. This application uses the realized seismic Seg Y as inputs, which relates the seismic parameters to the chosen surface. Also, in calculating this attribute specific horizon are used or intervals of interest as key inputs in the Window specification template to discriminate the different horizons on which the selected attribute function is applied (Figure 53).

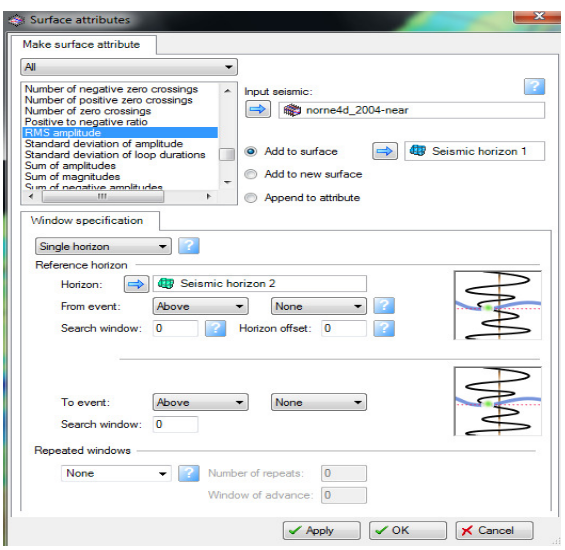


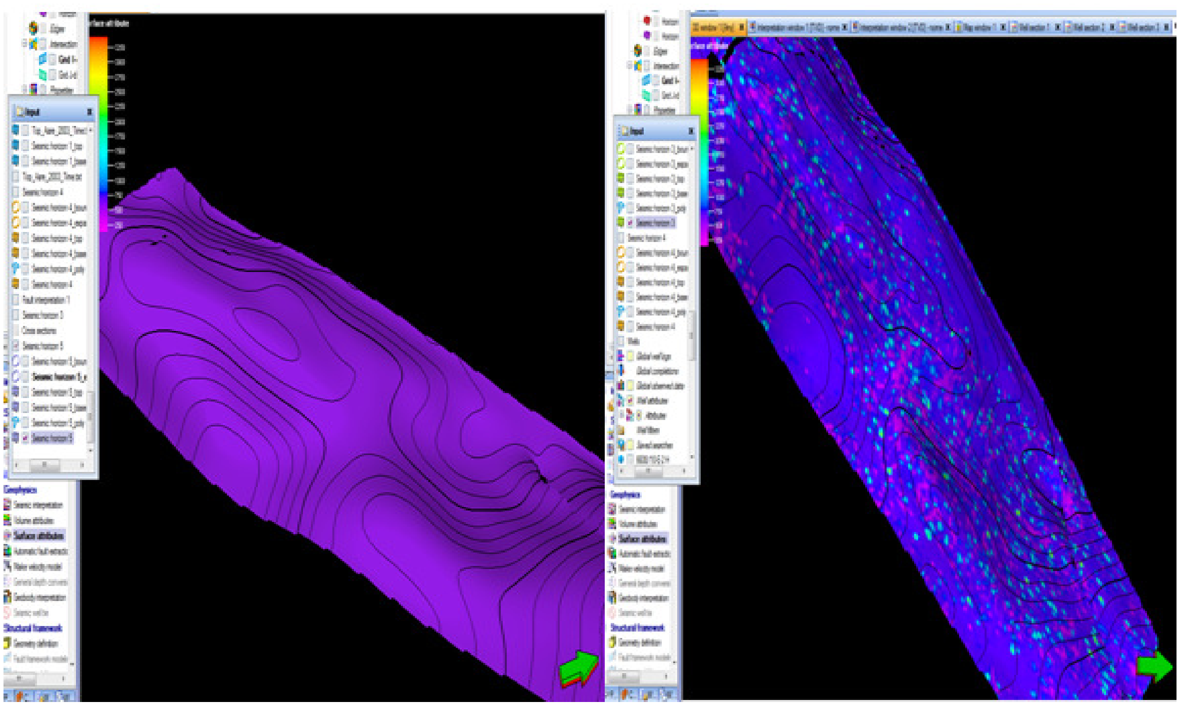
Figure 53: Template of the window attribute function, showing the different enlisted surface attributes, Inputted seismic volume, and the horizon window specifications.

There are different types of applied surface attributes, whose properties ranges from component parameters of the seismic to the surfaces, such as frequency, amplitude, thickness, energy, trace kurtosis and distribution etc. This helps to highlight specific properties to the given horizons which could be stratigraphic, structural, fluid etc. This was applied to the interpreted Norne reservoir top surfaces using different attribute on each surfaces.

6.1.1 Loop Kurtosis/ Arc Length

This measures the loop or peaked-ness that surrounds the given interpreted horizon; it provides a statistical distribution of the peaks. It uses the trapezoidal approximation as the basis to provide the amplitude response on the seismic trace peaks to the given horizon of interest. This specific function was applied to the Top of Ile (Horizon 3) formation.

The Arc length attribute relates to the reflection heterogeneity, which is used as an indicator of laterals changes in reflection patterns. It gives a firsthand clue without a log based facies distribution on the respective stratigraphic properties based on frequency distribution. This attribute was applied to the Top Tilje formation surface (Horizon 5); it was observed that the lesser the heterogeneity in the surface based on the frequency contents the color scale remains fixed (Figure 54).



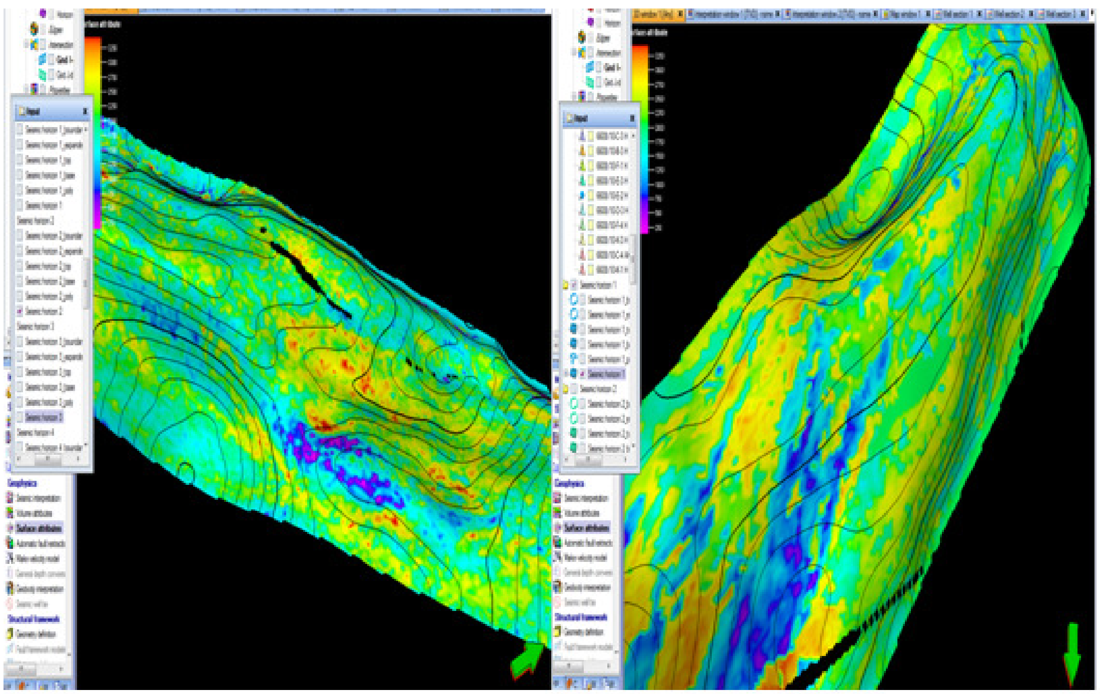
(a) (b)

Figure 54: Surface attribute functions as applied using; (a) the Arc length was applied to Top Tilje with the green color indicating less heterogeneity in the frequency (b) Loop kurtosis surface attribute was applied to the Top Ile (interpreted horizon 3).

6.1.2 Threshold Value/Upper Loop Area

The threshold surface attribute function is a user defined attribute where threshold parameters are defined and used as cut off to tweak the surfaces to the given parameter. This can be applied to amplitudes and given frequencies to infer probable changes in porosity and/or fluid properties. This was applied to the interpreted Top Garn top surface (Seismic horizon 2), where high amplitude patches of yellow to red color was preserved in areas of structural reliefs (Figure 55a). This could be due to fluid properties; however it would be interesting having an understanding of the frequency components of the reservoirs making it possible to compare the fluid fronts of these reservoirs with different vintages in the production history of the field.

The upper loop area attribute measures the area of the trapezoids by interpolating the zero crossings within the specific interpreted horizon. The area of each trapezoid is defined by multiplying the amplitude with milliseconds time window. This was applied to the BCU and the positive loop area used in generating the surface (Figure 55b).



(a) (b)

Figure 55: Surface attributes functions as applied using; (a) the threshold was applied to top of Garn (Surface Horizon interpretation 2) (b) Upper loop area surface attribute was applied to the BCU (Surface interpreted horizon 1)

6.1.3 RMS Amplitude

This attribute is a measure of the sum of the squared amplitudes divided by the number of applied samples in the given seismic volume. It is suggested that this amplitude has better capabilities to define geologic features and shed light to DHI (direct hydrocarbon indicators) from the surfaces. The probably reason for this effect is that if you sum the squares of the amplitude, you are simply `gaining –up' (increasing the amplitude) which reduces the background noises and/or amplitudes which are irrelevant to the main amplitudes. This attribute was applied to surface horizon 4 (Top Tofte), with typical structural trends of higher amplitudes within parts of the structures indicated with blue colors in Figure 56, this could be as a result of fluid or stratigraphic changes.

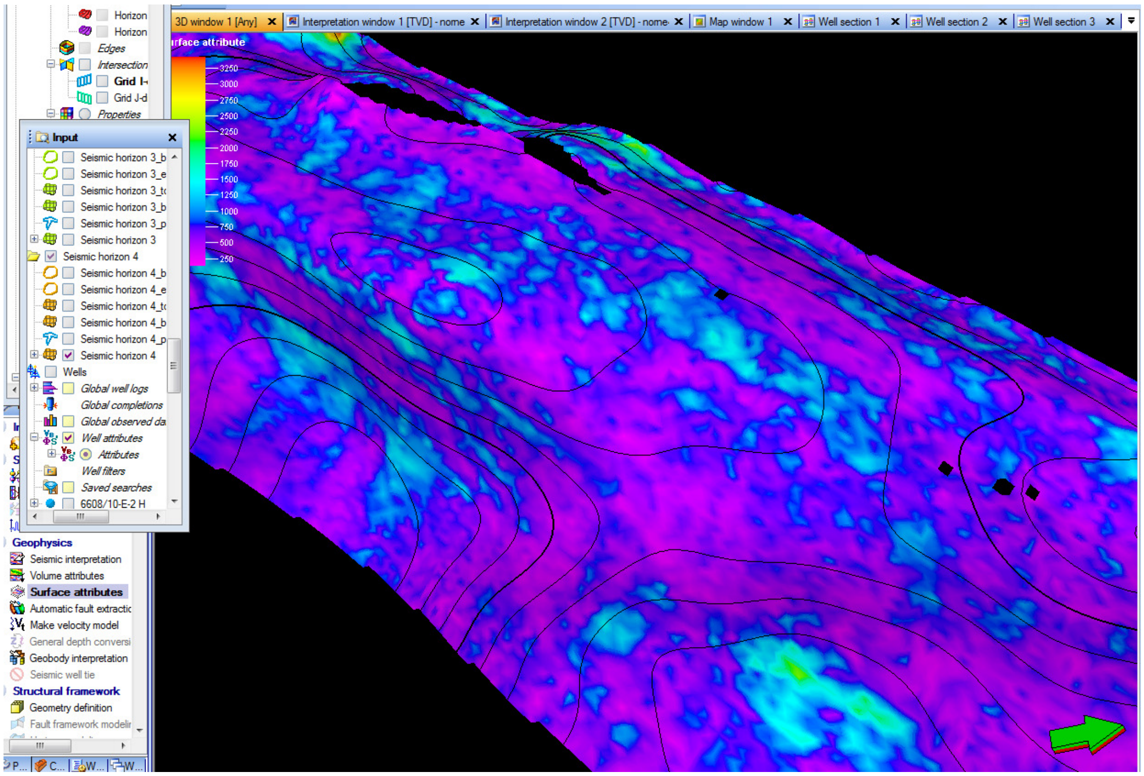


Figure 56: RMS surface amplitude as applied to the interpreted Tofte top surface.

6.1.4 Application of Surface attribute functions to the Norne data

The extensive list of different surface attributes means that the user must be aware of the specific advantages and purposes of each of these attributes to avoid abuse. In the application of this technique to the Norne seismic generated horizon surfaces, it provides a forward look into the properties (stratigraphic, fluid, structural, etc) of each of the top surfaces which provides a clue to other interpretations that would be done in the modeling. Furthermore, given that the frequencies and amplitudes are known for the reservoir sections, it would aid the evaluation of these parameters as to how they highlight specific events in the chosen horizon surface .It also provide the flexibility to test out user defined set parameters as to how they affect surfaces. Finally, as applied in each generated horizon surfaces in the figures above (54, 55, and 56) the Root mean square amplitude RMS, appears to provide a much robust interpretation of actual variability in amplitudes to structures.

The process of generating surfaces are not static, the making of the reservoir static models means that these attribute surfaces as better inputs to the modeling workflow. In a virgin exploration target where less data are available for control of data interpretation, using techniques like this could provide the needed leverage to test properties of your seismic and relate them geological realization of the subsurface.

6.2 Mapping

The generated horizon tops are converted to map sections and grid surfaces, the surfaces were inputted with a file format. The inputted surfaces were mapped using the input boundary as limits and setting a grid increment of 30 by 30 (Figure 57).Smoothing factor was applied to the each of the map surfaces and the corresponding surface attribute were retained in the mapping sections.

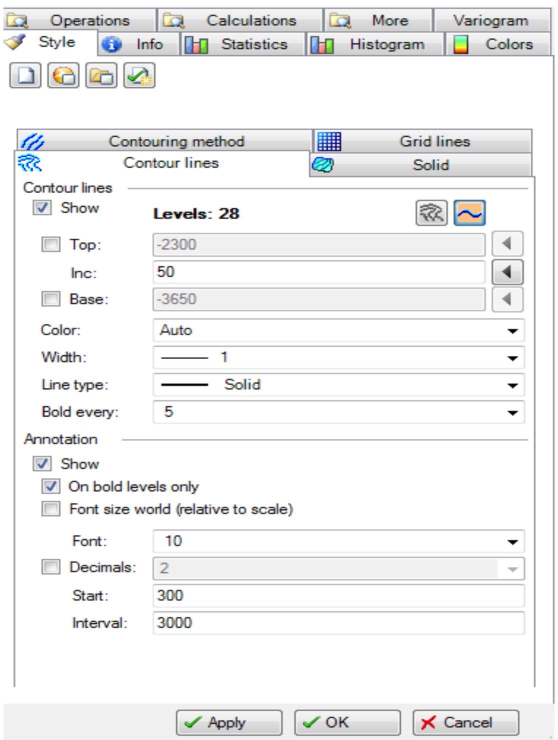


Figure 57: Contouring methods and templates use in creating the map sections.

The interpretations of the maps gives a 2 dimensional picture of the structural relief closures with related Horst structure and Graben fills (Figure 58,59,60,61 and 62).This maps are used to provide checks and quality control on the surface and they also form parts of the grid properties in the Horizon make process. These processes are part of the required steps or data inputs needed as a major input in the creating the static models. Using already available surface data such as the Not and Åre formation top makes it too easy since they provide direct inputs for modeling. The challenge and rigours of generating the surfaces (Bcu, Top Garn, Top Ile, Top Tofte, and Top Tilje) from the scratch provides a thorough understanding on the part of the user to interpret and quality check each process to provide the needed inputs for creating the static models.

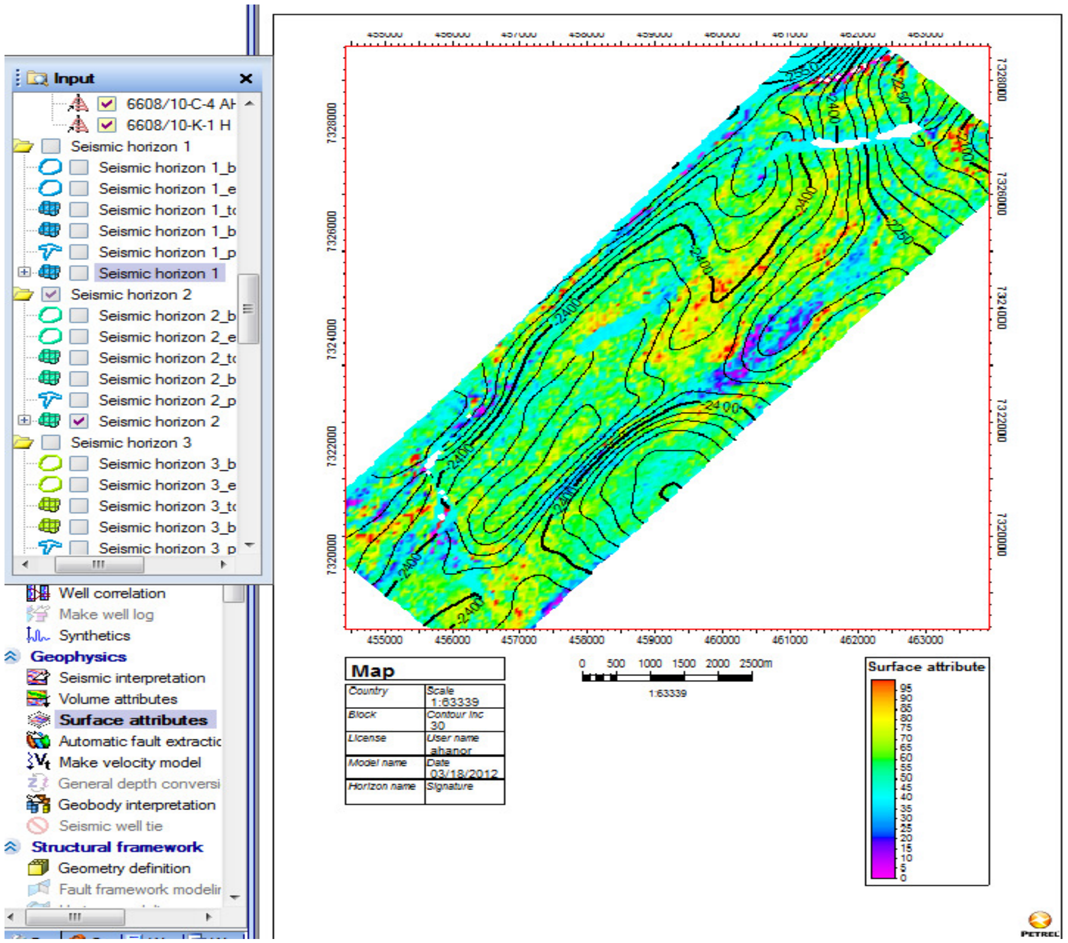


Figure 58:2D Map view of Interpreted Top Garn surface with the threshold surface attribute.

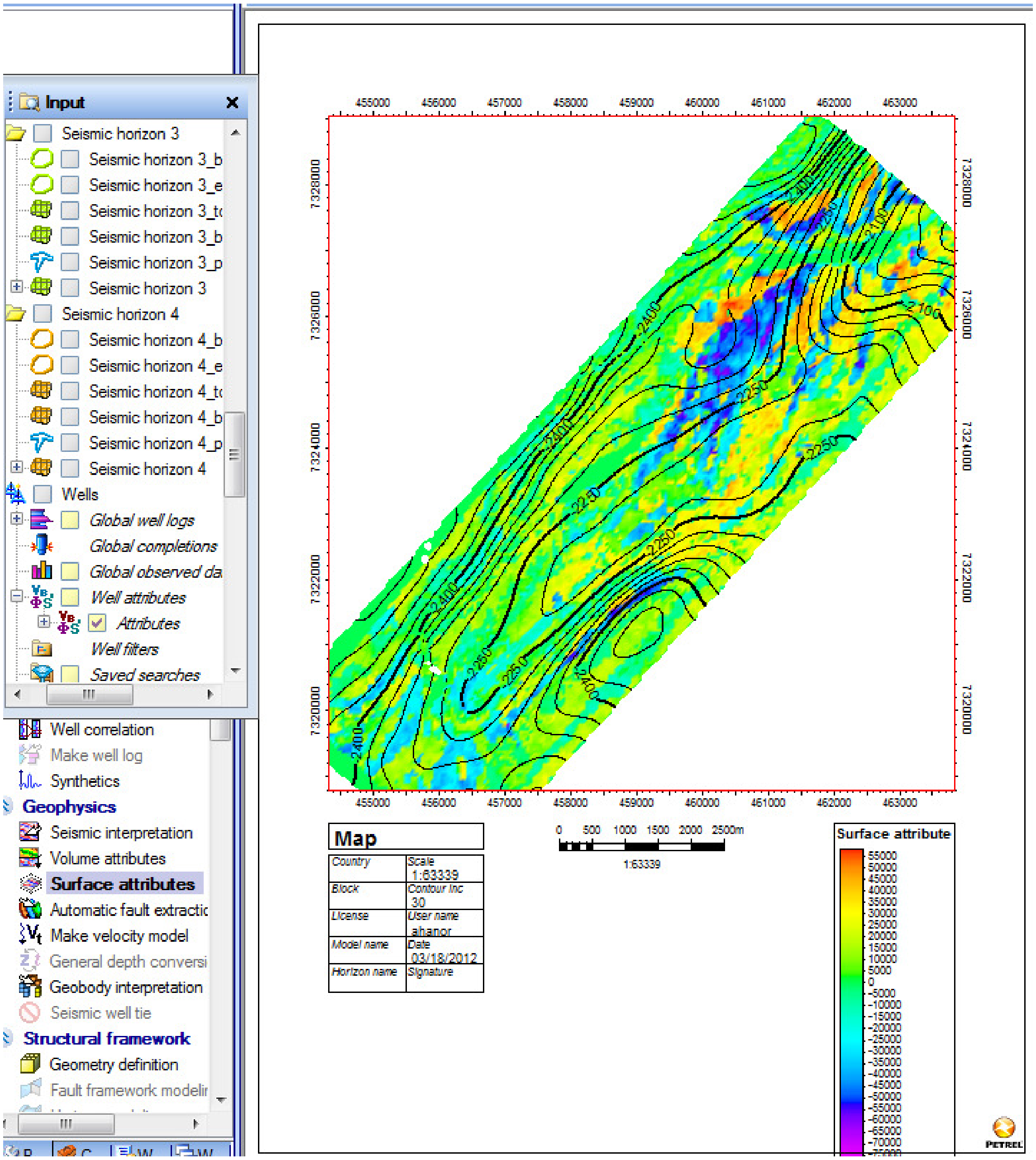


Figure 59:2D map view of the BCU surface with upper loop area surface attribute.

