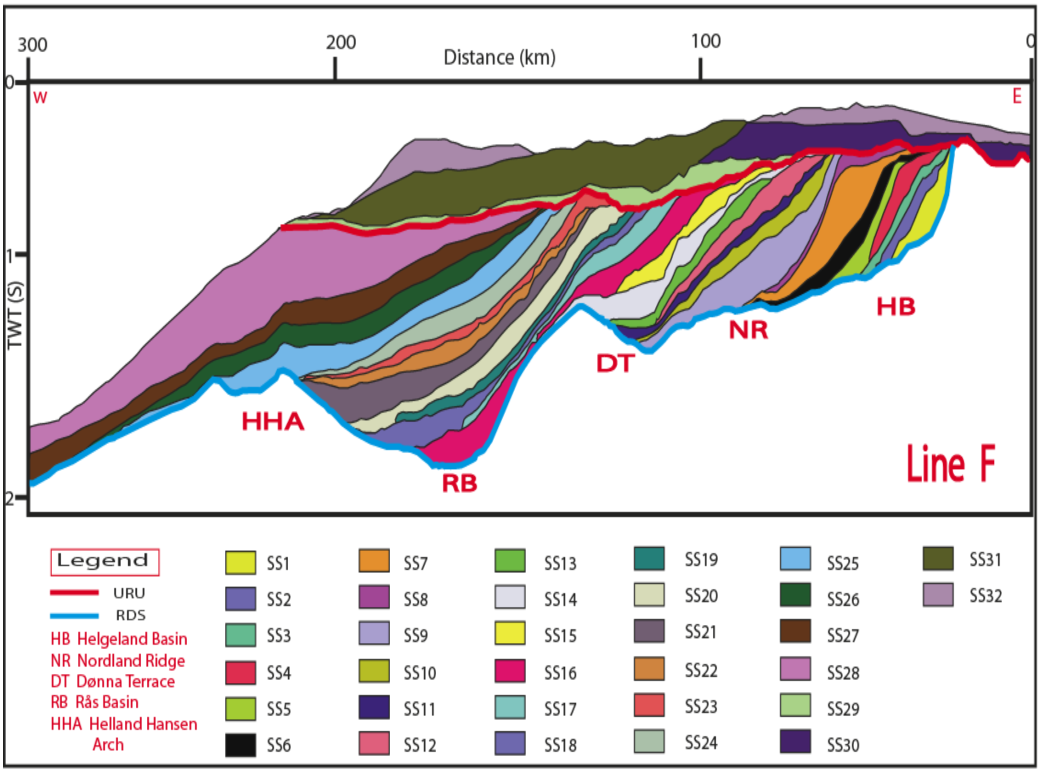
Master Thesis in Geosciences

# Late Cenozoic Sedimentary Outbuilding Offshore Mid-Norway: A Sequence Stratigraphic Analysis

By

**Amer Hafeez**



UNIVERSITY OF OSLO

FACULTY OF MATHEMATICS AND NATURAL SCIENCES

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# Abstract

Geologically the mid-Norwegian continental shelf (62°-69°30’N) has undergone several phases of rifting, uplifting and erosion, but the present shape of the shelf/margin developed during Plio/Pleistocene time. During late Neogene a thick succession of Naust Formation prograded westward. This prograding wedge built out as an interaction of several processes like climatic fluctuations, relative sea level changes, glacial processes, basin infill and development of continental ice sheets in Scandinavia.

The purpose of this study is to do sequence stratigraphic analysis of the Late-Cenozoic outbuilding. Ten 2D seismic lines of high resolution from offshore mid-Norway were interpreted. Sequence stratigraphic analysis reveals 32 seismic sequences developed by 30 glaciation during last 2.8 m.y. Facies analysis describes different kinds of sedimentary environments that was active during deposition of Naust Formation.

Ages of the seismic sequences within the Naust Formation (2.8Ma-Present) have been interpolated between key horizons dated in previous studies. The known glaciations from Iceland and Svalbard margin are correlated with this study. The correlations indicate chances of more glaciations during last 2.8 m.y than resolved by the existing date from Iceland and Svalbard margins if high resolution data is available.

Relative sea level changes occurred frequently during deposition of the Naust Formation. During early Naust time (SS1-SS13) the depocentre was northeastern Vøring Basin and northeastern Trøndelag Platform which gradually shifted towards the south with increase in sedimentation rate. After URU the tilting of the continental margin stopped and accommodation space was created by sea level changes and sediment loading resulting in the development of aggradating and weakly progradating stacking pattern.

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# 1. Introduction

The area off shore mid-Norway which lies between (62°-69°30'N) is known as the mid-Norwegian Continental Shelf (Fig. 1.1).

In the geological history, the mid Norwegian Continental Shelf has experienced several phases of rifting, uplifting and erosion. But the present shape of the mid Norwegian Continental Shelf was developed during Neogene, especially in Pliocene-Pleistocene. The shelf succession progaded by deposition of huge amounts of glacially derived sediments consisting of glacial debris and till. The clastic wedges and prograding clinotherms built out offshore mid-Norway. Previous studies show that, this large scale out building is the result of interaction of various processes like uplifting of mainland Norway, climatic fluctuations, sea level changes, glacial processes, basin infill and development of continental ice sheets in Scandinavia.

The purpose of my master thesis is to study this Late Cenozoic outbuilding offshore mid-Norway by sequence stratigraphic analysis. Further ahead I will relate this study to a discussion of uplift and erosion of the Norwegian mainland. The sequence stratigraphic analysis will be carried out on depth-distance seismic stratigraphic sections and time-distance diagrams (chronostartigraphic or wheeler-transform chart). The structural geology and stratigraphic studies of the mid-Norwegian continental shelf has been the object of many studies e.g Bukovics et al. (1984); Blystad et al. (1995); Brekke (2000); Faleide et al. (2002); Sejrup et al. (2004); Conrad et al., (2004); Stoker et al. (2005) & Smelror et al. (2007). Most of these studies are regional except few detailed studies. The project will pay special attention to the sequence stratigraphical evolution of the late Cenozoic succession.

The Cenozoic continental shelf offshore Norway is a shelf succession that has prograded westward e.g Solheim et al. (1996); Dahlgren et al. (2002b & 2005); Rise et al. (2005); Løseth et al. (2005) & Rise et al. (2010). The outbuilding of the shelf can be delineated in several stages defined by events of erosion and renewed deposition. The identification of surfaces like erosional unconformities, transgressive surfaces, maximum flooding surfaces and condensed

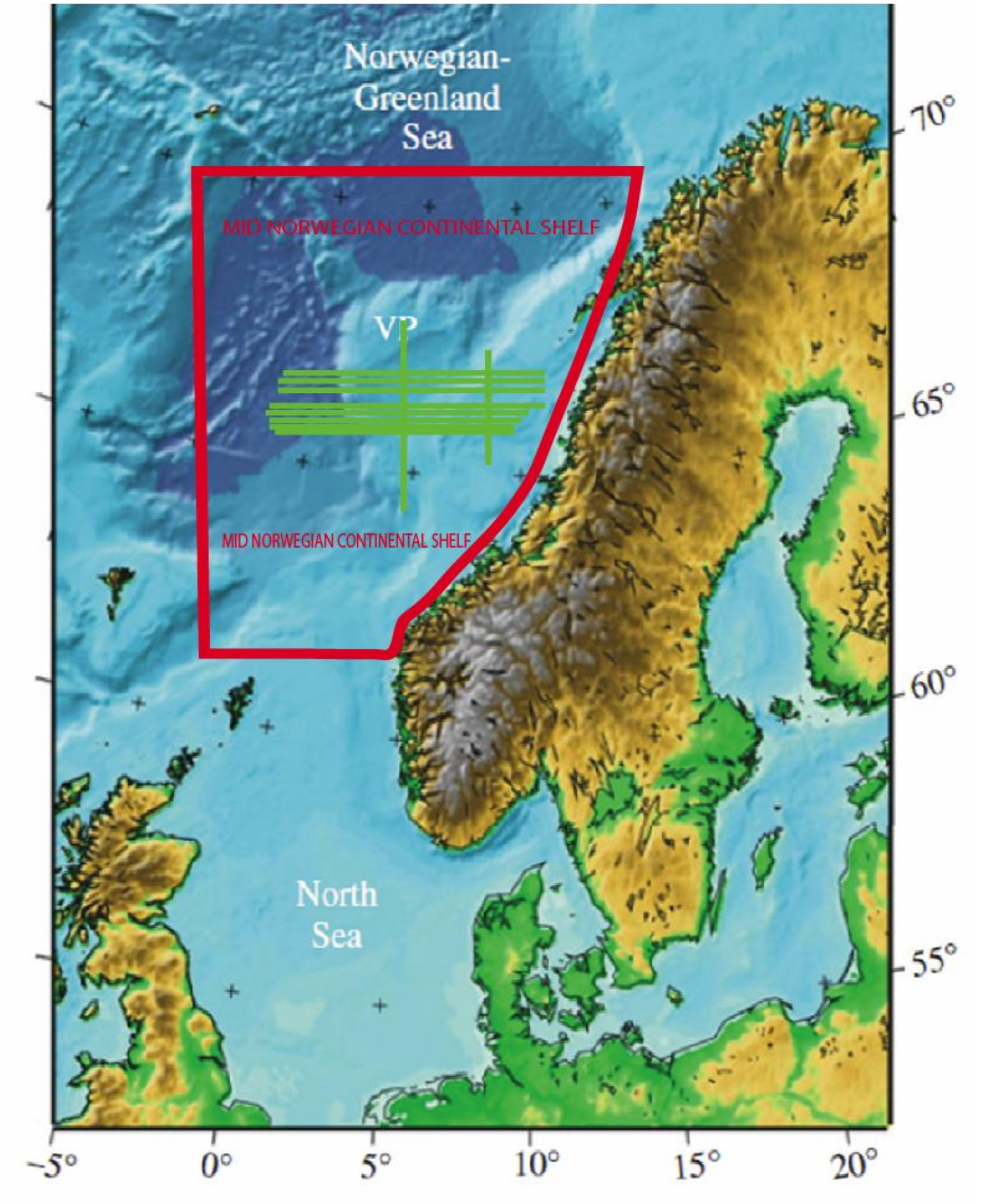


**Figure 1. 1** Location map of Mid Norwegian Continental Shelf with dataset of this study (modified from Faleide et al., 2010)

intervals by downlap, onlap, toplap and toplap truncations lapouts boundaries acting as a sequence boundaries and surfaces of increase in accommodation space will be defined as an important part of the study. Events of fall in relative sea level are on seismic lines documented by seismic surfaces defined by toplap truncation and onlap, whereas intervals of high relative sea level stand are represented by surfaces with downlap seismic lapouts. Identification of events of fall and rise in relative sea level, lowstand and highstand, is of critical importance in reconstructing the relative impact of the major controlling factors of the architectural style and facies distribution of the Cenozoic succession, tectonics and eustatic sea level changes. The sequence stratigraphy of the studied part of the late Cenozoic succession of the mid-Norwegian Continental Shelf will also be discussed in terms of the glacial history of Northern Europe, such as numbers of glacial events and their characteristics of duration and glacial ice dynamics.

In the master thesis project regional 2D lines and selected well logs will be used to study the Late Cenozoic clinoforms. The study of different types of clinoform geometries and genesis will be of prime importance to know the basin infill history.

# 2. Geological development of the mid-Norwegian Continental Shelf

The area off mid-Norway (62°-69°30'N) encompasses a passive continental margin. The tectonic development that has given rise to the present structural style of the Norwegian Sea passive continental margin can be dated back to Permo-Carboniferous time (Figure 2.1) (Bukovics et al., 1984; Blystad et al., 1995; Brekke 2000).

