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Sequence Stratigraphic Analysis of the Jurassic Period on the Horda Platform, Northern North Sea, Using State-of-the-Art 3D Seismic Interpretation- Tools and Methodologies

by

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Master's Thesis

Presented to the Faculty of Science and Technology

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Dedication

I dedicate this thesis to my family; my mother, father, brother and sister, and also my dearest grandparents for their love, support and faith in me.

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I would like to thank Sylvia Nordfjord for giving me the opportunity to carry out this thesis project and supervising me by providing with ideas and constructive comments.

I would like to express my gratitude to the support department at dGB Earth Sciences for technical software support during the rough stages of this project.

I would also like to thank and express my appreciation to my fellow students for technical, theoretical and moral support.

Finally, I thank my family and closest friends for always believing in me and giving me the unconditional love and support throughout my studies.

Abstract

Sequence Stratigraphic Analysis of the Jurassic Period on the Horda Platform, Northern North Sea, Using State-of-the-Art 3D Seismic Interpretation- Tools and Methodologies

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A sequence stratigraphic analysis of the Jurassic sequence on the Horda Platform is the main focus for this study. The analyzed interval comprises the stratigraphic record from three mega-sequences; the Base Cretaceous Unconformity to top Brent Group (Upper Jurassic), Brent Group (Middle Jurassic) to top of Statfjord Formation (Lower Jurassic), and Statfjord Formation to top Triassic. These mega-sequences were used as a steering framework for a tracked HorizonCube (HC) that is generated based on a SteeringCube. The HC generates a dense set of automated horizons tracked in a dip-field, which is used to create a WheelerCube. The WheelerCube can be used to interpret systems tracts and their respective bounding surfaces with distance versus relative geologic time.

The main objective of this thesis is to determine whether the results generated from these new sequence stratigraphic tools- and methodologies used in OpendTect (dGB Earth Sciences) will improve the sequence stratigraphic interpretation of seismic data, and if they are more time-efficient and user friendly.

WheelerCube interpretations based on 3D and 2D HC-tracking are compared with each other and with previous studies from the Jurassic sequence on the Horda Platform.

The results from this analysis show that the WheelerCube generated from the 3D HorizonCube-tracking displays a low resolution and inaccurate outcome. This result

leads to a different systems tracts interpretation than the WheelerCube from 2D HC-tracking. The different results depend on the HC-tracking, which is poor and time-consuming in 3D whereas good and time-efficient in 2D.

As a consequence of the poor HC-tracking in 3D, the WheelerCube does not improve the sequence stratigraphic interpretation compared to previous studies from the same area.

Suggestions for improvement of the sequence stratigraphic interpretation are creating a 2D grid of the WheelerCubes generated from 2D–tracking, as well as generating a smaller 3D cube that is less constrained by faults. Unfortunately, there was no time to perform these suggestions during the remainder of this thesis.

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NOMENCLATURE

HST: Highstand systems tract

LST: Lowstand systems tract

TST: Transgressive systems tract

U: Unconformity

SU: Subaerial unconformity

MFS: Maximum flooding surface

SB: Sequence Boundary

BCU: Base Cretaceous Unconformity

FM: Formation

GP: Group

HC: HorizonCube

SC: SteeringCube

IL: Inline

1.0 INTRODUCTION

The objectives of this study are (1) to use new seismic interpretation tools in order to describe and sub-divide stratigraphic units into sedimentary packages by studying seismic reflection patterns in time domains (Mitchum, Vail, & Sangree, 1977) and on a Wheeler transformed domain, and (2) to test if these newer types of modeling will improve the sequence stratigraphic interpretation of seismic data, and if they are more time-efficient and user friendly.

The study area is located on the Horda Platform which is situated on the eastern side of the Viking Graben in the northern North Sea approximately 80 km offshore Norway (Bolle, 1992) (Figure 1). The Viking Graben is 40-100 km wide, trends NNE and is flanked by terraces of fault blocks tilted away from the graben (Horstad & Larter, 1997; Osivwi, 2012). During the Permian-Triassic period the entire North Sea was an area of continental deposition which was subsiding rapidly (Bolle, 1992). Later on this area became a failed intracratonic rift system where fluvial deposits accumulated near the rift margins, and finer lacustrine sediments were laid down toward the center of the basins (Bolle, 1992).

The Horda Platform forms an easterly tilted block which is located on the margin of an Upper Jurassic rift where subsidence and structural rotation were small compared to the deeper graben where more pronounced block rotation took place (Stewart et al., 1995). According to Stewart et al. (1995) subtle movements may have been enough to influence the stratal stacking patterns on the platform.

Previous studies from this area state that the Jurassic strata were deposited during a long-term global transgression that began in the Triassic and reached its peak in the Turonian (Upper Cretaceous) (Fischer, 1981, 1982; Hallam, 1977; Haq, Hardenbol, & Vail, 1987; Vail, Mitchum, & Thompson, 1977). Moreover, according to Stewart et al. (1995) during the Jurassic period the Horda Platform received a steady supply of coarse clastic sediment from the eastern side of the developing graben system leaving an almost complete stratigraphic record of transgressions and regressions along the shore line.

This study focuses on the seismic volume NH0301 (block 31/2, 31/3, 31/5 and 31/6) located on the Horda Platform, northern North Sea, covering the Troll West Field (Figure 2). The analyzed Jurassic interval comprises the stratigraphic record from three mega-sequences; the area between the Base Cretaceous Unconformity (Upper Jurassic) and Brent Group

(Middle Jurassic), Brent Group to top of Statfjord Formation (Lower Jurassic), and Statfjord Formation to top Triassic.

This thesis synthesizes the application of sequence stratigraphic techniques which are compiled into an interpretation software called OpendTect (provided by dGB Earth Sciences). The methodology steps include (1) interpreting three mega-sequences and 44 faults in Petrel (Schlumberger), (2) perform SteeringCube- and HorizonCube modeling in order to process seismic data and tracking horizons in a dip-field on a 3D seismic cube and on a single inline, and (3) generate, analyze and compare a WheelerCube (i.e. Wheeler-diagram in 4D) and the systems tracts with previous studies to see if they give a more comprehensive interpretation of the area of interest.

Figure 2: Structure map of the study area at base Brent Group (Middle Jurassic) (after Sneider et al., 1995).

Figure 1: Location map of the study area (Horda Platform) indicated by a black square.

2.0 THEORY AND PREVIOUS STUDIES

2.1 General Sequence Stratigraphy

2.1.1 BASIC CONCEPTS OF APPLIED SEQUENCE STRATIGRAPHY

The geological term sequence stratigraphy is widely used in the petroleum industry and in the continuous search for hydrocarbons. Generally, it deals with the recognition and interpretation of genetically interrelated packages of sedimentary strata that can be delineated by unconformities and/or conformities within a framework of time surfaces (Nystuen, 1998). According to Catuneanu et al. (2011) this framework ties changes in stratal stacking patterns to the responses to varying accommodation and sediment supply through time. Moreover, Catuneanu et al. (2011) further states that stratal stacking patterns enable determination of the order in which these strata were laid down, and hence explaining the geometric relationships and the architecture of sedimentary strata.

When performing a sequence stratigraphic analysis, the main tools used are the stacking pattern of strata and the key surfaces that bound successions defined by different stratal stacking patterns (Catuneanu et al., 2011). The three types of sequence stratigraphic units are the sequences, systems tracts, and parasequences, where each type of unit is defined by specific stratal stacking patterns and their bounding surfaces (Catuneanu et al., 2011). These units are seen in the Wheeler diagram which is used to understand the relation of rock units in 2D space as a function of absolute geologic time (Wheeler, 1958).

A s*equence* is defined by Galloway (1998) as "a three-dimensional stratigraphic unit consisting of relatively conformable, genetically related strata bounded in whole or in part by surfaces of nondeposition or erosion (unconformities)". Generally, a hierarchy of sequences can be observed in shallow marine coastal successions (Mitchum & Wagoner, 1991; Wagoner, Campion, Mitchum, & Rahmanian, 1990) where it depends partly on the type of data available for study (Stewart et al., 1995). According to Stewart et al. (1995) "the large scale cycles are interpreted as low frequency (2nd order) sequences (Mitchum & Wagoner, 1991). The sequences are divided into different orders of duration, where 2nd order has a general time span of more than 4 million years, and 3rd and 4th order sequences have time spans between 1 – 4 million years to several thousand years (Stewart et al., 1995). The thick, low frequency 2nd order sequences are easier to define from reflection seismic profiles compared to 3rd and 4th order, which are thinner, have a higher frequency, and are generally beyond the resolution of conventional 2D seismic (Stewart et al., 1995).

Today there are different types of sequence stratigraphic approaches, because sequence stratigraphy is a genetic, process-based analytical approach to stratigraphic interpretation that involves conceptual depositional models, and there are nomenclatural preferences and arguments as to which stratigraphic surfaces is best to be elevated when it comes to choosing the sequence boundary (Catuneanu et al., 2011) (Figure 3A).

In this study the sequence stratigraphic approach used is the *genetic sequence* as defined by Frazier (1974) and Galloway (1989) (Figure 3B). The reason for choosing this approach lies within the geological data used, which is primarily the study of seismic data and the Wheeler-diagram, without the use of well log correlation- and core analysis.

According to Galloway (1989) "the genetic sequence paradigm emphasizes preserving the stratigraphic integrity of three-dimensional depositional systems and does not rely on widespread development of subaerial erosion surfaces caused by eustatic falls of sea level to define sequence boundaries." The maximum flooding surface (Frazier, 1974; Galloway, 1989; Posamentier, Jervey, & Vail, 1988; J. C. Van Wagoner et al., 1988) is used as sequence boundary when following a genetic sequence stratigraphic approach, which is a sedimentary veneer or surface that records the depositional hiatus occurring over a large part of the transgressed shelf and adjacent slope (Galloway, 1989). The maximum flooding surface is relatively easy to map across a basin due to their common association with regionally extensive shale units, and they are often easier to map on seismic lines and well logs then the subaerial unconformities (Catuneanu, 2006).
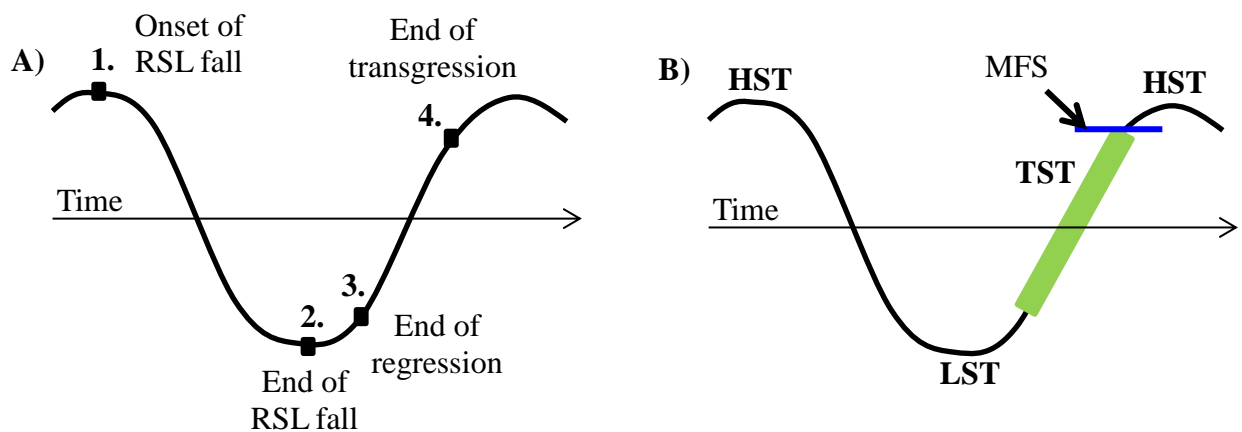
Figure 3: A) Timing of sequence boundaries for the various sequence stratigraphic approaches (modified from Catuneanu et al. 2010). 1.: Depositional sequence I (Mitchum, Vail, & Thompson, 1977) and depositional sequence II (Haq et al., 1987; Posamentier & Vail, 1988). 2.: Depositional sequence III (Christie-Blick, 1991; J. C Van Wagoner, Mitchum, Campion, & Rahmanian, 1990; J. C. Van Wagoner et al., 1988) and depositional sequence IV (Helland-Hansen & Gjelberg, 1994; Hunt & Tucker, 1992, 1995). 3.: T-R sequence (Embry & Johannesen, 1992; Johnson & Murphy, 1984). 4.: Genetic sequence (Frazier, 1974; Galloway, 1989). RSL: Relative sea level (Catuneanu et al., 2011). B) Genetic stratigraphic sequence approach defined by Galloway (1989) with maximum flooding surface as sequence boundary located at the end of a transgression.

2.1.2 KEY STRATIGRAPHIC SURFACES

It is important to recognize and identify the key stratigraphic contacts such as the sequence boundary, maximum flooding surfaces and unconformity surfaces because they indicate times when facies belts have shifted position and sediments have been eroded from the shelf areas and redeposited into the basin (Stewart et al., 1995). In addition, they have a significant impact on the field architecture and the modeling of regional reservoir distribution (Stewart et al., 1995).

The maximum flooding surface is, as mentioned previously (Ref. 2.1.1), the sequence boundary in this study. The sequence boundary is defined as a bounding surface of stratigraphic sequences (Nystuen, 1998). The maximum flooding surface is often represented on seismic data as high amplitude reflections with a good continuity (Stewart et al., 1995). This surface represents a change in stratal stacking patterns from transgression to highstand normal regression (Figure 3B), and is marked by a peak in magnitude on gamma ray logs

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(Catuneanu et al., 2011; Stewart et al., 1995). It is commonly associated as a downlap surface in seismic data, typically being downlapped by the overlaying highstand systems tract indicate margin progradation (Catuneanu et al., 2011).

The subaerial unconformity usually represents a hiatus, or hiatus combined with erosion (Nystuen, 1998), and is represented by top lap termination of seismic reflectors, and marks the end (top) of a regression on gamma ray logs. This surface indicates times when facies belts have shifted position and sediments are eroded on the shelf areas and later redeposited into the basin (Stewart et al., 1995).

2.1.3 SYSTEMS TRACTS

Systems tracts sub-divide sequences (Nystuen, 1998), and is defined by Brown and Fisher (1977) as "a linkage of contemporaneous depositional systems, forming the subdivision of a sequence". Generally, systems tracts reflect the dominance of different processes during the relative sea level cycle (Stewart et al., 1995). The regime variables; eustasy, sediment supply and subsidence are contributors to the control of basin- fill and architecture, and a change in one regime variable must be compensated for by an adjustment in other regime variables (Galloway, 1998).

The shoreline-related systems tracts consist of correlatable depositional systems genetically related to certain types of shoreline trajectory, i.e. forced regression, normal regression, and transgression (Catuneanu et al., 2011). This type of systems tracts are usually interpreted to form during specific stages of the relative sea-level cycle (Catuneanu et al., 2011).

The highstand systems tract is dominated by prograding shallow marine and deltaic facies deposited during the late rise and early fall of the relative sea level cycle (Stewart et al., 1995). Deposits from this systems tract form when sediment accumulation rates exceed the rate of increase in accommodation (Catuneanu et al., 2011). It rests on the maximum flooding surface and is located right below the sequence boundary (Stewart et al., 1995). The stacking patterns are represented by prograding and aggrading clinoforms with a downward dip, capped by a topset of fluvial, coastal plain and/or delta plain deposits (Catuneanu et al., 2011).

The lowstand systems tract includes deposits accumulating after the onset of relative sea-level rise, during normal regression, and rests on the unconformity surface and is right below the transgressive surface (Catuneanu et al., 2011; Stewart et al., 1995). The clinoform

structure of a lowstand systems tract shows onlapping reflectors, the stacking patterns exhibit forestepping and aggradation thickening downdip, and a top set of fluvial, coastal plain and/or delta deposits (Catuneanu et al., 2011). According to Catuneanu et al. (2011) "the lowstand systems tract sediments often fill or partially infill incised valleys that were cut into the highstand systems tract, and other earlier deposits, during forced regression". In passive margins this systems tract would be confined to the shelf margin as shelf margin deltas and in the basin as turbidites (Stewart et al., 1995).

Transgressive systems tract rests on a transgressive surface and is right below the maximum flooding surface/sequence boundary, and is deposited during relative rise of sea level (Stewart et al., 1995). The clinoform structure of a transgressive systems tract builds up a backstepping, onlapping, retrogradational stacking pattern (Catuneanu et al., 2011). The parasequences could also be aggradational if there is a high sediment supply (Catuneanu et al., 2011).

2.2 Previous Studies

2.2.1 STRUCTURAL SETTING OF THE HORDA PLATFORM

The Horda Platform is located to the east of the deep faulted Viking Graben in the Northern North Sea (Stewart et al., 1995). According to Stewart et al. (1995) "the North Viking Graben rift system was initiated in the Permo-Triassic as evidenced by the large half grabens seen below the Horda Platform with early Triassic syn-sedimentary infill". A more uniform thickness distribution is found in the late Triassic to Lower Jurassic, which drapes the syn-rift sediments and may be seen as a late post rift sag fill resulting from thermal subsidence following rifting (Stewart et al., 1995). More or less uniform subsidence continued, and the lower part of the Middle Jurassic (Brent Group) had few evidence of syn-sedimentary faulting (Stewart et al., 1995). Moreover, Stewart et al., (1995) state that faulting on the Horda Platform was generally north-south and individual fault blocks were tilted to the east, and renewed extension and rotation of fault blocks was initiated in the Early Bathonian and became more important in the Oxfordian. The actual major phase of tilting and rifting of these fault blocks occurred in the Kimmeridgian to Ryazanian, which resulted in the differentiating between the Viking Graben and the Horda Platform (Stewart et al., 1995). The group that could have been affected by these structural changes is the Viking Group with the Krossfjord, Fensfjord, Mid. Heather, and Sognefjord Formations.

2.2.2 DEPOSITIONAL SEQUENCE AND JURASSIC STRATIGRAPHY OF THE HORDA PLATFORM

The Horda Platform is a key calibration area when it comes to the sequence stratigraphy of the Late-Middle to Upper Jurassic (Fensgjord-Sognefjord Formations) of the North Sea (Stewart et al., 1995). The reason is the high amount of seismic data interpretation covering the Horda platform in addition to excellent sedimentological and biostratigraphic data from more than 30 wells (Stewart et al., 1995).

The Jurassic strata were deposited during a long-term global transgression that began in the Triassic and reached its peak in the Turonian (Fischer, 1981, 1982; Hallam, 1977; Haq et al., 1987; Vail et al., 1977), expressing itself as a progressive onlap in the basin (Sneider, Clarens, & Vail, 1995). The eastern margin of the North Viking Graben on the Horda Platform received a steady supply of course clastic sediments from the eastern side of the developing graben system during the Jurassic period. As a consequence of this an almost complete stratigraphic record of cyclical shore line transgressions and regressions (Stewart et al., 1995).

The Late-Middle to Upper Jurassic of the Horda Platform comprise sands that range from very fine grained, highly micaceous to course grained, which are deposited in shallow marine shelf to shore-face environments (Stewart et al., 1995). According to Stewart et al. (1995) no fluvial or coastal plain facies have been identified. High energy shore-face sandstones were deposited in north-south oriented linear trends parallel with the structural grain of the Viking Graben (Stewart et al., 1995). The sands are organized dominantly into 10-30 m thick coarsening-upwards units separated by condensed horizons (Stewart et al., 1995).

Figure 4 shows the stratigraphic synopsis of the Jurassic of the north eastern North Sea proposed by Stewart et al. (1995).

Period	Series/Epoch	Stage	Age [Ma]	Group	Formation	2nd Order Sequences	North Viking Graben	Horda Platform
Cretaceous	Lower	Ryazanian	139.8	Viking	Draupne		West ←	East →
Jurassic	Upper	Volgian	145.0	Viking	U. Heather		SB	
		Kimmeridgian	152.1	Viking	Sognefjord / Mid. Heather		SB / Heather FM	Sognefjord FM
		Oxfordian	157.3	Viking			MFS	
	Middle	Callovian	163.5	Viking	Fensfjord			Fensfjord FM
		Bathonian	166.1	Brent	Krossfjord / L. Heather / Tarbert		MFS	Krossfjord FM
		Bajocian/Aalenian	168.3	Brent	Tarbert / Ness / Etive / Drake		MFS / SB Hiatus / SB	Tarbert FM / Ness / Rannoch/Etive / Drake FM
	Lower	Toarcian	174.1	Dunlin	Drake		Dunlin GP	
		Pliensbachian	182.7	Dunlin	Cook / U. Amundsen		MFS / SB	Cook FM
		Sinemurian	190.8	Dunlin	Johansen / L. Amundsen			Amundsen FM
		Hettangian	199.3		Statfjord			Statfjord FM
Triassic	Upper		201.3	Hegre				

Figure 4: Stratigraphic synopsis of the Jurassic, east northern North Sea modified after Stewart et al. (1995). MFS: Maximum flooding surface, SB: Sequence Boundary.

2.2.3 KROSSFJORD, FENSFJORD AND SOGNEFJORD FORMATIONS

Figure 4 shows that Krossfjord and Fensfjord Formations (Middle Jurassic) prograde westward, and Sognefjord Formation (Upper Jurassic) retrogrades eastward. According to Stewart et al. (1995) the sequence boundaries in the Fensfjord (Middle Jurassic) and Sognefjord (Upper Jurassic) Formations conform to the definition of genetic stratigraphic sequence (Galloway, 1989) and parasequences (Wagoner et al., 1990) since no 3rd order erosive sequence boundaries have been confirmed within these formations. No erosional sequence boundaries were produced because the magnitude of relative sea level fluctuations were small (Stewart et al., 1995). Moreover, two orders of maximum flooding event are inferred: 1) 2nd order flooding intervals occurring at the point where the 3rd order sequence stacking pattern changes from backwards-stepping to forward stepping mode, and 2) maximum flooding surface bounding 3rd order high frequency sequences (Stewart et al., 1995) (Figure 4).