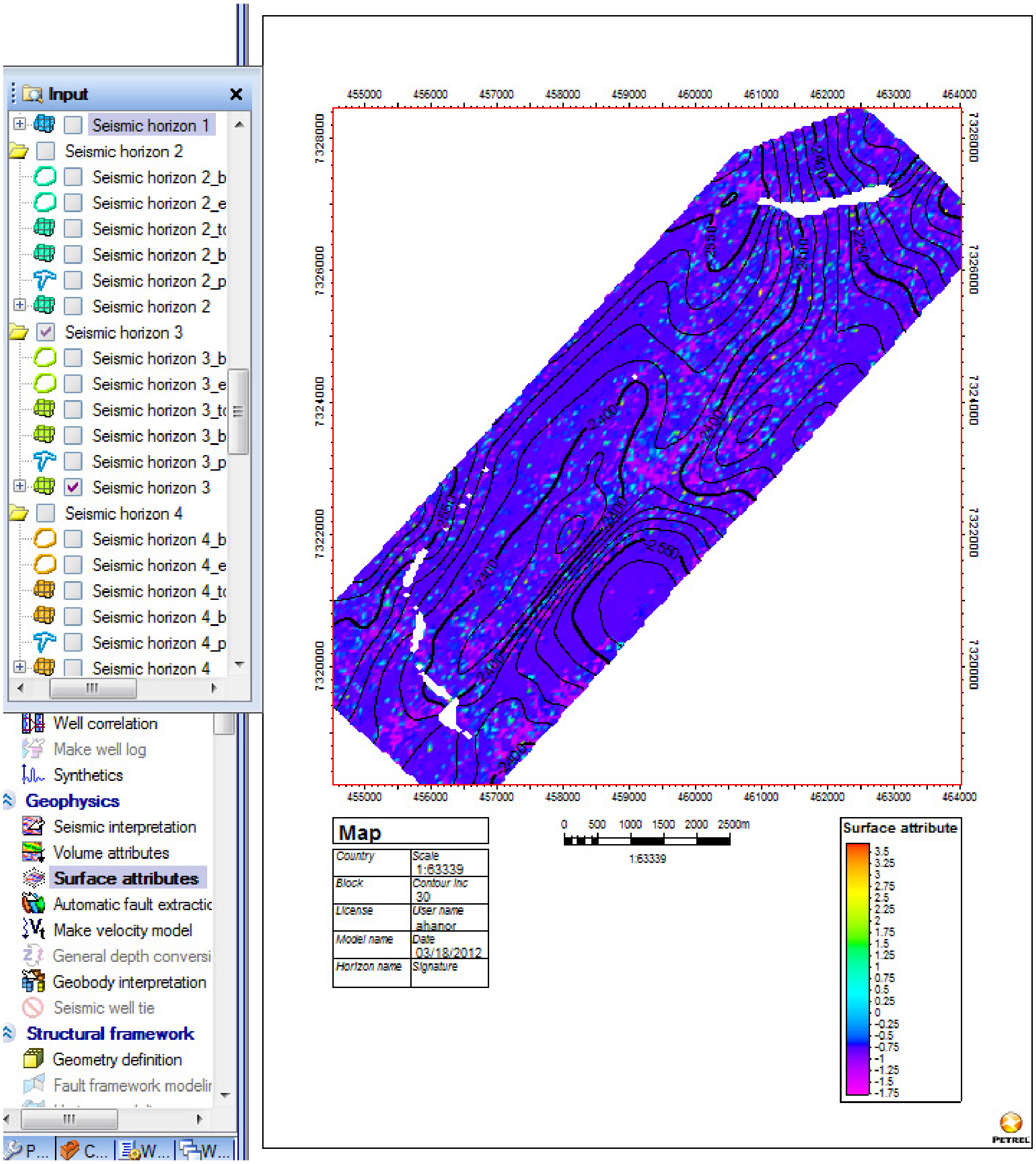


Figure 60:2D map view of the interpreted Top Ile with the Loop kurtosis surface attribute

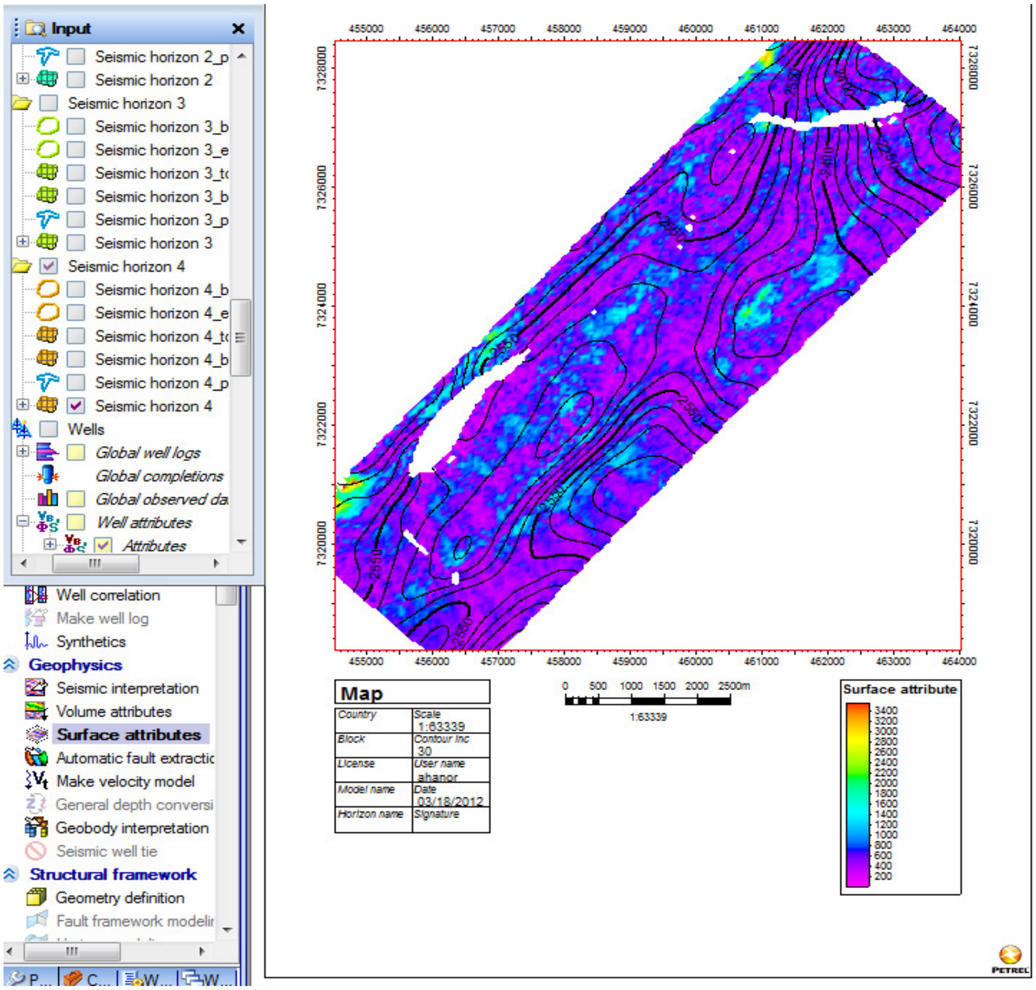


Figure 61:2D map view of interpreted Top Tofte with the RMS amplitude surface attribute.

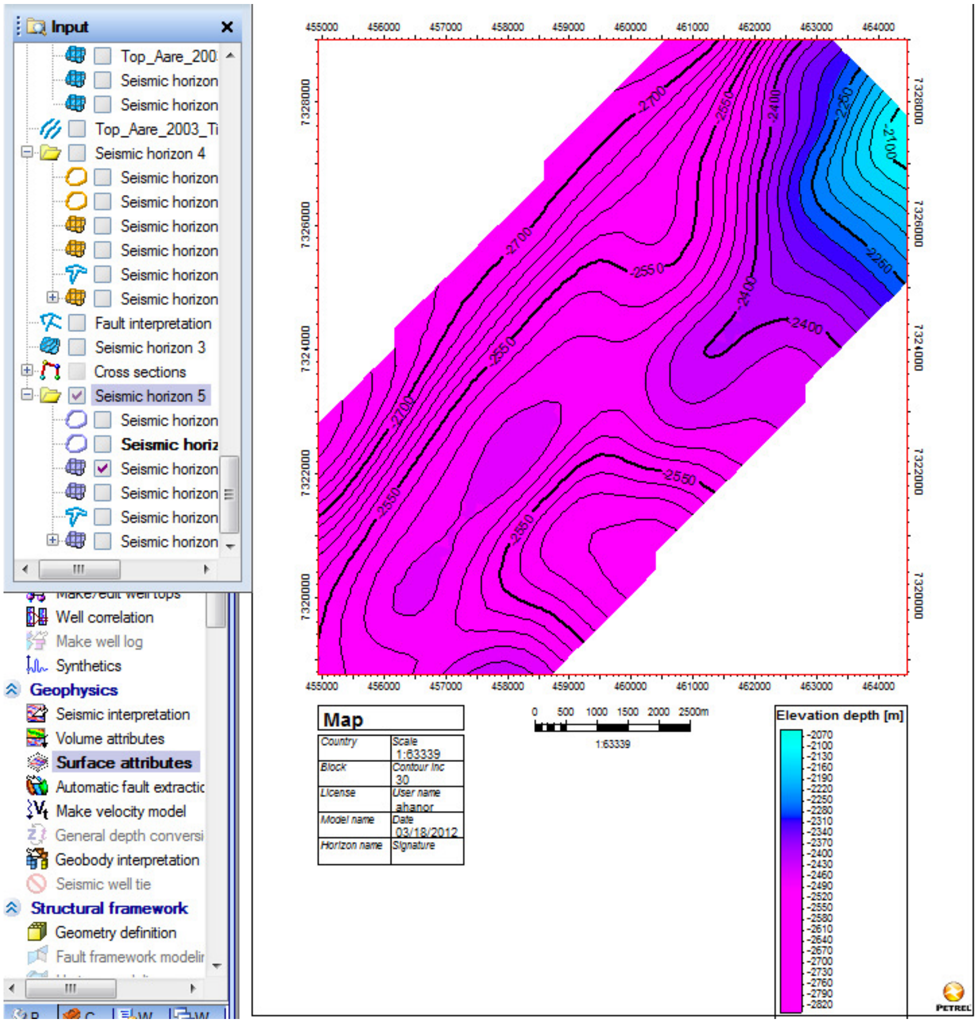


Figure 62:2D map view of interpreted Top Tilje showing the elevation depths

7. RESERVOIR MODELING

Delivering the reservoir static models involves using the key inputs of the interpreted horizon surfaces from seismic, interpreted fault polygons with other available data inputs from wells, fault stick inputs, seismic visualization and other reservoir modeling algorithm. The modeling workflow (Figure 63) starts from the structural modeling, which builds faults and horizon surfaces as the skeletons or frames for the models. Property modeling is used mainly to populate the structural models with lithologies, fluid or saturation using well log interpretations which are up scaled to the models. The process of reservoir modeling is much integrated by adopting different techniques at each phase of the model building.

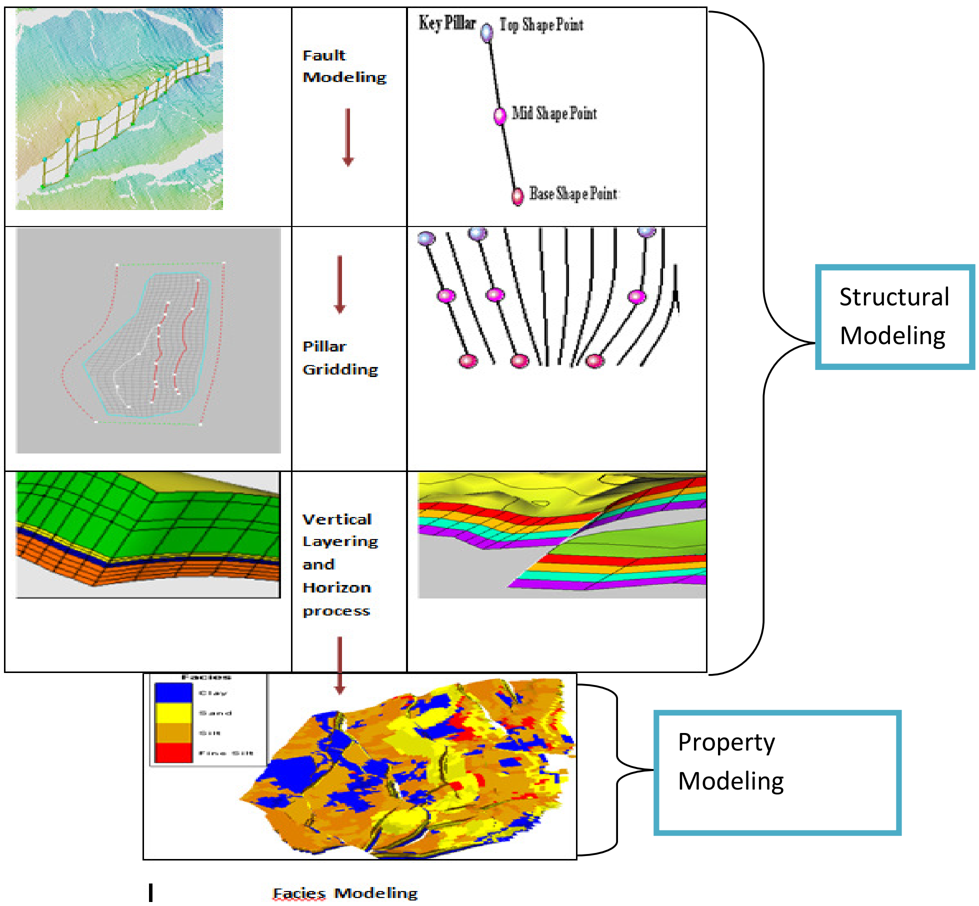


Figure 63: Modeling workflow with two main modeling methodologies of the structural and property modeling.

7.1 Structural Modeling

In this workflow typical consideration is given to the fault modeling and horizon making process. This process involves the use of different techniques in carrying out manual interpretation of faults and automatic fault extraction methods which are mainly adapted to creating fault patches in the 3D model frame. These interpretations are controlled based on geologic interpretations and adequate evaluation of each process methods aim to deliver the required deliverables in the models. Furthermore, interpreted horizons and surfaces attribute functions as previous described of the Norne field data are used in creating the needed structural surfaces and grid skeletons which form the necessary framework for the models.

7.2 Fault Modeling

The fault modeling process is done by applying manual based techniques of isolating faults by interpreting fault zones of interest in the seismic sections which are correspondingly used to create fault pillars and/or patches needed in the model. Secondly, recent advanced techniques such as Ant track or fault attribute volumes are adopted in this work flow to create automatic fault patches which are tested against manual interpretation and inputted fault stick data of the Norne seismic volumes.

7.2.1 Manual Interpretation/fault modeling

The process of generating the faults manually starts by having firm geologic interpretations of the faults, understanding their nature (whether they are planar, listric etc.) and the type of faults. In the Norne seismic volumes the faults are manually picked within each seismic inlines and crosslines in the reservoir section of the Norne seismic volumes .In the seismic Interpretation window in Petrel, the Interpret fault tab is activated and fault interpretation folder is created where all the interpreted faults are stored, the manual point mode is used to interpret the length and trend of the fault (Figure 64). The geologic controls used mainly in interpreting the faults are based on the displacements of the interpreted horizons or reflectors within each line, observed fault throws and terminations across the displaced sections.

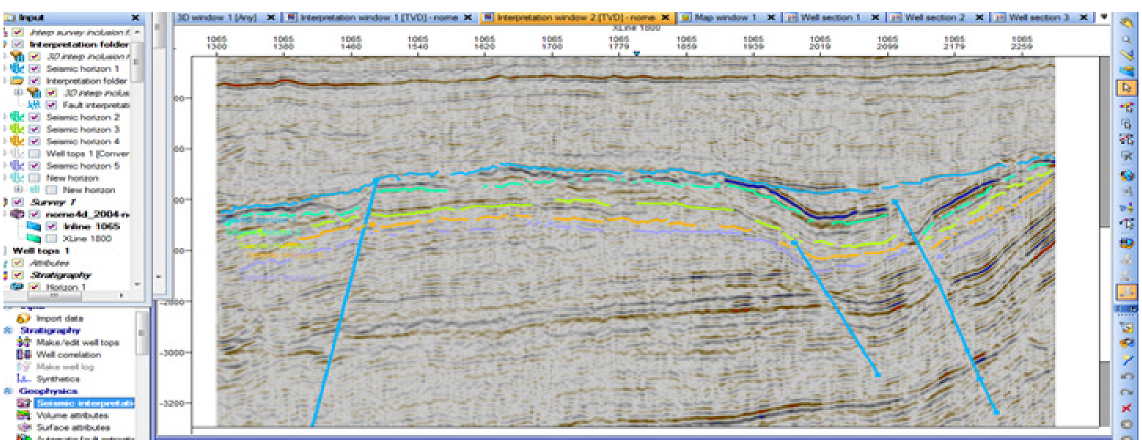
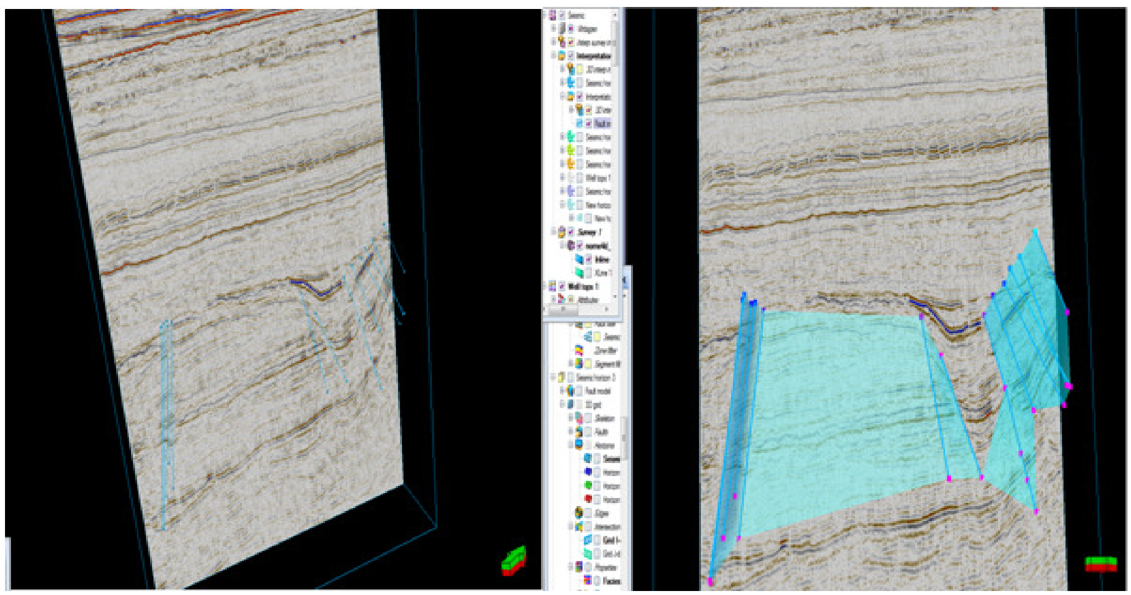


Figure 64: Seismic section showing the manually interpreted faults in the seismic interpretation window

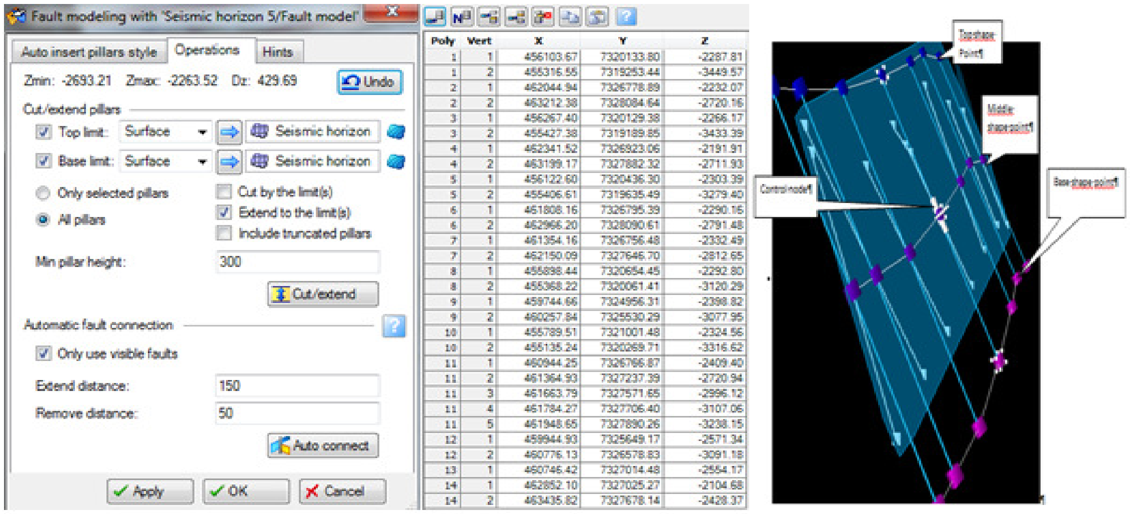
It is important that this interpretation is properly done such that it captures the actual geometrical shape and provides actual structural representation needed in creating the fault pillar grids. In the Norne seismic 3D volume, the reservoir section is dominated by minor and major fault planes, which are digitized in the 3D interpretation window to maintain their geometry across the several interpreted seismic lines (Figure 65). This process of fault digitization helps to maintain the orthogonality of the fault to avoid cases of faults cross cutting each other when making pillar grids. The faults are triangulated to maintain their orientation across the whole volume (Figure 65b). A single fault interpretation folder 1 was used as the only folder for all the interpreted manual faults, which means iterative corrections could be applied to the fault interpretation in a single swoop which makes the pillar grid process of the faults more efficient.



(a) (b)

Figure 65: The seismic section showing the digitized point mode faults and fault line surfaces (65a) and 65b shows the triangulation and/or digitization of the faults in the seismic volume.

This above process of manual fault pick interpretation in the section, digitization and triangulation are subset processes needed in the fault modeling. The modeled faults are needed as main inputs into the model frame as pillars, which are used with the respective horizon surfaces in the 3D grid. In this work flow each of the horizon surfaces in the reservoir section with their Top and Base are used in determining the fault depths to the respective horizons. The fault pillar heights, connectivity and their distances are iteratively chosen in the modeling workflow (Figure 66a). 14 fault polygons were modeled in the reservoir sections with each interpreted horizon surfaces in the reservoir section (Figure 66b).



Poly	Vert	X	Y	Z
1	1	456103.67	7320133.80	-2287.81
1	2	455316.55	7319253.44	-3449.57
2	1	462044.94	7326778.89	-2232.07
2	2	463212.38	7328084.64	-2720.16
3	1	456267.40	7320129.38	-2266.17
3	2	455427.38	7319189.85	-3433.39
4	1	462341.52	7326923.06	-2191.91
4	2	463199.17	7327882.32	-2711.93
5	1	456122.60	7320436.30	-2303.39
5	2	455406.61	7319635.49	-3279.40
6	1	461808.16	7326795.39	-2290.16
6	2	462966.20	7328090.61	-2791.48
7	1	461354.16	7326756.48	-2332.49
7	2	462150.09	7327646.70	-2812.65
8	1	455898.44	7320654.45	-2292.80
8	2	455368.22	7320061.41	-3120.29
9	1	459744.66	7324956.31	-2398.82
9	2	460257.84	7325530.29	-3077.95
10	1	455789.51	7321001.48	-2324.56
10	2	455135.24	7320269.71	-3316.62
11	1	460944.25	7326766.87	-2409.40
11	2	461364.93	7327237.39	-2720.94
11	3	461663.79	7327571.65	-2996.12
11	4	461784.27	7327706.40	-3107.06
11	5	461948.65	7327890.26	-3238.15
12	1	459944.93	7325649.17	-2571.34
12	2	460776.13	7326578.83	-3091.18
13	1	460746.42	7327014.48	-2554.17
14	1	462852.10	7327025.27	-2104.68
14	2	463435.82	7327678.14	-2428.37

(a) (b) (c)

Figure 66: Fault modeling operation operations with figure (66a) showing the surface/ horizon that defines the limit of the fault, with fault pillar heights and distances. Figure (66b) shows the worksheet data of the 14 manually interpreted fault polygons. Figure (66c) Shows each fault pillars with top,mid and base points witha control node used to define the shape of the pillars.

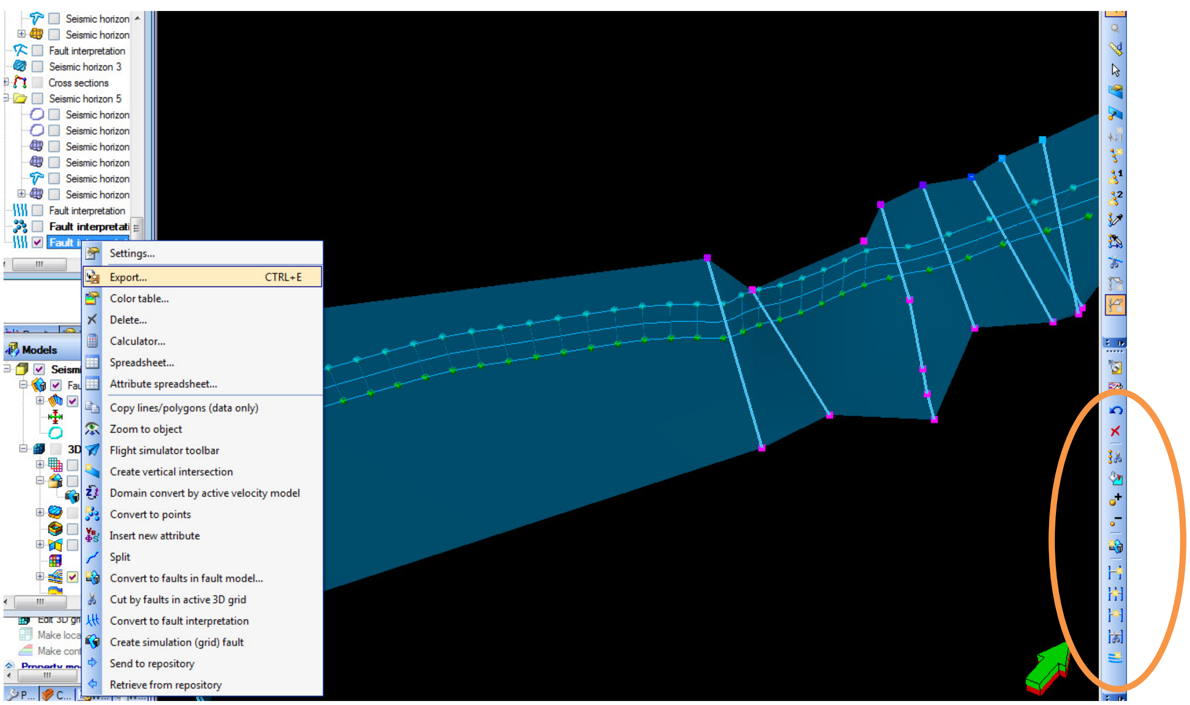


Figure 67: Interpreted faults connected with defined pillar dimensions with the circled area showing the I, J function tab use to define the truncations of each fault pillar.

7.2.1.1 Pillar Gridding

The process of fault modeling leads to fault gridding which is called pillar gridding, which represents the faults in a 3D grid system. The interpreted fault polygons in the fault interpretation folder1 are converted to fault sticks and polygons .In the reservoir section 14 sticks and polygons were generated (Figure 66b/65b). The stick represents line data of the interpreted faults and their geometry is maintained within the whole seismic volume through the modeling process of triangulation and digitization (Figure 67).