The Paleozoic was characterized by two stages of tectonic development followed by the formation of the Norwegian-Greenland Sea in the Cenozoic. The basement beneath the sedimentary succession on the Norwegian Continental shelf (NCS) was produced during the Caledonian Orogeny in the Early Paleozoic i.e. Silurian-Devonian, by the collision of the Laurentian and Baltican plates and formation of the supercontinent Pangea. In the Late Paleozoic to Early Triassic times the whole area was affected by extension resulting in crustal extension and initial rifting and break up of Pangea. During Late Jurassic to Early Cretaceous a second event of extension and rifting occurred. In Mesozoic time, particularly the Jurassic to Earliest Cretaceous, basins on the Norwegian Continental Shelf were filled by marine sediments, including petroleum source rocks, as well as reservoir sandstone bodies. Finally in the Early Cenozoic, a third major event of rifting occurred by the complete break up of Pangea in the northeastern Atlantic region, resulting in sea floor spreading, formation of oceanic crust and opening of North-East Atlantic Ocean, including the Norwegian-Greenland Sea (e.g. Blystad et al., 1995; Skogseid et al., 2000; Brekke 2001; Gradstein et al., 2004; Faleide et al., 2008). During Cenozoic time the Norwegian continental shelf was formed by progradation of sediments fed by erosion from mainland Norway. During events of deformation large dome structures and deep basins were formed within the shelf and along the continental margin. In Pliocene-Pleistocene time the modern continental shelf was shaped during westward progradation of clastic wedges, deposition and erosion from glacial ice flows and gravitational slides.

The passive margin of the Norwegian Sea is a result of the interaction of various factors like lithospheric scale processes, the composition and strucural framework of the Precambrian basement and the Caledonian root, climatic changes and tectonic forces. The Post-Caledonian growth of the Norwegian Sea continental margin can be directly connected to tectonic development of the Northeast Atlantic region (Smelror et al., 2007). The main tectonic events are further described below:

## 2.1 Paleozoic

The geological development during the Paleozoic is characterized by two pronounced major tectonic events, i.e. the Caledonian Orogeny and the rifting event from Carboniferous to Permian. During Ordovician–Early Devonian the Caledonian mountain chain was formed after the closure of Iapetus Ocean and collision between the lithospheric plates of Baltica and Laurentia. In the Early to middle Devonian the Caledonian mountain chain collapsed (Figure 2.2) (Gee 1975; Bukovics et al., 1984; Blystad et al., 1995; Smelror et al., 2007). The main building blocks of the Norwegian mainland are remnants of the deeply eroded Caledonian Orogen (Smelror et al., 2007).

## 2.2 Mesozoic

An extensional tectonic regime dominated all over the Norwegian Sea margin in the Late Permian to Early Triassic, This stress field represented the initial stage of the break up of the Pangean supercontinent (Smelror et al., 2007). The area of the present Norwegian-Greenland Sea was in Triassic time a lowland area, partly continental and partly marine. The structurally low crustal segment was thus subjected to host alluvial and fluvial depositional environments during continental settings that were episodically replaced by short-lived marine transgressions from the north. In Mid-Late Triassic time evaporites were deposited (Brekke et al., 2001; Müller et al., 2005; Smelror et al., 2007).

The Scandinavian Caledonides seem to have been the main source area for clastic material to the basins in the west on the present Norwegian Continental Shelf (Smelror et al., 2007). In Middle Triassic to Early Jurassic, there was a major phase of uplift and erosion along southern Norwegian mainland, resulting in the deposition of thick successions of stacked alluvial conglomerates, sandstones and fine grained clastics in alluvial fans and fluvial plains in extensional basins and along basin margins (Brekke et al., 2001; Müller et al. 2005; Smelror et al. 2007; Gabrielsen et al., 2010).

A major regional tectonic phase started in the Late Jurassic and continued into the latest Ryazanian times (e.g. Underhill, 1998; Brekke et al., 2001; Gabrielsen et al., 2001; Kyrkjebø et al., 2004; Smelror et al., 2007). This period of extensional tectonics gave birth to a horst and graben province in the North Sea and also on the mid-Norwegian continental shelf. The Halten Terrace was exposed to E-W and NW-SE extensional regimes (Koch and Heum 1995; Smelror et al., 2007). The Møre and Vøring basins started to develop within a region previously characterized by elevation and erosion.

Tilted, rotated fault blocks were developed at the Halten Terrace during Late Middle Jurassic to Early Cretaceous and were afterward buried at a depth of 2.5 and 5 km during post-rift subsidence (Figure 2.2) (e.g. Smelror et al., 2007; Faleide et al. 2010). The new structural framework of sub-basins bordered by elongated highs was of great importance for sediment distribution in Late Jurassic–Earliest Cretaceous. Open marine mudstone and clay, commonly organic-rich, occupied the deep water troughs, whereas clastic wedges representing fan deltas, estuaries and shoreface sandstone and mudstone facies bordered the marine basins towards intrabasinal highs and mainland Norway, correspondingly the same features were formed along the eastern side of East Greenland (e.g. Gjelberg et al. 1987; Brekke et al. 2001; Johannessen & Nøttvedt, 2008).

Sea level rise during Late Middle and Late Jurassic caused flooding of major parts of the rift margins. This resulted in deposition of mudstone and shale in the Melke and Spekk

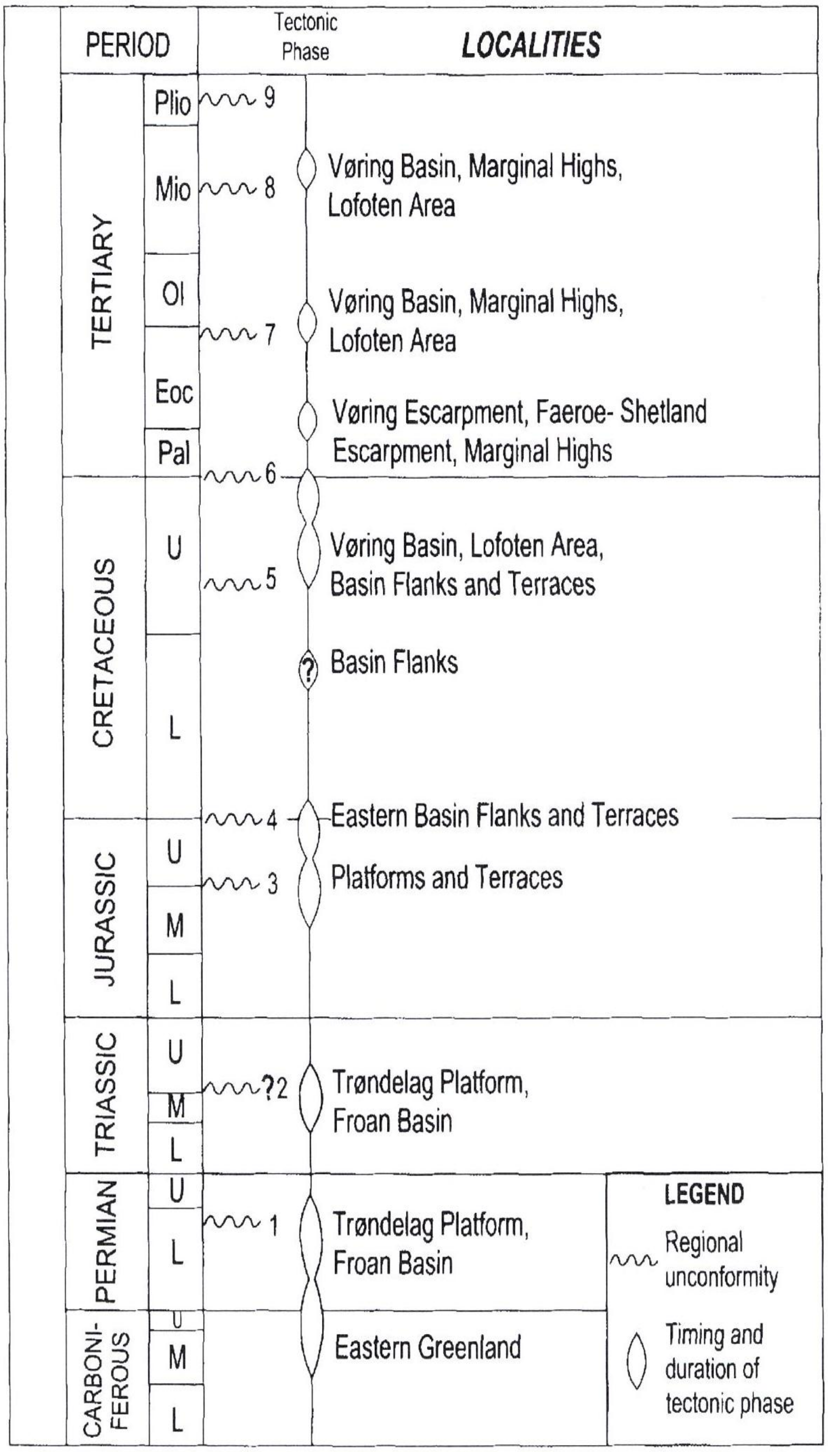


**Figure 2. 1** Tectonic history of Norwegian Sea Continental Margin (from Brekke, 2000)

Formations over larger parts of the present Norwegian-Greenland Sea area (Dalland et al., 1988; Brekke et al., 2001; Smelror et al., 2001 & 2007; Nøttvedt & Johannessen, 2008). The interaction of tectonic movements and rise of regional sea level created silled basins with restricted bottom water circulation. Off shore mid-Norway these silled basins become the ideal place for the deposition of organic rich shales like the oil prone Spekk Formation (Karlsen et al., 1995; Smelror et al., 2007).

The erosion of tectonic fault blocks appears on seismic sections as a regional unconformity, 'the base Cretaceous unconformity' (BCU), which was buried during Cretaceous and Cenozoic times. In the Early Cretaceous, condensed carbonates and carbonaceous marine shales were deposited on the embryonic platform areas and structural highs (Dalland et al., 1988; Smelror et al., 2007).

During earliest Early Cretaceous, faulting continued and during Cretaceous followed by crustal subsidence and formation of the deep-marine Møre and Vøring basins. During Late Early and Late Cretaceous thick successions of mudstone and turbidite sandstones accumulated in different parts of the basins off mid-Norway. Bounding platform areas were flooded and transformed into basin areas. During Latest Cretaceous to Early Paleocene a pronounced phase of uplift took place and gave rise to erosion of basin flanks and platform areas (Blystad et al., 1995; Brekke et al., 2001; Smelror et al., 2007).

## 2.3 Cenozoic

Crustal extension continued during Early Paleocene and culminated with continental separation in Early Eocene time with the intitial opening of the Norwegian-Greenland Sea (Figure 2.2). The western basins and areas north of the Jan Mayen Lineament may have been affected by uplift during this rifting period (Smelror et al., 2007). The present continental shelf started to be formed by outbuilding of large volumes of sediments from mainland Norway (e.g. Martinsen, 2008; Nøttvedt & Johannessen, 2008; Faleide et al., 2010).

### 2.3.1 Opening of the Norwegian-Greenland Sea

The final break up of continental crust between Norway-Greenland and opening of the Norwegian-Greenland Sea in Early Eocene was coupled with a renewed regional uplift of the marginal areas of the developing Norwegian-Greenland Sea. The outer parts of the Møre and Vøring basins were influenced by Late Cretaceous-Paleocene crustal extension, which later on shifted towards the central part of the basins with the passage of time (Lundin and Doré, 1997; Doré et al., 1999; Brekke et al., 2001; Smelror et al., 2007).

Tectonism and magmatism, continued for 15-20 m.y. from the initial faulting which started in Late Cretaceous till final continental separation at the Paleocene-Eocene boundary. At the final stages of the Norway-Greenland continental separation the magmatic activity was at its peak, pouring great quantity of lavas on the Vøring Marginal High and sill intrusions in the Møre and Vøring Basins adjacent (Henriksen et al., 2005).

### 2.3.2 Basin Inversion (Early Oligocene and Middle Miocene)

The basins along the eastern margin of the Norwegian Sea experienced compressional tectonics in the Cenozoic, one phase in the Middle Eocene/Early Oligocene and another in Middle Miocene (Doré and Lundin, 1996; Lundin and Doré, 2002; Smelror et al., 2007). Helland Hansen Arch was formed during these compressional events and also the Nordland Ridge, the latter has a long and complex history of uplifts and marine flooding events (Blystad et al., 1995).