Stewart et al. (1995) suggest that stacking of coarse grained sand bodies in west Troll and thinning eastwards in the inferred direction of the basin margin could cause axial (north to south) transport of sediment, and may reflect a gentle eastward tilt of the Horda Platform which began in the Late Callovian-Oxfordian times. This tilt (clearly indicated in the Kimmeridgian) caused a reduction in accommodation space and erosion occurred over Troll West resulting in higher energy depositional conditions because the area was uplifted above wave base for a longer period of time (Stewart et al., 1995).

2.2.4 BRENT GROUP

The Brent Group (Middle Jurassic) consists of deltaic lithofacies deposited during a regressive period which reaches its peak marked by a sequence boundary in the Early Bajocian (Stewart et al., 1995). According to Eynon (1981) the deltaic systems prograded from the south controlled by an area of domal uplift at the triple junction between the Central, Witch Ground and Viking Graben (Stewart et al., 1995). The delta retrograded from the Late Bajocian to Early Callovian and according to Helland-Hansen et al. (1992) there was a reworking of the delta top to form the Tarbert Formation. Differential subsidence resulted in a marked thickening of the Brent Group across the edge of the Horda Platform, and tectonic activity was limited during the deposition of the lower part of Brent Group (Stewart et al., 1995). The tectonic regime started to change from more or less uniform, slow subsidence to more rapid subsidence with associated fault block rotation during deposition of the upper part of the Brent Group (Stewart et al., 1995). Due to this change in subsidence rate there is a change from the sheet-like facies distributions and axial sediment transport systems of the Bajocian to local, basinal parallel facies distribution with depositional transport from the basin margin of the Late-Middle Jurassic (Stewart et al., 1995). A maximum flooding surface is located in the Late Bathonian as suggested by Stewart et al. (1995) which resulted from the relative sea level rise and retreat of the Brent delta system from the Horda Platform area (Figure 4).

2.2.5 DUNLIN GROUP AND STATFJORD FORMATION

According to Marjanac (1995) the Lower Jurassic Dunlin Group formally consists of Drake, Cook, Amundsen, Johansen and Burton Formations. The Johansen Formation consists of sandstones that are reinterpreted as a northwestward prograding delta, the Cook Formation also consists of sandstones (basinward-dipping and basinward-wedging sedimentary bodies), whereas Amundsen and Drake Formations have silty claystones and sandstones (Marjanac, 1995). The Dunlin Group is deposited during a regressive cycle with progradation westwards, and an erosional unconformity (sequence boundary) is located above the Johansen Formation (Early Pliensbachian) (Figure 4). The top of Statfjord Formation (Hettangian) marks the beginning of a regressive cycle, and transition from the non-marine Triassic below to the marine shales of the Lower Jurassic above (Sneider et al., 1995) (Figure 4).

2.3 DEPOSITIONAL ENVIRONMENT AND RESERVOIR STRATIGRAPHY

Deposition of very fine grained, highly micaceous to coarse grained sands from the Horda Platform took place on a coast-attached shelf as cyclic sequences with alternations between transgressive sandstones and siltstones, proximal progradational shoreface facies and coastal distributaries (Bolle, 1992; Stewart et al., 1995). No fluvial or coastal plain facies have been identified (Stewart et al., 1995). According to Bolle, (1992) the sequence architecture is controlled by minor regional sea level fluctuations that are framed in the major overall late Callovian to early Volgian regional transgression.

The Troll Field has a prominent oil-water contact seen as a flat-spot on seismic data (Figure 5). The oil- and gas reservoir contains medium- to coarse grained, hardly consolidated sands and fine micaceous sandstones and siltstones of Middle to Upper Jurassic age, located in the Viking Group (Bolle, 1992). Gamma-ray logs from the Viking Group in the central and northern North Sea show shales and claystones with some thin, areally restricted intercalations of sandstones (Bolle, 1992). The Viking Group consists of the Sognefjord, Heather, Fensfjord, and Krossfjord Formations that comprise a stacked shallow marine sandstone sequence (Bolle, 1992).
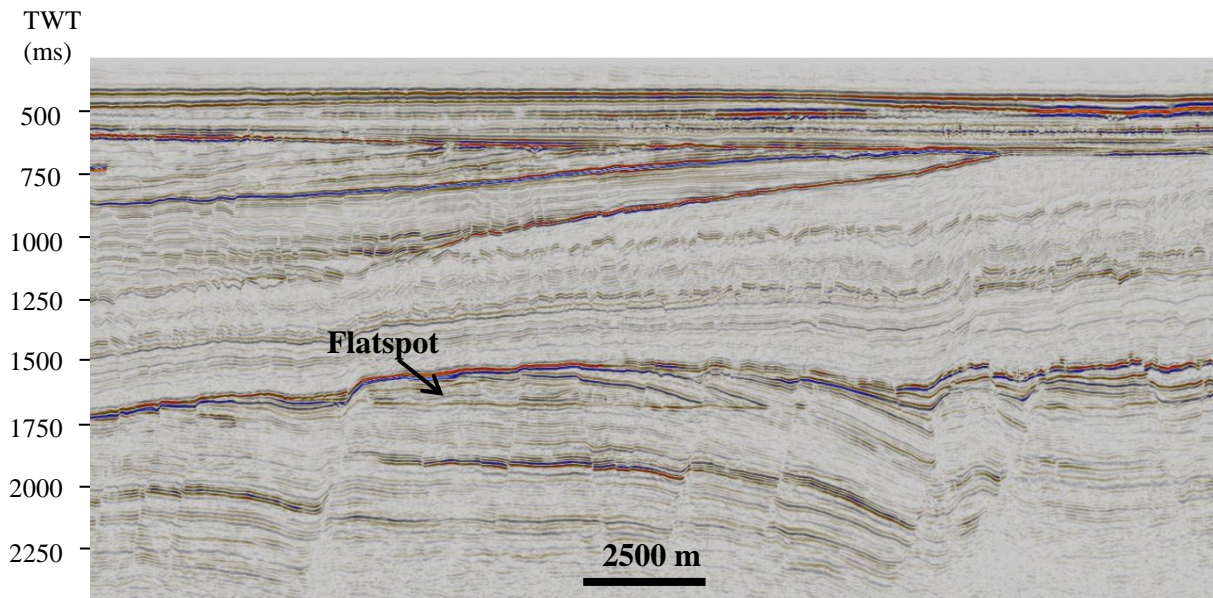
Figure 5: Inline 861 from the Troll West Field indicating the prominent flatspot (oil-water contact).

2.4 OpendTect

2.4.1 OPEN SOURCE SEISMIC INTERPRETATION SYSTEM

OpendTect is the only available open source seismic interpretation platform used in the oil and gas industry today (Groot, 2010). According to Groot (2010) "OpendTect allows interpreters to target and calculate attributes, test attribute parameters within a highly visual environment, and create their own attributes to find the optimal setting for their data".

2.4.2 STEERINGCUBE MODELING

A SteeringCube is a volume that stores information about the dip and azimuth of the seismic events in inline and crossline direction at every sample point ("How To Manuals," 2013). The purpose of the SteeringCube is to calculate multi-trace attributes on 2D or 3D seismic by extracting and filtering data along seismic events, auto-track chrono-stratigraphic horizons, and finally to compute attributes based on local dip-azimuth information only ("How To Manuals," 2013). The dip and azimuth information is used to improve attribute accuracy and object detection power ("OpendTect Workflows Documentation 4.4," 2012). The SteeringCube follows the dip trace by trace using full steering where the dip/azimuth is updated at every trace position ("OpendTect Workflows Documentation 4.4," 2012).

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When creating a SteeringCube it is recommended to apply a dip-steered median filter on the input seismic volume (Figure 6) in order to remove random noise and to enhance laterally continuous seismic events (Figure 7). If the seismic data is less noisy the dip steered median filter step-outs (inline/crossline/sample) should be lower, whereas for seismic with a lot of noise the step-outs should be higher. The dip-steered median filter does not sharpen edges (faults), whereas a fault enhancement filter should be applied to low quality seismic data in order to smooth the seismic with sharp fault breaks ("OpendTect Workflows Documentation version 4.4," 2012). In this thesis, only a dip-steered median filter is applied to the seismic data as this is the only input needed for the SteeringCube in order to create a HorizonCube.
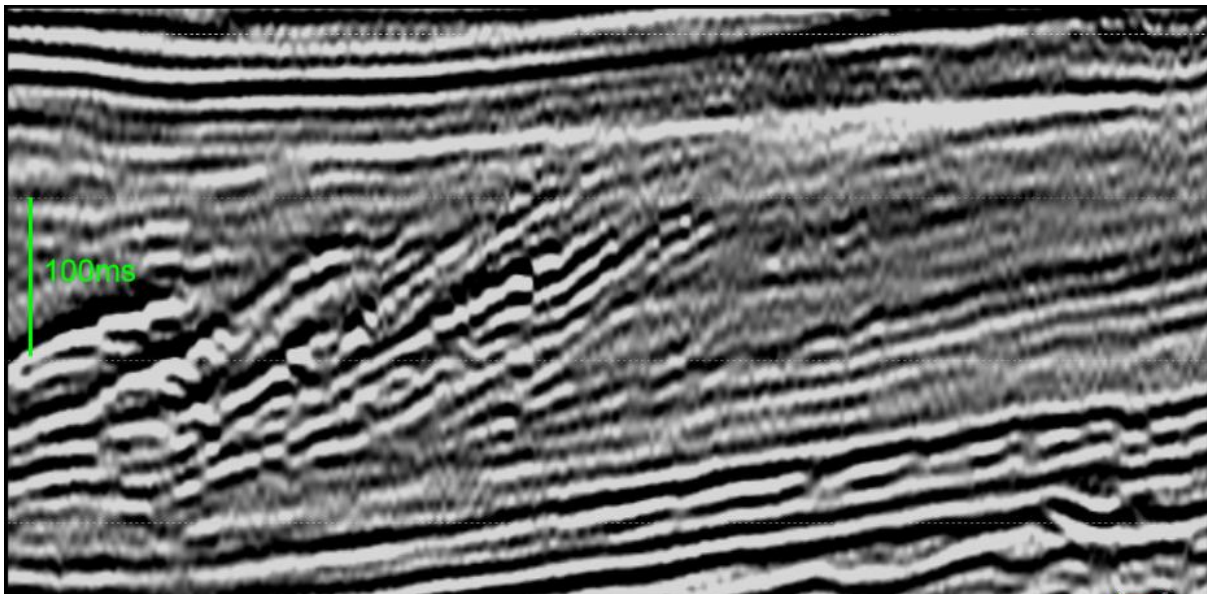
Figure 6: Example of seismic section without dip-steered median filter (Qayyum & Groot, 2013).
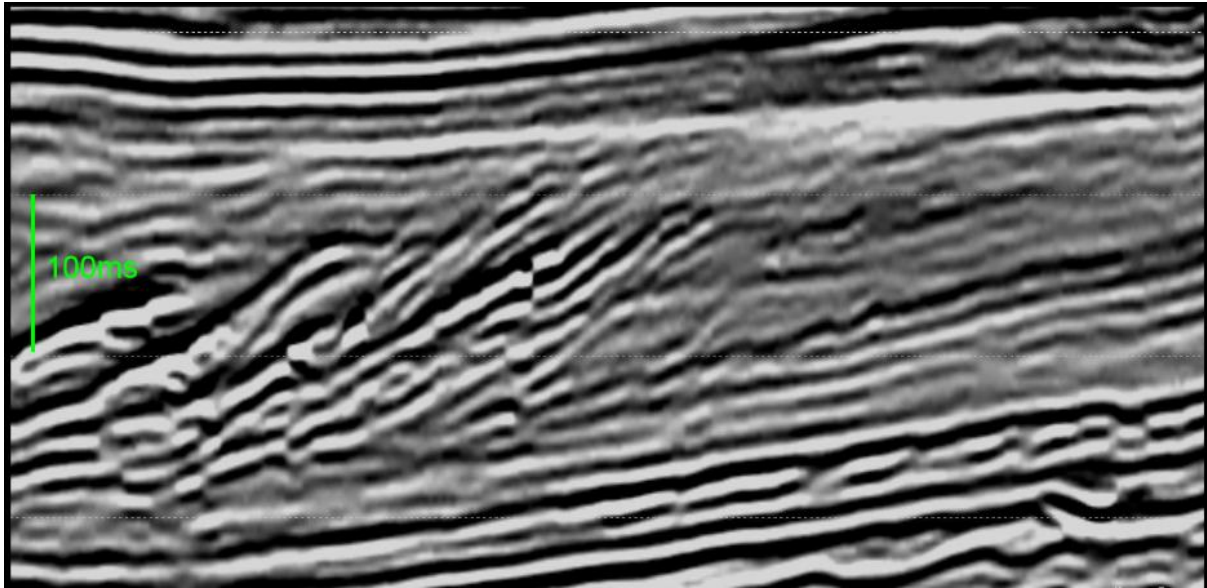
Figure 7: Example of seismic section after applied dip-steered median filter (Qayyum & Groot, 2013).

There are two types of SteeringCubes namely the Background SteeringCube (Figure 8) and the Detailed SteeringCube (Figure 9). The Detailed SteeringCube adds a mild smoothing to the seismic data where noise is removed but details such as dip associated with fault drag remains visible, i.e. local information is preserved (Qayyum & Groot, 2013). The Background SteeringCube is a heavily filtered/smoothed version of the Detailed SteeringCube where only the regional information is preserved displaying primarily the background structure with dip/azimuth information and details and noise removed (Qayyum & Groot, 2013).

The Detailed SteeringCube has three different types of steering algorithms that can be used; the BG Fast Steering, the FFT Steering, and Event Steering. According to Qayyum and Groot (2013) the BG Fast algorithm computes dip from the gradient of the unwrapped instantaneous phase, whereas the Fast Fourier Transform (FFT) algorithm computes dip from maximum amplitude in 3D Fourier transformed domain, and lastly the Event algorithm computes dip between similar events.
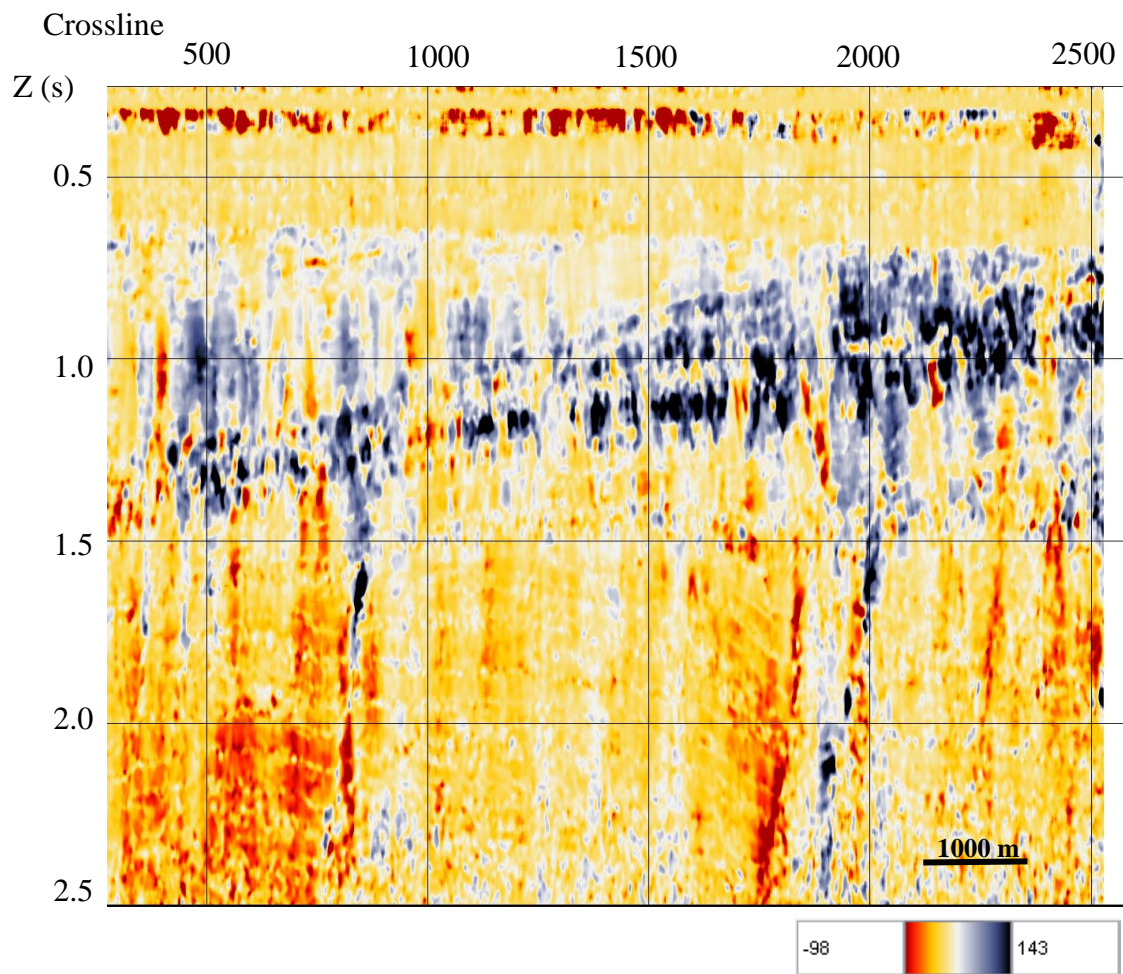
Figure 8: Example of background SteeringCube (BG, 5x5x5) on a seismic inline (861) on the Horda Platform.
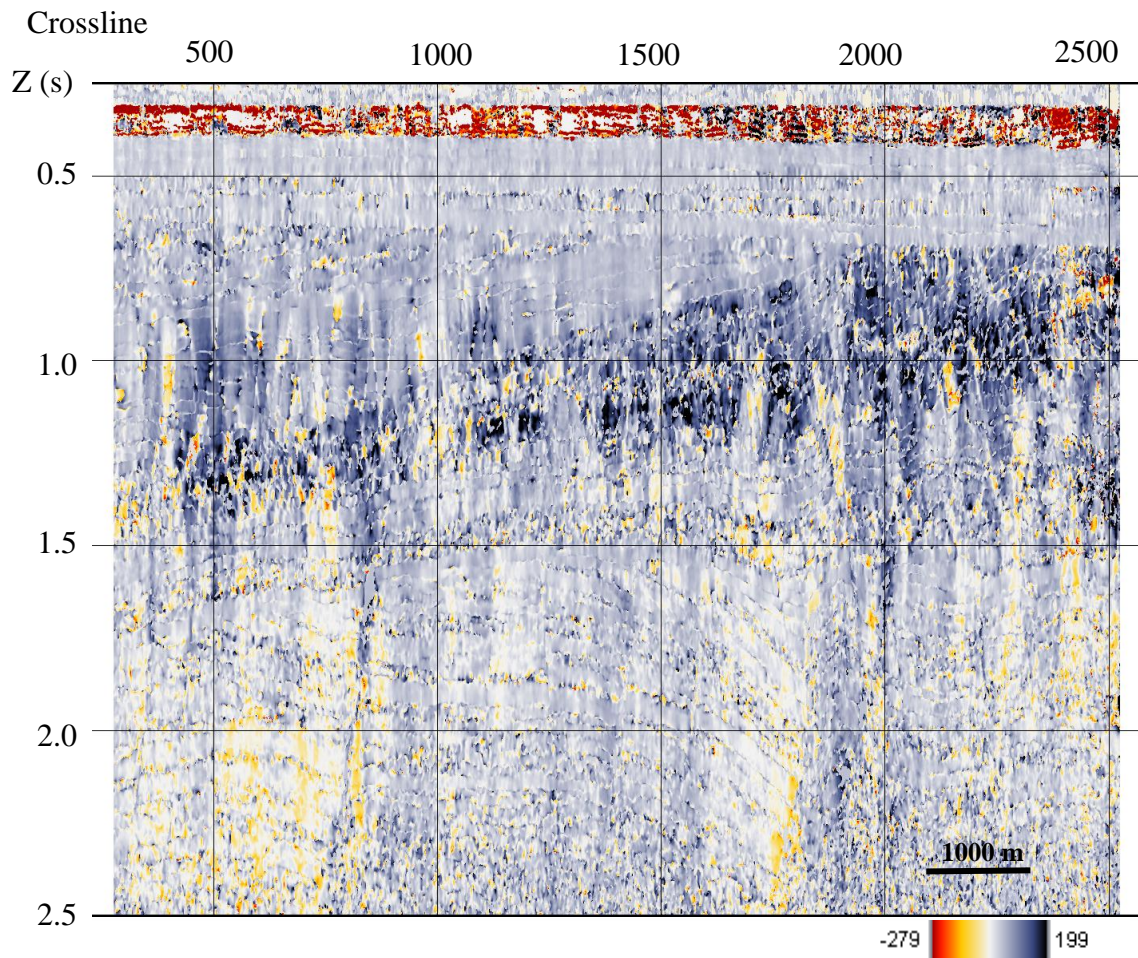
Figure 9: Example of detailed SteeringCube (FFT, 3x3x3) on seismic inline (861) on the Horda Platform.