This process converts the interpreted faults from the fault modeling workflow into pillars in 3D structural grid surface or model frame. However, the consistency of the pillars must be checked against the geologic understanding used in interpreting the faults. The options of the nature of fault planes whether vertical, curve and listric are important inputs needed in maintain the structural interpretations of the fault in the pillar (Figure 68a). The editing pillar options are used to maintain the shape points, make relevant adjustments like cross cutting pillars, truncations (I and J functions), fault connections and other required adjustments. (Figure 68b and 68c)

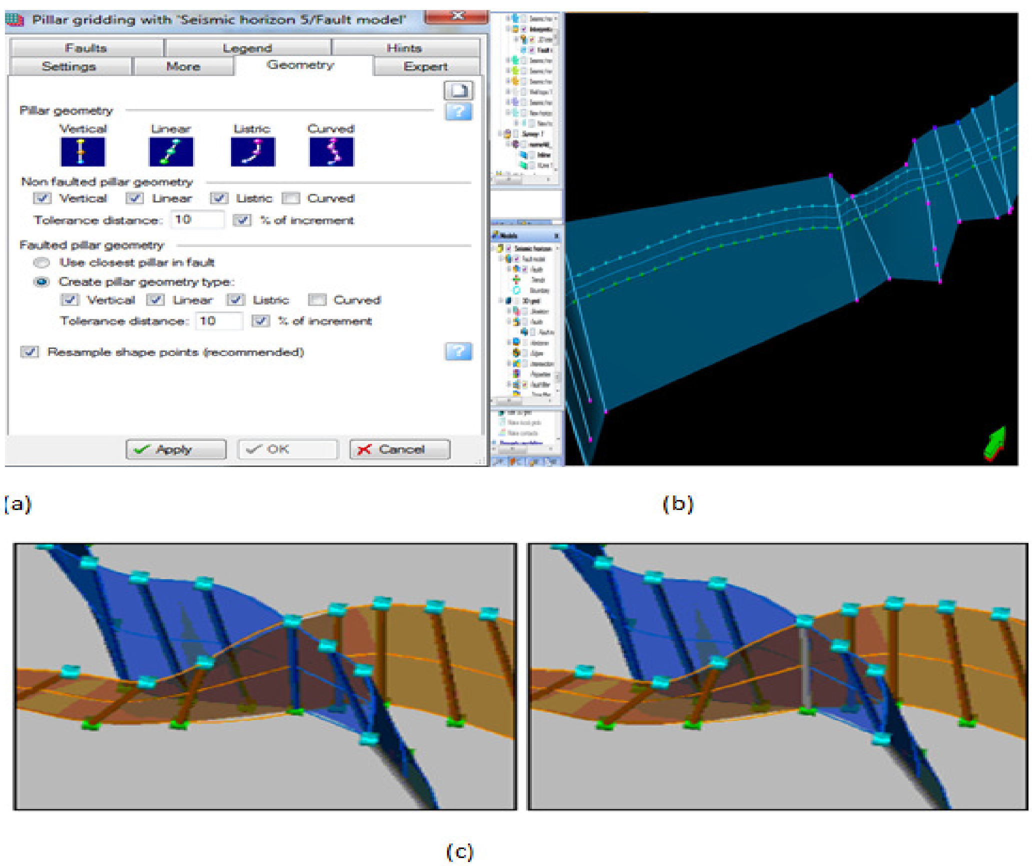


Figure 68: Pillar geometry type defined to show the nature of the fault in the 3D frame. (a) shows the fault geometry and pillar properties (b) the connected pillars of the interpreted norne manual faults and(c) crosscutting faults

Pillar gridding is used mainly to develop the skeletal framework of the faults, with the main purpose to guide the gridding framework and orient cells parallel to faults which are further converted into surfaces. The options of using the grids could serve the purpose of Geo- modeling of creating of static models and also in flow simulation grids.

The grid skeleton is a grid consisting of a Top, Mid and Base skeleton grid which are attached to the Top, Mid and Base points of the key pillars (Figure 69). The pillar grid parameters in the Norne field study consisted of the 3D grid increment 50 by 50, the gridding boundary area was limited to the depth surface, automatic rotation angle by faults and trends using the generated fault sticks. The observed problems of the grids were common with closely linked faults of shorter distances and also linking faults of different pillar geometry. The deep investigation to control the quality of the grid skeleton had been done to the Top, Mid and Base skeleton grids particularly folded grid cells and spikes grid events.

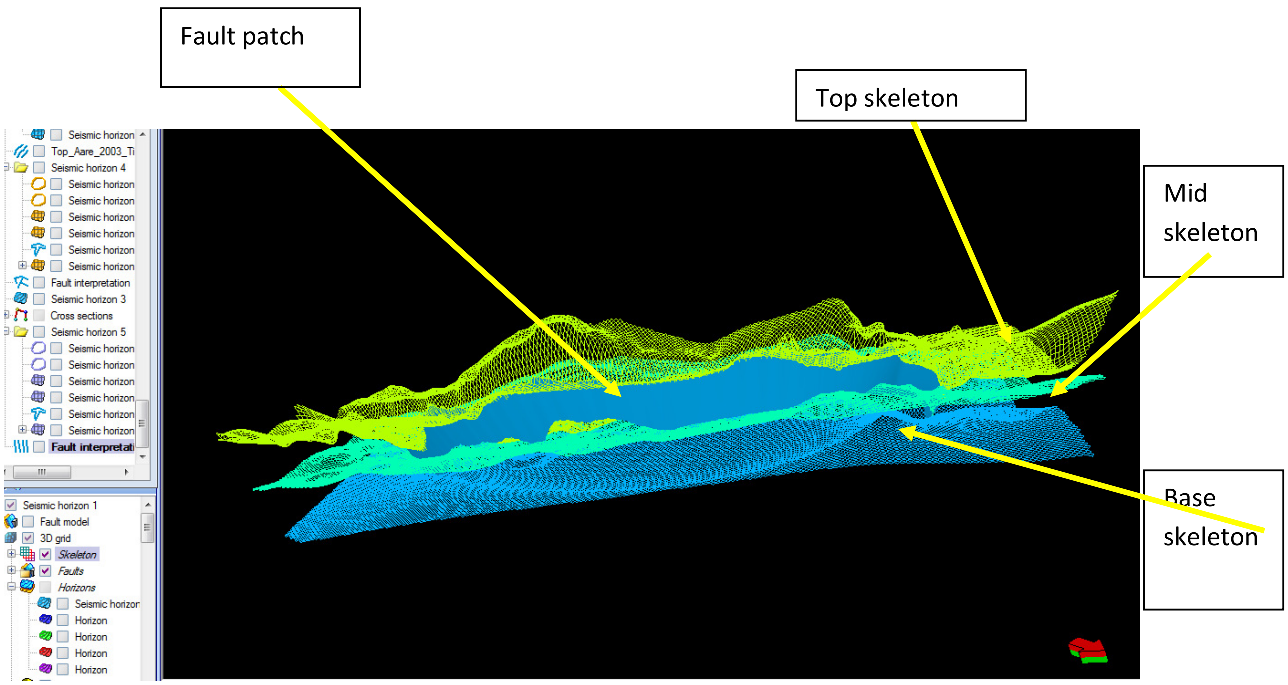
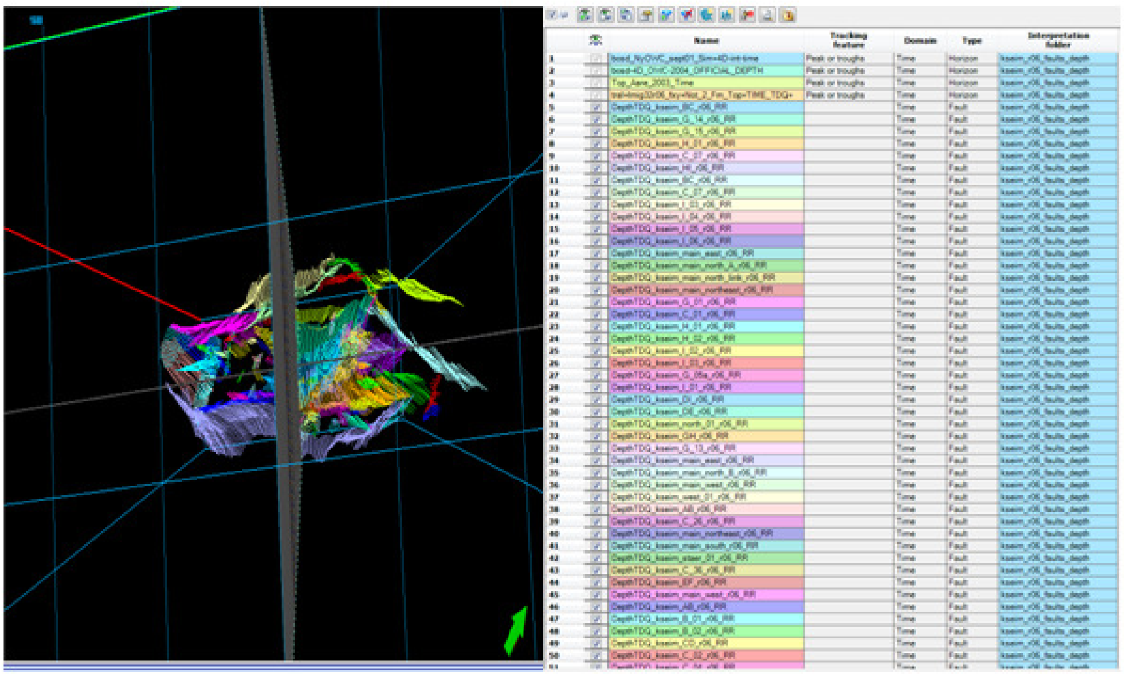


Figure 69: The grid skeleton with the top, base and mid skeleton. Showing the fault patch surfaces

It is important to state that this process is iterative since the generated fault pillars are closely involved with the gridding process. To produce an efficient fault pillar grids the modeling process must be effective enough to deliver the accurate fault interpretation from the seismic sections. Therefore it is necessarily to iteratively go back and forth on the fault modeling process in order to solve problems appearing in the gridding process.

The process of manually picking interpreting faults and creating pillars with guided techniques in fault modeling / gridding is a time consuming task. To guide this interpretation in the Norne field study the inputted fault sticks were used to quality check interpretations, which also were used to provide a quality control and visual inspection of the fault in comparison to the manual interpretation inputted fault sticks. The rendered sections of the fault with the seismic volume shows that the faults made segments of the reservoir and formed compartments on the interpreted seismic with the fault trends changing across seismic inlines and crosslines (Figure 70a and 70b). These fault sticks were not used as part of the modeling frame process since interpretations were based on different seismic vintages and line dimensions, they were only used as a control to modeling process.

A further advanced fault extraction technique was used as basis of comparison and quality control of the manual fault interpretations/modeling.



(a) (b)

Figure 70: Imported fault sticks showing main fault segments of the norne (figure a).Figure b shows the fault file of each imported stick.

7.3 Automatic fault Extraction Technique/Ant tracking

This process of fault extraction is a paradigm shift from the tedious manual interpretation of faults. Fault interpretation of large scale discontinuities/displacement of reflectors is easily interpreted in seismic sections since they are within resolvable or eye detection limits. However, sometimes it is difficult to capture minor faults within seismic sections. The reason behind its application to the Norne seismic data is to see how much it could contribute to the overall understanding in interpreting the seismic section in terms of the fault interpretations. Secondly, what are the added advantages that it could provide in terms of fault modeling process which is a key deliverable in the static 3D volume of the Norne seismic data.

The Ant track fault extraction technique was modeled in a pattern to emulate the characteristics or behavior of ant colonies in nature; the secretion of a hormone called pheromones helps the ant to follow defined pathways in their search for food or holes. Adopting this phenomenon in Petrel, 'virtual ants` or pheromones are used as seeds to seclude and/or interpret areas with discontinuity with the given seismic volume/voxels. The ant track is used to capture the discontinuity and also to deliver automatic fault extraction process for the models, the required key inputs are smoothened seismic volumes with chaos /variance attribute (Figure 31).

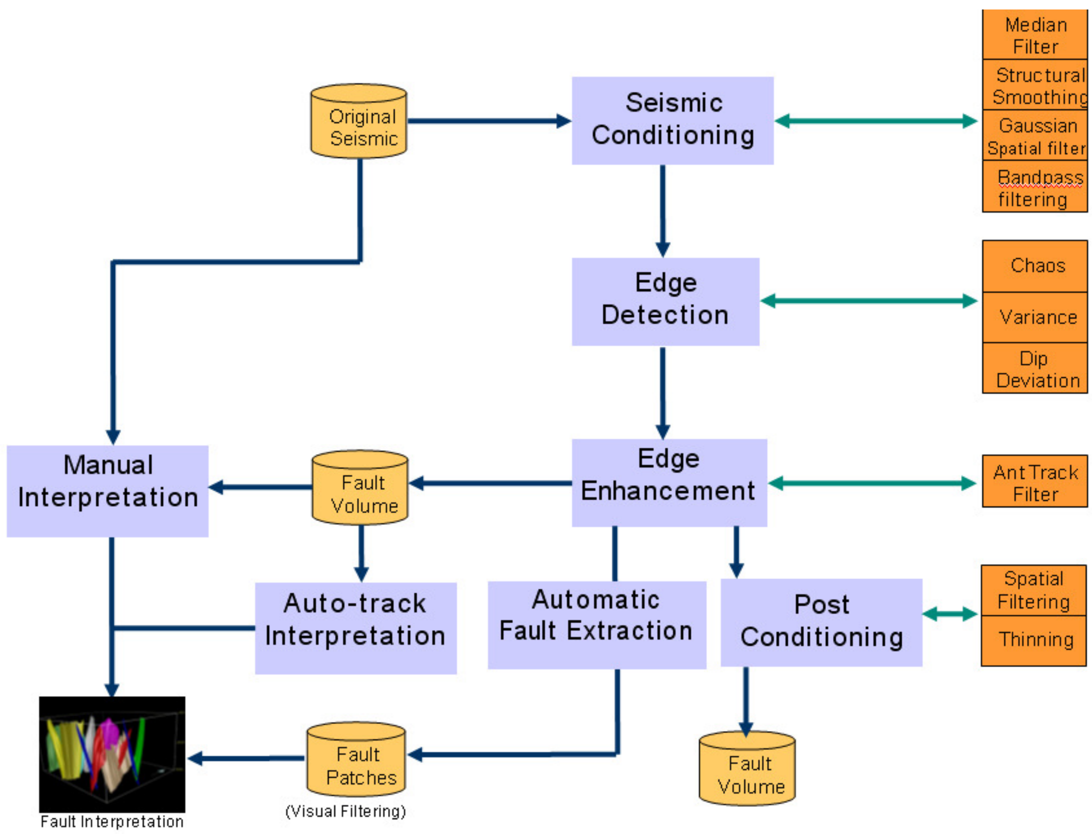
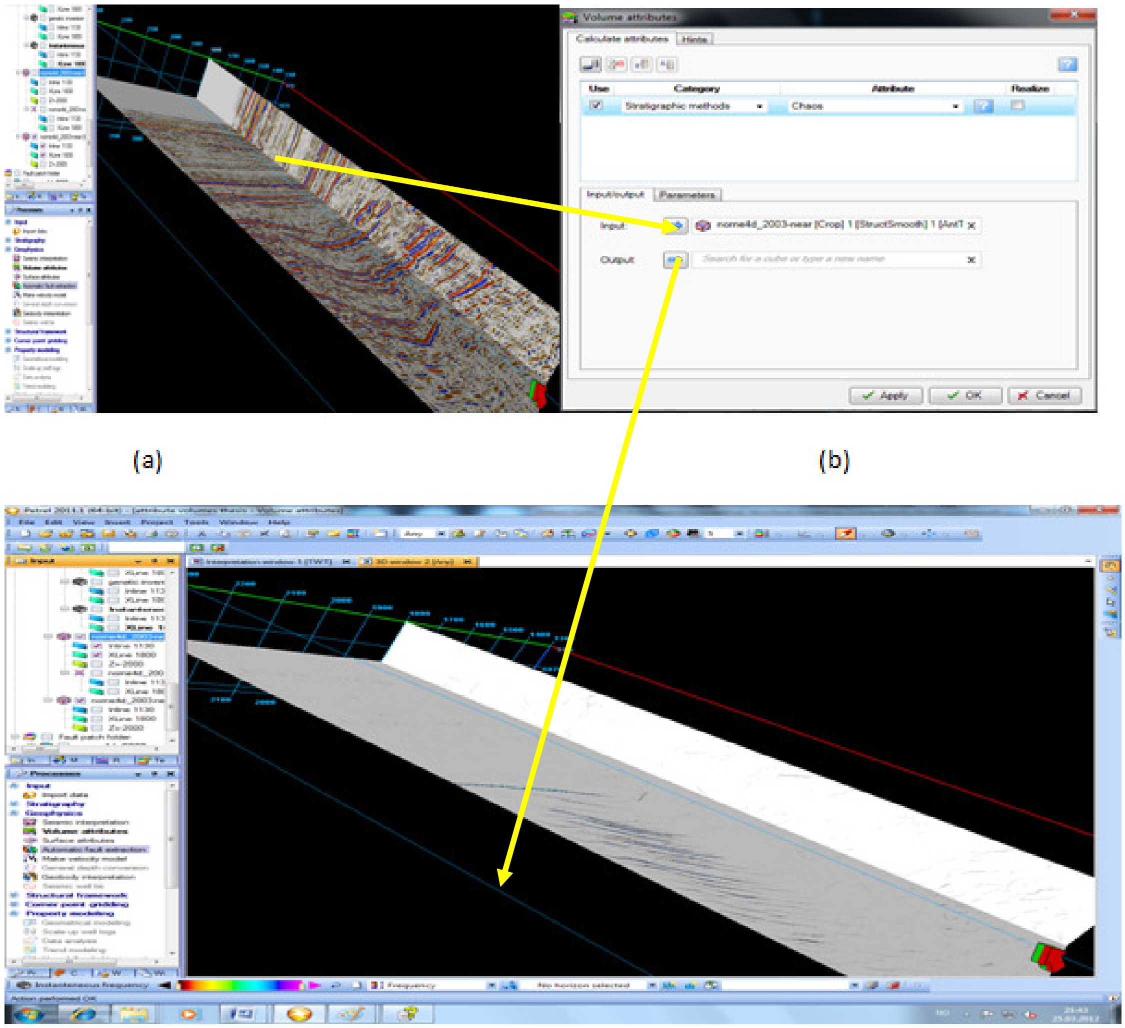


Figure 71: Diagrammatic workflow of the ant track process. (This picture was extracted from online Petrel manual)

The first process of generating ant track volume starts first by preconditioning the seismic volume (Figure 71). This means that the seismic volume should realized by creating physical copies and apply structural smoothening attribute (Figure 31). This is done to achieve the continuity of the reflectors to enable the ants to isolate easily discontinuous zones. The structural realized attribute volumes (Figure 72a) serve as input volumes needed to create chaos or variance volumes which are needed to determine the amount of disorganization or randomness in dip and azimuths as a basis to determine local chaotic textures and displacements for fault interpretation.



(c)

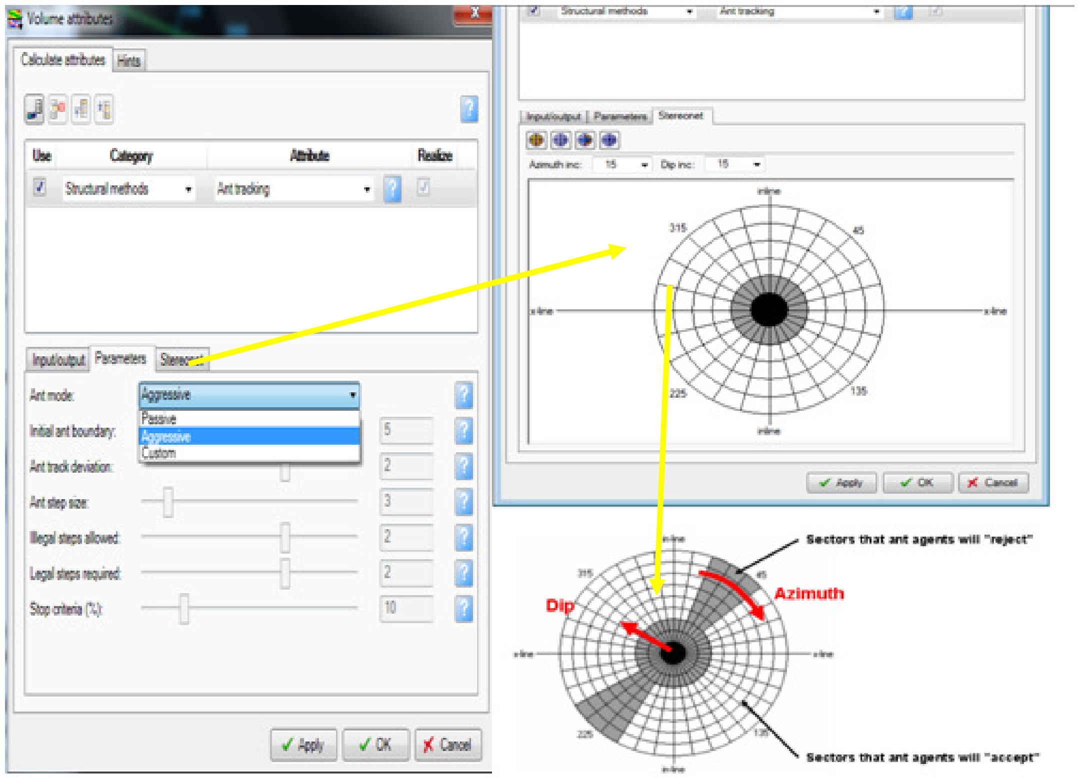
Figure 72:(a) Smoothened realized seismic volume. (b) Volume attribute template to generate the chaos. (c) Chaos Volume which helps to measure the discontinuity of the smoothened seismic volume

The generated chaos volumes (Figure 72c) are used as input volumes in the ant track template which is under the structural attribute volumes. The parameters of the ants are chosen to provide the coherent tracker called the `Swarm Intelligence' to detect discontinuities within each voxels. The user must determine the mode at which the ant agent would be used whether they are passive which is preferred to uncover major regional fault zones or aggressive which uncovers or extract both subtle and major fault. In the Norne ant extracted volume, the aggressive ant mode was applied to see how much it could illuminate subtle faults. Other parameters to toggle includes the initial ant boundary which determines the distance of the fault within each voxels, ant track deviation which enables the ants to search for a larger number of voxels and ant step size which is used to define the number of voxels that the ant agent would pass through in its search for discontinuities. (Table 1)

Name	Min	Max	Passive	Aggressive	Description
Initial Ant Boundary(Voxels)	1	30	7	5	Spacing of the initial ant agents. A larger number results in fewer ants ,and less detail captured
Ant track Deviation(Voxels)	0	3	2	2	Distance to look on either side of the tracking direction. Allows more connections between points
Ant Step Size (voxels)	2	10	3	3	Distance ant advances on a step(search distance to look for discontinuity), increasing allows ant to search farther but lowers resolution
Illegal Steps(voxels)	0	3	1	2	Defines how far beyond its search distance an ant can look if no edge was detected within its search distance. Larger value will connect more discontinuous faults
Legal steps(Voxels)	0	3	3	2	Number of the valid steps that must be taken after an illegal step before another illegal step can be taken
Stop criteria (%)	0	50	5	10	Percent of illegal steps (relative to all steps) that can be taken before an ant is stopped.

Table 1: A list and description of the ant agent parameters (Table extracted from Schlumberger Petrel manual)

The next parameter to toggle is the Stereonet tab which provides an orientation filters for the ant agents which places restriction to the azimuths and dips that the agents would allow for searching the seismic inlines and crosslines. Areas that are marked with gray shades are ignored by the ants which correspond to areas of particular inline/crossline zones (Figure 73a/73b) .The lack of adequate dip and azimuth parameters of the seismic volumes in the Norne data means that to optimize this technique with the stereonet would be a difficult prospect to achieve. To solve this challenge, sub -crop volumes were tested with different parameters as a basis to train the ants and optimize the actual parameter that would be preferred in the whole volume since this technique is a much CPU intensive process with approximate 20 minutes for a 100 Mbyte volume using with 2 Gbyte RAM and 1.7 GHz of CPU clock. This means that to see the effect of changing a parameter it takes a longer processing time, especially if you are to use the full field seismic volume.



(a) (b)

Figure 73: Frame (a) shows the ant parameter with ant mode, ant track deviation, ant step size. Frame (b) shows the stereonet showing sectors of the dip and azimuth with the seismic inline/cross lines

Using an azimuth increment of 15 and a dip increment of 15 on the seismic sub crop section (Figure 73b) distinct fault patches were automatically generated. Different Stereo net filters were applied on the sub crop (one advantage of using cropping technique in the visualization template) sections with observable changes in the areas of fault extractions within the sub crop section of the Norne seismic data (Figure 74 and 75). Using the automatic fault extraction tab in the process pane in Petrel with the ant track generated seismic volume as inputs, fault patches are automatically extracted for the full seismic volume of the Norne data (Figure 76).

The fault patches that were created from the automatic ant track process in the Norne seismic data when carefully considered were localized within the reservoir sectional fault zones but accuracy was a challenge due to lack of data in defining the stereo nets and the accurate ant parameters. This means from visual observation, that some manually interpreted faults with clear fault displacements were not picked by the ants while other fault surfaces were accurately captured. The fault planes that were interpreted included the main horst associated faults and other minor faults which were captured by the ants (Figure 74, 75 and 76b). Editing the fault patches is one way of correcting the nuances that the process might provide; this is done by visually inspecting the generated faults within the seismic sections. Also the patches that are extracted forms direct inputs into the pillar grid process by using the Extract fault patch tab (Figure 76a).

The ant track process has shown to provide unbiased objectivity and secondary control as an aid to interpreting fault zones manually. In the Norne field data it helped to localize the reservoir section zone as the area with more fault patches in the entire seismic volume. It also gives information to the fault details as to their trends /nature and provides a structural overview of the fault systems in respect to the entire seismic volume of the Norne seismic volume. Again it proves to provide a much faster interpretation and modeling of the faults when compared with the manual technique that is more cumbersome, using the extract fault patch tab which provides a quicker step to generate the fault into the 3D structural grids.