After the second phase of compression and uplift in the Middle Miocene, the outer parts of the Vøring Basin become the dominant site of clay sedimentation, and at the end of Miocene most of the Vøring Basin was filled with sediments (Brekke et al., 2001; Smelror et al., 2007).

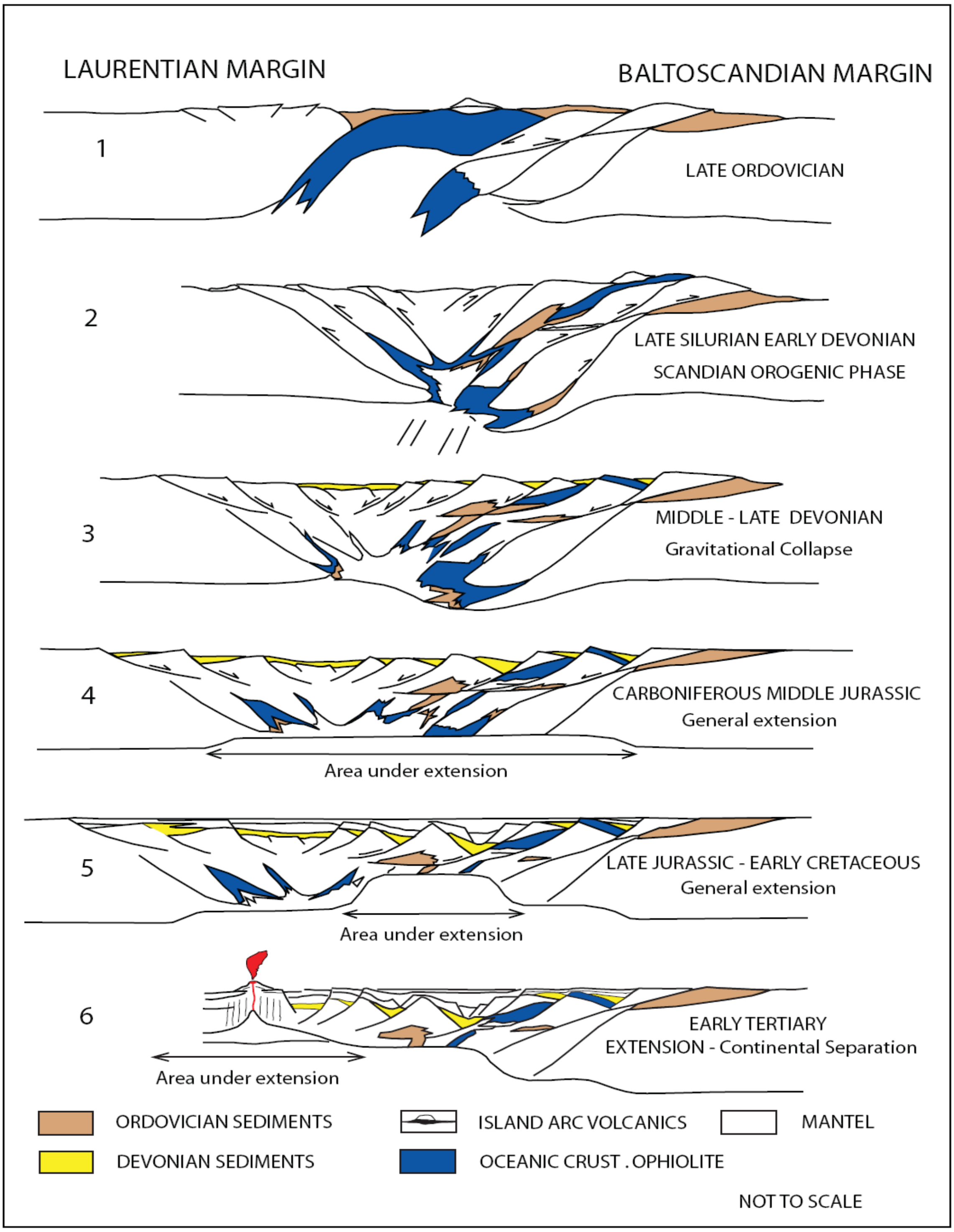


**Figure 2. 2** Diagram illustrating the tectonic development of Norwegian Continental Margin (after Skogseid et al., 1992 modified by Abbas, 2006)

*"On the prominent part of the shelf, a prograding coastal/deltaic sequence of Upper Miocene-Lower Pliocene sand and siltstones (i.e. the Molo Formation) developed from the Lofoten Islands in the north down to Haltenbanken (i.e. over a distance from 63-67°N)"* Smelror et al., 2007 pp. 399).

### 2.3.3 Late Pliocene/Pleistocene

Late Neogene was tectonically a very active period with the Norwegian mainland affected by km-scale uplift, extensive erosion and sediment transport towards the Norwegian Sea in the west. Large-scale sediment progradation took place by clastic wedges building out, displacing the shelf edge westward. This succession reaches the thickness of 2000 m within the Naust Formation. During Late Neogene the shelf edge off mid-Norway shifted 100-150 km westwards, while the edge of the more narrow Møre shelf moved 30-50 km to the west (Rise et al., 2005; Smelror et al., 2007).

During Pleistocene time, glaciers affected the shelf by both erosion and deposition. Gently dipping clinoforms consisting of till and glacier debris were developed by the progradation along the shelf off mid-Norway during several ice periods. For the last ice age, glacial maximum was attained about 20000 years ago and the shelf off mid-Norway was covered by ice sheets at a eustatic lowstand (Butt et al., 2002; Bugge et al., 2004; Rise et al., 2005; 2010; Ottesen et al., 2005; Smelror et al., 2007).

## 2.4 Structural elements of the Norwegian Continental Margin

The whole structural framework of the Norwegian passive continental margin encompasses a central area of NE-SW trending deep Cretaceous basins, the Vøring and Møre basins bordered by palaeo highs and platforms, and to the east the elevated mainland Norway. The platform areas situated in the west are known as the Møre and Vøring Marginal highs (Figure 2.3) (Brekke, 2000).

The Late Jurassic-Early Cretaceous Trøndelag Platform covers the eastern side of central part of the basin system. The NW-SE trending Bivrost Lineament is bordering the main basin area in the north. This lineament marks the boundary between the wide and deep Vøring Basin and the uplifted continental margin around the Lofoten Ridge (Figure 2.3) (Brekke, 2000).

Main structural elements on the Norwegian continental shelf include (Figure 2.3)Møre Basin, Vøring Basin, Jan Mayen Lineament, Bivrost Lineament, Trøndelag Platform, Vøring Marginal High, Møre-Trøndelag Fault, and Møre Marginal High. These elements are briefly described below, together with Storegga and the Storegga Slide which are major Holocene geomorphological features of the mid-Norwegian continental shelf and adjacent Norwegian Sea.

### 2.4.1 Jan Mayen Lineament

The Jan Mayen Lineament marks the boundary between the southern part of the Møre Basin and northern part of the Vøring Basin. Sinistral shift of basin axis and flank defines the Jan Mayen Lineament. Along the Jan Mayen Fracture Zone some kind of sinistral shift can be seen in the magnetic spreading anomalies in the ocean crust (Figure 2.3) (Blystad et al., 1995; Brekke 2000).

### 2.4.2 Bivrost Lineament

The Bivrost Lineament is a boundary between the Vøring Basin and the tectonically uplifted narrow continental margin around Lofoten to the north. The Bivrost Lineament can be

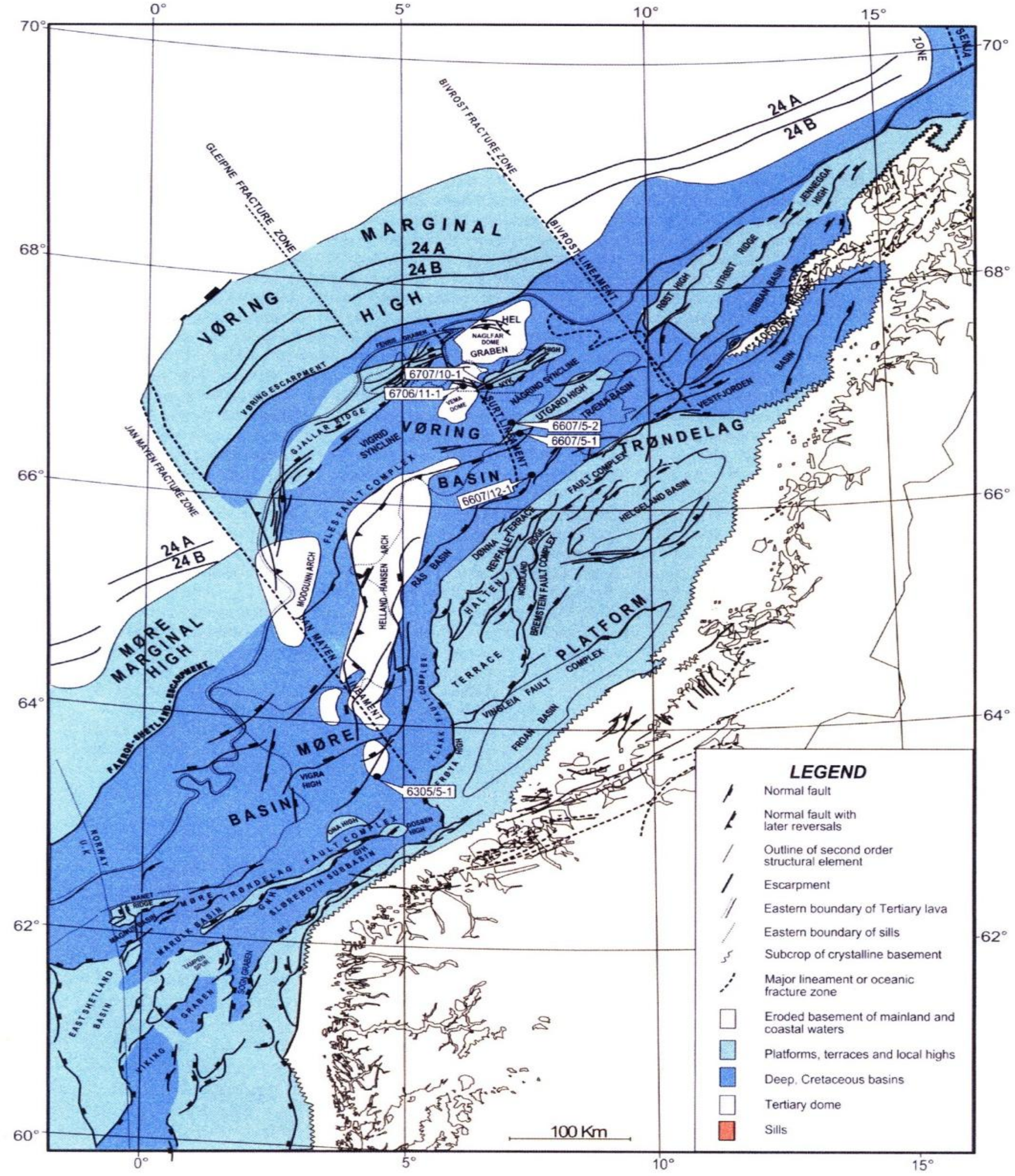


**Figure 2.3** Simplified Structural map of the Norwegian Sea continental margin (After Brekke, 2000)

further defined by a dextral shift in basin axes and flanks and its southeastern most part coincides with the northern limitation of the Trøndelag Platform (Figure 2.3) (Blystad et al., 1995; Brekke, 2000).

### 2.4.3 Vøring Basin

The Vøring Basin (64-68°N and 2-10°E) is a large sedimentary basin with grabens, sub-basins and structural highs (Bukovics and Ziegler, 1985; Blystad et al., 1995).

