**Evaluation of internal geometries within the Miocene
Utsira Formation to establish the geological concept
of observed CO₂ responses on 4D seismic in the
Sleipner area, North Sea**

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Abstract

CO₂ has been injected into the Miocene Utsira Formation at the Sleipner field in the Norwegian North Sea since October 1996. Repeat seismic surveying over the injection site in 1999, 2001, 2004 and 2006 have revealed the temporal development of the CO₂ plume. However, in order to help better understand future plume development and aid in locating a new injection site the geological evolution of the Utsira Formation and its resultant stratal architecture needs further development in the greater Sleipner area. Combined use of seismic and well data show that the base of the Utsira Formation, the Middle Miocene Unconformity (MMU), is heavily deformed by soft sedimentary deformation. The source for this deformation is mass sand mobilization and injection of Skade Formation sandstones in the otherwise dominantly argillaceous sediments of the Upper Hordaland Group. Skade Formation sandstones are observed thickening in up-folded, and mounded regions of MMU, where seismic data reveal V-shaped amplitude anomalies or 'chaotic', noisy areas. Outside the deformed areas the Upper Hordaland Group is an otherwise flat sequence of continuous acoustic reflectors that are offset by a pervasive network of polygonal faults. Onlapping reflection terminations of lower Utsira Formation reflectors onto the deformed surface of the MMU indicate that soft sedimentary deformation occurred at a shallow depth before deposition of the Utsira Formation. Stratal elements within the sand rich (0.98 N:G) Utsira Formation include: i) south westerly dipping clinoforms, ii) erosional scours, and iii) large-scale sand waves, suggesting high depositional energy and potential erosion of (c.1 - 2.5 metre thick) shale interbeds. During deposition of the Utsira Formation differential compaction within the Upper Hordaland Group has down-folded, and rotated intra-Utsira reflectors onto underlying MMU mounded features. Løseth's *et al.* (2003) and Jackson's (2007) models for gas and fluid expulsion from the mobilized sediments during burial, leading to differential compaction, is the preferred hypothesis for this phenomenon. The result of collapsed sediments on reservoir architecture is folding, and the creation of the anticlinal internal geometries where the CO₂ is injected today. CO₂ reached the top of the reservoir by 1999, via a sequence of small accumulations beneath interpreted as intra-formational shale beds. It appears from this rapid ascent that shale layers are laterally discontinuous, and perhaps eroded by the high-energy depositional model inferred.

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1. Introduction

Since October 1996 approximately 1 Million tonnes of CO₂ per year has been injected into the sand rich Utsira Formation at Sleipner Øst, located in block 15/9 of the Norwegian North Sea. This CO₂ sequestration programme carried out by StatoilHydro and its partners is seen as a viable, alternative method to reduce global CO₂ emissions and the potential associated global climatic impacts of anthropogenic derived CO₂ (Holloway, 2005, Torp & Gale, 2004). The CO₂ is separated from gas produced at the Sleipner Vest field and then injected back, in a supercritical state (Arts et al, 2004), into the shallow (c. 1000 m) saline aquifer of the Utsira Formation via the Sleipner Øst platform. Once the CO₂ has been injected it rises to the top of the reservoir via small accumulations beneath intra-formational shale layers. By 1999 the CO₂ had reached the top of the reservoir and began to spread laterally. Ultimately the CO₂ will dissolve into formation waters, and the resultant carbonic acid will gradually sink to the base of the reservoir owing to its relatively high density.

Since injection began the CO₂ migration has been monitored by several repeated seismic surveys acquired in 1999, 2001, 2004 and 2006, with the latest survey collected in 2008 being processed at the time of writing. When compared to the baseline 3D seismic survey of 1994, the 4D response gives a clear picture of the plume outline and its development over time. Extensive geophysical analysis of temporal plume evolution, along with forward modelling has been carried out to date by in house personnel at StatoilHydro. However, the geological concept of this response and the stratigraphic and structural characteristics of the Utsira Formation in the vicinity of the injection point need further development. The geological concept is relevant for improving an understanding of plume development; the ultimate fate of the injected CO₂; to refine the current geological model of CO₂ migration and to aid in locating a new injection point for future plans to increase current injection rates.

This paper presents the results of a three month project carried out from June to September 2008 investigating the geology of the Utsira Formation (specifically stratal geometries) and underlying upper Hordaland Group sediments in the immediate vicinity of the CO₂ injection point, in order to better understand the geological evolution specific to the area and its influence on CO₂ migration.

2. Dataset and Methods

2.1 Seismic Data

A migrated, high-resolution 3D seismic dataset acquired in 1994 provided the necessary geological detail on the subsurface, and seismic interpretation and visualization was carried out on a workstation with industry standard software. The seismic survey (ST98M11) covers a 335 km² portion of the south Viking Graben, in block 15/9 of the Norwegian North Sea, surrounding both the Sleipner Øst and Volve fields (Figure 2.1). Line spacing (otherwise known as bin spacing) is 12.5m and vertical time slice spacing is 4ms two-way time (TWT). The data has been processed with a minimum phase wavelet and has normal polarity, where a downward increase in acoustic impedance (or negative reflection coefficient) is represented by a peak, or maximum onset reflection event. In the figures presented in this paper all maximum amplitude reflection events (peaks) are displayed in blue or black, and all minimum amplitude reflection events (troughs) are displayed in brown or white. Resolution is excellent throughout the interval of interest (intra-Hordaland to Top Utsira) between approximately 800 ms to 1500 ms TWT. This is mainly due to the relatively shallow depth, whereby the higher seismic frequencies have not been so greatly attenuated, therefore maintaining a greater vertical and lateral resolution. The resolution is even great enough to image intra-Utsira reflection events that may represent the thin (c. 1-1.5 m) intra-formational mudstones and siltstones seen in wireline log data. Taking an average frequency of 40 Hz (see Appendix 1) and velocity of 2105 m s⁻¹ (Appendix 1) for the Utsira Formation interval, the vertical resolution is approximately 13 m using $1/4 \lambda$ to define vertical resolution. In reality seismic data can potentially resolve features down to $1/32 \lambda$ (Sheriff & Geldart, 1995).

Figure 2.1. Seismic shot point map showing the extent of the 1994 3D survey over the Sleipner Øst field and Volve platform, along with the 1999, 2001, 2004 and 2006 4D coverage. The wells used in the study are also included.

In addition to the baseline, pre-CO₂ injection seismic survey of 1994, numerous smaller-scale surveys were collected over the injection site during 1999, 2001, 2004 and 2006. Subtracting various combinations of these surveys allowed the generation of several time-lapse (or 4D) seismic surveys. The 4D cubes generated display the difference in response between the 2001-1994, 2004-1994, 2006-1994, 2004-2001 and 2006 to 2004 surveys. Not only do the 4D cubes generated allow an analysis of temporal plume development to be performed, but they are very useful when observing the geometry of intra-Utsira reflectors. This is the case as the CO₂ manifests itself in seismic as bright amplitude anomalies and can be observed as individual, layered accumulations, located beneath thin, intra-Utsira shale layers. The presence of CO₂ increases reflectivity and therefore seismic resolution due to the high compressibility of the CO₂ and by constructive tuning effects that occur at the top and bottom of the CO₂/formation water interfaces (Arts et al., 2004). A more confident interpretation of the internal reflection events of the Utsira can therefore be made in the vicinity of the CO₂ plume, where resolution is much higher relative to areas outside.

The smaller, repeated seismic surveys of 1999, 2001, 2004 and 2006 cover an area of c. 18 km². Line spacing is 12.5m and time-slice spacing is 4ms TWT. Like the 1994 survey a single, minimum phase wavelet was used during processing with normal polarity (i.e. a downward increase in acoustic impedance is represented by a peak).

2.2 Well Data

Comprehensive well data was made available for the study area and exists due to

Well name	Comment on well	Correlation	Bio	GR	DT	Wedge	CORE
15/9-8							
15/9-10				y		n	
15/9-11		y		y	y	y	
15/9-13	Close CO2 plume	y		y	y	y	
15/9-15		y	y	y	y	y	
15/9-16		y		y	y	no	
15/9-17		y	y	y	y	y	
15/9-19 SR		y		y	no	y	
15/9-9		no		y	?	In well	
15/9-A-9	Well-seismic mismatch	no		y	?	In well	
15/9-A-16	CO2 injector	y		y	no?	y	
15/9-A-23		y	y	y	some	y	Utsira sst
15/9-A-24		no		y	?	y	
15/9-A-28	Injector PW SLA	y		y	y	y	
15/9-C-2 H		y		y	no	y	
15/9-18		y		y	y	no	
15/9-D-1 H							
15/9-D-3 H		no		no	no	y	
15/9-F12 pilot		y		y	y	In well	
15/9-F7	Volve WP	no		y?	y?	?	
15/9-A11		no				?	Shale Above Utsira
15/9-F9	Volve WP	no				?	

Table 2.1. List of selected wells and the data available from them.

the extensive hydrocarbon exploration and production that has occurred in the Sleipner region during the last few decades. All exploration and production wells from, and in the region of, the Sleipner Øst, Sleipner Vest and Volve fields were available. Twenty two of these wells were selected for their data and for correlation. Table 2.1 lists the wells used and the data available from these wells.

2.3 Methods

Interpretation involved the following steps:

- (1) Seismic interpretation of relevant horizons to help constrain the geological model. These included:
 - (i) An intra-Hordaland reflector (termed the Intra-Oligocene Unconformity (IOU) in the rest of the text).
 - (ii) The Middle Miocene Unconformity (MMU. Lithostratigraphically defined as the top Hordaland Group/base Utsira Formation);
 - (iii) Top Utsira Sand/Base Utsira Wedge (TUS).
 - (iv) Pliocene flooding surface (PFS. Lithostratigraphically defined as the top Utsira Formation). Identification of these horizons is straightforward due to their conspicuous, high-amplitude appearance in seismic section, and from existing well and seismic picks (see Figure 4.2 for example).
- (2) Isochore map generation between the mapped horizons. The isochore maps were created by selecting the two required horizons and then subtracting the deeper horizon with the shallower horizon to leave the time difference between the two.
- (3) Seismic stratigraphic interpretation, including:
 - (i) Seismic facies and truncation mapping at two levels, Upper Hordaland Group (UHG) and intra-Utsira Formation. Within the two intervals reflection termination events were picked on a 32 x 32 inline/crossline grid using the 1994 3D seismic dataset. For the UHG reflection terminations indicate truncation against mobilized sediments/sand injectites (Figure 4.7). For the lower parts of the Utsira Formation reflection terminations indicate truncation of relatively flat lying Utsira Formation strata against the deformed, positive mounded structures of the base Utsira Formation (Mid Miocene Unconformity – MMU) (Figure 5.3, 5.5).
 - (ii) Detailed seismic stratigraphic and facies interpretation of representative 2D lines from the 1994 3D seismic dataset: trace (crossline) 3089, (in)line 3874 and (in)line 2904. Utsira Formation internal reflectors were picked in great detail in a manner similar to Galloway (2001, 2002). Galloway (2001, 2002) showed that the process is repeatable by different interpreters and that the internal reflection events do represent geological features rather than being seismic artefacts.
 - (iii) Incorporation of wireline log and biostratigraphic data to support interpretations.
 - (iv) Selection and interpretation of two intra-Utsira Formation reflectors (U1 and U2) based upon subdivision of the interval from interpretation of seismic, wireline and biostratigraphic data. These reflectors were picked throughout the entire 1994 3D dataset.