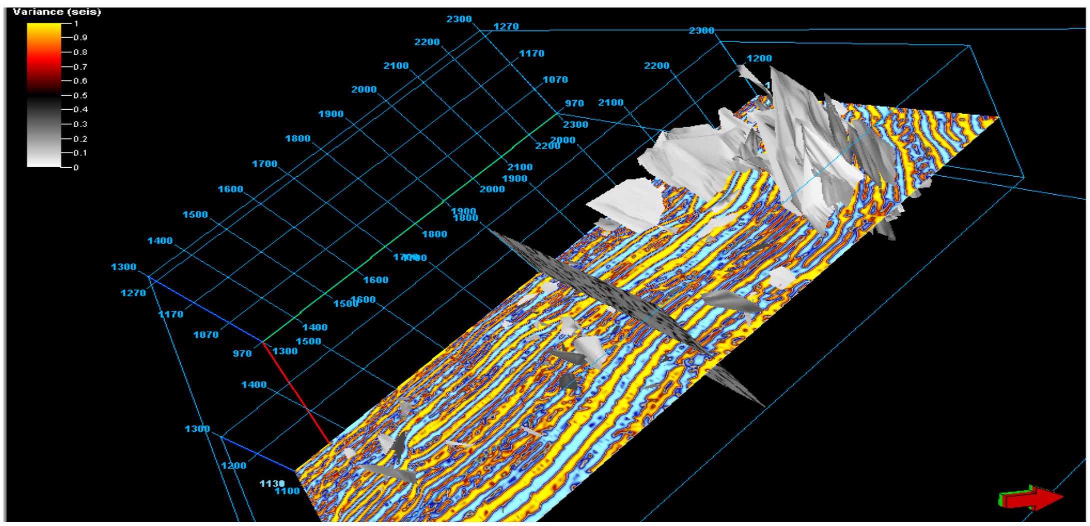


Figure 74: Fault patches generated with a cropped seismic section of the whole Norne seismic volume

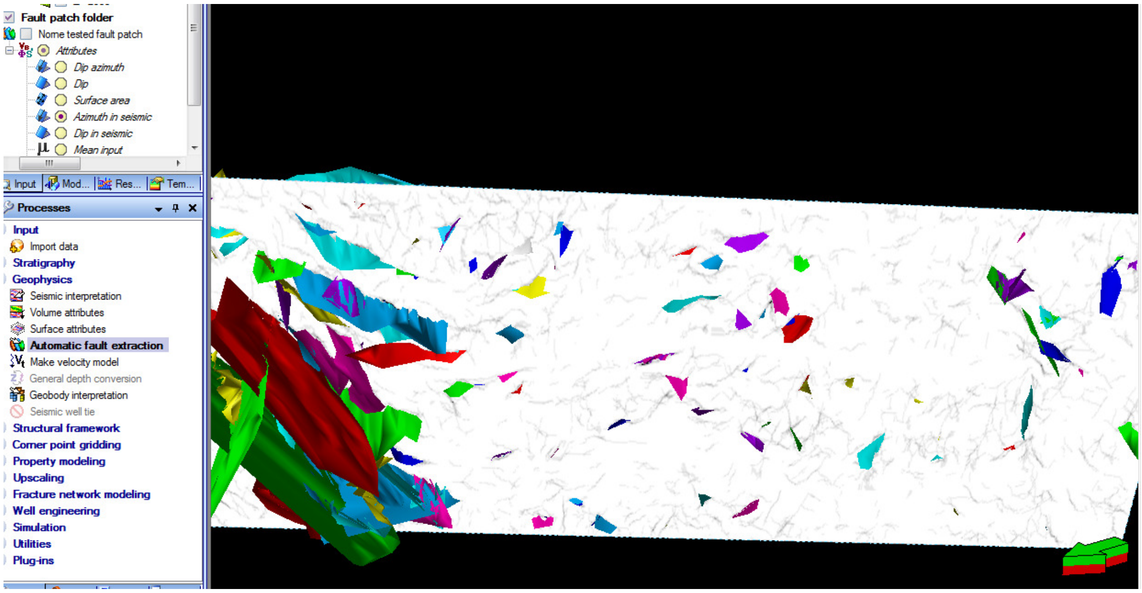


Figure 75: Extracted fault patchs with the choas attibute cropped seismic section of the whole Norne seismic volume.

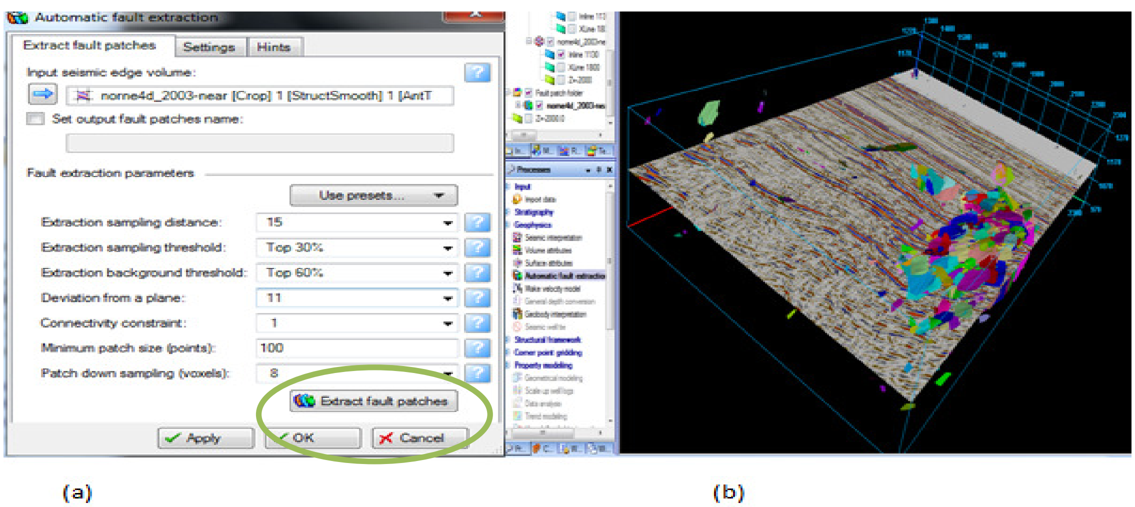


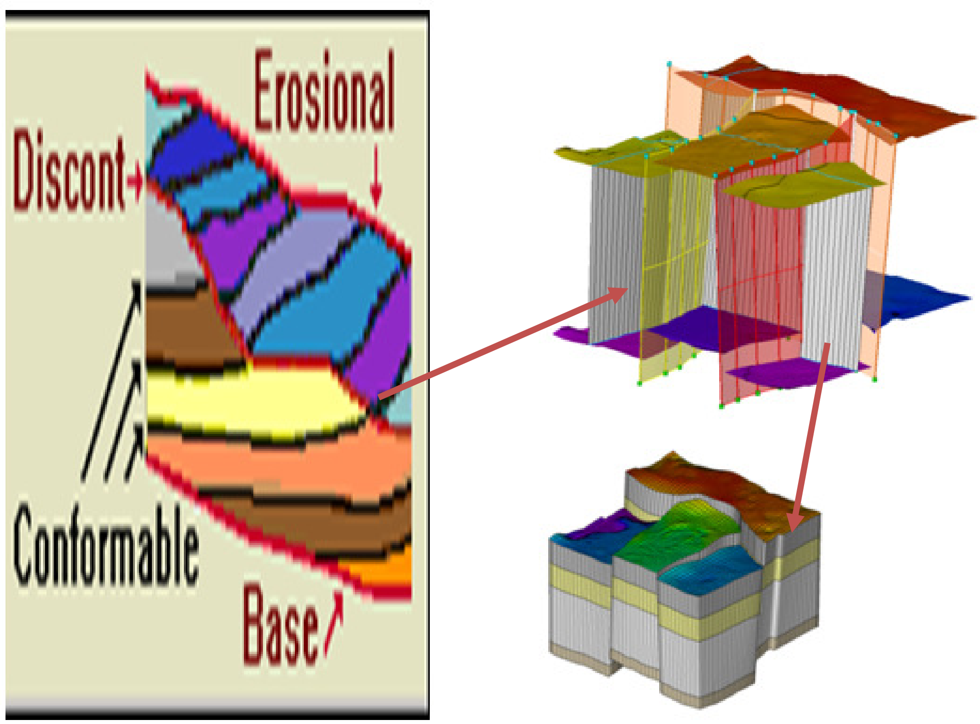
Figure 76: Frame (a) The automatic fault patch tab used to generate fault surfaces in the 3D grid model as seen with the circled green area. Frame (b) shows the whole Norne seismic volume with automatic fault surfaces generated.

In the Norne structural fault models the automatic fault process was adopted as a test case, much is needed to get accurate parameters in creating the ant agent, since this techniques offers a much faster and better solution to manual based interpretations and fault modeling.

7.4 Horizon making

This process is closely linked to the surface attributes and horizon interpretations which provides the needed inputs of surfaces of the respective interpreted surfaces of the BCU,and Top Garn ,Ile , Tofte Tofte and Tilje top surfaces.This process involves the creation and inserting these surfaces into the 3D grid.From the seismic interpretation window the make horizon tab is used to create each horizon surfaces which can be used as inputs into the Make Horizon process (Figure 78).

The modeling options for the horizons, geologic rules are provided to model each of the horizon as to whether they are erosional,base or conformable.The base type is the surface that onlap to the base, the conformable type is a surface that is conformable to the depositional surface(Figure 77).The BCU surface was treated as erosional, while the other reservoir tops were treated as comformable (Figure78) which means that user defined isochores(lines of equal thickness) would be used to carrying out the model of the zones.



(a) (b)

Figure 77: Plate (a) illustrates the geologic rules which is used as a basis in modeling the horizons.Plate(b) illustrates the zone and layering concept used in the structural modeling of the horizons.

The surface boundaries were used as key inputs from the seimic interpretation as the key dimension of the horizons, which means that the Edge control in the 3D frames is defined from this inputted dimensions.The settings allowed the use of a Convergent gridder method which is used to fill gaps in any undefined area,the fault displacement was set for each interpretated modeled horizon as 100.This gives 0 as the minimum to 100 as maximum displacement of the active faults to the modeled horizons, however these parameters are iterative as the models horizons are updated.

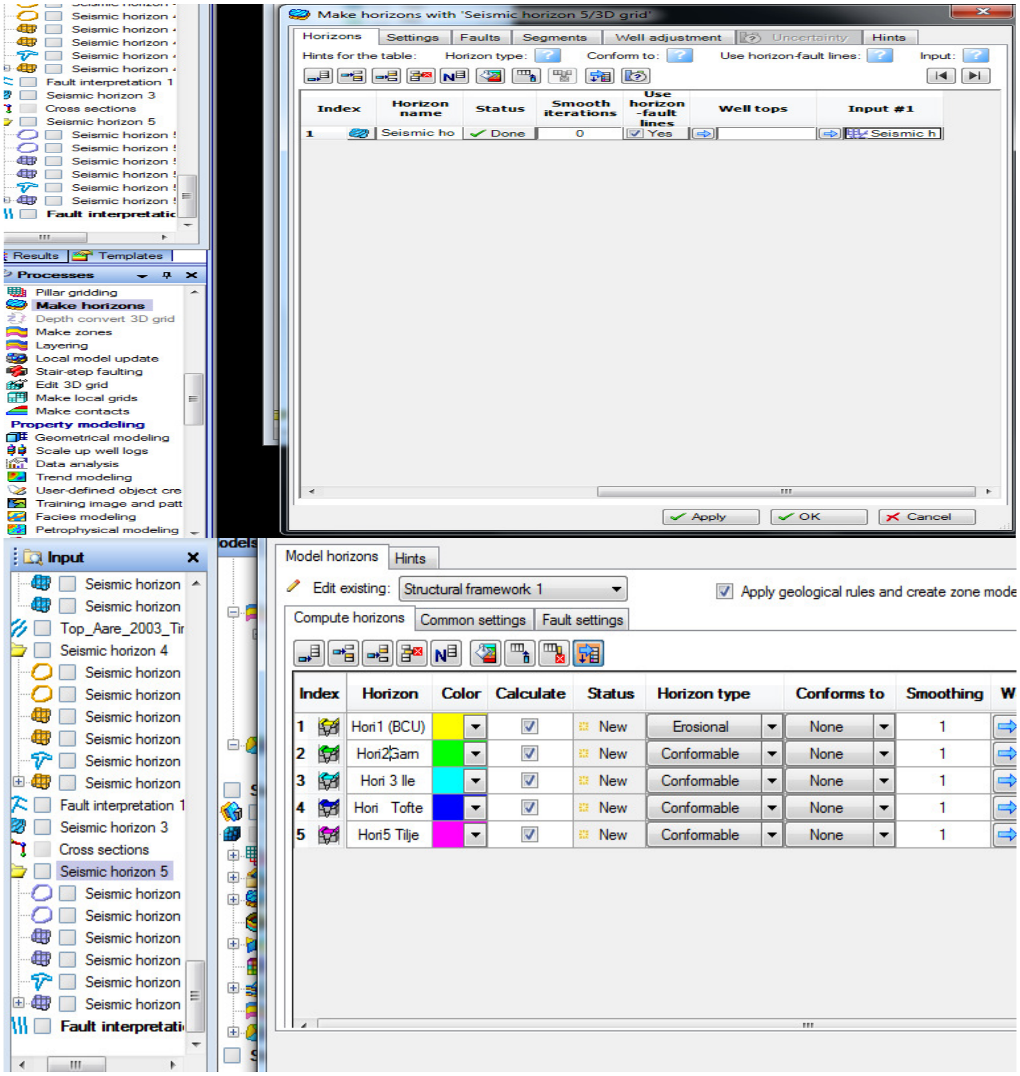


Figure 78: The modelled horizon pane, with interpreted horizons (BCU, and top Garn, Ile, Tofte, Tilje Formations as key inputs in the Make Horizon process.

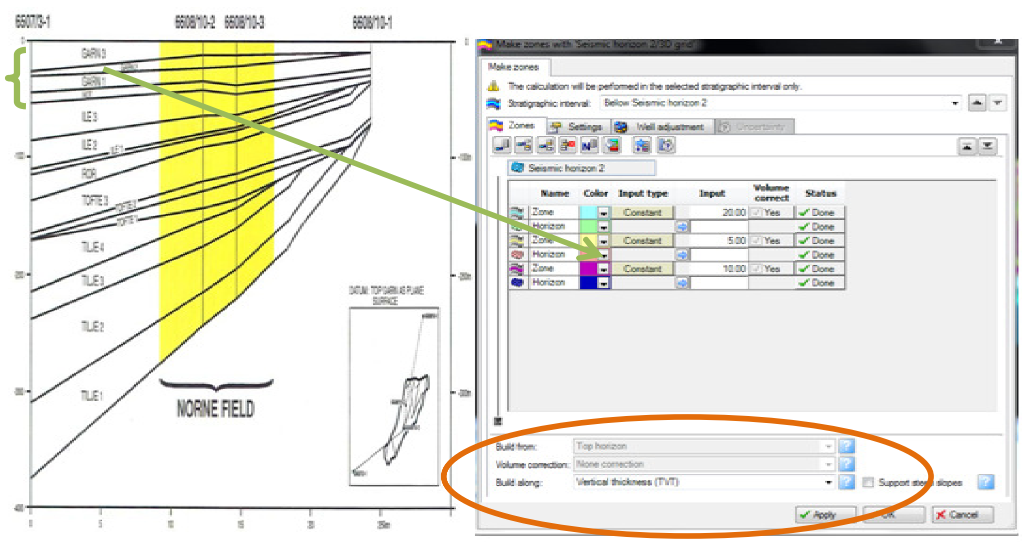
7.4.1 Make Zone process

In this workflow the Make Zone process proved relevant in differentiating each of the reservoir tops into their corresponsing reservoir zones.Zones can be added to models by introducing thickness data in the form of isochores, constant thickness and percentages.They are also interpreted and fitted into well log intervals to provide detail control to models.

This process has a parameter setting that is divided into three parts; the first is the Build From selection, Build Along selection and Volume Correction selection. It means that the zone could be built from the BCU horizon surface down to the Top Tilje Fm horizon or using both the base Tilje horizon and the BCU.The process of building from the top involves adding the isochores from the top of the stratigraphic interval or using a specific thickness interval. To build using both the top and base horizons could only be done with a reference zone defined as Rest zone. The constant thickness input approach was used due to lack of defined isochores.

The zone thickness of the Build Along selection can be done using True Vertical Thickness (TVT),True Stratigraphic Thickness (TST) or Along pillars. TST is the thickness of the zone as measured perpendicularly to the upper and the lower horizon of the zone. TVT gives the vertical thickness between the upper and the lower horizon of the zone.The Along Pillar is vertical thickness of a zone along the pillars.The TVT was used to build the zones which suits a constant thickness profile as adopted in this work.The Along pillars concept was not robust enough since some of the pillars were not vertical.

The Volume Correction is applied as a measure of the deviation of the isochore mismatch with the modelled horizons/zones.This error could be accounted for by proportionally or equally spliting them across the several zones, it was used as a check to quality in the zone process. (see figure 79b)



(a) (b)

Figure 79: Plate (a) The Norne stratigraphic formational units with subdivision, which was used as zones in the model frame. Plate (b) shows the model zone of the Top Garn reservoir with the circled area with 3 formation unit zones ,with the circled section showing the parameters type of the Build from, Volume Correction and Build along using TVT thickness

The Garn Formation is differentiated into three reservoir units of about 35m thick (Swiecicki et al 1998). Three zones were created for the Garn formation with Garn1 with an approximate thickness of 20m, Garn 2 with thickness profile 5m and Garn 3 with 10m (Figure 79 a/b).The Ile formation was differentiated into three reservoir units with an approximate thickness of about 40m used as the input thickness which is in agreement with Dalland et al (1988) description of the Ile unit This zonation was further cascaded to the Tofte(Figure 80) and Tilje reservoirs with the former having 3 differentiated units and the latter with 4 units of corresponding thicknesses respectively.

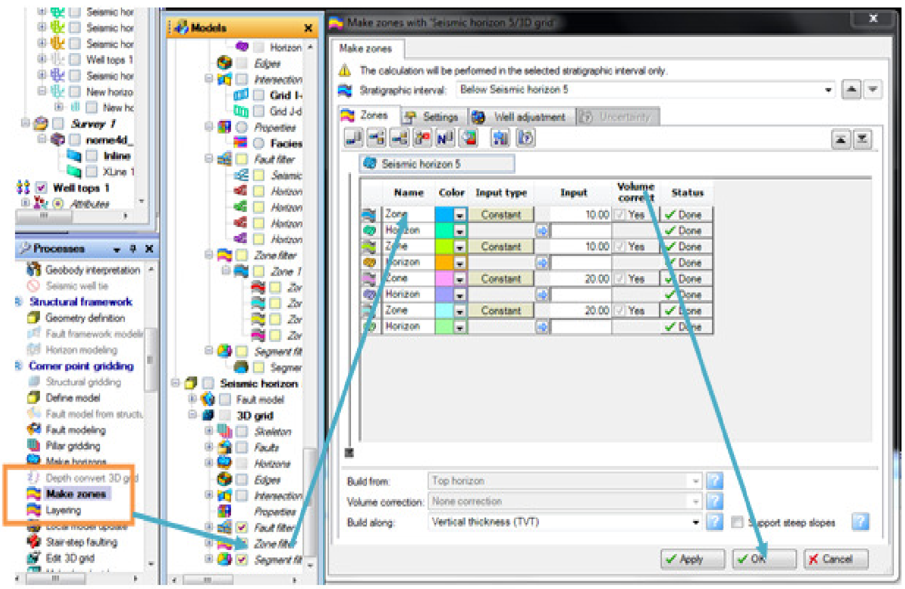


Figure 80: The Make zone process workflow, showing the Zone filter, TVT ,Volume correction tabs as applied to the TIlje Formation with 4 zones.

7.4.2 Layering

This process is used to provide a finer resolution to the zones, which requires providing the vertical resolution of each zone, cell thickness and corresponding layer properties in the models. The layer zone divisions in Petrel have the option of using Proportional method, Follow top, Follow base to define the layers. Proportional division is a constant number of cell layers at every pillar .The Follow top division is a cell layering with constant thickness parallel to the top of the zone, while the Follow base division involves cell layering parallel to the bottom of the zone

The layering process it is initiated by toggling the layering tab in the process pane(Figure 81) . Each interpreted reservoir zone was assumed as a single layer with a 1:1 zone to layer ratio of proportional method, this presents an idealistic representation of the units. However, it is known that the reservoir units like the Ile Formation has calcareus layers which could be isolated within the zones, also shaley layers /stringers are not uncommon in some of the reservoirs which means that detailing these events could be differentiated from well log correlation and fitting their interpretations into the zones / horizons thereby updating the models.

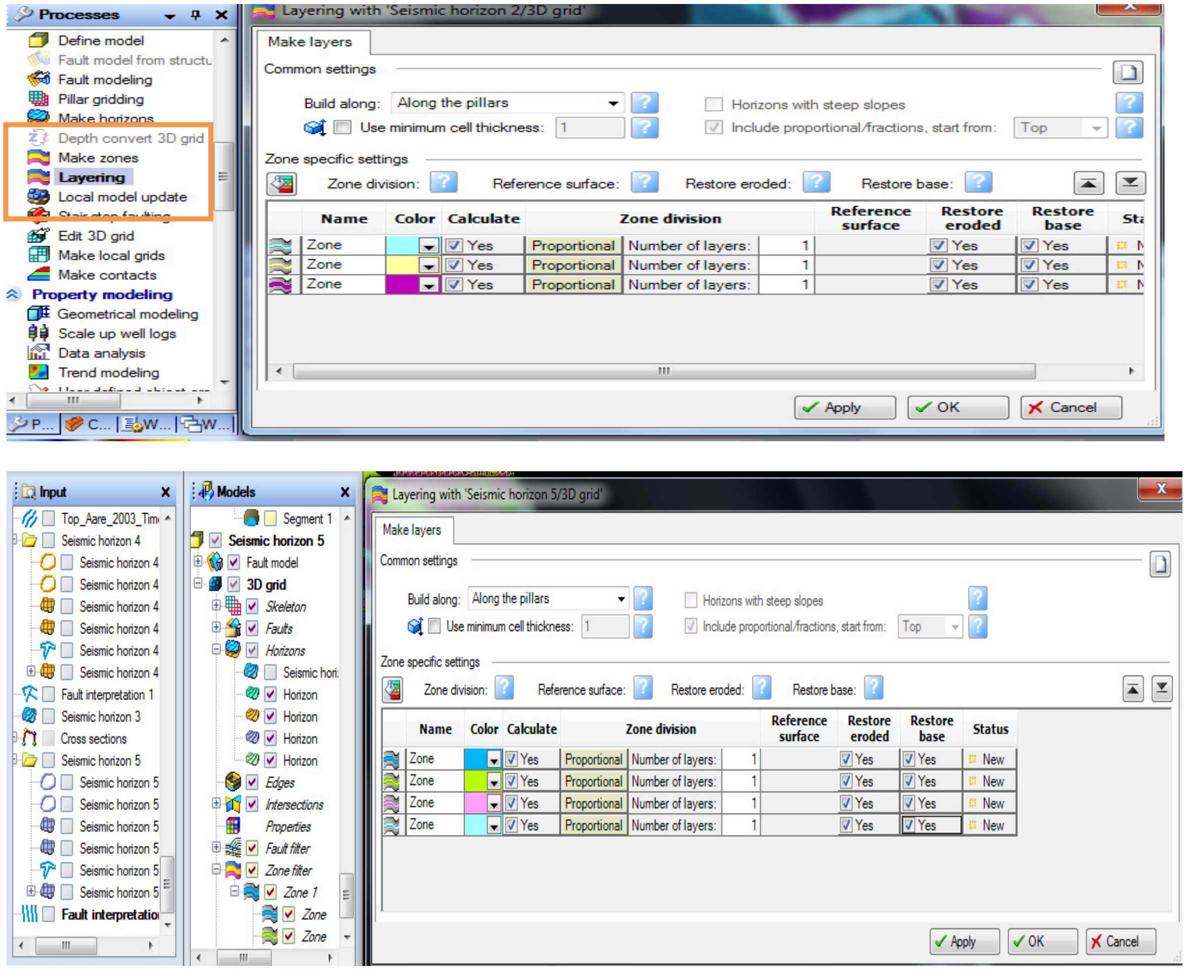


Figure 81: Layering technique initiated with the layering tab indicated with the squared boxed area in the process pane in Petrel

7.4.3 3D structural grid Surfaces

The final structural modeling is in the creation of 3d structural grid surfaces, which comprise both the fault modeled pillar grids/models and the horizon surfaces. The skeletal framework of the base, mid and top skeletons inputted with the edges which provides the structure frame as geo-modeling grids which could serve as simulation grids for dynamic fluid analysis or static model for other modeling work. The zones / layering of the each of the reservoir models with filters are displayed in the 3D grid except for the BCU top skeleton which is an unconformity surface. (Figure 82, 83, 84, 85 and 86)

It is interesting that the positive horst structural reliefs were characteristically defined as areas within the model which had positive features in the grid and the negative relief captured the graben deposits. 3D Visualization of the structural model with the Norne seismic volume is one good way of performing a visual inspection of the 3D structural frame model as a quality control process which gives a better picture of the variability of the grid surfaces across the seismic inline and cross lines (Figure 87)

This 3d grid surfaces of the reservoir tops of the Garn ,Ile, Tofte , Tilje Formations (Figure 83,84 ,85 and 86) forms the input grids for property modeling (populating the grid surfaces with other properties) which might include facies, saturation models, trend, petrophysical modeling etc.

