TECTONO-STRATIGRAPHIC STUDY OF THE CENOZOIC
NORTHERN NORTH SEA: INFLUENCE OF FLUID FLOW AND
DIAGENESIS

A dissertation submitted to the University of Manchester for the degree of Master of Science by
Research in the Faculty of Engineering and Physical Sciences

2011

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SCHOOL of EARTH, ATMOSPHERIC and ENVIRONMENTAL
SCIENCES.
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ABSTRACT

This study embraces the Norwegian sector of the northern North Sea between latitudes 60° and 61° over an area of 11,000 km². Tectono-stratigraphic study carried out highlights new basin features which have relevant implications for deposition, fluid migration and hydrocarbon exploration in the northern North Sea.

Strong spatial and temporal correspondence exists between the older Mesozoic structures and rift topography and the subsequent depositional and deformational processes in the Cenozoic northern North Sea. This reflects in the resultant basin physiography which influenced erosional elements, controlled sedimentation and depositional styles, and affected the occurrence and distribution of syn- and post-depositional features.

The BCU structural framework comprises master fault system, braided fault network, and linkage fault array which influenced distribution of sediment remobilization complex and sediment deposition in the Cenozoic during fault reactivation and fluid migration events. Important Paleocene-Eocene elements include focused sedimentation controlled by compensational stacking, sandy clastics system subject to sediment remobilization and point source deposition, and late Paleocene fault-bounded graben-like linear depression which is marked with thickening deposition in the upper part of the Paleocene unit.

The Oligocene-Miocene is characterized by sediment mounds (constrained to early Pliocene), diagenetic front and polygonal faulting, whose distribution is controlled by the prevailing inversion-influenced basin physiography. The prevailing depositional setting and sediment transport are reflected in resultant basin relief and large channel-lobe system. These portray important implications for Utsira sands which are significant for CO₂ sequestration in the North Sea.

This study presents a 3D seismic analysis of sedimentation, post-depositional influence of fluid flow and diagenesis, and the link to underlying tectonic elements in the northern North Sea.
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ACKNOWLEDGEMENT

I want to express my profound gratitude to my supervisor Dr. Mads Huuse for his support in the course of this study. To his kind and brilliant tutelage I owe so much.

I also appreciate Prof. Jonathan Redfern for encouraging me towards choosing this research course module.

The 3D seismic dataset for this project was made available courtesy Petroleum Geo-Services (PGS) Ltd. Petrel seismic interpretation tool used in this study was provided by Schlumberger.

I owe the following esteemed recognition for their gracious help towards the success of my research program; the Olowoshiles, the Adeyoolas, the Morakinyos, Orene, Theodora Abhulimen (Mama), my Basin Lab colleagues, and my parents and siblings. May they live in beautiful sunshine.

This said to say that. That being what is scripted.
Etched as in eternal brass, in curious hidden rheology
Ere time dropped its ink on this fading parchment.
It holds fast in the cloak of enduring remanence.
That - the truth of One.
The One who sets the corridor of gigantism, the mysterious aisle of Carboniferous.
1.0 GENERAL INTRODUCTION

1.1 PREAMBLE

This M.Sc. by Research thesis provides a tectono-stratigraphic analysis of the northern North Sea (NNS) with the aid of 3D seismic dataset. Though well researched and documented in literature, a good proportion of the regional interpretation of the Norwegian North Sea in past decades derived from the use of 2D seismic survey and boreholes. The advent of 3D seismic imaging has greatly improved on our current understanding of seismic stratigraphy and basin evolution because of the increased lateral coverage and spatial resolution it offers (Cartwright & Huuse 2005). Therefore, the major aim of this study is to improve on the current knowledge of the tectono-stratigraphy and fluid-sediment (including diagenetic) interactions of the Cenozoic northern North Sea (NNS, hereafter so referred).

It is noteworthy to indicate that the figures and tables used in illustration are compiled in the section after the main text. This is to enhance order due to the large number of figures referenced.

1.2 STUDY LOCATION AND SETTING

The study area embraces the Norwegian sector of the NNS between latitudes 60° and 61°N and longitudes 1° and 4°E. The areal extent of survey is about 11,000 km². It presents a good quality dataset that affords a basin-to-basin coverage across the North Viking Graben (NVG). Important producing fields in the Norwegian sector incorporated in the survey include the entire Troll gas province, Brage field, the northern segment of Oseberg, Kvitbjørn, Huldra, Fram, and Gulfaks. This will help to relate the implications of the structural elements to the location of these fields with respect to hydrocarbon accumulation and migration. The North Viking Graben occupies the central part of the survey. On the eastern margin of the graben, the survey extends to the basin margin of the East Shetland Basin and the southern margin of Tampen Spur. The western margin borders the Norwegian shoreline and covers the Lomre Terrace, Uer Terrace, and the northern
segment of Oseberg fault complex (Fig. 1). This regional coverage makes possible an adequate scale for regional reconstruction of the basin history of the Cenozoic NNS.

1.3 AIM AND OBJECTIVES

The scope of this study embraces the investigation of sedimentation and tectonics of the Cenozoic fill in the northern North Sea with a view to improve on our current understanding of the depositional and structural controls in the area. Detailed attention has been given to Paleocene-Miocene successions whilst the post-Miocene (Utsira) succession is superficially dealt with in building complete stratigraphic divisions. In more specific terms, this study attempts to carry out:

- A review of the seismic stratigraphic framework and associated depositional systems, (notably focused sedimentation vs. hemi-pelagic drapes)
- An examination of seismic facies distribution in resolving the complex depositional history
- An investigation of the sediment mobilization mounds in the Oligocene-Miocene succession with a view to their origin and timing
- A study of the influence, distribution and variability of suspected diagenetic Opal A/CT front and polygonal fault network as syn- or post-depositional factors in the affected interval
- A review of the basin history in the light of the revised tectono-stratigraphic and fluid flow evolution.
2.0 STUDY CONTEXT AND GEOLOGICAL SETTING

2.1 CONTEXT OF STUDY

The Northern North Sea is a prolific Mesozoic hydrocarbon province known for some giant discoveries (Fraser et al. 2002; Husmo et al. 2002; Fig. 1). The Cenozoic NNS, however, has fewer discoveries unlike the central North Sea (Ahmadi et al. 2003; Jones et al. 2003). The study explores the area with a view to defining new implications that will prove helpful to exploration in the Cenozoic NNS. The pre-rift structural fabric and the regional stress field played important roles in the structural evolution, by rejuvenation of inherited structures (Nøttvedt 2000; Skilbrei & Olesen 2005). Discrete phases of crustal extension (and hence differential vertical movements) accompanied by fault block rotation and sub-basin development, are punctuated with periods of thermal cooling and basin subsidence (Faleide et al. 2002; Hansen et al. 2004; Odinsen et al. 2000; Ziegler 1990). These structural signatures are apparent in folding, faulting and graben step-over in the study area, and they also reflect some implications for the overlying Cenozoic fill. The Jurassic Viking Graben is segmented in a consistently right-stepping sense (Fossen et al. 2000, 2010). The control of the structural trend on later inversion-related pulses of uplift (Andresen et al. 2009; Clausen et al. 2000; Huuse 2002) is considered in this study. This work builds into the framework the existence of a small, transverse Paleocene graben-like trough, of which little is known about in previous works. This work also attempts to characterize the role of differential vertical movements (Faleide et al. 2002; Huuse 2002; Martinsen et al. 1999) in contributing to depocentre shifts of the Cenozoic depositional packages. It also assesses the influence of Neogene inversion as it relates to the depositional styles of the Oligocene-Miocene units and especially the Utsira depositional package (Isaksen & Tonstad 1989; Gregersen & Johannessen, 2007). A satisfactory depositional model for the Utsira sandstone has long been difficult to proffer (Rundberg 1989; Rundberg & Eidvin 2005). Many suggest that the basin-restricted sands could be typical of a shelfal depositional system, contourite drift system, turbiditic origin, high-energy shallow marine setting (Galloway et al. 1993; Galloway 2002; Gregersen et al. 1997; Martinsen et al. 1999; Rundberg 1989). This work has tried to put forward a model based on the depositional styles predominant in Oligocene-Miocene times according to the mapped stratal geometries. The study has also considered the nature of the mid-Miocene
unconformity (Huuse & Clausen 2001) based on resultant basin physiography and stratal geometry in order to shed more light on its nature, whether the hiatus is sub-aqueous or sub-aerial (Martinsen et al. 1999; Faleide et al. 2002; Rundberg & Eidvin 2005).

The mineralogical composition of the Cenozoic fill has been shown to reflect in the seismic velocities (Jordt et al. 2000; Nøttvedt 2000, Thyberg et al. 2000). Velocity variation has been tied to the smectitic content of the mudstones (Thyberg et al. 2000). Biogenic siliceous sedimentation and alteration of Opal-A to Opal-CT also contribute to velocity increase in the Oligocene mudstones (Rundberg 1989; Rundberg & Eidvin 2005; Davies 2005). Based on this some workers link soft sediment deformation and ‘mounding’ of Oligocene-Miocene mudstones to clay diapirism facilitated by density inversion (Jordt et al. 2000; Nøttvedt 2000). Other workers believe that the mounds were associated with fluid conduits through which focused fluid migration from the Jurassic units, initiated sediment remobilization in the overlying successions (Andresen et al. 2009; Cartwright et al. 2007; Huuse et al. 2010; Løseth et al. 2003; Jackson & Stoddart 2005; Shoulders et al. 2007). This work investigates the evolution of the mounds in connection with distribution of injectites (Huuse, 2008; Huuse et al. 2010; Szarawarska et al. 2010) and their basinal location, and the role and effect of diagenesis in accounting for the basin physiography and soft-sediment deformation (Cartwright 2007; Davies & Cartwright 2007; Davies et al. 2009, Neagu et al., 2010). This work also puts in perspective the temporal constraints of the sediment remobilization mounds (Jackson & Stoddart 2005). In close link to the mounds in the Oligocene mudstones is the pervasive polygonal fault system (Cartwright 1996; Cartwright & Lonergan 1996; Cartwright et al. 2003; Walsh et al. 2000; Watterson et al. 2000). Its relationship and occurrence with sediment mounds were studied with a view to understanding the deformation constraints in the Oligocene-Miocene units.

Overall, this work is an integrated study of the Cenozoic fill in the northern North Sea. It presents a platform for more in-depth study of the Cenozoic evolution of the NNS. It draws premises from the work of Rundberg (1989) and Jordt et al. (1995, 2000). The presentation style of this study is a result/observation – based approach. Effort has been made to keep the amount of speculation brief in order to cover as much observationally-constrained evidence as possible.
2.2 GEOLOGICAL SETTING

2.2.1 Tectonic evolution and depositional history

The NNS basin is a wide sagged depocentre with Cenozoic sediment infill of c. 2500 m (Faleide et al. 2002, Huuse, 2002; Hansen et al., 2004; Andresen et al., 2009). It is a by-product of two main Mesozoic rift events, which succeeded the accretionary Paleozoic events (Caledonian and Variscan), that affected NW Europe (Coward et al. 2003; Fossen et al. 2010; Skogseid et al. 2000). The study area defines the location of the North Viking Graben, which falls between the Sogn Graben to the north and the Central Viking Graben to the south. The NNS rift system is bordered by the Fennoscandian landmass and Øygarden fault zone to the east, and the East Shetland Platform and British Isles to the west (Fig. 1 & 2; Christiansson et al. 2000; Huuse & Clausen 2001; Huuse et al. 2001). The graben is part of the northern arm of a series of linked half grabens that form the North Sea basin (Beach et al. 1987; Færseth et al. 1995; Ter Voorde et al. 2000; Odinsen et al. 2000). The inherited structural grain of the basin is dominated by roughly N-S trends intersected, towards the north of the study area, by NE-SW trending faults (Fig. 2; Blystad et al. 1995; Kyrkjebø et al. 2004). The basin formed and the structural trends result from the Caledonian suture system and several extensional events following it (Doré et al. 1987; Lundi & Dore 2005; Ter Voorde et al. 2000). The latest of these phases are the pronounced Permo-Triassic and Jurassic-Cretaceous rift events (Færseth et al. 1996; Fossen et al. 2000; Gabrielsen et al. 1990; Nøttvedt et al. 1995; Roberts et al 1995). The structures in this area are characterized by large rotated fault blocks, associated with lithospheric extension and thinning, and sub-basin development in asymmetric half-grabens (Christiansson et al. 2000; McKenzie 1978; Odinsen et al. 2000). Crustal models indicate marked crustal thinning beneath the Viking Graben in the NNS attributed to the Jurassic-Cretaceous rifting (Christiansson et al. 2000; Fossen et al. 20010; Kyrkjebø et al. 2000; Odinsen et al. 2000; Skogseid et al. 2000). Deep reflection data reveals the emplacement of a lower-crustal body characterized by an 8+ km/s and an average bulk density of 2.95 g/cm³ beneath the Horda Platform, it is suggested to have probably formed during the Caledonian orogeny (Christiansson et al. 2000; Odinsen et al. 2000). The Permo-Triassic axis lies near Horda Platform and appears to have affected a wider area while the Jurassic axis follows the present Viking Graben (Steel and Ryseth 1990;
Each phase was followed by a period of thermal relaxation and subsidence. Suggested thermal equilibrium reached with the basin becoming a wide area with low relief shows that the Jurassic rift phase had ceased in latest Cretaceous time (Faleide et al. 2002; Gabrielsen et al. 2001). The post-rift sedimentation filled in and buried the rift topography (Huuse 2002; Kyrkjebø et al. 2000). The Cretaceous facies were overlain by mud-dominated successions of the Cenozoic as the basin subsided on thermal relaxation and experienced several differential vertical movements (Faleide et al. 2002; Jordt et al. 2000).

The development of the Cenozoic infill and architecture strongly bears on shift in depocentre, change in sediment outbuilding direction, sediment provenance and composition that were dictated by differential tectonic movements and climatic factors which accompanied sea level changes (Figs. 3a & 3b; Jordt et al. 2000; Rundberg 1989; Rundberg & Eidvin 2005; Thyberg et al. 2000; Ziegler 1990). The exhumation of the North Sea Basin margins and the subsidence of the basin centre (Huuse 2002) were accompanied by a period of tectonism and magmatism, attributed to the arrival of the Iceland mantle plume, in the early Tertiary during the continental break-up and subsequent seafloor spreading in the North Atlantic to influence the depositional systems (Fig. 4; Ahmadi et al. 2003; Anell et al. 2009; Brekke et al. 2001; Lundi & Dore 2005; Nielsen 2009; Ziegler 1992). Sediments were sourced mainly from the eastern Fennoscandian Shield and western East Shetland Platform (Hansen et al. 2004; Kyrkjebø et al. 2000). The post-Danian sequence can be divided into 3 lithostratigraphic groups: Rogaland, Hordaland and Nordland based on the work of Deegan & Scull (1977) and Isaksen & Tonstad (1989). The Paleocene to early Eocene interval was characterized by deposition of deep marine mudstone with prograding sediment wedges occupying the depocentres developed on the basin margins as the clastic source areas were uplifted (Faleide et al. 2002; Jordt et al. 2000; Kyrkjebø et al. 2000). Southern Norway and the Scotland-Shetland hinterland also supplied significant amount of coarse clastics into the area, which were deposited as submarine fan complexes in a relatively deep basin, thus making the early Paleogene sand-prone (Ahmadi et al. 2003; Jordt et al. 2000; Rundberg 1989). At early Eocene times, a large area of the NNS witnessed the Balder ash deposit associated with the magmatic activities in the North Atlantic rift zone (Jordt et al. 1995, 2000; Rundberg 1989; Thyberg et al. 2000). The Paleocene-Eocene transition marks the culmination of extensional deformation and sediment basin formation since the Caledonian
orogeny ended (Fig. 4; Lundi & Dore 2005; Skogseid 2000). Later events were dominated by basin inversion, compressional regime and climatic transition in the period generally taken to have been tectonically quiescent (Anell et al. 2009, 2010; Nielsen et al. 2009, 2010).

The Eocene-Oligocene deposition was influenced by compressional strain (Rundberg & Eidvin, 2005) and experienced a high sediment supply (Jordt et al. 1995, 2000, Rundberg 1989). Huuse & Clausen (2001) suggested the high sediment supply indicates global control on sedimentation (i.e. climate and eustasy) based on $\delta^{18}$O correlation. The dominant influence of climate as transition occurred from greenhouse to icehouse conditions when major mid-Cenozoic plate reorganization, involving seafloor spreading in Greenland, westward jump in seafloor spreading axis to Jan Mayen Fracture Zone, establishment of seaway link to the Arctic and build-up of ice in the Antarctica, altered the paleogeography significantly (Figs. 4; Anell et al. 2009; Fyfe et al. 2003; Rundberg & Eidvin 2005). In response, structural activity became compressional and basin inversion prevailed in the NNS (Rundberg & Eidvin 2005). The ocean circulation encouraged upwelling and there was marked incoming of bio-siliceous sedimentation (Neagu et al. 2010; Rundberg & Eidvin 2005; Thyberg et al. 2000). The mid-Miocene was characterized by a major regional hiatus (Faleide et al. 2002; Huuse & Clausen 2001; Løseth et al. 2003). It is however being debated whether there was sub-aerial or sub-aqueous exposure (Rundberg & Eidvin 2005). On the whole, the basin shallowed from relatively deep-marine conditions during the late Paleocene, to shallow-marine and locally fluvial conditions in the Early Miocene (Jordt et al. 1995, 2000, Kyrkjebø et al. 2000, Rundberg 1989). After the extensive regional unconformity, the Utsira sands were deposited as the basal part of the Nordland Group (Jordt et al. 1995, Galloway 2002, Rundberg & Eidvin 2005).

Debate still persists on the mechanism responsible for Neogene uplift (Anell et al. 2009, Nielsen et al. 2009, 2010). In the light of sustainable evidence, isostasy, climate and erosion have been claimed to work in feedback loop to account for the Neogene paleogeography and deposition (Huuse 2002, Huuse & Clausen 2001; Nielsen et al. 2009, 2010). High sediment influx of thick clinoform wedges, fed by dramatic supply of sediment at the instance of glacial erosion, prograded basinward as sea level fell (Kyrkjebø et al. 2000, Jordt et al. 2000). In late Pliocene and Pleistocene, glaciations of Fennoscandia eroded the proximal Tertiary and older deposits.
from the Norwegian margin (Kyrkjebø et al. 2000, Jordt et al. 2000. Rundberg 1989) after which Pleistocene and Quaternary sediments were deposited.

2.2.2 Post-depositional deformation

The Cenozoic fill, especially Paleocene-Miocene succession, has undergone syn- and post-depositional alterations involving polygonal faulting, fluid-flow phenomena and Opal A/CT conversion which are commonly attributed by many workers to differential compaction, mud diapirism, overpressure, fluid migration, diagenesis and seismicity (Cartwright 1996, Huuse 2008, Lonergan et al. 1998, Løseth et al. 2003, Jackson & Stoddart 2005, Davies 2005, Davies et al. 2009, Ireland et al. 2010). Polygonal faulting is commonly expressed as layer-bound extensional faults in mud-dominated facies (Cartwright & Huuse 2005; Cartwright et al. 2003). Causal mechanisms proposed for its initiation and development include density inversion, syneresis, volumetric compaction, dewatering and gravity sliding (Cartwright 1996; Cartwright & Lonergan 1996; Cartwright et al. 2003; Lonergan et al. 1998; Walsh et al. 2000; Watterson et al. 2000). A strong link to diagenesis was proposed by Davies et al. 2009). The non-tectonic origin is still under debate as there is no model with full explanation of its initiation and propagation (Cartwright et al. 2003). Opal A/CT silica diagenesis is prominent in the NNS marked by a reaction front in the Oligocene with increase in density and resistivity (Rundberg 1989; Rundberg & Eidvin 2005) thus enhancing seismic imaging due to acoustic impedance contrast (Davies et al. 2006; Huuse & Mickelson 2004; Ireland et al. 2010; Rodriguez et al. 2009). Diagenetic conversion of the diatomaceous deposits (Schieber et al. 2000; Thyberg et al. 1999; Thyberg et al. 2000) is inferred to account for characteristic geometry and morphology of the reaction boundary (Davies 2005) which advance (generally) non-concurrently with the host stratigraphical boundaries (Neagu et al. 2010). The advance front is normally associated with differential compaction folding, polygonal faulting and regional anticlines and synclines (Davies 2005; Ireland et al. 2010; Neagu et al. 2010). The implication of the thermo-chemical nature of this reaction for basin fill and physiography is however eluding exhaustive clarification. Opinions are divided between active and fossilized nature of the reaction front based on its present day temperature relationships (Brekke 2000; Neagu et al. 2010; Rundberg 1989). It is thus a key tool in predicting the paleo-geothermal conditions. The spatial and temporal constraints of fluid-rock interaction in the NNS are of prime significance in understanding fluid
3.0 DATABASE, METHODS AND STUDY FRAMEWORK

3.1 DATABASE AND METHODOLOGY

3.1.1 Database

The database for this research project consists mainly of 3D seismic in SEG-Y 8-bit format. Data was made available by the Petroleum Geo-Services (PGS) Ltd. The inline length is about 75 km and the cross-line length is about 148 km, giving coverage of about 11,000 km². The survey output is in 50 m bin spacing and is sampled at inline and cross-line spacing of 50 m. The seismic cube extends to a two-way travel time (TWT) depth of 3 seconds over a sedimentary fill incorporating part of the Mesozoic. The post-rift Cenozoic sediment infill in the northern North Sea, NNS, hereafter so referred, is adequately profiled within the TWT depth range of the survey. The inlines range from 13000 to 24800 while the cross-lines range from 1 to 1500. There are 751 samples per trace at an interval of 4 ms. At a frequency of about 50 Hz for the dominant wavelength, estimated over an interval spanning 1000-2000 ms, and based on Rayleigh criterion (with minimum resolution as a quarter of a wavelength, \(\lambda\)), the vertical resolution is coarser than 10 m and horizontal resolution based on bin spacing is 50 m (because \(\lambda/2\) at around 20 m is less than bin spacing), with a velocity of 2 km/s assumed. The improved spatial and vertical resolution of 3D seismic provides for good imaging of basin architecture. The survey was processed to zero-phase with amplitude range from -40,314.96 to +40,000. With the additional constraint provided by the hard sea floor reflection, the negative amplitude pink reflection was identified to represent an increase in acoustic impedance while the positive amplitude blue reflection images a decrease in acoustic impedance (Fig. 5). The seismic data coverage shows some gaps but is sufficient for good regional interpretation.

This seismic dataset is part of NNS – CNS MegaSurvey coverage acquired by PGS. The background information reveals that the mega survey comprises over 240 original 3D surveys with the acquisition orientation range between N-S and E-W directions. The dataset is therefore a merge with amalgamated survey patches which is sometimes evident in the attribute extractions from surface horizons generated (Fig. 5). For a 3D survey which is ideally acquired based on midpoint, offset and azimuth parameters, the spatial distribution of traces is, in most cases,
irregular in the space subset sampled. More significant is the irregularity in offset and azimuth directions, the outcome of which is the footprint of acquisition patterns as evident in the low amplitude swath and square imprint observed in Figures 34 and 35. This effect is amplified when applying procedures such as 3D dip move-out (DMO) or 3D pre-stack migration (Canning & Gerald 1998). The artifacts, if not rightly identified, may lead to incorrect interpretation.