- (4) Volumetric and geometrical based attribute analysis, including:
- (i) Generation of a time-dip map for the Intra-Oligocene Unconformity (IOU) to reveal fault geometry and distribution.
 - (ii) Coherency cube and time-slice analysis to study structures in the Upper Hordaland Group. The coherency cube was generated from the 1994 3D seismic dataset.
 - (iii) Amplitude extraction for selected windows between the IOU and MMU horizons, in order to reveal the distribution of amplitude anomalies within this interval (discussed further in section 4.3)
- (5) Incorporation of the 4D response to the proposed depositional history. The 2001, 2004 and 2006 4D vintages were analysed in the region of the injected CO₂ plume to see what geological features could be deciphered as a result of the increased reflectivity from the presence of the CO₂.

Horizon Name	Lithostratigraphic Context
IOU – Intra-Oligocene Unconformity	Intra-Hordaland Group
MMU – Middle Miocene Unconformity	Top Hordaland Group
TUS – Top Utsira Sand	Top Utsira Sand (Upper shale layer)
PU – Pliocene Unconformity	Top Utsira Wedge/Top Utsira Formation
U1 – Intra-Utsira 1	Lower Utsira through-going reflector
U2 – Intra Utsira 2	Middle-Upper Utsira through-going reflector

Table 2.2. List of horizons picked

3. Geological Background

3.1 Regional Geology

The Sleipner field is located on the eastern flank of the south Viking Graben, in sector 15/9 of the Norwegian North Sea (Figure 3.1). During the Late Jurassic the underlying north to south trending structural framework of the asymmetric Viking Graben was established when rifting from arctic areas spread southwards into the North Sea (Zanella and Coward, 2003). This major extensional phase was characterised by rapid fault-controlled subsidence, the formation of a series of graben and half-graben basins and clastic syn-rift sedimentation (Fyfe *et al.*, 2003). By Early Cretaceous times active rifting dissipated and the North Sea and south Viking Graben entered a prolonged period of passive post-rift thermal subsidence as an epicontinental sag basin. Thick, mud-rich clastic sequences dominate the post-rift sedimentary basin fill, with up to 5 km of the smectite rich Shetland, Rogaland, Hordaland and Nordland Groups being deposited (Ziegler, 1981)). Tectonically, the Cenozoic era was a relatively quiescent period, punctuated by up to six phases of basin margin uplift associated with uplift of the surrounding British and Scandinavian

Figure 3.1. Regional structure map of the northern North Sea and Norwegian continental margin, with the outline of the study area shown.

landmasses and shelves (Head *et al.*, 2004). These transient phases of uplift enhanced erosion of surrounding provenance areas and rejuvenated siliciclastic sediment supply into the Viking Graben, mainly during the Palaeocene, Eocene, Oligocene and Miocene.

From the Oligocene to middle Miocene the northern North Sea basin continued to subside steadily as a shallow marine sag in which sedimentation was dominated by the thick, mud-rich successions of the Hordaland Group (Figure 3.2) (Head *et al.*, 2004). Within the Hordaland Group three sand-dominated sequences are also present, the Frigg, Grid and Skade Formations (Fyfe *et al.*, 2003). In the greater Sleipner area only the Skade Formation can be found in the Upper Hordaland succession.

Figure 3.2. Stratigraphic correlation chart for the Cenozoic Hordaland and Nordland Groups. NNS – Northern North Sea; ENS – Eastern North Sea; CNS – Central North Sea (From: Fyfe *et al.*, 2003).

The Skade Formation was defined by Isaksen and Tonstad (1989) and has been interpreted as a prograding shelf-deltaic unit in UK waters, which develops basinward into an open marine sequence of fine- to medium- grain sized turbiditic and channel sands in the Norwegian sector of the Viking Graben (Fyfe *et al.*, 2003). It is proposed that the Skade Formation was deposited during a minor tectonic phase in the late Oligocene where uplift of the Viking graben rift flanks rejuvenated siliciclastic sediment supply (Jackson, 2007).

The top of the Hordaland Group is marked by the regionally extensive Middle Miocene/Styrian Unconformity (MMU) (Ziegler, 1981), which formed in response to uplift and sub-aerial exposure of the North Sea Basin margins, and a temporary hiatus in sediment supply (Fyfe *et al.*, 2003). Locally up to 400m of uplift may have occurred along with tilting of the Horda Platform (Ghazi, 1992). A change in marine oxygen-isotope ratios at this time, indicate polar ice cap expansion and associated glacio-eustatic sea-level fall (Fyfe *et al.*, 2003). Connection between the Norwegian-Greenland Sea and the North Sea became restricted and the resultant shallowing and denudation of uplifted areas led to replenished sand supply from rivers draining

the Fennoscandian Platform to the east and the Shetland Platform to the west (Fyfe *et al.*, 2003; Head *et al.*, 2004; Gregersen & Johannessen, 2007). In the Viking Graben these sands comprise the main component of the Utsira Formation, which in turn, forms the lowermost part of the otherwise mud-dominated Nordland Group.

The Utsira Formation was first studied comprehensively by Deegan and Scull (1977) and is believed to represent a basin-restricted lowstand deposit, which unconformably overlies the Hordaland Group shales (Figure 3.3). It is dominantly sand-rich, with thick sand units separated by interbedded clays, and is clearly defined in well logs due to its blocky, low-gamma response. Biostratigraphic data from an exploration well to the south of the Sleipner field dates deposition of the Utsira Formation from late Middle Miocene (c. 11 Ma) to earliest Late Pliocene (c. 3 Ma). It forms an elongate, north-south trending deposit that extends >450 km north-south between 61°40'N and 58°N, and 75-130km east-west between 1°E and 3°50'E (Gregersen & Johannessen, 2007). The eastern and western limits of the Utsira Formation are defined by stratigraphic onlap onto the Middle Miocene Unconformity and the northern and southern limits are defined by a facies transition into more shaly sediments (Gregersen & Johannessen, 2007). Formation thickness maps define three main depocentres (Figure 3.4), with the Sleipner field being located in the southern depocentre (Kirby *et al.*, 2001). Locally the Utsira Formation can be >300 metres thick in the southern depocentre with thickness variations being attributed to the deformed underlying Middle Miocene Unconformity. Work to date suggests that the Utsira Formation was deposited as either: (i) a sand-ridge complex formed by strong marine currents through a narrow seaway (Rundberg, 1989; Eidvin *et al.*, 2002); (ii) a linked strandplain to marine-shelf sandy shoal complex (Galloway 2001, 2002); or (iii) an amalgamated submarine fan complex (Gregersen *et al.*, 1997; Gregersen, 1998). Regardless of its precise depositional environment the Utsira was deposited initially during a sea-level low-stand. An increase in the iron-silicate mineral glauconite and shale bed thickness and occurrence up sequence indicate a transgressive motif to the upper part of the Formation and perhaps the first indications of the Pliocene flooding event that finally halted siliciclastic sediment supply into the basin centre (Head *et al.*, 2004).

Figure 3.3. Regional east-west 2D seismic line showing the basin restricted Utsira Formation. The Utsira Formation is thickest in the basin centre and onlaps onto the MMU to the east and west. Note the deformed underlying MMU, which is the result of soft sediment mobilisation; the overlying shale drape and prograding Plio-Pleistocene complex. (From: Gregersen & Johannessen, 2007).

Increased subsidence rates in the Pliocene led to the development of the flooding surface that separates the Utsira Formation from the overlying shelfal mudstones,

claystones and siltstones of the Nordland Group. Initially a basinally restricted shale layer was deposited, and this acts as the cap rock for the Utsira Formation. Following this is a westward prograding glacio-marine succession that downlaps onto the underlying Utsira Formation and its shale drape was deposited (Figure 3.3) (Gregersen & Johannessen, 2007).

Figure 3.4. (a) Two way travel time structure map to Top Utsira Sand, with injection well 15/9-A-16 marked on. (b) Utsira Sand isopach map, showing the three main depocentres. (From: Kirby *et al.*, 2001).

3.2 Soft Sediment Deformation

Parts of the Hordaland Group have undergone syn- and post-depositional soft sediment deformation altering both the seismic character of the Hordaland sediments and deforming its top surface (i.e. the MMU). Three main types of structural deformation have been described: (i) Polygonal faulting (Cartwright, 1994; Shoulders *et al.*, 2007); (ii) Sand injection (Larsen, 1994; Cosgrove & Hillier, 2000; Shoulders & Cartwright, 2004; Briedis *et al.*, 2007; Shoulders *et al.*, 2007) and (iii) Sediment mobilization (Løseth *et al.* 2003; Jackson & Stoddart, 2005; and Jackson, 2007).

The deformation that has occurred in the Upper Hordaland Group is significant to this study due to its effect on the depositional history, structural evolution and stratal architecture of the Utsira Formation. Therefore the specific features found within the Hordaland Group in the study area will be described to further understand the geological history of the Hordaland Group to top Utsira Formation interval.

4. Upper Hordaland Group

The Upper Hordaland Group as it is presented, represents the interval between the intra-Oligocene unconformity (IOU) and the Middle Miocene unconformity (MMU) (Lithostratigraphically defined as the Top Hordaland Group/Base Utsira Formation transition) at its base and top respectively. This interval corresponds to the seismic stratigraphic unit CSS-4 of Jordt *et al.* (1995), and SU1 of Jackson (2007) (studied c. 400 km to the NNE in the Lomre Terrace region). For simplicity this interval shall be termed the Upper Hordaland Group here. Wireline log data show the unit is dominantly mud rich, with some variably thick intra-formational sandstones of the Skade Formation (Figure 4.1). The unit also varies in thickness, due to its uneven and mounded top surface, which is the result extensive soft sedimentary deformation that has affected the interval. An analysis into the features of the Upper Hordaland Group in the Norwegian sector of the Viking Graben is not unique and the sedimentary, structural and seismic characteristics have been covered by a variety of authors (e.g. Løseth *et al.*, 2003; Jackson & Stoddart, 2005; Jackson, 2005). It is however important to detail its specific features here, in the region of the Sleipner Øst field and CO₂ injection point, due to their influence on the structure and stratigraphy of the Utsira Formation.

Figure 4.1. Gamma ray and sonic wireline log response through the Upper Hordaland Group shales and Skade Formation; and the Lower Nordland Group Utsira Formation and overlying shale drape.