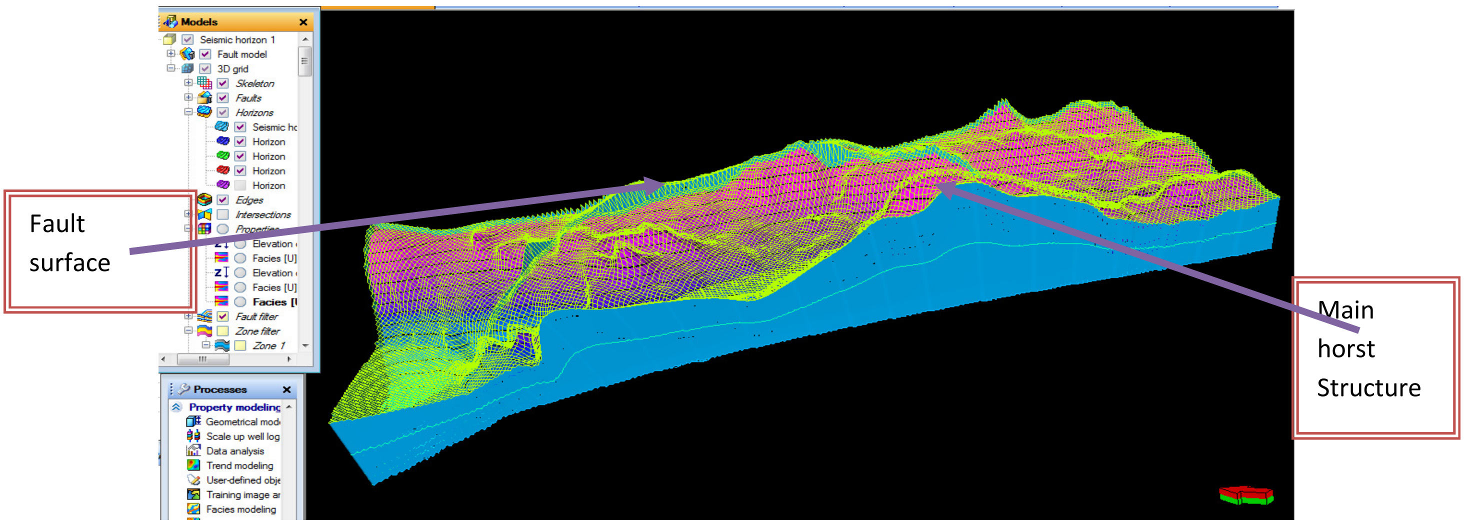


Figure 82: Interpreted 3D structural grid skeleton for the BCU surface

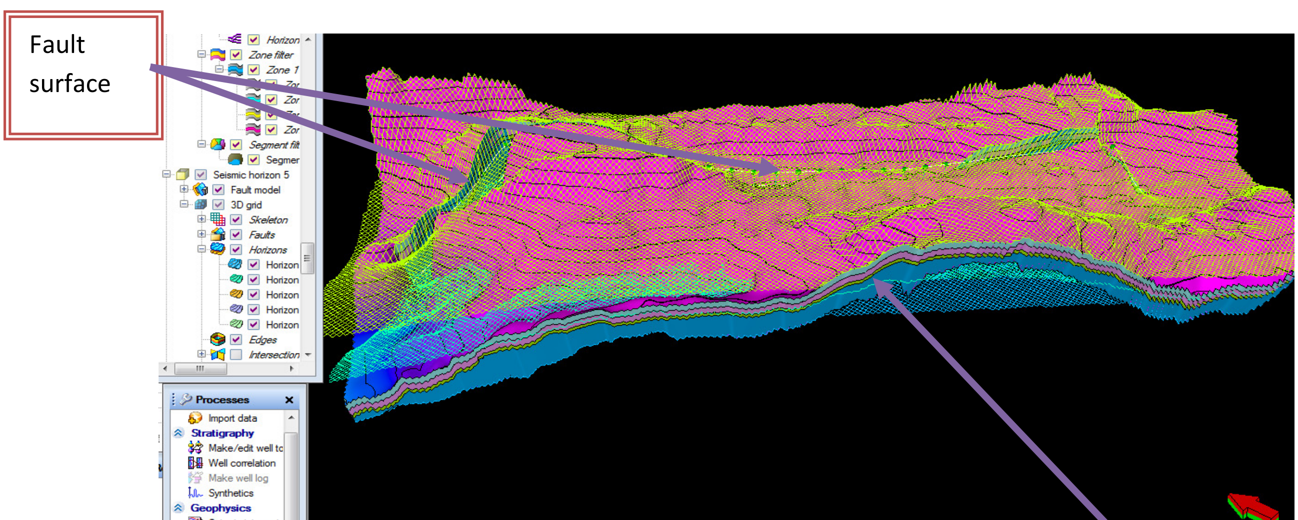


Figure 83: Interpreted 3D structural grid skeleton for the Top Garn surface

Main
horst
Structure.

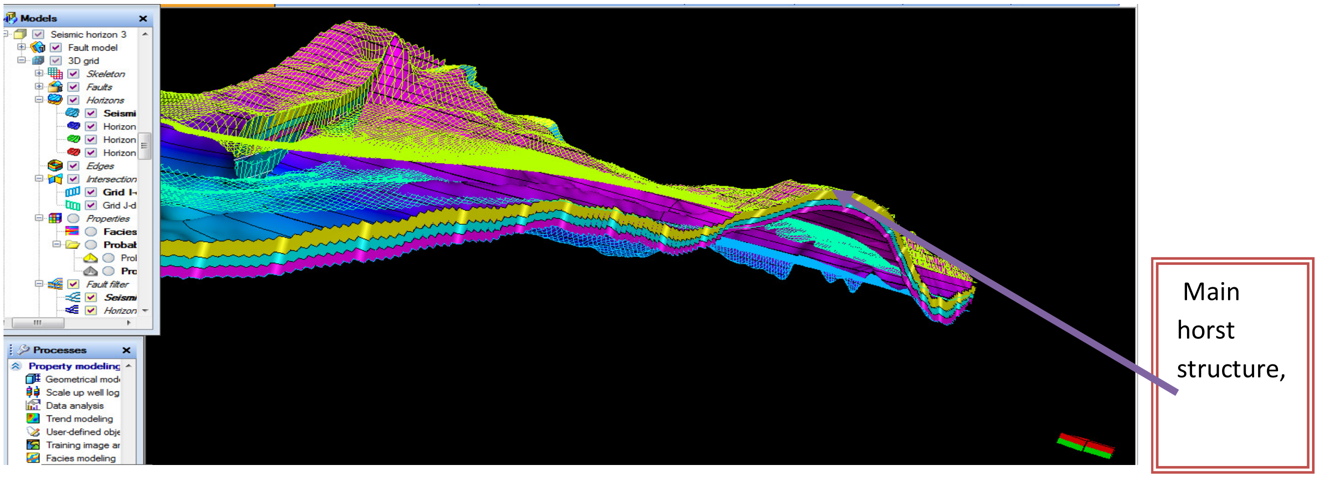


Figure 84: Interpreted 3D structural Grid skeleton for Top Ile surface

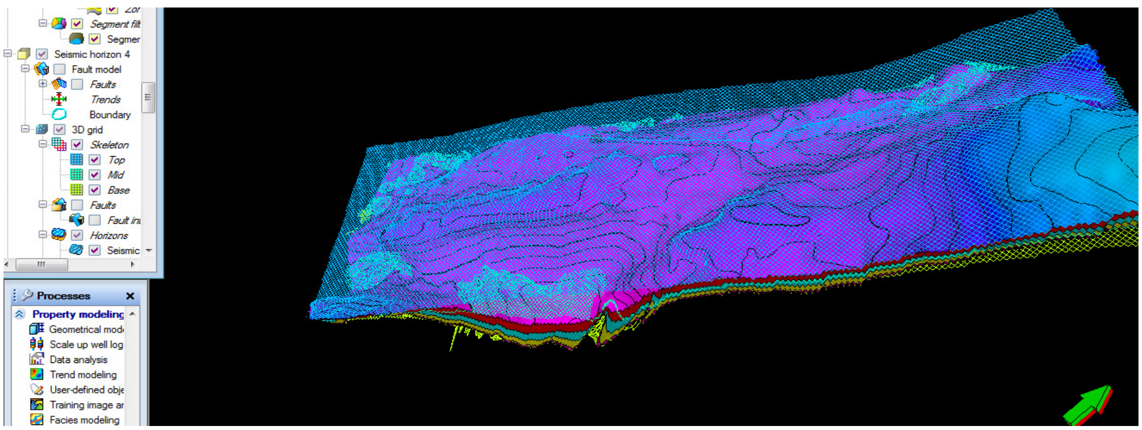


Figure 85: Interpreted 3D structural Grid skeleton for Top Tofte surface

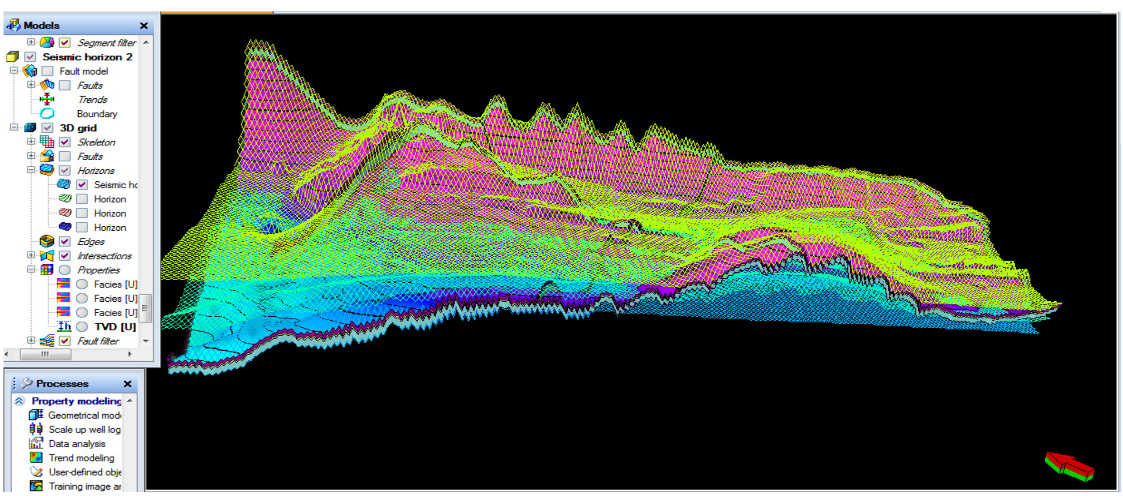


Figure 86: Interpreted 3D structural Grid skeleton for Top Tilje surface

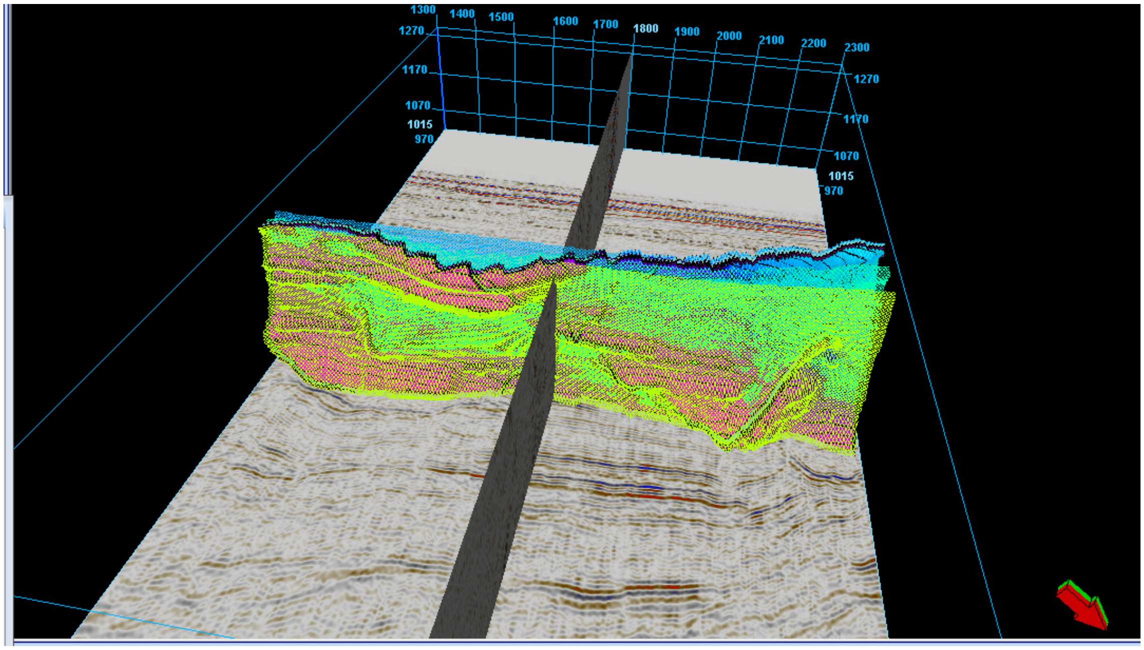


Figure 87: Model to seismic tie as a quality control inspecting the 3D structural framework.

8. Property Modeling

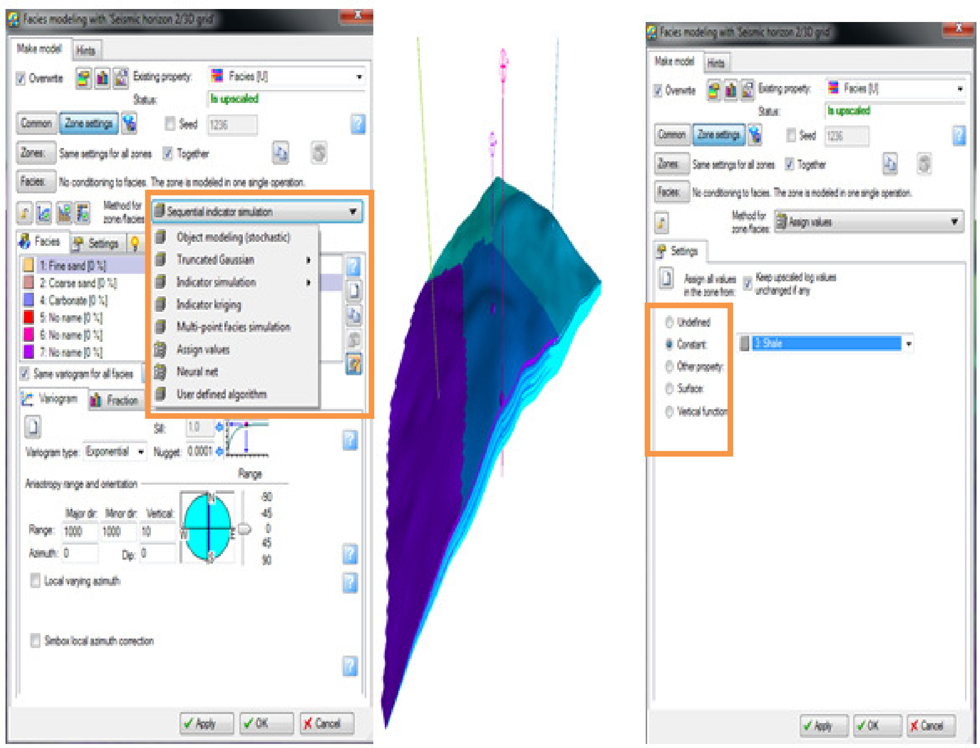
The 3D static models from the structural modeling workflow of the interpreted reservoir surfaces of the Norne seismic data are populated with discrete properties from inputted well logs to understand the property distribution and/or heterogeneity of each reservoir surfaces. The property modeling workflow in this study consists of facies well log interpretation for facies modeling where discrete facies are distributed thoughout the model grid, well Upscaling, data analysis and Petrophysical modeling.

8.1 Facies Modeling

The process of facies modeling involves the property distribution of up scaled discrete facies in the 3D model. This process is initiated by well log interpretation of different lithologies as facies types, which are upscaled to the model dimension as discrete values or interpolated to define property trends across the 3d model frame. Two basic algorithms or techniques (Deterministic and Stochastic) are applied in the process of estimation or interpolation of discrete facies property.

The Deterministic algorithm is applied when single estimated result with the inputted facies data from well log is needed, which means that particular cells in the Model grid have single facies values. This is much applied when denser data are available (e.g. more wells) in relation to the model frame and it provides quicker property simulation since less smoothening or extrapolation of properties are needed across the model. Deterministic algorithm is further classified into four basis methods in Petrel, which includes the Indicator Kriging, Assign values, Neural Net, and User defined algorithm (Figure 88a).

The Indicator Kriging is use for discrete distribution of property by honoring a predefined histogram using the kriging estimation technique as the basis to express spatial variability in discrete facies. Assign value method is applied to update the discrete output values of upscaled facies properties; five options are provided which includes Undefined, Constant, Other property, Surface and Vertical function (Figure 88c). The Neural Net method works by using the train estimation process which is a classification algorithm to create discrete property. The User defined algorithm provides the flexibility to export working Ascii file from Petrel in standard Geo-EAS format which allows the user to define properties which could be specific or tailored to the models. It allows the external file to be reimported into Petrel workflow (Figure 88a).



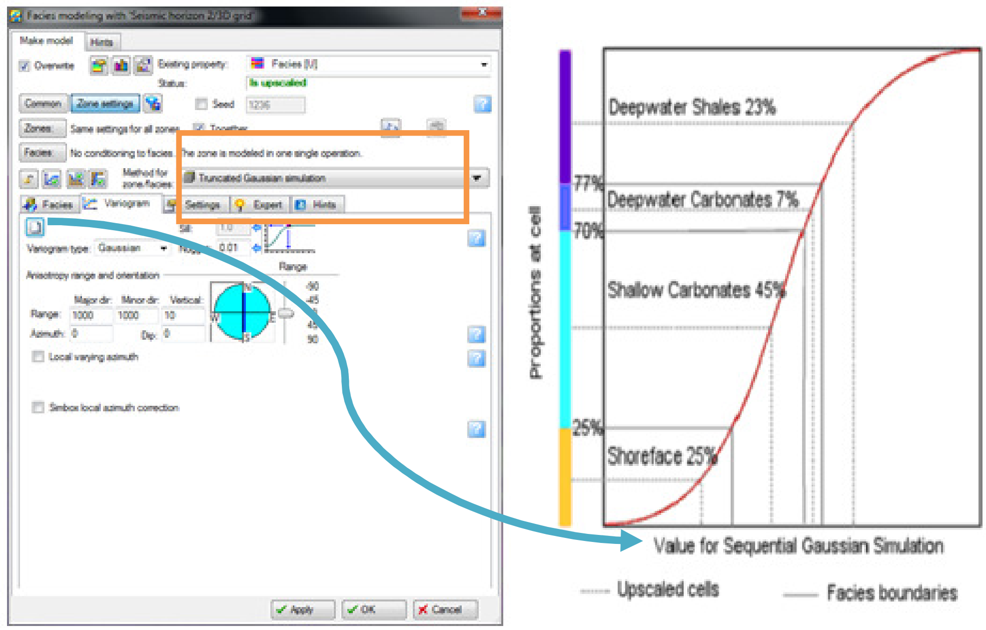
(a) (b) (c)

Figure 88: Facies modeling templates.(a) The pink rectangular box shows the different methods used for facies modeling , with zone and variogram settings .(b) captures facies simulations in Petrel using the sequential indicator simulation (c) shows in the pink box the five types of assign value method.

The stochastic algorithm uses random seeding to the input data to maintain the variability; it is mainly applied with sparse data density especially when using few wells as imports in the property/facies building process. The randomization of property using this technique poses challenges to uncertainties on models in honoring the geologic interpretation of the discrete properties (facies), which means that data analysis and property trends are critical quality control measures needed in using this algorithm with upscale discrete log properties. Furthermore, the seeding of discrete data could be applied at different iterative levels which are used as a control of the degree of randomization in testing out the property distribution. The algorithm is divided into other sub categories or methods as Object modeling, Truncated Gaussian with trends/simulation, Sequential Indicator/Simulation and Multi-point facies simulation (Figure 88a and 88b).

The object modeling is use to populate the models using objects as a discrete facies property. Definition of the object dimension, geometry, trends, facies code and type of fractions are needed inputs. This technique has probable application in populating Geobodies extractions from seismic probes with reservoir properties. It also could provide object expressions to large scale sedimentary structures such as channels in fluvial systems. The Sequential Indicator simulation is applied when objects or facies bodies are ill-defined by allowing stochastic distribution of properties; key inputs includes random seeds, variograms, frequency distribution of upscaled well points with discrete facies zones (Figure 88a).

The Truncated Gaussian simulation is a stochastic modeling technique for discrete properties with predefined variogram and trends (Figure 89). It is used mainly where there are transitional facie sequences changes for example in carbonate to lagoon /shoreface deposits, this is because it defines a cut off range in the Probability density function (PDF) curves for each upscaled facies sequence which are defined by the user based on log interpretation. The result of the process is based on the chosen Variogram type that is selected, seed and up scaled well logs as inputs. It is claimed to be adequate in modeling carbonate environment since it is a pixel based method which could take large amount of data with faster simulation.



(a) (b)

Figure 89:Facies modeling algorithm (a) shows the model tab of the truncated Gaussian simulation (b) Shows the TGS/SIS modeling of determining facies boundaries of transitional depositional settings with up scaled cell values which are used for the sequential Gaussian simulation.The green curve arrow points to the facies points which are used as direct inputs in the simulation.

The Truncated simulation with trends is used for stochastic analysis with define transition in facies and common trends (Figure90). Like the truncated simulation the variogram is tweaked as probability trends which are simulated. It is applied in geologic settings where there is an observable trend in facies successions; for example, in deltaic systems of pro, front and plain successions, this transition is based on well-defined zonal interpretation of the transitions which are up scaled for trend simulation.

Multi-point facies simulation is a more advanced technique which adopts a pixel based algorithm to create objects related models (Figure 88a). It applies the sequence simulation algorithm but it is mainly adopted to create models in complex geologic settings with rather complicated simulation or facies distribution. The critical input is the training image (TI) which is like the variogram in the sequential indicator simulation to create prototype objects needed to run the simulation in the model. This also could find great application in using geobody inputs from seismic and attribute function as objects needed in populating the 3D models.

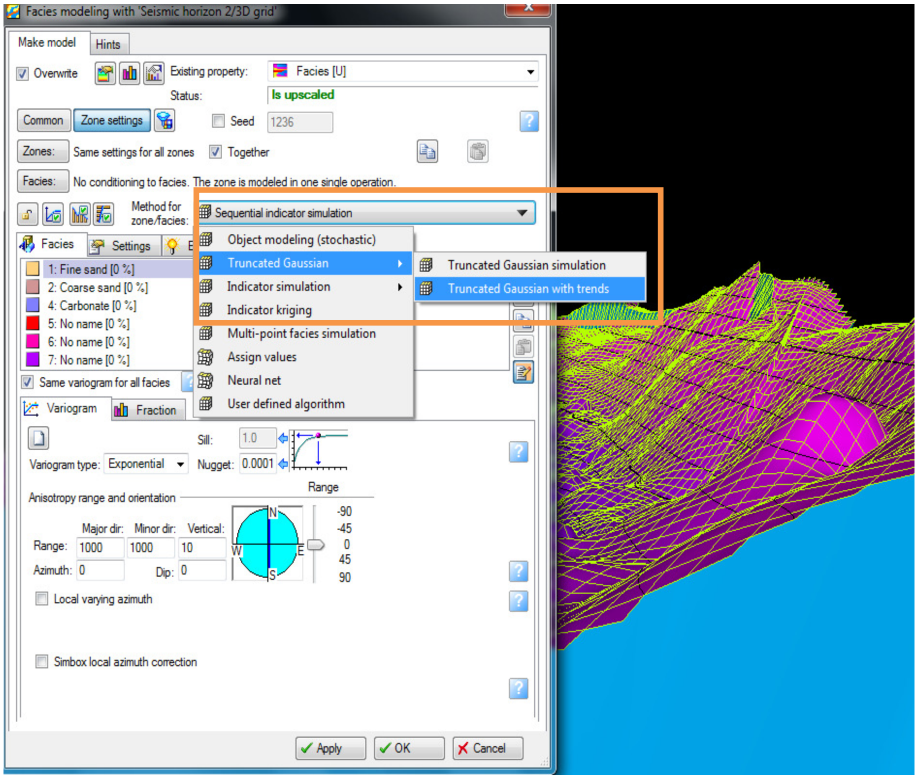


Figure 90: The truncated simulation with trends as captured in the pink rectangular box.

In application to the Norne field data, since the well sample points (11 wells) are rather sparse in comparison to the 3D grid models, the deterministic algorithm with single point extrapolation would not be robust enough to populate the models with discrete facies, hence stochastic algorithm was applied. The reservoir formation tops and properties were distributed using mainly the sequential indicator sequence where the properties were extrapolated using upscaled well log interpretation of facies within the interpreted reservoir log sections, seed selection with variograms scales defined. Data analysis was used to cross check the facies interpretation after the process of up scaling the well logs to the reservoir models.

8.2 Facies log Interpretation

Facies log interpretation based on the imported well logs of wells 6608/10-E-2H,6608/10-3H,6608/10-F-1H,6608/10-B3H,6608/10-C-3H,6608/10-D-3H,6608/10-F-4H,6608/10-K-3H,6608/10-C4H,6608/10-K-1H and 6608/10-B4CH.The convectional well log template was activated showing the different logs available for interpretation which includes the Resistivity, Gamma Ray , Neutron and Density logs etc. The facies interpretation is based on differentiating the log motif of each interpreted reservoir surface based on two main lithologic facies of Sands and Shales which is a rather coarse interpretation. The inputted Top Åre and Not reservoir interpretation from the Statoil horizon reference interpretation was used to delineated and control the interpretation of the other reservoir surfaces. The interpretation from both horizons (Not and Åre formation tops) showed that the reservoir thickness was approximately 200m from the well sections (Figure 91).

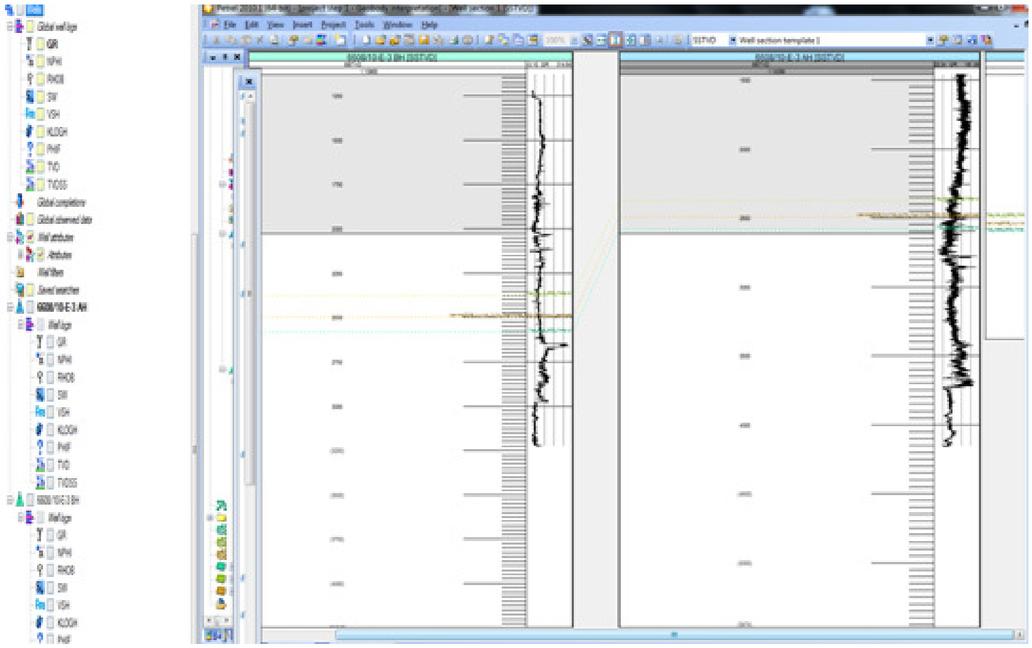


Figure 91: The Statoil inputted formation tops of the Åre and Not reservoir used to control the interpretation of the other interpreted reservoirs

The Gamma ray log was mainly used since it was available for correlation purpose across the entire inputted wells. The neutron and density was used as quality control of the Gamma ray interpretation in the wells where they were available. The Gamma ray was interpreted with a cut off range with high values of gamma log interpreted as shales and low values as sands. The neutron density log show areas of shale zones with high separation of both logs which help to establish shaley lithologies. The interpretation of each reservoir surface showed that the reservoir was not purely composed of sands with intercalated shales observed in some of the reservoir surfaces. These interpretations were further delivered to the well correlation panel based on different TVDSS (True Vertical depth SubSea) of each wells (Figure 92).