In constraining the seismic stratigraphic framework, well data were obtained from published sources and the online Norwegian Petroleum Directory’s Factpages (NPD, 2010. http://www.npd.no/engelsk/cwi/pbl/en/index.htm). Well data were available as PDF files and not as LAS files, and thus could not be imported and quantitatively tied to seismic data. Moreover, the resolution and graphic quality of the available completion logs are in some cases below standard. Best attempt has been made to improvise with the sparse well information sourced from the online database. The available well information was incorporated into this research in order to substantiate the findings. Key wells with good location and fairly robust information for lithologic controls were selected from 103 wells examined (Fig. 6 & Table 1). Some other wells in addition to key wells were cited at various points based on the need for them. Completion logs mostly accounted for the basic information owing to their more frequent availability.

3.1.2 Methodology

Seismic horizon picking was initiated with a coarse grid (cross line spacing of 50 and inline spacing of 100) on the relevant regional seismic boundaries using 2D seeded and guided auto-tracking. A finer grid was used in areas of poor resolution and reflection continuity to embrace more seed points. 3D auto-tracking was employed subsequently to fill in the gaps in preference to wavelet tracking and correlation constraints. Gridded surfaces were generated from which TWT thickness maps derived. Time thickness maps were generated to estimate the vertical thickness of sediments; this may lead to deviation from the true stratigraphic thickness where structural dips of the gridded surfaces are high. In analyzing seismic facies and features of interest, attribute extractions and rendering were carried out predominantly using coherence, RMS, dip azimuth, dip angle, chaos attributes. Stratal slicing was used where it became necessary to isolate intervals of interest within the major stratal boundaries.
Sedimentary thickness alone does not make up for true reconstruction of the structural evolution of a basin. Unjustified deductions may result in using isopachs to determine subsidence without knowledge of the paleobathymetry (for which evidence can be sparse or imprecise) as it may be wrong to assume an initial flatness for depositional profiles. It is therefore difficult to predict paleotopography without paleobathymetry data and analysis of the nature of the depositional units. Isopach maps in this study are analyzed for depositional units considered as profile-bounded chronostratigraphic units. A profile is the surface which represents sediment surface at a single point in time, in form of bedding planes, hiatal or erosional unconformity surfaces (Bertram & Milton 1989). The basinal pelagic deposit may be relatively considered independent of basin topography and paleobathymetry, in contrast to deposited units on the basin margins whose distribution can be subject to accommodation generation by subsidence and sea-level increase. Implications derived from isopach maps have been weighed in combination with TWT depth maps and in light of other factors such as possible sediment supply direction, stratal architecture, available biostratigraphic information etc. It is therefore important to note that the isopach maps are time thickness distribution maps which estimate thickness interval between seismic picks, and they may need to be subject to depth conversion, decompaction, mass balance and paleobathymetric analyses before true paleogeographic setting can be deduced.

A velocity of 2000 km/s was considered a good average, based on the velocity estimates in the work of Jordt et al. (2000), in constraining (at fair estimation) well ties for the Cenozoic fill. Where well completion logs were found to give inconsistent age boundaries, as is usually the case in the chaotic basinal part of Eocene-Oligocene units, the reflection character from the well-constrained area was followed. In general, gamma, sonic and resistivity logs were combined to make meaningful interpretations, though their resolution is sometimes subject to poor graphic quality. Biostratigraphic study has not been carried out because it is outside the scope of this project. Age determinations are therefore estimates from published sources.

The seismic dataset used in this study is not in depth domain. Hence seismic sections and images displayed have considerable vertical exaggeration. Z-scale (TWT) aspect ratio used to enhance display is 7.5. The implication is that dip values can at best be approximate as angular relationship may show element of distortion due to display optimization (Stewart 2010).
This study relies on these available datasets to study the sedimentation and tectonics of the Tertiary NNS.

### 3.2 STRATIGRAPHIC FRAMEWORK

The lithostratigraphy of the North Sea is diverse (Fig. 7). The northern North Sea segment is often built on the framework of Deegan & Skull (1997), and Isaksen and Tonstad (1989). The main lithostratigraphic elements are shown in Figure 7. Detailed lithologic definitions are available in the online database of the Norwegian Petroleum Directorate. In conjunction with the work of Deegan and Scull (1997), Jordt et al. (1995, 2000) divided the Cenozoic fill into 10 major sequence stratigraphic units. Rundberg (1989) and Rundberg & Eidvin (2005) went further in clarifying and improving on the division of sequence CSS-3 by separating Opal-CT mudstone unit in the Upper Oligocene from carbonaceous mudstone in the Lower Oligocene, which were grouped together by Jordt et al. (1995, 2000). This work integrates their divisions in setting a framework for the seismic stratigraphy of the study area (Table 2). 17 key stratal surfaces were mapped and grouped into 9 major units (Figs. 8 & 9; Table 3). They have been divided into Rogaland, Hordaland and Nordland groups, with the exclusion of unit 1 which is attributed to the Late Cretaceous. In establishing stratigraphic framework in the NNS, recognition of regional sequence boundaries was based on erosional unconformity and downlap surfaces since seismic reflections are generated by acoustic impedance contrast at unconformities rather at lithic boundaries (Huuse & Clausen 2001; Henriksen et al. 2005). These surfaces are time-lines (Vail et al. 1997a) whose significant bearing on stratigraphic architecture reflect on paleo-geographic reconstruction (Henriksen et al. 2005). Their objective recognition involves identifying reflection terminations such as onlap, toplap, downlap, (erosional) truncation, and changes in seismic facies (Huuse & Clausen 2001).

Table 2 shows the comparison of Jordt et al. (2000) and Rundberg classifications. The classification in this study is an amalgamation of these two as Jordt et al. (2000) classification is not sufficiently comprehensive (Rundberg & Eidvin 2005). Therefore the classification in this study correlates seismic picks with their equivalent boundaries defined in published literature,
and goes a step further in introducing a division in the lower Oligocene wedge, and also between the upper and lower Utsira lobes (Tables 2 & 3).

The seismic stratigraphic analysis has integrated part of the Upper Cretaceous and the Base Cretaceous Unconformity as far as the seismic section permits mainly with a view to building a foundation for the structural trend in the study area. A few minor picks were also mapped to help in analyzing the basin physiography and will be shown in sections where they complement interpretation. In setting the divisions, the mid-Miocene unconformity, being the boundary between Hordaland and Nordland groups, has been used as a mega-sequence boundary to provide additional constraint in determining the seismic stratigraphic divisions. The seismic picks were mainly constrained with the Troll well transect Rundberg (1989) and well 30/3-3 (Chart 1) interpretation of Jordt et al. (1995, 2000) presented in Thyberg et al. (2000). However, there is uncertainty about the equivalent unit to CSS 5 because, in the study area, it is unclear to which unit it can distinctly be attributed (Rundberg & Eidvin 2005) because CSS 4 unit from the work of Jordt et al. (1995, 2000) extends to the base of mid-Miocene Unconformity. Table 2 & 3 show unit 2 top-bounding surface (C4) recognized as Top Paleocene, to be slightly below tuffaceous balder (which coincides with the top of CSS 1). For example, in well 30/3-3, C4 is located at 1.99 s while in Rundberg (1989) and Thyberg et al. (2000) the Balder is placed above C4 horizon. Rundberg (1989) places top Balder at 1.93 s. C4 horizon pick is very consistent as top Paleocene boundary over the entire study area.

A fair representation of the lithostratigraphy has been provided on an E-W composite transect based on the available completion log information (Fig. 10). The lithologic representation reflects the dominant sandy clastic input westward and the hemipelagic facies eastward. The lithologic definition has been limited to the main units discussed in this study. Detailed sequence stratigraphic and facies characterization cannot be made with the sparse well information available as PDF copies. However, relevant seismic, sequence and litho-stratigraphic considerations are discussed in the course of this study as various units are analyzed.
4.0 SEISMIC STRATIGRAPHY AND BASIN ELEMENTS

Key observation elements for the stratal units and surfaces form the core of the observations analyzed in this section. The framework for analysis is built around seismic stratigraphy such that it allows for integration of different study aspects in order to offer a comprehensive view of ideas being put forward.

4.1 BASE CRETAEOUS UNCONFORMITY (C1) AND EARLY CRETAEOUS (C1i)

This section focuses on the Base Cretaceous Unconformity. The Early Cretaceous surface is included at the end of this section and briefly analyzed.

4.1.1 General description and erosional features - BCU

Limited to the cut-off depth of 3000 ms TWT of the available seismic dataset, the Cretaceous Unconformity C1 was mapped on the graben flanks, fault-blocks and the Viking graben step-over with much of the part in the graben itself lying below 3000 ms TWT (Fig. 8). It is therefore not a comprehensive surface but has sufficient coverage to afford the understanding of the structural framework. The surface is easily recognized based on changes in facies and tectonic style (Kyrkjebø et al. 2004) between the faulted and rotated pre-rift strata and relatively unfaulted post-rift strata. It defines an erosional unconformity which is notably seen in East Shetland, Gulfaks, Oseberg and terrace areas, and Troll uplifted blocks where the reflections of the underlying rift units show truncations against it and the units above downlap onto and unconformably overlie it (Figs. 8 & 9). At the graben margin the Cretaceous unit onlap onto the surface. From the adjacent flank to the top of the Troll fault-blocks the BCU surface is truncated by other surfaces i.e. Early Cretaceous (C1i), Late Cretaceous (C2) and Base Tertiary (C3) (Fig. 8). The rift blocks at Horda Platform show simpler stratatal geometry and modest fault rotation, the unconformity C1 surface has a less-tilted angular unconformity in this area. Two-way travel time (TWT) structure map of the surface shows the high to be about 1150 ms TWT on Horda Platform and deepening sharply to more than 3000 ms TWT in the graben (Fig. 11). The seismic reflection is a high impedance boundary consistently showing strong reflection except over areas
on the crest of Gulfaks and Oseberg blocks where the reflection amplitude is weak (Figs. 11 & 12). The weak-amplitude site on Oseberg measures about 21 km in length, the area on Gulfaks is about 13 km while the site on Statfjord-Brent has an average length of 22 km along the crestal axis of the uplifted blocks (Fig. 12). The reflection amplitude shows variation from strong to weak intensity and at times it shows polarity reversals where the underlying reflection package is acoustically soft. At the weak-amplitude sites, more commonly on Gulfaks and Oseberg, the reflection is nearly absent and lacks character even when acoustic shadow or leakage anomalies are not apparent (Fig. 13). Local high-amplitude reflections (notably in yellow patches) are commonly observed from Oseberg-Øst - Brage area to Troll flank across the relay zone and terrace area (Figs. 11 & 12).

In the area where the BCU (C1) surface is truncated by other surfaces, the reflection characteristics are often erosional and the underlying stratal geometry shows truncations against the BCU. The Troll area, as seen in the inset of Figure 12, shows that the BCU sub-crops the surfaces above through to the Base Tertiary surface. The sub-crop patch is oval in shape with the long axis length about 37 km and the short axis length about 18 km. In the NE segment of the study area, there is an occurrence of a local sediment wedge deposited at the foot of the uplifted footwall in Lomre Terrace area (Fig. 14). The uplifted footwall crest shows erosional truncation against the overlying deposit. The sediment package has a dish to saucer-like and is about 170 ms TWT at its thickest point. It rests unconformably on the lower Cromer Knoll unit which has a convex bounding surface. The downlap onto the basal Cromer Knoll unit has a low-angle dip while the onlap to the uplifted block is steep. The sediment wedge is observed to be compensationally stacked on the underlying unit (Fig. 14). The wedge is angular unconformity bounded and its high-angle onlap onto the uplifted block appears to have undergone some degree of rotation. The sediment package has a spread of about 6 km in both inline and cross-line directions restricted to the point where the differential relief of the uplifted block is at level with the surrounding topography. Its internal reflection characteristic comprises moderate-high amplitude reflections with concave (synclinal fold) geometry at the thickest section. The degree of 'synclinal folding' decreases upward while the thickness of the subunits increases upward.
4.1.2 Structural style

The area without data coverage and between East Shetland and the Norwegian margin roughly delineates the axial trend and extent of the North Viking Graben (Figs. 9 & 13) which occupies the structurally lowest part of the NNS (Fig. 11 & 15). The graben’s width ranges from about 39 km to about 50 km measured perpendicular to the graben axis. The switch in axial trend from NNW in the south to NE in the north divides the graben into 2 segments at the Huldra-Kvitebjørn area (Fig. 1) and imparts a right-stepping trend to the graben. The structural and tectonic styles are markedly different when comparing the western and the eastern sections of the study area. The high-relief faulted blocks appear to comprise the distribution trend of the producing fields (Fig. 1).

4.1.2.1 The western half of the study area

The western half of the study area which borders the East Shetland Basin is generally of lower relief, relative to the eastern half, shallowing up to about 1600 ms TWT and is dominated by the Statfjord-Brent and Gulfaks uplifted fault-blocks (Fig. 11). The blocks trend approximately NS. The Statfjord-Brent elongate block is slightly curved in plan view. In the SW segment, a left lateral step occurs in the fault block crest (Fig. 11). The displacement is in NW-SE direction. The shift is associated with a slightly W-shaped (or roughly L-shaped) topographic low between the displaced blocks. The low's width measures about 3 km at the centre and ranges from 5-7 km at its two ends.

4.1.2.2 The eastern half of the study area

The eastern half of the study area is affected by a variety of structural features and has a more complex tectonic style relative to the western half. The BCU shallows to above 1200 ms TWT (Fig. 11). The main physiographic features trend in the NW-SE direction as the axial crestal trend on Troll shows, with the Oseberg and Oseberg Øst trending in similar direction. The master-fault system of the eastern half comprises mainly westward dipping faults except the X & Y faults which dip east and northeast, and the eastern Oseberg Øst conjugate fault dipping NE. The Oseberg fault block is back-tilted while Oseberg Øst-Veslefrikk block, projecting basinward from Brage field block, is a horst structure whose width ranges from 3 - 6 km. The Oseberg back-tilted area between the uplifted blocks is occupied by a topographic low that extends to
about 7 km in width (Figs. 1 & 11). The Brage fault and Troll faults (Figs. 11 & 15) share similar fault evolution style. They are segmented into 3 parts. The middle segment of the faults ranges in length from 16 - 24 km and trend in the NE-SW direction. The two end-segments of the faults vary from NNW-SSE trend to N-S trend (Figs. 11 & 15). The faults tip out and lose offset in the northeast segment of the study area. A broad gently-dipping ramp-like terrace defines a relay zone and straddles the area between Oseberg Øst and Lomre Terrace. Across the relay zone is an array of 'linkage' fault structures aligned progressively in NE-SW direction and range in length from about 4 - 16 km and separated at an average interval of about 1-2 km (Figs. 15, 16 & 17). They are roughly linear to the west of the Brage fault middle segment, and are linear-curvilinear to the east. On Troll, the 'linkage' faults run oblique to the previous trend in NW-SE (Figs. 15 & 16). The 'linkage' faults sometimes connect and are breached by other intra 'linkage' faults (Fig. 16). In the southeast segment on the Horda Platform, the fault pattern becomes markedly polygonal (Figs. 12, 15, 16 & 18). The fault cells measure 400 - 900 m on average and propagate consistently through the Paleogene mud-rich units above (Fig. 19). Most of the polygonal faults terminate at or near the Cretaceous Unconformity C1 surface. The polygonal faults have been rotated along with the sediment packages. They dip consistently eastward in the vicinity of main fault Y which itself dips to the east. The dip direction is switched westward as they approach the main fault A which also dips west (Fig. 19). The polygonal faults constitute a single tier fault system and their offsets vary between 20-25 ms TWT. The faults are associated with subtle wavy undulations which are visible from the stratal geometry in Figure 19. The undulations are similar to drag folds which occur in conjunction with faults.

Another important feature is the linear trough-like depression running across the eastern half of the study area in the NW-SE direction (Figs. 11 & 15). It is bounded by two oppositely dipping faults. The width on the platform is about 4.5 km but is about 2.5 km on the terrace where the relief is lower (Fig. 11). The bounding faults extend to the base of the rift blocks in the Mesozoic. The narrow structure (Paleocene linear trough) is like a mini graben-like depression and will be more analyzed in a later section. North of this depression, the NE corner shows a different structural style which will be discussed in conjunction with the Paleocene unit 2.
4.1.3 Well information

According to well data available overlying and underlying lithologies vary from claystone, calcareous claystone, marl to heterolithic sands. For example, in the Horda Platform area, the common lithologies are claystone and marl (Fig. 21; wells 31/6-8, 31/6-6 & 31/6-5; NPD 2010); while in terraces close to the basin margin and in areas of faulted uplifted blocks where erosional truncations are common, lithologies include calcareous claystone and sand (Fig 20; well 31/2-5). In some areas, the surface coincides with the base of the Shetland Group limestone and in others the Shetland Group is completely absent. When present the limestone is seen as a bright high amplitude reflection representing impedance contrast between the limestone-rich layer and the underlying mud-dominated lithology. In the Troll-Oseberg area, the high amplitude reflections at the BCU are typically associated with limestone-rich layer boundary as noticed in wells 30/3-3, 31/2-5, 31/4-4 and 30/6-14 (Fig. 20; NPD, 2010). The weak-amplitude sites on Gulfaks and Oseberg are usually devoid of strong continuous reflection. The Gulfaks area is usually disturbed by acoustic shadow and turbidity which may lead to masking of reflections. The Oseberg weak-amplitude site which is less characterized by chaotic acoustic disturbance (which may have masked reflection as in the case of Gulfaks area) is not associated with notable limestone-rich/calcareous layer as observed in well 30/6-16 (Fig. 13).

Well 34/10-17 on Gulfaks indicates Santonian sediments overlying late Jurassic unit with a hiatus adjudged not less than 60 Myr. On Oseberg back-tilted fault block, well 30/6-1 indicates hiatus in the range of 60 Myr as well. However, in well 30/6-16, exposed Toarcian sediments are overlain by Santonian unit with hiatus about 95 Myr. Well 30/6-10 indicates Campanian sediments overlying Oxfordian sediments with hiatus of about 72 Myr. Well 30/6-16 is located north of well 30-6-1 (Fig. 2) with well 30/6-10 in between them. This reveals that older sediments may be increasingly exposed northward on the Oseberg block. A long erosional hiatus of about 80 Myr is also evident in well 31/2-5 in Troll area where a thin layer of Cretaceous deposit overlies Jurassic sediments (Fig 20).

4.1.4 Early Cretaceous surface C1i

The Early Cretaceous surface C1i (Fig. 8; Table 3) is similar in structural style to the surface C1 and does not require detailed analysis as it is not within the main scope of this study. However, it
is noteworthy as shown in Figure 22 that C1i is mostly absent on the high where the underlying Jurassic deposits sub-crop. In the back-basin Early Cretaceous C1i shows bi-directional downlap on the BCU. There is a curved elongate trough about 3km in width which divides the NW-SE projection on the terrace (Figs. 11 & 23). The time thickness map (Fig. 23) shows the depocentres are located in the structural lows with minimal deposition on the crest of fault-blocks. The relay ramp also serves as depocentre with sedimentation trending the northerly-located elongate trough into the relay zone area. Two similar sediment routes are also present on the Oseberg Øst block (Fig. 23), these routes coincides with the locations where the intra linkage faults on Oseberg Øst Horst are observed in Figure 15. The area to the east of Troll high is overlain by sediments which thicken towards the Norwegian mainland. Sediment thickness range is about 0 - 300 ms TWT. In the Statfjord-Brent area, local depocentres are present between the uplifted fault blocks.

4.2 LATE CRETACEOUS UNIT 1 (~ 75-66 Ma) C2-C3

4.2.1 General description

Unit 1 is Upper/Late Cretaceous unit bounded below by Late Cretaceous surface C2. The upper limit is base Tertiary surface C3 (Fig. 8; Table 3). The unit is attributed to the Jorsalfare formation according to Isaksen & Tonstad (1989). The base Tertiary C3 is a strong negative (hard kick) amplitude reflection whose log behavior reflects upward increase in gamma-ray intensity and upward decrease in velocity. Surface C3 is discussed in the following section. This unit can best be regarded as being limited in extent to the basin slope and the terraces. It is present in Shetland and the basinal area is thin or absent on the crest of Gulfaks block. It is also present in the NE segment. On the adjacent eastern high and Troll areas towards the SE the unit is absent. Surface C2 is encountered at about 1380ms TWT where it wedges out against the platform margin and Gulfaks block and increases in depth to about 2600 ms TWT (Fig. 24). The basin axis generally plunges southward. Stratal geometry of the surface as shown in the time-structure map displays aforementioned Paleocene linear trough which measures about 4.5 - 5.5 km in width. A subtle linear structure, almost similar to the Paleocene trough, is present in the
northwest segment trending NE-SW. Four structural anticlinal highs marked A, B, C and D are clearly observed trending roughly N-S to NNW-SSE (Fig. 24). The inter-axial distance varies from 18 km for A-B, 32 km for B-C to 15 km for C-D making basin-centered interval B-C the broadest. The highs follow the trend of the Jurassic rift blocks. The anticlinal trend propagates into the overlying units and is not limited to this unit. The basinal area between B and C is observed to have a plateau-like relief which evolves progressively into a structural low at the southern limit of the study area (Figs. 24 & 25). The unit shows minor undulating relief especially in the southern basinal area and some chaotic acoustic signature (Fig. 25). The seismic reflection characteristic of this unit shows marked difference at the basin compared to the basin margin. The reflection of the bounding surfaces weakens and the package becomes chaotic (Fig. 26) at the basin. Close to the margins, the seismic facies are fairly continuous reflections which at times become near-transparent seismically. The TWT thickness map shows thickening in the basin and maximum thickness c. 300 ms TWT. The deposition thins towards the eastern slopes and margins of the Viking Graben area with no significant influence on distribution by the rift topography (Fig. 27). The significant thickening trend in the basin seems to follow the NW-SE direction. The chaotic basinal area, though prone to less degree of picking confidence, is characterized by irregular 'moth-eaten' isolated thicks of various sizes. Notable ones have short axis length of 3-6 km and long axis length of 5-11 km. The thicks may have been associated with injected sediments in the chaotic facies.