4.1 The Intra-Oligocene Unconformity

In seismic data the intra-Oligocene unconformity occurs as a relatively flat lying, high-amplitude reflection event, with overall low-angle dip basinwards to the west/south west (Figure 4.2). Recognition, picking and correlation of the distinct reflector is

Figure 4.2. Local east-west seismic line showing the studied interval within the Cenozoic post-rift basin fill. BT – Base Tertiary; IOU – Intra-Oligocene Unconformity; MMU – Middle Miocene Unconformity; TUS – Top Utsira Sand; PFS – Pliocene Flooding Surface.

straight forward allowing confident interpretation throughout the entire Sleipner area. Underlying reflection events are seen to truncate at a low angle onto the horizon, whilst overlying reflectors onlap to the east and open up, and thicken in a basinward direction to the west. These observations lead to the interpretation that the intra-Oligocene unconformity represents a seismic sequence boundary (consistent with the interpretation by Jackson (2006)), formed during a time of lowered eustatic sea-level, accompanied by tectonically driven basin margin uplift to the east during the Late Oligocene (Martinsen *et al.*, 1999, Fyfe *et al.*, 2003, Jackson, 2006). No biostratigraphic data are available for this interval in the Sleipner area, so determining the duration of hiatus and erosion are not possible. The uplift of the eastern margins of the Viking Graben during late Oligocene times allowed pulses of coarser grained clastic sediments to be supplied to the basin, leading to the deposition of the sand rich Skade Formation in the lower reaches of the Upper Hordaland Group.

A close look at a time structure map of the intra-Oligocene unconformity reveals a good correlation with the structure of deep seated, underlying Mesozoic rotated fault blocks that border the eastern margins of the south Viking graben (Figure 4.3). The most pronounced relationships are the structural high of the picked horizon that is located directly beneath the Sleipner Øst platform and directly above the structural high of the underlying Sleipner Øst field footwall crest, and the N-S trending, westward increase in dip situated above the strike of a major bounding fault. It can be deduced from these observations that variations in basin subsidence normal to the strike of the eastern South Viking rift margins occurred during the Late Oligocene to early Pliocene where the trend finally dissipates. This is probably the result of variations in the compaction of the mud-rich post-rift basin fill, which thickens basinwards, and therefore would be expected to consolidate more in this direction.

4.2 Polygonal Faulting

A distinctive characteristic of the post-Cretaceous to latest Oligocene sedimentary basin fill is the presence of a pervasive network of planar, to slightly listric normal faults (Figure 4.4). These faults cut-through and displace the intra-Oligocene unconformity and tip-out onto the Lower Miocene unconformity. When viewed in cross-section fault throws are seen to range from sub-seismic to 50 ms TWT, and individual reflectors within many fault bounded blocks show the characteristic flexure of fault drag folds. The subtlety of the displacement along the faults mean they do not clearly show up on the picked intra-Oligocene horizon in map view. However, using geometrical and volumetric based attribute analysis, the strike of the fault planes can be viewed. Both a time-dip map created for the intra-Oligocene unconformity horizon (Figure 4.5 (a)) and a time slice through a coherency data cube (Figure 4.5 (b)), reveals the polygonal geometry of the fault planes, with some excellent examples of quadrilateral and pentagonal fault arrays in plan view. Typical along-strike lengths range from c. 0.2 to 1 km, and individual faults abut onto adjacent faults at a high angle ($> 60^\circ$). The fault network is seen to be more significant to the west, within the thicker mudstones of the deeper parts of the basin.

Figure 4.3. (a). IOU time-structure map with selected wells posted. Overall dip is low angle to the west south west. Comparison with a time-structure map for the Base Jurassic unconformity (b) reveals similar structural trends. Most notable are the two structural highs that overlie one another in each map (circled); and the N-S trending area of pronounced dip on the IOU that corresponds to a large underlying fault (F1).

Figure 4.4. Pervasive polygonal fault network in the Upper Hordaland Group. Note the intensity of the faulting and that fault tips often reach but do not displace the MMU. The IOU has been picked as a trough beneath the IOU pick in other figures as it shows more clearly fault displacement along the reflector.

It has been noted by Løseth *et al.* (2003) that due to their volcanic provenance, the Upper Hordaland shales are rich in the clay mineral smectite (montmorillonite), which during burial and compaction is subject to dehydration. The associated volume loss from the expelled mineral-bound waters leads to contraction and brittle failure, in a way analogous to the formation of polygonal mud-cracks that form in the muds of a dried out lake bed. Pore-fluid pressures would also be expected to increase as fluid was expelled. With its upward migration being hampered by the low permeability shales hydrostatic pressure could grow to exceed lithostatic stress causing hydrofracturing and mass fluid expulsion. The stress state within the basin at the time of faulting is likely to be the main control on the orientation of the faults that form (Cosgrove, 2001). No preferred orientation is observed within the polygonal fault network on the local scale of this study, but a more regional study of polygonal faults found in the

Figure 4.5. (a) Dip map generated from the picked IOU horizon. (b) Coherency time-slice taken at 1208ms TWT. Both methods of attribute analysis reveal in plan view, the geometry and extent of the polygonal fault network found within the Upper Hordaland Group. Fault intensity increases westwards. No preferred orientation is inferred.

Hordaland Group of the North Sea by Clausen *et al.* (1999) indicates the faults trend NW-SE.

The significance of the polygonal fault network to this study is their influence on fluid migration through the Hordaland Group mudstones. Owing to the mud-rich content of the Hordaland Group, vertical and lateral permeability are likely to be very low, but the polygonal faults, which are in their very nature (at least at the time of formation) dilational, may act as loci for vertical fluid migration (Shoulders *et al.*, 2007). This enhanced permeability could have contributed to the formation of the soft sedimentary deformation features that are present in the Upper Hordaland Group (e.g. Løseth, 2003). A topic for further discussion once these features have been addressed in the following section.

4.3 Seismic Facies

Three distinct seismic facies (SF) are present within the Upper Hordaland Group (Figure 4.6 & 4.7): i) Parallel seismic facies (SF1); ii) V- and W-shaped amplitude anomalies (SF2), and; iii) Chaotic areas (SF3). These reflect the post depositional, soft sedimentary deformation that the interval has been subjected to.

Figure 4.6. Representative line showing the three typical seismic facies (SF) of the Upper Hordaland Group: i), ii) and iii). Overlying these the MMU is heavily deformed.

i) Parallel Seismic Facies

The parallel seismic facies are relatively flat, moderate amplitude, parallel to sub-parallel reflection events that are displaced by the complex of polygonal faults described. They are the most widely distributed seismic facies and most typical for the Upper Hordaland Group. They cover a large portion of the more westerly areas and represent undisturbed sediments that have preserved their depositional layering. Distribution is very closely confined to areas of level-lying Top Hordaland Group.

ii) V and W shaped amplitude anomalies

The V and W shaped amplitude anomalies are more localized and isolated. In cross-section they appear as bright reflection events that dip steeply and show a discordant relationship with the surrounding parallel reflectors, which truncate onto their margins. They are exclusive to the Upper Hordaland interval and none are seen significantly cross-cutting the intra-Oligocene Unconformity. Observation of many different examples show that many these features cross the entire Upper Hordaland Group interval and merge into reverse faults that offset the Top Hordaland Group

reflector. These examples are often thickest and brightest at their lowest reaches, whilst their protruding 'limbs' thin and reach into reverse faults that exhibit equivalent dip. Other examples are less significant and fill a smaller proportion of the Upper Hordaland Group. Smaller, more isolated examples tend to be imaged much more clearly, have a very clear V shape in cross-section and have a conical shape in three dimensions. The larger W-shaped and more complex examples appear as an amalgamation of the individual V-shaped events. In cross-section the anomalies are exclusively found beneath folded areas of LMU.

Both the seismic character and structural association with overlying folded MMU and reverse faults is similar to the "force-fold development" over remobilized sandstones described by Cosgrove and Hillier (2000).

Figure 4.7. Post-depositional, soft sedimentary deformation is abundant in the Upper Hordaland Group and its expression in seismic data is conspicuous, with amplitude anomalies, chaotic areas and deformed reflectors (e.g. the MMU surface).

Similar amplitude anomalies are seen deeper down within the Lower Tertiary basin fill, but these do not appear to be genetically related to the Upper Hordaland anomalies, due to their presence over 700ms (TWT) beneath (Figure 4.2).

The V-shape could be misconstrued and dismissed simply as parabolic-shaped anomalies that are an artefact of the seismic imaging and processing technique. However, work by authors such as Cosgrove & Hillier (2000); Løseth (2003); Shoulders & Cartwright (2004); and Shoulders *et al.* (2007) and well-data presented in later in the discussion suggests these events reflect injected sandstones, the occurrence of which, has been well documented within the Hordaland Group.

iii) Chaotic seismic facies

Closely associated with the V and W shaped amplitude anomalies are chaotic areas of seismic data. In cross-section these are areas of low-moderate amplitude, with discontinuous and incoherent reflection events. They are most commonly found in close proximity to, and generally above, or in-between, the bright V and W shaped anomalies.

Owing to their high amplitude and discordance with the encompassing parallel and relatively continuous reflectors, it is possible to map distribution of Upper Hordaland Group acoustic anomalies with volume based amplitude extraction (Figure 4.8). A

Figure 4.8. (a) Max trough amplitude anomaly map, extracted between a window 50ms above the IOU and 30ms below the MMU. The extraction has been laid onto an illuminated time-structure map of the MMU with contours, to show the close association between the MMU mound distribution and amplitude anomaly distribution within the Upper Hordaland Group. (b) Same amplitude extraction with noise extracted to improve clarity of the anomaly distribution.

variety of windows were chosen for analysis to determine the optimal volume interval to define the anomalies. This trial and error method established that an interval between 30ms above the Intra Oligocene Unconformity horizon, and 50ms below the Lower Miocene unconformity horizon was most successful in revealing the anomalies and avoiding any reflectors near to the associated horizons. It was also noted that maximum trough amplitude extractions produced a cleaner, more defined image than maximum peak and root mean squared (RMS) amplitude extractions. In addition to this technique the anomalies were also picked manually on a medium resolution (every 32 inline and crossline spacing, i.e. every 400m on the x and y axes) grid. Both methods yielded amplitude anomaly distribution maps.

Figure 4.8 shows that the distribution of amplitude anomalies found within the Upper Hordaland Group are reasonably well organised into clusters. These are predominantly found in the east of the study area in the vicinity of the Sleipner Øst and Volve fields. Three distinct clusters are also present in the south west. Comparison with a time-structure map for the Top Hordaland Group shows a close association with the positive mounded topography at this level, suggesting a genetic relationship between injected sands and deformation of the MMU.