In the west, the Vøring Basin is surrounded by the Vøring Escarpment along the Vøring Marginal High, and in the east it is bounded by fault complexes along the edge of the Trøndelag Platform. Fles Fault Complex intersects the basin area, which continues along the basin axis from the Jan Mayen Lineament in the south and in the north to the Bivrost Lineament (Figure 2.3). The Vøring Basin has been intruded by mafic sills of Paleocene-Eocene age. These sills are observed in the east of the inner lava flows and hide the seismic signature of the underlying strata. These features are associated with continental separation (Bukovics et al., 1984; Blystad et al., 1995; Brekke, 2000).

Within the Vøring Basin there are several structural highs and sub-basins. The most prominent high is the Helland Hansen Arch in the central southern part of the basin, formed during Cenozoic compressional tectonics. Gjallar Ridge occurs in the northwestern part of the basin and in the north the Utgard and Nyk highs occur. The highs subdivide the basin in several sub-basins. The Dønna Terrace at the western side of the Nordland Ridge is also a part of the large Vøring Basin. Serveral faults and lineaments cut the Vøring Basin (Blystad et al., 1995).

### 2.4.4 The Vøring Marginal High

The Vøring Marginal High lies to the west of the Vøring Escarpment, being flanked by the Jan Mayen and Bivrost lineaments (Figure 2.3). The Cenozoic sediments are lying on top of thick Lower Eocene flood basalts. These flood basalts are possibly underlain by continental crust which gradually thins and becomes transitional to the crust while approaching towards the west (Blystad et al., 1995; Brekke, 2000).

### 2.4.5 Møre Basin

The base Cretaceous unconformity (BCU) defines the base and outline of the Møre Basin. The boundary of the basin is in the northwest delineated by the Møre Marginal High, in the northeast by the Jan Mayen Lineament, in the southeast and south by the Møre-Trøndelag Fault Complex, to the east by the Halten Terrace and the Trøndelag Platform, and in the southwest by the Faeroe-Shetland Escarpment (Figure 2.3). The basin can be defined by structural elements of a NE-SW to ENE-WSW trending system of fault controlled highs, ridges and small basins (Blystad et al., 1995; Brekke, 2000).

There is an overall NE-SW structural grain in the basin. The Cretaceous succession in the axial part of the basin may be up to 6 km thick (Brekke, 2000).

### 2.4.6 The Møre-Trøndelag Fault Complex

The Møre-Trøndelag Fault Complex (Blystad et al., 1995) has been reactivated several times in the geological history. The ENE-WSW trending structure follows the dominating orientation of Caledonian deformation structures in the northwestern gneiss region. Due to tectonic reactivation the fault complex seems to have affected the Precambrian basement and rocks of Lower Paleozoic, Devonian and Jurassic ages (Bering 1992; Grønlie et al., 1994; Brekke, 2000).

### 2.4.7 The Møre Marginal High

The Møre Marginal High (Blystad et al., 1995) is located northwest of the Faeroe-Shetland Escarpment. In the northeast the high is bounded by the Jan Mayen Fracture Zone and in the southwest by the Faeroe Plateaue, into which the high continues as an integrated part. To the west, the Møre Marginal High is bounded by a zone of crust being transitional to normal oceanic basaltic crust (Figure 2.3). On top of thick Early Eocene flood basalts there have been deposited younger Cenozoic sediments. The Faeroe-Shetland Escarpment represents the front of basalt flows and basaltic deltas (Smythe et al., 1983; Blystad et al., 1995; Brekke, 2000).

### 2.4.8 Trøndelag Platform

The Trøndelag Platform is a 160 km wide area between the Norwegian mainland and the Vøring Basin. The Halten Terrace, to the west of the Trøndelag Platform (*sensu strictu*), may also be considered a part of the large platform structure. Other structural elements that shape the Trøndelag Platform and its surroundings include the Nordland Ridge, Helgeland Basin, Frøya High, Froan Basin, Vingleia Fault Complex and the Ylvingen Fault Zone (Figure 2.3). In the NW the Trøndelag Platform is bounded by the Revfallet Fault Complex and in the south by the Klakk Fault Complex. In the west it is bounded by the Bremstein Fault Complex and towards the east by crystalline basement outcrops at the sea floor along the coast (Bukovics et al., 1984; Blystad et al., 1995; Brekke, 2000).

### 2.4.9 Storegga, Storegga Slide and the North Sea Fan

The Storegga Slide is a huge slide complex formed by the collapse of mainly clay-rich glaciomarine sediments within the Møre segment of the Norwegian Continental shelf for about 8100 years ago (Vorren et al., 2008). During the Late Pliocene-Pleistocene, the area was a major depocenter of clastic sediments delivered from mainland Norway, dominantly of glaciomarine processes and gravity sediment flows (Hjelstuen et al., 1999 & 2004). The Storegga itself is a prominent escarpment representing the inner, eastern faults delineating the slide scar, running all together about 290 km. The scar covers an area of 34 000 km$^2$. About 5600 km$^3$ of material was involved in a series of individual slides and the debris flow sediments occupy an area of 112 000 km$^2$ in the Norwegian Sea (Figure 2.4) (Vorren et al., 2008).

The North Sea Fan is a big Late Cenozoic-Pleistocene submarine fan complex deposited at the northern outlet of the Norwegian Channel, running from south to north along the coast of western Norway (Nygård et al., 2005; Hjelstuen et al., 2004) (Figure 2.4).

The Late Plio-Pleistocene normal marine sediments are thin in the Storegga Slide area, due to the repetition of slide events (Figure 2.5) and generally low sediment supply (Evans et al., 2002; Hjelstuen et al., 2004; Rise et al., 2005).

## 2.5 Stratigraphy

The pre-opening structural framework off mid Norway is dominated by Late Jurassic-Early Cretaceous phases. Late Paleozoic – Early Mesozoic rift phases occurred in Carboniferous-Permian and Permian-Early Triassic. Sediment successions related to these rift phases are poorly identified because they are masked by younger tectonism and thick sedimentary strata of Mesozoic and Cenozoic (Faleide et al., 2010).

In the Jurassic the Viking, Fangst and Båt groups were deposited on the Mid Norwegian Continental Shelf. The Viking Group contains source rocks for hydrocarbons on the mid-Norwegian Continental Shelf i.e organic rich facies of the Melke and Spekk formations. These formations consists of mudstone and shales. The Fangst Group is composed of

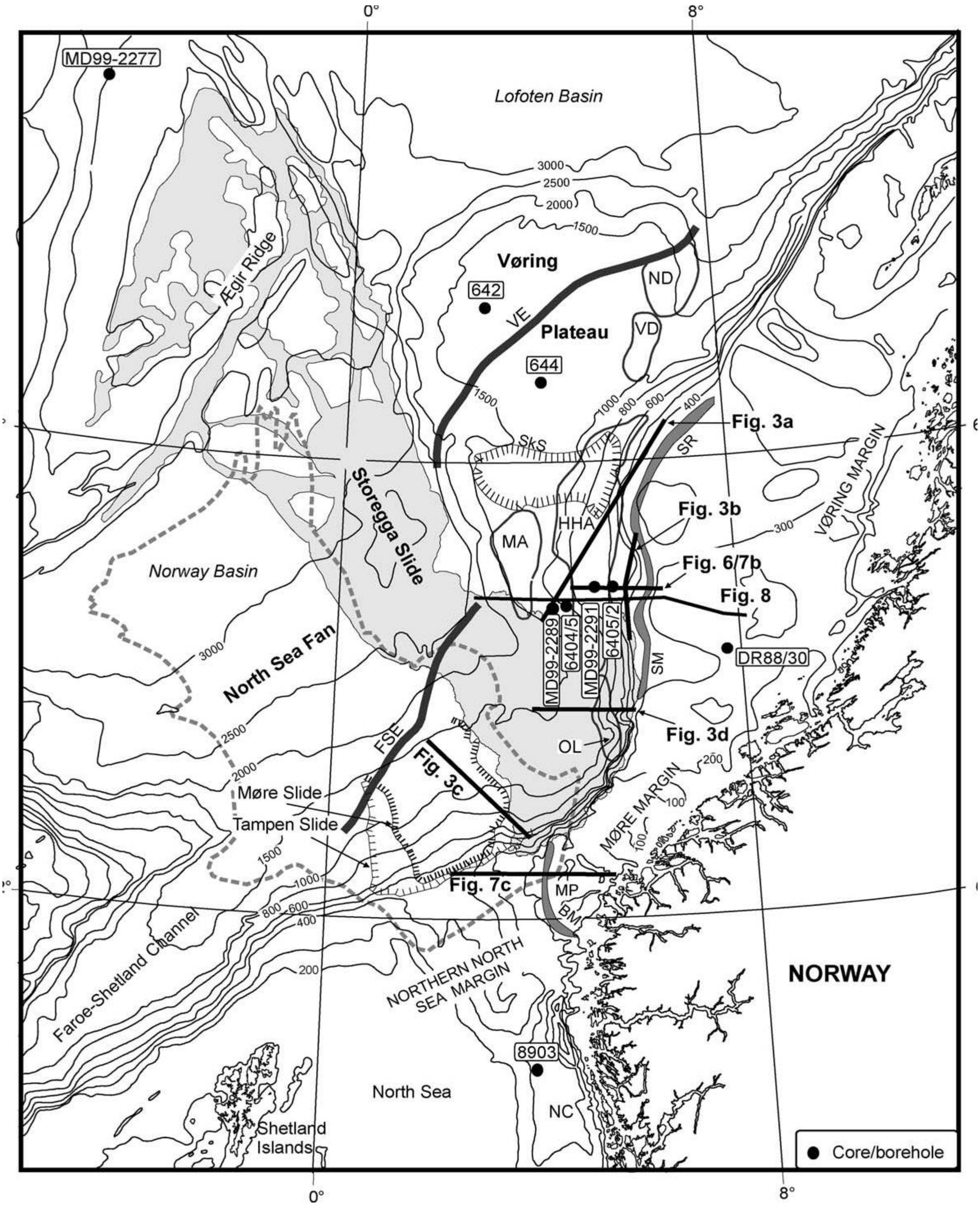


**Figure 2. 4** Outline of Storegga Slides and North Sea Fan (From Haflidason et al., 2005)

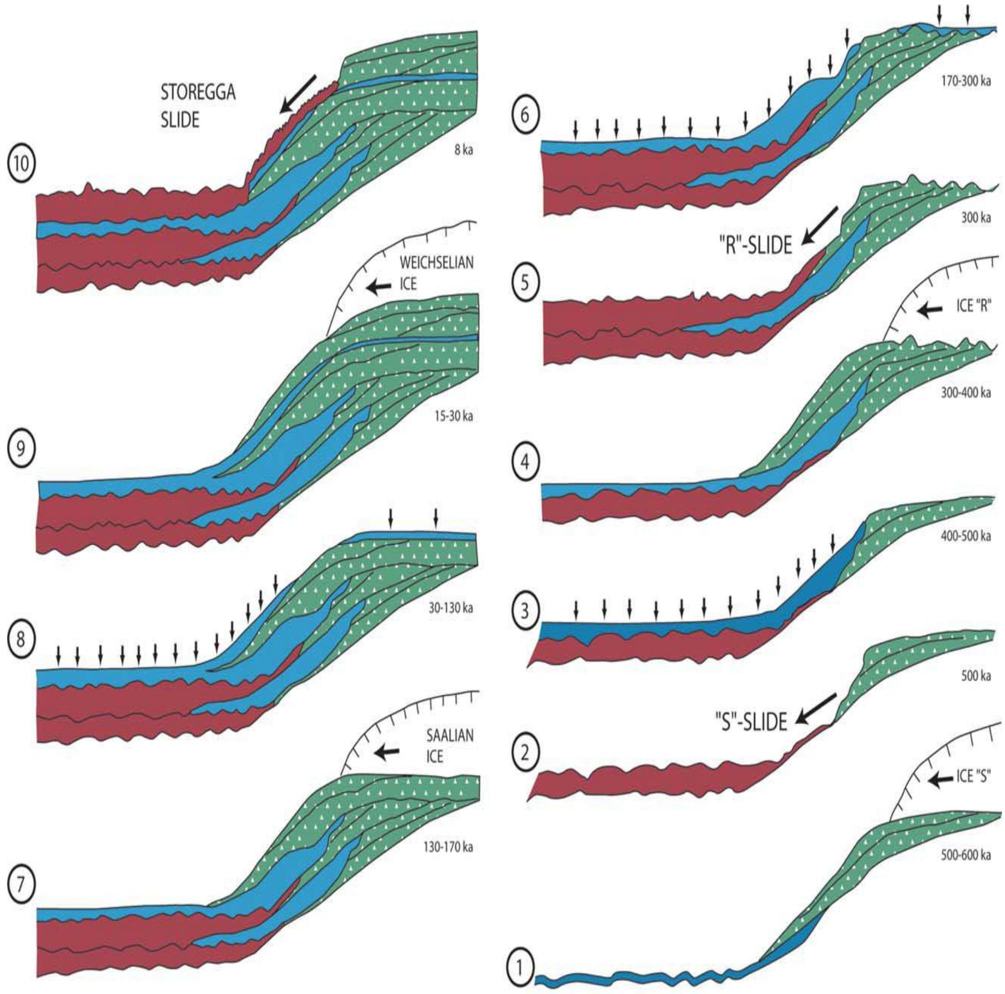


**Figure 2. 5** The slides events Storegga Slide (from L. Rise et al., 2005)

marginal marine and shallow marine deposits, mainly sands. The Cretaceous Cromer Knoll and Shetland Groups deposits also include carbonates. The Paleogene Rogaland Group is composed of shallow marine shale, marginal marine sandstones and volcanic deposits of Eocene basalt. Neogene has two groups the Hordaland and Nordland Groups (Figures 2.6 & 2.7).