4.2.2 Well information

Well data shows the Upper Cretaceous unit 1 was deposited in the Maastrichtian times (e.g. well 29/6-1; NPD 2010). Most well data show that the unit is dominated by calcareous claystones of Late Cretaceous age with distinct minor interbeds of white to buff chalky limestone which decreases with depth as noted in well 30/5-1. Well 30/6-22 indicates the local presence of marl as it is the only available well with this lithological characteristic. The basinal chaotic area is likely shalier according to wells 30/5-1 and 30/4-1 (NPD 2010) at the southern part of the study area. Close to the margins, wells indicate the unit becomes slightly silty. Well 34/10-19, just outside the study area, indicates lower Jurassic overlain by Shetland deposit with hiatus that may be up to 100 Myr (NPD 2010). In the biostratigraphic report of well 29/6-1, the unit is known to have abundant calcareous and planktonic foraminifera (NPD 2010)
4.3 SURFACE C3 - (~ Danian) - BASE TERTIARY

4.3.1 General description

The Base Tertiary C3 surface comprises consistent, strong, hard-kick amplitude marks the transition in upward velocity drop from underlying Late Maastrichtian C1 unit to the overlying Paleocene C2 unit. The Base Tertiary time-structure map shows the graben axis plunging southward on a regional scale (Fig. 28). It is observed on Troll an anticlinal structure exists similar to others present to the west with average separating interval of about 37 km from the D structure. It trends in same direction as others to impart a NNW-SSE trending structuration to the rotated fault blocks. Here on the mapped surface, the Paleocene trough outline is clearly expressed running through the stretch of the eastern half. Its width ranges from about 5 - 6km and with an extensional NNE-SSW maximum stress field (Fig. 28). A significant difference between C2 and C3 is the subsidence of the area over the relay zone (Fig. 11), thus expanding the basin margin towards the east on the Norwegian side. This creates deepening at the foot of the uplifted blocks. Local subsidence also occurred close to the Gulfaks and in the south (Fig. 28). The southwest segment of the study area has also increased in depth and experienced more subsidence. The highlighted southward basinal area, which shows a deepening trend as well, coincides with the area adjacent to the underlying Oseberg block. The deepest part of this surface is about 2400 ms TWT and shallows up to about 980 ms TWT with depth differential a little more than 1400 ms TWT. The surface truncates the Cretaceous unconformity (adjacent to the area where basin subsidence was previously identified) over an area extending about 37 km N-S on Troll (Figs. 12 & 22).

4.3.2 Slope depositional elements and erosion

In reference to Figures 29, 30, 31 and 32, the RMS amplitude extraction and seismic sections bring into focus the existence of an Early Paleocene fan-like system on the uplift flank. The depositional elements comprise high amplitude bright anomaly (indicating higher acoustic impedance contrast relative to the encasing facies) concordant with the Base tertiary surface. The outline of the slope features taper towards east and fan out westward. The fan system (as it may
be termed based on observed geometry) comprises 3 well defined fan-like lobes tagged A, B and C. Fan A has a maximum spread-out distance of about 15 km. Fan B measures about 7.5 km while Fan C is averagely 7 km. Their axial length ranges from 8-9 km. The localities marked X and Y show similar fan system signature. On the seismic section, they thicken towards the slope and their reflection character slightly discontinuous and segmented. The locality X seems to form part of the slope fan system and the locality Y appears to be the extension of X. The A, B & C fans are more clearly defined and less ambiguous. The bright anomaly near the southern limit cannot be seen to represent similar fan-like deposit signature on seismic section. The Paleocene linear trough extends farther beyond the fan deposit near the northern limit of Fan A and possibly had limited influence on the distribution of the fan deposits (Figs. 29 & 30). Report for well 31/2-19S penetrating fan C comments on 131m thick sand (with poor hydrocarbon shows) encountered near the base of Lista Formation (Figs. 29, 30 & 31; NPD 2010). Well data (35/11-11 & 35/11-7) at localities X & Y reveal the existence of two sand units in the Paleocene unit (NPD 2010). The top sand units are 55 m and 40 m thick while the basal sands are 89 m and 35 m thick respectively.

Erosional features are common occurrence on this surface as can be seen, for example, in the Uer Terrace area (Fig. 33). Cross-line width of incisions ranges from 700 - 1000 m with fairly smooth U-shaped troughs and a NE-SW orientation. The inset view distinguishes it from pock mark morphology which represents a crater-like feature on (paleo) sea-bed believed to be formed by rapid expulsion of gas and liquid from the subsurface.

4.3.3 Other features

The Base Tertiary is similar in reflection amplitude to Late Cretaceous surface (Figs. 26 & 34). High amplitude is noticeable in the southeastern segment close to Brage and Oseberg (Fig. 34). Well 31/4-6 in the area indicates that the presence of limestone coincides with the high amplitude reflection. The chaotic signature persisted in the basinal part of the study area noted earlier to have undergone deformation and inversion. A low-amplitude swath is present in the region near the slope fan system. There is also a square imprint in the NW segment in Gulfaks area. Similar features with straight-sided geometry can be observed in the variance attribute map (Fig. 35). These features are most likely acquisition artefacts as noted earlier in Figure 5. The Horda Platform area is dominated by polygonal fault deformation in a similar fashion and trend
to that seen on surface C1 (Fig. 36). In addition, it is clear that an 8 km fault trace is developing parallel to the trough-bounding fault (Fig. 35). The northeastern segment shows incoherent signature of no regular pattern in the area known in the previous section to be underlain by the Late Cretaceous calcareous claystone (Figs. 34 & 35). The area coincides with the location of observed erosional features (Fig. 33).

4.4 SURFACE C4 (Top Paleocene ~55 Ma)

This is the top bounding limit of Paleocene unit 2 and is truncated towards Norway by base Pleistocene Unconformity (Fig. 8). Overlying sediment wedges and Frigg unit downlap onto this surface. The Top Paleocene (Fig. 37) is about 2150 ms TWT deep and shallows to about 640 ms TWT, with a TWT depth differential of about 1510 ms TWT. Its TWT depth differential is more than that of Late Cretaceous surface C2 by over 300 ms TWT mainly as a result of deposition on the basin margins and uplifted highs. The basinal area has extended further with its axis trending NE-SW, and forms a broad elongate basin. The central part of the survey’s northern limit has undergone increased deepening. Sharp-tip fold/anticline also occurs where the underlying Oseberg rift-flank is located. A prominent additional feature is the Dornoch Delta (Ahmadi et al. 2003), with lobate outline, in the west whose maximum extent is about 7.5 km x 44 km to the slope break (Fig. 37). The Paleocene linear trough, though present, has become less prominent, while the inversion structure trend is still strongly expressed.

The NE segment in the eastern half continues to present a different character relative to the southeast. The contour relief is wavier than in the south as the surface is deformed by low-relief gentle doming. The variance attribute extraction is replete with semi-circular to circular cells with subtle angular polygonal fault traces which are less prominent (Fig 38). Typical cell diameter measures 2 - 6 km. The south, on the other hand, is polygonally faulted (Fig. 39). The basinal area west of Troll is also deformed by polygonal faults with average cell diameter of 1 km (fig. 40). Well data (e.g. 35/11-7) shows that the NE segment contains significant amount of sandy clastics in the mud-dominated facies while the south is mainly argillaceous. The switch in facies occurs in the vicinity of the northwesterly trending linear trough.
4.5 PALEOCENE UNIT 2 (~ 65-55 Ma) C3 - C4

4.5.1 General description

The unit comprises Vale, Lista, Sele and the tuffaceous Balder (Isaksen & Tonstad, 1989; Jordt et al. 1995, 2000). The earliest Eocene-dated Balder is included here for discussion purpose. The sandy sub-units include Heimdal and Hermod sands (Fig. 10). Clastic sediments occur at various locations within the mud-dominated facies and are sometimes termed intra-Lista sands. Paleocene unit 2 is bounded above by Top Paleocene surface C4 and below by Base Tertiary surface C3 (Fig. 8). It is markedly truncated towards Norway by the Base Pleistocene surface C12. The unit overlies the Late Maastrichtian calcareous claystone in the Viking Graben and East Shetland margin. Towards the Norwegian margin it unconformably overlies Jurassic-Early Cretaceous sediments where the rift highs are characterized by erosional truncations. The unit is characterized by thick prograding wedges close to the basin margin. The wedges downlap the C3 surface at the margins but the unit is fairly conformable at the graben center (Figs. 8, 19, 25, 33 & 41). The seismic character of this unit is discontinuous to chaotic at the graben center where the seismic reflection pattern shows highly disturbed signature. The basinal chaotic facies make mapping of the surfaces centered above the graben slightly difficult due to poor seismic resolution. The chaotic character also extends to the northwestern segment but begins to assume some regularity in bedding in the southwest.

4.5.1.1 The western margin

The clinoformal packages of a broad semi-circular lobate complex dominate midway between the northwestern and southwestern segments with N-S extent of about 54 km. The lobate complex is attributed to mainly Dornoch Delta and other precursor deltas (Ahmadi et al. 2003). The eastward prograding lobate complex broadly divides into two parts; the low frequency low-angle dipping wedges, and the higher frequency relatively high-angle clinoforms (Fig. 41). They are separated by a downlap surface on which the overlying high-angle clinoforms downlap. The upper deltaic deposits have an average thickness of about 300 - 320 ms TWT. The overall Dornoch Delta complex of the upper deltaic deposits is clearly progradational with a relatively minor but still significant aggradational component. Clinoforms A and D show some erosional
truncations. From the upper deltaic clinoform geometry the paleo water depth estimates for clinoforms A, B, C, D & E measured from the clinoform breakpoint to the downlap are 145, 200, 150, 430 & 500 ms TWT respectively. The paleo-water depth maximum of 500 ms TWT, at velocity estimate of 2.2 km/s for Paleocene deposit (Jordt et al. 2000), is about 550 m.

4.5.1.2 The eastern margin

The thickness of the Paleocene unit also becomes more uniform and aggradational close to its top especially towards Horda Platform (Figs. 19 & 33) in the eastern half. In the northeastern part of the study area, the unit has low to moderate amplitude with reflection intensity and frequency increasing towards the upper bounding surface (Fig. 33). This area is strongly characterized by undulating relief close to the top of the packages with dispersed discordant to mounded high-amplitude packages towards the base of the unit (Fig. 33), while the Horda Platform area is pervasively deformed by polygonal faulting with intermittent high amplitude reflections within the unit (Fig. 19).

4.5.2 Unit 2 sediment mound complex

4.5.2.1 Description and morphology

The contrast in deformation style, as observed in previous sections, is noticeable in the NE segment of the study area when compared with the Troll and Horda Platform areas (Fig. 42). The deformation cells on the Top Paleocene surface are larger than the polygonal fault cells in the south. This contrast is also imaged in a unique tectonic style characteristic of the underlying BCU surface in the NE corner (Figs. 43 & 44). The features described below are expressed in alteration of the primary stratification of the Paleocene unit.

Close observation reveals a gentle relief mounding at the Top Paleocene surface in direct spatial correspondence with internal moderate-high amplitude and regular to semi-chaotic facies beneath (see the inset figure of the mounded area in Fig. 42). Average lateral extent of the mounded brights beneath is 2.5 km. This is in close agreement with the lateral extent of the mound culmination of about 3 km above. The mounding relief is clearly more accentuated than the slightly undulating basal Late Cretaceous and Base Tertiary surfaces. The vertical amplitude of the mounding relief is coherent with both the location and thickness of the semi-chaotic
reflection beneath. Associated with the mounding relief are several faults on the crests which dip in both directions. These mounding expressions are widespread in the NE segment (Figs. 33, 45, 46, 47 & 48) and appear to represent local jack-up in relief of the Top Paleocene surface. The reflection brights beneath jack-up relief may not always have a semi-chaotic mound forms. They can be expressed as lateral amplitude brights with flat, saucer and convex geometries (Figs. 45 & 46). These sill-like amplitude reflections have a size range typically not less than 1 km and may be more than 3 km in lateral extent. For example, the twin-segment amplitude bright (showing hard kick) in Fig. 45 is 3.2 km in extent and is directly related to the 3.5 km extent of the jack-up relief above. Discordant enigmatic amplitude reflections are also present in the Paleocene unit. They are usually located in the basal part of the host Paleocene unit (Figs. 45 & 46) and sometimes occur in association with amplitude reflection mounds (Figs. 47 & 48). They have characteristic V-shape with high-angle (~ 40-70°) twin limbs and pointed base. They can also exist as mono-limb discordant reflections and sometimes incorporate a basal segment between the limbs (Figs. 45 & 47).

The morphology of a typical mound in Figure 48 shows a chaotic internal facies mix. Its culmination is rather fractured and segmented. The internally-chaotic mound is conical and steep-sided; its roof is more than 2.2 km in width and tapers towards the concave base. On the other hand, the stratal boundaries directly below base Tertiary C3 are notably convex. The mound expressions in Figure 47 have a convex roof (~ 1.5 km lateral extent) while the base is relatively flat. A significant observation in Figure 48 is the thickness variation of the stratal unit above the conical mound. Above the roof, thickness is about 55 ms TWT; on the western flank it is about 75 ms TWT; and on the eastern flank it averages 80 ms TWT with reference to the interval indicated in Figure 48.

4.5.2.2 Northeast BCU morphology and acoustic columns

The structural template provided by the underlying BCU in the NE segment show faults on the terrace with characteristic branching or braided network (Figs. 43 & 44) and connection at several nodes. The faults generally trend NE and are associated with the rift topography (Figs. 45 & 46). The interspersed high-amplitude enigmatic and discordant reflections are usually located above the faults. There are also various high-angle dipping or vertical columnar expressions of acoustically disturbed zones in the area. They are expressed as vertical discontinuity zones. They
are also associated with the enigmatic reflection mounds and brights and usually connected to their base (Figs. 45 & 48). These conduit-like columns usually emanates from the Mesozoic unit below. The acoustic column identified in Figure 45 is over 1000 ms TWT with narrow width of about 500 m. Stratal boundaries disturbed by the acoustic columns are usually marked with upward convex ridge-like push (Figs. 45, 46 & 48). These high-angle or near-vertical columns, and sometimes the discordant amplitude anomalies (Fig. 48), connect to mounds and other interspersed reflection brights and appear related to their distribution.

The faulted stratal units of the underlying Mesozoic deposit are observed to demonstrate incoherent folding and thickness variation especially eastward (Figs. 45 & 46). This is clearly imaged in Figure 33 where a sediment wedge was previously identified.

4.5.2.3 Well information

Well 35/11-3S close to the mound in Figure 47 correlates mounded bright reflection to a 92 m-thick sand in the penetrated part. The sands are coarse-very coarse, sub-angular to sub-round, poorly to moderately sorted and locally cemented in well 35/11-3S. It should be noted that sandy units in the eastern half are of common occurrence only in the NE segment for the Paleocene unit. Sand distribution in the northeast segment of the Paleocene unit occurs in two main units according to well data. Of the available 5 wells (Fig 43), existence of 2 separate sand units is only peculiar to wells 35/11-7 and 35/11-11(Table 4; NPD 2010) which are within the regional spread of the Early Paleocene sub-marine fan system. If the top sand unit thickness is correlated with the Paleocene unit gross thickness, the net sand thickness tends to increase with the gross thickness. The least thickness is found in the westernmost well 35/10-3.

4.5.3 Thickness distribution

The time thickness map (Fig 49) shows TWT thickness distribution for the Paleocene unit. Minimum sediment thickness is about 90 ms TWT in the basin and the maximum is estimated at over 800 ms TWT just to the SW of Sognefjorden on the Norwegian mainland. Three main depocentres can be identified as active during Paleocene (Fig. 49). The NE depocentre thickens towards Norway while it splits into the SE and SW as it progresses further south. The Troll area
shows marked thinning in a near V-shaped thickness low in plan-view extending for as long as 48 km and about 10-22 km in width (Fig. 49). The northern limit of the thickness low nearly coincides with the Paleocene linear trough. The other reactivated extensional faults, notably Troll faults A, B and Brage faults (Fig. 24), define its E-W extent. It has been observed from available well data that Unit 2 is particularly thick and sandy on the terraces while it is relatively thinner and argillaceous on the platform (Figs. 37 & 42) and the switch in facies occurs around the 2-way dip closure on Troll. This also coincides with the location of Paleocene linear trough.

The Dornoch delta is lobate and has sharp margin at the slope break (Fig. 49). Its thickening trend and sediment build-up is higher southward and reduces northward thus presenting a delta top plunging northward. The basinward sediment spread pattern from the delta is slightly more indented in the south close to where deposition thins over a near circular area (Fig. 49).

4.5.4 General well information

Based on the available well data, approximate clay distribution colour scheme was derived as seen in Figure 50. Well data reveals that lithology was dominated by greenish - grey claystones and some occurrence of calcareous claystones. The blue clay presence is only indicated locally to avoid undue extrapolation due to insufficient well control. Biostratigraphy report (NPD 2010) of well 29/6-1 in the SW segment shows that the early Paleocene was dominated by abundant, diverse calcareous benthonic and planktonic foraminifera which were succeeded by almost exclusively agglutinating foraminifera. The well interval reveals the existence of land-derived pollens. Well 30/6-1 in the southern area contains lignite. The lithology in this area varies from green to grey claystone with more sandy clastic interbeds landward (wells 30/4-1, 29/6-1 etc) which become fissile and silty towards the basinal Viking Graben (wells 30/5-1 & 30/6-16). Wells 29/3-1 and 29/6-1 proximal to Dornoch Delta contain greenish (olive) claystones. In the Troll and platform areas, wells 31/2-5, 31/2-6, 31/2-9, 31/3-1 and 31/6-6 (NPD 2010) indicate neritic-bathyal fossil assemblage, and also reworked fossils near the base. Wells 31/3-1 and 31/6-6 also recorded high input of dinoflagellate cysts with coaly particles, amorphous materials, woody particles and spores in the upper part of the Paleocene unit.
4.5.5 The Paleocene Linear Trough

4.5.5.1 Description

The Paleocene trough defines a transverse linear depression trace which has been consistently apparent in the surfaces analyzed so far (Figs. 11, 22, 28 & 37). It is in trend with the northeastern limit of the Troll gas field. Variance attribute extraction of the Top Paleocene shows the sub-linear trough bounding faults to define a width within 5-7 km range (Fig. 51). The bounding fault traces are semi linear. The trough is mainly defined in the NE segment and trends NW-SE approximately orthogonal to the older rift structure. The trough bounding faults extend into the Mesozoic and seem to terminate around the acoustic basement (Figs. 52 & 53). The faulted downthrown block has strata boundaries within the Paleocene unit which are observed to show a sag in a bow-shaped depression. Major thickening is observed near the top of the Paleocene unit and the fault throw is usually between 40-50 ms TWT. A third developing fault is associated with the trough evolution. The third fault c is usually the boundary of an expanded trough trace in the top Eocene/Oligocene boundary surface (Fig. 56). The faults bounding the trough are not well developed but are segmented on the top Eocene/Oligocene surface. The linear trough is defined in the Paleocene unit by faults a & b. The fault planes are mostly planar and dip at high angle.

The zoom-in maps (Figs. 54 & 55) provide a close-up view of the linear trough and the depression trace extends beyond the study area, this has been confirmed in a larger dataset from an ongoing PhD project. The thickening trend of the Paleocene unit in the location of the trough is remarkably visible and in trend with the linear depression. The location of the depression trace has been plotted on the residual bouguer and magnetic anomaly maps. The depression does not match with a unique diagnostic feature on the bouguer map probably due to the small size of the trough and may not have produce any anomaly on a regional scale. However, with the magnetic anomaly map, there appears to be a structural trend in spatial correspondence with the location of the Paleocene linear trough.
4.6 EOCENE UNIT 3 & SURFACE C5/C6 (Top Eocene-Oligocene boundary ~ 34 Ma)

4.6.1 General description - Eocene/Oligocene Boundary

The top Eocene/Oligocene boundary is a composite surface which forms the base of the lower Oligocene wedge and the lower Oligocene unit (Figs. 8, 9 & 56). It is represented as the Oligocene Unconformity westward but is marked as top Eocene eastward and then truncated farther eastward by the Pleistocene Unconformity. It is truncated by the intra lower Oligocene C6i surface on Troll (Figs. 8 & 57) where doming and uplifted area appears to have been truncated by erosional hiatus. The surface reflection characteristic is hard to estimate from the surface attribute extractions due to discontinuity imprints of polygonal faults and the chaotic signature of the basinal area due to poor seismic resolution. The lowest point on the surface is about 1800 ms TWT and the maximum relief is about 600 ms TWT with a depth differential of 1200 ms TWT. Most structural elements on older surfaces are less obvious to make out on this surface (Fig 56).

4.6.2 Description - Eocene Unit 3 ~55-34 Ma

The Eocene unit is bounded above by the Eocene/Oligocene boundary and below by the Top Paleocene surface (Fig. 8). The unit is dominated by mudstone facies, while the sandy sub-units comprise the deepwater sands of Grid and Frigg Formations (Fig. 10). It is characterized by low-moderately high reflection amplitude. The basal part eastward is marked by fairly continuous lateral and moderately high amplitude reflection which downlap basinward onto the Top Paleocene surface (Figs. 19, 20 & 57). Close to the southern border limit in the SW segment is a high amplitude mounded reflector (C4i - Top Frigg) which 'tails' westward (Fig. 8). The long-axis length of the mounded part is about 19 km while the short-axis length averages 9 km. The maximum thickness of the lobe is 250 ms TWT and its thickness variation closely simulates digitate bird-foot geometry along the trend axis of the sinuous distribution (Fig. 58). The bulk of the Eocene unit is dominated by chaotic-semi transparent facies. It is pervasively deformed by polygonal faults in the eastern half (Fig. 57) while the basinal part overlying the Viking Graben is mostly characterized by chaotic disturbance.
4.6.3 Thickness distribution and depositional trend

Eocene unit 3 has a maximum thickness of 670 ms TWT (Fig. 59). Relative to Paleocene unit there is a southward shift in depocentre which seems constrained to the area between the Dornoch delta and the Frigg lobe. The thickest part of the unit is deposited in this region (Depocentre A) with thickening trend towards SW. Depocentre B is fairly elongate in the NW-SE direction and appears to show some distributary connection with Depocentre A but the definition is poor due to the chaotic basinal facies. The sediment distribution in depocentre C departs slightly from the elongate style and widens eastward. Depocentre D trends predominantly in the NE-SW and branches out slightly SE at the eastern limit of the study area (Fig. 59). Depocentre B & C are subtly separated by thickening lows coinciding with the location of Oseberg block and Huldra field. A northward widening low in Troll area also separates depocentre C & D; which coincides with the NE corner where large fault offsets are absent (Fig. 9). The thickening variation in the eastern half is closely in trend with location of faults previously discussed, whose offsets could be as high as 100 ms TWT. A composite section in the SW segment reveals that Eocene unit is compensationally thicker in the sites of topographic lows above the Paleocene unit while the unit is thinner over the Dornoch delta and Frigg deposit lobes (Fig. 60).

4.6.4 Well information

The Eocene unit predominantly comprises non-calcareous greenish-olive grey claystones according to well data (NPD 2010). The basal unit in Troll area is marked by limestone streaks and cemented clay (wells 31/2-2, 31/5-3, 31/2-9), and basinward the basal unit is dominated by red clays (wells 30/3-1, 30/3-3). The Frigg lobe is penetrated by well 29/6-1 with well sorted medium-coarse grained sands. Fine-coarse grained sand streaks and interbeds are also observed towards the western margin (wells 29/3-1, 30/2-2, 30/3-1, 30/4-1, & 34/10-23).