4.4 Middle Miocene Unconformity

Marking the top surface of the Upper Hordaland Group is the Middle Miocene or Styrian Unconformity (Ziegler, 1981). In seismic the Middle Miocene unconformity (Top Hordaland Group/Base Utsira Formation) is an uneven interface with pronounced circular and irregular shaped mounds that can protrude over 100 meters above mean level of the surrounding, more-or-less flat lying surface (Figure 4.9 (a)). These soft sedimentary deformation features are an abundant feature of the top surface of the Upper Hordaland Group throughout the Viking Graben and have been interpreted as the product of mud-volcanism (Fyfe *et al.*, 2003), mobilized mud masses (Løseth *et al.*, 2003; Jackson & Stoddart, 2005; Jackson, 2007), and sand injection (Løseth *et al.*, 2003) in other areas of the Viking Graben. Overlying the unconformity is the sand-rich Utsira Formation, which contains seismic reflection events that terminate by either onlap or downlap onto the uneven morphology of the unconformity. Galloway (2002) and Jackson (2007) propose the unconformity represents a sequence boundary, formed during a time of lowered relative sea-level during the Late Oligocene to Early Miocene in response to further basin margin uplift.

The mounds present on the MMU vary in scale, from smaller isolated mounds that range from c. 750m to 2000m in diameter and c. 50m to 130m in amplitude, to elongate and interconnected sequences, to larger, more amalgamated and irregular shaped mounds up to 10 km in diameter. They are most prevalent in eastern areas, particularly in the vicinity of the Sleipner Øst and Volve fields, apart from three well defined circular mounds that are situated in the south west. Away from the uneven regions the Lower Miocene unconformity is remarkably flat-lying, with a very subtle dip to the west.

Cross-sectional views show that the mounds are often bounded on their margins by slightly listric reverse faults that displace the Lower Miocene unconformity reflector and events within the Upper Hordaland Group. Commonly, the reverse faults are seen to join onto the flanks of similarly dipping V and W-shaped amplitude anomalies, or they may dissipate into more chaotic regions of seismic data. None of these faults are seen to cross-cut the intra-Oligocene unconformity as they appear exclusively constrained to the Upper Hordaland Group. All scales of mounds

Figure 4.9. A. Time-structure map for the Middle Miocene unconformity (Top Hordaland Group) showing uneven and mounded soft sedimentary deformation. This is most pronounced in eastern areas around the Sleipner A and Volve platforms. B. Isochore map showing the variation in TWT between the IOU and MMU. The presence of the positive topography on the MMU causes distinct thickening of the UHG sediments.

observe such faults, even subtle upturned dish-shaped structures that have been displaced by less than 20 meters. These type of structures just described can be found above V-shaped anomalies, and appear analogous in their structure to the “forced folds” observed by Cosgrove & Hillier (2000) above sand injectites and mobilized sand near the Alba field; and by Hansen and Cartwright (2006) above saucer-shaped igneous sills.

The effect of the mounds on the overall thickness of the Upper Hordaland Group is shown in Figure 4.9 (b). Due to the relative flat-lying IOU pronounced thickening is observed in mounded regions.

4.5 Skade Formation Sandstones

As Figure 4.8 shows, there is a very close association between the mounded topography of the Lower Miocene unconformity and the distribution of amplitude anomalies that can be found in the seismic response of the Upper Hordaland Group. Fortunately, due to the extensive hydrocarbon exploration and production in the area there is sufficient well coverage to reveal the source of the amplitude anomalies.

Wireline log data show the Upper Hordaland Group is dominated by mud rich successions, with high and consistent gamma-ray responses being typical. This trend is broken by the presence of the sand-rich Skade Formation. Skade Formation sandstones typically have a blocky, low-gamma ray response, with a sharp base and top surface (Figure 4.1). The thickness of these sandstones is extremely variable, from being completely absent in some wells (e.g. 15/9-11, 15/9-17 and 15/9-A-24) to being up to nearly 207m thick in Well 15/9-A-28. Due to the large thickness variations and unpredictability in occurrence, correlating the Skade Formation between wells, particularly without the aid of seismic, is not possible, and perhaps an unwise exercise.

Plotting the thickness of Skade Formation sand found in each well onto the time-structure map for the Lower Miocene unconformity shows a good relationship between sand presence and thickness, and MMU mound location (Figure 4.10 (a)). This also corresponds to the distribution of amplitude anomalies mapped. The thickest sands can be found within mounded structures and these are shown to thin near to the mound edges, and then become completely absent in wells that are located away from the mounds. Production well 15/8-A-28 for example, penetrates through the crest of a large c. 130m tall mound that underlies the Sleipner A platform, and shows a sand thickness of nearly 207 meters is present in the Upper Hordaland Group. Whilst exploration well 15/9-11, which is situated approximately 1km away from the nearest mound, has no sand present in the same interval.

The thickness of sand found in each well was also plotted against the Upper Hordaland Group isochore thickness at each wells particular location. This plot, shown in Figure 4.10 (c) & (d), also indicates that the greater sand thicknesses are present where the Upper Hordaland Group isochore is largest (i.e. where there is the presence of a mound).

Using the observations from the well data, it was possible to make a correlation of the Skade Formation for a two dimensional arbitrary seismic line, which passes through four wells showing a presence of sand for the Upper Hordaland Group interval (Figure 4.11). This correlation cuts through a large mound under the Sleipner Øst field. A clear correlation is made between the seismic response and the

Figure 4.10. (a) MMU time-structure map with wells posted with Skade sand thickness. A good correlation is made between MMU presence and greater sand thickness. (b) Table displaying wells used to study thickness of sand in the UHG and an indication of whether the well penetrates an MMU mound. (c) Plot of the data presented in Table (b). (d) Logarithmic plot of data in Table (b). All data show a positive correlation between Skade sand thickness and MMU mound presence/size. Well 15/9-8 is anomalous, showing 34m of sand where the MMU is flat lying.

Figure 4.11. Arbitrary Seismic line and well correlation for the Skade Formation. A clear response occurs in seismic where well data show a change to sand. This allows picking of the sand body in 2D. Note the very prominent lateral change in seismic facies in the UHG interval. SF (i) – Seismic facies (i) discussed in text. Seismic is 1994 vintage.

picks made for Skade sand in the wells used. The top surface of the Skade Formation appears as a downward discontinuity from moderate amplitude reflectors that appear consistent with the parallel seismic facies i), to higher amplitude discordant reflectors of the V and W-shaped, and chaotic seismic facies. The basal surface of the Skade Formation shows the reverse of this trend. No obvious, coherent reflection event marks the top and base of the Skade Formation continuously. This is perhaps surprising considering the abrupt change in lithology that is indicated in well data. If it is considered that the sand body represents a post-burial mobilized sediment mass subject to injection into the overlying polygonal faulted Hordaland Shales, then it could be envisaged that small-scale, sub-seismic sand injections are pervasive along the top surface of the sand body. The effect of these features would be to diffuse the top Skade Sand surface, producing a more transitional shale-sand interface, thus reducing the seismic response (Hurst & Cartwright, 2007).

Picking the top and base of the Skade Formation reveals a large sand body with a very uneven upper and lower surface. Overlying the sand body, reflectors appear folded, in correspondence with the geometry of the sand beneath. In the line presented the sand body is over 200m thick at its core and pinches out to the north and south. The internal seismic response is a combination of seismic facies ii) and iii), and does not show features that are consistent with a deep marine sand body in its original depositional form. As previously noted the Skade sand is interpreted to be deep marine sand that is the product of gravity flow systems. Deep marine fan systems typically may show one or more of the following features: (i) bi-directional downlap, (ii) mounded geometries (iii) 'gull-wing' channel levee geometries in cross-section, (iii) coherent internal reflectors, (iv) channel systems in amplitude extractions (Stow *et al.*, 1996). However, none of these diagnostic features were observed to suggest this is the case in the study area.

Instead it seems more likely that the Skade sandstones have undergone extensive post-depositional deformation in such a way as described by Løseth (2003), Jackson and Stoddart (2004) and Jackson (2007). With the main evidence being (i) the massive sand bodies that are distributed within the mounded and deformed areas of Upper Hordaland Group sediments, and (ii) accompanying sand injectites that appear as V and W shaped amplitude anomalies.

It was not possible to pick the Skade Sand in 3D throughout the study area due to the time constraints of the work carried out. In light of this, it is however viewed that the combination of seismic and well data show satisfactorily that the sands of the Skade Formation cause the amplitude anomalies, that the amplitude anomaly maps reveal the distribution of the sand in plan view, and that the presence of Skade sand is responsible for the deformed MMU interface.

5. The Utsira Formation

The late middle Miocene to earliest late Pliocene, sand rich deposits of the Utsira Formation unconformably overlie the Upper Hordaland Group and represent the lowermost member of the predominantly shale rich Nordland Group (Figure 5.1). In seismic, the Utsira Formation is bound by distinct acoustic reflectors emanating beneath from the Lower Miocene Unconformity and above from the Pliocene Flooding Surface (PFS) (Jordt *et al.*, 1995; Jackson, 2006) (Figure 5.2)). In the vicinity of Sleipner Øst and the CO₂ injection point the Utsira Formation can be subdivided into three main units on the basis of well and seismic data:

- i) A c. 95 – 315 metre thick lower main unit, termed the Utsira Sand.
- ii) A 5 - 6.5 metre thick shale found in the upper reaches of the Formation.
- iii) An upper, wedge shaped unit of sand that thickens to the east and pinches out along a N-S trending line approximately in the middle of the study area.

Figure 5.1. Gamma ray and sonic wireline log response through the Upper Hordaland Group shales, and Lower Nordland Group Utsira Formation and overlying shale drape. In this correlation the Utsira wedge, separated from the main underlying Utsira Sand body, is seen to pinch out to the west.

Despite that the Utsira Formation has a remarkably high sand content throughout the Sleipner area (0.98 Net:Gross), there are a number of c. 0.5 – 2 meter thick intra-formational shales present within the sands. These appear as high gamma-ray spikes in amongst an otherwise blocky gamma ray response (Figure 5.1), and may be responsible for some low amplitude responses on 3D seismic data. The presence of the intra-formational shale layers allows further subdivision of the Utsira Formation units, by using careful well correlation and seismic facies analysis, along with the incorporation of available biostratigraphic data. The focus of this section is to present, in detail, the geological features of the Utsira Formation observed in seismic,

Figure 5.2. Trace 3089 showing the seismic character of the Utsira Formation and the subdivision of the Formation on the basis of through going reflectors. Horizons U1 and U2 were picked throughout the entire dataset.

in order to build a geological model that is consistent with the observed 4D response of CO₂ migration. This will build on the current geological model of the Utsira Formation in the Sleipner Field region, and the existing well-correlation.

5.1 Stratal Architecture in the lower Utsira Formation

The entire Utsira Formation interval exhibits a complex, but organised stratal architecture that reflects the depositional system that predominated in the Sleipner area of the south Viking Graben during the late middle Miocene to earliest late Pliocene (Figure 5.3). On the basis of through-going reflectors observed in seismic data it is possible to divide the Utsira Sand body into four main seismic sequences (Galloway, 2001; Galloway 2002).