The target of the well interpretation was localized within the reservoir section and isolated facies zones were interpreted in respect to the interpreted surfaces. It is also important that user defined interpretation of the facies units, zonal logs/isolation, and time stratigraphy are updated into the Global well log settings. This helps to position or isolate user based interpretational to the Global well properties of each of the wells to the 3D structural model for up scaling purpose.

The purpose of this interpretation is providing discrete properties of the facies in modeling the 3D grid. The grid cells must carry single value properties or each cells of the grid must carry geologic properties in the actual representative scale of the cells (Geocellular modeling). Since the grid dimensions are larger in relation to the discrete log properties, the well logs have to be scaled up to the grid dimension. The facies interpretation of the wells are necessary entry inputs for the process of Upscaling or what is also referred to as blocking of well logs.

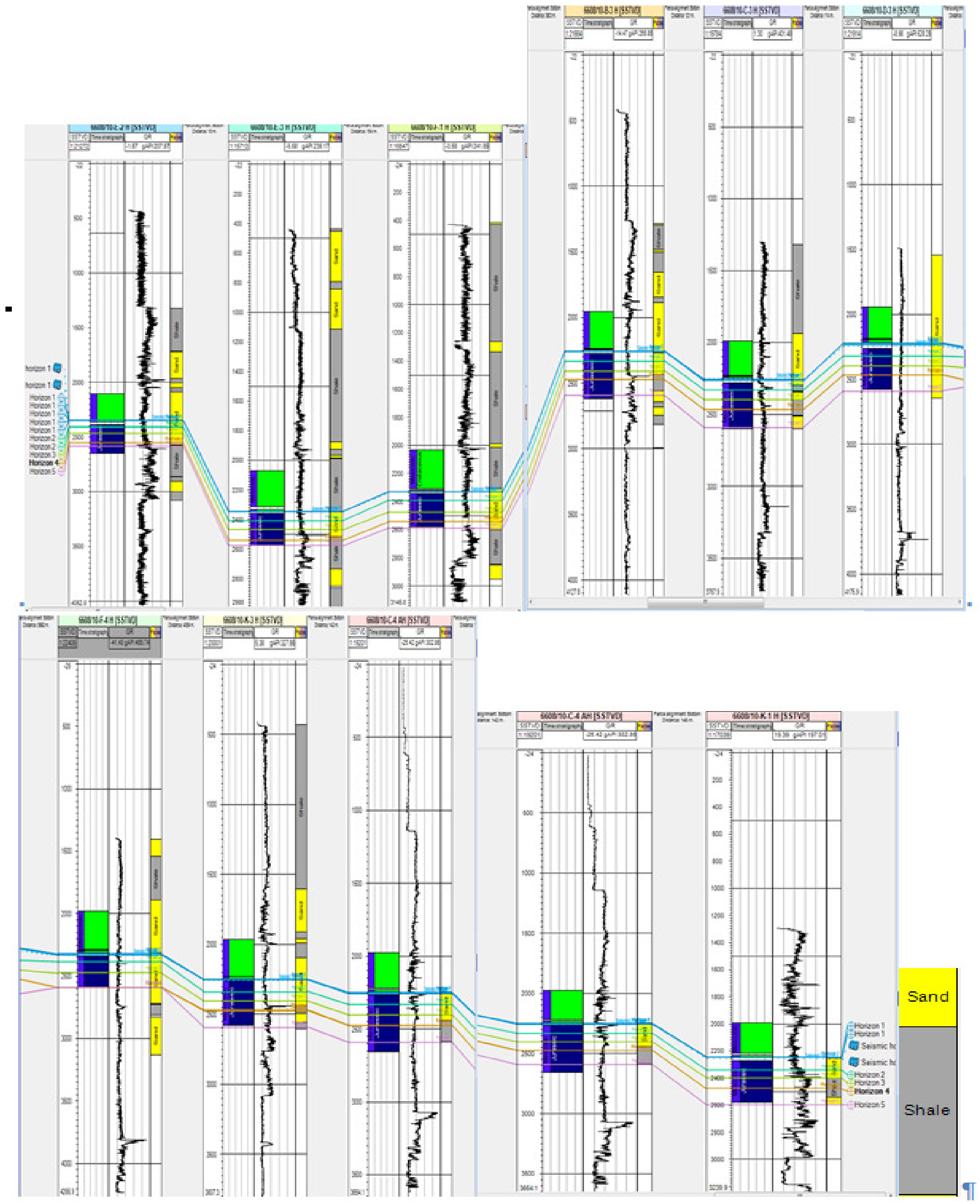


Figure 92: Well correlation panel for the interpreted horizons with the interpretation key bar with yellow depicting sand and shales depicted with gray color.

8.3 Upscaling of well logs as applied to the Norne well log data

The process of well log up scaling is required to post values in each cells of the 3D grid where each of the wells is situated; to achieve this average well properties are used to populate each of the cells. This makes it possible to relate the well properties to the grid directly and this also means that the upscaled cells properties value along the well path will be static in the whole of the 3D grid property with the upscale zones.

In this process discrete log values or continuous log averages are used (Figure 93). The discrete log samples the most frequent occurring log values to the up scaled grids cells while the Continuous logs averaging uses the averages of logs that samples a particular cell, this is further divided into 3 types known as the Arithmetic, Geometric or Harmonic. The arithmetic averages are known to deliver higher upscale cell values in comparison with the rest (Arithmetic avg >Geometric avg> Harmonic avg) which means different scenarios can be used in this upscaling of either providing optimistic case to a pessimistic model based averages. The arithmetic averages has commonly delivered good results in Porosity upscaling and siliciclastic reservoirs , the geometric averages and harmonic averages would find good application in mainly carbonate reservoirs where variability in pore dimension is not uncommon.

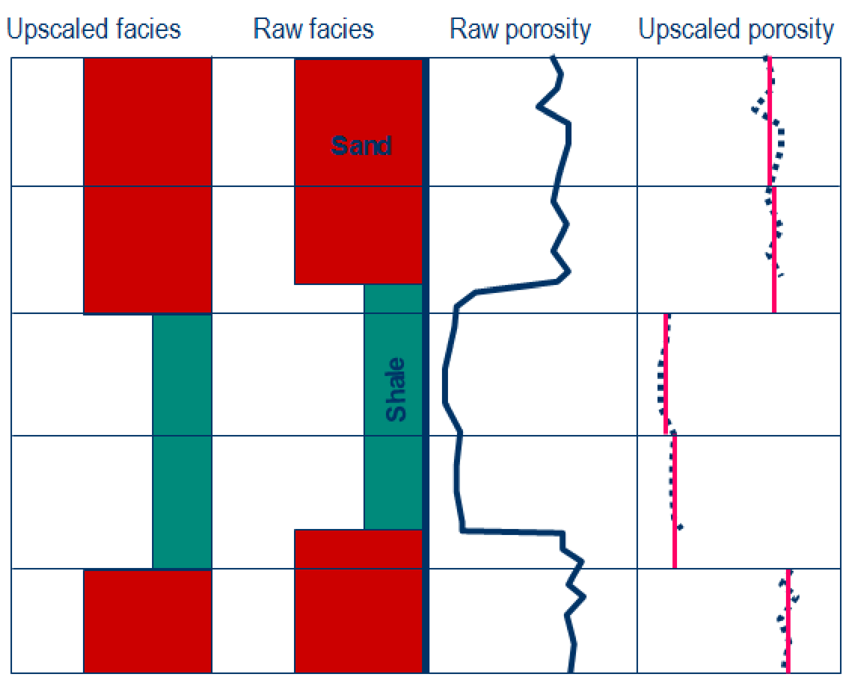


Figure 93: Comparison of Upscaled to normal facies discrete log profile with indication of data biasing due to the upscale process.

The process of up scaling the interpreted wells in the Norne well data starts by choosing a new property to upscale or use an existing property which was formally upscaled, the key input is the interpreted well log (interpreted facies zones). Secondly , the wells are chosen by toggling the tab All , which means that the facies interpretation of each wells in the global log is used in this upscaling. This also means that not all well properties could be used in this process, the user has the liberty to choose specific wells and properties for up scaling. Thirdly, to choose the setting parameters for the upscaling in terms of the averaging method, log treatment as lines or points and method of upscaling are applied.

In terms of the setting properties the logs are treated as lines or points; the setting using points means that the logs are treated as points and only the point values would be used in making this averages. Line averages mean that the logs are treated as lines such that line values outside upscaled cells can also be used interpolated averages in between log points (Figure 94). This was considered robust in the Norne upscaling workflow so as to capture the interpreted facies boundaries in the logs. The upscaling methods are dived into simple, through cell and Neighbour cells.

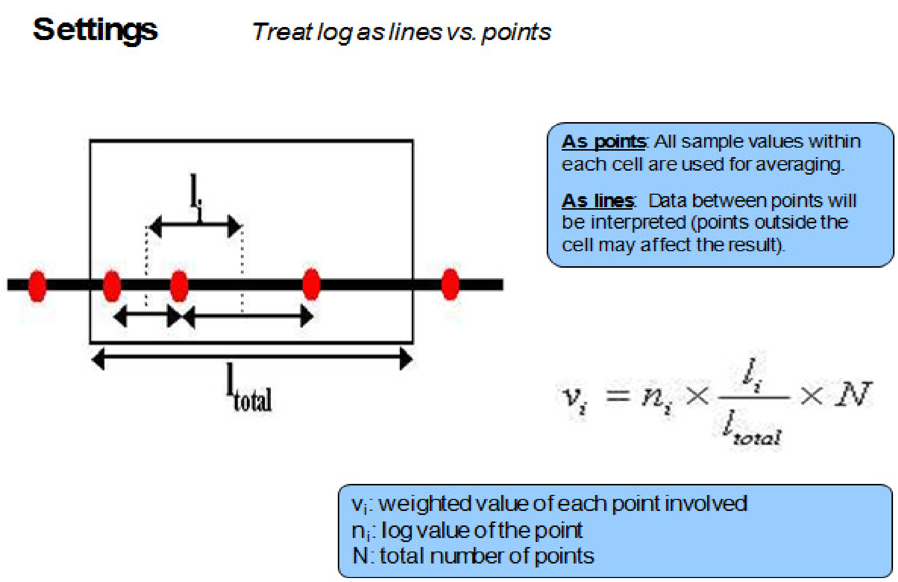
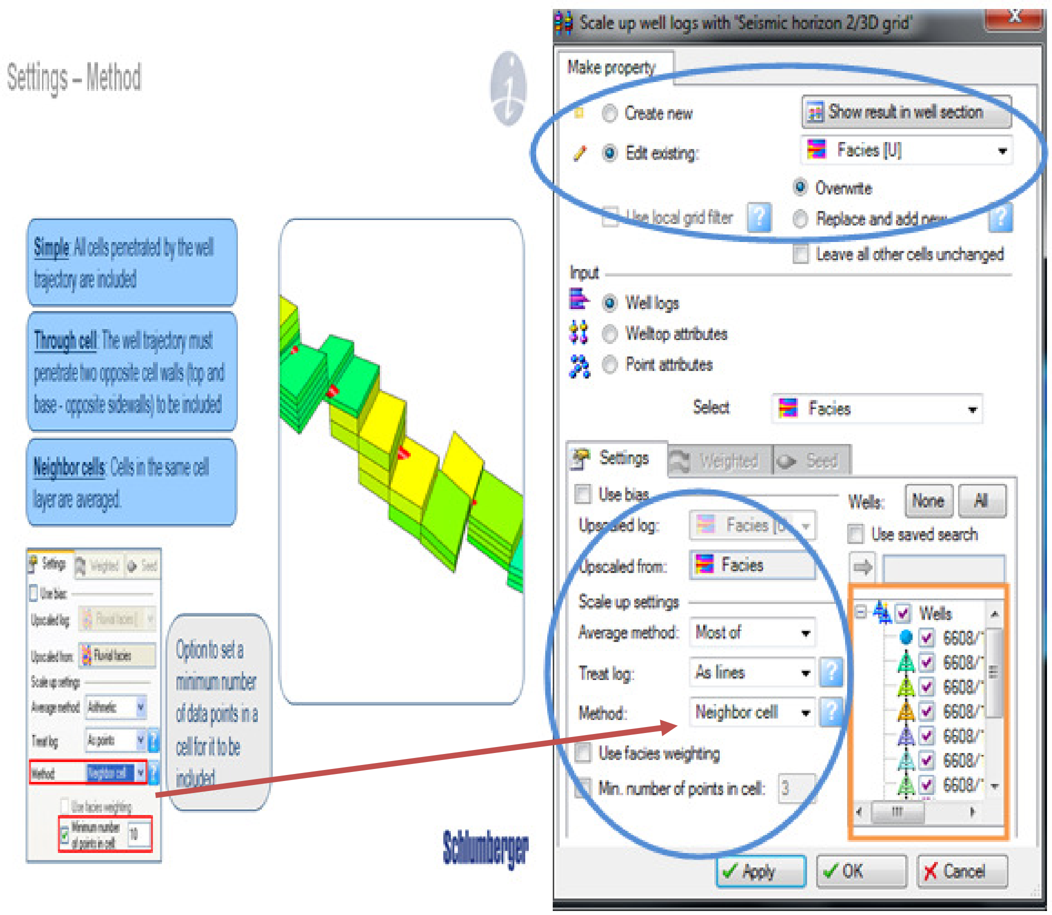


Figure 94: Two main setting for the logs as lines or point data with weighted averages used in the up scaling.

The simple method is used to give property values to cells as much as the wells penetrate the cells, no matter how tiny the cells are in dimension. The Through cell method gives a value to a cell only when opposite cell walls are penetrated by the cells; this is to ensure that only a tiny section of the well path does not provide only the reasonable confidence to post values to the cell as in the case of the simple method. The last method is the Neighbor cells which is similar to the simple method where all cells are posted with values as far as the well penetrate them, the variant is that cells adjacent one another in same layer would be averaged. This is robust in that it keeps out the nuisances of changing vertical barriers or layers into horizontal due to averaging. This method was used in carrying out the upscaling process as applied in the Norne field (Figure 95b).



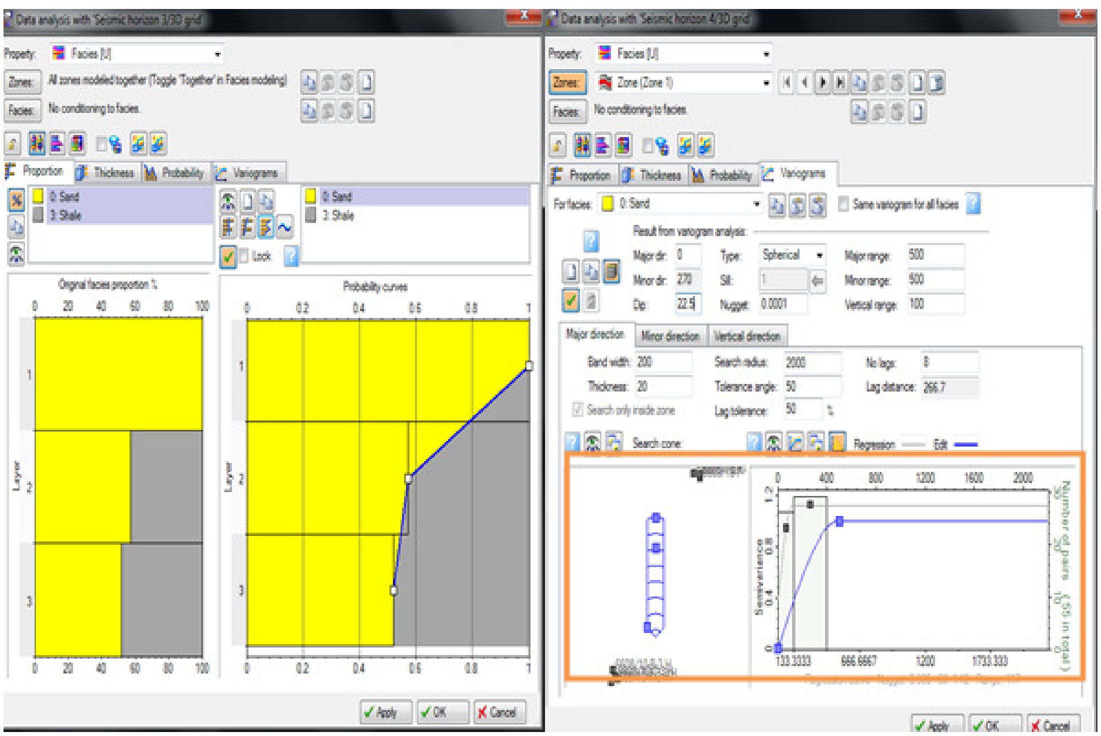
(a) (b)

Figure 95:(a) Petrel manual based explanation of the Scale up settings/methods.(b) application of the Upscaled to the Garn Formation reservoir with the Pink tab showing the upscaled 11 wells, the top blue circled area shows the options of editing or creating new upscaled facies and the averaging settings of log treatment as lines, neighbors cells, are satisfied in the bottomed circled area.

8.4 Data analysis

The upscale well logs with different averaging methods require the process of data analysis as a basis to control the property of the models whether discrete (facies properties) or continuous models (e.g. Permeability models).The main templates in facies data analysis include the facies proportion, Thickness, Probability and Variogram settings. This analysis is calculated based on reference zones and up scaled facies properties. The top of the Garn, Ile, Tofte and Tilje formations and their modeled zone layers were used as inputs from interpreted seismic horizons. The proportion analysis showed generally high percentage of Sands in comparison the Shale units, it ranges from about 100 percent rich sands in high case to as low as 65 percent sands, and the shales had 9 percent cutoff for low case scenario to high case of 33.3 percent cutoff (Figure 96). The cut off base interpretation of the logs from the Gamma ray log interpretation is a critical quality control of the facies ratio from first pass interpretation.

The facies thickness represents the vertical facies thickness at each of the upscaled well locations, each of the model top reservoir surfaces shows different ranges of vertical thickness which ranged from as low as 6m to as much as 100m (Figure 97).The proportional thickness of the sand to shale ratio captured much thickened sections of sands in respect to the shale thickness generally, the interpreted Garn formation has thickened sand thickness of about 100m from the data analysis, with the Tofte, Ile and Tilje formation recording some sand to shale proportions.



(a) (b)

Figure 96: Plate (a) shows the data analysis on the Ile reservoir top with a high proportion of sand to shale. (b) Shows the variogram settings with a regression analysis of the facies unit to each well location (pink boxed area). Major, Minor direction and ranges of dip and azimuths settings are seen in the background display.

(a) (b) (c)

Figure 97: Data analysis with thickness variability indicated with figure (a) showing the thickness profile of the tofte reservoirs top surface which varies in proportion to about 140 m. (b) Ile formation top reservoir thickness profile with about 20m to 70m thick sands.(c)The Garn reservoir tops shows thickness profile of about 20m thickness with a proportion of 100 percent.

Probability template was done was done using the probability sand fraction, as key inputs. The sand fraction had greater part of the probability distribution as compared to the shales. Different probability transformations are available to determine the statistical skewness and distribution of the facies based on inbuilt regression analysis and probability density functions. (Figure98)

The variogram properties are set which form the basis for the sequential indicator approach of the stochastic algorithm applied in the facies modeling of the interpreted Norne reservoirs. A spherical variogram parameter was chosen, the azimuth values were inputted from Statoil report on Geologic modeling of SSW to NNE (N22.5E) (Statoil Norne report, 2001).The regression analysis is toggled to provide a statistical reference of the spatial wells in respect to the facies analysis of the wells. Other variogram parameters of minor, major, and vertical direction and their ranges were toggled and iteratively applied in the modeling (Figure 96b).

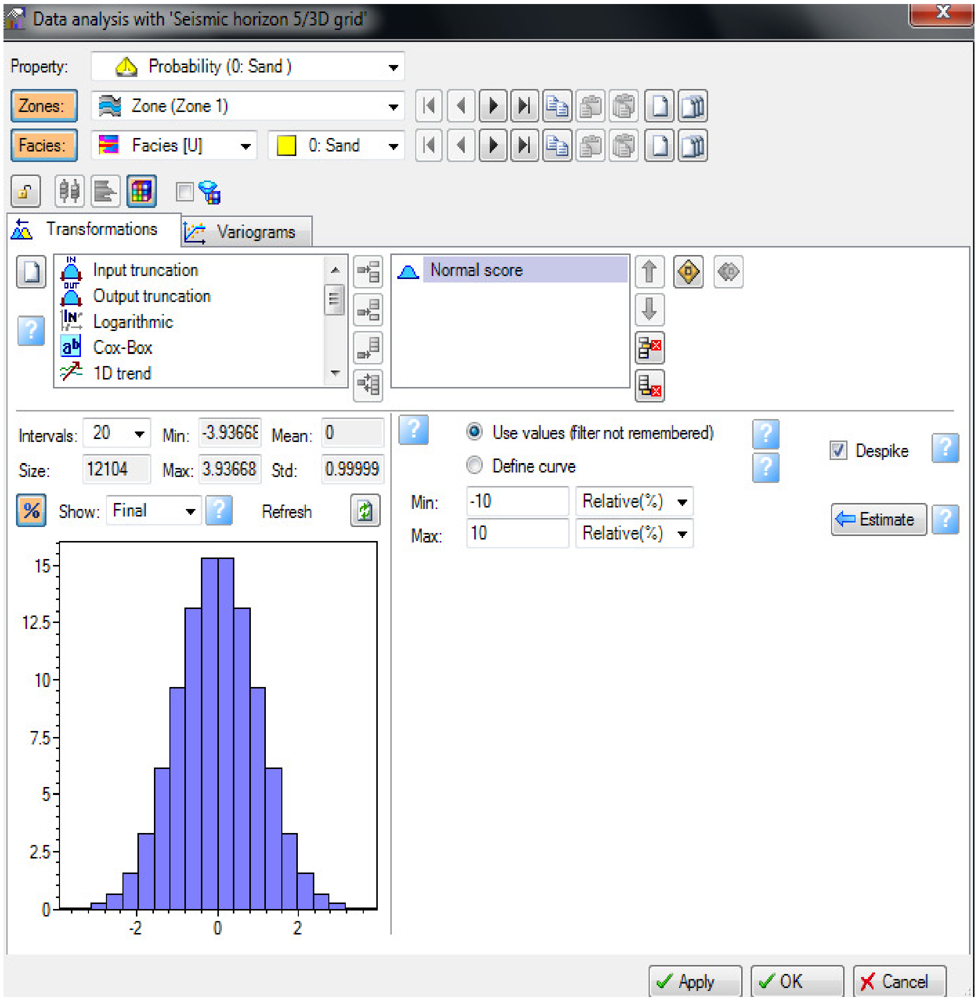
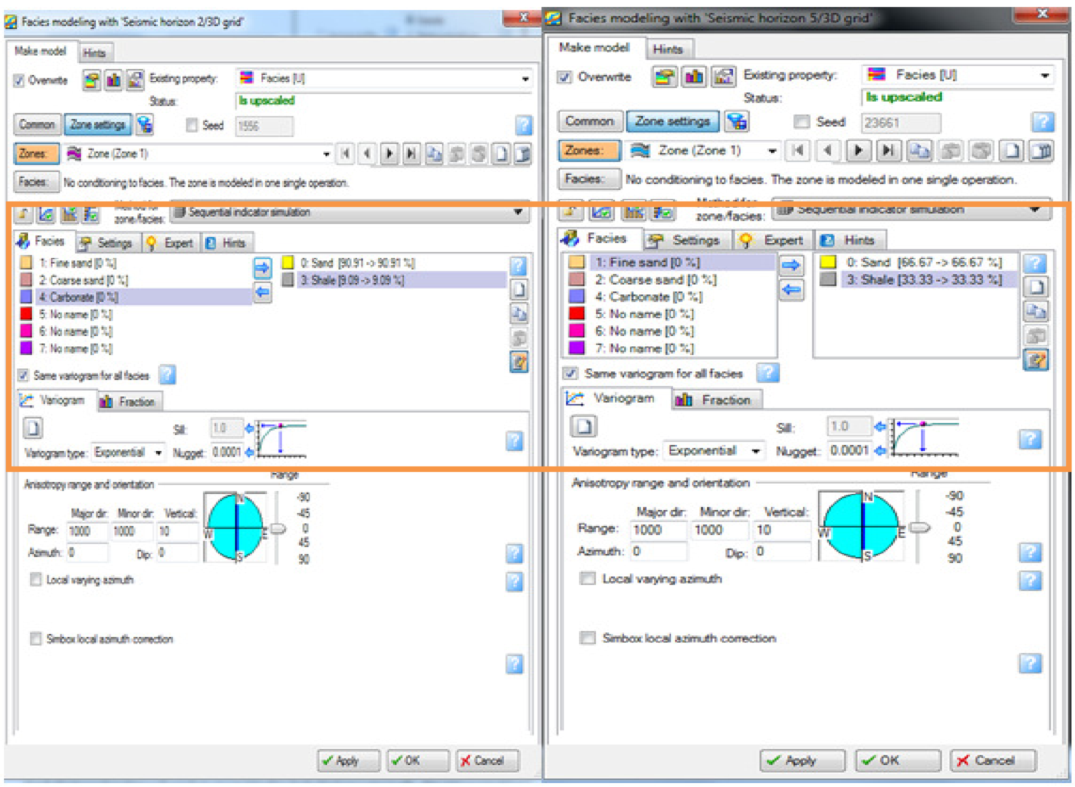


Figure 98: The probability filter of the facies analysis with a normal distribution to capture the skewness of the facies data as exemplified with the Top Tilje formation

8.5 Facies modeling as applied to the Norne

The background understanding of the different facies modeling algorithm, with interpreted and upscaled well logs formed the necessary inputs in the static 3D grid of the interpreted reservoirs. The sequential Indicator simulation was used based on limited well data in when compared to the volume of the 3D grid. The up scaled facies properties were used as the key inputs and similar settings were used for all the zones in each of the reservoir surfaces. The inputted sand to shale ratio varies from 90 percent sand rich facies to as much as 33.33 percent shales (Figure 99). The variogram properties were delivered from the data analysis workflow (Figure 96b).