Biostratigraphy report, for well 31/6-6 on Horda Platform (Fig. 6), identifies presence of abundant radiolarians with some agglutinating benthic foraminifera. Westward on Troll (well 31/2-5) arenaceous/calcareous foraminiferal assemblages dominate with some fish remains. Towards East Shetland Basin margin, agglutinating foraminiferal assemblages dominate with occasional floods of large flattened radiolaria in well 29/6-1.
4.6.5 Distribution of sediment injection

Sediment injection in the Eocene has been exhaustively dealt with in terms of morphology, occurrence and possible lithology in this study area and in the North Sea as a whole (Cartwright 2010; Cartwright et al. 2008; Huuse & Mickelson 2004; Huuse et al. 2004; Huuse 2008; Huuse et al. 2010; Jonk et al. 2005; Rodrigues et al. 2009; Shoulders et al. 2007; Szarawarska 2010). The focus here is to highlight the distribution relative to the basin structural elements (Fig. 61). Similar discordant and concordant amplitude events with semi-chaotic acoustic columns, as observed in this unit (Figs. 62 & 63), have been described while considering the Paleocene unit. It is observed that the distribution of these elements is prevalent along the Oseberg-Huldra-Gulfaks axis in the NW-SE direction for the Eocene unit. The distribution in the Uer terrace area occurs in the Paleocene unit in close association with the uplifted and eroded footwall in the NE segment. The basinal area where the distribution is centered is observed to be in trend with the central inversion anticline structure, which coincides with the Oseberg-Huldra uplift flank.

4.7 LOWER OLIGOCENE WEDGE UNIT 4 (~ 34-32 Ma)

4.7.1 Description

The Lower Oligocene Wedge is bounded by the Oligocene Unconformity (C6 - a 'hard' reflection marker) at the top and the Top Eocene surface (C5) at the base. In between these two major surfaces is intra-Oligocene wedge surface (C6i) which divided the unit into upper and lower sub-units. This unit wedges out basinward and is truncated by the Pleistocene Unconformity at the eastern limit (Figs. 8, 9 & 64). The lower sub-unit is characterized by subtle polygonal fault traces which are not easily defined due to its semi-transparent to semi-chaotic seismic facies. The upper unit is dominated by semi-transparent to semi-continuous lateral reflections which show subtle polygonal faulting as it wedges out basinward (Figs. 65 & 66). The intra wedge surface (C6i) is distinct towards the northern limit of the study area. It truncates the Top Eocene at the zone of doming and uplift towards the Troll area (Fig. 66). The thickness maximum for this unit is about 370 ms TWT and the thickening trend is similar to that of Paleocene unit in Troll area (Figs. 49 & 64) with the depocentre close to Sognefjorden. Similar U-shaped thickness low
trending N-S observed for the Paleocene unit is present on Troll. The U-shaped thickness low for the lower sub-unit has a N-S extent of about 45 km while the upper sub-unit is about 30 km. The depocentre for the upper sub-unit is in trend with the thickness low while that of the lower sub-unit is distributed around the flanks. The thickness low coincides with the area where the intra Oligocene wedge surface truncates the Top Eocene surface (Fig. 67).

Well information (wells 31/2-2, 31/2-6 & 31/3-1; NPD 2010) reveals that the unit is dominated by brownish claystone which is in contrast to the greenish-grey claystone in the underlying Eocene unit. The upper part of the unit is dominated by silty claystone to sandy siltstone, and there is a conglomeratic zone about 20 m thick in well 31/2-2. The unit contains radiolaria, diatoms, and occasionally, shell fragments.

4.7.2 Eocene-Oligocene domal uplift

Seismic sections across the thickness low reflect doming, which suggests uplift, of the stratal units. A qualitative assessment of the uplift trend can be made as shown in Fig. 68. The mid-Miocene surface (C9) and the Top Eocene (C5) in addition to intra wedge (C6i) surface are relatively level when compared to others, and based on the thickness variation appear to be truncation surfaces. (The intra Oligocene trace strongly shows that mid-Miocene has truncated the Oligocene unit above the domed area). They divide the stratal units into two megacycles of doming episodes with the first terminating at Early Oligocene after which doming resumed and stopped at the mid-Miocene surface. Average vertical amplitude for megacycle 1 is 120 ms TWT, and for megacycle 2 it is 90 ms TWT.

4.7.3 Oligocene Unconformity (C6)

The Oligocene Unconformity (Faleide et al. 2002; Fyfe et al. 2003; Jordt et al. 1995, 2000; Rundberg 1989; Rundberg & Eidvin 2005) surface is very much similar to the Eocene/Oligocene surface (Figs. 55 & 69). However, the anticline structures and graben trace are no longer boldly expressed. The elongate chaotic basinal area is broad with average width of 55 km. The basinward dipping surface truncates part of the underlying Oligocene wedge unit and also the Eocene unit (Fig. 8). The overlying Oligocene stratal units onlap onto the Oligocene Unconformity surface. The basin shows a moderate westward deepening progression in the SW segment with about 30 km NW-SE extent. The other intra-basinal low relief is reflective of dual
elongate catchments connected by a narrow strip. The East Shetland Basin margin has a lobate to semi-circular geometry in topographic relief. Depth range TWT structure map is between 600 - 1700 ms TWT (Fig. 69). A segment of fault - A trace is still visible in the SE corner of the study area. Westward over the Paleocene trough and close to the East Shetland Basin margin the picking confidence is affected by poor resolution due to the chaotic nature of the seismic facies.

4.8 Oligocene Unit 5 (~ 32-24 Ma) and Lower Miocene Unit 6 (~24-15 Ma)

The Oligocene unit (Figs. 8 & 9; Table 3) is bounded at the top by the near-base Miocene surface (C8) and at the base by the Oligocene Unconformity (C6). The top bounding surface was thus termed because it could not be accurately tied to well but was determined based on structural style, seismic facies change and stratal geometry. The Oligocene unit 5 is divided into low-velocity upper (5b) and high-velocity lower (5a) Oligocene units by the non-stratigraphic, stratal cross-cutting Opal A/CT (C7) diagenetic reaction front (Jordt et al. 1995, 2000; Thyberg et al. 2000; Rundberg 1989; Rundberg & Eidvin 2005). It is dominated in the eastern half of the study area by siliceous mudstones facies, which pass westward into the sandy facies of the unnamed sandy unit and Skade Formation (Fig. 10). The Oligocene (-Miocene) unit in the NNS is well researched in literature (Faleide et al. 2002; Galloway 2002; Gregersen & Johannessen 2007; Jordt et al. 1995, 2000; Rundberg 1989; Rundberg & Eidvin 2005; Thyberg et al. 2000), reference can be made to these sources for detailed analysis. The focus here is to highlight key tectono-stratigraphic elements that will build on current understanding in order to put in the proper context the debated depositional settings.

4.8.1 Near-base Miocene Surface (C8)

The near-base Miocene surface is strongly deformed by folding, polygonal faults and sediment jack-up/mound structures (Figs. 8, 57 & 70). Its TWT depth range is 610 - 1260 ms TWT with a depth differential of 650 ms TWT. The surface in some areas is truncated by the mid-Miocene Unconformity (C9), notably, at the eastern region near the Base Pleistocene Unconformity and at the graben-centered positive relief (Fig. 8). The physiographic relief defined by the surface is characterized by basinward-dipping flanks at the eastern (where is slightly linear in plan-view)
and western (where it has a bi-lobate plan-view outline) margins (Fig. 70). The basin relief is defined by the twin regions of elongate NW-SE to N-S trending topographic high and low. The topographic high at the western part of the basin has an anticlinal geometry in cross section and will be more analyzed later. The topographic low is at the eastern part of the basin. It widens and plunges northward with an E-W extent about 25 - 45 km (Fig. 70). The topographic low is in the region noted for pervasive polygonal faulting and Opal A/CT diagenetic conversion. Situated between this low and the eastern gently dipping flank in the south is an enigmatic elevated/jack-up region with curly outline. The enigmatic structure, including Opal A/CT surface (C8) will be discussed when considering the post-depositional processes.

4.8.2 Oligocene unit 5 -description

4.8.2.1 Facies description

The lower unit 5a is characterized by low-moderate amplitude with semi-transparent seismic facies at the eastern margin of the graben area where it wedges out towards Norway (Fig. 67). The facies become chaotic in the basin and are defined by semi-transparent to discontinuous reflections at the East Shetland Basin margin (Fig. 60). The lower unit is defined based on seismic facies character and the location of the non-stratigraphic Opal A/CT boundary. The upper unit 5b is characterized by bedded continuous facies at the eastern limit of the study area, with marked onlap onto the Oligocene Unconformity. The lateral reflections become discontinuous with several polygonal fault offsets in the topographic low. The facies are generally chaotic at the region of graben-centered uplift, and begin to assume some regularity towards the western limit.

4.8.2.2 Well information and thickness trend

Well data shows the lower unit 5b is dominated by Opal CT cemented mudstones (rich in biogenic silica) which pass into sand-dominated facies westward. The upper unit 5b shows occurrence of sands and siltstones interbeds at the eastern area (wells 31/2-2, 31/2-6 & 31/6-8; NPD 2010) but is largely dominated in the east and topographic low area by brownish micaceous siliceous mudstones with occasional calcareous stringers (e.g. wells 30/3-3 & 31/2-9; NPD 2010). In the western area common lithology is defined by sand/clay interbeds (e.g. as in well 29/3-1; NPD 2010). TWT thickness shows a thickness maximum of 740 ms TWT (Fig. 71).
Thickness trends show basinward finger-like progressions from the western margin to elongate lobe-like thicks in the chaotic basinal area. The definition of this trend is not high due to seismic disturbance in the basinal area. A composite thickness map between the near-base Miocene and Top Paleocene (which are high-confidence picks) shows a clearer trend (Fig. 72). The composite thickness provides a better resolution over the chaotic facies and reduces the possibility of over-interpretation. The thickening trend resembles a giant splay system with an eastward fanning-out geometry. This composite trend relates with integrated deposition of turbiditic lower Oligocene (unnamed) sands and Skade Formation sands (Fig. 10) alluded to in literature (Fyfe et al. 2003; Rundberg & Eidvin 2005) during the period of overall climatic deterioration and eustatic sea level fall (Anell et al. 2010). Notable on the map is proximal thickening SW segment of the study area in two separate 'thicks'. The southernmost thick coincides with the Eocene depocentre in Fig. 59. The second proximal 'thick' coincides with the location of thickening in Figure 71 and has a NW-SE extent of about 28 km. Intermediate between the proximal and distal deposition is a NW-SE region (with an average NE-SW extent of about 20 km) of NE trending narrow progressions which are separated by circular, oval, bean-like to narrow zones of thickness low. The distal deposition is characterized by lobe-like zones of thickening, and follows the anticline trend of swath C discussed in Figure 74. There is also reduced thickening over the location of Gulfaks and Dornoch Delta reflected in the outline geometry.

### 4.8.3 Mid-Miocene Unconformity (C9)

The mid-Miocene unconformity has a regional extent which is truncated in the east by the Base Pleistocene Unconformity. The surface, in similar fashion to near-base Miocene and in same locations, is deformed by enigmatic jack-up structures (Fig. 73). The western half of the study area however, as the contour relief shows, is marked by broad NE-SW spread of basinward-stepping channel-like progressions which appear to emanate from a semi-circular front. Close to the basinward terminations of these narrow progressions are a string of 'roughly-circular' depressions (with average diameter of ~ 10 km) which grade into a broadening topographic at the northern limit. The channel-like progressions connect to the broad circular relief in the Oseberg-Brage area. Depth range of mid-Miocene Unconformity is 470 - 1100 ms TWT with a depth differential of about 630 ms TWT.
4.8.4 Lower-Miocene unit 6

4.8.4.1 General description

The Lower Miocene unit is the topmost part of the Hordaland group and is bounded by mid-Miocene Unconformity at the top and near-base Miocene surface below (Table 3; Fig. 8). The unit corresponds to with the coarse unit C2 claystones of Rundberg (1989) and UH-4 unit of Rundberg & Eidvin (2005). The stratal unit is restricted to two N-S to NW-SE trending topographically low regions separated by the graben-centered NW-SE high in an apparent truncation by mid-Miocene Unconformity and downlap onto the uplift flank of near-base Miocene surface. (Figs. 8, 74, 75, 76, 77 & 78). The seismic reflection character comprises moderate-high amplitude with laterally continuous bedded facies to slightly discontinuous reflections when offset by polygonal faults. Well data shows that the unit is glauconitic with occurrence of claystones, siltstones, sands, and minor limestone stringers and lignites (e.g. wells 29/3-1, 30/3-1 & 30/3-3).

4.8.4.2 Thickness distribution and basin inversion elements

The thickness map indicates the distribution for the Lower Miocene unit (Fig. 74). The thickness range is between 0 - 350 ms TWT with distribution in four major N-S to NW-SE swaths. The easternmost swath A is a thickening low (average E-W extent 30 km) that corresponds to the area where the unit is truncated by mid-Miocene Unconformity. Swath B (E-W extent of 25-30 km) corresponds to the synclinal topographic low where marked diagenetic conversion signature is observed and pervasive polygonal faulting occurs. The unit in swath B thickens basinward with depocentre close to Oseberg-Brage-Veslefrikk area. Its thickness distribution follows a N-S spread. A corresponding area of thickening is swath D which has finger-like radially-distributed progressions which reflect circular to narrow differential thickening at the margin of swath C. The differential thickening trend increases in size and lateral extent southward, with the diameter of the two largest two 'thicks' within 7 -10 km range. Figures 77 & 78 shows the cross-sectional view across the 'thicks' on both flanks of swath C. the stratal units are characterized by reflection terminations as previously noted. Swath C is unique with multi-variate residual high geometries in the uplift region that broadens northward over a NW-SE extent of 18 - 42 km, and connect to
the deposit fill in swath B (Figs. 8, 74, 75 & 76). The orientation of this anticlinal swath c follows the trend of distal deposition associated with sandy facies in Figure 72. The table inset (Fig. 74) summarizes the geometry and sizes of thickening lows in swath C. The narrow to braided differential thickening zones which dissect swath C in mainly NE-SW correspond to areas of lensoid-mounded depositional fills in concave lows which are between the residual highs (Fig. 75). The thickening axis of the lensoid fills are tilted towards the gentler, extended flank of the filled lows.

The extent and distribution of thickening swaths define the broad wavelength of anticlinal and synclinal relief observed along the near-base Miocene surface and intra Oligocene trace (Figs. 8, 68 & 76). The western, basinal, domal uplift is directly centered over the North Viking Graben and trend NW to the region above the Gulfaks blocks. The eastern domal uplift is centered on Troll. The trends are in spatial correspondence with the anticlinal trends observed on the Base Tertiary and Top Paleocene surfaces. Directly above the positive structure, a gentle sag in the overlying Pliocene clinoforms can be observed (Fig. 76). This indicates a post-depositional sag in the clinoforms, and hence a partial collapse in relief of the anticline structure below.

4.8.5 Utsira unit 7a (~15-5 Ma)

The Utsira is a twin-lobe system divided by the intra-Utsira lobe surface (C10i) system (Fig. 8). Their surface relief is similar to that of mid-Miocene Unconformity (Figs. 79 & 80). The basinward progressing finger-like structures connect to a giant lobe structure in the basinal Oseberg-Huldra region. The composite basinal lobe measures a long-axis length of 48 km and short-axis length of 40 km for the Top Utsira (C10), while intra Utsira lobe structure measures 38 km x 25 km. The two surfaces show increased deepening in the north of the study area and both downlap onto the mid-Miocene Unconformity. Depth range for intra Utsira surface is 440 - 1070 ms TWT with depth differential of 630 ms TWT. Depth range for Top Utsira is 430 - 1080 ms TWT with depth differential of 650 ms TWT. The lobes are overlain by the early Pliocene sand/shale unit (well 29/3-1; NPD 2010) and Pliocene clinoforms which downlap onto Utsira lobes. The broadly lenticular lobes are characterized by low-moderate lateral amplitude reflections which occasionally are discontinuous and convergent where they downlap onto the mid-Miocene Unconformity surface.
The associated thickness maps (Figs. 81, 82 & 83) show that lower Utsira lobe is more proximal than the upper Utsira lobe, as confirmed in the strata geometry shown in Figure 8. The composite thickness map shows two regions of deposition connected by narrow channel-like zones of thickening. A region of thickness low over location of mound structure delineates its outline in plan view. The NE limit shows area of thickening with three thickness lows defining the location of NE jack-up structures. The distal area of deposition appears to have increased along NW-SE oriented circular regions at its western limit relative to its eastern limit. The seismically disturbed area shows reduced thickening which corresponds to area of seismic mounded/jack-up facies which are analyzed later (Fig. 81).

Well data (29/6-1) shows that Utsira unit is dominated by glauconitic sands rich in calcareous benthic and planktonic foraminiferal assemblage e.g. sponge spicules and dinoflagellate cysts and shell debris. There is local occurrence of muddy and silty beds.

4.8.6 Miocene channel system

Variance attribute extraction on intra Utsira surface shows the sinuous pattern that defines the sediment routing network during deposition of Utsira (Figs. 84, 85 & 86). The sinuous down-channel distance is in the order of tens of kilometer with a strong directional trend in the progressing northeast. The network shows a meandering pattern with some linear segments which occasionally reflects a marked switch in direction. Such occurrence is observed at the western limit of lower Utsira lobe. Termination of sinuous structure occurs in the region of lobe deposition (Fig. 85). The sinuous pattern becomes braided and characteristically snaky northward (Fig. 86). The network pattern in this area is relatively more complex and comprises interwoven multi-variate forms with varying dimensions. Width of sinuous structure has been observed to measure within a range of 200-1400 m. Some channel morphometrics are provided in Figure 84 to give an estimate of the size distribution.

4.9 OLIGOCENE - MIOCENE DEFORMATION & DIAGENESIS

The Oligocene-Miocene succession is marked with deformed and altered seismic facies. The constraints of deformation are analyzed below.
4.9.1 Stratal doming and mounds (remobilization complex)

4.9.1.1 Distribution: sediment mound complex

Based on the anomalous topography of the overlying strata over mounded zones of the Oligocene-Miocene strata, distribution of the mounded zones can be estimated from the surface maps as expressed, for example, on near-base Miocene and mid-Miocene Unconformity surfaces (Figs. 70 & 73). A variance (coherence) attribute extraction of the mid-Miocene Unconformity is characterized by isolated zones of high incoherence which correspond to zones of chaotic mounded facies on seismic sections (Fig. 87). The NE segment mounds comprise four isolated sub-circular to irregular bodies with long-axis length about 2 - 4 km in the non-polygonally faulted part of the Oligocene unit. A string of similar coherence anomalies occur in the basinal along a NW-SE trend axis. Their distribution extends from the inversion syncline region to Gulfaks around the flank and crest of the graben-centered uplift. Their occurrence is dominantly in the chaotic basinal area.

The largest of the coherence anomalies is located in Oseberg-Brage area. In plan view, it has a wide dual-tail base which reduces to a rounded termination northward. The base has an E-W of 17 km and length along N-S strike line is 28 km. It is located in the polygonally-faulted region (Fig. 88). The base has connected ball-like shapes (diameter = 2.8-3.5 km) which appear drawn-out into curvilinear-wavy geometry. The polygonal fault cells diameter, in contrast, are usually less than 2 km. The outline assumes a meandering pattern northward. Smaller adjacent anomalies display sigmoid to semi-chaotic pattern.

4.9.1.1 Seismic facies description: sediment mound complex

For better clarity, the analysis is focused on the Brage and NE segment mounds in the area of good seismic resolution (Figs. 88, 89 & 90). The mound is characterized by raised-level to mounded relief which push against the overlying lower Miocene and Utsira units with possible indication of post-Utsira deformation and stratal alteration. The mounded crests are usually separated by bowl-shaped sub-circular depressions with diameter/long-axis length between 700 - 6000 m. The steep-sided mounds are defined by internally sub-continuous to chaotic facies bounded by sub-vertical oppositely dipping faults or semi-chaotic columns (Figs. 89 & 90). The mounds or jack-up structures are either chaotic or non-chaotic based on their internal reflection
characteristics (Figs. 65 & 89). The chaotic internal facies are marked by discontinuous, low-high amplitude, discordant sub-vertical to v-shaped reflections with no particular preferred orientation. The vertical amplitude and style of uplift corresponds to the thickness and geometry of the basal reflection brights (Figs 89 & 90). The basal amplitude events are usually a mix of discontinuous reflection brights with mounded top and relatively flat base when the internal facies of jack-up structure is less chaotic. Fault offset/jack-up displacement can be as high as 100 ms TWT. The base of the chaotic Brage mound shows a push-down concave geometry in some areas. The jack-up structures are usually connected at their base to columns of acoustically disturbed zone which are linked to the underlying Jurassic strata (Fig. 65).

The bowl-shaped depression stratal units which separate jack-up mounded topography are also observed, in basinal areas, to have marked domal crest in similar manner to jack-up mounds, thus giving them lensoid geometry. The overlying Pliocene clinoforms, which onlap onto the top Utsira, show mounded relief and push-up which is in close spatial correspondence with jack-up mounds and lensoid Utsira unit. Upward arching of the overlying clinoforms also occurs away from the mound structure where Utsira unit is not restricted between mounds (Fig. 91). The vertical extent of arching in overlying clinoforms could be over 100 ms TWT.

4.9.2 Opal A/CT diagenetic reaction front (C7)

4.9.2.1 Stratal geometry

The Opal A/CT diagenetic boundary is a non-stratigraphic boundary best defined in the eastern half of the study area where it is well resolved seismically and passes into the Oligocene Unconformity Fig. 8). The western half is characterized by chaotic facies which make the surface prone to lower level of confidence in horizon picking (Fig. 92). Therefore the western area, though similar in trend to Oligocene Unconformity and near-base Miocene, is not strongly considered in making deductions moreso with the non-stratigraphic nature of the surface. It is characterized by hard-kick reflection boundary between the denser, less porous Opal-CT mudstones and the relatively low-velocity Opal-A rich overlying mudstones (Jordt et al. 2000; Rundberg & Eidvin 2005; Thyberg et al. 1999, 2000). The siliceous-rich mudstone dominates in the eastern part where the diagenetic front is well defined before passing into sand-dominated facies westward where the Oligocene strata are seismically disturbed.
Opal transition horizon C7 is a high-amplitude marker which defines a thermo-chemical diagenetic reaction front marking the conversion of biogenic silica from amorphous Opal-A to cryptocrystalline Opal-CT. In the study area, it is characterized by several polygonal fault offsets which may have altered the original morphology of the diagenetic reaction front. It is a dissolution - re-precipitation phase change attributed to increasing temperature and sediment age leading to a progressive or abrupt reduction in sediment porosity and fluid expulsion. Increase in the dry bulk density of the silica phase results as diagenesis enhances rates of sediment compaction and subsidence during early burial, relative to conventional exponential porosity reduction and compaction with depth (Compton 1991, Davies 2005 & Neagu et al. 2010). Hence the diagenetic front is imaged as a horizon of high impedance contrast marking the transition to a denser, less porous Opal-CT unit with higher resistivity and compressional velocity. This is notable in well log trace as abrupt increase in sonic and density levels as shown in the previous works (Neagu et al. 2010, Rundberg & Eidvin 2005).