Surfaces bounding three sequences were picked in 3D throughout the survey area (Figure 5.2), and additionally in three 2D lines selected for detailed seismic facies analysis. The nomenclature used for the sequences (U1 and U2) is based on seismic sequence subdivision of the Utsira Formation by Galloway (2001, 2002). The top of the lowermost unit (U1) is defined by a low-angle through-going maximum onset reflection event that is traceable throughout the entire seismic dataset. Subtle erosional truncation of underlying events onto this surface would suggest that it represents an unconformity or deflation surface. Within this lower Utsira sequence three main architectural elements are present: i) low-angle accretionary surfaces; ii) small symmetrical and asymmetrical mounds, and iii) subtle scour marks.

Low-angle, south westward-dipping surfaces are interpreted as clinoforms and represent time-equivalent accretionary surfaces indicating progradation and sediment construction of the Utsira sand body to the south west at the time of deposition. Clinoform bottomsets are seen to either downlap onto the MMU or onto the bottomsets of their adjacent counterparts. Topsets, where present, characteristically onlap onto the mounded topography of the MMU. Preservation of clinoform topsets and bottomsets reduces up sequence, where only low-angle foresets are observed. Where the entire sigmoidal form of a clinoform is preserved, its amplitude can reveal the palaeowater depth at the time of deposition. Analysing the amplitude of several clinoforms indicates water depths at the time of deposition were on the order of 100 metres (Appendix 2), typical of mid- to outer shelf environments (consistent with a more regional study by Galloway, 2002, and biostratigraphic analysis of the Utsira Formation e.g. Wilkinson, 1999; Eidvin *et al.*, 1999; Piasecki *et al.*, 2002). Complete preservation of clinoforms reduces up sequence, leaving only low-angle foresets.

Accompanying the low-angle surfaces are rare, isolated, mounded depositional features that have an organised internal structure and show accretionary margins. These are asymmetrical and interpreted as very large sub-aqueous dunes that are the product of high-energy sub-marine currents. Using an average sonic velocity for the Utsira Formation of 2105 m s⁻² (see Appendix 1 for derivation) the example featured in Figure 5.3 c is approximately 60 metres in amplitude, with a wavelength of more than 2 km. This is within the scale of large marine shelfal sandwaves described in detail by Johnson and Baldwin (1996). The bidirectional downlap of some of these features has led some authors to interpret them as deep marine fan lobes (e.g. Gregersen, 1998), but as Galloway (2002) emphasises, no accompanying channel-form features are present in the Utsira Formation along with the fact that water depths of 100-200 metres are not satisfactory for deep-basin gravity transport

Figure 5.3. Detailed seismic facies analysis of three 2D seismic lines: (a) Trace 3089; (b) Line 3874; (c) Line 2904. The main Utsira Formation has been subdivided into three units: Lower, Middle and Upper based on the through going reflectors U1 and U2 marked in bold. Overall stratal architecture is parallel to sub-parallel with both continuous and discontinuous acoustic reflectors. Trace 3089 is orthogonal to depositional strike and best depicts low-angle clinoform surfaces. Key stratal elements have been interpreted from analysing the seismic facies: S – Erosional scour; WF – Wave-form; SW – Large-scale sand wave; AM – Accretionary Margin; OL – Onlapping reflection termination; DL – Downlapping reflection termination; F – Fill. Structurally related elements are also highlighted: Faults marked in red; MM – Mobilized Mound; SDC – Syn-depositional compaction. Gamma ray and sonic logs from nearby wells have been included to show the response through the sequence. Further Nomenclature: IOU – Intra-Oligocene Unconformity; MMU – Mid-Miocene Unconformity; U1 – Lower Intra-Utsira through-going reflector; U2 – Mid-Upper Utsira through-going reflector; PFS – Pliocene Flooding Surface; IP1 – Intra-Plio-Pleistocene reflector. Arrows indicate reflection terminations. See Appendix 4 for un-interpreted seismic lines. (d) Base map showing 2D seismic line location in the study area.

systems. Detailed analysis of 3D data during the study also did not reveal any channelized structures within the Utsira sand body. Numerous low-relief erosional scours are seen to truncate underlying reflectors. They are often accompanied by overlying and onlapping reflection terminations, indicating the infilling of the scour mark. Their presence is a further indication of high-energy bottom-currents, which disturbed and redistributed Utsira sandstones. A likely significance to the internal stratigraphy of the Utsira Formation is the erosion of formerly continuous shale layers and potential juxtaposition of sand-rich beds. It was not possible to map these features in three dimensions due to their subtlety, but Galloway (2002) presents mapped examples in the south Viking Utsira sand shoal.

Figure 5.4. Seismic line showing complex internal stratal geometries within the lower Utsira Formation

5.2 Seismic Response

Acoustic reflectors in the lower Utsira are not continuous and either: i) reduce in amplitude until they become absent; ii) change polarity, or; iii) abruptly truncate onto high angle surfaces.

A reduction in reflector amplitude may be interpreted as either the lateral pinch-out or facies change in the subsurface geological feature (e.g. intra-formational shale), or a reduction in bed thickness so that the source for the reflector falls below seismic resolution. Clearly it would be advantageous to disambiguate this disparity in interpretation, however this is not possible and other methods must be adopted when considering lateral shale layer continuity.

Changes in reflector polarity are observed across small-scale, low-displacement normal faults. The presence of these appears sporadic, yet they are found throughout the formation (these have also been observed by Galloway, 2002).

5.3 Lower Utsira Formation Depositional Framework

The relationship of the Lower Utsira Formation to the MMU is unconformable, and represents a seismic sequence boundary that occurred during relative sea-level fall and incipient sand influx. The widespread onlap of reflection termination events of

intra-Utsira reflectors onto the positive topography of the MMU indicates the sand- and mud-filled mounds of the Upper Hordaland Group were present on the palaeo-seafloor at the time of deposition of the late Miocene, lower Utsira sediments (Figure 5.5). It can be interpreted from these observations that the Utsira sands routed through and around the palaeo-seafloor highs, successively filling in the lower-lying regions, whilst onlapping onto the margins of the mounds. The seismic facies indicate the relationship is fairly simple with the inundation of sand simply filling the low-lying areas before completely burying the mounds. The expression of prism shaped sand bodies and sigmoidal clinoforms building from the margins of some LMU mounds shows the influence on depositional energy (Figure 5.4). In the lee areas of mounds, these accretionary sedimentary features could build where current velocities were reduced.

A lower Utsira Formation isochore map complements the interpretation that MMU topography was present during Utsira deposition (Figure 5.6 (b)), where pronounced thinning occurs over the crest of the MMU mounds. The isochore map shown in Figure 5.5 b was extracted between the picked MMU horizon and the top of the lower-most Utsira seismic sequence (U1). If the formation of the MMU mounds occurred after deposition of the Utsira Formation this pronounced thinning would not be observed, and in addition, one would expect the isochore map to be relatively isochronous. A time-structure map for the top U1 sequence shows its low-angle westward dip and its discordance with the time structure map for the MMU. Instead of matching the deformation observed on the MMU the horizon is either absent where it onlaps, or it forms a depression associated with the compaction of the underlying mound (Figure 5.6 a).

The presence of erosional scours, large accretionary sandwaves and high sand percentage suggests a relatively high energy of deposition and a predominance of sediment reworking by strong sea-floor currents. An abundance of the iron-silicate mineral glauconite in the lowest parts of the Utsira formation (data from mineralogical analysis of lower Utsira sediments in well 15/9-13) confirm the marine environment and suggest slow deposition in a continental shelf setting. These conclusions attest more to Galloway's (2001, 2002) interpretation of the Utsira Formation being a continental shelf sand shoal deposit rather than Gregersen *et al.* (1997) and Gregersen (1998) interpretation that the Utsira Formation represents sands deposited in a deep water fan.

5.4 Central and Upper Utsira Stratal Architecture

Central and upper parts of the Utsira Formation represent the intervals between U2-U1 and U2-U3 respectively. Central parts of the Utsira Formation contain a sequence of relatively parallel, flat-lying and wavy reflection events, which are generally laterally discontinuous (Figure 5.3). No sigmoidal clinoforms are observed, but the low-angle westward dip observed in the lower part of the Utsira Formation is maintained. Furthermore, no mounded sedimentary structures are present. Scour features, and small displacement normal faults are not abundant but are expressed subtly in seismic cross-section. Wavy reflectors are abundant and interpreted as large sub-aqueous sandwaves resulting from the high energy reworking and winnowing of sediments.

Perhaps the most striking features present in the central parts of the Utsira Formation are downlapping reflection terminations that truncate onto the crestal regions of underlying MMU mounds (Figure 5.7). Analysis throughout the entire study area

Figure 5.5. MMU time-structure map with white ticks representing onlapping reflection terminations onto the positive topography of the deformed surface. This confirms that soft-sedimentary deformation of the Upper Hordaland Group took place before deposition of the overlying Utsira Formation.

Figure 5.6. (a) Time-structure map for intra-Utsira U1 horizon. Void areas indicate reflector termination by onlap/downlap onto MMU mobilized mound. Note low-angle south-westerly dip and much lower relief than the underlying MMU structure (Figure 4.9 a). (b) Isochore map between MMU and U1 horizon showing thinning over MMU topography, indicative that deformation of the MMU occurred before deposition of the lower Utsira sediments.

Figure 5.7. MMU time-structure map with white ticks representing downlap reflection terminations onto the positive topography of the deformed surface. The rotation of intra-Utsira reflectors downwards onto underlying mounds indicates that after deposition of the Utsira sediments mounded areas of UHG consolidated greater than flat-lying areas. Downlapping reflection terminations in flat areas are due to westward dipping clinoforms.

reveals this relationship is pervasive and constrained by the presence of mounded MMU topography. Individual reflection events are seen to maintain their depositional dip until they approach a mound, whereby the dip of the reflector rotates downwards before abruptly terminating onto the peak of the underlying mound. In addition to the downlapping reflection terminations, more continuous reflectors higher up in the sequence form concave-upward, dish-shaped depression above underlying mounds. In cross-section these appear as synclines and directly mirror the underlying mounded topography. The vertical extent of the depressions continues through the entire Utsira Formation, Utsira wedge and into the lowermost late Pliocene sediments. A time-structure map for intra-Utsira reflector U2 illustrates the distribution of the down-folded Utsira deposits (Figure 5.8). A close correlation with the structure of the MMU suggests the depressions formed in response to enhanced consolidation of the MMU mounded regions. Compaction of the mounds would lead to an associated volume loss, causing pre-compaction Utsira sediments to collapse and fill the underlying void. The timing of mound consolidation was coeval with sedimentation of the Utsira Formation and overlying Plio-Pleistocene sediments. Several examples of thickening packages and onlapping sequences fill the core of the depressions. An isochore map between U2 and top Utsira Formation shows the thickening of Utsira sediments in regions above MMU mounds (Figure 5.9 b).