The result of facies the model (Figure 100, 101, 102 and 103) of the Garn, Ile, Tilje and Tofte formations suggest a high sandy proportion when compared to the shales (shales as used here involves the total combination of fines, calcareous units, glauconitic horizons etc, as lower gamma interpretation from well logs is a coarse interpretation of fines as used in this study). However, the shale patches seem to be rather of higher cut off as seen in the dark patches of Figure 100, 101,102 and 103), this is accounted for by the user defined interpretation cut off range for shales which might be rather high. The upscaling methods also need to be iteratively backdated with different methods to capture their impact to the facies process in terms of how much bias the up scaling has impacted the modeling. This means that the process is an iterative one where adequate controls are required to be followed from the interpretation to data analysis with quality control of upscaled well logs. This means that petrophysical modeling has to be done as secondary modeling to the facies modeling process.



(a) (b)

Figure 99: Plate (a) Sand cut off of 90.91 percent with shale ratio of 9.09 percent was used as the facies cutoff for the Garn reservoir top. (b) Shows an up scaled facies cut off for sand and shales of 66.67 to 33.3 percent for the Tilje formation (See the pink boxed area)

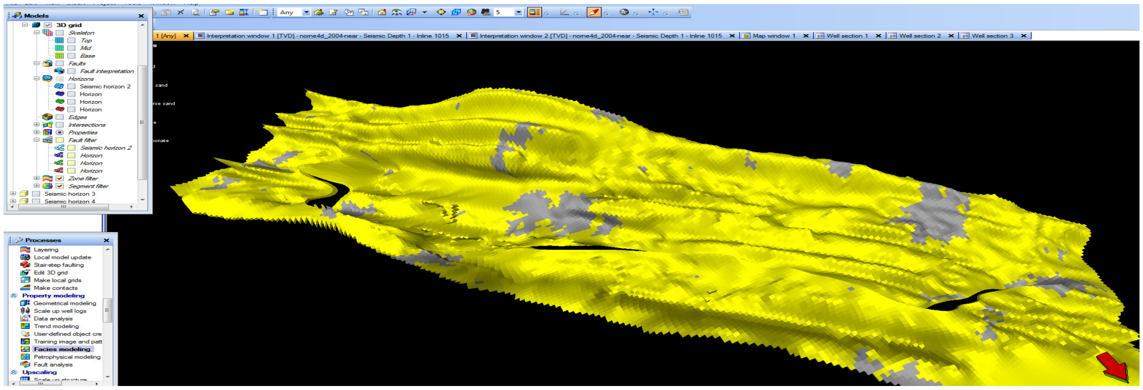


Figure 100: Facies model of the Garn reservoir.

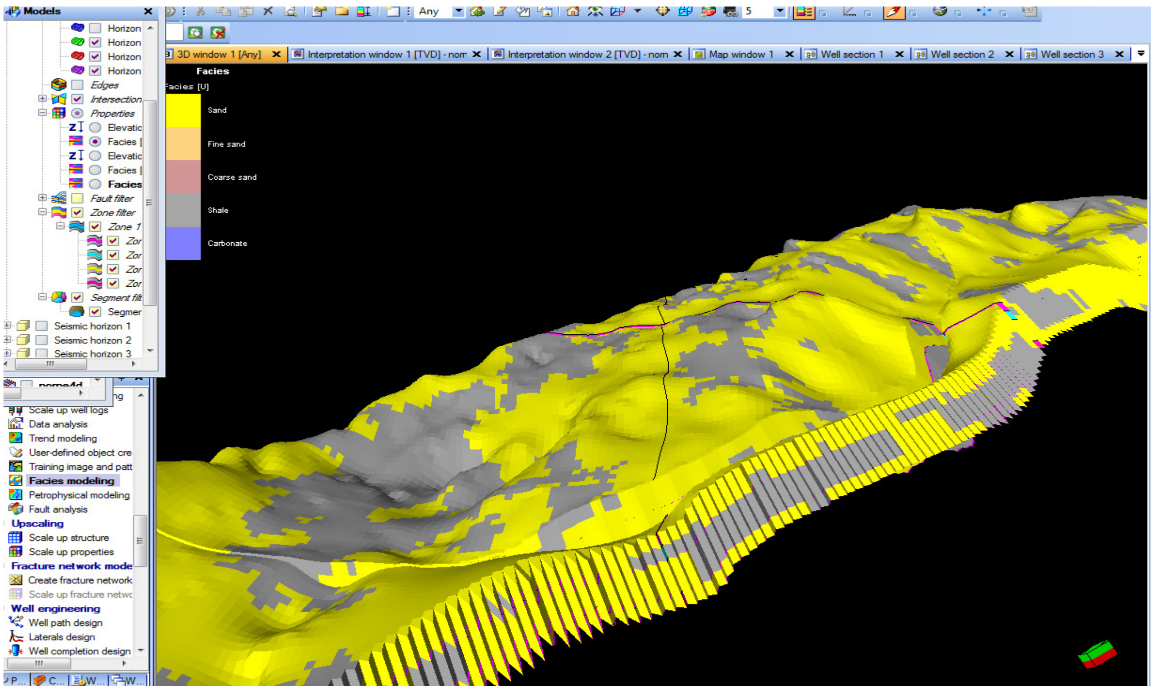


Figure 101: Facies model of the Ile reservoir.

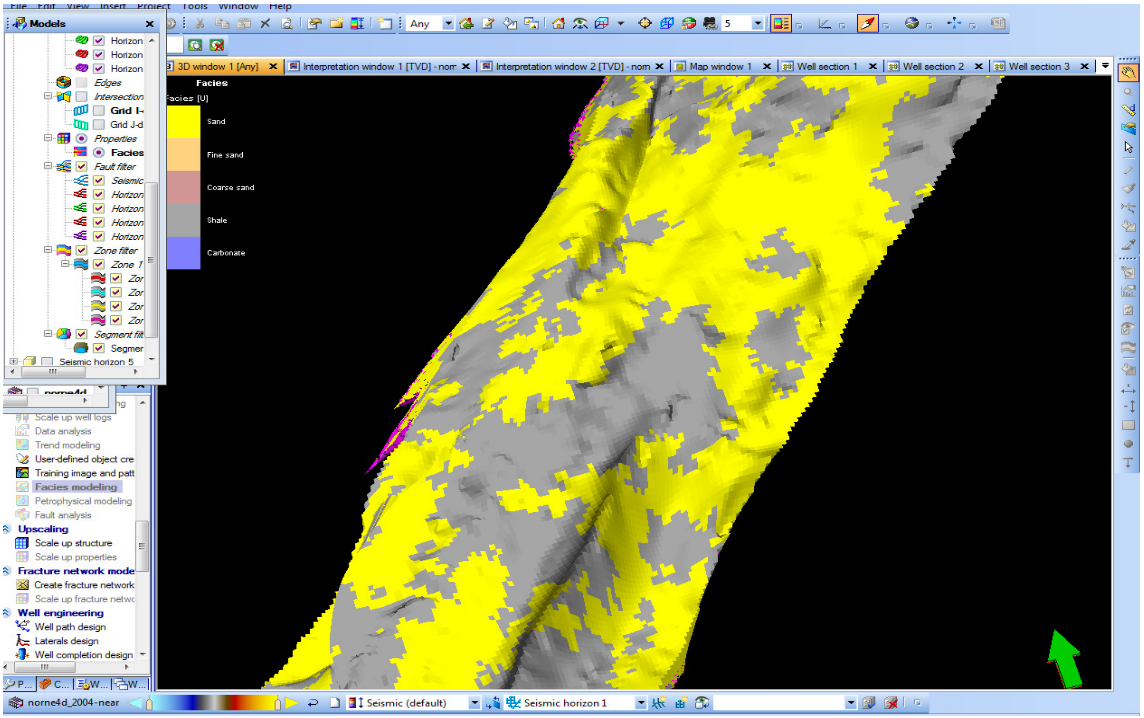


Figure 102: Facies model of the Tofte reservoir

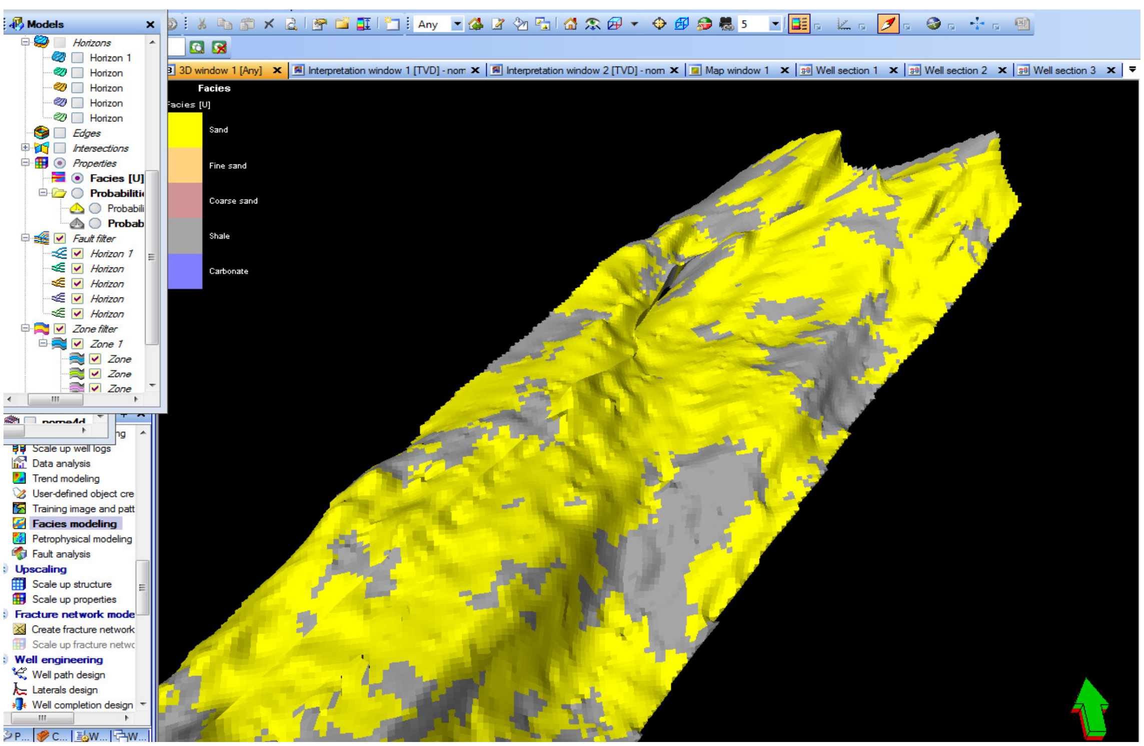


Figure 103: Facies model of the Tilje reservoir

8.6 Petrophysical Modeling

It is the process of using petrophysically assigned properties values or attributes as a basis of modeling. The main input is the facies models with the sand and shale attributes, which provides a petrophysical distribution of the sand to shale ratio. Its workflow adopts similar modeling algorithm as the facies modeling with the two main processes of Deterministic and Stochastic models. The available algorithm in Petrel includes the Sequential Gaussian simulation(SGS),Gaussian random function simulation (GSLIB),Kriging, Kriging Interpolation, Kriging Gslib, Moving average, Functional, Closest, Assign values, Neural Net, and User defined algorithm.

The main inputs required are the upscaled well logs, input distribution, variogram and trends. The Gaussian random function simulation was chosen since it offered a much robust and faster co-collocated co- simulation option compared to the SGS with a non-sequential algorithm for easily parallelization. The trend option was toggled with a logarithm function of the sand /shales as inputs from the facies modeling workflow (Figure 104).The variogram setting was maintained from the pre adopted interpretation of the facies modeling.

The result of the process on the reservoir formational tops shows that generally the sand ratio probability is about 70 to 80 percent, while the shales amounted to about 10 to 30 percent of the reservoir tops (Figure 105, 106, 107, 108).This is reasonable from the geologic knowledge of the reservoir which is sand rich with shaley intercalations, calcareous layers, glauconitic composition and fine sands forming part of the overall reservoir composition. From the diagram of the probability models the main Norne horst structure has been shown to be sand rich, which means that not only it has good structural of closure as seen from the maps , it also appears to be rich in sand .This model provides a reasonable confidence in understanding the spatial distribution of facies. The values of the several assigned probabilities in the model provide a secondary data analysis to the facies process.

Finally, the critical deliverable to this process is that not only does it function with facies input but it can be used for poroperm models and saturation models where you could tell much about the positions of fluid fronts within the reservoir.

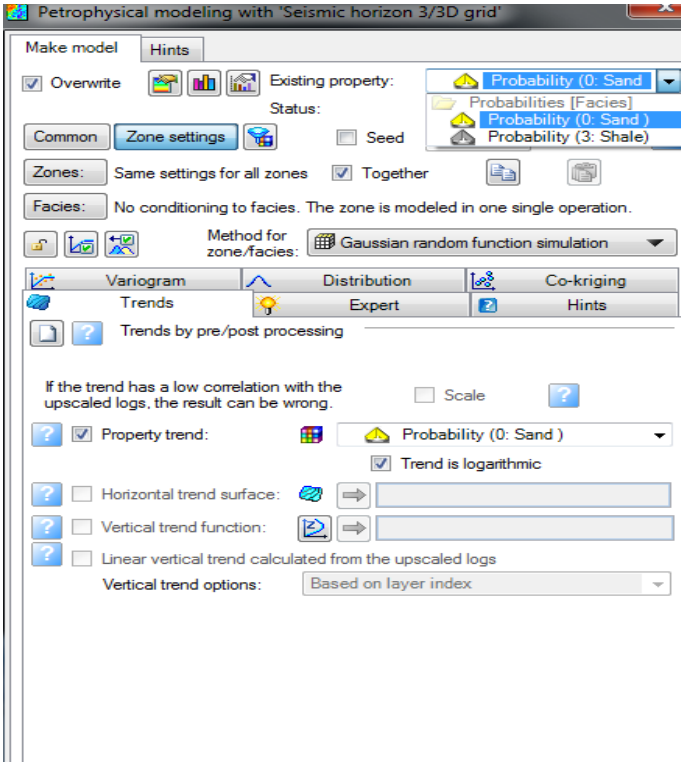


Figure 104: Petrophysical settings workflow with the Gaussian random function simulation.

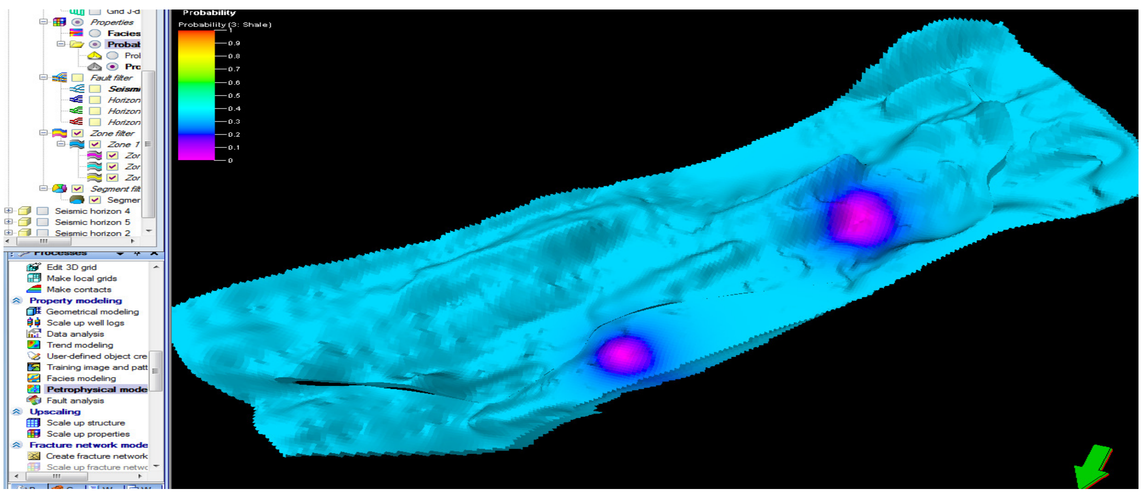


Figure 105: Ile reservoir probability model with shale ratio of 0.3 with a general background colour of blue from the probability colour scale, lower values are indicated with pink.

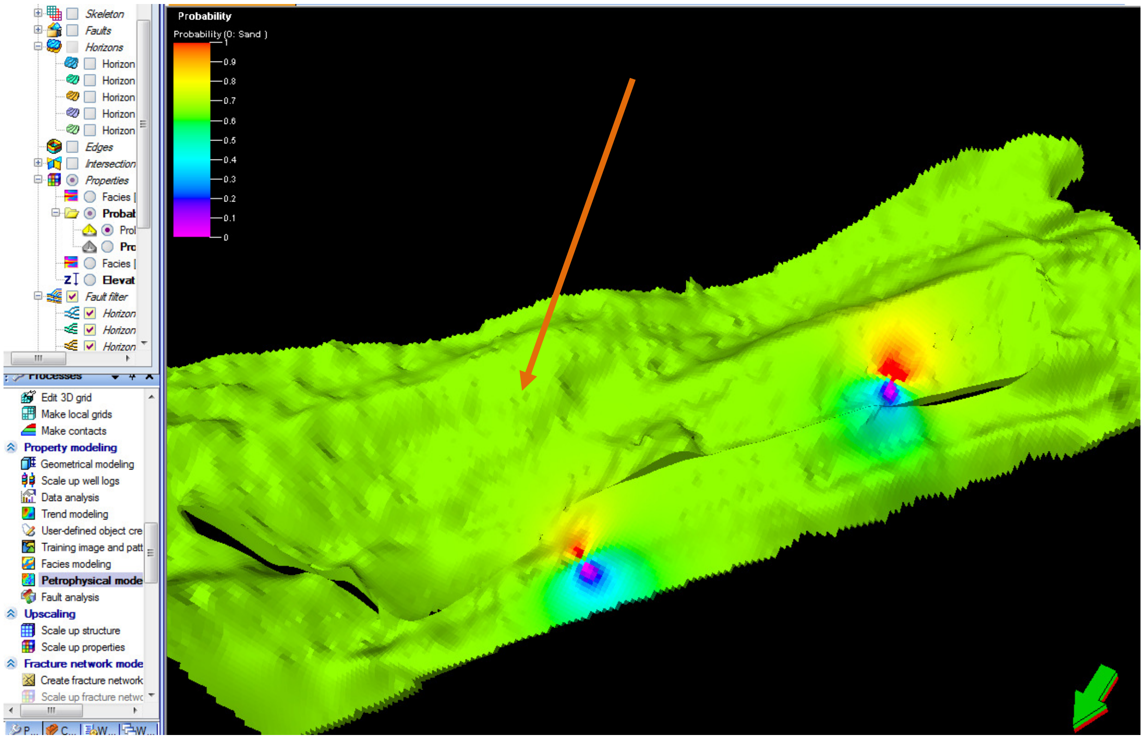


Figure 106: Tofte reservoir probability model with sand ratio of 0.7 to 0.8 with a general background colour of green from the probability color scale. Pink arrow shows the position of the Norne Horst.

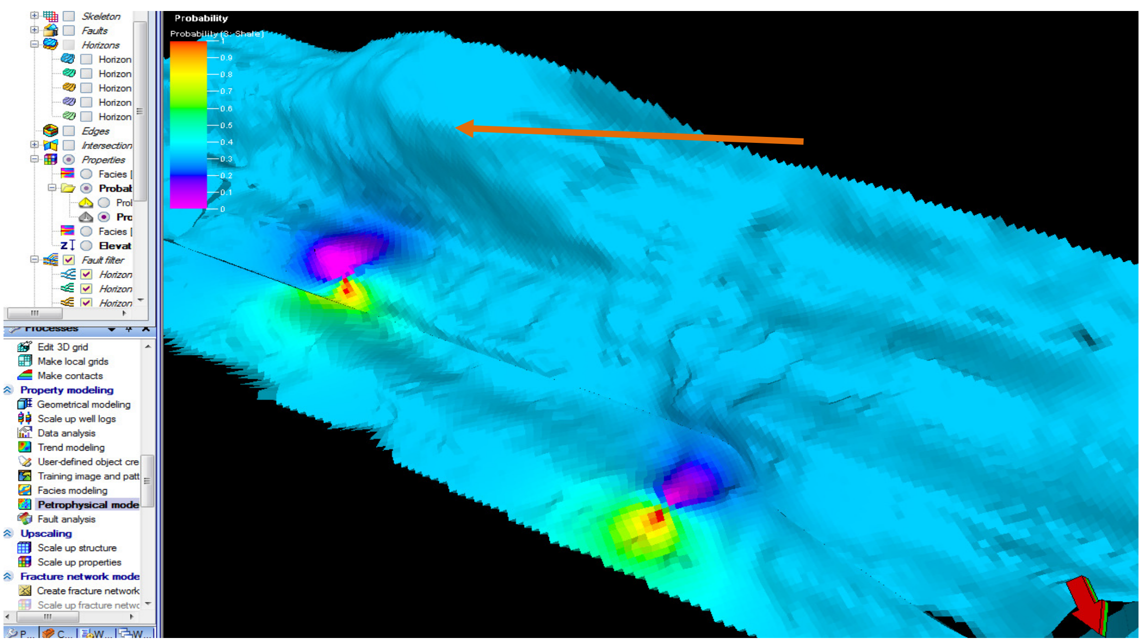


Figure 107: Tilje reservoir probability model with shale ratio of about 0.2 to 0.3 with a general background colour of blue from the probability color scale, lower values are indicated with pink arrow showing the position of the Norne Horst.

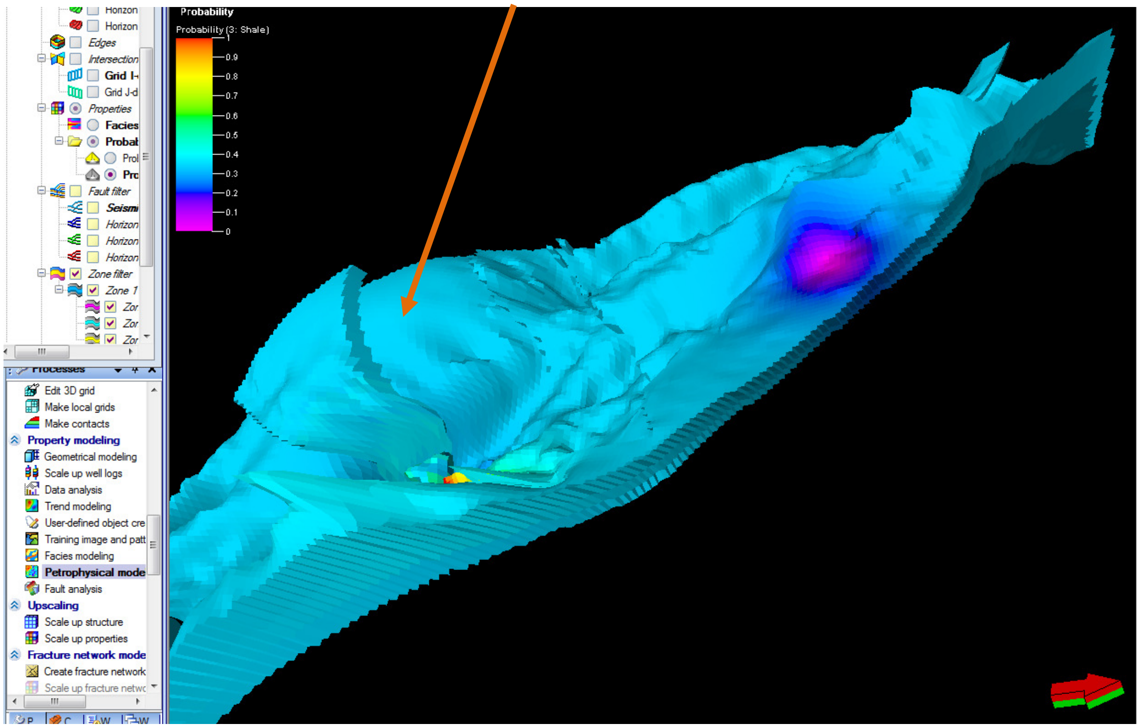
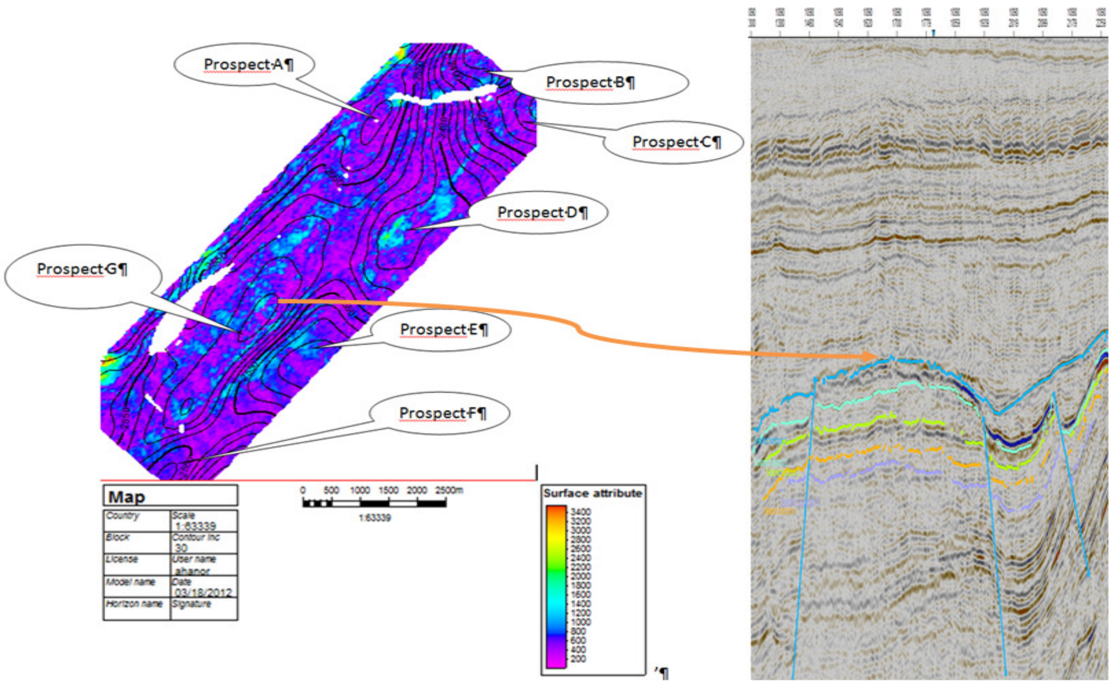


Figure 108: Garn reservoir probability model with shale ratio of about 0.2 to 0.3with a general background colour of blue from the probability color scale, lower values are indicated with pink arrow showing the position of the Norne Horst.