The focus is to characterize its morphology. It is in stratigraphic concordance with polygonally-faulted reflections towards its eastern limit but cross-cut the stratal reflections basinward with increasing topographic relief (Figs. 93 & 94). The reaction front is concordant with the near-base Miocene surface (and the basal half of lower Miocene unit) to a good extent but becomes discordant where significant jump in reaction front relief occurs basinward. The degree of concordance becomes less with the mid-Miocene Unconformity. On a broad scale, the basinward increase in relief of Opal A/CT boundary is in trend and spatial correspondence with the westward increased thickening of lower Miocene unit 6 (Figs. 8 & 94). The area of increased relief also coincides with the region of marked polygonal fault development in the synclinal depression east of the graben-centered uplift, and the region characterized by blue illitic clay in the Paleocene unit. At the base of Brage mound/jack-up structure, the Opal A/CT reaction boundary shows a push-down geometry which propagates as far top Paleocene surface (C4).

Stratal geometry of Opal A/CT boundary is commonly expressed in three forms (Fig. 93):

- Sharp-tip ridge - expressed as terraced segments of reflections with sharp-tip culmination due to marked upward ascent of the diagenetic boundary.
- Domal terraced ridge - expressed as gentle doming relief of linked segments of amplitude events.
Level (flat) front: expressed as horizontal segments of reflections which sometimes cross-cut dipping faulted strata

While diagenetic reaction boundary has been linked to differential compaction in the overlying strata (Davies 2010), marked topographic relief of the Opal A/CT boundary in the study area does not show in some parts such relationship as expected especially where sharp increase in relief occurs (Fig. 93).

4.9.2.2 Thermal control

In sediments of fairly similar composition, temperature remains a significant control in the rate of advance of diagenetic front. An active front subject to present-day geothermal gradient is expected to be 'sea bottom simulating', else the front morphology is in thermal disequilibrium and hence 'fossilized' (Neagu et al. 2010). The paleo seabed is likely bow-shaped in contrast to the terrace geometry of the present seabed. Since the present temperatures are less than the maximum paleo-temperatures, datasets of the paleo geothermal gradient, water depth, and depth below paleo seabed would be required to derive a good estimate of the paleo-temperatures along the reaction front. An attempt is made here to characterize the temperature distribution along the Opal-CT horizon using individual and average geothermal gradient values. The estimates are extrapolations based on bottom hole temperature (BHT) and do not represent exact values, but are intended for generating a general trend of the paleothermal conditions. Geothermal gradients have been estimated from selected wells with bottom-hole temperatures and definable depth to the Opal-CT front. The derived estimates are based on Seabed temperature of 4°C which was used by Rundberg (1989) in the study area. From the available completion log data and well reports sourced from online database (NPD 2010), the Opal A/CT boundary was identified based on sonic and resistivity kicks at depths correlated with well locations incorporated into seismic dataset (Fig. 95).

The depth range at which Opal A/CT is encountered in wells is 637 - 1268 m. The temperature at the incoming of Opal A/CT is 22.7 - 46.5 °C at geothermal gradient range of 24.4 - 40.6 °C/km. Data plot (Chart 2) shows temperature cluster within 1 - 1.2 km depth range. Temperature trend shows that the estimated temperature values are strongly subject to burial depth. The high temperature values are associated with wells in the central area as shown in Figure 95 where the
Opal A/CT is encountered at depths within the common depth range for available wells. This location coincides with Veslefrikk - Oseberg Øst area. The low temperature distribution is associated with wells in Brage-Troll area where the Opal A/CT boundary is encountered at shallow depth.

A plots trace with an average geothermal gradient of 31.9 °C/km for the various depth values is provided to highlight the disequilibrium in the first plots trace with present-day geothermal gradient. If the front were active, it would have generated a more ordered plots trace like the second average gradient trace (Chart 2). The average gradient trace shows at least that the Opal A/CT horizon will at least 'bottom simulates' a paleo seabed with a more uniform geothermal gradient.

4.9.3 Polygonal faults: constraints

The focus is to make observations with respect to influence of polygonal faults on diagenetic boundary and sediment mounds. Pervasive polygonal faulting is topographically restricted, in the upper Oligocene and lower Miocene units, to the structural low between the eastward rising flank of Oligocene Unconformity and the flank of the graben-centered anticline. The westward decrease in development appears to become significant in the area where the Oligocene-Miocene mud-rich unit passes into sand-dominated facies based on well data. The polygonal fault array shows several directions of orientation of fault planes in plan view (Fig. 88). The fault offsets increase with depth but they tip-out towards the mid-Miocene Unconformity with subtle folding of relief. It is observed that polygonal faults experience dip switch on both sides of mounded seismic reflections. The dip switch is associated with subtle doming of relief and depressions in stratal geometry (Fig. 94). At the zones of dip switch there is no differential change in diagenetic boundary topography. The keystone geometry is provided by the sediment mound at the centre with oppositely dipping faults, where dip switch is associated with the jack-up structure. The dip switch around the mound is linked to the narrower base as is characteristic of focused fluid flow. The chaotic facies of the mound associated with push-down in the stratal geometry of underlying horizons may be indicative of fluidized nature of the mounded facies.
4.9.4 Inter-relationship of major basin elements

Close observation reveals that the polygonal fault network in the Oligocene-Miocene interval sediment mound structures is disrupted by distribution of jack-up structure in the areas of greater incoherence reflected in variance attribute extraction (Fig. 88). Polygonal faults of the same tier propagate through the Opal-CT mudstone unit, though the fault traces do not have high definition. The diagenetic boundary does not show pronounced local effect on the overlying topography when significant upward ascent of reaction boundary occurs. In relation to the major basin elements, significant occurrence of sediment jack-up is observed to directly overlie the relay zone where Brage fault connects to Oseberg Øst Horst faults (Figs. 11, 15 & 96). The area is also characterized by a group of 'linkage' faults which traverse the relay zone. The region is the topographic low observed on the near-base Miocene relief where the three major elements of deformation and stratal alteration (polygonal faulting, diagenetic boundary ascent and sediment mound/jack-up) are significantly expressed. The discordant and concordant amplitude events, which are related to sediment injection and remobilization, are in trend with the location of inversion anticline (Fig. 61) and Oseberg blocks. This is also true for the sediment mounds in the chaotic basinal area which are close to the flank of the inversion anticline. The Oseberg, Huldra and Gulfaks axis is in trend with this location. The NE segment mounds are located directly above the location of branching fault network on BCU surface (Fig. 44). It coincides with the location of Paleocene mounding facies as well (Fig. 65). The general observation is that there is close spatial correspondence between the distribution of soft sediment alteration elements in the younger Cenozoic succession and the Mesozoic structures (Fig. 96).
5.0 DISCUSSION

This section presents interpretation and inference established on the framework of observations above. To make informed deductions, the inferences were supported with interpretations from published sources.

5.1 BCU (C1) AND EARLY CRETACEOUS (C1i)

The BCU surface mapped strongly suggests a diachronous nature as it often shows merging unconformities (Figs. 12, 20 & 22) with other surfaces where it sub-crops and exhibits different characteristics. The pervasive erosional nature of the Base Cretaceous Unconformity, limited to this study area, is mostly accountable for the amplitude variation of the surface. This is further strengthened by the erosional truncation of the underlying deposit. It thus presents an indication that the surface cuts through facies with different lithologies and varying mechanical competence. The sediment wedge adjacent to the uplifted and eroded footwall suggests deposited sediments were sourced from the footwall (Fig. 14). This is supported by the proximity of the sediment wedge to the uplifted footwall. The upward decreasing degree of rotation and folding of the onlapping part of the wedge may indicate that deposition was contemporaneous with the block uplift, while the upward increasing thickness of the sub-units suggests increased erosion as uplift becomes accentuated. The stratal sub-units portray a dynamic interplay between uplift and adjacent sedimentation. The presence of the wedge and eroded fault-block crest also confirms the erosional nature of the BCU. The local nature of the sediment wedge restricted to area where differential uplift of the footwall is observed relative to the adjacent topography implies that the sediment wedge is a re-deposition package. This is likely an evidence of sub-aerial exposure in the area. Local deposition like this may be critical in assessing the basin hydrocarbon potential. The sediment wedge lies above the BCU and thus can be dated Cretaceous. The rotation of onlapping part reinforces the fact that rifting continued into the Cretaceous as noted by Christiansson et al. (2000), Fossen et al. (2000) and Odinsen et al. (2000).

The varying hiatuses on the BCU support the diachronous nature of the surface (Kyrkjebø et al. 2004). They indicate that erosion of the uplifted rift margin and platform may have persisted for
a long period and that the high relief area probably served as sediment source. It can thus be inferred that erosion continued through Cretaceous times to Paleocene as supported by the merging unconformities. The weak amplitude sites are often devoid of limestone-rich hardground development and may have been sub-aerially exposed as proposed by Zachariah et al., 2009. The footwall crest of the uplifted blocks may have existed as footwall islands and served as the source of coarse clastics (Zachariah et al., 2009). The area where the BCU sub-crops also indicates sub-aerial exposure (Fig. 22). The size estimates of the weak amplitude sites and the sub-crop area of the BCU may not be large enough to make them dominant sediment sources; their role however, in supplementing sediment supply is still significant for local sedimentation.

The sediment distribution as shown in the thickness map for the Lower Cretaceous unit suggests erosion of the crest may account for the sediments in the back-basin (which is thus termed as it occupies the structural low that resulted from the back-tilting of the Oseberg block). This is also supported by the existence of depocentres between Gulfaks and Statfjord-Brent blocks. Pronounced erosion of the blocks where older sediments are exposed may also be source of sediment supply to the terraced relay zone. The thickening trend of the Lower Cretaceous sediment wedges east of the Troll high suggests they are sourced from Fennoscandian landmass (Fig. 23), and may have contributed little or no sediments to the Viking Graben because of the intervening high on the uplifted blocks and the broad area of the platform. Another possibility is absence of the unit on the intervening high due to erosion. The thickness map (Fig. 23) expresses the overriding influence of the rift topography in controlling deposition of the Lower Cretaceous sediments. The depocentres are adjacent to the uplifted blocks and emphasize their role in sediment supply and routing. The distribution of depocentre gives a picture of restricted basin segments which are linked by structural lows.

The alignment of the producing field distribution with the general structural trend shows that the Mesozoic deposits provide good framework to accommodate petroleum systems in the NNS (Fraser et al. 2002). The marked contrast in tectonic styles in the study area (Fig. 11) suggests that the eastern half was more tectonically active than the western half. This is certain to impact different depositional styles and basin features which result in younger Cenozoic fill. Therefore, the regional sequence bounding surfaces may not present uniform characteristics from one
margin to the other. The eastern margin also overlies the area where the previously discussed crustal body above the mantle is located (Christiansson et al. 2000; Odinsen et al. 2000), this may have contributed to the structural complexity in this area.

The lateral shift at the southern limit of the East Shetland Basin margin (Fig. 11) resembles a fault relay structure. A closer look based on the left lateral offset in the fault block crest strongly suggests a sinistral strike-slip displacement and may signal a significant implication for plate movement and basin evolution. A similar displacement pattern in the structural fabric of the North Sea is attributed to transfer fault offset (Zanella et al. 2003). An extended map area into the adjoining areas would have helped to put this displacement in proper perspective.

The Huldra-Kvitbjørn area (Fig. 1) constitutes a graben stepover (Fossen et al. 2010). The graben stepover or relay structure results from the interaction and overlap of the generally N-S trending faults and the NE-SW trending faults. The relay zone (Figs. 11 & 15) serves as a site of displacement transfer between two faults by means of ductile folding of the stratigraphy (Willemse, 1997). Due to fault interaction in relay zones, communication is enhanced to allow for fluid migration (Fossen et al. 2010). This portrays an important implication for leakage anomalies which may not be unrelated to the formation of sediment mounds in the Oligocene-Miocene strata. The master fault system of Brage and Troll faults (Figs. 11 & 15) is in agreement with the common knowledge that faults propagate through accumulation of slips and may experience displacement transfer across relay zone (Fossen et al. 2010). The relay is breached by through-going faults when different fault sets interact and link during growth (Figs. 15 & 16). It is believed that the fault propagation started with the bounding segments and was later breached by through-going faults across the relay zone (Soliva et al. 2008).

Fault system comprises individual echelon stepping fault segments that are separated by areas of relatively low displacement (i.e. segment boundaries) or connected by distinct bends in the fault trace (Young et al. 2001). It can thus be ascertained that the dominant N-S master fault orientation is succeeded by a NE-SW orientation as relay is breached based on evolution style of the fault segments (Fig. 15). The broad terraced relay zone between Oseberg and Troll contains 'linkage' fault array system oriented NE-SW in an echelon-stepping style which translates orientation to NW-SE on Troll blocks (Figs. 15, 16 & 17). It suggests that the growth of the 'linkage' faults is controlled by the strain distribution of the master faults. The 'linkage' faults
separation at near-regular interval on the terrace indicates uniform stress distribution. The distribution of these 'linkage' faults may impart geothermal transfer, fluid migration and seal integrity. The interaction of fault relay and 'linkage' fault array is observed to be closely linked with the distribution of fluid-flow structures in the Tertiary NNS. This is because fault intersection geometry influences for preferential fluid communication (Van Rensbergen et al. 2003). The growth style of the 'linkage' fault sets may also impart the development of polygonal faults where the sedimentary facies permits. This is remarkably evident in the existence of polygonal faults in Horda Platform (Figs. 18 & 19), with dip direction influenced by the master faults. The area is dominated by claystone, marl and calcareous claystone compared to the Troll-Oseberg area where the BCU usually has the Jurassic sands exposed (Figs. 20 & 21). This reinforces the facies dependence of polygonal fault development (Cartwright et al. 2003). The interplay of facies and fault relay may present a critical factor in the propagation of polygonal faults.

5.2 LATE CRETACEOUS UNIT 1 (Maastrichtian ~ 75-66 Ma) C2-C3

Late Cretaceous unit 1 was deposited in the Maastrichtian as most well data show (e.g. well). The Maastrichtian unit 1 is bounded at the top by base Tertiary marks an upward transition from Late Cretaceous calcareous claystone to Paleocene deep-marine mudstones. This unit marks the cessation of Cretaceous deposition before the onset of Tertiary sedimentation, effectively marking the end of Shetland group before shift to Cenozoic sequences of Rogaland group. In agreement with the seismic reflection signature, the unit has a fairly uniform lithology dominated by calcareous claystone.

A, B, C and D are inversion structures that trend along the buried Jurassic rift blocks; this indicates that they developed when Jurassic structures became tectonically active in later times as the inversion relief is visible as well on the Base Tertiary and Top Paleocene surfaces suggesting the inversion postdates the Paleocene times (Fig. 25). The thickening trend in the basin reveals sagging of the basin in the NW-SE direction. This trend is similar to the underlying rift trend. Minor reactivation of extensional faults occurred in Shetland in Late Cretaceous according to Coward et al. (2003) which resulted in north-westerly trending faults.
This thickening may reflect a close link with the minor reactivation. It is thus possible that thermal relaxation is not the absolute factor controlling deposition in Late Cretaceous but may have be supplement by other minor controls.

The chaotic basinal area coincides with the location of the plateau-like inversion structure where fluid expulsion and deformation are thought to account for the chaotic signature (Rundberg & Eidvin 2005). The foraminiferal assemblage suggests an open marine, outer shelf deposition environment thus indicating a near-sea level condition. The hiatus indicated in well 34/10-19 hints at still-exposed Gulfsks crest at the northern limit of the study area and shows that the unit may thin out further northward outside the study area on the uplifted block. The deposition of this unit seems to have been 'smoothed' much of the rift topography in the west and over the graben. Sediments were most likely sourced from East Shetland and at this time sediment input from Norway hinterland had ceased as the unit is rare or absent on the platform in Late Maastrichtian.

5.3 BASE TERTIARY C3 - (~Danian)

The Base Tertiary C3 surface is an important composite regional sequence boundary of high significance, denoting an important switch in events, facies and depositional style. It marks the transition in upward velocity drop from underlying Late Maastrichtian calcareous claystone to greenish grey Paleocene mudstones at the initiation of siliciclastic deposition (Ahmadi et al. 2003; Isaksen & Tonstad 1989). The stratal geometry of this surface looks similar to that of Late Cretaceous C2. This confirms that the inversion structures which characterize the two (2) surfaces occurred later in geologic time. The trending along underlying Jurassic topography suggests close link between rift blocks and the evolution of inversion structures in the later compressional regime. Compared to Late Cretaceous surface C2 with depth differential of about 1200 ms TWT, its depth differential of more than 1400 ms TWT shows the Early Paleocene experienced basin subsidence and generate more accommodation (Fig. 28). This deepening trend shows that subsidence was centered above the Mesozoic rift system. This is probably an indication of tectonic activity towards the Norwegian hinterland (Jordt et al. 2000).
The surface C3 is not only a time-significant hiatus but also erosional in nature which makes it more of a composite regional sequence boundary. Erosion is prominent in Troll area where Paleocene deposit directly overlies the Jurassic deposit (Figs. 12 & 22) and the unconformities merge thereby reinforcing the composite nature of the Base Tertiary. Positive structure may have persisted as a result of compaction anomaly directly over the sandy facies of the Troll Field. Significant erosion may therefore confirm the persistence of sub-aerial relief in the early Paleocene times. The fan-like features may be termed slope-fan system based on their 3D morphology and location. They are typical of gravity depositional elements characteristic of slope sedimentation (Close 2010) along the faulted margins towards Norway. Gravity flows are common in the Paleocene North Sea (Ahmadi et al. 2003). Given the geometry of the slope fans (along the steep depositional gradient) indicating transport from the east, erosion of the crest of the Troll faulted blocks would be ideal to contribute to deposition of a slope fan system in the developed depocentre directly beneath at the base of the slope. The positive structure in Troll area was probably a temporary barrier to sediment from the Norwegian coast and may be unlikely for direct flow to overstep the high at the early stage. This makes it a little uncertain to accurately determine the nature of the splay, as slope sedimentation is a complex function of slope grade, sediment grain-size and feeder system according to Close (2010).

The feeder system configuration may have been associated with distributary complex based on the distribution of the fan lobes. The erosive down-cutting of the base Tertiary unconformity where the Cretaceous Unconformity sub-crops adjacent to the slope fans also indicates the Jurassic sands were probably eroded to feed the fans downslope. Another possible scenario is to have coarse clastics eroded from Fennoscandian hinterland and transported across Troll if the platform is strongly tilted towards the basin. A core sample of the slope fan would have aided better correlation of the sediment source by conducting analysis for provenance of the sand grains, in comparison with Jurassic sands.

The basal sands (89 m & 35 m thick respectively) that are present at localities X and Y likely resulted from the same process that led to fans A, B & C. The greater spread and run-out distance may be as a result of the extended terrace in the northeastern segment. It is proposed that focused sedimentation dominated at the initiation of Paleocene sedimentation on the eastern margin and was succeeded by progradation of hemipelagic drapes. The Paleocene trough does not seem to
have had overriding influence on the distribution of the fan system. The thickness trend as shown in Figure 55 along the trough location is clearly separate and different from the slope fan distribution. The fault-bounded depression is thus better constrained to have initiated later than Early Paleocene.

Another important feature of the prevailing paleogeography is the build-up of limestone-rich deposit, as confirmed from well 31/4-6 data, on Brage further south. High amplitude reflection (Figs. 31 & 34; NPD 2010) is known from well data to coincide with limestone/calcareous layer is common occurrence towards the south on the platform. It was noted earlier that the graben axis plunges south, the time structure map (Fig. 28) also reveals that Brage area has a lower relief relative to eroded high on Troll. It is therefore suggested that the southern limit may have been submerged at this time, and open marine to shelfal setting may have dominated the area.

The compressional phase field that dominates reactivation and led to inversion represented in the broad reach of the N-S oriented signature, even to the platform area, confirms the basin-wide nature of the event (Fig. 28). When compared with related variance maps, the low-amplitude swath shows that the signature may have been affected by seismic processing (Figs. 5, 34 & 35). The swath is similar to other imprints left as acquisition artefacts and can be regarded as one of such. Wrong identification of these patches can lead to erroneous interpretation.

5.4 SURFACE C4 (Top Paleocene ~55 Ma)

At end Paleocene times, the Top Paleocene has undergone increased subsidence. The deep marine deposits and the broadening of the basin extent support this. This is also in agreement with kaolinite/smectite ratio, a clay mineralogy measure based on the fact that kaolinite is more enriched in proximal facies while smectite is associated with highstand regime and deep marine conditions (Thyberg et al. 2000). The upward-decreasing kaolinite/smectite ratio is indicative of a more distal setting towards the end of Paleocene times. It is suggested that subsidence increased in Late Paleocene i.e. the upper part above the Intra Paleocene downlap surface as progradation commenced from Norway and deltaic sedimentation advanced from East Shetland. The increased subsidence was likely contemporaneous with the sea-level rise as noted by Faleide
et al. (2002). The existence of Dornoch Delta and perhaps other precursor deltas represents the advance of deltaic sedimentation in the Paleocene times and incoming of fan systems.

The doming geometry characterizing the surface in the NE segment can be related to the prevailing facies which well data attributes to the presence of sandy clastic in contrast to the polygonally faulted south which is mainly argillaceous (Fig. 37). A sandy facies is expected to behave differently relative to clay when subjected to mechanical deformation. This is indicated in the larger deformation cells observed in the NE segment relative to the polygonal fault cells in the south. The doming is suggested to be related to differential compaction anomaly where sandy clastics exist. Facies variation is thus a crucial factor in sediment deformation style.

The Top Paleocene as a downlap surface constitutes a sequence boundary. Thyberg et al. (2000) confirms a high concentration of MnO and sometimes P2O5. These are indicators of low sediment supply and starved depositional surface suggesting marine condensation Thyberg et al. (2000).

5.5 PALEOCENE UNIT 2 (~ 65-55 Ma) C3 - C4

The Paleocene unit was deposited during a period of marine transgression and basin subsidence; substantial paleo-water depth increase enabled a deep marine depositional setting (Ahmadi et al. 2003; Faleide et al. 2002; Kyrkjebø et al. 2000; Rundberg 1989) subject to tectonic, climatic and eustatic causes (Anell et al. 2009, Huuse 2002; Jordt et al. 2000). The nature of the bounding surfaces shows that the Paleocene unit is bounded by two regional unconformities (Anell et al. 2010; Thyberg et al. 2000). The prograding wedges and lobate deltaic complex indicate a marked shift from basin-centered deposition of the Cretaceous to the basin margin in the Cenozoic. The following sections demonstrate that the thickness variation, to a limited extent, of the unit, combined with the morphology of the bounding surfaces, indicate that deposition is partly due to localized depositional process control or due to basin subsidence and paleo water depth increases or a combination of both.
5.5.1 Depositional setting, clay mineralogy and diagenetic alteration: western margin and basinal area

The incoming of high-angle clinoforms indicates accommodation generation, in contrast with low-angle early Paleocene strata, at the East Shetland Basin margin for the advance of deltaic-shelfal deposition. This may indicate some autocyclicality as a result of basin-influenced depositional control. The basinward dip direction of clinoforms indicates sourcing from East Shetland. The erosional terminations of clinoforms A & D indicate intermittent fluctuation in the paleo-water depth (Fig. 41). There may have been some erosional activity updip during marine transgression and as landward transition of the wave base occurs. The sedimentary structures in the genetic packages will aid the identification of any possible wave-influenced erosion updip. The occurrence of such structures, however, is below seismic resolution.