2.4.3 HORIZONCUBE MODELING

A HorizonCube is used as an automated method for mapping seismic horizons ("How To Manuals," 2013). The purpose of the HorizonCube is to track the horizons using a dip-based tracking algorithm so that the mapping becomes easier and more efficient. The process of dip-steering is that the dip-azimuth of the seismic events can be used to create a local horizon at each position in a 3D volume by following the dip and azimuth information from the center outwards ("OpendTect Workflows Documentation 4.4," 2012). The advantage of using dip-steered auto-tracking as opposed to a conventional amplitude auto-tracking is that the dip-steered method tracks in dip fields which are more continuous than the amplitude fields ("How To Manuals," 2013). Also, the resulting horizons can be patchy and discontinuous when using the amplitude auto-tracking method ("How To Manuals," 2013). Finally, most of the sequence stratigraphic surfaces change seismic phase from one area to

another due to a lateral change in facies ("How To Manuals," 2013) therefore these surfaces can be hard to map using a conventional mapping method.

There are two types of HorizonCube modeling which are the model driven and the data driven. When using the model driven technique the tracking of the seismic events is either relative to the upper or lower horizons, or proportional (Figure 10). The purpose of the model driven technique is mainly visualization (e.g. stratal slicing). On the other hand, by using the data driven technique the seismic events follow the dip by utilizing the SteeringCube as input. The data driven technique is mainly used for sequence stratigraphic purposes, but this method requires the use of high quality and clean seismic images.
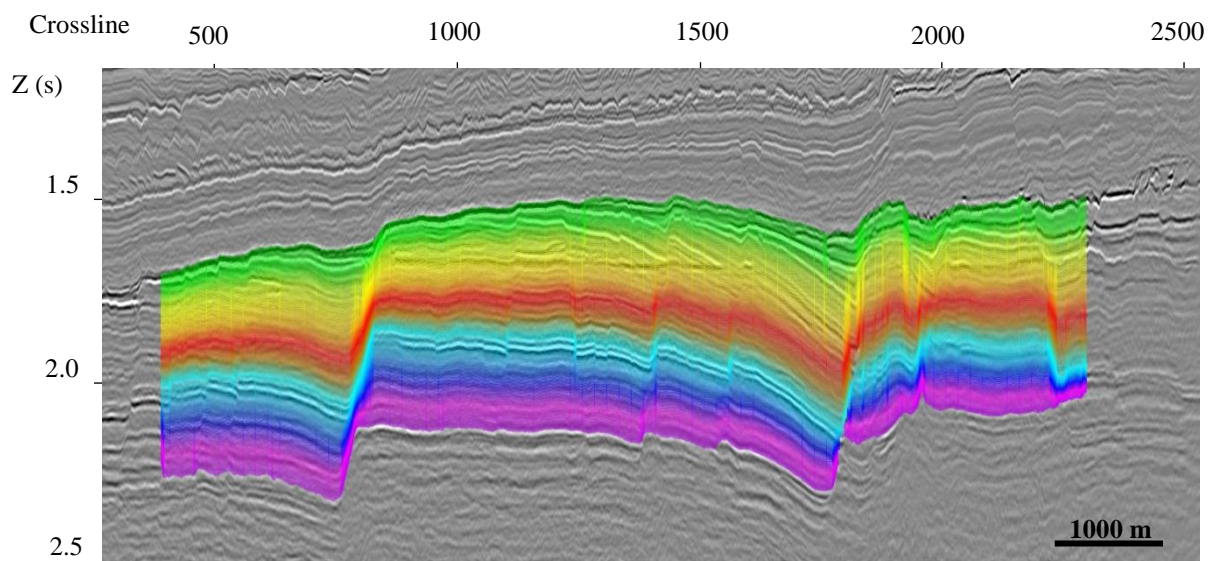
Figure 10: Example of model driven HC-tracking with proportional tracking of seismic events from seismic inline 861 on the Horda Platform.

When selecting the data driven modeling the HorizonCube differentiates between two types of applications; the continuous and the truncated (Figure 11). The first is used for low frequency models, geological modeling and attribute visualization in 3D ("How To Manuals," 2013), whereas the latter is applied for sequence stratigraphic interpretation, wheeler transformation and attribute visualization in 3D ("How To Manuals," 2013). When truncating the HorizonCube the closely spaced events are removed, and a maximum density value is used as input parameter referring to the number of events within a seismic sampling rate ("OpendTect Workflows Documentation version 4.4," 2012). All horizons within a truncated and continuous HorizonCube represent correlated 3D stratigraphic surfaces that are assigned a relative geologic age (Groot & Qayyum, 2013).

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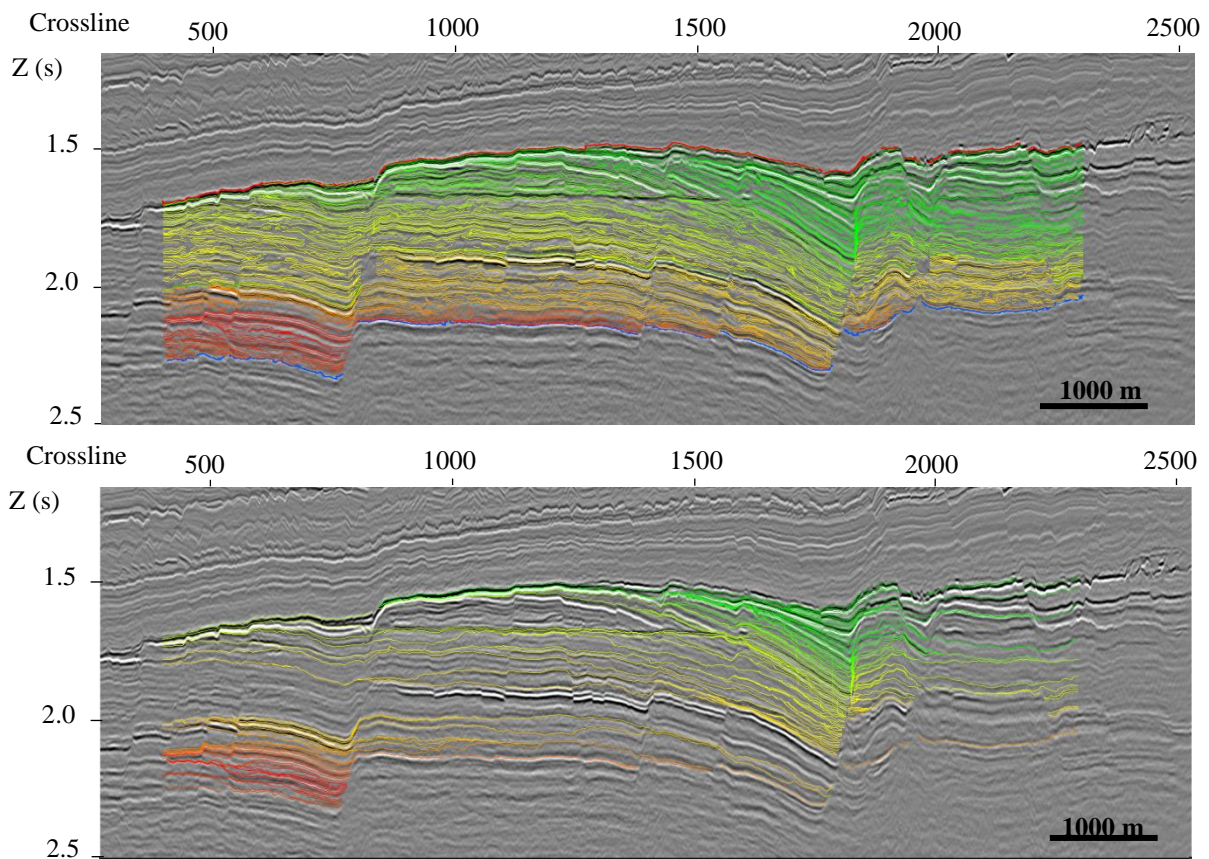
Figure 11: Example of data driven HC-modeling with truncated (top) versus continuous (bottom) events on seismic inline 861 on the Horda Platform.

Generating a HorizonCube is an iterative process, meaning that several HorizonCubes need to be generated in order to end up with a satisfactory one where the tracking honors the correct seismic reflectors and structural features. The workflow in Figure 12 shows the inputs needed in order to generate a HorizonCube. The outputs of the HC are Wheeler transformations, sequence stratigraphy analysis, inversion and well correlation.

Commonly the default parameters are good enough to use, however, it might be necessary to change the filtering parameters if the tracking is not adequate. By realizing areas with high noise disturbance from the SteeringCube one can change the filtering parameters (inline/crossline/sample) to remove this noise and use the new SteeringCube as input to the data driven HorizonCube. This method is used to optimize the HorizonCube-tracking (Figure 13).
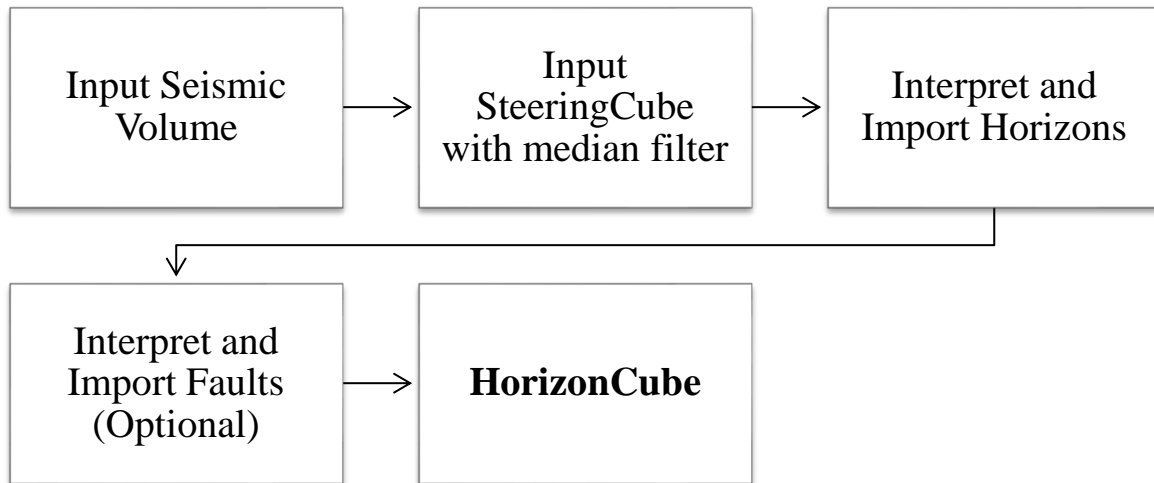
Figure 12: Workflow for generating a HorizonCube.
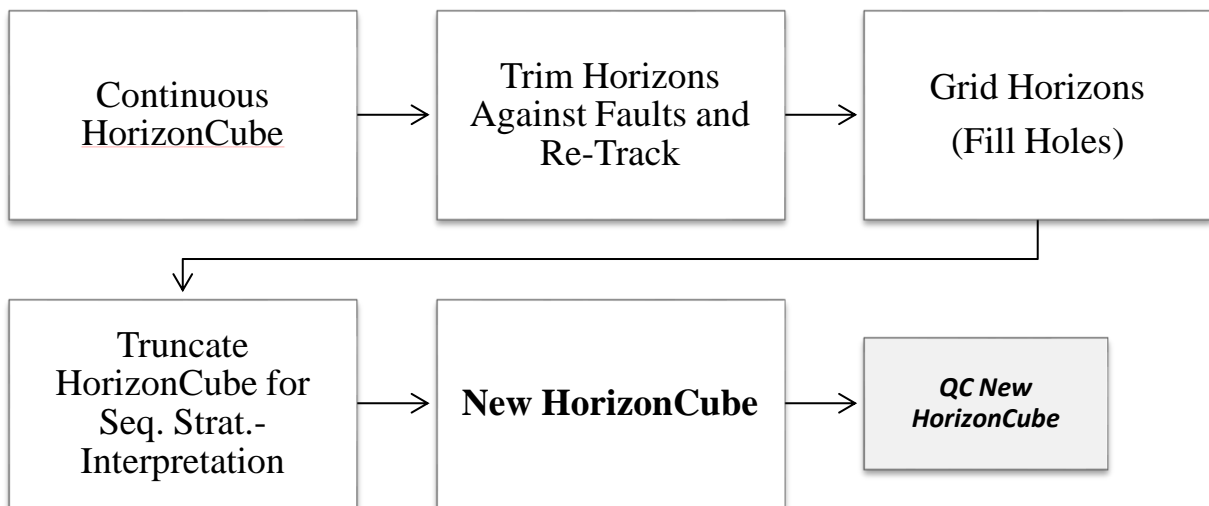
Figure 13: Workflow for optimizing the HorizonCube.

2.4.4 WHEELER TRANSFORMED DOMAIN

A Wheeler transform is the seismic equivalent of the Wheeler diagram (Qayyum & Groot, 2012), and it is generated using the HorizonCube and seismic volume as input parameters. The Wheeler diagram displays rock units plotted in a 2D chart with absolute geologic time (y-axis) versus distance in space (x-axis) showing the temporal-spatial relationship between rock units (Qayyum & Groot, 2012). In a Wheeler transformed domain the seismic data is flattened along flattened chronostratigraphic horizons, displaying relative geologic time on the y-axis (Qayyum & Groot, 2012). An example of a WheelerCube, which is in four dimensions, is shown in Figure 14.
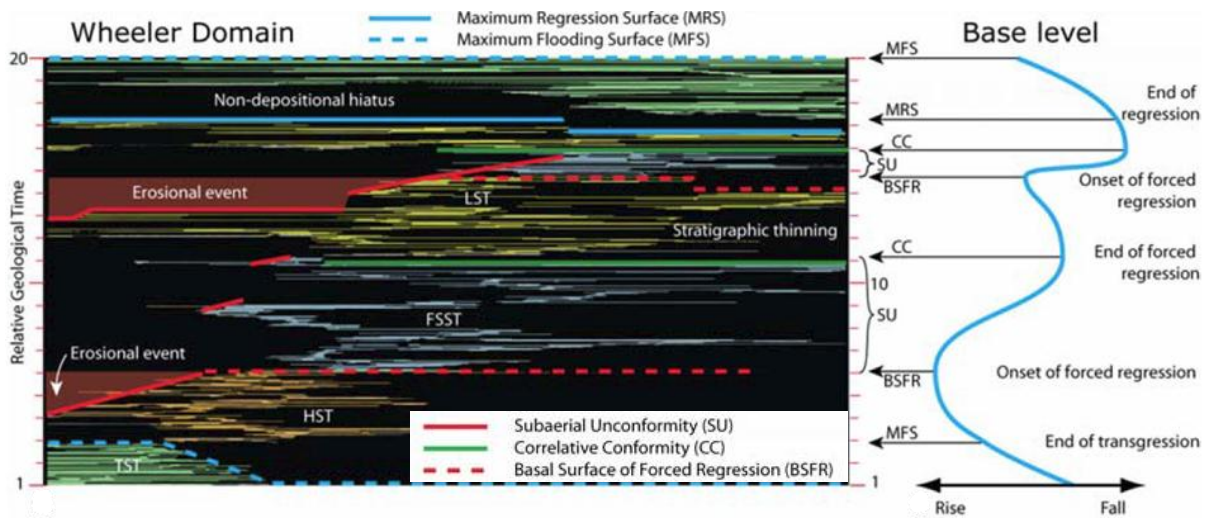
Figure 14: Wheeler transform of systems tract interpretation (left) and the corresponding base level curve indicating relative rise and fall generated in OpendTect (Bruin & Bouanga, 2007). TST: Transgressive systems tract, HST: Highstand systems tract, FSST: Falling stage systems tract, and LST: Lowstand systems tract.

3.0 METHODOLOGY

3.1 Seismic Interpretation in Petrel

The first step before interpreting the seismic data was to do a seismic-well tie in order to determine the age of the formations of the three mega-sequences. The time-depth relationship was extracted by using the sonic and density logs to create a synthetic seismogram by using a wavelet extraction from ~1500 - ~2500 ms. A synthetic seismogram for well 31/2-1 was created and the seismic reflectors were time-shifted in order to fit the BCU-reflection, which was used as correlation marker as it is a strong, prominent reflection and easy to recognize on the seismic. The different lithological well top depths of the Jurassic strata and Troll West Field formations are from the Norwegian Petroleum Directory, and these were assigned to the wells penetrating the interval of interest, i.e. from the BCU until top of the Statfjord Formation (Figure 18).

Three megasequences were interpreted in Petrel, the Base Cretaceous unconformity, the Top Brent Group and the Top Statfjord Formation. The horizons were manually tracked every 40 inline/crossline intervals, and time surface- and time-thickness maps were generated for each horizon.

A total of 44 faults were interpreted in Petrel and used as input in OpendTect when later performing sequence stratigraphic interpretation. Moreover, the surface maps and time-thickness maps were generated for the megasequences by the 'Make/edit surface' process in Petrel.

3.2 Sequence Stratigraphic Application and Interpretation in OpendTect

The megasequences and faults interpreted in Petrel were imported into OpendTect by using a Petrel Connector provided by Schlumberger (Ocean Store).

3.2.1 STEERINGCUBE MODELING

In order to know which type of steering algorithm to use, three different types were tested out on a seismic inline (IL861), in addition to different values for the dip-steered median filter. These SteeringCube types were the BG Fast Steering, Event Steering, and lastly the FFT Steering. The purpose of testing the different algorithms was to see which type

generated the best input SteeringCube to the HorizonCube. The background SteeringCube was used as input to the dip-steered median filter since the smoothing in unfaulted areas works better with this type of dip-steering.

The final SteeringCube (Figure 27) for the seismic volume in this study was computed using a sliding 3D Fourier analysis technique where the cube is transformed to the Fourier domain and the dip is determined ("OpendTect Workflows Documentation 4.4," 2012). The type of steering used was a standard 3x3x3 Fast Fourier Transform (FFT) with a median filter applied and a heavily smoothed background SteeringCube as input.

3.2.2 HORIZONCUBE MODELING

Since HorizonCube modeling is an iterative process, several different HorizonCubes were generated in order to test the different parameters and SteeringCubes used as input. The HorizonCube was created using the FFT SteeringCube generated, the three interpreted mega-sequences; the BCU, Brent Group and Statfjord Formation, and the interpreted faults as input parameters (Figure 15). The megasequences were first gridded then trimmed against the faults before adding them into the HorizonCube workflow.

The chosen HorizonCube modeling was data driven, and the tracking started at the center tracking continuous events with a fixed spacing of 16 ms, filling spaces larger than 20 ms by 100 traces. The stepout was set to 1 (inline) and 4 (crossline). When the workflow for this process was complete, the HorizonCube was truncated using a maximum density of 2 (the default parameter). Two final HorizonCubes were created to test the difference of HorizonCube tracking in 3D and 2D.
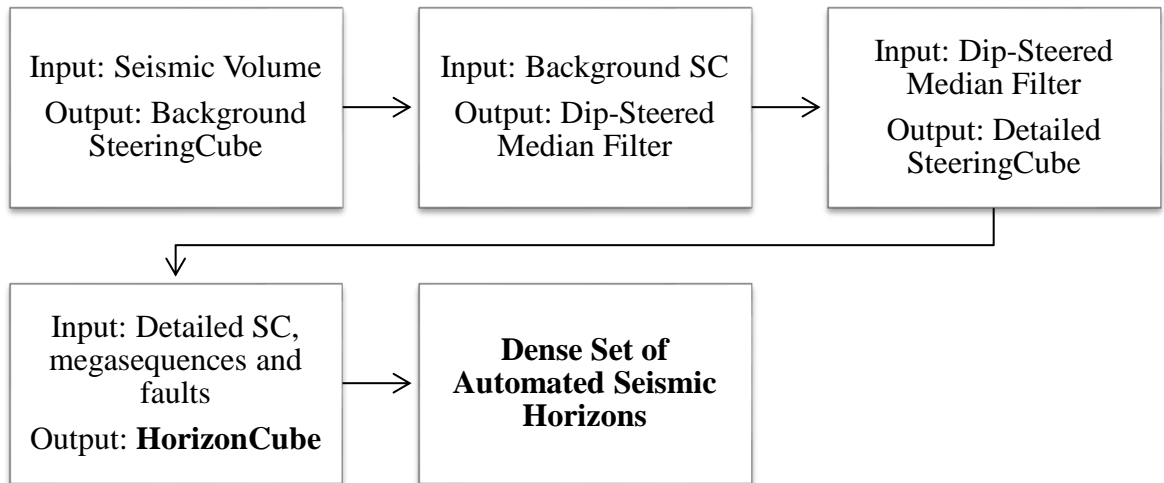
Figure 15: Workflow for generating a HorizonCube. Input parameters include seismic volume, dip-steered median filter, background and detailed SteeringCubes, horizons and faults.

3.2.3 CREATING THE WHEELERCUBE

The WheelerCube was generated by using the HorizonCube as input together with the seismic volume of the study area (NH0301). The WheelerCube is displayed in the Wheeler transformed domain, where the main difference between 2D Wheeler diagram and 4D transformed domain is that the vertical axis for the first is in absolute geologic time, whereas for the latter it is in relative geologic time ("OpendTect Workflows Documentation version 4.4," 2012).

3.2.4 DIVIDING INTO SYSTEMS TRACTS AND IDENTIFYING KEY STRATIGRAPHIC SURFACES

As explained previously in section (2.1.2), Stewart et al., (1995) sub-divided the sequences into systems tracts reflecting the dominance of different processes during the relative sea level cycle. The systems tracts were assigned to the proper interval by selecting the genetic sequence model and label corresponding sequence stratigraphic surfaces.

Moreover, the systems tracts from the 3D WheelerCube were identified by correlating the tracked HorizonCube-lines with the time-lines on the WheelerCube, starting from the top of Statfjord Formation until the BCU. The systems tracts were separated by bounding surfaces where the transgressive systems tracts are capped by the maximum flooding surface, i.e. the sequence boundary, and the highstand systems tracts are capped by an unconformity.

Empty spaces seen on the WheelerCube were interpreted as non-depositional hiatuses or truncated strata.