The Nordland group of Early Miocene-Recent age is of prime importance in the present study. The Nordland Group consists of the Kai/Molo and Naust formations (Figure 2.6) (Eidvin et al., 2007). The type section of the group is within the North Sea Tertiary basin. The type section is composed of alternating sandstone, claystone and siltstone. The Nordland Group is distributed throughout the Mid Norwegian Continental Shelf, except the lower part which is absent on the Nordland Ridge (Dalland et al. 1988).

### 2.5.1 Kai Formation

The Kai Formation is composed of alternating claystone, siltstone and sandstone with limestone stringers. Pyrite, glauconite and shell fragments are also common (Dalland et al. 1988).

The Kai Formation was deposited in the synclinal structures which developed during the Miocene structural inversion. The thickness of the Kai Formation varies above Nordland Ridge. It is not present on two separate domes, one 20 km long and 7 km wide NE-SW striking high and another high which is 30 km long and upto 15 km wide. In these areas the Naust Formation lies directly above the Palaeogene and older rocks. Around the Lofoten Margin the Kai Formation wedges out northward along the Bivrost Lineament. Around the Lofoten margin, westward prograding clinoform-bounded clastic wedges by well preserved topsets, foresets and bottomsets have been interpreted within the Kai Formation. The top of the Kai Formation can be defined by downlap of low angle westward prograding clinoforms of Naust Formation (Løseth et al. 2005).

### 2.5.2 Molo Formation

The Molo Formation is considered as time equivalent of Kai Formation (Løseth et al., 2005). Different ages have been assigned to the Molo Formation like Eocene/Oligocene to Pliocene but new age from the data of exploration wells from Trøndelag Platform is assigned to be Late Miocene to Early Pliocene (Eidvin et al., 2007). The formation is most probably sand dominated. Along the inner shelf from Møre to Lofoten Molo Formation is exposed on the seabed and make a 500 km long ridge. The Molo Formation is distributed over an area of about 500 km i.e. from the coast off Møre (63°15'N) to the Lofoten Islands (67°50'N). It is a part of prograding depositional system of clastic wedges separated by very steep clinoforms. In the inner part topset beds are eroded but the outer part normally contains these top set beds. The bottom set is preserved throughout the formation (Eidvin et al., 2007).

### 2.5.3 Naust Formation

The Naust Formation is composed of sand, silt, clays and occasionally with coarse grained clastics in the upper portion. The Naust Formation is distributed on the whole Mid-Norwegian Continental Shelf (Dalland et al., 1988).

The Naust Formation comprises a thick succession of low angle sediment wedges and sheet like units which prograded westward. This thick succession of low angle sediment wedge is composed of several incoherent seismic units (till, galciogenic debris, slide deposits) which are interbedded with stratified units deposited during interglacial periods (Rise et al., 2005; 2010). According to Hjelstuen et al. (2005) these sequences were deposited between c. 2.6 and c. 0.5 Ma. But according to Eidvin et al. (2000) the base of Naust Formation is 2.7-2.8 Ma which is most widely used nowadays and this age constraints is based on biostratigraphic data correlated with dated deep sea drilling cores. Rise et al. (2010) assigned 2.8 Ma for the

base of their oldest unit N. The westerly dipping clinoforms appear as high amplitude reflectors on seismic sections (Hjelstuen et al., 2005). The lower boundary of the Naust

Formation can be recognised as a downlap surface which marks the bounding surface to the underlying Kai Formation. Towards the east the Naust Formation is bounded below by the delta prone Molo Formation (Ottesen et al., 2009)

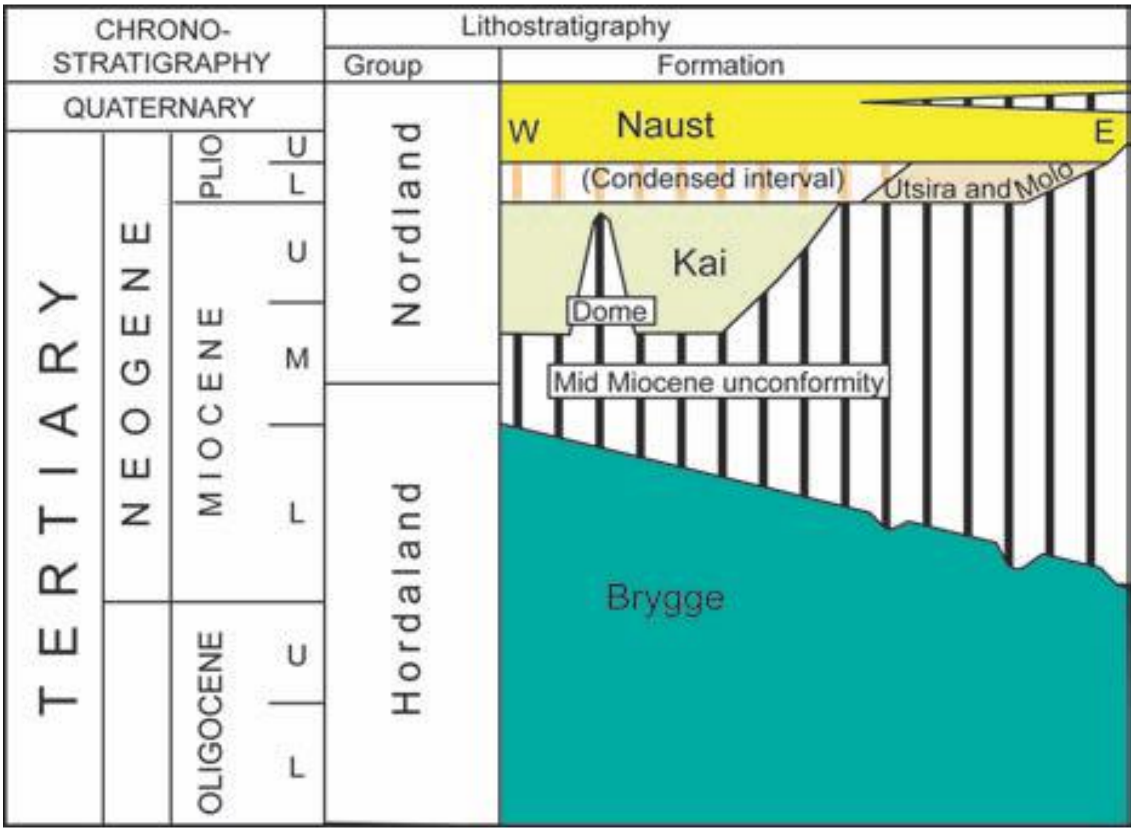


**Figure 2. 6** Simlified Oligocene and Neogene stratigraphy of the mid-Norwegian Continental Shelf (Løseth et al., 2005)

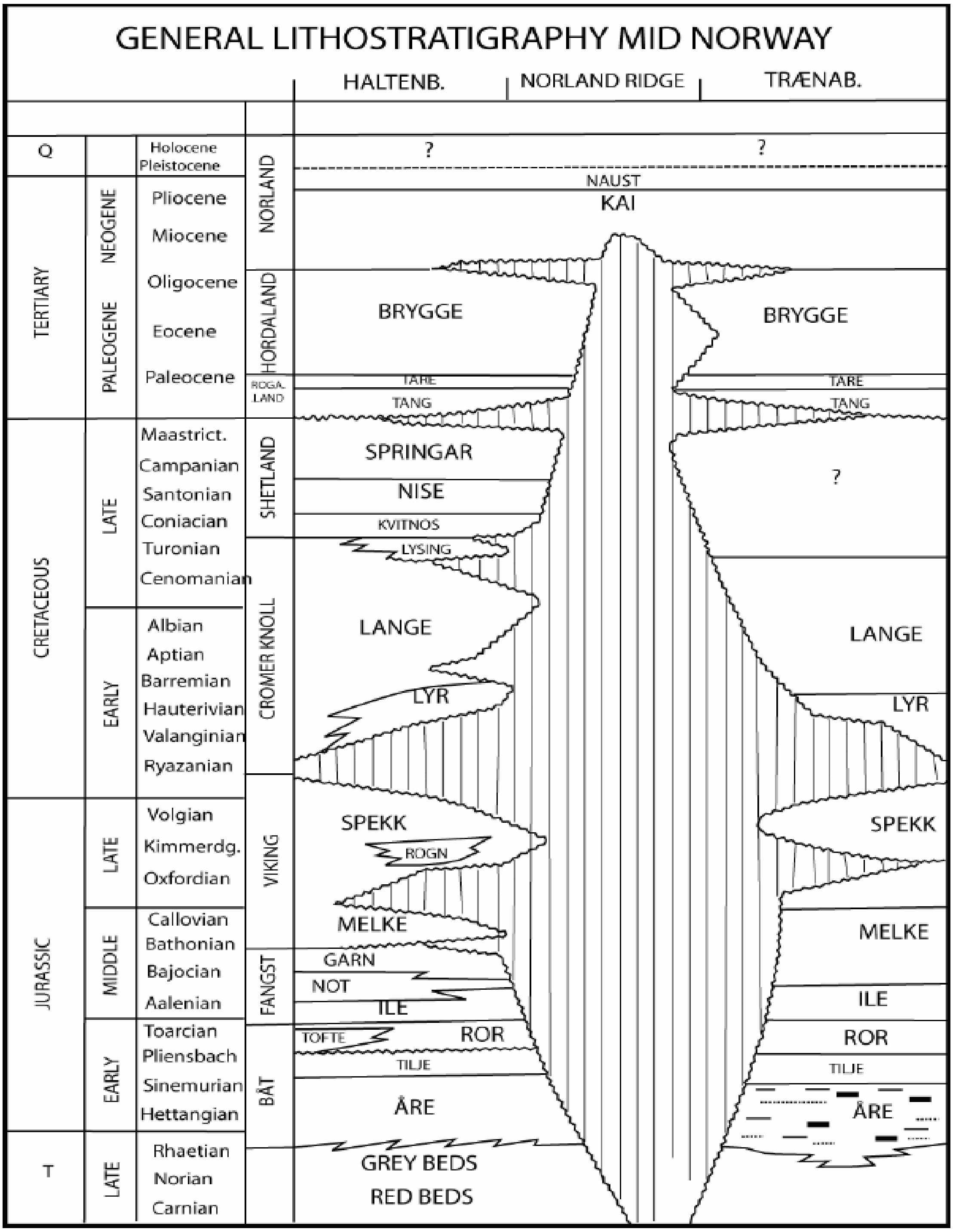


**Figure 2. 7** Generalized lithostratigraphy off mid-Norway redrawn (from Dalland et al., 1988)

# 3. Data and methods

This chapter will describe the data and methods used in this study. A seismic sequence stratigraphic approach was applied to interpret the multichannel 2D seismic reflection data. The details are given below.