The aggradational packages of clinoforms B, D & E may suggest sea-level increase or increased accommodation, and support the opinion that more rapid increase in paleo-water depth occurred later in Paleocene (Faleide et al. 2002). The $\delta^{18}O$ curves agrees with this fluctuating trend towards the end of Paleocene times (Fig. 4). At least 2 phases of sea-level increase are suggested based on the aggradational to progradational geometry of the clinoforms. The basinward progradation of the clinoformal packages makes the Paleocene unit a lowstand systems tract on the whole, as revealed in published literature (Anell et al. 2010; Henriksen et al. 2005). It must however be noted that basin subsidence also contributed to increased accommodation based on the deep marine facies that prevailed and the deepening trend on the base Tertiary. The ‘intra-Paleocene’ downlap surface on which the clinoforms downlap likely experienced marine condensation as transgression prevailed. Such period has been described in published literature before the younger Paleocene sediments were deposited (Faleide et al. 2002; Henriksen et al. 2005).

Three main depocentres experienced active deposition during Paleocene. Sediment thickening shows that deposition proceeded from East Shetland Platform area to fill the SW depocentre. Deltaic deposition later commenced at Dornoch Delta based on the downlapping onto the early Paleocene deposit. The onset of deltaic sedimentation signifies incoming focused sedimentation in the western half in contrast to progradational wedges in the east. The near-circular area where sedimentation is less (Fig. 49) appears to coincide with the location of the small conical detached
segment of Statfjord-Brent block in the south (Fig. 11). This block may have controlled deltaic sediment spread in the area thus suggesting a localized uplift of the block.

Biostratigraphy report (NPD 2010) of well 29/6-1 in this area reveals that the early Paleocene was dominated by abundant, diverse calcareous benthonic and planktonic foraminifera to suggest an outer shelf - open marine environment. They were succeeded by almost exclusively agglutinating foraminifera to indicate bathyal depositional environment - a major change in water circulation must have prevailed. The land-derived pollens in well 29/6-1 and lignite in well 30/6-1 suggest terrigenous influence. It is likely that temporary sea-level drop occurred in during Paleocene before transgression resumed, and that during this interlude terrigenous influence became prominent. The period at the intra Paleocene downlap surface (Fig. 41) as indicated earlier may corroborate sea-level lowering before onset of prograding sediment wedges. The suggested terrigenous incursion and intermittent sea-level lowering, likely accompanied by basin subsidence, make possible the deposition of deepwater sandy clastics when lowstand conditions prevailed. Ahmadi et al. (2003) confirms such gravitational deposition elements at the western margin of the study area, and the existence of sandy interbeds in wells supports this. Significant sediment influx from Dornoch Delta where the overall thickness is in the range of 500-600 ms TWT shows a later commencement of deposition in this area (Fig. 41). While sea-level increase is suggested, significant accommodation generated can be attributed to basin subsidence.

Sediment thickness distribution favoured the margin during Paleocene times while the basin witnessed low rate of argillaceous sedimentation as noted in the available wells. The bulk of silty-calcareous clay in Oseberg area may have been deposited during shallow marine condition due to the relatively high relief of the footwall blocks. Greenish claystones adjacent to Dornoch Delta (Fig. 50) are likely as derived from pedogenic sources (Rundberg, 1989) in agreement with terrigenous influence because of their landward proximity.

The Gulfaks and Statfjord-Brent blocks area, where faults might have acted as fluid conduits, show some occurrence of seismic disturbance which are characteristic of sediment intrusions as a result of fluid expulsion. The area is dominated by grey and silty claystones. Calcareous claystones seems to have been concentrated around the uplifted areas on Horda Platform (where polygonal faulting is prevalent) and adjacent to Oseberg and Brage.
The basinal greenish claystones are shown in some well data to be micaceous (e.g. wells 30/6-16 & 30/3-3). Thyberg et al. (2000) analysis of CSS 1 confirmed the chlorite content in the area and also weak increase in illite attributed to diagenetic transformation with smectite as the precursor mineral. Wells 31/4-3, 31/4-4, 31/2-5 and 35/10-1 (NPD 2010) contain blue-grey clays in the interval (Fig. 50). Keller (1964) acknowledged that blue clay is attributed to blue illite through diagenetic transformation of smectite in areas where Potassium is available. Thyberg et al. (2010) also noted the dissolution of smectite in the presence of Potassium to precipitate authigenic Quartz and produce illite. The illite-smectite (IS) transformation is generally considered to occur between 60 and 100°C (Peltonen et al., 2009; Thyberg et al., 2010). The depth ranges from 2-3 km for a geothermal gradient around 35°C. The basinal area where diagenesis is emphasized is within this depth range. The basin coincides with the area where Opal A/CT diagenesis, as discussed later, is prominent. Therefore it can be inferred that clay mineral diagenesis constitutes an important process in the Tertiary Northern North Sea. Further to this, wells 30/5-1, 30/6-5 and 30/6-16 (NPD 2010) indicates the claystones becoming shaly and sub-fissile to fissile, most likely due to diagenetic compaction. Another important factor to note in the basinal area is that the crust is relatively thinner (Odinsen et al., 2000) and may allow for elevated temperature regime, which typically in the North Viking Graben is 35 - 41 °C/km (Kubala et al. 2003). Kubala et al. (2003) also reported a temperature anomaly near Troll Field, which is also in support of elevated geothermal gradient in the area. This area coincides with the location of Jurassic fault structures and linkage fault system in an extended relay zone (Fig. 15). Fault structures in relay zones are good communication paths which can act as important geothermal vents (Rowland & Sibson, 2004; Fossen et al., 2010) to facilitate heat transfer and catalyze diagenetic transformation. Also noteworthy is the velocity data in well 30/3-3 which approximates 2.3 km/s, with an abrupt departure from the 2-2.1 km/s of the overlying unit (Thyberg et al., 2000). Although the influence of burial depth is significant, diagenetic alteration probably had considerable effect as well based on the notable occurrence of the blue illitic clay in the central basinal area.

5.5.2 Depositional setting: eastern area

Well data shows sandy claystones in the NE segment which pass into predominantly argillaceous lithologic unit in southwest. The facies switch is coincident with change in relief as the elevated
platform area is approached (Fig. 33). The critical factor in influencing this facies difference can be traced to the interplay of sediment supply direction controlled by locations of point sources of sediment and the suggested two-way dip topographic relief on Troll, which has its crestal axis in approximately N-S direction. Marked sediment thinning in Troll area (Fig. 49), which is coincident with sub-cropping BCU area (Fig. 22), suggests the presence of a topographic relief as a major influence on drainage patterns and sediment transport routes in Paleocene times. The unit is markedly thin above a suspected structural high and sediment distribution appears to have been concentrated on the structure's flanks (Fig. 49). The positive structure subjected to sub-aerial exposure in Earliest Paleocene and affected by erosion which contributed to the build-up of slope fan system on the basin flank, may have persisted to control deposition in Troll area. The strong influence of a sub-marine high would have had significant implications for current circulation and sediment routing, hence the sediment distribution pattern. This is more evident in the slightly divergent thickening variation trend in the Oseberg which probably resulted from the north and south currents. Mud-rich facies, based on well data (NPD 2010), dominate on the high-relief area while sand-rich mudstones seem to have been selectively restricted to the northeast area of the slope and terrace adjoining the high. It is therefore evident that local topography, if not dominant, influenced the sediment distribution in the Troll area, in addition to point sediment sources.

The NE depocentre reveals sediment influx from the Norwegian hinterland (Rundberg, 1989; Jordt et al., 2000; Thyberg et al., 2000) and was similarly affected by the widespread volcanic ash deposit, based on the volcanogenic lithology of Unit 2, that characterized the period when the North Atlantic Igneous Province was active (Ahmadi et al. 2003; Anell et al., 2010). A most likely sediment source of sandy clastics influx is Sognefjord area in Norway as the trend of thickening increases towards an eastern source. Sognefjord is in close proximity and was likely the transport route draining the Norwegian hinterland to feed the margin. The sourcing of sediments from the Fennoscandian mainland indicates the area had undergone erosion probably due to uplift in the Paleocene, or that the basement is exposed due to run-off. Sudden influx of clastic sediments into basins offshore may be an indicator of erosion at the sediment provenance region, which may be caused by uplift, isostasy, climatic causes, local tectonics or sea level controls (Anell et al., 2009; Huuse 2002; Jordt et al., 2000; Molnar & England 1990). The higher relief of Horda platform in combination with the downstepping Uer Terrace (Fig. 24) could have
constrained Sognefjord drainage to meander slightly northward before emptying into the basin at
the sediment entry point.

Depositional environment at the eastern margin according to the biostratigraphy report varies
from neritic to bathyal. Most of the wells indicated the presence of reworked fossils of
Cretaceous age to suggest erosion and deposition close to the base of the Paleocene unit. This is
in agreement with the observation expressed earlier about the erosive phase that dominated in
early Paleocene times. The high input of dinoflagellate cysts in some wells, with coaly particles,
amorphous materials, woody particles and spores in the upper part of the Paleocene unit support
well circulated waters and coastal proximity. High abundance of bisaccate pollens in well 31/6-6
are reported to probably reflect special transport by strong current (NPD 2010). This may be an
indirect indication of strong current flow or medium-high energy condition, a situation that fits
into the rationale for the presence of a high on the Troll controlling current flow.

5.5.3 Post-depositional sediment mobilization

Chaotic signature in the basin (Rundberg 1989) has been suggested to be stratal deformation
likely traceable to severe fluid expulsion and migration associated with large-scale sediment
2005; Løseth et al. 2003; Rundberg & Eidvin 2005). The mounding relief (Løseth et al. 2003,
2009), in the form of subtle anticlines observed in the northeast, resembles folds in which the
final overall shape and trend are dominated by the shape of some forcing member below (Hansen
& Cartwright 2006). Such forced-fold geometry is attributed to differential compaction and
vertical jack-up diagnostic of intrusive origin as commonly reported for Eocene and Miocene
sediments in the North Sea (Andresen et al. 2009; Cosgrove & Hillier 2000; Rodrigues et al.
2009; Szarawarska 2010). By analogy to similar features in e.g. Alba field, Volund injectite
complex (Cosgrove & Hillier 2000; Huuse 2008; Szarawarska 2010) etc, the mounding relief is
interpreted as forced-fold system. They are expressions of syn- or post-depositional sediment
remobilization and injection (Andresen et al. 2009; Cosgrove & Hillier 2000; Huuse 2008;
Shoulders & Cartwright 2004).

The discordant - concordant amplitude reflections are similar in geometry to intrusive sand
bodies widely recognized in literature (Cartwright 2010; Cartwright et al. 2008; Huuse &
Mickelson 2004; Huuse et al. 2004; Huuse 2008; Huuse et al. 2010; Løseth et al. 2009; Rodrigues et al. 2009; Shoulders et al. 2007; Szarawarska 2010). They exhibit bright hard-kick reflections due to impedance contrast with the encasing mud-dominated Paleocene strata. The cross-cutting acoustically chaotic columns were put in proper perspective in the works of Løseth et al. (2003) and Jackson & Stoddart (2005) as fluid conduits permitting hydrodynamic flow, driven by pressure differential (Duranti & Mazzini 2005; Huuse et al. 2010) from the overpressured Jurassic source rocks below (Moss et al. 2003). It is proposed that the close spatial correspondence of the fluid conduits with the overlying mounds and discordant amplitude events (Figs. 45 & 48) makes them feeder conduits for sediment emplacement in the encasing host rock above (Huuse et al. 2010; Jackson & Stoddart 2005; Løseth et al. 2003, 2009). This study presents evidence of sediment remobilization in the Paleocene northern North Sea which hitherto has been rarely documented in literature.

The supply of sandy clastic into the basin was prominent during deposition of Lista Formation (Ahmadi et al. 2003). The anomalous net sand thickness in well 35/11-3S (NPD 2010) may suggest the intra Lista sand thickness has been augmented injected sand mound in the well vicinity. This indicates part of the poorly-moderately sorted intra Lista sand may not be entirely depositional but likely emplaced by injection, as is the case in the South Viking Graben (Wild & Briedis 2010). The underlying Mesozoic deposits show incoherent sediment thickness and folding which may signify differential compaction and collapse due to sediment flowage (Fig. 33). It is therefore suggested that the Paleocene sand system was sufficiently augmented by input from overpressured (Moss et al. 2003) Jurassic source when sediment injection was triggered (Huuse et al. 2010). The sediment remobilization complex is a response to an overpressure-driven focused fluid migration (Cartwright 2010; Duranti & Hurst 2004; Huuse et al. 2010; Jonk et al. 2005; Løseth et al. 2003; Szarawarska et al. 2010). The localization of occurrence to the NE segment lends credence to the importance of seismic facies in determining sediment response to fluid-controlled deformation. In addition to the coincident location of the branching fault array (Fig. 44), they constitute critical factors in predicting seal integrity and hence, distribution of leakage anomalies, fluid migration and susceptibility to geo-hazards (Cartwright et al. 2007; Huuse et al. 2010; Løseth et al. 2009). Fault-guided forceful fluid ejection can be deduced from the characteristic deformation geometry of the host strata with the spatial constraint dependent on the containing pressure threshold.
The thickness variation above the mound in Figure 48 makes a strong case for sediment withdrawal to the flanks. Forcible and sustained sediment injection may induce stress in the acoustically soft overlying unit, which is below the acoustically hard and tuffaceous Balder (Ahmadi et al. 2003; Jordt et al., Thyberg et al., 2000; Rundberg 1989), as sediment emplacement occurs. Crestal faulting is suggested to result from deformation of the tuffaceous Balder as sediment injection initiates mounding.

5.5.4 The Paleocene Linear Trough

This study establishes, perhaps in greater extent for the first time, the existence Paleocene linear trough that evolved in the NE-SW direction most likely in the Thanetian-Ypresian. The trough evolution is strongly linked to Late Paleocene times as marked thickening commenced near the top of the Paleocene unit and mostly limited to it (Figs. 52, 54 & 55). A strong proposition is to take it as a prominent feeder in the early Paleocene times that fed the slope fan system, but its geometry and observed thickening trend supports a late Paleocene evolution with the bounding faults extending into Mesozoic strata. Its orthogonality to older rift structures would also require proper resolution and integration with the known prevailing structural trends and tectonic evolution in the northern North Sea. If it evolves in the Late Paleocene, its occurrence will coincide with the Paleocene-Eocene thermal maximum in the North Sea (Fig. 4). Although it would be preferred to characterize this structure as a type of mini graben-like depression, such conclusion will only be a suggestion as there may be need for further study and more comprehensive dataset to fully resolve its nature and evolution. These observations are thus made with a view to providing for objective analysis and assessment of the structure and its implications.

5.6 EOCENE UNIT 3 & SURFACE C5/C6 (Top Eocene-Oligocene boundary ~ 34 Ma)

5.6.1 Geology and depositional settings

The semi-transparent facies as denoted by the reflection character supports the uniform lithology of this unit as noted by Jordt et al. (2000) and its associated uniform velocity distribution thereby implying uniform sediment source. The smectitic hemipelagic deposit has a composition typical of basic volcanic sediments and dry bulk composition close to that of Icelandic basalts (Thyberg
et al. 2000). The fine-grained deep marine facies common to this unit indicate low sedimentation rate. The Eocene unit has the lowest net accumulation rate in the Cenozoic and may indicate reduced topography or flooding of the hinterland and sediment provenance area (Anell et al. 2010; Faleide et al. 2002; Jordt et al. 2000). The dominance of the mudstone facies is revealed in the characteristic deformation by polygonal fault in the basinal parts and towards the east (Fig. 57; Cartwright 1996; Cartwright et al. 2003). The high amplitude reflection near the base is attributed to occurrence of limestone streaks in Troll and platform area (wells 31/2-2, 31/5-3, 31/2-9, 31/6-6; NPD 2010). Basinward, some wells (30/3-1, 30/3-3) indicate the basal unit to contain red clays which are characteristic of deep marine environment and well-oxygenated bottom waters (Rundberg 1989).

The deep water condition of the Eocene times is also supported by the existence of Early Eocene Frigg submarine fan (Jones et al. 2003) which downlap onto the Top Paleocene surface, and Grid sands (Fig. 10). The radial, digitate thickening spread (Fig. 58) of the Frigg unit reflects a channel system (Nichols & Fisher 2007; Wynn et al. 2007). Well 29/6-1 (Fig. 8) penetrating the Frigg unit indicates that the sands are well sorted, sub-round and medium-coarse grained typical of submarine channel deposit. The digitate geometry of the Frigg fan comprising 3 main channel lobes in the study area is strongly representative of channel-influenced density flow (Straub et al. 2009) and lowstand fan (Fig. 58; Jones et al. 2003). This advocates temporary lowering of sea level near the margin of East Shetland Basin in earliest Eocene. Jones et al. (2003) noted that the Frigg being the lowest sequence likely reflected an initial basin-centred phase of deposition, but its morphology here (Fig. 58) is strongly in trend with funneling of sediments into the deeper basin through sub-marine channels.

The thickening trend is dominated by 2 main depositional styles; compensational stacking and fault controlled deposition. The SW segment portrays a shift in depocentre and is dominated by compensational stacking (Fig. 60). In order to minimize potential energy associated with elevation gradients, flow-event deposits tend to preferentially fill topographic lows. The sediment transport field is temporarily fixed in space until sufficient topography develops to advance deposition (Straub et al. 2009). This compensating depositional style is the main cause of depocentre shift southward from the Dornoch delta area (Fig. 59) and influenced the outbuilding direction which persisted into the Oligocene times (Fig. 60). The basin physiography
is therefore the main controlling influence for deposition in the western margin by constraining the transport route of sediment sources. It would be expected to have the focused and constrained flow deposit some channel-turbidite sands farther basinward e.g. as represented by Grid sands (Fig. 10). Wells 29/3-1, 30/2-2, 30/3-1, 30/4-1, & 34/10-23 (Fig. 50; NPD 2010) provides evidence of fine-coarse sand streaks and interbeds in the adjacent region where the focused sedimentation may have opened to.

The marked influenced of underlying rift topography is brought to fore more vividly in the thickening trend shown in the eastern area and the basin in close association with fault offsets (Figs. 19 & 59; Jones et al. 2003). This puts forward a strong case for the underlying fault structure acting as control for deposition in the Eocene times thereby resulting in an elongate depositional trend. The influence of older structural elements is related to resumption of post-rift thermal subsidence which accounted for increased subsidence in the Eocene times (Jones et al. 2003). It is therefore obvious that the subsidence which occurred can no longer be attributed to only marine transgression without invoking a tectonic control, thereby linking Eocene sequences to major tectonic events in the North Atlantic. Sediment thinning observed on some of the underlying Mesozoic structures supports basin margin uplift as subsidence is centered on the rift (Jones et al. 2003). The reactivation of the rift structures in early Eocene is related to volcanism associated with NE Atlantic spreading and Labrador Sea floor spreading (Fig. 4).

Northeast to eastward thinning of the Eocene unit was suggested to reflect marked decrease in sediment supply attributed to climatic factors (Jones et al. 2003; Jordt et al. 2000). The absence of large fault offsets in the northeast corner (Fig. 9) and farther east away from Troll in the study area (Figs. 19 & 59) indicates less fault-influenced accommodation generation. Since Eocene unit in northern North Sea is characterized by low sedimentation rate, sediments may have been preferentially deposited further basinward where large fault offsets afford greater accommodation leading to thinner unit on the margin. Another possibility is reduction of the unit by erosion on the margin.

The Paleocene-Eocene transition can be said to represent a major switch from NE-SW spreading of the Paleocene Graben to dominantly N-S to NNW-SSE spreading axis of the old Mesozoic structure. Based on the stratal geometry and doming of the Top Eocene, the compressional regime affected the NNS in Late Eocene - Early Oligocene (Figs. 9 & 57). The Eocene is
affected by two main erosional unconformities; the Oligocene unconformity and the intra-Oligocene surface (C6i) unconformity which cut into Eocene surface in the Troll area, thereby strongly suggesting an erosional and composite top Eocene Oligocene boundary (Figs 8, 9, 33 & 57). It is also known that the Top Eocene corresponds with long-term δ18O increase, suggesting eustatic sea-level fall due to global climatic deterioration (Fig. 4; Anell 2010; Huuse & Clausen 2001; Rundberg & Eidvin 2005). It is strongly suggested that the post-Eocene compression and doming was leveled by the two unconformities as long-term sea-level fall prevailed. The appearance of fault trace of the Paleocene trough the top Eocene-Oligocene surface may be the signature of differential compaction as burial depth increases.

The fossil assemblages in the Eocene are representative of a bathyal to outer neritic depositional environment. Of note is the incoming of significant siliceous microfossils whose distribution is also confirmed by Thyberg et al. (1999) and Rundberg (1989). The reactivation of older Mesozoic structures in the Eocene (Jones et al. 2003) may have encouraged good water circulation, during Seafloor spreading in Labrador Sea (Fig. 4; Anell et al. 2010; Jones et al. 2003) which enhanced or initiated the enhancement of increased siliceous microfossil population. This likely occurred as prolonged greenhouse-icehouse transition (Huuse 2002; Huuse & Clausen 2005; Rundberg & Eidvin 2005) began based on δ18O curve. It is suggested that both climatic and tectonic controls influenced water circulation in the Eocene that probably enhanced the presence of siliceous microfossils.

5.6.2 Post-depositional process

The distribution of injection anomalies which were introduced in the previous section are characteristic of sand injectites as noted in the Tampen Spur area by Huuse & Mickelson (2004) in the Eocene unit. Their noticeable distribution along uplift flanks of reactivated older structures brings to focus their significance as products of sediment remobilization in the areas of hydrocarbon producing fields. Their association with vertical chaotic zones interpreted as fluid conduits (Jackson & Stoddart 2005; Løseth et al. 2003) reflects their relationship with leakage anomalies (Cartwright et al. 2007; Løseth et al. 2009). This study agrees with their model and the implications the authors identified to be associated with these fluid flow phenomena.
5.7 LOWER OLIGOCENE WEDGE UNIT AND EOCENE-OLIGOCENE TRANSITION

5.7.1 Lower Oligocene wedge geology

The Lower Oligocene wedge unit is dominated by non-calcareous brownish mudstones which coarsens upward into silty mudstones and sandy siltstones based on completion well logs. This agrees with the seismic facies character of the lower and upper sub-units. Rundberg (1989) confirms this lithology and upward increase in kaolinite which suggests proximal facies. It is suggested that the upper sub-unit is characterized by silty mudstones, sandy siltstones and sometimes conglomeratic deposits while the more polygonally faulted lower sub-unit is dominated by non-calcareous brownish mudstones. The depocentre of this unit suggests clastic influx characterized by terrestrially derived organic matter with 3.5% TOC (Rundberg 1989) from the Sognefjorden area, hence the carbonaceous nature of this brownish mudstone. This lithology and the presence of shell debris, radiolarian and diatoms (Thyberg 1999; Rundberg 1989; Rundberg & Eidvin 2005) support a shelfal depositional setting.