The 2D WheelerCube interpretation was performed the same way as the 3D interpretation, however, in addition to correlating the HC-tracked horizons with corresponding WheelerCube lines it was also possible to notice some stratal terminations from the HC-tracking. The stratal terminations indicated whether the system was prograding or retrograding represented by downlapping or onlapping reflectors, respectively.

The systems tracts were added to the seismic section in OpendTect by using a HorizonCube-slider, which illustrates the spatial relationships of each single chronostratigraphic horizon (Figure 16 and Figure 17). The base level curve was automatically generated by OpendTect based on the genetic sequence model and the assigned systems tracts.
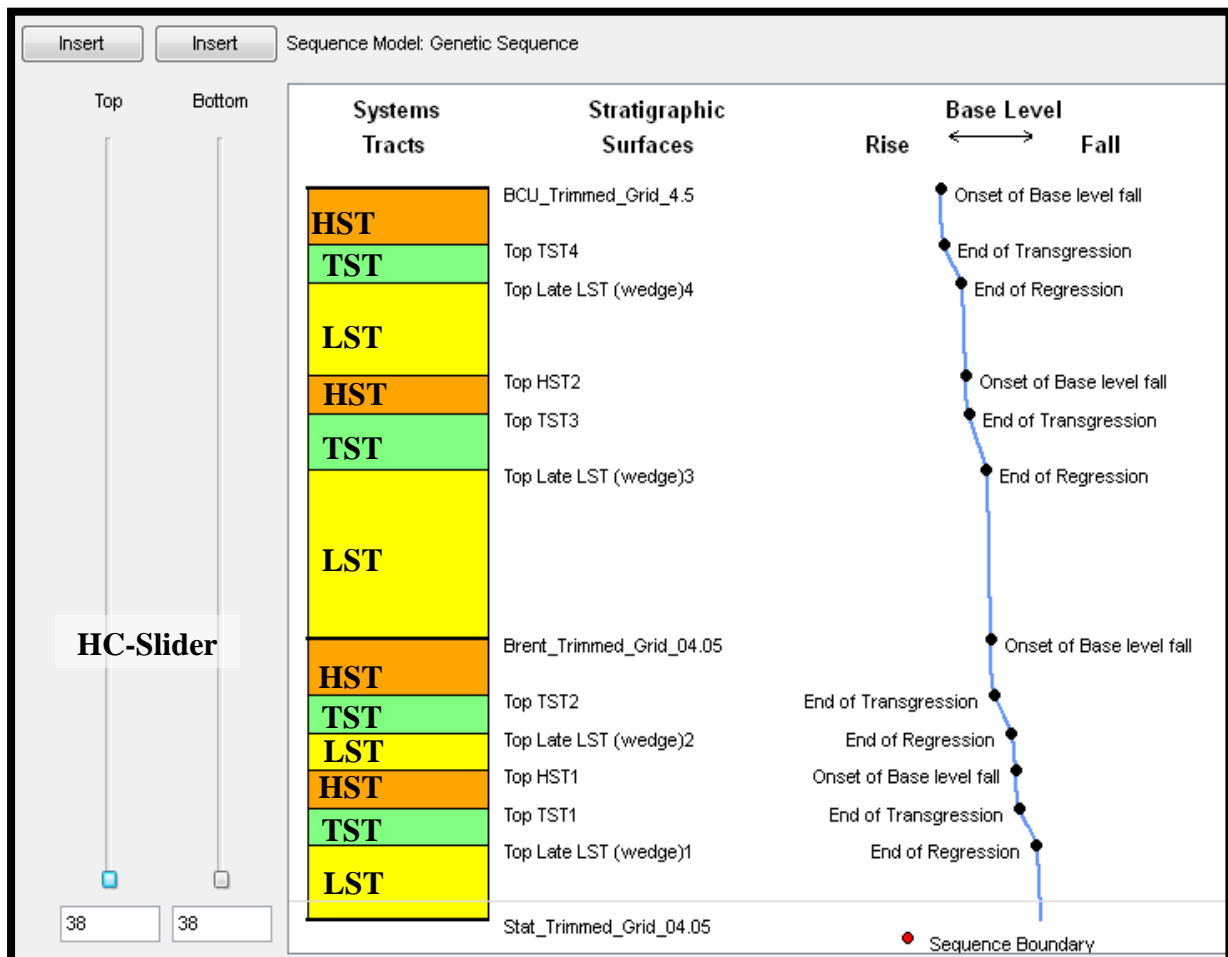
Figure 16: Assigning systems tracts to its proper interval for 3D HorizonCube by using the HorizonCube-slider.

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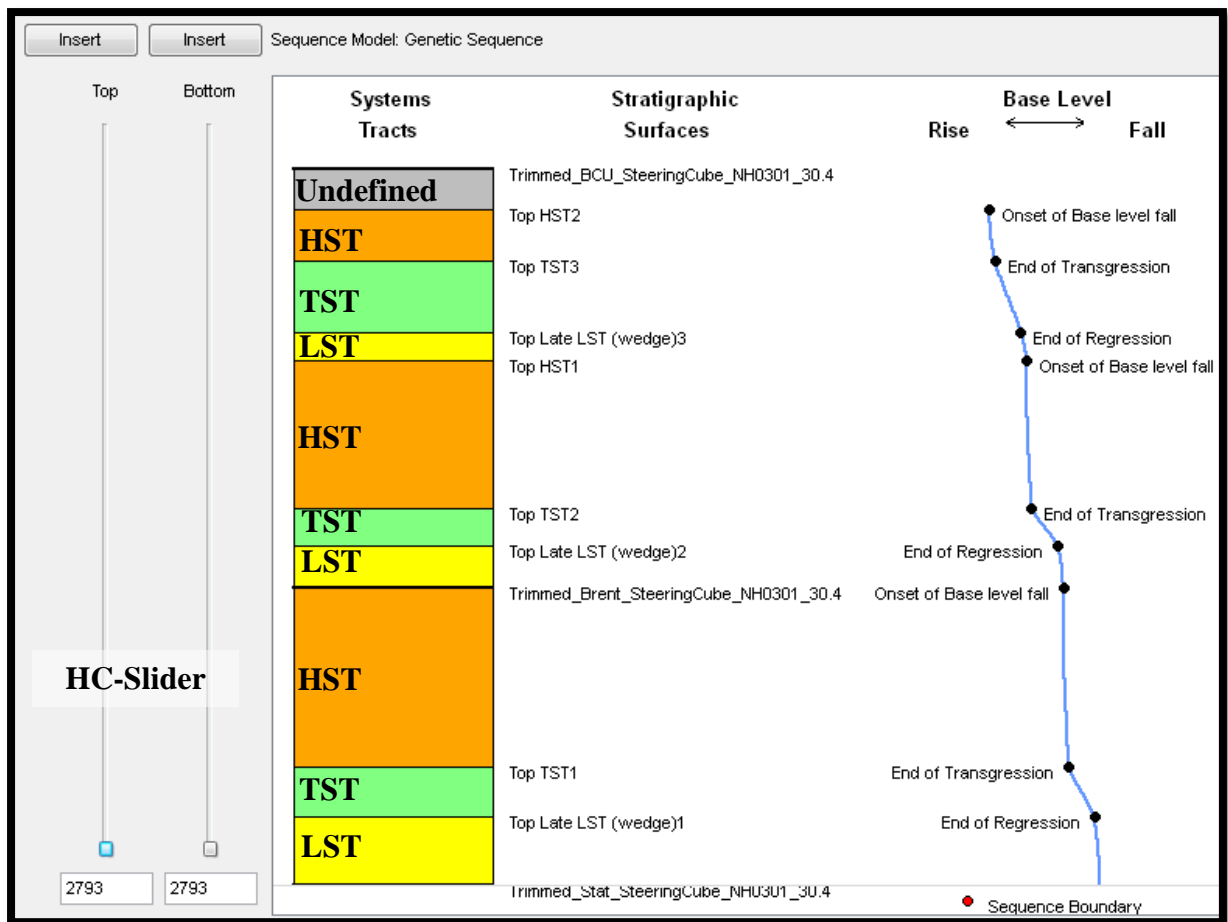
Figure 17: Assigning systems tracts to its proper interval for 2D HorizonCube by using the HorizonCube-slider.

4.0 SEQUENCE STRATIGRAPHIC INTERPRETATION OF DATA

4.1 Interpretation in Petrel

The seismic line in Figure 18 displays the result of the time-depth well-tie, where the formation tops are located very near their corresponding seismic reflectors. In Figure 19 the main faults interpreted are displayed.
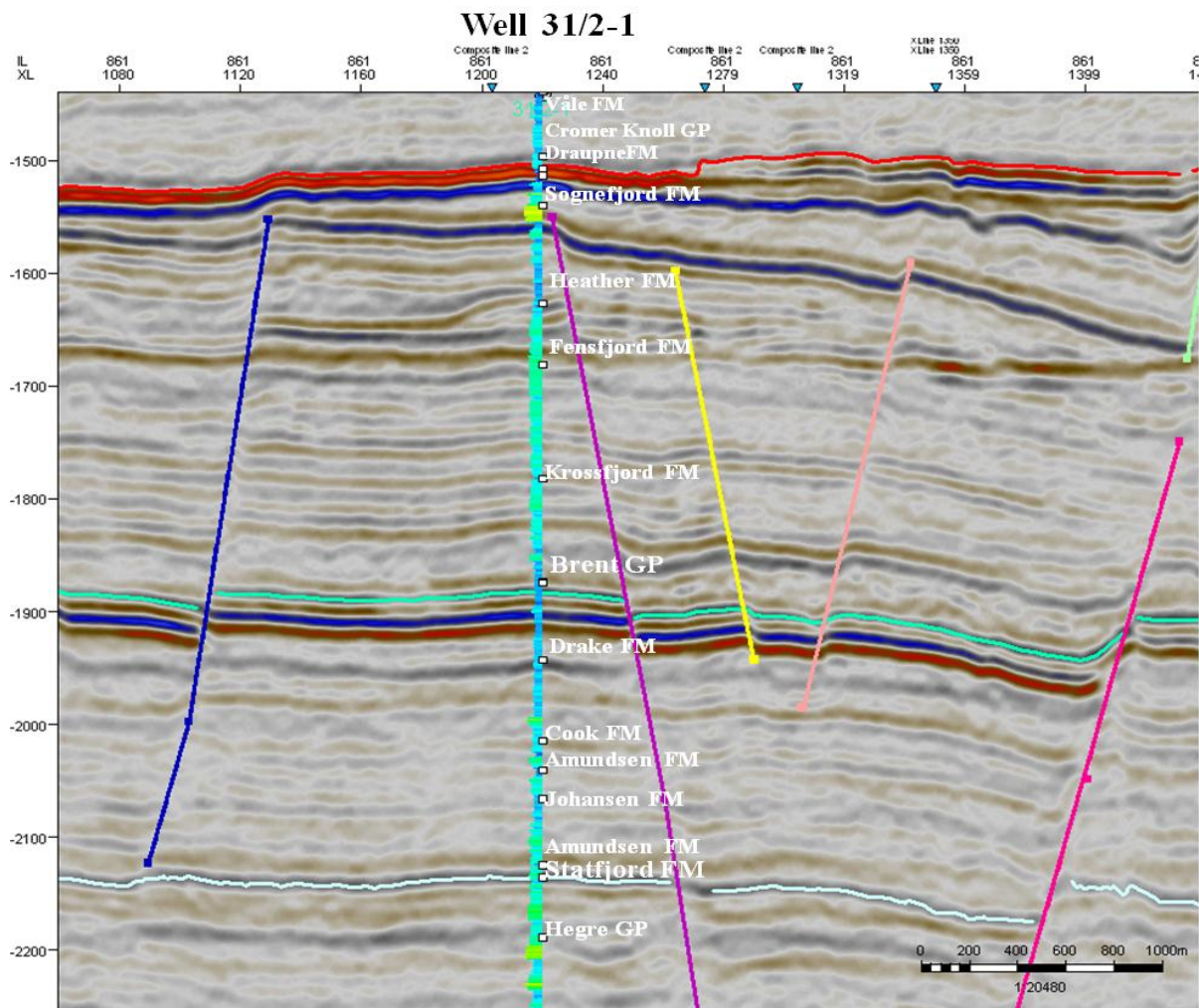
Figure 18: Seismic inline 861 displaying well 31/2-1 with formations located at correct depths by performing a time-depth conversion and wavelet extraction. X-axis is in TWT (ms).
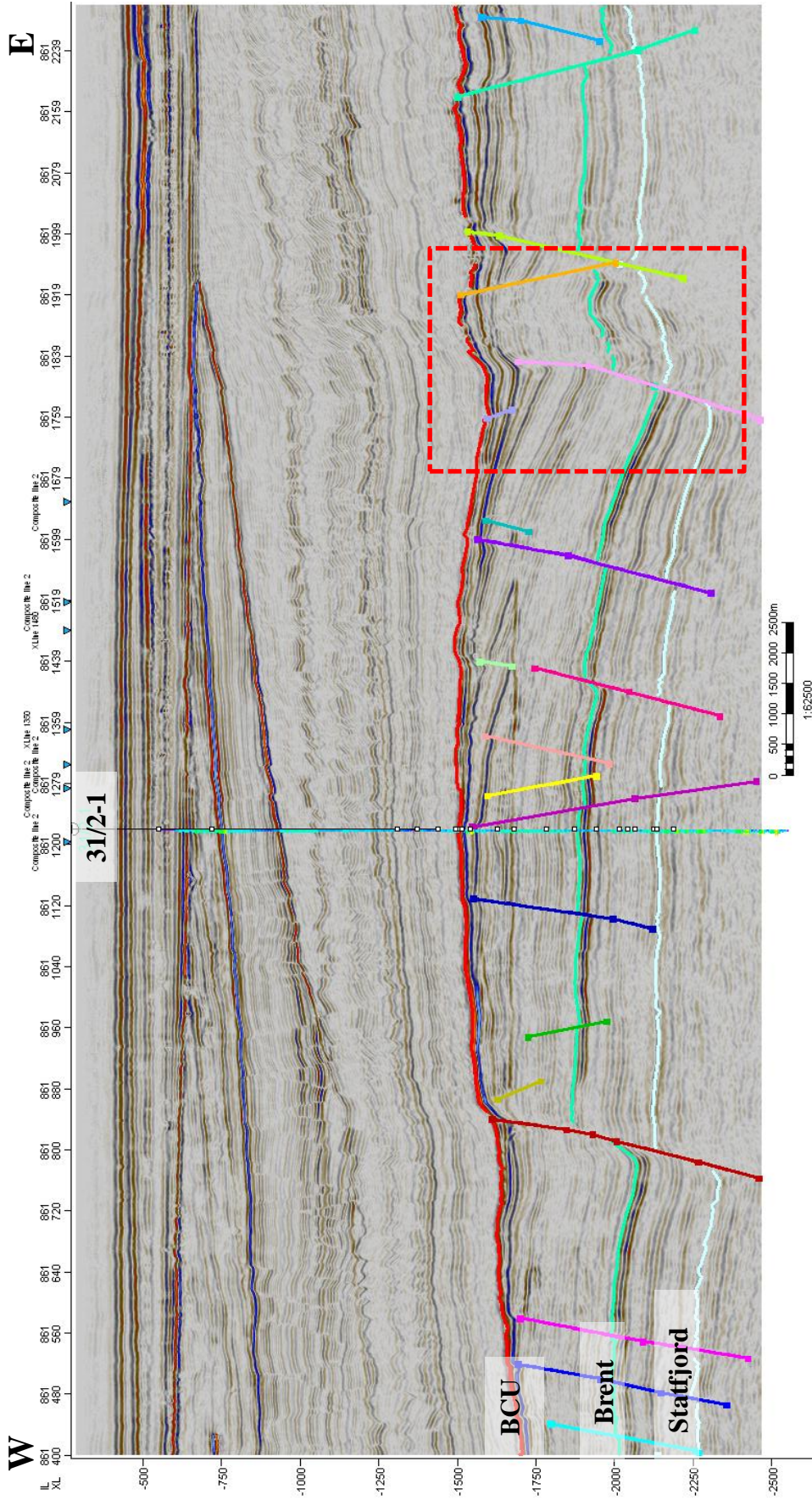
Figure 19: Seismic inline 861 displaying main faults and the three megasequences interpreted. Rotated fault block is indicated by red, stabled box. Y-axis is in TWT (ms).

Three surface maps (time-structural maps) of the interpreted megasequences are shown in Figure 20, Figure 21 and Figure 22 showing the geological structures covered by the seismic volume NH0301. A time-structural map indicates where structural highs and lows are located. The three surface maps have more or less the same structural features and trends, where the main structural highs (trending N-S) are located to the east and the main structural lows are located west. The time-structural maps illustrate three major normal faults striking N-S with a dominantly westerly dipping direction leading to the structural high located on the eastern side of the fault.

The majority of the interpreted faults strike NNE-SSW, whereas only a couple of faults strike E-W. The fault heave increase with depth, as seen especially close to the shelf edges in the structural lows, indicated by red boxes on the surface maps.

Figure 20: Surface map of the Brent Group with fault polygons. Red, stapled boxes indicate main structural lows. Black arrows indicate three faults with structural high to the east and structural low to the west of the fault.

Figure 21: Surface map of the Base Cretaceous Unconformity with fault polygons. Red, stapled box indicates a structural low. Black arrows indicate three faults with structural high to the east and structural low to the west of the fault.
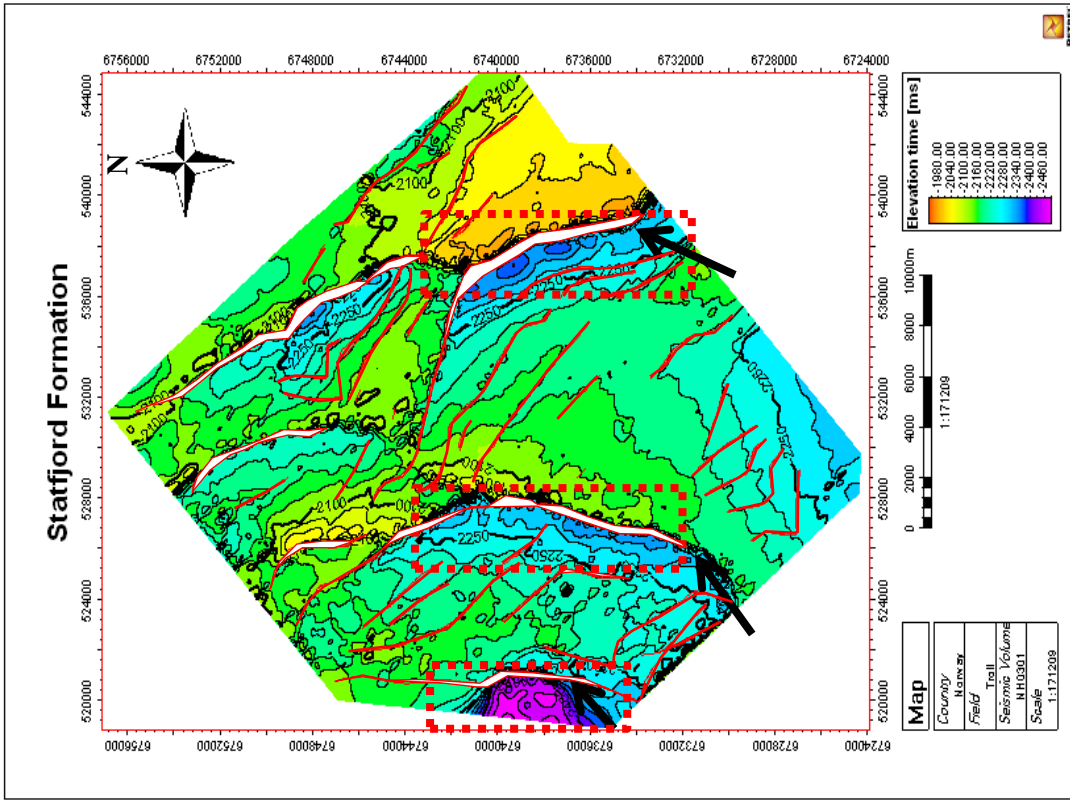
Figure 22: Surface map of the Statfjord Formation with fault polygons. Red, stapled boxes indicate main structural lows. Black arrows indicate three faults with structural high to the east and structural low to the west of the fault.

The time-thickness map between the BCU and Brent Group shows that the main depocenter is located furthest towards east where the greatest sediment accumulation is located (Figure 23). The sediments thicken to the SE (indicated by a purple and dark blue color) and are thinning to the NW (indicated by a green and yellow color). There is another depocenter located right after the shelf edge furthest to the west, and there is a significant thinning of the sediments located on top of the shelf edge (Figure 23).

The time-thickness map between Brent Group and Statfjord Formation shows generally a homogenous sediment thickness over the entire area (Figure 24).

Figure 24: Time-thickness map displaying more or less homogenous sediments. Black, stapled box indicated crossing horizons represented by the negative values (green, yellow and red color), which indicates that the interpolation of the Brent GP and Statfjord FM is not satisfactory.

Figure 23: Time-thickness map displaying sediment accumulation and thinning, and main depocenters highlighted by red, stapled boxes.

4.2 SteeringCube

Figure 25 displays the seismic inline 861 without a dip-steered median filter applied, whereas Figure 26 has been filtered. The difference between before and after applying this filter to the seismic data is not significant as the NH0301 seismic cube is already of high-resolution. Therefore, the seismic does not need to be filtered for making the reflectors more continuous.

The generated SteeringCube (Figure 27) displays positive and negative dip values, where the hot colors are negative dips and the cold colors are positive dips. The higher positive values are located above the reservoir and interval of interest (~1,5 – 2,3 s), whereas the majority of the negative dip values are located in the interval of interest and typically around major fault zones. The SteeringCube in crossline direction displays areas with more noise disturbance (spikes in dip) typically located around the major faults (Figure 28).