Figure 5.8. Time structure map for the intra Utsira U2 reflector. Dip is low-angle to the south and south west. Rotation and collapse of reflector above MMU mounds indicates the mounds were consolidating more than the surrounding relatively flat-lying MMU areas during deposition of the upper part of the Utsira Formation.

Figure 5.9. (a). Isochore map between U1 and U2 horizons. Between these two intra-Utsira horizons variations in thickness are much less pronounced than in the lower Utsira (MMU-U1). Voids indicate gaps in U1 horizon due to onlap/downlap. (b) Isochore map between intra Utsira U2 and top Utsira Formation. The Upper Utsira Formation is also relatively isochronous, apart from areas of thickening associated with syn-kinematic depositional units filling areas of enhanced consolidation above MMU mounds. Note this thickness variation is the reverse trend seen in the lower Utsira isochore map (Figure 5.6 b)

Formation of the depressed regions of Utsira Formation has led to the creation of 'mounded', convex-upward regions of Utsira Formation within intra- MMU- mound areas that are situated above complex MMU mounded regions. The positive structure of these features is created by marginal downward bed rotation towards nearby mounds. This observation is most pronounced in the east where the morphology of the MMU mounds is more intricate. It should be noted at this point that the 15/9-A-16 well injection site is located in such an area.

5.5 Central and Upper Utsira Formation Depositional Framework

The central and upper regions of the Utsira Formation represent a relatively continuous succession of westward accreting sedimentary fill. Isochore maps extracted between the intra-Utsira picked horizons, U1 and U2, and U2 to top Utsira Formation horizon show thicknesses are far more uniform than the Lower Utsira successions. The influence of underlying MMU mounds no longer represented areas of non-deposition, but instead their enhanced consolidation actually created accommodation space for Utsira sand to fill.

5.6 Upper Shale Layer

Separating the Utsira Sand from the upper Utsira Sand Wedge is a fairly consistently thick (c. 5-6m) and laterally continuous shale bed (Figure 5.1). High, spiky gamma-ray responses are typical along with a decrease in sonic travel-time, and wireline-log data show an abrupt upward transition from the underlying blocky, low gamma-ray sandstones. These characteristics lead to the interpretation that the transition from sand to shale represents a marine-flooding surface, heralding the initial deposition of the more mud-prone and deeper marine facies of the late Pliocene and glaciomarine facies of the Pleistocene. It was at this time, during the late Pliocene, that basin subsidence rates increased, increasing relative sea level and effectively shutting off, or restricting sand deposition to more landward regions (Fyfe *et al.*, 2003).

A time-structure map for the picked shale horizon shows low angle dip to the east along with subtly depressed areas that correspond to mounded parts of the MMU (Figure 5.10a).

5.7 Utsira Wedge

In seismic the upper most sand prone unit of the Utsira Formation is a wedge-shaped package that thickens to the west and has a north-south pinch-out line that lies roughly in the centre of the study area (Figure 5.10). This unit overlies the 6.5 metre shale found at the top of the main Utsira Sand Body and represents temporary re-establishment of a sand-dominated depositional system, at least in eastern areas. The top and base of the unit are uneven and have an overall low angle dip to the south west. They also show subtle bowl and more amorphous shaped synclines that can be correlated to underlying mounds on the MMU.

A key difference between the top and base wedge time-structure maps is the presence of a north-south trending ridge protruding from a high area to the north, and pinching out into lower lying regions in the south. This ridge is present on the top wedge structure and is c.12 km long by c. 4 km wide. It appears to be a large relict

Figure 5.10. (a) Time structure map for base Utsira Fm. Wedge (Upper 6.5m shale). (b) Time structure map for top Utsira Formation (PFS). The Ridge structure marked is a pronounced feature on the Top Utsira Formation causing the Isochore (Figure 5.11) to thicken in time. It is interpreted to represent a first-order, very large migrating sandwave that was migrating from the east basinward towards the crest of the underlying Utsira Sand body.

depositional mound form due to its positive top structure. Galloway (2001, 2002) and Chadwick (2004) observed on a more regional scale the uneven and mounded form of the Utsira Formation top surface. Accompanying the linear ridge are structural lows above underlying MMU mounds, confirming the continued deflation of the UHG sand filled mounds at the time of Utsira wedge deposition. An isochore map extracted between these two surfaces shows the north-south trend of the pinch-out line, the eastward thickening of the sand wedge and thickening accompanied by the curvi-linear ridge form (Figure 5.11).

Figure 5.11. Isochore map for upper Utsira Sand Wedge. The pinch-out line is irregular and trends north to south. From this line the wedge thickens in an eastwards direction. An area of thinning above the marked mound in the east is accompanied by a curvi-linear ridge, or channel shaped feature of thickening.

Correlating the wedge in well and seismic data is straightforward due to the pronounced change in gamma ray and sonic response, and the distinct high amplitude acoustic reflectors that result from the upper and lower, shale-sand, sand-shale interfaces. Detailed studies of seismic data using volumetric based attribute analysis (e.g. amplitude extraction and coherency) did not resolve any internal

features of the wedge owing, presumably, to the predominantly consistent rock-properties of the unit.

Well data show a sharp contact with the underlying shale unit and the overlying Pliocene mudstones, and the characteristic gamma ray response is blocky and shows no fining-up or coarsening upward trends. Grain size analysis from well 15/9-13 confirms quartz grain sizes are relatively consistent and average 150 microns, indicative of fine sand. Mineralogical studies reveal the lowest parts of the wedge contain an enhanced content of the iron silicate mineral glauconite, a trend also noted at the base of the main Utsira Sand body. These observations are diagnostic of slow deposition in a marine continental shelf environment, perhaps analogous to the Upper Jurassic/Lowermost Cretaceous glauconite-rich Greensand deposits found outcropping in the Wessex Basin, Dorset, UK. Head *et al.*, (2004) interpret a transgressive motif to the Upper parts of the Utsira Formation on the basis of incoming glauconitic deposits and an increase in shale bed thickness and occurrence. The lack of grain sorting, blocky gamma-ray response and presence of the calcareous benthic foram *C. Grossus* in well 15/9-13 indicate a relatively high energy submarine environment at the time of deposition. Similar to that of the main Utsira Sand body.

5.8 Utsira Formation in the vicinity of the 15/9-A-16 well injection point

The 15/9-A-16 CO₂ injection site is positioned within one of the thicker areas of Utsira Formation (>250 meters), where the MMU is low-lying. Surrounding the deeper region, mainly to the east and west are MMU mounds which can reach up to approximately 110 metres high above mean MMU level. All three main Utsira Formation units are present in the vicinity of the injection point. The time-structure maps for both the top of the Utsira Sand and top Utsira Formation show positive topography, favourable for entrapment of injected CO₂. The lows underlying the injected CO₂ are favourable for capture of the CO₂ once it has dissolved into the formation waters and descended to pool at the base of the reservoir. Current reservoir models have incorporated these gross-features, however work carried out on the horizons during this project have further refined them to a higher resolution, manually picked grid, helping to pick out more structural subtleties.

The internal characteristics of the Utsira Formation are fairly complex in the vicinity of the CO₂ injection point. The close proximity of underlying MMU mounds to the east and west means the internal reflectors are folded and appear convex upward in east-west seismic cross-sections. North to south transects reveal more flat-lying and wavy discontinuous reflectors. Reflection events are generally discontinuous, exhibit erosional truncations and also onlapping reflection terminations in association with the infilling of the bowl shaped depressions.

Seismic data collected in 2006 over the injection site gives a clearer picture of the internal reflection geometries due to the enhanced resolution provided by the presence of CO₂ (Figure 5.13). Numerous reflection events are observed to die out laterally, or truncate onto other reflectors. Others are through-going and maintain high-amplitudes.

5.9 Application of 4D seismic to Utsira Geological Model

Although the 3D seismic data allows a detailed picture of the gross-structure of the Utsira Formation and its internal geometries to be established, 4D data allow more in depth analysis in the immediate vicinity of the plume due to the effect of CO₂ enhancing seismic resolution; and the temporal evolution of the plume shown in 4D data gives insights into migration baffles and preferred migration routes. 4D data show that by 1999 the CO₂ had already breached the c. 6.5m shale layer and entered the Utsira Formation wedge. Once the CO₂ reached the Utsira wedge it spread laterally following the structural relief of the wedge top surface. The temporal development in its areal distribution is shown in Figure 5.12.

Figure 5.12. Temporal plume development superimposed onto the top Utsira Formation time-structure map (courtesy of Brodahl).

Bright reflection events occur through all levels of the Utsira Formation, from injection point to top Utsira wedge and represent the accumulation of CO₂ beneath intra-formational shale layers. These were mapped out in intricate detail to reveal the areal distribution of CO₂ at various intervals throughout the Utsira Formation for the 2001-1994 (Figure 5.14) and 2006-1994 (Figure 5.15) 4D vintages. From applying this process it became apparent that many of the accumulations are small and discontinuous and appear to represent the pooling of CO₂ beneath somewhat laterally restricted shale layers. Several of the accumulations are however much more extensive and continuous, indicating more significant barriers to CO₂ migration (Figure 5.13).

Analyses of seismic facies from the 4D data reveal clear laterally discontinuous

Figure 5.13. Utsira Formation intra-formational reflectors are picked out in greater resolution by the presence of injected CO₂. (a) Baseline 2004 3D survey through the future injection site. Internal reflection events are reasonably well defined, but when compared to the 4D response from 2001 (b), 2004 (c) and 2006 (d) greater definition can be made. Reflection events are both continuous and discontinuous indicating pooling of CO₂ beneath intra-formational shale layers. 1 – Laterally continuous reflection events, 2 – laterally discontinuous reflection events, 3 – possible fill in to a scour – 4. 5 – Velocity pull-down anomaly from reduced sonic transit time through the CO₂ plume. Left - Amplitude map showing plume extent by 2006 and the location of the lines shown above.

reflectors that appear to represent a lateral change in lithology. Due to the relatively small period of time it took for CO₂ to reach the top of the Formation (c. 3 years after injection began) it must be inferred that the shale layers within the Utsira Formation do not represent significant barriers to the migration of CO₂ but are baffles.

6. Discussion – Geological Evolution of the Upper Hordaland to late Pliocene interval in the vicinity of Sleipner

Based on the observations and interpretations made for the Upper Hordaland Group to top Utsira Formation interval, the following geological model is preferred.

From the Cretaceous period the region underwent post-rift thermal subsidence, with the resultant post-Cretaceous sedimentary succession being dominated by thick successions of argillaceous sediments, punctuated by phases of coarse clastic supply from gravity flow processes. During the upper Oligocene dehydration of the smectite-rich Upper Hordaland Group shales during diagenesis led to the development of a pervasive polygonal normal fault network (Løseth, 2003). Associated with faulting are syn-kinematic growth-units that thicken towards the footwalls of fault blocks. The slightly listric form of these faults caused fault block rotation and the accommodation space necessary for the wedge shaped growth units to be deposited in.