5.7.2 Intra Oligocene Wedge Unconformity

It is strongly suggested that sedimentation was interrupted by an erosional hiatus represented by intra Oligocene wedge surface which show marked down-cutting (Fig. 66) into the domal lower sub-unit and Eocene unit (Fig. 68). Sedimentation resumed for the upper sub-unit to fill the accommodation generated along the thickness low axis as shown in Figure 64. These observations may not rule out a sub-aerial exposure in the Troll area. Therefore, this work proposes the existence of intra Oligocene wedge surface as an erosional unconformity reflected in marked facies change, and it represents a marker horizon which until now has not been recognized in published literature close to the Norwegian landmass in the northern North Sea. Jordt et al. (1995) recognized a contemporaneous local hiatus in the central North Sea. If considered in association with the erosional hiatus here, it may mean that the Early Oligocene hiatus is more regional, howbeit in separated parts of the North Sea, than is suggested.
5.7.3 Inversion and domal uplift

As observed on the stratal geometries (Figs. 67 & 68) and the top Eocene/Oligocene surface architecture, the mid-Cenozoic plate re-organisations put the northern North Sea in compressional regime (Rundberg & Eidvin 2005). The stratal geometries in Troll area (Fig. 68) all through to the mid-Miocene surface hint at a fixed uplift axis close to Norway. The selective nature of the uplift, which excludes the NE corner of the study area (Fig. 65), makes a strong case for further consideration. The location is in spatial correspondence with the area affected by BCU sub-crop and marked with evidence of erosion as shown by thickness variation which is similar to that of the Paleocene unit (Figs. 49 & 64). The erosion in this area, and the resumed doming after the unconformities in the Oligocene strata, may reflect a degree of uplift in the location of the physiographic anomaly. It will require further study to put this anomaly in proper perspective with deep structure elements because it may not be sufficient to entirely attribute the observed erosional morphology, at top Eocene and at mid-Miocene horizons, to the existence of a positive structure in Troll area during the Paleocene times without some pulse of uplift. Anell et al. (2010) and Faleide et al. (2002) suggested in this area the influence of episodic behaviour of Iceland Plume, or compressional effect of intra plate stress related to North Atlantic plate boundary and Alpine compression. With a similar axis of doming and erosional truncation observed in the same area in the Oligocene succession (Fig. 68), it may be worth considering as well, to provide a comprehensive view, the influence of partially eclogitized rock-body (Christiansson et al. 2000; Ter Voorde et al. 2000) at the crust-mantle boundary.

5.7.4 Eocene-Oligocene transition

Clastic switch to brownish mudstone from the greenish smectitic Eocene mudstone, long-term \( \delta^{18}O \) increase associated with greenhouse-icehouse transition (Fig. 4), appearance of biosiliceous microfossils in mid-late Eocene which continued into Oligocene, and termination of the first doming megacycle at the Eocene/Oligocene boundary (Fig. 68) make the mid-Cenozoic Eocene-Oligocene transition very significant in qualifying the Cenozoic history. The transition has been attributed to influence global climatic deterioration, eustatic sea-level fall in association with local tectonic controls (Anell et al. 2009, 2010; Huuse & Clausen 2001; Huuse 2002; Jordt et al. 1995; Nielsen et al. 2009, 2010; Rundberg & Eidvin 2005).
The broad elongate N-S basin spread of the residual Oligocene Unconformity physiography may support the arctic seaway link (Rundberg & Eidvin 2005) established on spreading of the Norwegian and Greenland Seas which improved connection of oceanic waters to the NW Europe (Fyfe et al. 2003). This is suggestive of ocean water circulation which enhanced bio-siliceous that began in mid-late Eocene. The depth differential of 1100 ms TWT shows a return to the Late Cretaceous/Earliest Paleocene paleo-water depth level. It suggests, with deductions made so far, the end of a megacycle characterized by:

- Dominant hemi-pelagic deposition in the east, and focused/deltaic sedimentation in the west which was partly influenced by compensational stacking.
- Deep-marine facies and fossil assemblages in the period of accelerated differential subsidence and sea-level increase.
- Reactivation of older structures which imparted and constrained sedimentation and associated tectonic events.
- Regional tectono-magmatic events reflected in volcanogenic clastic influx and initiation of NE-SW oriented Paleocene trough.
- Thermal maximum reflected in prevailing greenhouse conditions.
- Basin inversion elements which later truncated by erosion after the onset of compressional regime.

5.8 OLIGOCENE-MIOCENE DEPOSITIONAL SETTING

The definition of the near-base Miocene surface constitutes a key element in deciphering the depositional setting of the hitherto controversial (Rundberg & Eidvin 2005) depositional setting of the Oligocene-Miocene succession and in improving on our understanding of the deformational constraints. The transition from deep marine pelagic deposits to shallow marine facies of the Oligocene deposits indicates that the basin has shallowed substantially, which is in agreement with shallow-marine to shelfal depositional settings noted according to published works (Fyfe et al. 2003; Galloway 2002; Jordt et al. 1995, 2000, Kyrkjebø et al. 2000, Rundberg 1989) and the fossil assemblage in the Oligocene succession. The surface relief and topography
can be interpreted as diagnostic of focused sedimentation based on the architecture characteristic of sub-marine channel - lobe system, meaning that during prevailing lowstand period the distal lobes were fed sediments channelized from the shelfal areas into the basin. This is typical of a sea-level fall regime.

It is known in literature that the Oligocene period, during which Oligocene regional hiatus prevailed, was associated with global sea level fall and abundant clastic supply (Fyfe et al. 2003; Huuse & Clausen 2001; Rundberg & Eidvin 2005). This can be interpreted to have been reflected in the observed shallow marine facies distribution during a period characterized by eustatic sea-level fall and global climatic deterioration (Anell et al. 2009, 2010; Huuse 2002; Jordt et al. 1995; Nielsen et al. 2009, 2010). This western area is confirmed by Rundberg & Eidvin (2005) to contain sands of which are typical of density flow system (Straub et al. 2009). This depositional style is fairly reflected in the thickness distribution as in Figure 72 which shows the composite Eocene-Oligocene thickness. It is suggested, in light of clear observations, that the shift in depocentre is attributable to compensational stacking (Fig. 60) which is obvious as well in the Oligocene interval. The thickness maps (Figs. 71 & 72) support the depocentre shift which compensates topographically for the Dornoch Delta location. The depocentre tagged proximal deposition (Fig. 72) is suggested, based on its location, to represent basinward shift in deposition (characteristic of lowstand conditions) from the location of earlier Eocene deposition. This spatial translation is interpreted to account for thickening in the location. The thickening strands which connect to distal deposition may be interpreted as channel-routes for distal lobe deposition. The NW decreasing thickening trend can be interpreted as deposition influenced by proximity to sediment source and possible channel migration as sedimentation occurred. The thickening lows between connecting channel routes likely indicate areas of sediment bypass. It is therefore proposed that the prevailing depositional style was controlled by sub-marine channel-lobe system and that the depocentre shift is caused by persistent influence of compensational stacking and marked sea level fall which correlate with long-term δ18O increase.

The presence of bio-siliceous sedimentation is closely linked to significant change in ocean water circulation which resulted from the Greenland Sea floor spreading which established seaway link to Arctic Sea (Fyfe et al. 2003; Rundberg & Eidvin 2005; Thyberg et al. 1999). This is linked to the Opal-rich mudstone facies of the Oligocene unit.
The structural activity in the margin is controlled by compressional strain developed in response to movements along major fracture zones (Fig. 4; Anell et al. 2009; Fyfe et al. 2003; Rundberg & Eidvin 2005). The near-base Miocene topography is interpreted to have been affected by this compressional regime. The graben-centered uplift and the domal relief of the intra-Oligocene trace in addition to the topographic low in between them can therefore be interpreted as inversion structural elements as clearly illustrated in Lower Miocene unit thickness map (Figs. 68, 74 & 76). The existence of the positive relief is further evidenced by the reflection termination and downlap of the lower Miocene strata onto the near-base Miocene surface as observed in Figure 78. This confirms that the positive structure pre-exists the deposition of the lower Miocene unit. The inversion elements altered the paleogeography significantly and are suggested to weigh heavily on depositional style and setting. This trend is similar to the Megacycle 1 trend and because it has a similar style and shows spatial correspondence with the underlying units, it is termed Megacycle 2 which terminates at the regional mid-Miocene Unconformity (Fig. 68).

The switch from Eocene deep-water gravity flow to shallow-marine/shelfal facies (reflected in glauconitic content and characteristic fossil assemblage) in the Oligocene-Miocene interval is suggested to have been influenced by the resultant basin physiography which shallowed significantly (Faleide et al. 2002; Fyfe et al. 2003; Thyberg et al. 2000). The thickness distribution of the Lower Miocene unit suggests that channelized sedimentation likely ponded on the western flank of the inversion anticline before overstepping the incised anticline (Fig. 74).

The geometry of the inversion anticline is interpreted to reflect pathways which developed as channelized sediments are transported across the elongate barrier. The thickening trend of deposits in the inversion syncline can be attributed to a physiography which favours modified N-S oriented deposition, and hence a N-S current system. This agrees with some published propositions about the depositional setting about Utsira sands being modified by a N-S basinal current and along-strike sediment transport (Galloway 2002; Rundberg & Eidvin 2005). The characteristic elongate N-S deformed positive relief, as seen in plan-view thickness map and seismic sections (Figs. 74, 75 & 76), is not a product of acquisition artefacts. The unique morphology trends along the inversion trend observed in the basin. The swath also coincides with the area dominated by sandy facies in the Oligocene unit. Intense seismic disturbance and chaotic facies is typical of this area to underscore the additional significance of sediment
mobilization and fluid flow phenomena seismically imaged in chaotic mounding and discordant clastic intrusions. On a larger scale, the axis of the graben-centered positive relief strikes along a N-S orientation while the geometrical long axis of the residual highs on the anticline are preferentially E-W on a smaller scale. Thus the residual highs can be said to have controlled the extensive sub-aerial to sub-aqueous channel system depending on the prevailing paleo water depths.

The positive relief, in addition to basinal compression, is also subject to sediment mounding as evidenced by seismically disturbed strata, and the sagging of the overlying Pliocene (Fig. 76) which show post-mounding collapse due to fluid expulsion. The uniquely deformed positive relief swath marks the boundary where bio-siliceous mudstones that are affected by remarkable degree of diagenesis pass into the sandy facies westward, with gross sand thickness of about 400 m in block 34/10 as indicated by Rundberg & Eidvin (2005). It is therefore expected to have a low degree of diagenetic degree of diagenetic compaction because of the strong control provided by change in facies and low amount of siliceous clay. This differential compaction may as well have contributed to the residual relief in this area, with less subsidence in the positive swath, and greater subsidence on the other hand in the synclinal polygonally-faulted swath. Sediment mounding cannot be ruled out in influencing the resultant sediment distribution in the intervening lows among the residual highs on the deformed anticline. The mounds’ morphology and the associated compensating depressions can act as local control in determining the flow direction of channelized flows. As the trend of the anticline follows the distribution of the sandy distal deposition discussed in Figure 72, there is also a fairly strong case for differential compaction over the anticlinal area due to the dominant sandy facies. While this is likely, the downlapping of the lower Miocene strata onto the near-base Miocene (Fig. 78) makes the effect of differential compaction a secondary influence, as much of the overlying sediments are observed to have been deposited after the time of uplift. However, differential compaction possibly accentuated the positive relief. It is important to note from the downlapping nature of the lower Miocene unit strata to the near-base Miocene the pre-existing nature of the inversion anticline relative to the deposition of the lower Miocene sediments. The eroded and channelized sediments from the elongate barrier are interpreted to have fed sediment supply in the inversion syncline in agreement with the existence of the positive relief before deposition of the lower Miocene unit.

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Massive fluid expulsion and sediment mounding are also temporally constrained to Miocene (and possibly early Pliocene) times during oil migration peak in the North Sea (Jackson & Stoddart 2005). It may then be inferred that fluid flow sediment mobilization only had a latter effect on the broad positive relief of the inversion anticline and pathways for channelized deposits before the compactional sagging of the overlying Pliocene clinoforms. Hence this downplays the influence of sediment mounding in entirely accounting for the elongate basin-centered uplift.

The Miocene surfaces show a northward deepening trend with a representative northward plunging axis that bears on the direction of flow. NE oriented channel transport system which switches to basin-restricted N-S flow and resultant long-shore sediment transport. This dual sediment transport style can be invoked to have influenced the Miocene sedimentation. The Utsira sands are clearly imaged as sediment lobes characteristic of fan deposit. Further to this, the similarity in western relief of the Utsira surfaces and mid-Miocene signifies that the sediment transport system attributable to mid-Miocene unconformity continued during the deposition of Utsira lobes and portrays an architecture representative of a channel-lobe system. The sinuous character of the coherence signatures (Figs. 84, 85 & 86) is characteristic of channel system architecture (Wynn et al. 2007) which cut into underlying strata; they are therefore interpreted as expressions of big braided-sinuous channel network (that prevailed in the Miocene) which traverse an elongate barrier (inversion anticline) to feed basin-restricted sedimentation in the inversion syncline. Moreover the sinuous elements correspond to typical channel architecture in seismic section (Fig. 84) observed. This illustrated setting backed by observed basin features will explain the long-term controversy and debate concerning Miocene sedimentation (Galloway et al. 1993; Galloway 2002; Gregersen et al. 1997; Martinsen et al. 1999; Rundberg 1989; Rundberg & Eidvin 2005) and portray significant implications for an improved understanding of the Utsira depositional setting which is crucial to the CO₂ sequestration project in the North Sea. This study presents for the first time a good input factor for reconstruction of the Oligocene-Miocene paleohistory and to provide better constraint for associated reservoir model.

The nature of the mid-Miocene Unconformity can also be better constrained in light of this, as related to a broad and extensive channel system which likely drained the study area. This makes the nature of hiatus likely sub-aerial westward where the braided channel morphology translates
to sinuous meandering channels. The thickness distribution of Utsira lobes are characteristic of a regressive cycle which result in proximal erosion and basinward deposition. This is confirmed by the basinward shift in deposition of upper Utsira lobe. It is therefore proposed that the deposition Utsira lobes are controlled by extensive channel system, but modified by N-S current flow. This setting is needed to explain the aggradational system of block sands (Rundberg & Eidvin 2005) characteristic of Utsira sands and explain the mix of planktonic and benthic foraminifera they contain.

It is hard to have consistent paleo water depth estimates for the Miocene units because of the difficulty in separately distinguishing the units from one another, but the water depths are estimated to be not more than 150 – 200 m for Utsira sands (Faleide et al. 2002). The water depths must be shallower westward as a suggested coastal area is approached. The lignitic content of the deposits, which often in literature has mainly been guessed as reworked, may now mean that the coast is not so far away in the western area. The prevailing dual sediment transport style may also mean that the mid-Miocene unconformity is composite i.e. sub-aerial westward and subaqueous in the basinal area.

5.8 OLIGOCENE-MIOCENE POST DEPOSITIONAL PROCESSES

The Oligocene-Miocene compressional regime serves as an important constraint for the syn- and post-depositional alterations of the stratal geometry. The main deformation elements comprise polygonal faulting, diagenesis and sediment remobilization complex.

The sediment mounds and jack-up structures have seismic expressions similar to the ones considered in the Paleocene unit (Figs. 48 & 65). Large fault offsets and ridge-like doming spatially linked to basal mounded facies (Figs. 89 & 90) can also be interpreted to indicate genetically-related upward ‘jack-up’ movement. In addition, the Oligocene remobilization/injection system has been studied in published works in the study area by Jackson & Stoddart (2005) Løseth et al. (2003), and similar expressions occur in other parts of the North Sea (Andresen et al. 2009; Cartwright 2010; Duranti & Hurst 2004; Duranti & Mazzini 2005; Huuse et al. 2004; Huuse et al. 2010; Huuse & Mickelson 2004; Jonk et al. 2005; Løseth et al.
2009; Szarawarska et al. 2010). While this work agrees with their interpretation and triggering mechanism that mounded facies and discordant amplitude events are zones of sediment mobilization/injection fed by focused fluid conduit from the petroliferous Jurassic basin, the observation here contrasts with the temporal constraints suggested by Jackson & Stoddart (2005) that mobilization occurred prior to Pliocene clinoform deposition accompanied by venting of gaseous fluids into paleo water column.

The subtle fold geometry of the Pliocene clinoforms (Fig. 91), which are similar in character to forced folds over injection anomalies (Hansen & Cartwright 2006) that were previously interpreted for the Paleocene unit (Fig. 48), clearly indicates that mobilization likely post-dates the lower Pliocene clinoforms. Similar subtle folding present directly above lensoid Utsira unit between the mounded ridges (Fig. 91) and the termed 'gradient anomaly' point on Pliocene clinoform bottom-set strongly support a post-Utsira alteration in morphology. It may have been caused by compensational compaction. Obviously, compaction has had effect on the Pliocene clinoforms as burial depth increases. This, however, does not absolutely rule out that the sediment mounding post-dates the Pliocene clinoforms as reflection terminations are not readily observed in the depressions. A post-depositional mobilization will imply that sediment flowage and 'redistribution' may have occurred to accommodate injected sediment. *In-situ* remobilization is not uncommon; such phenomenon was proposed by Szarawarska et al. 2010 in which the host sediments can be fluidized and remobilized to accommodate injected intrusion. In addition, evidence of *in-situ* remobilization is clearly indicated by thickness variation in overlying unit above Paleocene mound (Fig. 48) where it is suggested that sediments were preferentially mobilized to the flank of the jack-up mound as gradual 'ceiling deformation' occurs. It is therefore proposed that the timing of the mobilization in the basinal Oligocene area could have been in the Early Pliocene.

The distribution trend across different structurally styled (chaotic – Fig. 89, polygonally faulted and unfaulted – Fig. 90) facies in the Oligocene indicates the widespread nature of the leakage events, and that the phenomenon is not facies-restricted. In this widespread distribution, it is possible that the fluid expulsion and sediment mobilization which took place occur in episodic events. This may account for a different timing put forward by Jackson & Stoddart (2005) who used the mounds in the NE segment of this study area to constrain their timing of mobilization.
and attribute related Pliocene depression to later collapse of the mounds. The implication for hydrocarbon migration is to account for the proportion 'undiscovered' hydrocarbons which is thought to have been released into the paleo water column (Jackson & Stoddart 2005). A good possibility for a post-Early Pliocene mobilization is that young seal which existed at this time may not be effective trap system for migrated hydrocarbon.

Polygonal faults occurrence are indicators of intra-formational strain developed in mud dominated facies (Cartwright & Huuse 2005; Cartwright 1996; Cartwright & Lonergan 1996; Cartwright et al. 2003; Lonergan et al. 1998; Walsh et al. 2000; Watterson et al. 2000). The occurrence of sediment mounds with polygonal faults supports a pre-existing fault network which was disrupted by sediment intrusion (Figs. 88 & 94). This is also supported by the 'flow' pattern of the mound whose spread and orientation may have been influenced by the fault network. Similar relationship studied by Shoulders et al. (2007) in Faroe-Shetland Basin confirms this notion. A polygonal fault dip switch is occurs in zones of doming and depressions which do not reveal any close link to the advancing diagenetic reaction front (Fig. 94). The associated folding may suggest the strata have been partly influenced by the prevailing compressional regime in the Oligocene-Miocene. This influence of prevailing tectonic regime was suggested while discussing polygonal fault development in the Paleocene (Figs. 18 & 19) based on the trend and dip switch which occurred in the vicinity of master fault system. It is therefore suggested, subject to a more in-depth future analysis, that, polygonal fault development may not be entirely of non-tectonic (Cartwright et al. 2003) origin. The injection of basal mound into host succession can also result in rotation of the fault plane as the overlying strata undergo ‘jack-up’ and are mobilized. This appears to have had significant influence in the Oligocene polygonal fault dip switch.

Opal A/CT reaction boundary has been a subject of many published works which have linked its occurrence to differential compaction and polygonal fault development (Davies 2005; Ireland et al. 2010; Neagu et al. 2010). Some morphological relations presented by Davies (2010) do not show associated configuration with respect to differential compaction in the overlying strata (Fig. 93). This suggests there are other controls which account for the Opal A/CT front progression in the overlying strata. The temperature distribution (Chart 2), front morphology and depth constraints of the diagenetic front suggest the front is not in equilibrium with present-day
seafloor. Some workers have attributed this to 'arrest' or fossilization of diagenetic front (Brekke 2000; Neagu et al. 2010; Rundberg 1989). If this is assumed, it can be suggested this took place around mid-Miocene based on the degree of concordance of the deformed Opal A/CT front during elevated paleogeothermal regime. In addition, the large-scale correlation between the thickening trend of Lower Miocene unit and the upward ascent of diagenetic front may suggest that accommodation was further enhanced when diagenesis was active. Although no perfect simulating horizon in the overlying strata exists for the Opal A/CT horizon, these observations support constraining the fossilized diagenetic front in this study to around mid-Miocene times. This is about the time massive fluid and gas expulsion occurred in the North Sea, making an enhanced heat transfer, which influenced opal A/CT diagenesis, a more certain possibility.

The occurrence of basin-restricted diagenesis, polygonal faulting and sediment mobilization in the inversion syncline highlights the importance of the prevailing paleogeography (Figs 74 & 96). The subsidence of the syncline is interpreted to have facilitated shallow burial which influenced polygonal fault development. It also likely resulted in increased geothermal gradient as burial depth increased. This is supported by the medium-high temperature level in the region, which is also likely to be responsible for increased smectite-illite conversion (Thyberg et al. 2010) as noted in Paleocene unit in the same area (Figs. 50 & 95). It is known that diagenesis is accompanied by compaction and pore-fluid release (Brekke 2000; Davies 2010; Neagu et al. 2010; Rundberg & Eidvin 2005; Thyberg et al. 1999, 2000) suggested that marked diagenetic may have contributed to pore-fluid increase and hence low seismic velocity in the overlying Upper Oligocene unit (Jordt et al., Nøttvedt, Thyberg et al. 2000).

The distribution of sediment mobilization and injection elements shows that they are in spatial relationship with older Mesozoic structures. Their location directly above uplifted fault margins, fault networks and relay zone, strongly suggests that they are also controlled by the buried rift structure and topography (Fig. 96). This is also confirmed by the distribution of some of the injectites and clastic intrusions along rift flanks of older structures, and inversion anticline flank. The location of large sediment mound/jack-up structure above the relay zone in Brage area, and the location of NE segment mounds and injectites over BCU branching fault network area are in spatial correspondence with the underlying rift structures (Fig. 96). These locations are areas of enhanced fluid migration where fault communication, connectivity and relay zone occur (Fossen
et al. 2009). Zones of connecting fault network and relay are commonly associated with leakage anomalies. This phenomenon indicates they are linked with enhanced fluid migration. It is therefore proposed that the rift and inversion structures are the strong controls on the distribution and occurrence of post-depositional soft-sediment deformation.
6.0 CONCLUSION

This study has attempted to document the tectono-stratigraphy of the Cenozoic northern North Sea with emphasis on the BCU and the Paleocene-Miocene interval. In the course of this work, the Cenozoic stratigraphic sub-divisions were updated with inclusion of intra Oligocene wedge Unconformity based on facies change and stratal geometry.