## 3.1 Data

The interpreted data are part of multichannel 2D seismic reflection survey named MNR carried out by Fugro Multi Client Services AS and TGS-NOPEC on the Mid –Norwegian Continental Margin (Figures 3.1 & 3.2). The high resolution 2D seismic data were interpreted to mark the seismic surfaces on seismic interpretation software named OpendTect (a product of dGB Earth Sciences). This is a complete open source seismic interpretation tool which allows to visualize and interpret multi seismic data using attributes and modern visualization techniques (http://www.dgbes.com/index.php/products.html).The data which have been interpreted consist of eight 2D regional seismic dip lines and two strike lines along the Mid-Norwegian Continental Margin (Figures 3.1 & 3.2). Dip lines extends from the Trøndelag Platform to the Vøring Marginal High, covering up to an area of 400 km in E-W direction. The two strike lines define an area of 500 km from the Trøndelag Platform to the Vøring Marginal High, extending in the N-S direction. Vertically along the seismic sections the main focus was 2 seconds two way travel time (TWT) (approximately 2.7 km in depth) along which we can cover the prograding clinoforms bounded deposition units of the Naust Formation.

The data coverage along the dip lines is very good. Seismic surfaces like onlap surfaces, downlap surfaces and toplap truncations can be picked very easily however along the strike lines and across the Helland Hansen Arch it is very difficult to pick some of these surfaces because of poor coverage.

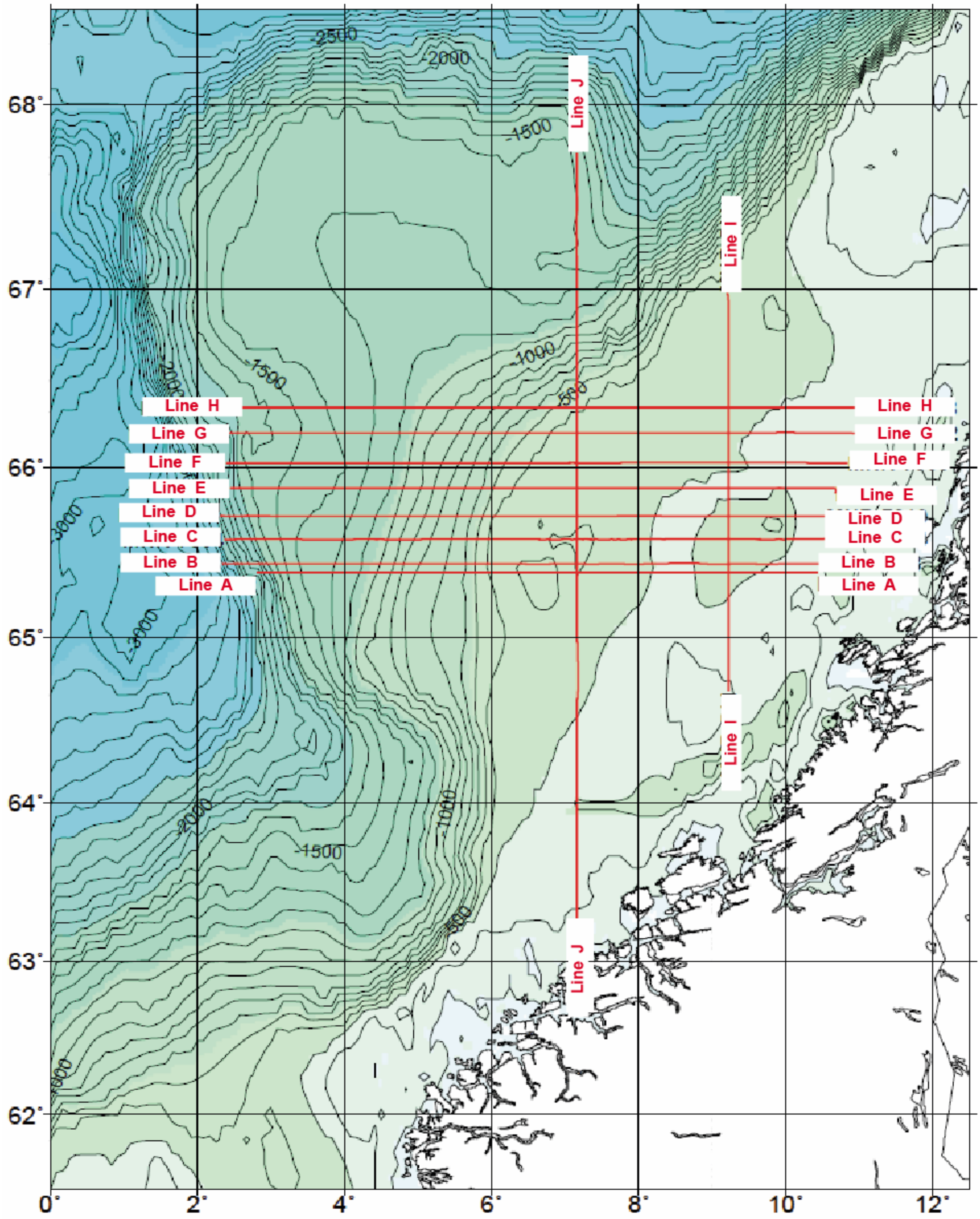


**Figure 3. 1** Bathymetric map of Norwegian Continental Shelf with interpreted seismic data

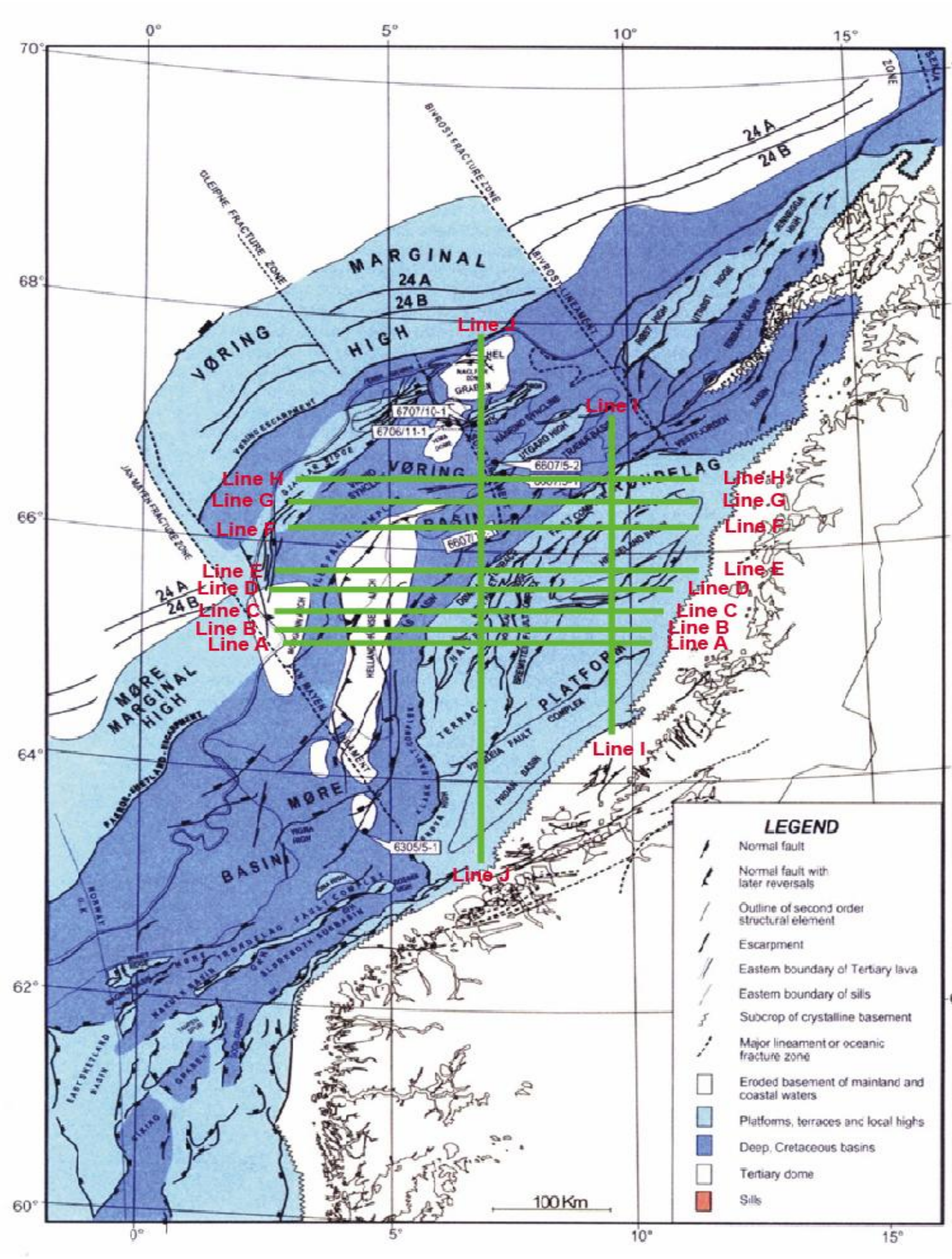


**Figure 3. 2** Simplified Structural map of the Norwegian Sea continental margin with interpreted 2D seismic lines (modified from Brekke 2000 p. 328).

## 3.2 Sequence stratigraphy

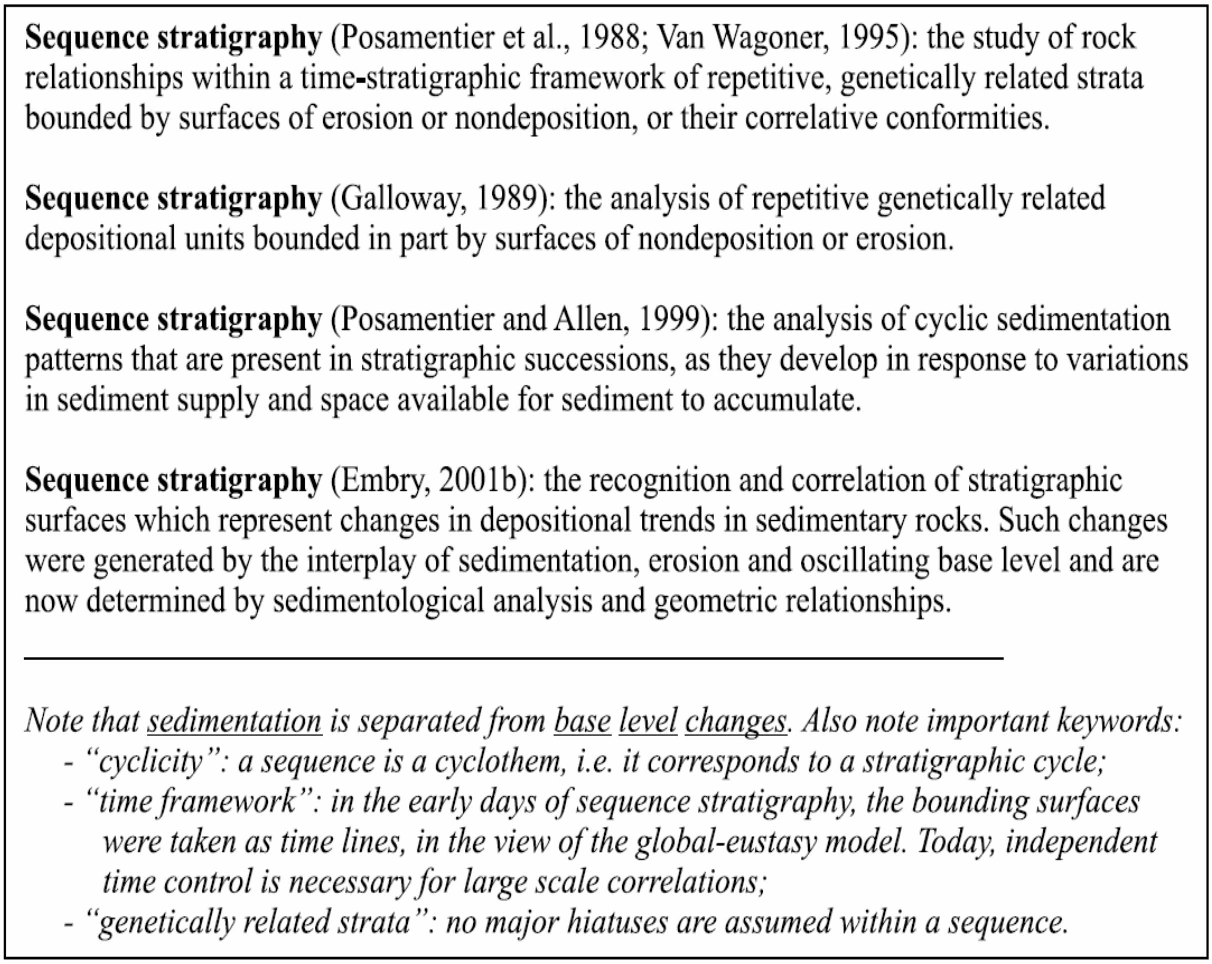
Sequence stratigraphy is a well established analytical tool to investigate rock successions. It can be defined as a branch of stratigraphy that deals with the subdivision of sedimentary succession into genetically related sequences bounded by unconformities and their correlative conformities (Helland-Hansen et al., 2009). The main types of definitions of a sequence have been published and are regularly applied in the literature (Figure 3.3).