On a regional scale at this time minor basin margin uplift to the east (Fyfe *et al.*, 2003) subtly eroded some of the Upper Hordaland deposits forming the IHU and also rejuvenated coarse clastic sediments derived from raised provenance areas to the east. Locally, the result of increased clastic sediment supply led to the deposition of Skade Formation sandstones in deep water fans (Figure 6.1-1) (Fyfe *et al.*, 2003).

Polygonal faulting ceased during the Late Oligocene to early Miocene and a fall in eustatic sea-level accompanied by tectonically induced basin margin uplift led to the formation of the MMU. During the hiatus, or during polygonal fault formation/reactivation it is likely that gas sourced from deeper basinal sediments in the oil/gas generative window and leaking hydrocarbon traps flowed vertically through the polygonal faults, which acted as conduits for subsurface fluid migration (Cosgrove & Hillier, 2000). Evidence for this process comes from sand-injectites found within Tertiary basin fill at c. 2000-2200ms TWT (Figure 4.2) that manifest themselves as V-Brights in seismic; and 'gas chimneys' observed in seismic by Løseth (2003); Jackson & Stoddart (2005); and Jackson (2002), that emanate from deep, underlying structural hydrocarbon traps upwards into the Cenozoic basin fill in other parts of the Viking Graben. Gas flowed vertically along fault planes and charged the poorly consolidated Skade Formation sandstones. Continued deposition of Upper Hordaland shales sealed the gas/water mixture into the un-cohesive Skade sands leading to disequilibrium compaction and an increase in pore-fluid pressure in a process best described by Cosgrove & Hillier (2000), Løseth (2003) and Jackson (2007). Owing to the relatively shallow depth of burial, high fluid pressures and poor consolidation, the Skade sands and surrounding mudstones became mobilised and began to deform removing the original depositional architecture.

Ductile mass sand and mud movement occurred on a large scale, forming massive bodies of sand that folded and uplifted overlying sediments into sand and mud-filled mounds (Figure 6.1-2). Løseth (2003) notes the ductile qualities and weakness of smectite rich Upper Hordaland mudstones. Despite the weak and ductile properties of Upper Hordaland shales the increase in fluid pressure appears to have also encouraged brittle failure and sand injection into reactivated polygonal faults, leading to the observed

Figure 6.1. Simplified geological model of Upper Hordaland Group to Pliocene sediments in the Sleipner area, south Viking Graben.

V-Brights with associated reverse fault bound, upturned saucer shaped blocks that protrude above the MMU. An analogous process in theory has been described by Cosgrove & Hillier in the formation of 'forced folds' over conical sandstone intrusions and Hansen & Cartwright (2006) in the 'formation of forced-folds above saucer shaped igneous sills'. The conical shape of the sand injectites and their thinning towards their outer edges have a similar geometry to said 'saucer shaped sills' and a comparison by Cosgrove & Hillier (2000) to sand injections indicates a similar process of emplacement and resultant structural deformation. The product of soft-sedimentary deformation of the Upper Hordaland Group is the mounded structure of the MMU, which was present as a deformed palaeoseafloor during the late Oligocene to mid-Miocene depositional hiatus.

Clastic sediment supply rejuvenation was associated with basin margin uplift and relative sea-level fall. Westward accreting shelfal sands of the lower Utsira Formation filled the underlying mounded topography of the MMU as is clearly shown by the onlap and downlap reflection terminations and abrupt thinning of lower Utsira sequences onto the mounds (Figure 6.1-3). Detailed seismic facies analysis show abundant high-energy

depositional features consistent with Galloway's (2001, 2002) interpretation of the Utsira Formation representing a lowstand shelfal sand shoal.

Sustained slow deposition of the Utsira Formation loaded the gas and fluid charged mobilized sand and mud masses causing them to release their bound fluids (Jackson, 2007 postulated this mechanism to disequilibrium compaction observed in the Løvre Terrace). Pre-existing faults created during polygonal faulting and sediment mobilization probably aided this process. Associated enhanced consolidation and deflation of the mounded Upper Hordaland Group areas lead to subsidence of overlying Utsira sediments causing bed rotation and downlap onto mound crests, and the formation of bowl-shaped synclines that mirror underlying MMU mounds (Figure 6.1-4). This process was coeval with mid- late Utsira Formation deposition and persisted into the Plio-Pleistocene, where thickening packages are clearly visible filling the voids.

A phase of clastic sedimentation supply cessation or relative sea-level rise allowed deposition of the upper 5 - 6.5m shale to be deposited onto the uneven and 'mounded' Utsira sand body (Figure 6.1-5). This was followed by a pulse of rejuvenated sand supply from the east, depositing the eastward thickening Utsira sand wedge. The thickness of the wedge was very closely controlled by the morphology of the top of the Utsira sand body, which has a structural high in central parts of the area covered by the survey, and dips to the east and west from this roughly north-south trending high. The wedge pinch-out line can be attributed to the location of this high, where the sand wedge prograded to. In light of the fact that the pinch-out line follows roughly the trend of the underlying Utsira Sand top structural high suggests it reached the crest, passed over and bypassed the westward dipping slope to be deposited further basinward. Unfortunately the limitations of the dataset do not allow this hypothesis to be tested.

After the limited phase of Utsira wedge sedimentation, basin subsidence rates rapidly increased causing relative sea-level rise, a reduction in sedimentation energy and a shut down in clastic sediment supply. This major flooding event represents the PFS and was succeeded by argillaceous marine and glacio-marine sediments (Figure 6.1-6). Continued UHG consolidation occurred into these sequences. Perhaps a relic of gas release during UHG consolidation is the abundant shallow gas found present in the Plio-Pleistocene sediments. These appear conspicuously in seismic data as bright anomalies, and their interpretation as gas has been confirmed in well samples. Unfortunately the distribution of shallow gas does not correlate to underlying UHG mounds, but it probably more resembles the distribution of porosity and permeability in the Plio-Pleistocene successions.

7. Conclusions

- Seismic data from the Sleipner area shows that Upper Hordaland Group sequences have undergone extensive post-depositional soft-sedimentary deformation, resulting in the deformed Middle Miocene Unconformity.
- The combined analysis of well and seismic data indicate that the main lithology to undergo mobilization are deep marine fan sands of the Upper Hordaland Group Skade Formation, with subordinate mobilization of accompanying UHG shales.
- Skade Formation sands are thickest beneath mounded MMU areas where they either appear as massive amalgamated units that do not show characteristic seismic features of a deep marine fan (i.e. 'gull-wing' shaped channel-levee systems, bi-directional downlap), or as conical-shaped sand intrusions.
- The phase of soft sedimentary mobilization occurred during erosion/hiatus in the Lower Miocene, deforming the palaeoseafloor.
- Rejuvenated clastic sediment supply in the Late Miocene led to the deposition of the south-westerly prograding Utsira Formation, which onlapped and filled in lows on the deformed MMU.
- Seismic facies analysis of the Utsira Formation shows that both the depositional environment for the Utsira Formation and the structural evolution of underlying UHG sand and mud mounds have influenced reservoir architecture.
- Stratal elements in the Utsira Formation include: low-angle south westward dipping clinoforms and sigmoidal clinoforms, through going surfaces, large-scale asymmetrical accretionary sand waves, low-amplitude scours with fill, laterally discontinuous layers, wavy layers and low-displacement faults.
- Loading of the deformed MMU led to enhanced consolidation of mobilized mounds and rotation of bedding within the Utsira Formation. This created downlapping reflection termination events onto the crest of mobilized mounds, localized sagging within Utsira and post Utsira sediments, syn-kinematic infilling above the mobilized mounds, and convex upward folding of intra-Utsira areas flanked by underlying MMU mounds (e.g. in the vicinity of the CO₂ injection point).
- This enhanced consolidation continued into the Plio-Pleistocene where the presence of shallow gas may indicate that UHG mound consolidation was promoted by the expulsion of the fluids and gas emplaced during mobilization.
- 4D seismic data show the development of the injected CO₂.
- Even though the Utsira has remarkably high sand content (0.98 Net:Gross at Sleipner) it is apparent that the CO₂ pools beneath intra-formational shale layers that have been folded during surrounding MMU mound consolidation.
- The increase in seismic resolution reveals that the shale-layers responsible for slowing the upward migration of CO₂ could be discontinuous due to lateral termination of acoustic reflection events. This fits the high-energy depositional model where erosion of shale beds may have occurred in abundance. Furthermore the increase in seismic resolution improves confidence in the 3D interpretation of intra-formational layering within the Utsira Formation.

8. References

- Arts, R., Eiken, O., Chadwick, A., Zweigel, P., van der Meer, L., and Zinszner, B. 2004. Monitoring of CO₂ injected at Sleipner using time-lapse seismic data. *Energy*, 29. 1383-1392.
- Briedis, N. A., Bergslien, D., Hjelbakk, A., Hill, R. E. and Moir, G. J. 2007. Recognition Criteria, Significance to Field Performance, and reservoir Modelling of Sand Injections on the Balder Field, North Sea. In Hurst, A. and Cartwright, J. eds., *Sand Injectites: Implications for hydrocarbon exploration and production*. AAPG Memoir 87. 91-102.
- Cartwright, J. A. 1994. Episodic basin-wide hydrofracturing of overpressured shale sequences in the North Sea basin. *Marine and Petroleum Geology*, 11. 587-607.
- Cosgrove, J. W. and Hillier, R. D. 2000. Forced-fold development within Tertiary sediments of the Alba Field, UKCS: evidence of differential compaction and post-depositional sandstone remobilization. In Cosgrove, J. W. and Ameen, M. S. (Eds). *Forced Folds and Fractures*. Geological Society, London, Special Publications, 169. 61-71.
- Cosgrove, J. W. 2001. Hydraulic fracturing during the formation and deformation of a basin: A factor in the dewatering of low-permeability sediments. *AAPG Bulletin*, 85-4. 737-748.
- Deegan, C. E. and Scull, B. J. 1997. A proposed standard lithostratigraphic nomenclature for the Central and Northern North Sea. Report of the Institute of Geological Sciences, No. 77/25. Bulletin of the Norwegian Petroleum Directorate, No. 1.
- Eidvin, T., Riis, F. and Rundberg, Y. 1999. Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields). *Norsk Geologisk Tidsskrift*, 79. 97-128.
- Eidvin, T., Rundberg, Y., Smelror, M. 2002. Revised chronology of Neogene sands (Utsira and Skade Formations) in the central and northern North Sea. In Hurst, A. (Ed.), *Onshore-offshore relationships on the Nordic Atlantic margin*, v. 2. pp. 51-53. Abstracts and Proceedings of the Norwegian Geological Society (Norsk Geologisk Forening).
- Fyfe, J. A., Gregersen, U., Jordt, H., Rundberg, Y., Eidvin, T., Evans, D., Stewart, D., Hovland, M. and Andresen, P. 2003. Oligocene to Holocene, in Evans, D., Graham, C., Armour, A. and Bathurst, P., (eds). *The Millennium Atlas: petroleum geology of the central and northern North Sea*. London: The Geological Society of London. 279-287.
- Galloway, W. E. 2001. Seismic expressions of deep-shelf depositional and erosional morphologies, Miocene Utsira formation, North Sea Basin. *Marine Geophysical Researches*, 22. 309-321.