Figure 26: Seismic Inline 861 with dip-steered median filter applied.

Figure 25: Seismic Inline 861 with no filter applied.

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Figure 28: Seismic Inline 861 displaying FFT SteeringCube in crossline dip. Red line: BCU, Green line: Brent Group, Blue line: Statfjord Formation. Red boxes indicate areas with high noise disturbance.

Figure 27: Seismic Inline 861 displaying FFT SteeringCube in inline dip. Red line: BCU, Green line: Brent Group, Blue line: Statfjord Formation.

4.3 HorizonCube

The HorizonCube tracking in the 3D volume is poor as the HorizonCube does not follow the faults used as input (highlighted area on Figure 29, Figure 30 and Figure 31). In particularly, the noisy areas shown on the SteeringCube in crossline dip direction (Figure 28) make it difficult to track the HC properly in these specific areas.

Truncated HorizonCube-tracking on a 2D section is shown in Figure 32. The tracking in 2D is a lot more precise and detailed than in 3D.
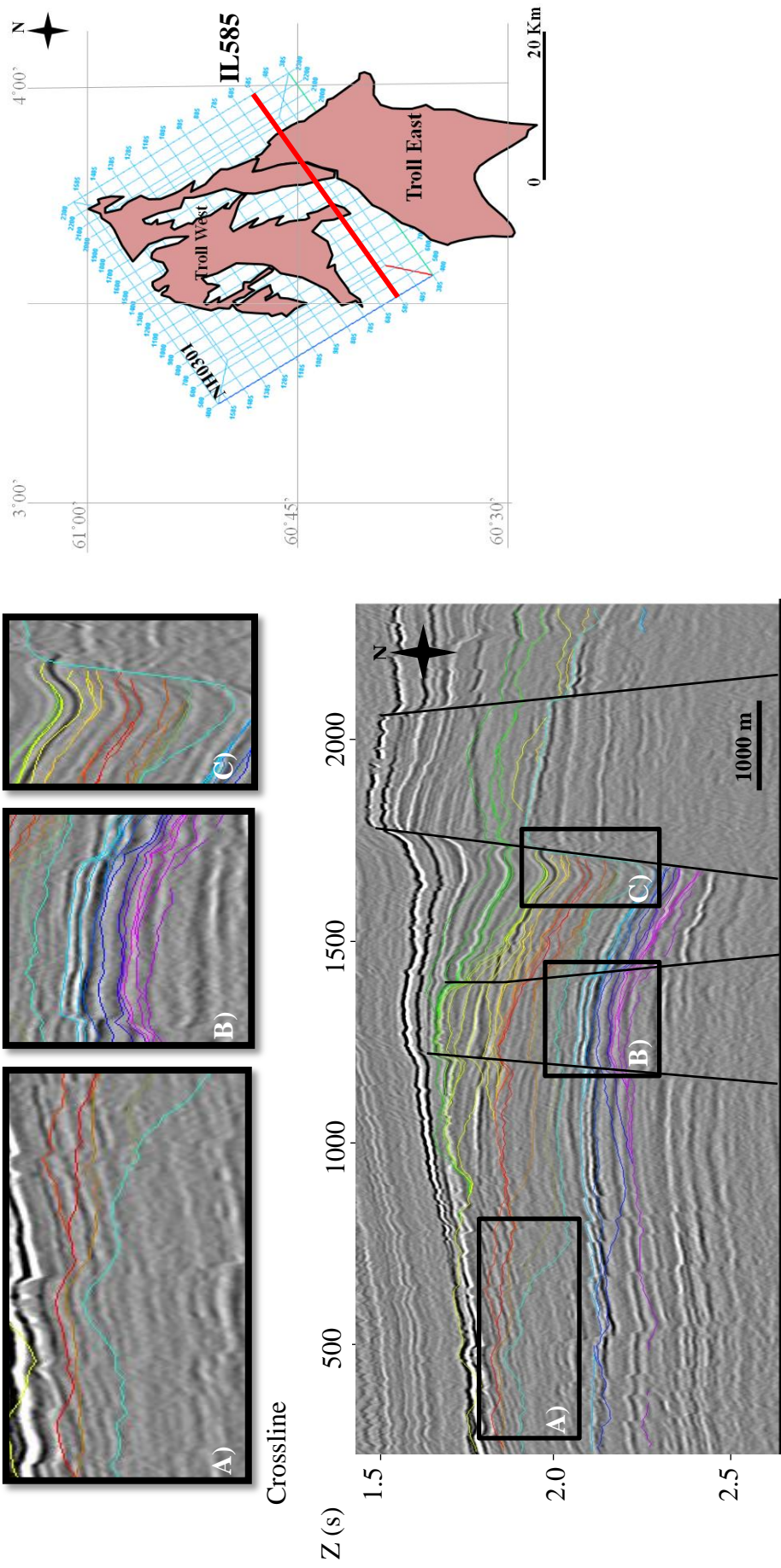
Figure 29: Seismic inline 585 with HorizonCube tracking in 3D volume.
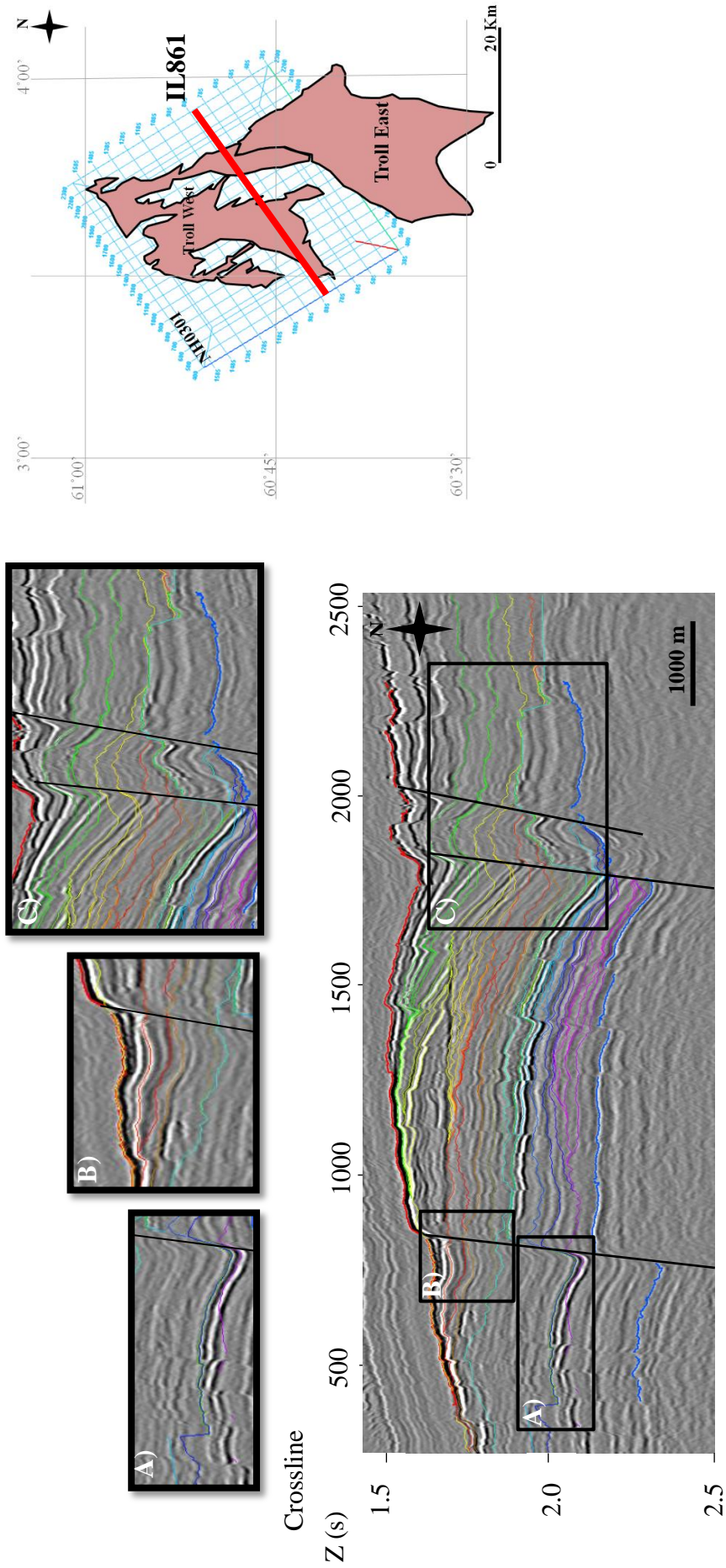
Figure 30: Seismic inline 861 with HorizonCube tracking in 3D volume.
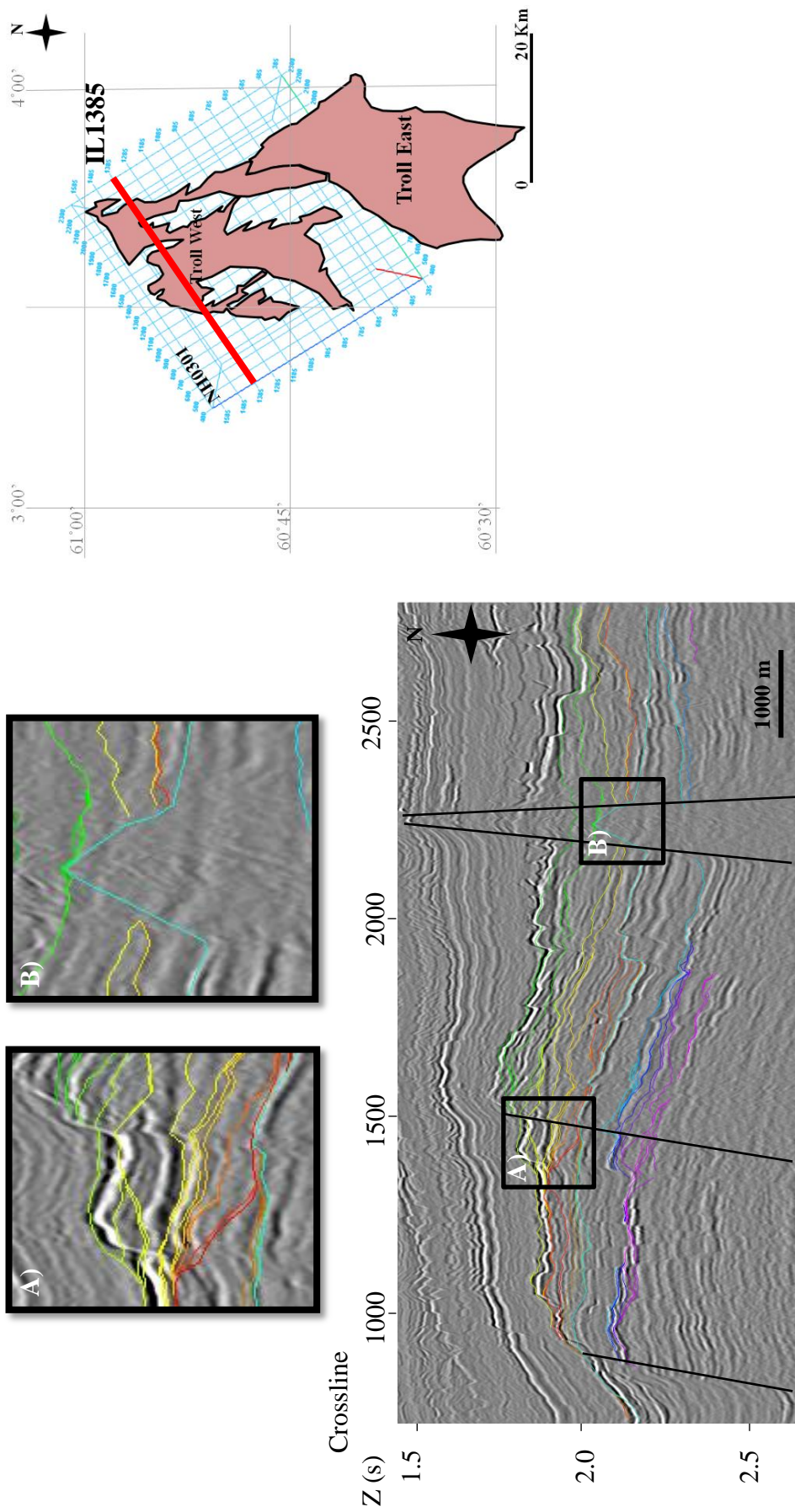
Figure 31: Seismic inline 1385 with HorizonCube tracking in 3D volume.
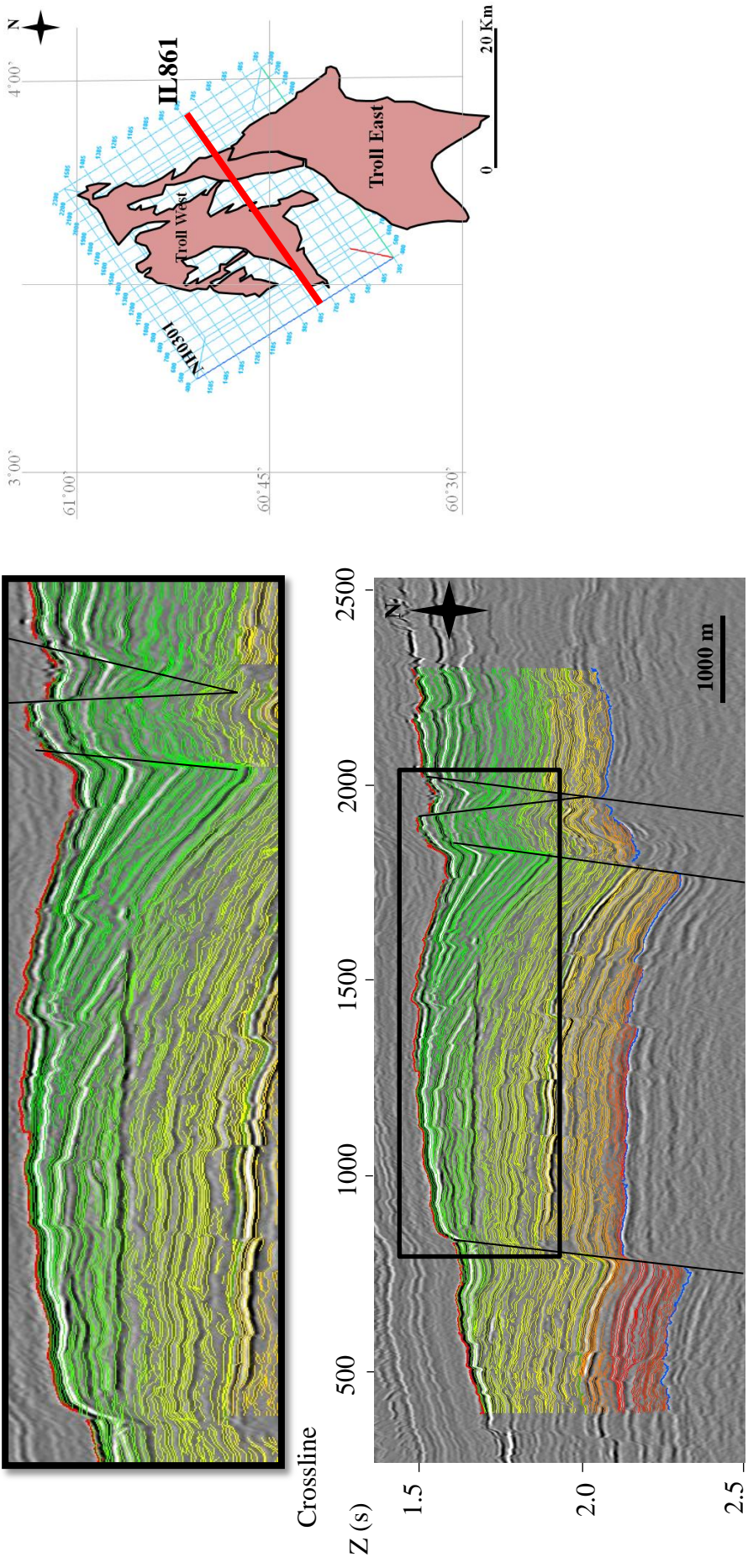
Figure 32: Seismic inline 861 with HorizonCube tracking on a 2D section.

4.4 WheelerCube

The generated WheelerCube displays variations in sequence stratigraphy interpretations and the temporal and special relationship (ref. 2.1.1). Primarily, two WheelerCubes were generated, one for the entire study area, i.e. the Jurassic sequence on the Horda Platform (3D volume), and one for only one single 2D inline. These WheelerCubes are based on the time-lines generated by the HorizonCube tracking, which again is supposed to honor the stratal termination patterns seen on the seismic data.

The WheelerCubes show significant differences both visually and theoretically. Firstly, the WheelerCube for the 3D volume displays fewer time-lines, whereas the WheelerCube for IL861 has numerous chronostratigraphic surfaces creating a more detailed sequence stratigraphic framework to interpret. Secondly, the thickness (in relative geologic time) of the time-lines is different between the two WheelerCubes, where they are thicker in the 3D Wheeler transform compared to the single 2D inline Wheeler transform. In theoretical terms, the two Wheeler transforms provide two separate interpretations as to where the systems tracts are assigned and their bounding surfaces, and thereby also the depositional cycles.

There are some evident errors seen in the 3D WheelerCube caused by the HorizonCube tracking wrong reflectors. Also, presence of faults makes the WheelerCube interpretation difficult. The HorizonCube tracking struggles to follow the correct horizons around the tilted fault block. The HorizonCube also tracks the flatspot as a reflector which is not the case as it represents a fluid response, the oil-water contact.