The BCU is a significant structural template for Cenozoic depositional constraints and deformation. This is reflected in close spatial correspondence between the Mesozoic rift topography and structures and the depositional settings and deformation elements of the Cenozoic northern North Sea.

The uplifted Troll area where the BCU sub-crops suggests the presence of a high which controlled sediment distribution and likely acted as sediment source for the early Paleocene slope fan. Deep section of seismic dataset and further work may be required to fully account for the evolution of the NW-SE trending Paleocene trough which has rarely been recognized in published literature. This is necessary to ascertain if it is an evolving 'mini graben-like' feature or a depression which may have served as prominent feeder for sediment transport. Paleocene sandy clastics include remobilized sands which impart forced-fold relief to the NE segment of the study area. Pronounced smectite-illite conversion in the basinal Paleocene unit is reflected in the distribution of blue clay which suggests basin-restricted diagenetic alteration.

The switch of the Eocene sediment depocentre from the Dornoch Delta area at the east Shetland Basin margin is interpreted to be due to compensational stacking which persisted into the Oligocene. The Oligocene-Miocene depositional setting is defined by interaction of channel-lobe gravity deposit and basin-constrained elongate N-S depositional environment. This is characterized by a basin-centered N-S elongate anticlinal relief. Its morphology has modified locally by sediment mounding primed by clastic injection. The intervening lows constrain pathways for channel-like progressions and sediment transport. The identification of extensive channel network during the Miocene hints at a sub-aerial hiatus especially at the western margin of the study area. This additional information can be used, when integrated with well data, to better constrain a good depositional model for Utsira sands which remain crucial to CO\textsubscript{2} sequestration.
The western half of the study area is strongly influenced by focused/deltaic sedimentation which incorporates Paleocene-Eocene deep-water facies settings that translated subsequently to shallow depositional environment in the Oligocene-Miocene. This is in contrast to the eastern half in Troll which is subject to hemipelagic deposits, relatively less input of sandy clastics in addition to slope fans and clastic intrusions, and more influence of buried rift topography.

Two main cycles of compressional regime is suggested based on the stratatal architecture of Oligocene-Miocene succession observed in the Troll area, and the graben-centered positive relief westward; one at the end Eocene-earliest Oligocene and the other in early Miocene. The resultant basin physiography from prevailing compressional regime (which may have been accentuated by diagenetic compaction) is associated with characteristic basinal distribution of diagenetic alteration, polygonal faulting and large-size occurrence of sediment mounds.

Injection and remobilization elements are closely related to rift flank locations and zones of fault-enhanced fluid communication which coincide with distribution of linkage and branching fault array in relay zone.

Post-depositional processes altered the Cenozoic infill substantially. Seismic mounded facies area jack-up structures temporally constrained to Early Pliocene fluid expulsion events, in contrast to pre-Pliocene view invoked in literature for the study area. Polygonal faults may not entirely result from non-tectonic origin as fault development reflects some tectonic influence at zones of fault dip switch. Diagenetic reaction boundary is representative of fossilized front based on disequilibrium with present-day Seabed.

It may be necessary to further constrain the propositions brought to light in this study with incorporated well data and other relevant tools, as they suggest need for review of our current understanding of the northern North Sea.

Overall, it can be proposed (while not overlooking factors like climate, isostatic control and eustasy) that tectonics exerted appreciable control on basin evolution and depositional history of the northern North Sea.
7.0 FIGURES AND TABLES

Figure 1  Study area and Norwegian sector field locations. The structural trend closely approximates the distribution of producing fields.
Figure 2 Structural framework of the North Sea and the study area outline (from Zanella and Coward, 2003).
Figure 3  

(a) Paleogeographic setting of the North Sea showing the sediment outbuilding directions (from Jordt et al., 2000).

Figure 4 Seismic stratigraphic subdivisions and main tectonic and climatic events during the Cenozoic in the North Atlantic (After Anell et al., 2010), and the $\delta^{18}$O ice-greenhouse indicator for the Antarctica (Miller et al. 2005).
**Figure 5** Dataset parameters. Reflection amplitude constraints - this figure shows sea floor reflection as high negative amplitude. The polarity reversal on the Pleistocene Unconformity illustrates a transition from the 'soft' mud-rich Paleogene facies to the 'hard' Pliocene facies. Inset is the instantaneous amplitude extraction of the seafloor. It highlights the amalgamated survey patches which were acquired over time.
Figure 6  Survey extent and location of wells. Seismic section profiles have been constructed to tie-in with the location of some key wells.
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**Table 1** Well list.
Figure 7  Lithostratigraphy of basins close to the Fennoscandian Shield (after Rasmussen et al. 2008). The basin of interest is the Northern North Sea which dominantly comprises clay and sand.
Table 2  Comparison of seismic units defined by this study and equivalent units from classifications by Jordt et al., 2000; Thyberg et al., 2000 and Rundberg, 1989; Rundberg & Eidvin, 1995.
Chart 1 Sample well tie for regional boundaries using well 30/3-3.
Figure 8 Well transect and seismic section AA’ showing seismic stratigraphic divisions (see figure 2 for transect’s location, refer to Table 3 for label representations).
Figure 9  Well transect BB’ showing mapped seismic surfaces (see figure 2 for transect’s location, refer to Table 3 for label representations).
Figure 10  Well transect AA’ showing lithological representations superimposed on the mapped units. The lithological distribution was estimated from PDF copies of completion logs from the Norwegian Petroleum Directorate online database (see figure 2 for transect’s location, refer to Table 3 for label representations). The color scheme & labels emphasize the lithology of the dominant mudstone facies, while the yellow shades for sands are only intended to show separate sand units.
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Table 3 Seismic stratigraphic sub-divisions and age (Anell et al., 2010; Jordt et al., 2000; Rundberg & Eidvin, 2005) representations.  
*Note that this is not scaled chronostratigraphically.*
Figure 11  Perspective view of TWT structure map of BCU (C1) surface and its structural elements. The graben area is not mapped because it is beyond the dataset TWT depth limit.
Figure 12  Perspective view of instantaneous attribute map of BCU (C1) horizon showing low-amplitude signatures on the fault blocks. The marked weak amplitude areas indicate possible sites of sub-aerial exposure. The view inset shows how the BCU sub-crops the Base Tertiary (C3) near Troll faulted margin. This area adjoins the location of Paleocene fans and likely contributed eroded clastics to the fans.
Figure 13  Seismic section across the Oseberg block showing lack of strong reflection on the base Cretaceous (angular) Unconformity. The associated well log shows that the claystone directly overlies the Mesozoic sands with no obvious hardground development.
Figure 14 Cross line 1500: local sediment wedge adjacent to uplifted and eroded footwall. The eroded footwall provides evidence of sub-aerial exposure in this area.
Figure 15  Perspective view of variance attribute imaging of the structural trends of Base Cretaceous Unconformity (C1) surface. The fault distribution in the eastern half includes master (main) faults, linkage faults, and polygonal faults.
Figure 16 Variance attribute imaging of the linkage faults on the Base Cretaceous Unconformity, C1 surface (see Fig. 15 for location). The image highlights the orientation and distribution of the 'linkage' faults evolving to bridge the main faults.
Figure 17  Seismic section showing linkage faults which propagate through the Mesozoic strata and the BCU (see Fig. 13 for section location).
Figure 18: Instantaneous amplitude and variance attribute imaging of the polygonal faults on Cretaceous Unconformity C1 surface (see Fig. 16 for location).
Figure 19  Seismic section of rotated polygonal faults which propagate through Base Tertiary C3 and Cretaceous Unconformity C1 horizon (see Fig. 18 for location; refer to Table 3 for label representations). The polygonal faults dip orientation is strongly influenced by the dip of the main fault.
Figure 20  Seismic cross line section correlated with completion log of well 31/2-5. The carbonate-rich thin layer constitutes some hardground development in this area.
Figure 21  Seismic inline section correlated with completion log of well 31/6-6.
Figure 22 Perspective view of Early Cretaceous surface C1i superimposed on sub-cropping Cretaceous Unconformity (C1) attribute map. The view inset shows at the same location the BCU sub-cropping the Base Tertiary (C3).
Figure 23  Perspective view of TWT thickness map between C1 and C1i draped on Cretaceous Unconformity (C1) surface. The thickness distribution is largely restricted to the structural lows.
Figure 24  Perspective view of TWT structure map of Late Cretaceous (C2) superimposed on BCU (C1) variance attribute surface. The surface extent is limited to the basin margin and is absent on the platform.
Figure 25  Cross line 205 section showing inversion structure in Upper Cretaceous/Paleocene units. The region is disturbed and probably deformed by extensive fluid expulsion.
Figure 26 Instantaneous amplitude map of Upper Cretaceous C2 with basinal area showing low amplitude and chaotic signature.
Figure 27 TWT thickness map of Late Cretaceous unit 1. Isolated thick is mostly areas of local thickening in the chaotic basinal region. The anomalous thick in the basinal chaotic facies may (to an extent) be due to the influence of fluid flow injection.
Figure 28  Perspective view of TWT structure map of base Tertiary surface C3. Annotations show relative changes in basinal depth with respect to the Upper Cretaceous C2 surface as seen in Figure 24.
Figure 29 RMS amplitude extraction (100 ms search window relative to Base Tertiary, C3) of the Early Paleocene slope fan system. The lobes straddle the uplifted margin where some measure of deepening exists as noted in base Tertiary TWT map.
Figure 30  Perspective view of the Early Paleocene slope fan system with a composite section transect below. The more dispersed signature at highlighted locality X may likely be part of the 3-lobe fan system.
Figure 31  Seismic section across the Early Paleocene slope fan system (see Fig. 29 for location). Logs are attached to provide additional constraints for high amplitude clastics and carbonate.
**Figure 32** Seismic section (cross line view) across the lower Paleocene slope fan system.
Figure 33 Cross line 1465 section showing erosional incisions on base Tertiary C3 (see fig. 34 for location). The sediment wedge is beneath where basal discordant reflection brights are common. Inset is a perspective of the incision. This confirms it is not pockmark. The Mesozoic deposits are highlighted to show inconsistent strata morphology which may be caused by sediment evacuation during fluid expulsion.
Figure 34  Instantaneous amplitude extraction map of base Tertiary C3.
Figure 35  Variance attribute extraction map of base Tertiary C3. Area of high degree of incoherence coincides with the low amplitude basinal area of chaotic signature shown in Fig. 34. The low amplitude swath also has a defined imprint of artefact on the variance map.
**Figure 36** Variance attribute extraction map of base Tertiary C3 showing polygonal fault pattern (see Fig. 35 for location). The polygonal fault pattern is well defined on the Horda Platform area.
Figure 37  Perspective view of TWT structure map of Top Paleocene C4 surface. The areas marked sandy and argillaceous on the Troll area are based on the available well data. The NE segment contains sandy clastics within the dominant mud-rich facies while the SE segment is mainly argillaceous.
Figure 38  Variance attribute extraction map of Top Paleocene C4 of the NE segment (see Fig. 37 for location). The distribution of fault cells is imparted by the mounded relief to give the characteristic semi-circular to near-circular pattern in the NE segment.
Figure 39  Variance attribute extraction map of Top Paleocene C4 of the SE segment (see Fig. 37 for location). It shows polygonal fault pattern among the master faults.
Figure 40  Variance attribute extraction map of Top Paleocene C4 of the basinal area near Troll (see Fig. 37 for location).
Figure 41  Cross line 750 section showing Dornoch Delta depositional packages. The high-frequency clinoforms downlap onto the early Paleocene strata. The overall aggradational-progradational clinoforms indicate prevailing relative sea-level fluctuations.
Figure 42 Inline 21200 section highlighting reflection characteristics and varying facies character of the Paleocene unit 2 (see Fig. 6 for location; refer to Table 3 for label representations). The zoom-in view (inset) of the mounded area shows some crestal faults at the top of the mounds.
Figure 43  Variance attribute extraction map of BCU and fault array display on the relay terrace which may act as possible fluid migration pathway in the NE segment.
Figure 44  Perspective view of variance attribute extraction of BCU and fault array network on the relay terrace acting as fluid migration pathway in the NE segment. The faults interconnect at points which serve leakage nodes for sediment mix emplacement in the overlying host strata. *Scale: cell grid = 5 km.*
Figure 45  Cross line 1345 section highlighting intrusive bodies in Paleocene unit 2 and possible fault/fluid pathways beneath (see Fig. 43 for location).
Figure 46  Cross line 1320 section highlighting intrusive bodies in Paleocene unit 2 and possible fault/fluid pathways beneath.
Figure 47 Seismic cross line 1310 section highlighting sediment mound system Paleocene unit 2 (see Fig. 43 for location). The forced-fold relief is related to the emplaced mounds below which are in turn fed by discordant conduits.
Figure 48  Seismic cross line 1295 section highlighting sediment mound system Paleocene unit 2 (see Fig. 43 for location). The pull-up in the acoustic column occurs below the calcareous claystone between C2 and C3. The pull-up, therefore, is possibly linked to re-cemented calcareous deposit in the late Cretaceous unit.
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**Table 4** Sand thickness correlation from well completion logs for Paleocene Unit 2. Well 35/11-3S thickness is augmented by sand injectites while basal sand is common for wells in the region of submarine fans (Fig. 30).
Figure 49  Perspective view of TWT thickness map of Paleocene Unit 2. The ‘spotty’ thicks are common to the chaotic basinal area. They present a good representation of the thickness variation but may also be prone to less picking confidence due to the chaotic character in the area.
Figure 50  Clay distribution of Paleocene unit 2. Colour scheme shows dominant clay lithology distribution as observed from well completion logs. The un-coloured area within the data boundary is where greenish clay is dominant. The white lithology labels show the minor lithology in the Paleocene unit.
**Figure 51** Variance attribute extraction of Top Paleocene C4 NW-SE trending faults. The bounding fault traces of the Paleocene trough are approximately orthogonal to the reactivated older rift structures.
Figure 52  West-located seismic section of the Paleocene trough (see Fig. 51 for location).
**Figure 53** Troll seismic section of Paleocene trough (see Fig. 51 for location).
Figure 54  Zoom-in views of the fault-bounded Paleocene trough on the TWT maps of base Tertiary and the BCU. Note that the width of the depression on BCU decreases towards the basin at deeper depth.
**Figure 55** Zoom-in view of the thickness distribution along the Paleocene trough. The trough location is marked on residual bouguer anomaly map. The dotted extension indicates projected reach of the structure as observed on a larger dataset from an on-going PhD project. The size of the trough may be too small to produce a recognizable signature on the residual bouguer. Comparison with the magnetic map suggests there may be a trend in congruence with the Paleocene linear trough.
Figure 56  Perspective view of TWT structure map of top Eocene/Oligocene boundary (C5-C6). The basin seems to have started filling and shows less deepening trend relative to Top Paleocene (Fig. 37).
Figure 57  Cross line 1000 section highlighting the polygonal fault distribution of the Eocene-Oligocene units.
Figure 58  Perspective view of TWT thickness Frigg sand lobe. The thickness distribution shows a bird-foot digitate geometry similar to sub-marine channel flow.
Figure 59  TWT thickness map of Eocene unit 3. Associated depositional trend controlled by compensational stacking, distributary system and underlying rift topography. This thickness map excludes the Frigg unit.
**Figure 60** Composite section showing compensational stacking characterizing the deposition of the Eocene unit (see Fig. 59 for location, and Table 3 for label representations).
Figure 61  Sediment injection distribution superimposed on instantaneous attribute extraction of the BCU. The injectites are of high occurrence in Gulfaks, Oseberg and Uer Terrace areas. White patches represent occurrence of injectites.
Figure 62  Seismic section showing occurrence of Eocene sediment injection in the Gulfaks area (see Fig. 61 for location, and Table 3 for label representations).
Figure 63  Seismic section showing occurrence of sediment injection in the Oseberg-Huldra area (see Fig. 61 for location, and Table 3 for label representations). Semi-chaotic acoustic column below discordant amplitude event is highlighted.
Figure 64 TWT thickness map of the Lower Oligocene wedge unit 4. Inset are the TWT thickness map of the sub-unit (B) above intra Oligocene surface and the TWT thickness map of the sub-unit (C). The U-shaped thickness low suggests an eroded unit in Troll area.
Figure 65  Seismic cross line section 1475 showing stratal geometries in the NE segment and sediment remobilization (see Fig. 64 for location, and Table 3 for label representations).
Figure 66  Seismic cross line section showing stratal geometries in the NE segment and associated uplift (see Fig. 64 for location, and Table 3 for label representations). The C6i surface ‘downcuts’ into the domal underlying units. Resumed doming is observed in the strata above.
Figure 67  Seismic cross line section 650 showing stratal geometries in Troll area and associated uplift (see Fig. 64 for location, and Table 3 for label representations).
Figure 68  Seismic inline section 21300 showing stratal geometries in Troll area. Two megacycles of uplift can be identified. It should be noted that Opal CT (C7) is a non-stratigraphic boundary (see Fig. 64 for location, and Table 3 for label representations).
Figure 69 Perspective view of TWT structure map of Oligocene Unconformity (C6).
**Figure 70** Perspective view of TWT structure map of near-base Miocene (C8). The surface is deformed by sediment mounds in Brage area and in the NE corner. A basinward advancing system from the shelfal-lobate area connects to lobe-like progressions in the anticlinal zone.
**Figure 71** Perspective view of TWT thickness map of Oligocene unit 5. The definition of the thickening trend is low over the chaotic basinal area.
Figure 72  Perspective view of composite TWT thickness map of near-base Miocene and Top Paleocene interval. The thickness distribution affords a better definition to show a channel-lobe trend.
Figure 73  Perspective view of TWT structure map of mid-Miocene Unconformity (C9). The prominent circular depressions are interpreted as anticline flank bypass features which are located at the eastern flank of the basin-centered anticline.
Figure 74 Perspective view of TWT thickness map of Lower Miocene unit 6. The central segmented marked thinning coincides with area of graben-centered uplift. Inset is descriptive summary of residual highs between channel routes. The residual highs are likely areas deformed locally by sediment mound, creating transport pathways for the channelized deposits in the intervening lows. They also coincide with the lobe-like progressions on near-base Miocene surface.
Figure 75 Composite seismic section and zoom-in view showing anticlinal relief along the NW-SE axis (see Fig. 74 for location and Table 3 for label representations). The C8 horizon is emphasized on the highs to highlight the anticline relief. The location of anticinal relief coincides with chaotic sand-rich facies in the Oligocene unit prone to clastic sediment injection. Below the C8 horizon are several chaotic – v-shaped anomaly brights commonly associated with sediment mounding and injection.
Figure 76 Seismic section showing the cross-sectional view across anticline (see Fig. 74 for location, and Table 3 for label representations). The chaotic facies below the uplift is dominated by sandy facies and is marked by several discordant anomalies typical of clastic intrusions.
Figure 77  Seismic section showing zoom-in view of the western flank of anticlinal relief (see Fig. 76 for location and Table 3 for label representations). Note reflection terminations against the top-bounding mid-Miocene Unconformity (C9).
Figure 78  Seismic section showing zoom-in view of the eastern flank of anticlinal relief (see Fig. 76 for location and Table 3 for label representations). The strata downlap onto the near-base Miocene (C8) confirms the pre-existing nature of the positive structure before deposition of the lower Miocene unit.
Figure 79  Perspective view of TWT structure map of intra Utsira surface (C10i).
Figure 80  Perspective view of TWT structure map of top Utsira surface (C10), the basinal lobe is fed by sediments transported from the southwestern shelfal system.
Figure 81 Perspective view of TWT thickness map of Utsira unit 7a.
Figure 82  Perspective view of TWT thickness map of lower Utsira unit.
Figure 83  Perspective view of TWT thickness map of upper Utsira lobe. The thickness map is limited to the areal extent of lower Utsira lobe, but coverage is still sufficient for analysis.
Figure 84  Variance attribute extraction of intra Utsira surface (a) showing the Miocene channel system channel system. Inset is seismic section (b) showing the channels in cross section.

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Figure 85  Zoom-in view: variance attribute extraction of intra Utsira surface showing the Miocene channel system. The SE segment shows northward avulsion on the flank of lower Utsira lobe (see Fig. 84 for location).
Figure 86  Zoom-in view: variance attribute extraction of intra Utsira surface showing the Miocene channel system (see Fig. 84 for location).
Figure 87 Variance attribute extraction of mid-Miocene Unconformity showing the distribution of sediment jack-up structures.
Figure 88  Zoom-in view: Variance attribute extraction of mid-Miocene Unconformity. It shows in plan view the flow pattern of sediment jack-up structure in polygonally-faulted host strata (see Fig. 87 for location).
Figure 89  Seismic section showing sediment mobilization mound in polygonally-faulted basinal area (see Fig. 87 for location and Table 3 for label representations). The thickness of the basal mound brights corresponds to the offset in the non-chaotic jack-up structure.
Figure 90  Seismic section showing sediment mobilization mound in non-polygonally faulted NE segment (see Fig. 87 for location and Table 3 for label representations).
Figure 91  Seismic section showing sediment mobilization mound and subtle folding in overlying Pliocene clinoforms (see Fig. 87 for location and Table 3 for label representations).
Figure 92 TWT structure map of Opal A/CT reaction front (C7). The southern area of diagenetic zone appears to show several sub-circular depressions in surface relief.
Figure 93  Seismic section showing morphology of Opal A/CT reaction front (see Fig. 92 for location and Table 3 for label representations).
Figure 94  Seismic cross line section 575 showing Oligocene-Miocene deformation elements (see Fig. 92 for location, and Table 3 for label representations). The polygonal faults are clearly expressed in the mud-dominated facies above Opal CT unit. The push-down below the chaotic mound is also obvious in several strata below.
Figure 95 Location plots of wells used in derivation of temperature estimates for Opal A/CT boundary. Well distribution coincides with area of observed diagenesis.
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**Table 5** Temperature gradients estimates for the Opal A/CT boundary from well data. Estimations are based on the assumption that Seafloor temperature is 4°C (m SB = depth relative to Seabed, TVD = total vertical depth, BHT = bottom hole temperature).
Chart 2  Temperature – depth plot for the Opal A/CT boundary. The depth range is clustered between 1 – 1.2 km. The average geothermal gradient plot shows a more regular trend than the plot for specific gradients.
Figure 96  Spatial template for physiographic constraints of soft sediment deformation elements. The distribution of the Cenozoic deformation elements is correlated with the BCU older rift structures.
REFERENCES


Vail, P.R., Mitchum, R.M. & Thompson, S. 1977a. Relative changes of sea level from coastal onlap. In: C.E. Payton, Editor, Seismic Stratigraphy-Applications to Hydrocarbon Exploration, AAPG. Memoir, 26, pp. 63–82.