With respect to other stratigraphic types like biostratigraphy, lithostratigraphy, chemostratigraphy, or magnetostratigraphy, which depends upon type of data collected, sequence stratigraphy has the importance of being constructed from the geometric relationship of genetically related strata formed by deposition during some certain set of allogenic control factors at the time of sedimentation and can thus be predictive of facies in unexplored areas (Catuneanu, 2002).

## 3.3 Seismic sequence stratigraphy

Seismic sequence stratigraphy is a branch of sequence stratigraphy in which sedimentary rocks are subdivided into different sequences on the base of regionally extended unconformity surfaces and their correlative conformities by picking the seismic surfaces of onlap, downlap and toplap truncations.

Seismic stratigraphy developed in the 1970s by the work of Vail (1975) and Vail et al., (1977). The basic stratigraphic unit is called a depositional sequence. It can be defined as "*a stratigraphic unit composed of a relatively conformable succession of genetically related strata bounded at its top and base by unconformities and their correlative conformities*" (Mitchum et al., 1977).



**Sequence stratigraphy** (Posamentier et al., 1988; Van Wagoner, 1995): the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities.

**Sequence stratigraphy** (Galloway, 1989): the analysis of repetitive genetically related depositional units bounded in part by surfaces of nondeposition or erosion.

**Sequence stratigraphy** (Posamentier and Allen, 1999): the analysis of cyclic sedimentation patterns that are present in stratigraphic successions, as they develop in response to variations in sediment supply and space available for sediment to accumulate.

**Sequence stratigraphy** (Embry, 2001b): the recognition and correlation of stratigraphic surfaces which represent changes in depositional trends in sedimentary rocks. Such changes were generated by the interplay of sedimentation, erosion and oscillating base level and are now determined by sedimentological analysis and geometric relationships.

*Note that sedimentation is separated from base level changes. Also note important keywords:*

- *"cyclicity": a sequence is a cyclothem, i.e. it corresponds to a stratigraphic cycle;*
- *"time framework": in the early days of sequence stratigraphy, the bounding surfaces were taken as time lines, in the view of the global-eustasy model. Today, independent time control is necessary for large scale correlations;*
- *"genetically related strata": no major hiatuses are assumed within a sequence.*

**Figure 3. 3** Some key definitions of sequence stratigraphy (after Catuneanu, 2002)

### 3.3.1 Sequence boundaries and unconformities

Unconformities represent the bounding surfaces of depositional sequences and can be called a "sequence boundary (SB)". In the "Exxon school of sequence stratigraphy" (e.g. Vail et al., 1977; Van Wagoner et al., 1988) sequence boundaries were thought to have developed due to subaerial exposure of rocks and sedimentary successions during fall in relative sea level. These subaerial unconformities were thought to be extended down into the basin as correlative conformities (Mitchum et al., 1977).

Unconformities can be picked on the seismic section by truncations, erosional channels or onlap surfaces. As mentioned ahead in this study these surfaces can also be developed by erosion of thick ice sheets when they ground the shelf during their movement but at depths below the sea level. These types of erosional unconformities are not always easy to identify and separate from subaerially formed sequence boundaries. Nevertheless, unconformities in a glacially formed shelf succession are of critical importance in terms of formation and dynamic interplay between palaeowater depth, ice sheet thickness, ice sheet buoyancy and sedimentation below floating ice sheets and the calving front of an ice sheet (Laberg & Vorren, 2000). Thus, *glacial sequence stratigraphy* deviates from ordinary non-glacial sequence stratigraphy.

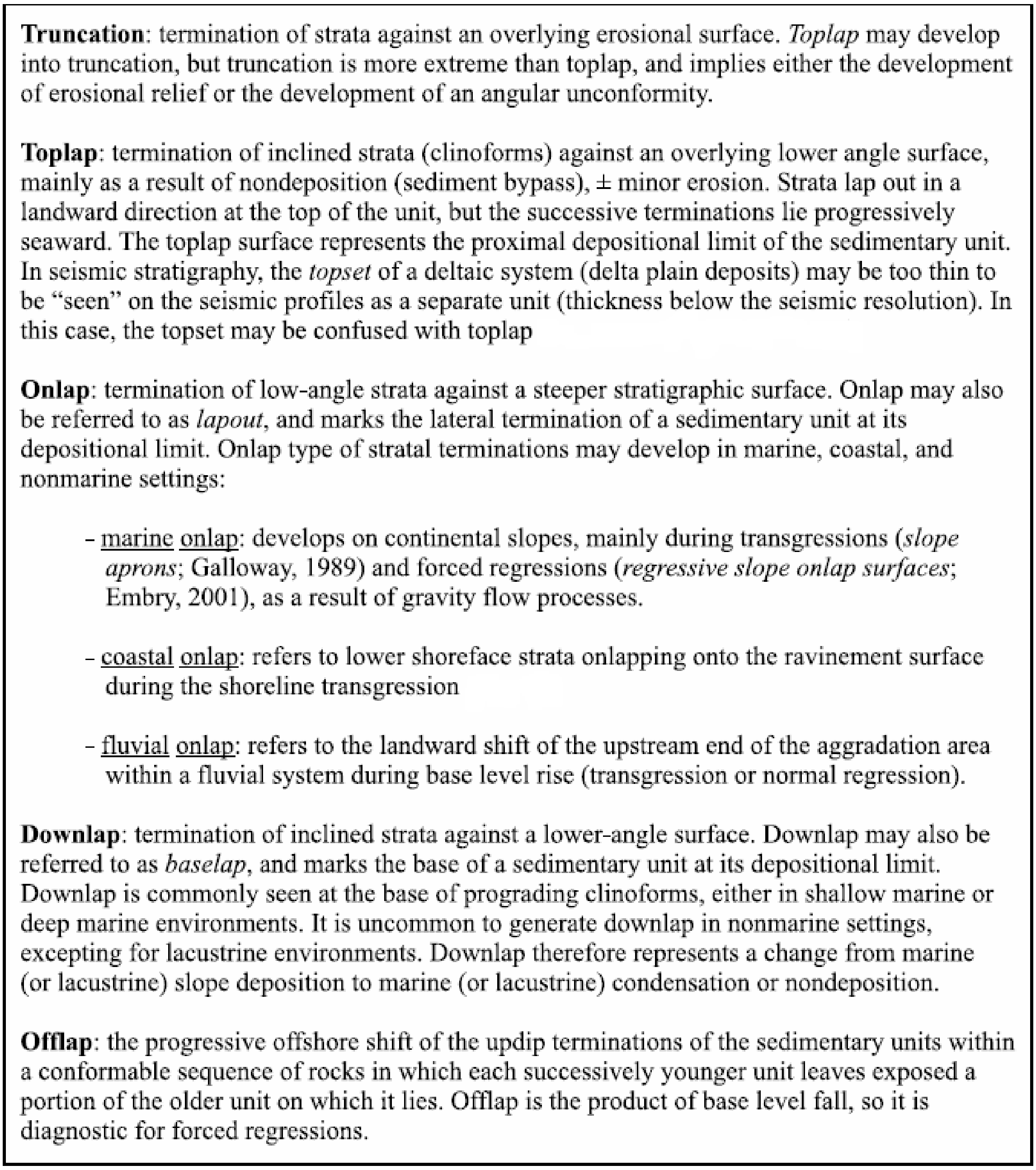
### 3.3.2 Stratal terminations

Stratal terminations can be categorized by the geometric relationship between strata and the stratigraphic surface against which they are truncating. The main terminations are onlap, toplap, downlap, offlap and erosional truncation (Catuneanu, 2002). Their definition and model is shown in Figures 3.4 & 3.5.

## 3.4 Clinoforms

The term clinoform was used by Rich (1951). According to him the clinoform can be referred to as the sloping component of a bounding surface with sigmoidal geometry. Steel and Olsen (2002) used the term for the full sigmoidal geometry i.e. topset, forset and bottom set (Figure 3.6). There are different types of clinoforms like shelf slope basin clinoforms, shoreline clinoforms and subaqueous delta clinoforms (Helland-Hansen et al., 2009). For the thesis point of view I will focus on shelf slope basin clinoforms. Clinoforms built out on the Mid Norwegian Continental Margin in Neogene time give present shape of the shelf as it is obvious in seismic data. As the term “clinoform” represents the surface, the term “clinotherm” means the sedimentary wedge containing clinoforms or bounded by clinoforms (e.g. Slingerland et al., 2008).

Shelf slope basin clinoform successions preserve the advancement of a shelf margin and can be as high as hundreds of meters (Helland-Hansen et al., 2009). A brief dscription of geometry of clinoforms is given below.



**Truncation**: termination of strata against an overlying erosional surface. *Toplap* may develop into truncation, but truncation is more extreme than toplap, and implies either the development of erosional relief or the development of an angular unconformity.

**Toplap**: termination of inclined strata (clinoforms) against an overlying lower angle surface, mainly as a result of nondeposition (sediment bypass), ± minor erosion. Strata lap out in a landward direction at the top of the unit, but the successive terminations lie progressively seaward. The toplap surface represents the proximal depositional limit of the sedimentary unit. In seismic stratigraphy, the *topset* of a deltaic system (delta plain deposits) may be too thin to be "seen" on the seismic profiles as a separate unit (thickness below the seismic resolution). In this case, the topset may be confused with toplap

**Onlap**: termination of low-angle strata against a steeper stratigraphic surface. Onlap may also be referred to as *lapout*, and marks the lateral termination of a sedimentary unit at its depositional limit. Onlap type of stratal terminations may develop in marine, coastal, and nonmarine settings:

- marine onlap: develops on continental slopes, mainly during transgressions (*slope aprons*; Galloway, 1989) and forced regressions (*regressive slope onlap surfaces*; Embry, 2001), as a result of gravity flow processes.

- coastal onlap: refers to lower shoreface strata onlapping onto the ravinement surface during the shoreline transgression

- fluvial onlap: refers to the landward shift of the upstream end of the aggradation area within a fluvial system during base level rise (transgression or normal regression).

**Downlap**: termination of inclined strata against a lower-angle surface. Downlap may also be referred to as *baselap*, and marks the base of a sedimentary unit at its depositional limit. Downlap is commonly seen at the base of prograding clinoforms, either in shallow marine or deep marine environments. It is uncommon to generate downlap in nonmarine settings, excepting for lacustrine environments. Downlap therefore represents a change from marine (or lacustrine) slope deposition to marine (or lacustrine) condensation or nondeposition.