Figure 33 and Figure 34 show the WheelerCubes generated from the HorizonCube tracking in 3D and 2D, and Figure 35 and Figure 36 show the most reasonable interpretation assigned for these WheelerCubes.
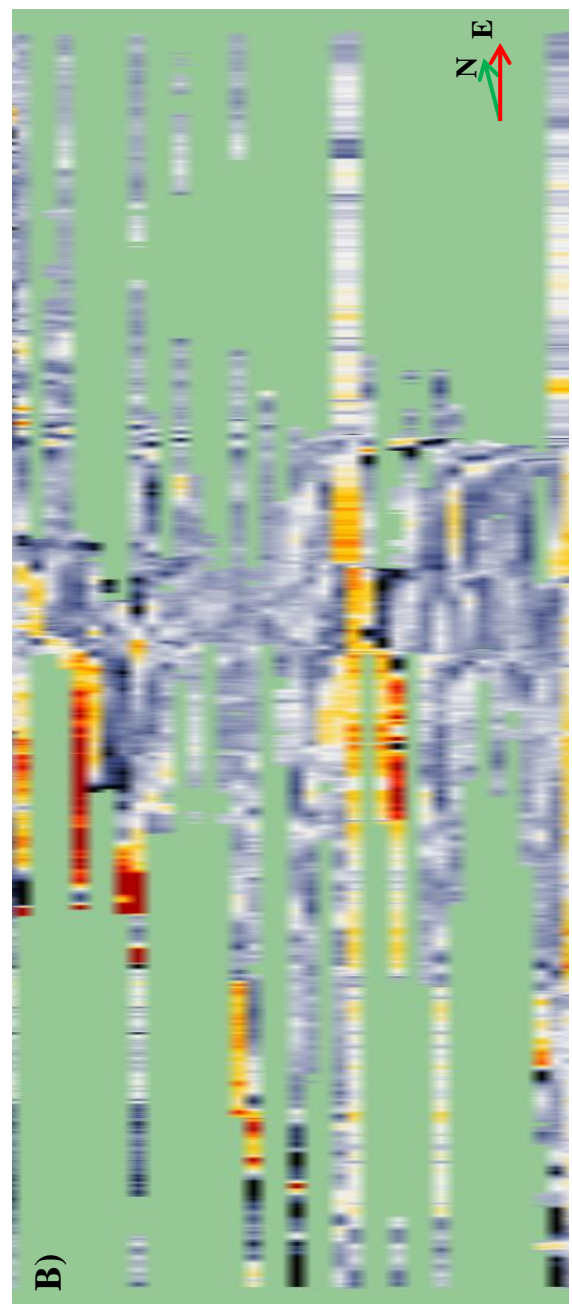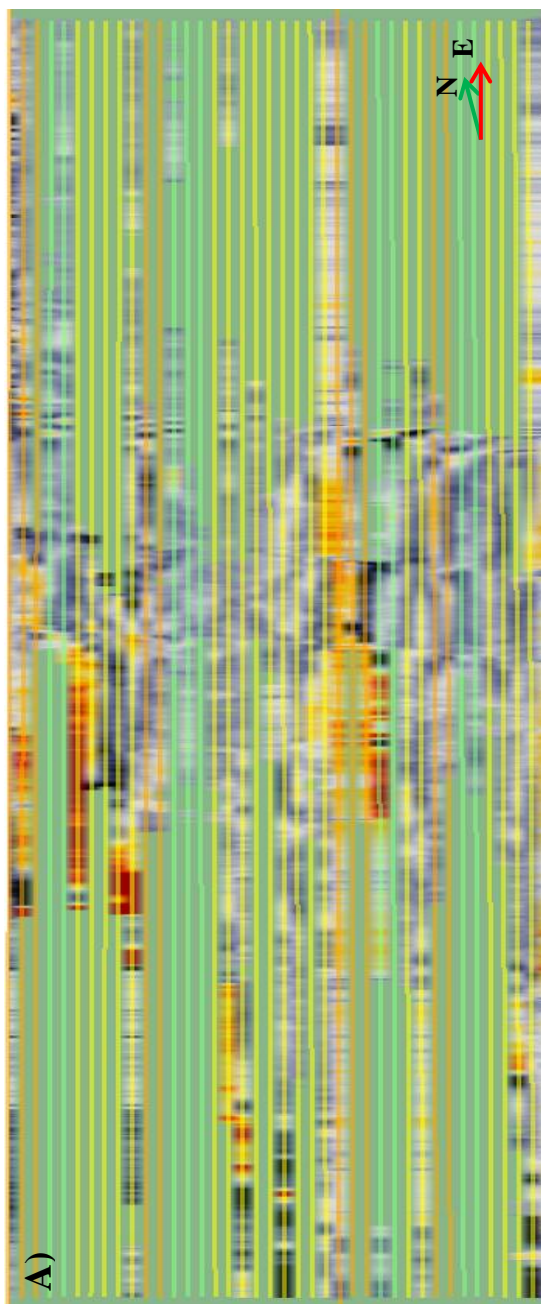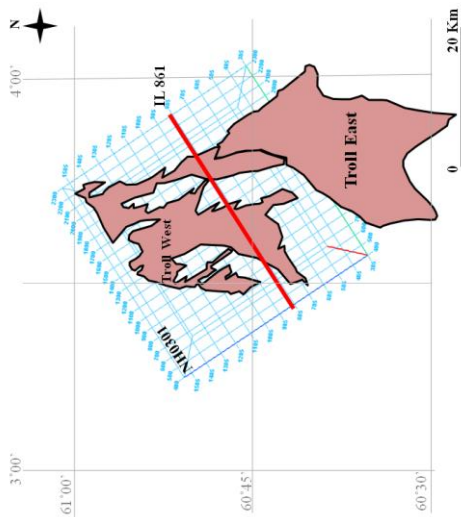
Figure 33: A) The colors represent the thickness per systems tract in TWT (s) units (Qayyum et al., 2012). LST: Yellow, TST: Green, HST: Orange, Grey: Undefined. B) WheelerCube of IL861 with HorizonCube tracking for 3D volume used as input.
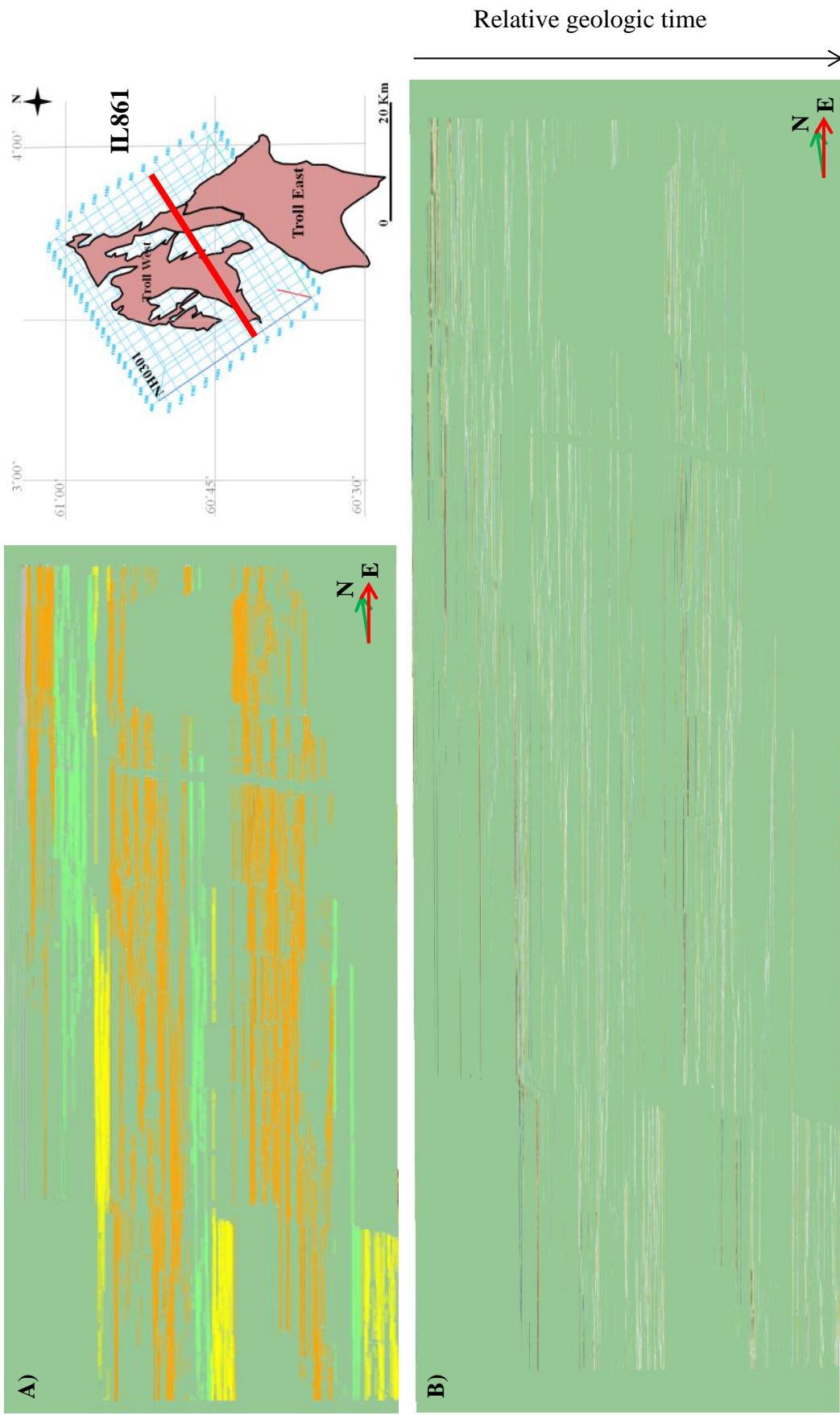
Figure 34: A) The colors represent the thickness per systems tract in TWT (s) units (Qayyum et al., 2012). LST: Yellow, TST: Green, HST: Orange. B) WheelerCube of IL861 with HorizonCube tracking for a single inline used as input.

4.4.1 INTERPRETATION OF WHEELERCUBE FROM 3D HORIZONCUBE TRACKING

Three full sequences are identified with maximum flooding surfaces as sequence boundaries. The depositional cycles are defined by Stewart et al. (1995) as 2nd order sequences with a time span of more than 4 million years (Ref. 2.1.1). The stratal terminations on the seismic section (Figure 35B) are difficult to recognize as the HorizonCube struggles to follow the proper horizons and neglects the structural features in this area (Ref. 4.3). Therefore, the main interpretation is based on the composition of the WheelerCube. Also, because of the incomplete and unsatisfactory tracking in 3D, an exact age-definition is difficult to determine for the systems tracts (Figure 35A). However, the megasequences can be recognized from the Wheeler transformed domain and on the seismic section (i.e. imported horizons), so the approximate ages for these areas are possible to determine.

Starting from the bottom of the 3D WheelerCube, the base level curve and 2nd order sequences (Figure 35C) shows an overall regression from the first maximum flooding surface (MFS) until subaerial unconformity (SU2), indicated by a drop in base level in Figure 35C. This regression is followed by an overall transgression starting at SU2 and lasting until the MFS in sequence 3, seen in Figure 35D as lowstand systems tracts and transgressive systems tracts. The higher, 2nd order sequences display transgressive/regressive events throughout the study area, from the first sequence LST (top of Statfjord Formation) until the top unconformity (U).

Four lowstand systems tracts are interpreted basinward, and one is interpreted landward, represented in the seismic inline (Figure 35B) as onlapping, retrograding reflectors. The LST located below SB1 represents the top of Statfjord Formation of Lower Jurassic age (Hettangian). However, this LST is located on a chronostratigraphic horizon which stretches eastward where there is no corresponding horizon tracked by the HC in the seismic inline. Therefore, the LST is only interpreted to represent a part of this time-line, whereas the more eastern part is undefined. The same problem is seen from the time-line interpreted as sequence 2 HST, where the western part is undefined as it is not represented by any tracked reflector on the seismic section.

A small lowstand systems fan is interpreted basinward just above SB2 as it is independent from the other lowstand systems tracts. It is represented by an incorrect, light blue time-line generated by the HC seen in Figure 35B. The LST located in sequence 2 is interpreted to be a thick, retrograding/aggrading package of deposited sediments with an overlying TST and HST of Middle Jurassic age. This large LST seems to be aggrading which

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indicates more shoreline deposits. Moreover, there is an incised valley interpreted to the east of this LST, which could work as a sediment conduit to the coeval prograding depositional system. However, the HC-tracked horizons merge in this area (marked in Figure 35B with a red box) making the HC-tracking map several horizons as one instead of separate events. Therefore, the LST looks to be a separate event even though it most probably is not. This problem is also the case for the overlaying TST and HST where the smaller systems tracts located more landward are interpreted separately, but should actually be connected with the more basinward systems tracts.

The sequence 3 LST rests on the SU3 and right below the U1 and BCU. The interpretation in this area is difficult as the BCU might have removed parts of stratigraphy on top of the fault blocks, and other structures which affect the HC-tracking and thereby also the output of the WheelerCube.

Four maximum flooding surfaces are interpreted on top of the transgressive systems tracts and act as sequence boundaries (Figure 35B). However, these relative, geologic time-lines do not always follow the geologic structures and traces on the seismic by crossing both the faults and the horizons in some places. In addition, the flat spot (which is the oil-water contact) is interpreted to be a chronostratigraphic horizon (SB3), which is not truly the case.

Three subaerial unconformities are interpreted located on top of the HST. The subaerial unconformities are not easy to recognize on the seismic by truncating events, so the interpretation is mainly based on the systems tracts generated from the WheelerCube. The time-line SU2 falls on the seismic reflector representing the Brent Group of Middle Jurassic age, where the HST is resting on top of SB2. The more eastern part of this time-line is located on the shelf edge created by the tilted fault block seen on the seismic in line Figure 35B, and is therefore interpreted to be a subaerial unconformity (eroded) continuing westward.

The WheelerCube has several areas where no deposition is indicated by green, empty spaces. These areas could be interpreted as hiatus, but when studying the seismic line the HC should have tracked more horizon events in these areas. Also, the majority of the horizon-slices generated by the HC are located primarily in the center of the study area (Figure 35B), therefore the relative geologic time-line generated by the WheelerCube is located in this same specific area, where the surrounding spaces are interpreted to be areas of non-deposition.

4.4.2 INTERPRETATION OF WHEELERCUBE FROM 2D HORIZONCUBE TRACKING

Two complete sequences are interpreted from the 2D WheelerCube, and two half sequences. The overall trend shows two regressive depositional cycles indicating a drop in relative sea level, with smaller transgressive cycles in between. The regressive cycles are represented in the WheelerCube as thick, 2nd order (sensu Stewart et al., 1995) HSTs with the subaerial unconformity located in top. The stratal termination patterns of the tracked time-slices (reflectors) in Figure 36B are difficult to interpret as they are numerous, short interpretations which rarely show any specific trend individually. As a consequence of this the colors of the reflectors are used as guidance when comparing the seismic line and the WheelerCube in Figure 36D, as these colors represent the timing and thus the thickness of the systems tracts.

A LST of Lower Jurassic age is interpreted as resting on top of Statfjord Formation, and represents the Cook, Amundsen and Johansen Formations. Following this LST is a TST represented in Figure 36D as retrograding time-lines. On top of the TST is the maximum flooding surface, which is the first sequence boundary of an estimated age of approximately 180 Ma. The first full sequence HST represents the prograding Drake Formation (~174 Ma) and the Brent Group (~168 Ma). The subaerial unconformity (SU1) resting on top of the HST has an age of approximately 168 Ma.

The LST in sequence 1 is interpreted to be of approximately 166 Ma as it represents a thick sandstone wedge which could be the Krossfjord Formation. The following TST is interpreted to be the Krossfjord Formation retrograding, and a maximum flooding surface is located on top indicating the next sequence boundary.

In sequence 2 the HST represents the prograding Fensfjord Formation of Middle Jurassic age (~163 Ma). The SU2 marks the division between this HST and the next systems tract which is the Heather Formation located in a LST followed by a TST with retrograding sediments with an approximate age of 157 Ma.

The HST containing the Sognefjord Formation is the last systems tract interpreted and is found in the Upper Jurassic, close to the BCU. The age of the time-lines above the unconformity (U) is difficult to determine as this area has undergone erosion.

When comparing the WheelerCubes generated from the 2D and 3D HorizonCube tracking there are evident differences between them. Firstly, the Wheeler transform for a single inline displays numerous, thinner chronostratigraphic events. Secondly, this 2D Wheeler indicates a higher accumulation of sediments deposited westward than what is indicated from the 3D Wheeler transform. The overall depositional trend is first a regression followed by a transgression for the 3D Wheeler transform, whereas the opposite is interpreted in 2D.
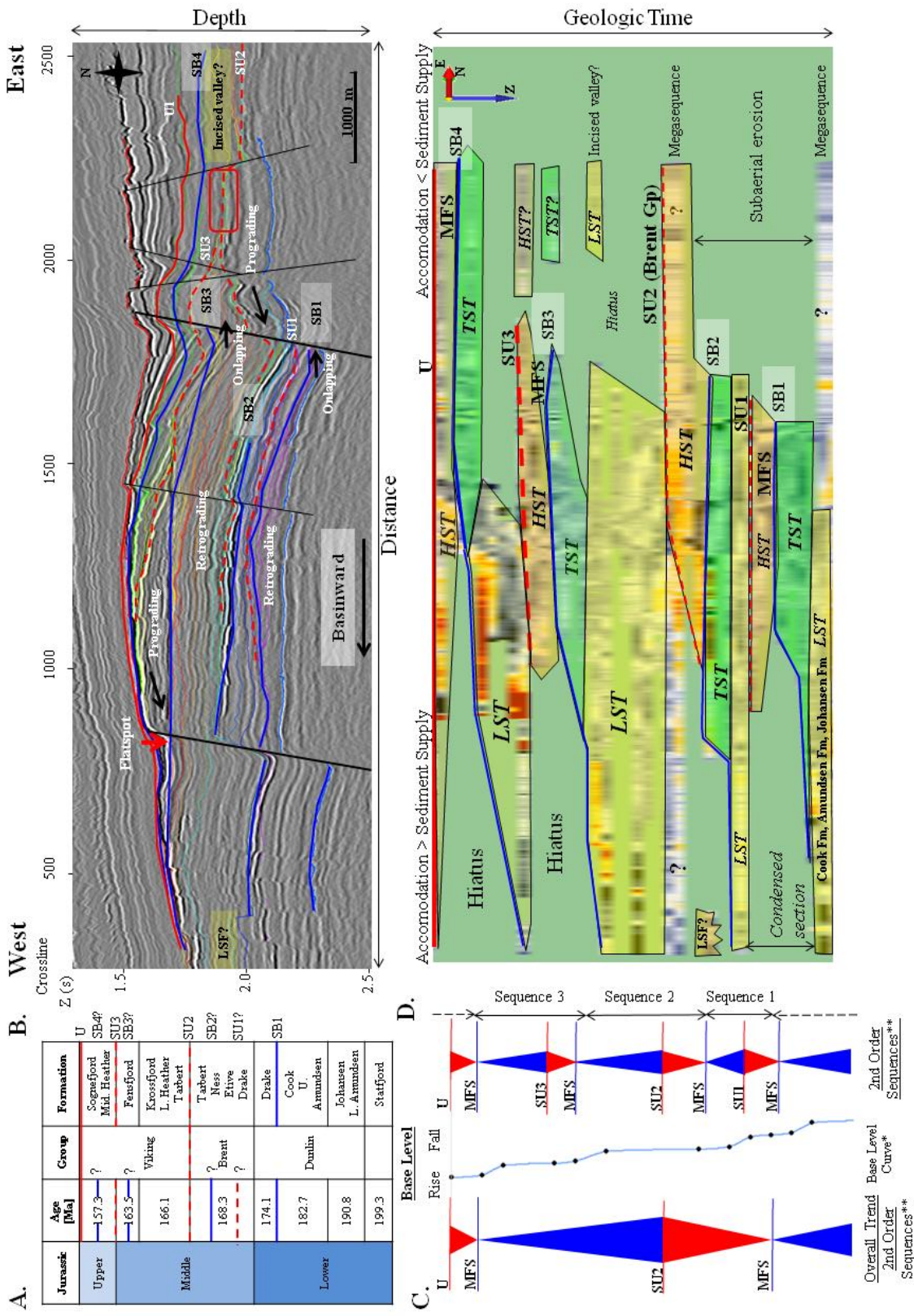
Figure 35: A) Stratigraphic table for the Jurassic Period, seismic volume NH0301, Troll West Field. B) Seismic section of area of interest (IL861) with truncated HorizonCube and megasequences displayed. Time-slice colors represent thickness of the systems tracts. C) Relative base level curve and 2nd order cycles. D) Wheeler transformed domain of IL861, with interpreted systems tracts and their bounding surfaces. Genetic sequence approach (Frazier, 1974; Galloway 1989). *Imported from OpendTect. **As defined by Stewart et al. (1995).
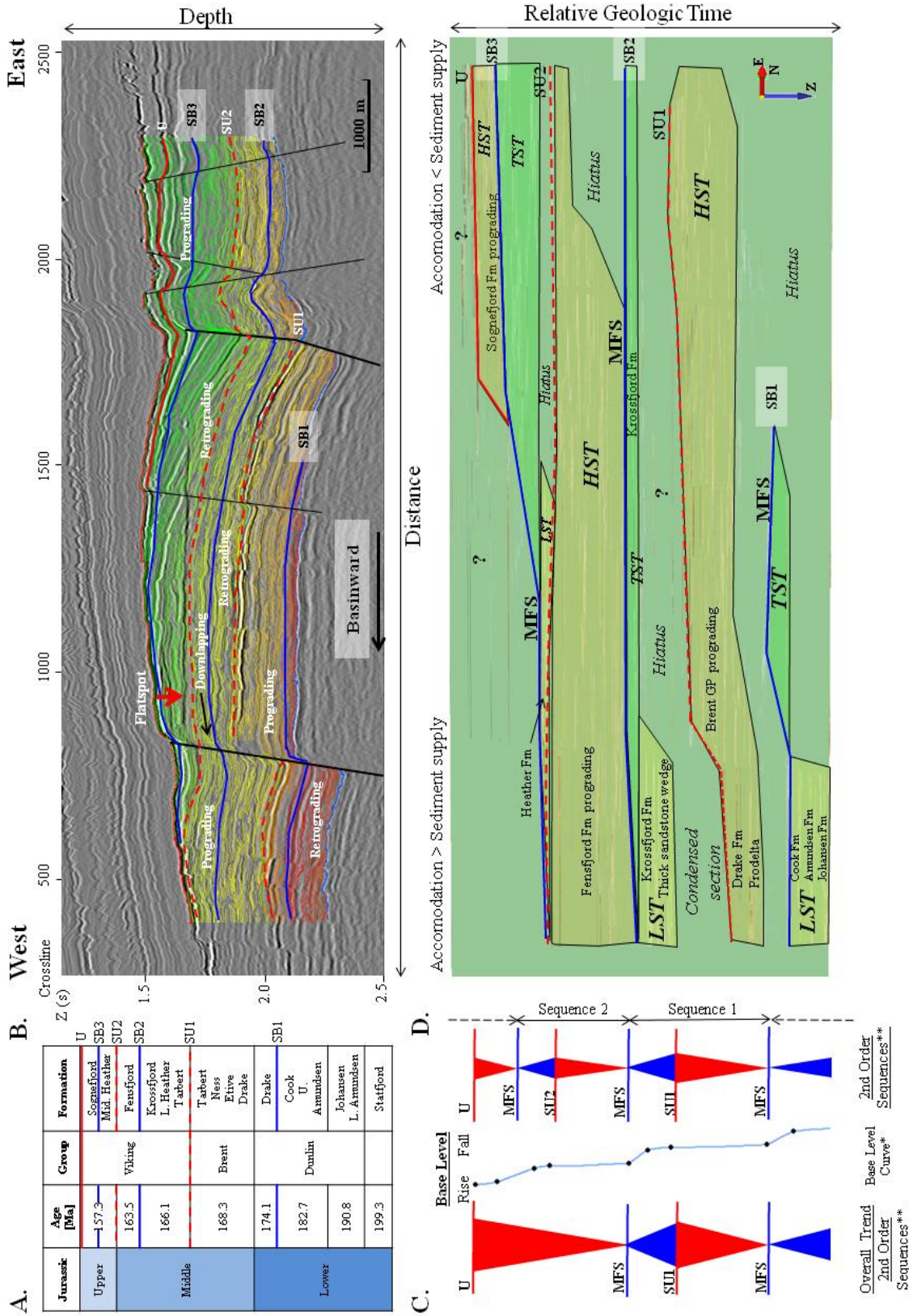
Figure 36: A) Stratigraphic table for the Jurassic Period, seismic volume NH0301, Troll West Field. B) Seismic section of area of interest (IL861) with truncated HorizonCube and megasequences displayed. Time-slice colors represent thickness of the systems tracts. C) Relative base level curve and 2nd order cycles. D) 2D Wheeler transformed domain of IL861, with interpreted systems tracts using a genetic sequence approach (Frazier, 1974; Galloway 1989). *Interpretation imported from OpendTect. **As defined by Stewart et al. (1995).