9. Prospectivity of the Norne seismic volume from structural and facies models

The purpose of the reservoir facies modeling is to evaluate the facies distribution from seismic volumes with available wells and determine probable prospect locations /drillable positions. Using the structural map, surface attribute and inputted fault modeled surface, 7 prospect locations were identified based on their structural closures(Figure109 a). These prospects are localized within the main horst structure across the seismic volume (Figure 109b). Screening the prospects further, using Statoil inputted fault surfaces with polygons, seven fault segments was observed to segment reservoir surfaces(user defined segments). Furthermore, using the inputted fault modeling surfaces from Statoil interpretation, several reservoir segments were identified (E, C, G, D) (Figure 110b).

The graben related faults and other minor fault typically form these segments of the reservoirs, which provides complex reservoir architectures to the reservoir surfaces. Statoil division of the field into segments C, D, E, G (Figure110b) seems to relate the reservoir sections with the main structural closure of the Horst and the different structural axis of the faults. Pre drillable well locations would typically be defined based on these structural elements, where targets would be based on the horst highs and fault assisted closures, this is depicted with seismic inline 1090 with 4 predrill able locations identified within the seismic profile (Figure111).



(a) (b)

Figure 109: (a) Using the structural surface to determine prospect location within main structural closure (b) The pink arrow shows the horst identified as the main closure element from seismic section inline 1090.

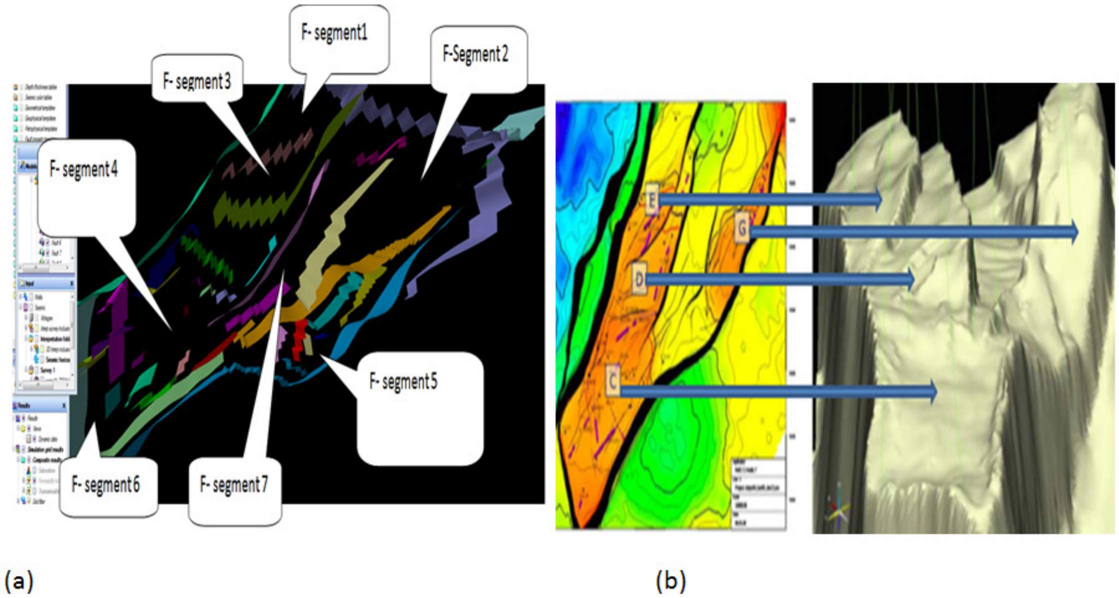


Figure 110: (a) The modelled fault surfaces from Statoil based interpretation, showing the different fault segments/compartments. (b) Seismic reference section from Statoil which indicates the horst elements to each segment.

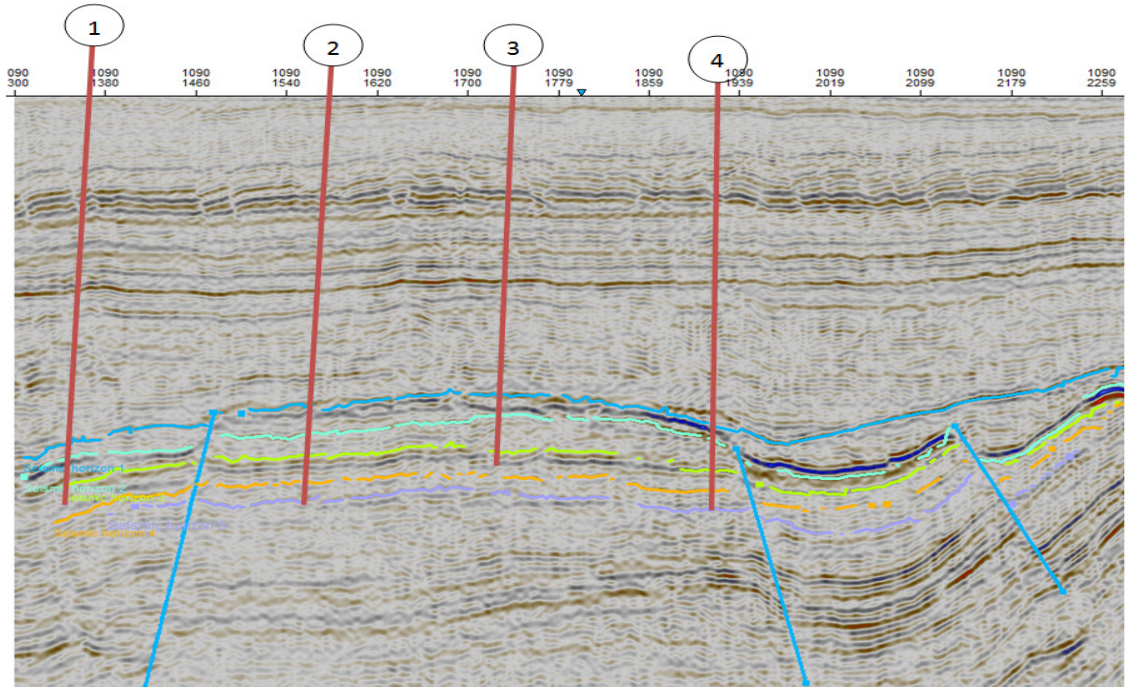
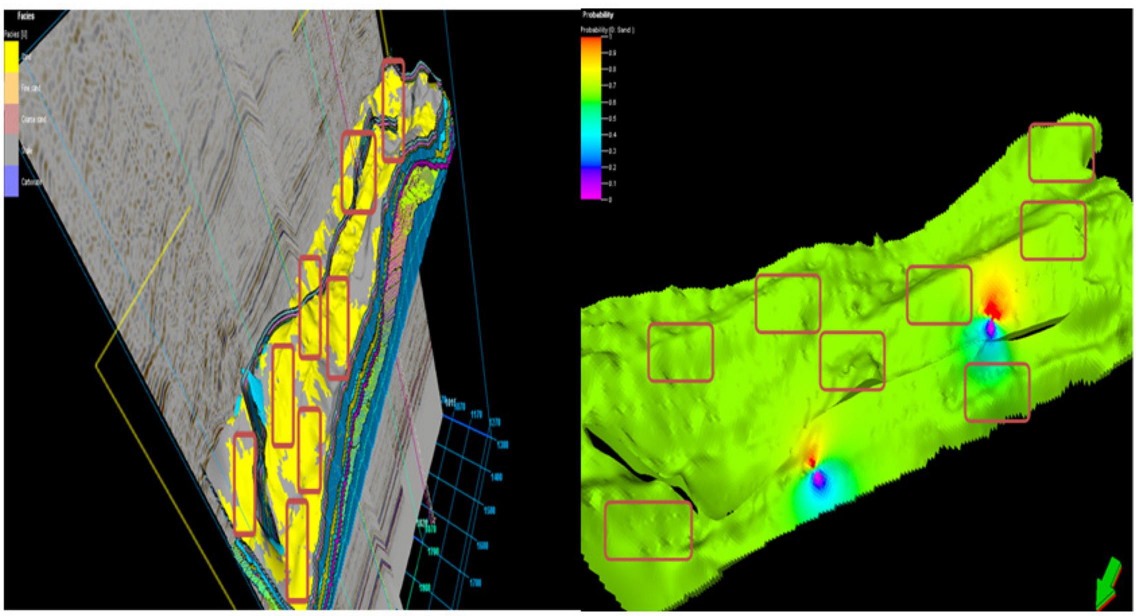


Figure 111: Seismic inline 1090 with user identified pre-drillable location within the horst crested areas

The facies model was used alongside the structural interpretation to indicate possible drillable areas where sand rich facies are localized in order to increase the confidence in deciding the well location. Visualization of the seismic with the facies /probability sand facies model indicates 70 to 80 percent confidence of having sand sections in the reservoir main horst structures (Figure 112). The 11 wells used in the interpretation and/or populating the models show that, given appropriate controls, the technique could be highly relevant in exploring virgin areas and/or reinterpretation of existing models.

The Norne field is much matured in terms of the production, which means that other property modeling away from discrete facies models needs to be done in other to capture the saturation profile across the prospected horst structures. Modeling saturations (water saturation), porosities and permeability would provide added advantage in understanding the changes in the fluid position/front in the static models; it could also serve the advantage of properly understanding the nature of the faults as to their retardation effects in fluid communication in the reservoir simulation model (the sealing properties of the faults /fault transmissibility functions).



(a) (b)

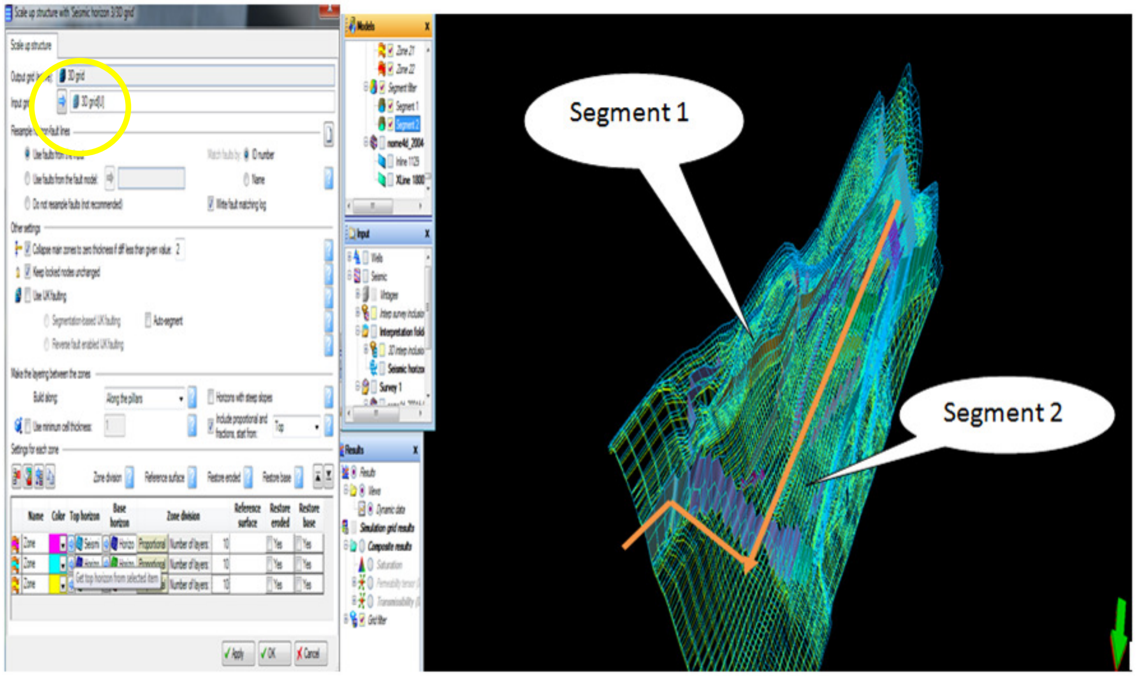
Figure 112:A seismic to facies model visualization (a) pink boxed section localizing sand sections with parts of the horst sections .(b) Probability sand facies model with high sand ratio of about 70 percent localized in parts of horst structures.

9.1 Upscaling/Simulation grid input of the Norne

The importance of the reservoir modeling is to create a 3D grid dimension were simulation of the fluid could be run for dynamic purposes/history matching. The reservoir grids of the reservoir are upscaled with initially model zone segments/layer dimension redefined to provide a much efficient simulation grid. This process starts in Petrel using the interpreted 3D model (in this case facies model) as main inputs. The faults from model fault patches are retained in the process; however ,this could be segmented in the IJK segments as seen applied in the upscaled Statoil model where segment 1 and 2 where differentiated for probable simulation of the different segments across the main bounding faults(figure 113b).(*it is important to stress that geologic segments due to structural relief/faulting are different from simulation grid segments*)The functions are similar to the layering and Make Zone process, where appropriate options are required so as to build up the upscale layers in True Vertical Thickness TVT, True Stratigraphic Thickness TST or along fault pillars. The process requires the zones and layers numbers to be collapsed together so that grid properties could be aligned easily to zonal upscaled cells.

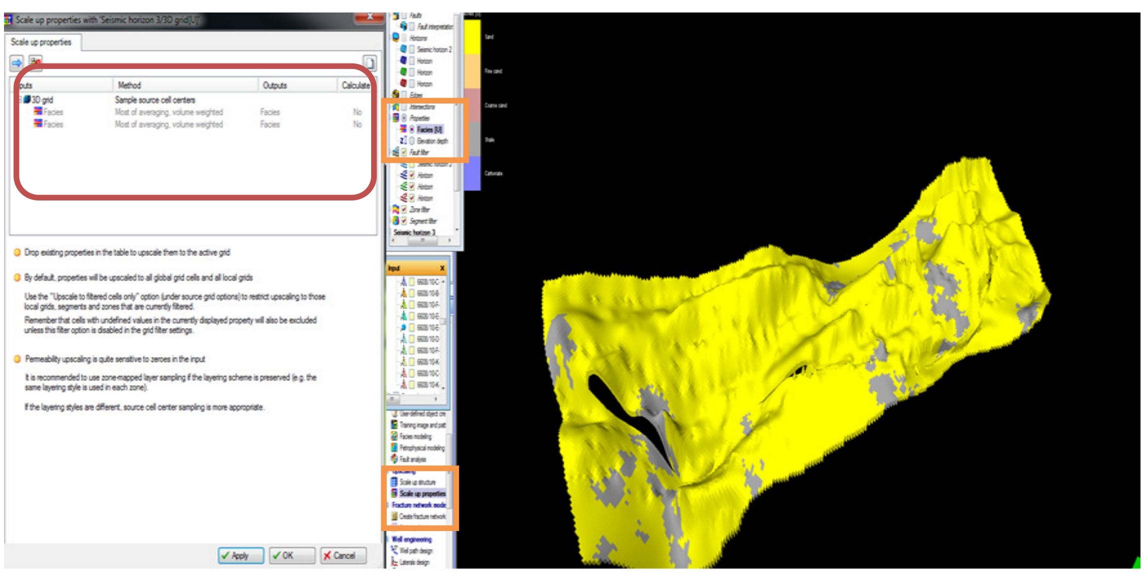
Furthermore, after the process of upscaling the 3D grids, their respective properties are also upscaled. This was done using the discrete facies model as input properties for each of the interpreted reservoir 3D models in the field so as to transfer the resolution from a geologic based dimension into simulation. This process is done using the scale up property tab function in the process pane in Petrel, and also applying a scale up averaging method which appropriates a much coarser grid for the property. The Most of Average Volume Weighted method was used for the facies scale up since it gives an additive or arithmetic mode of the properties which assigns the most strongly represented source value for the cells (for example, a particular coarse cell overlapping fine cells containing a total of 1000m3 of sand, 2500m3 of silt and 3000m3 of shale would be automatically scaled to shale). Other methods includes the Harmonic, Geometric, Root mean squared, Minimum, Maximum and Powered.

From the upscaled property grid surface it was noticed that the reservoir surface facies grids were becoming more homogenous in sand lithologies as the shale patches were averaged out (Figure114 b). The technique would be interesting in determining the scaled up properties of porosity, permeability models and fluid saturations for simulation process. This would mean simulation CASES can be run for each of these identified properties.



(a) (b)

Figure 113: Upscale 3d Grid process. (a) The upscale input process template with inputted 3D grid and resizing of layers/zones. (b) Segmentation of the Norne input models into two main segments with the fault surface used in segmenting the volume



(a) (b)

Figure 114: Property upscaling (a) Property upscaling template with the interpreted Tofte reservoir surface using the moving average volume weighted method as depicted in the boxed area. (b) Upscaled facies property with the scale up property tab in the process pane. Result shows a much homogenous sand model with less shale patches (see pink boxes to capture tab)

10. Discussion

The process of carrying out integrated reservoir modeling from this work shows that a combination of wide range procedures and ideas is required. It is a purely an iterative workflow, which is developed from having an understanding in a broader view of the regional geologic framework to developing the model in its finite dimension in the Petrel workflow.

The use of volume visualization and rendering has not only shown its advantages in visualizing multiple data inputs within a given window time display in the Petrel tree. It also creates the added function where you could actually view the various data types (seismic volume, wells, horizon, time slice and properties) in a single window and picture their relationship in 3D space. Visualizing time slices within the reservoir sections (with a dynamic interpretation mindset) proved that structural events like fault surfaces could be fitted into the seismic interpretation workflow from time slice based realizations

The process of realization of seismic sections, opacity filters, cropping of the reservoir sections was used to deliver the interpretations of the seismic volumes and also provides key inputs for the different seismic attribute template/modeling workflows. Furthermore, it has also helped to provide a basis of quality control of the models especially when seismic to model base ties are performed to determine the altruistic contents of the model in relation to the seismic volume. Locating /evaluating prospects with surface based contours is a one step process, using visualization of the relevant surfaces /volumes and models provides a 2 step function in delivering prospect based evaluation with visualization of the seismic data.

The positive gains of applying attributes and seismic realizations (creating physical copies or virtual copies) on the Norne seismic volume has shown by extension that the frequency smoothing effect could be very valuable when applied to noisy data sets; since this technique has the adequacy to toggle (change) the resolution and filter the frequency component of the pristine data. Other applications of the these techniques include zone isolation and cropping of the reservoir sections where Ant agent parameter in ant track process are pre tested before final parameter application to the whole seismic volume. Cropped zone sections in the reservoir section were also used to provide swifter interpretations.

Application of different seismic attributes functions (geometric, structural, complex attribute etc.) alongside the visualization templates has brought a better sense of illuminating the seismic volumes, providing structural clarity with smoothing of the seismic reflectors, structural events and horizons. This has really brought a better sense in understanding the response of the seismic volumes to the different seismic derivative functions as to highlighting geologic events. The BCU and the other reservoir surfaces, alongside the main Norne horst and faults were positively illuminated for seismic interpretation after the applications of different attribute functions. Variance and chaos attributes with structural smoothing were also critical inputs needed in carrying out automatic fault extraction/ant track process as tested in this study.

The process of reservoir modeling requires a high quality control of the input data. The integration of different data inputs poses the challenge to the user in the ability to combine and integrate the knowledge and skills in geology, geophysics, geostatistics and petrophysics. The main process is initiated from scratch by interpreting the seismic volumes within sections of the reservoir level which is the zone of interest .Geologic based understanding / licenses, in combination with window based visualization/seismic attributes, are used to interpret faults and the reservoir surfaces of the BCU, Top Garn , Ile, Tofte, and Tilje formations. These form the required inputs needed in performing the structural modeling framework. Other hard data used to constrain the interpretation includes the Top Åre and Not formation picks, fault sticks, interpreted oil-water contact surfaces etc. The Not and Åre formation Tops, Statoil reference Top interpretations, and the OWC were used to control and/or reference the interpretation of the seismic in depth, since adequate checkshots were not available for the whole volume section at the time of study. However, the absence of inputted Top of the reservoirs brought a positive gain in that data paucity could provide a test for exploration targets/modeling.

The fault modeling process requires the user to follow few rules in other to maintain fault orthogonality and direction. Large scale planar faults with minor sets which were mainly associated with the margins of the horst structures were mostly interpreted in the reservoir section. The fault modeling and pillar gridding process was closely monitored to ensure that the geologic based interpretation is preserved in the modeling frame and also trends /orientation of the fault sticks were considered as important inputs in the pillar gridding. The Norne inputted fault stick and the automatic fault extraction process were used as quality control/testcase to maintain interpretation, provide additional overview of fault segments and compare the value of user based interpretation.

The interpreted horizon of the reservoirs and their respective surface maps were used as direct input in the Make surface process. This is pre initiated with a surface attribute function which retains the seismic properties to each of the surfaces; thereby making each reservoir surface seemingly dynamic with observed properties .This process (Make horizon) allows the user to create the surfaces needed in the structural 3D grid. Surface smoothing and refining the properties of each of the reservoir surfaces are also important window based application needed to align the surface to the interpreted structural relief. Furthermore, zones and layering were user defined in the 3D structural modeling frame based on geologic differentiation of each reservoir surfaces. These form the necessary skeletons in the 3D structural grid.

The process of populating the structural models with discrete properties forms the basis of property modeling. The facies modeling workflow is initiated by well interpretations

(11 wells chosen based on their vertical profiles, as deviated wells were not considered appropriate in the facies process) of the field and correlation of the interpreted reservoir surfaces. The gamma log was used to discriminate sand and shaley facies. This is followed by upscaling the wells to the 3D grid using corresponding upscaling techniques which satisfies the available well inputs and data/property distribution needed in populating the models. Furthermore, comparing different modeling algorithms, the upscaled wells facies properties are spatially distributed by stochastic simulation which honors rather less dense spatial dimensions of the wells. This process is also iterative in that quality control and patience is needed to toggle the different property frames or algorithms. Also geologic /statistical analysis is key understanding in carrying out proper data analysis. It must be said also the geologic control based on hard data must be considered to confine the nuances of multiplicity in algorithms/techniques.

The property modelling was done on another level with petrophysical property modelling which uses the facies attribute as input properties. The Gaussian random function simulation (GSLIB) was used as the main algorithm alongside upscaled well log. These models were done for each of the reservoir surfaces with the average petrophysical property indicating the reservoirs are 70 to 80 percent sand rich with shale ratio of 10 to 30 percent. The importance of these models has shown that structural closures associated with the Norne horst tend to be sand rich which would serve as plausible exploration targets. However, it must be said that since the Norne field is a mature oil field which has been produced for a longer time, saturation models of using old and newly drilled wells would provide additional information as to understand the current process as impacted by production.

The property modelling is not exclusive to facies process; porosity/permeability (poroperm) models could be done which would deliver a much wider investigation. To confine the limit of this study, prospect analyses were inferred based on the reservoir models, structural maps and seismic volume visualization. Structural closures were used to screen out 7 prospect locations and delimit their location in seismic to the structural/property models. These models could also be used in field simulation which means the grid dimension should be upscaled through the process of grid upscaling. Also fault multiplier functions, and permeability multipliers would be relevant in this process, which means that structural modeling could also be done qualitatively in understanding properties like fault sealing capacity, fault gouge ratio etc which are assigned to simulation grids (dynamic modelling) to calibrate flow units and barriers to flow in history matching of the Norne field.

11. Conclusion

The seismic visualization, rendering and seismic attribute of the Norne seismic volume has provided better display of the data and enhances the seismic interpretations. Key visualization techniques applied include different volume wall displays/transparency effect, cropping, realization of virtual cubes, opacity filters. Each of the visualizations and seismic attributes has shown to provide distinct advantages and when appropriately combined by the user lead to a better or effective delivering of interpretations.

The Norne field 3D seismic interpretations were done with the Top Not Formation and Top Åre Formation used as control surfaces. The OWC inputs, faults sticks, Eclipse models, with the inputted 11 wells used alongside in creating the static structural and property models. The reservoir section of the Norne field was defined in most of the lines by the high structural relief of the Norne Horst, with the reservoir section typically forming a wedge shaped structure which tapered to the North, with observed parallel reflectors of the Top BCU, Top Garn, Ile ,Tofte and Tilje reservoir surfaces. The Base Cretaceous Unconformity was interpreted with typical features of erosional unconformity; which was correlatable across the seismic in line and crosslines of the whole volume. From structural flattening technique use to restoring the surfaces to present day structural setting, it was observed from the seismic that approximately 100m thick sand had been eroded off parts of the Norne horst by the erosional event forming the BCU. Other internal terminations and/or unconformities were observed in the section of the reservoir, which was about 200m in thickness from well section.

Large planar faults and minors faults were observed to segment the reservoir into compartments. The automatic ant track fault picking process as a good potential in interpreting the faults in virgin exploration targets or areas and also it could provide quicker methods to analyze faults in updating simulation models. However, the manual fault modeling process was used to maintain and model the interpreted faults with polygons in the reservoir structural models.

The interpreted horizons of the reservoir sections were converted into surfaces with different attributes applied. This were further converted into Horizons surfaces in the 3D grid skeleton through the make horizon process, where zones and layering were applied to each of the interpreted reservoir surfaces.

Property modeling was initiated with facies and petrophysical workflows to populate the 3D skeleton with discrete facies properties. This process shows that sand dominates much of the identified structural relief in the Norne seismic lines. However this modeling could be stretched to include saturation to determine fluid mobility in the Norne field due to the long period of production. This modeling provides a good basis for propect analysis and also for dynamic simulation of the field.

Conclusively, the process of making models involves a whole range of collective data and integration. It involves dynamic or iterative process of inculcating available data/information, with knowledge to the modeling workflow, which means that they are subject to updates (not static in true sense). Other models and techniques like the fault property modelling (sealing capacity), porosity, permeability and saturation models would be considered as alternative models in the Norne field. Finally, the cascading of geologic ideas into the models requires the user to query actions (modeling efforts) with good quality control schemes especially hard data/geologic understanding to query the inconsistencies or deviations in the models.

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