- Galloway, W. E. 2002. Palaeogeographic setting and depositional architecture of a sand-dominated shelf depositional system, Miocene Utsira Formation, North Sea Basin. *Journal of Sedimentary Research*, 72. 476-490.
- Ghazi, S. A. 1992. Cenozoic uplift in the Stord Basin area and its consequences for exploration. *Norsk Geologisk Tidsskrift*, 72. 285-290.
- Gregersen, U., Michelsen, O. and Sørensen, J. C. 1997. Stratigraphy and facies distribution of the Utsira Formation and the Pliocene sequences in the northern North Sea. *Marine and Petroleum Geology*, 14. 893-914.
- Gregersen, U. 1998. Upper Cenozoic channels and fans on 3D seismic data in the northern Norwegian North Sea. *Petroleum Geoscience*, 4. 893-914.
- Gregersen, U. and Johannessen, P. N. 2007. Distribution of the Neogene Utsira Sand and the succeeding deposits in the Viking Graben area, North Sea. *Marine and Petroleum Geology*, 24. 591-606.
- Hansen, D. M. and Cartwright, J. 2006. The three-dimensional geometry and growth of forced folds above saucer-shaped igneous sills. *Journal of Structural Geology*, 28. 1520-1535.
- Head, M.J., Riding, J. B., Eidvin, T. and Chadwick, R. W. 2004. Palynological and foraminiferal biostratigraphy of (Upper Pliocene) Nordland Group mudstones at Sleipner, northern North Sea. *Marine and Petroleum Geology*, 21. 277-297.
- Holloway, S. 2005. Underground sequestration of carbon dioxide – a viable greenhouse gas mitigation option. *Energy*, 20. 2318-2333.
- Hurst, A. and Cartwright, J. 2007. Relevance of Sand Injectites to Hydrocarbon Exploration and Production. In Hurst, A. and Cartwright, J. (eds) *Sand injectites: Implications for hydrocarbon exploration and production*. AAPG Memoir 87. 1-19.
- Isaksen, G. H. and Tonstad, K. 1989. A revised Cretaceous and Tertiary lithostratigraphic nomenclature for the Norwegian North Sea. *Bulletin of Norwegian Petroleum Directorate*, No. 5.
- Jackson, C. A. L. 2007. Application of three-dimensional seismic data to documenting the scale, geometry and distribution of soft-sediment features in sedimentary basins: an example from the Lomre Terrace, offshore Norway. In: Davies, R. J., Posamentier, H. W., Wood, L. J. and Cartwright, J. A. (eds). *Seismic Geomorphology: Applications to Hydrocarbon Exploration and Production*. Geological Society, London, Special Publications, 277. 253-267.
- Jackson, C. and Stoddart, D. 2005. Temporal constraints on the growth and decay of large-scale mobilized mud masses and implications for fluid flow mapping in sedimentary basins. *Terra Nova*, 17. 580-585.
- Johnson, H. D. and Baldwin, C. T. 1996. Shallow clastic seas. In Reading, H. G. (ed) *Sedimentary Environments: Processes, Facies and Stratigraphy*. Third Edition. Blackwell. Oxford. 232-280.

- Jordt, H., Faleide, J. L., Bjørlykke, K. & Ibrahim, M. T. 1995. Cenozoic sequence stratigraphy of the Central and Northern North Sea Basin: tectonic development, sediment distribution and provenance areas. *Marine and Petroleum Geology*, 12. 845-879.
- Kirby, G. A., Chadwick, R. A. and Holloway, S. 2001. Depth mapping and characterisation of the Utsira Sand Saline Aquifer, Central and Northern North Sea. British Geological Survey Commissioned Report, CR/01/218. 26pp.
- Larsen, M. 1994. The Balder field: Refined reservoir interpretation with the aid of high resolution seismic data and seismic attribute mapping. *North sea oil and gas Reservoirs – III*, Kluwer Academic Publishers, 115-124.
- Løseth, H., Wensaas, L., Arntsen, B. and Hovland, M. 2003. Gas and fluid injection triggering shallow mud mobilization in the Hordaland Group, North Sea. In Van Rensbergen, P., Hillis, R. R., Maltman, A. J. and Morley, C. K. (eds), *Subsurface Sediment Mobilization*. Geological Society Special Publications, 216. 139-157.
- Martinsen, O. J., Bøen, F., Charnock, M. A., Mangurud, G. and Nøttvedt, A. 1999. Cenozoic development of the Norwegian margin 60-64°N: sequences and sedimentary response to variable basin physiography and tectonic setting. In Fleet, A. J. and Boffy, S. A. R. (eds) *Petroleum Geology of Northeast Europe: Proceedings of the 5th Conference*. 293-304.
- Piasecki, S., Gregersen, U. and Johannessen, P. N. 2002. Lower Pliocene dinoflagellate cysts from cored Utsira formation in the Viking Graben, northern North Sea. *Marine and Petroleum Geology*, 19. 55-67.
- Rundberg, Y. 1989. Tertiary sedimentary history and basin evolution of the Norwegian North Sea between 60°N - 62° N – an integrated approach. Unpublished Dr. Ling thesis. University of Trondheim, Norway, (Reprinted 1991 in report of the Institute for Geology and Rock Mechanics, University of Trondheim, Norway, No. 25).
- Sheriff, R. E., and Geldart, L.P. 1995. *Exploration Seismology* – 2nd ed. Cambridge University Press. pp 592.
- Shoulders, S. J. and Cartwright, J. 2004. Constraining the depth and timing of large-scale conical sandstone intrusions. *Geology*, 32-8. 661-664.
- Shoulders, S. J., Cartwright, J. and Huus, M. 2007. Large-scale conical sandstone intrusions and polygonal fault systems in Tranche 6, Faroe-Shetland Basin. *Marine and Petroleum Geology*, 24. 173-188.
- Stow, D. A. V., Reading, H. G. and Collinson, J. D. 1996. Deep Seas. In Reading, H. G. (ed) *Sedimentary Environments: Processes, Facies and Stratigraphy*. Third Edition. Blackwell. Oxford. 395-453.
- Torp, T. A., and Gale, J. 2004. Demonstrating storage of CO₂ in geological reservoirs: The Sleipner and SACS projects. *Energy*, 29. 1361-1369.

- Wilkinson, I. P. 1999. Biostratigraphical and palaeo-ecological application of calcareous microfaunas from the Utsira Formation in Norwegian Well 15/9A-23. British Geological Survey Technical Report, Stratigraphic Series No. WH99/124R, BGS, Keyworth, UK.
- Zanella, E. & Coward, M.P. 2003. Structural Framework. in: Evans, D., Graham, C., Armour, A. & Bathurst, P., (eds). The Millennium Atlas: petroleum geology of the central and northern North Sea. London: The Geological society of London. 45-59.
- Ziegler, P. A. 1981. Evolution of sedimentary basins in north-west Europe. in: Illing, L. V. and Hobson, G. D. (eds). Petroleum geology of the continental shelf of North-West Europe. London: Heyden and Son. 3-39.

Appendix 1

Average frequency and velocity for the Utsira Formation.

Figure A-1.1. Power spectrum for the Utsira Formation interval across the study area. Dominant frequency in the range 20 – 50 Hz. Average frequency c. 40 Hz.

Well	TVD (m)			TWT (ms)		OWT (ms)	Average Velocity (m/s)
	Top Utsira	Base Utsira	Interval	Top Utsira	Base Utsira	Interval	
15/9-10	884	1102	218	924	1139	107,5	2027,91
15/9-11	825	1099	274	870	1126	128	2140,63
15/9-13	847	1053	206	890	1081	95,5	2157,07
15/9-15	883,5	1129	245,5	927	1161	117	2098,29
15/9-16	842,9	1088	245,1	889	1119	115	2131,30
15/9-17	832	1045	213	856	1063	103,5	2057,97
15/9-18	865,5	1105,5	240	906	1134	114	2105,26
15/9-19 SR	847,8	1107,5	259,7	873	1085	106	2450,00
15/9- 8	863	1176	313	901	1148	123,5	2534,41
15/9-9	844	1092	248	880	1135	127,5	1945,10
15/9-A-11	886	1125,5	239,5	872	1103	115,5	2073,59
15/9-A-16	909	1164	255	894	1135	120,5	2116,18
15/9-A-23	896	1142	246	878	1108	115	2139,13
15/9-A-24	883,5	1142,5	259	865	1117	126	2055,56
15/9-A-28	890	1068	178	874	1044	85	2094,12
15/9-A-9	888,5	1123	234,5	871	1102	115,5	2030,30
15/9-C-2 H	841,5	1053	211,5	866	1072	103	2053,40
15/9-D-1 H	834	1078	244	875	1111	118	2067,80
15/9-D-3 H	747	1061,5	314,5	872	1095	111,5	2820,63
15/9-F-12 pilot	882	1065,5	183,5	875	1056	90,5	2027,62
15/9-F-7	883	1064	181	878	1079	100,5	1801,00

Average (Mean) Velocity (m/s) = 2105,33

Appendix 2

Calculating water-depth from a sigmoidal clinoform:

Figure A-2.1

By applying the theory that the position of clinoform topsets more or less represent base level (i.e. sea-level), and that bottomsets represent the basin/platform floor, palaeo-water depths can be calculated from the amplitude of sigmoidal clinoforms.

To calculate rough palaeo-water depths for the lower Utsira Formation the amplitude of sigmoidal clinoforms were measured in two-way travel time (TWT), divided by two to get their amplitude in one-way travel time, and then multiplied by the average velocity of the Utsira Formation (see Appendix 1).

For Example:

Cliniform A in Figure 5.3 (a) has its topset at 1052 ms TWT and bottomset at 1136 ms TWT.

Taking the average velocity of the Utsira Formation to be 1200 m s^{-2} the palaeo-water depth is:

$$\text{Cliniform amplitude (OWT)} = (1136 - 1052)/2 = \underline{42\text{ms}}$$

$$0.042 \times 2100 = 88.2 \text{ or c. } \underline{90 \text{ meters}}$$

Appendix 3

Skade Formation seismic correlation without interpretation

Figure A-3.1

Appendix 4a

Trace 3089

Figure A-4.1

Appendix 4b

Line 3874

Figure A-4.2

Appendix 4c

Line 2904

Figure A-4.3