4.5 Systems Tracts Interpretation

OpendTect automatically generates the base level curve according to what type of depositional sequence model is used for the systems tracts interpretation. When comparing the interpretation from the 3D and 2D HorizonCube-tracking it is evident from Figure 37A that more lowstand deposits are interpreted in the 3D WheelerCube, whereas more highstand deposits are interpreted in the 2D WheelerCube (Figure 37B). However, the lowstand sediments are deposited towards west, meaning that both figures indicate a prograding system in this direction.
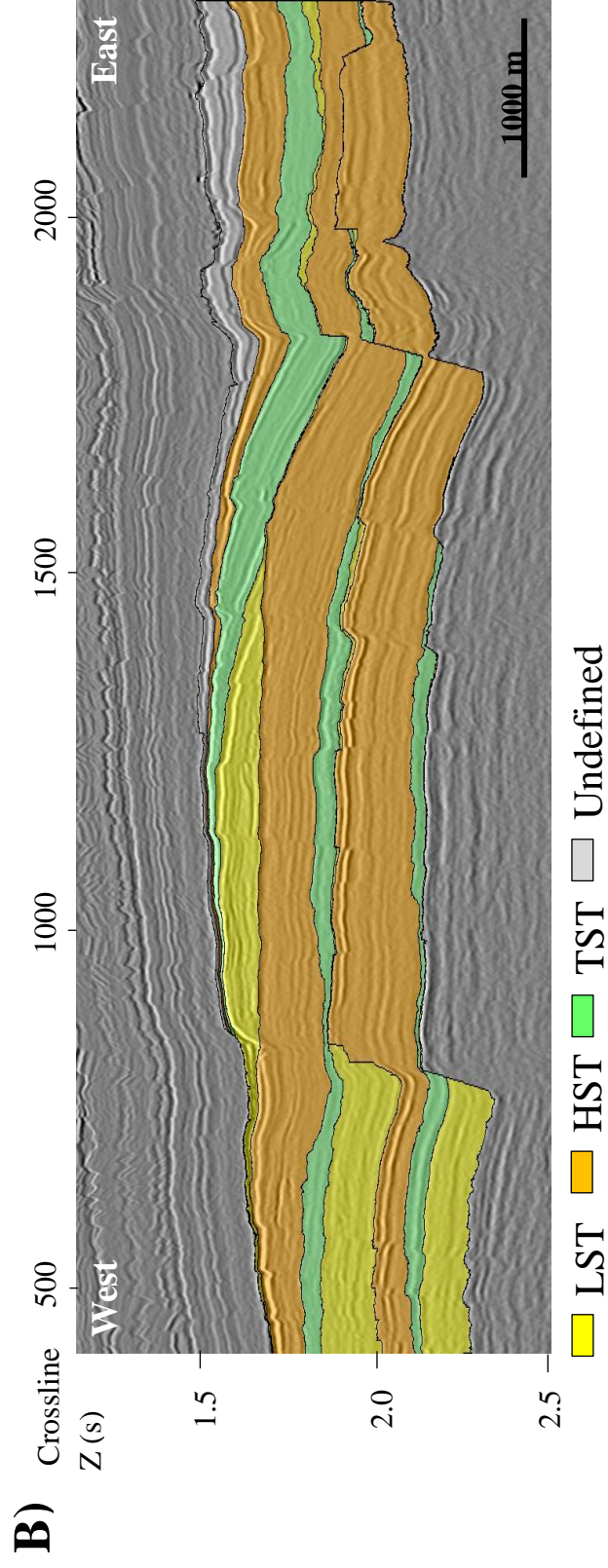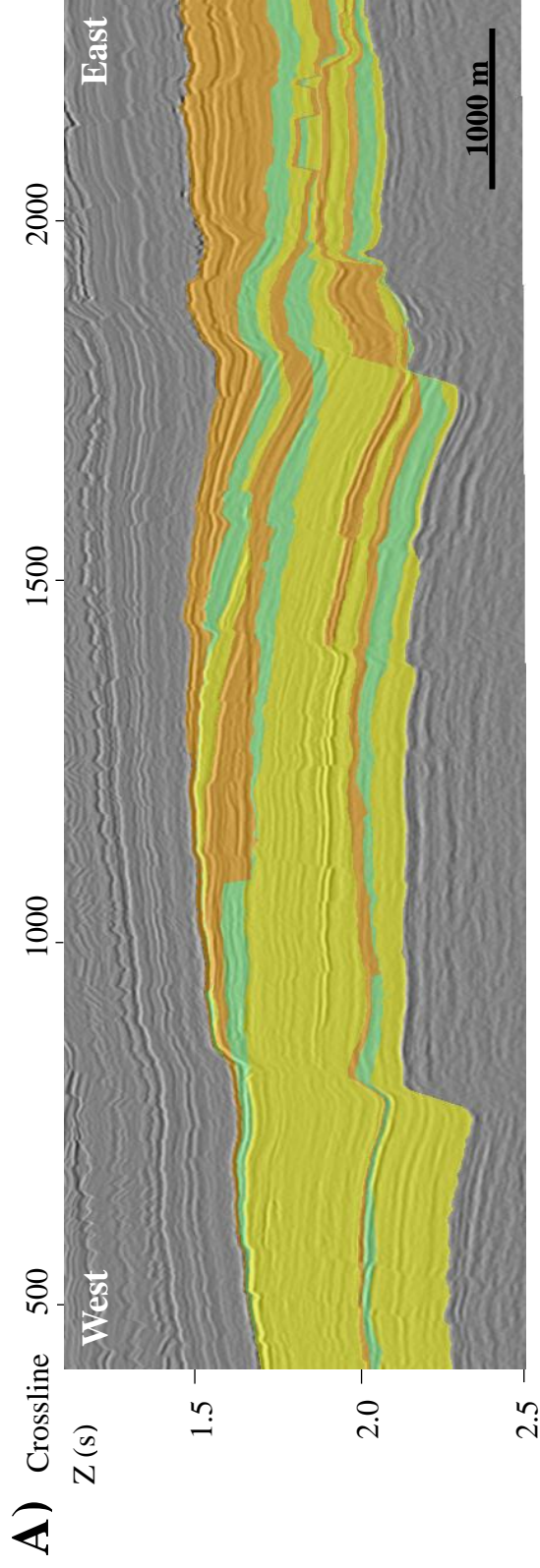
Figure 37: Assigned systems tracts to the A) 3D HorizonCube-tracking and B) 2D HorizonCube-tracking for inline 861 by using the HorizonCube-slider in OpendTect. Colors represent thickness of systems tracts in TWT.

LST ■ HST ■ TST ■ Undefined

5.0 DISCUSSION AND FURTHER WORK

5.1 Comparison with Previous Sequence Stratigraphic Analysis

The differences and similarities between the sequence stratigraphic analyses from previous studies and the results obtained in this thesis can be seen from Figure 38 and Figure 39. Figure 38 explains the stratigraphic synopsis of the Jurassic period in the east northern North Sea proposed by Stewart et al., (1995), whereas Figure 39 shows the sequence stratigraphic interpretation generated from the 2D WheelerCube.

The interpretations of the generated 3D and 2D WheelerCube examples are on a small regional scale, i.e. ~8 km, whereas the sequence stratigraphic analysis proposed by Stewart et al. (1995) is on a much larger scale of ~40 km. However, the relative sea level rise and fall are still recognized from the transgressive/regressive events from both scales.

When comparing the two interpretations seen in Figure 38 and Figure 39, there are both differences and similarities between them. Firstly, when it comes to the differences Figure 38 suggests that the first 2nd order sequence is a regression from Hettangian until Early Pliensbachian capped by an erosional unconformity, whereas Figure 39 suggests a transgression in this same time interval capped by a maximum flooding surface in the Early Toarcian. However, a maximum flooding surface marking the end of a transgressive cycle is also found in Figure 38 in the Early Toarcian similar to the 2D interpretation generated from the HorizonCube. Also, the prograding Brent Group is seen in Figure 38 as a regressive cycle with an erosional unconformity on top followed by a hiatus in the Bajocian/Aalenian. This same regression is seen in Figure 39 as a highstand systems tract representing the prograding Brent Group, capped by a subaerial unconformity and followed by a condensed section.

Moreover, Tarbert, Krossfjord and Fensfjord Formations belong to the 2nd order transgressive sequence from Early Bathonian to Early Oxfordian seen from Figure 38 modified after Stewart et al. (1995). Figure 39 suggests a retrogradation of Krossfjord Formation from Early Bathonian until the maximum flooding surface located in Middle Bathonian. The Fensfjord Formation is interpreted to be located in a highstand systems tract, prograding westward with a subaerial unconformity on top (Early Oxfordian). The Heather Formation is interpreted to be depostied during a regression in Figure 38, whereas during a transgression in Figure 39. The Sognefjord Formations is interpreted in both figures to be deposited during a regression from Kimmeridgian until Tithonian/Volgian capped by an unconformity.
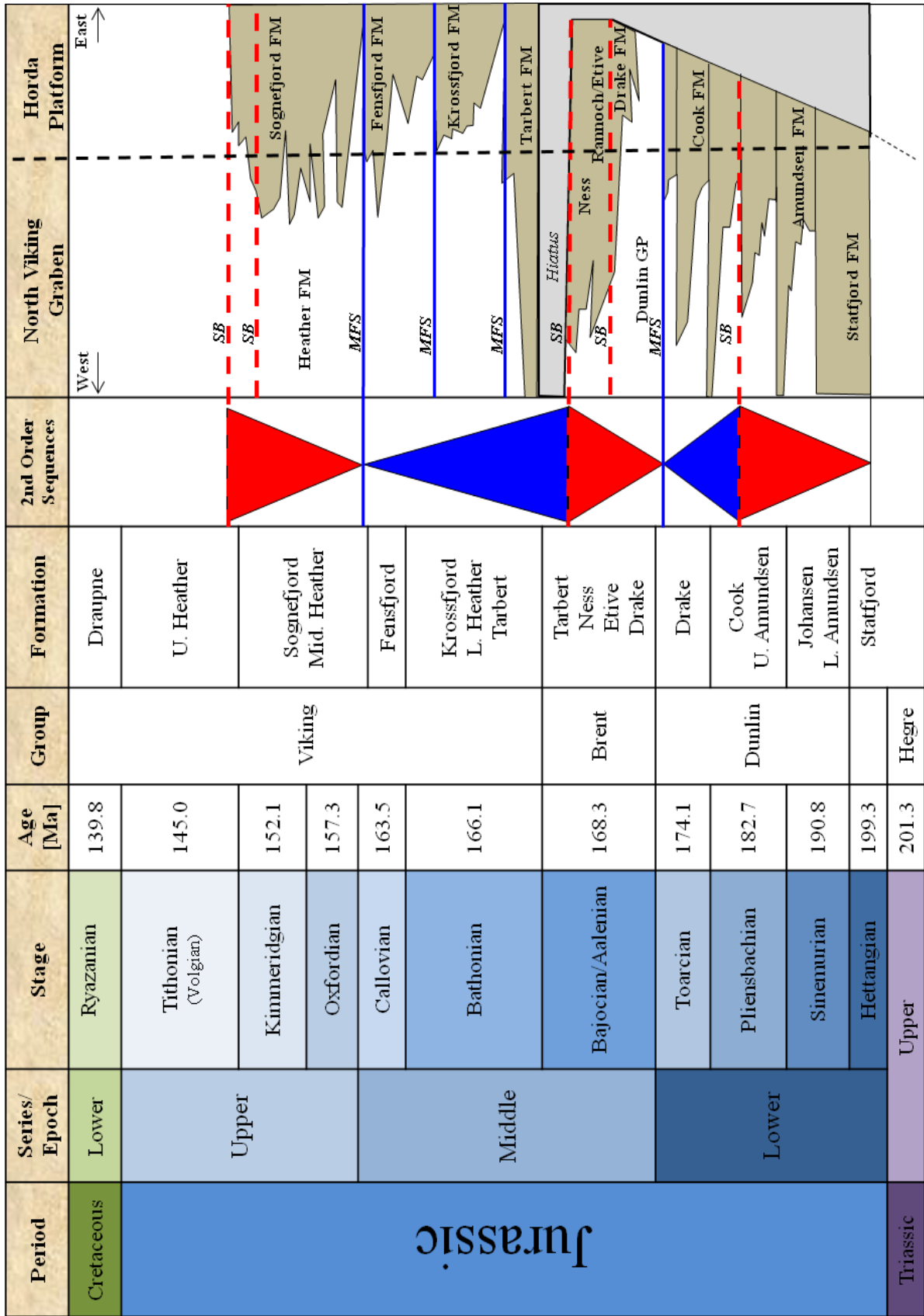
Figure 38: Stratigraphic synopsis of the Jurassic in the east northern North Sea modified after Stewart, Schwander, and Bolle (1995).
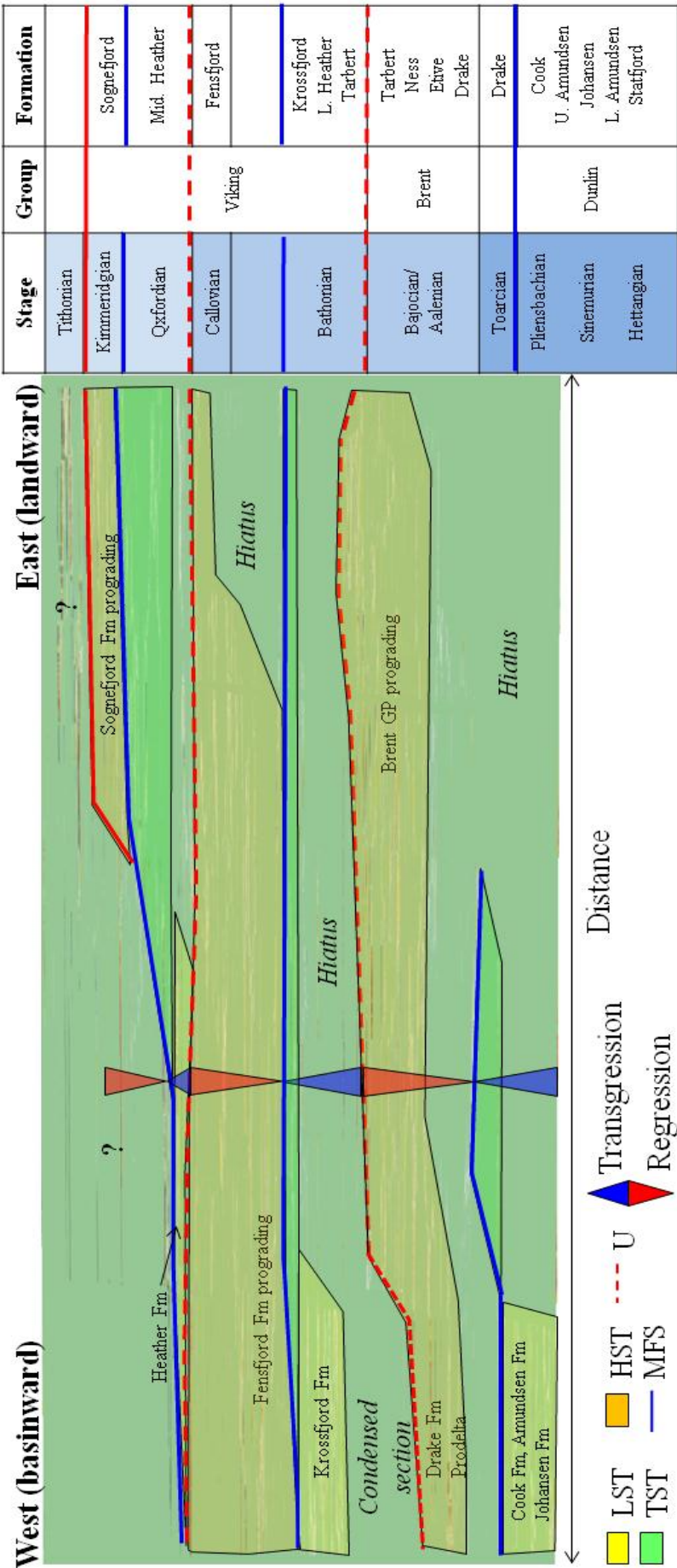
Figure 39: Sequence stratigraphic analysis of the Jurassic Period generated from 2D Wheeler transformed domain. The depositional cycles are low frequency, 2nd order cycles.

5.2 Optimizing the HorizonCube and WheelerCube

The HorizonCube tracking in 3D is poor as it does not follow the proper seismic time lines and the chronostratigraphic events. In addition, this process is very time-consuming as the HC-tracking in 3D takes up to 24 hours to run. If the outcome of the HC-tracking is not satisfactory, it is necessary to change the filtering parameters for the SteeringCube and re-do the workflow in Figure 40.
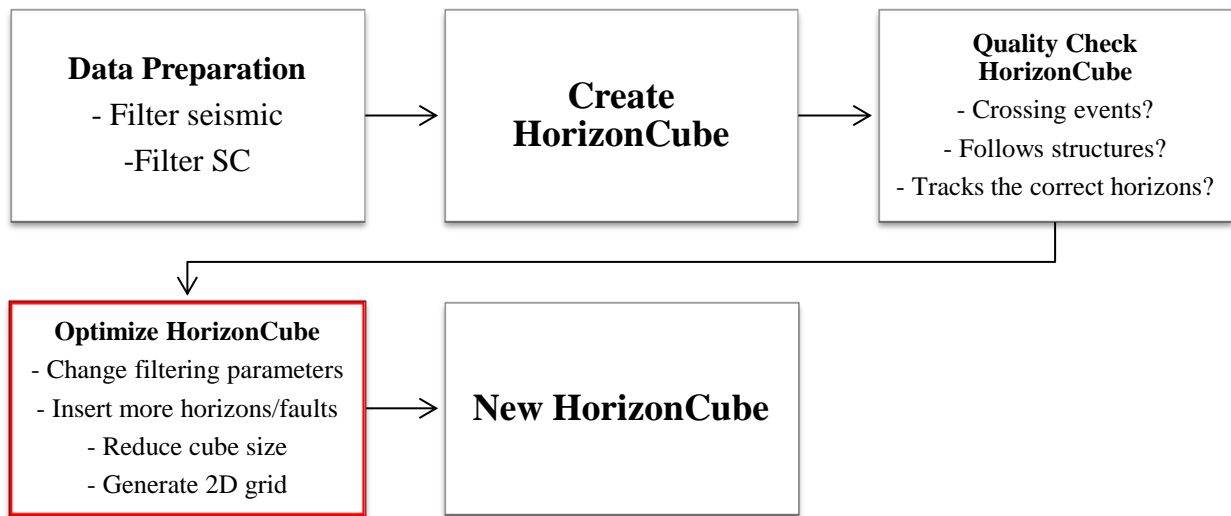
Figure 40: Workflow for optimizing the HorizonCube.

By changing the filtering parameters for areas with a lot of noise (spikes in dip), there could potentially be improvement in the HC-tracking. Figure 41 shows an inline 861 with highlighted areas that are experiencing a lot of noise disturbance. It is recommended to change the filtering in the crossline dip to remove as much noise as possible by increasing the step-out and time range values.
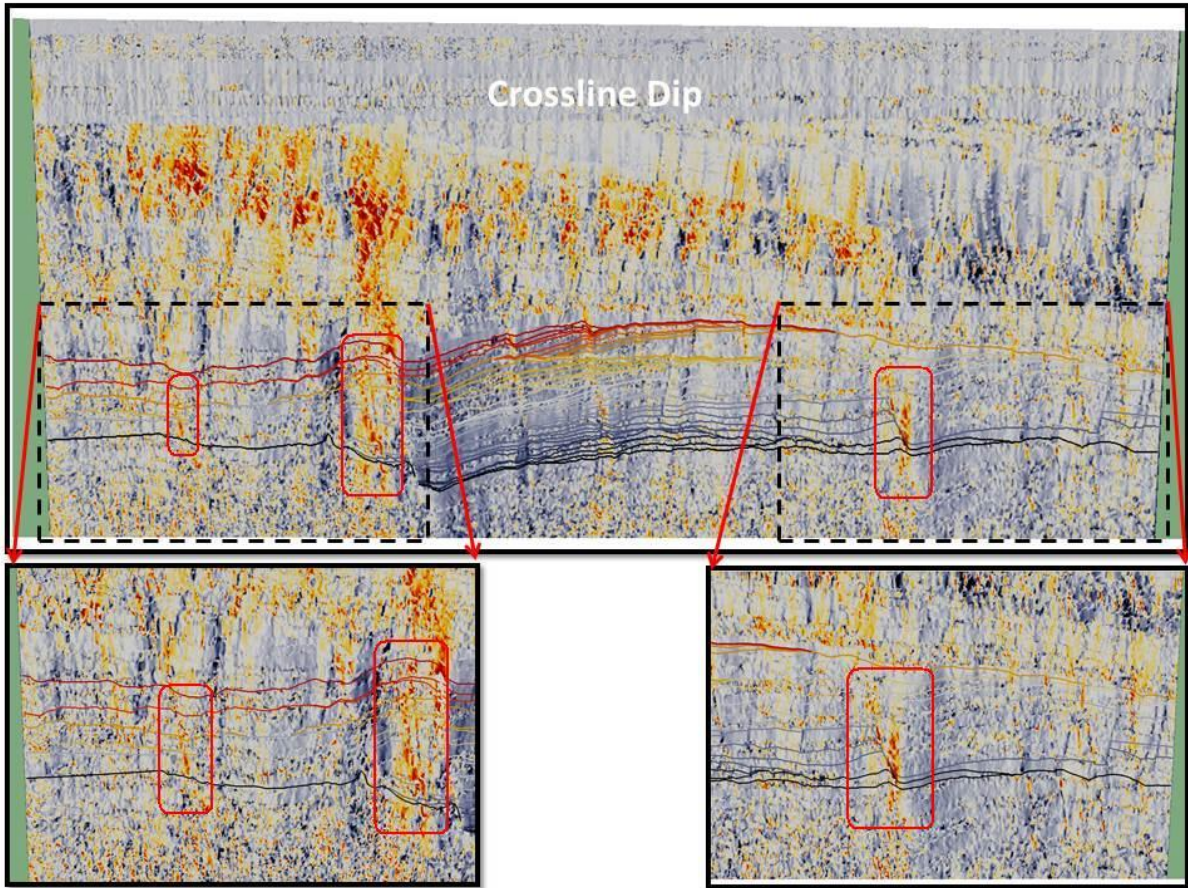
Figure 41: SteeringCube with 3D HC-tracked events in crossline dip of IL861 displaying errors highlighted by red boxes.

The HC-tracking also depends on the input framework horizons and faults, i.e. how precise and accurate the interpretation is. By performing a thorough horizon- and fault mapping, i.e. ensuring that the correct reflectors are mapped and that the horizon terminates close to the fault, this could potentially improve the HC-tracking. Also, it is important to quality check (QC) the HC-tracking outcome and identify any crossing horizons or areas where the HC does not honor structural features. If the QC is not satisfactory, then it could be necessary to re-do the mapping-step in the workflow (Ref. 2.4.3, Figure 12).

Another way to optimize the HorizonCube is to interpret and import more horizons and faults to the HorizonCube. If more input information is provided for the HC-modeling the tracking has more parameters to be guided by and hence the tracking may become easier.

In this project, two additional horizons were interpreted by using the 3D autotracking in OpendTect; the Krossfjord and Johansen Formations. The result of adding these horizons to the 3D HorizonCube (Figure 42) are still spikes and un-tracked areas. Again, the HC-

tracking is poor because the autotracking does not follow the correct horizon reflectors. A suggestion to further work is to track more horizons in a conventional, more time-consuming way and later use them as input horizons to the HC. The results could be improved greatly and the output WheelerCube interpretation could become both more accurate and more comprehensive as the WheelerCube displays more time-lines.
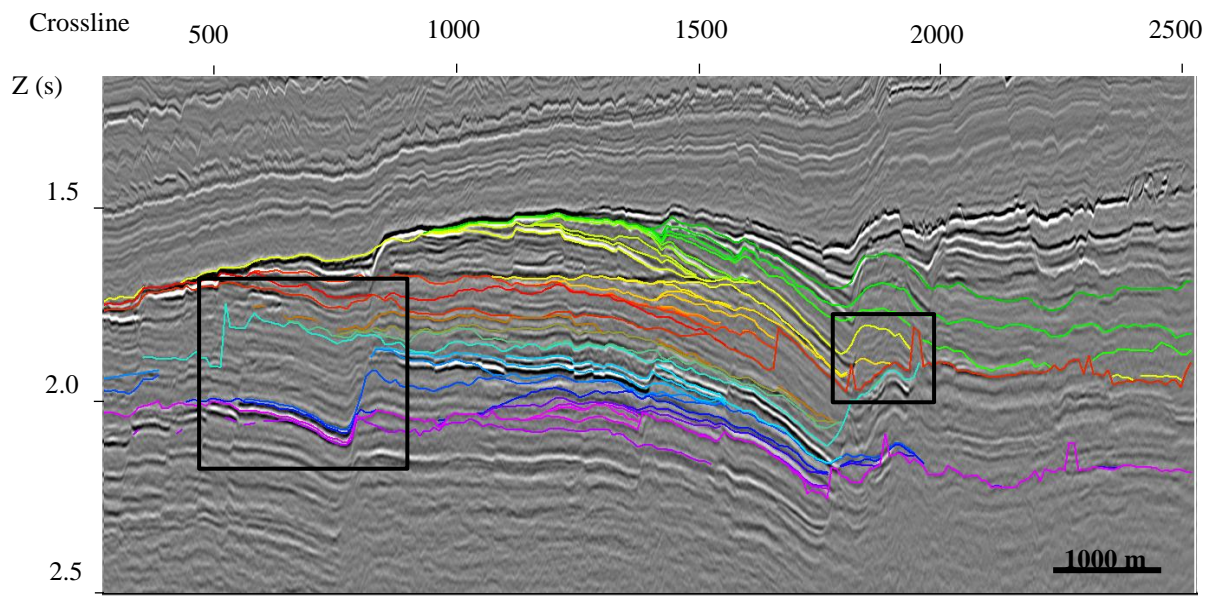
Figure 42: 3D HorizonCube (IL861) with five input horizons: The BCU, Brent GP, Statfjord FM, Krossfjord FM and Johansen FM. HC-modeling was data driven (truncated events). Black boxes highlight areas that are un-tracked and include spikes.

By performing HC-tracking on a smaller cube volume which is less affected by faulting and other structural features, this could result in a better HC-tracking outcome. Also, by reducing the cube size, the HC-tracking time is also reduced, which is a significant benefit since tracking in 3D generally takes a long time (at least 12 hours).

Moreover, for further work another suggestion for improving the interpretation of the sequence stratigraphy for the Jurassic Period on the Horda Platform is that instead of performing HC-tracking in a 3D volume, it is possible to do HC-tracking on some inlines and create a 2D grid (Figure 43A). Figure 44 and Figure 45 show the WheelerCube interpretations with assigned systems tracts for the inlines 1385, 861 and 585. By creating a 2D grid the HorizonCube tracking becomes more accurate and a lot more time-efficient. This leads to an easier and more detailed WheelerCube interpretation that clearly shows the transgressive and regressive events.
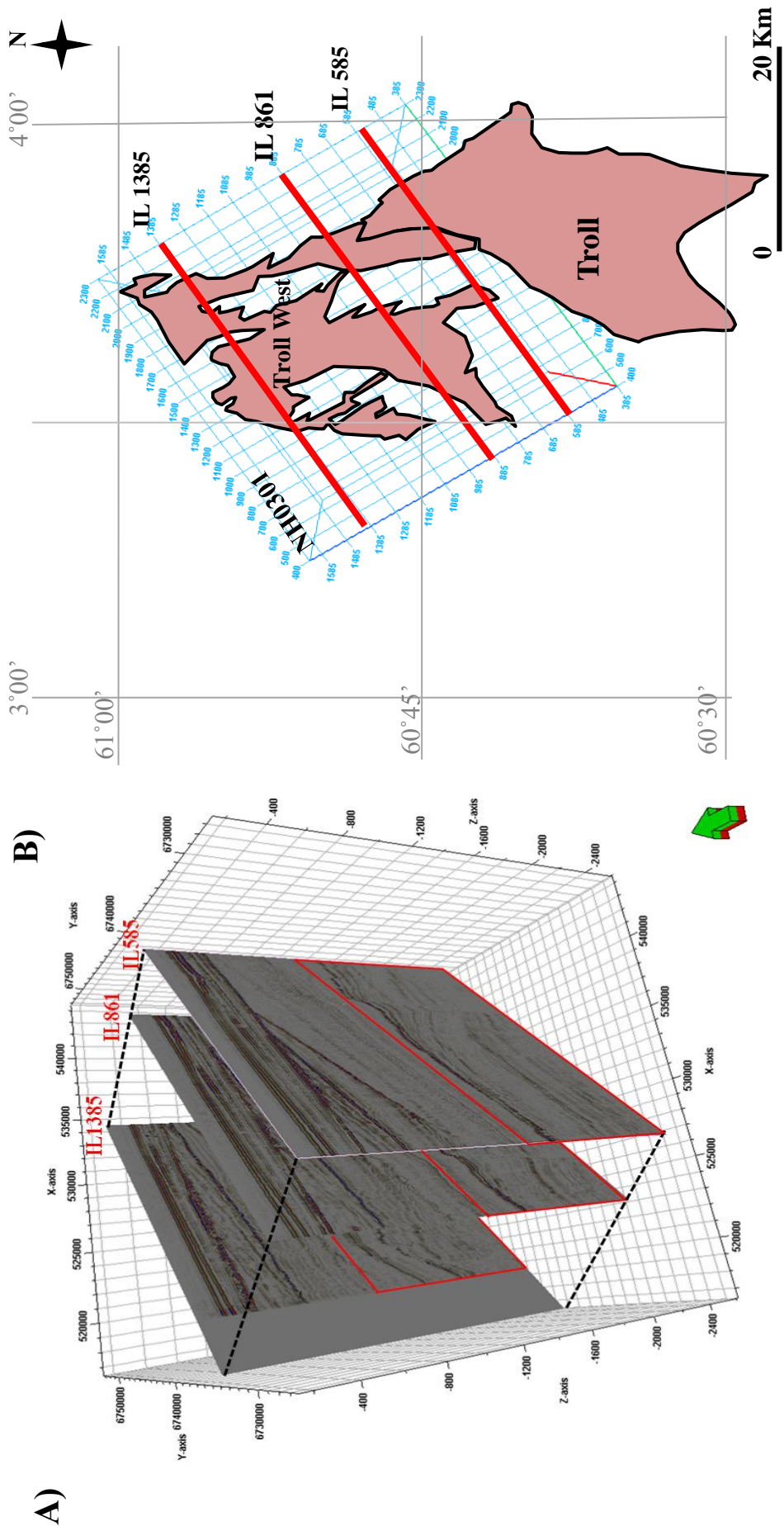
Figure 43: A) 2D-grid of inlines 1385, 861 and 585. Red boxes highlight area of interest. Z-axis is in TWT (ms). B) Location map of inlines 1385, 861 and 585 from seismic volume NH0301, Troll West Field.
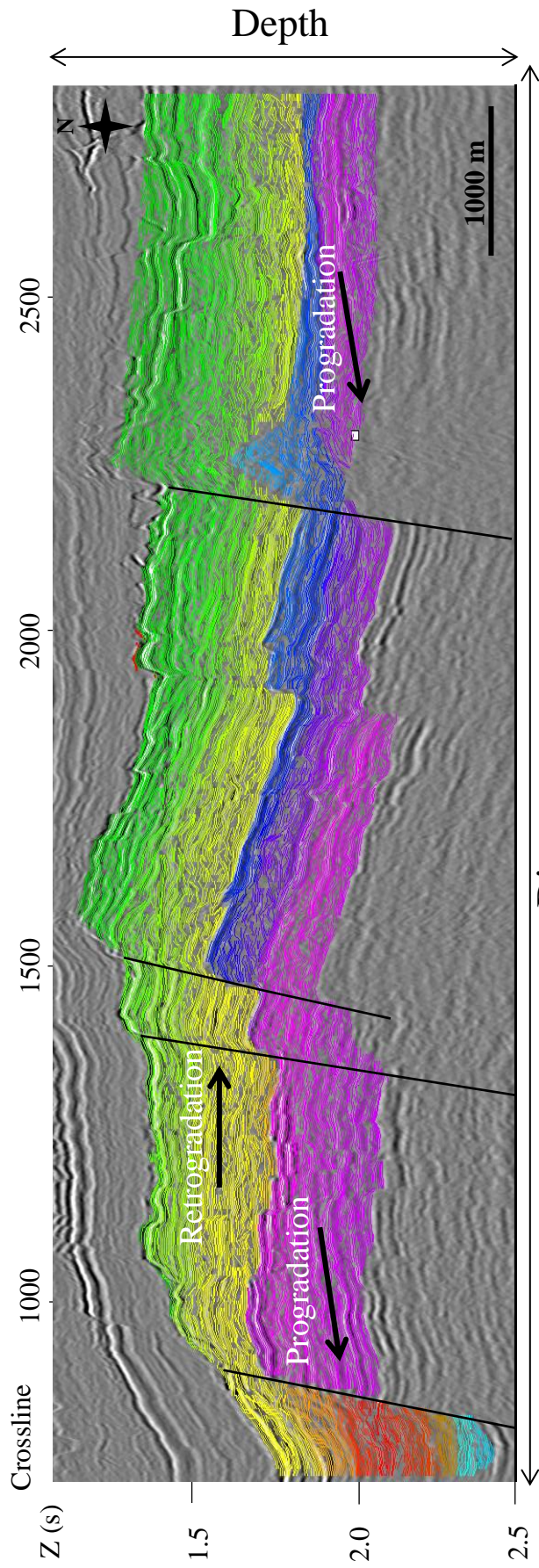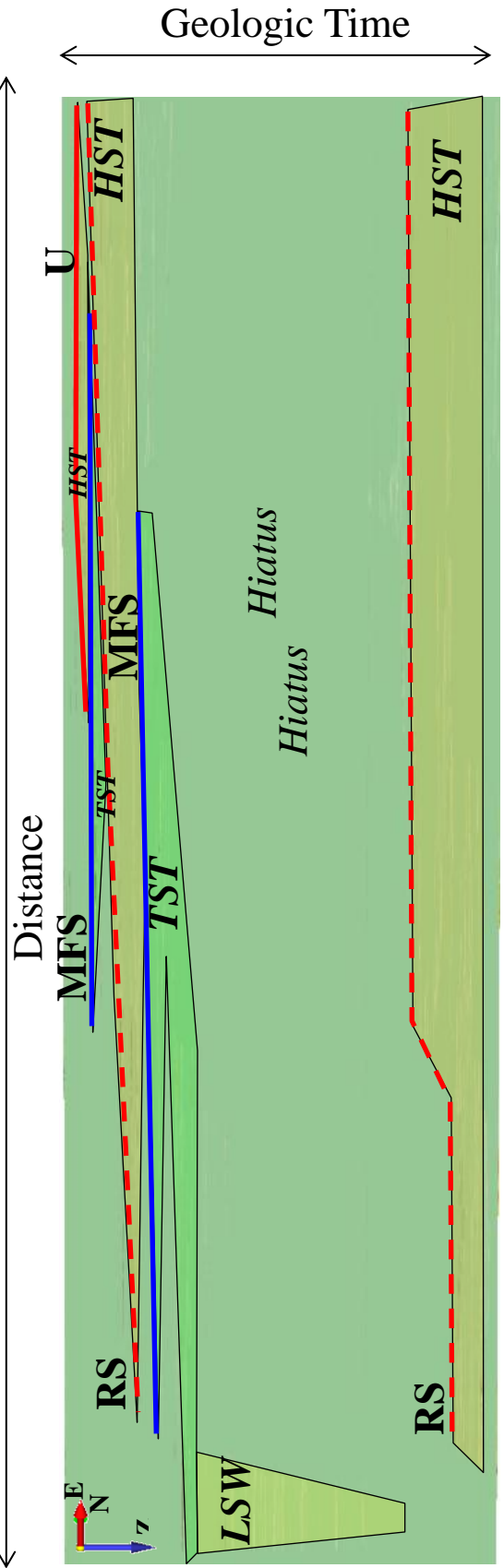
Figure 44: A) Seismic inline 1385 with truncated HorizonCube. Colors represent systems tract thickness in TWT (s). B) WheelerCube for IL1385.
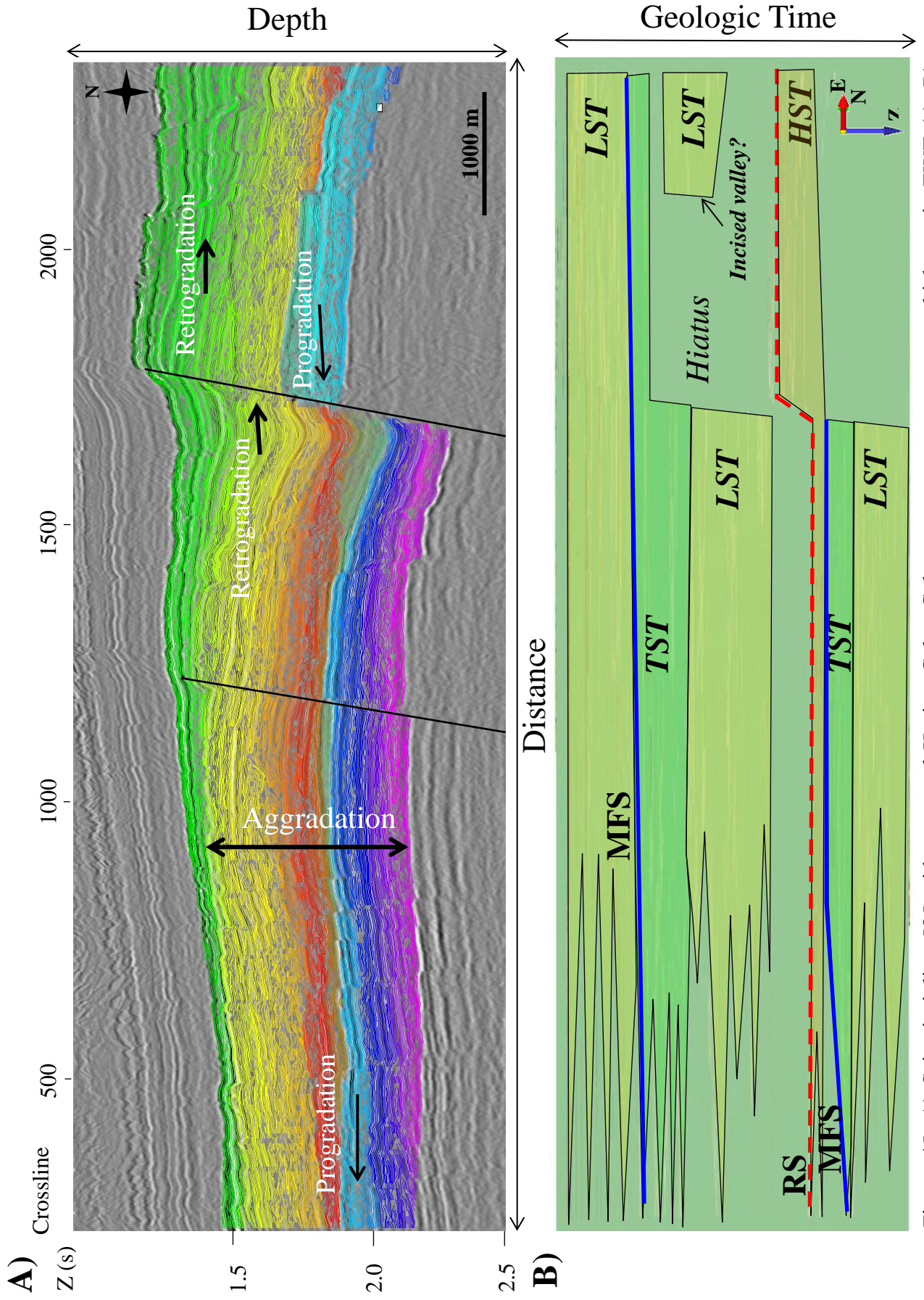
Figure 45: A) Seismic inline 585 with truncated HorizonCube. Colors represent systems tract thickness in TWT (s). B) WheelerCube for IL585.

5.3 Petroleum Significance

Modern seismic interpretation is all about getting as much geological value of seismic data as possible. The HorizonCube generates a dense set of 3D automated horizons which should automatically terminate against mapped fault planes with extremely tight intersections (Groot, 2010). According to Groot (2010) an advantage of dip-steered auto-tracking is that by tracking in dip fields lead to a set of continuous, chronologically consistent horizons, rather than patchy horizons from conventional tracking in amplitude domains. Therefore, more geology could be extracted from the 3D seismic by the use of this type of tracking, and hence detailed attributes can be generated for better understanding of the subsurface. One of these attributes is the Wheeler transformed domain which has a crucial role when it comes to building detailed sequence stratigraphic frameworks and interpreting the seismic data (Qayyum & Groot, 2012). The Wheeler domain can help predict reservoir age, systems tracts, and areas of prospectivity (Qayyum et al., 2012). According to Qayyum et al. (2012) Wheeler transforms are today a key element which aims to increase geologists insight into the depositional history of sedimentary packages, improve seismic facies and lithofacies predictions, and provide accurate targeting of reservoir, source rock, and seal potential. By flattening 2D and 3D seismic data, moving data from the structural domain to the Wheeler domain, this will increase the understanding of the spatial distribution and timing of sediment deposition (Qayyum et al., 2012).

This study reveals that tracking in a dip-field by the use of the HorizonCube attribute on 3D seismic data is a time-consuming process, and the results presented in section 4.4.1 are not satisfactory enough for extracting the amount of geological data needed to generate a proper, detailed seismic- and Wheeler interpretation. However, HC-tracking on a 2D seismic line gives very good results both for tracking chronostratigraphic surfaces in the structural- and Wheeler transformed domain. As mentioned in section 5.2, a suggestion for further work is to create a 2D grid of the 2D WheelerCubes or smaller 3D WheelerCubes, and from these WheelerCube interpretations it may be possible to identify sequence stratigraphic traps, seal and potential reservoirs.

6.0 CONCLUSION

In conclusion, the results obtained from the state-of-the-art methodologies studied in this thesis show mainly similarities when comparing the interpretation of the Jurassic sequence on the Horda Platform from the 2D Wheeler transformed domain with previous studies from the same area. However, the generated WheelerCubes from the 3D and 2D HorizonCubes show two different interpretations for the depositional cycles, where an overall retrograding system is interpreted form the 3D WheelerCube, whereas an overall progradation/regression is interpreted from the 2D WheelerCube.

This type of detailed sequence stratigraphic modeling provides important information about the subsurface which can be used in the petroleum industry for both prospect evaluation and optimization of producing fields. A well functional HC could definitely help to better understand the depositional environments and facies distribution, as well as to illustrate the strata architectural patterns and geometries in order to predict the potential hydrocarbon for exploration.

As a consequence of the poor HC-tracking in 3D, for this study the WheelerCube does not improve the sequence stratigraphic interpretation compared to previous studies from the same area. Moreover, the HC-modeling is an iterative process and is thus time-consuming as HC-tracking takes at least 24 hours to run. However, the HC-tracking on a 2D seismic line is both time-efficient and precise, so the resulting WheelerCube is easy to interpret and generates a much more comprehensive interpretation of the Jurassic sequence. But this takes away some of the main benefits of this methodology, which is to be able to stratal slice through the 3D data.

A 2D grid of the WheelerCubes generated from 2D HC–tracking is proposed as one solution to improve the interpretations and to save time. However, there was no time to do this during the remainder of this thesis. Another suggestion to try out could be to generate a smaller 3D cube that is less affected by faults, and that also could have been conditioned more. The application does not seem to be mature enough or user friendly for what it is intended to do.

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