**Offlap**: the progressive offshore shift of the updip terminations of the sedimentary units within a conformable sequence of rocks in which each successively younger unit leaves exposed a portion of the older unit on which it lies. Offlap is the product of base level fall, so it is diagnostic for forced regressions.

**Figure 3. 4** Stratal termination types (definitions from Mitchum 1977, Emery & Myers 1996; modified from Catuneanu, 2002)

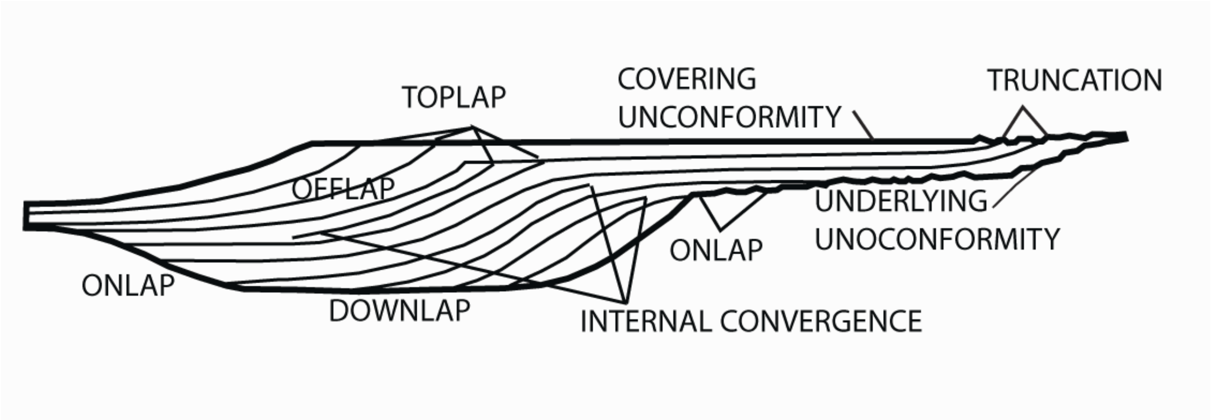


**Figure 3. 5** Stratal terminations within a seismic sequence (from Mitchum et al., 1977)

- **Topset beds** represent the proximal part of a clinoform. These are normally horizontal. In some part of recent project they are preserved and will be discussed in upcoming chapter.
- **Foreset beds** are the inclined portion of clinoforms. They characterize the deposition of sediments at slope.
- **Bottomset beds** are the lateral part of clinoforms. This preserved as bottomst bed. Usually they are formed by fine grained material of prograding delta. These are not observed in this study.

## 3.5 Parasequences and stacking patterns

Parasequences are defined as “a relatively conformable succession of genetically related strata bounded by marine flooding surfaces and correlative conformities downdip (Van Wagoner et al., 1988).

A stacking pattern is a building block of vertically succession of parasequences. Three kinds of stacking pattern can be identifying in a sedimentary succession.

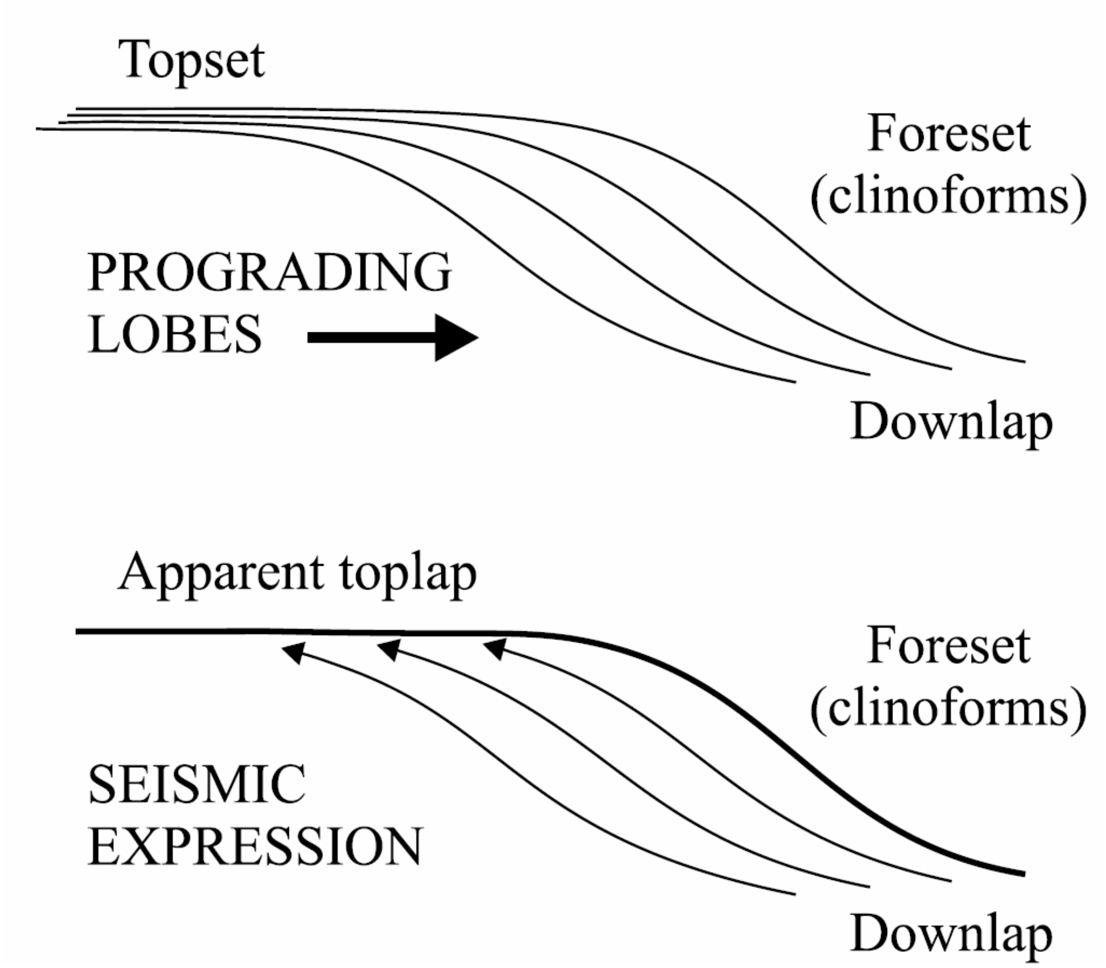


**Figure 3.** 6 Stratal terminations within a seismic sequence (from Mitchum et al., 1977)

- **Progradational** stacking pattern is mostly observed in this study. This pattern builds when rate of sedimentation exceeds the rate of accommodation (Van Wagoner et al., 1988). Facies shift towards the basin and on the seismic section appear as clinoform surfaces and clinotherms.

- **Aggradational** stacking pattern forms when rate of sedimentation is equal to the rate of accomodation (Van Wagoner et al., 1988). There is no shift in facies and on seismic section appear as horizontal reflectors.

- **Retrogradational** stacking pattern forms when rate of accomodation exceeds rate of sedimentation (Van Wagoner et al., 1988). The facies shift towards the landward direction.

## 3.6 Facies analysis

Facies analysis includes the delineation and interpretation of reflection geometry, amplitude, continuity frequency and interval velocity (Emery & Myers, 1996). Seismic facies analysis makes use of different seismic parameter to get information related to stratigraphic significance. We can distinguish different sedimentary sequences from their general seismic appearance. The reflection configuration reveals the information about lithology, type of stratification, depositional process and environment (Roksandic, 1978). Different types of reflection configuration are shown in the Figure 3.7.

Sigmoid and oblique configuration is characteristic of progradational pattern on shelf margin. Reflection free configuration with or without diffractions can be found in moraines and till. Diffractions are the response of boulder and larger blocks (Roksandic, 1978).

## 3.7 Trajectory analysis

A shoreline trajectory shows the cross sectional path of the shore line as it migrates through time (Helland-Hansen & Martinsen, 1996). The direction of the shoreline shift through time and space is a function of relative sea level changes, sediment supply, bathymetry and subsidence from loading and unloading (Helland-Hansen & Martinsen 1996; Helland-Hansen et al., 2009). The trajectories can be subdivided into the descriptive categories (Figure 3.8)

- Vertical perspective (descending or ascending order which describes the vertical movement) (Figure 3.8)

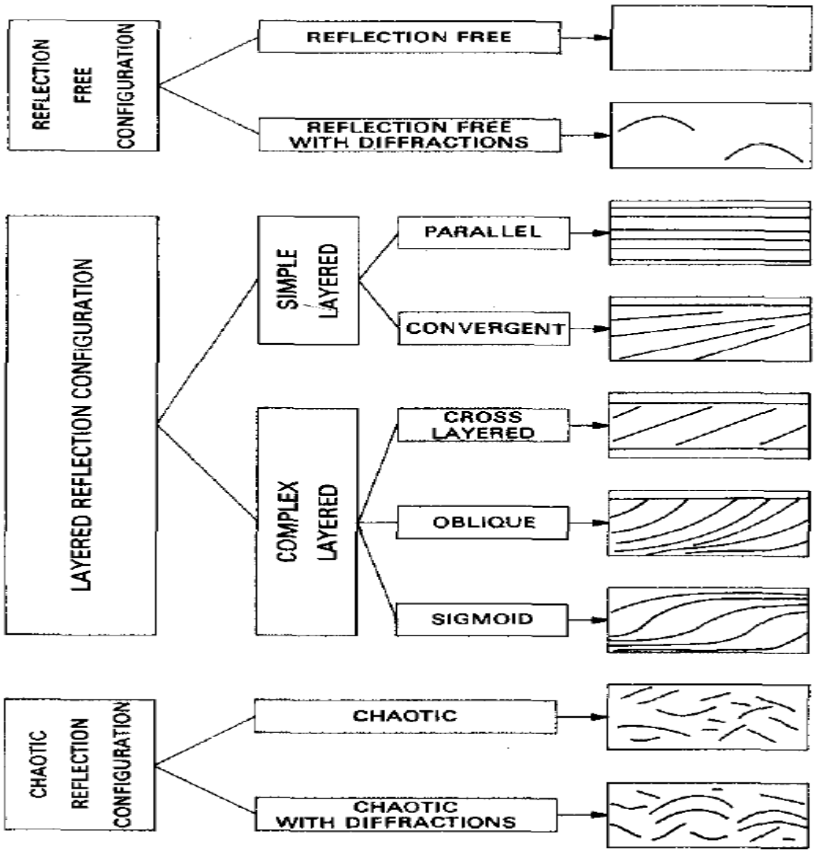


**Figure 3. 7** Different types of reflection configuration (from Roksandic, 1978)

- Horizontal perspective (regressive or transgressive) (Figure3.8)
- Stationary shoreline (potential stabilization of the shoreline takes place by sediments by pass to the basin floor) (Helland-Hansen et al., 2009) (Figure 3.8)

## 3.8 Chronostratigraphic chart

Chronostratigraphic charts display the time relationships of the depositional systems and their relationships to the surfaces of non-deposition, condensation and erosion. A chronostratigraphic chart has a spatial horizontal axis while time at the vertical axis. They can be easily constructed from seismic data and construction of these charts give confidence to the interpreter that their interpretation makes sense in time as well as in space (Emery & Myers, 1996).

## 3.9 Procedure to interpret the seismic data and analyze the seismic sequences

The following procedure has been applied in the present study;

- Identify the unconformities and their correlative conformities by the termination pattern.
- Mark the stratal termination with arrows to further enhance the unconformities e.g Regional Downlap Surface (RDS) is marked by downlaps and Upper Regional Unconformity (URU) by toplap truncations.
- After picking the 1st and 2nd order unconformities, 3rd order unconformities are picked between URU and RDS.
- These surfaces are interpreted as onlap and toplap surfaces and mapped in OpendTect.
- On the basis of these surfaces 32 seismic sequences are defined on the dip lines.
- The interpreted surfaces of the dip lines are tied with the surfaces of strike lines to view the extension of the seismic sequences.
- Thickness of the prograding is converted into metres from TWT by taking the velocities from the Reemst et al. 1996 for depth conversion.
- Chronostratigraphic chart is built to flatten the horizon and analyze in Wheeler domain.

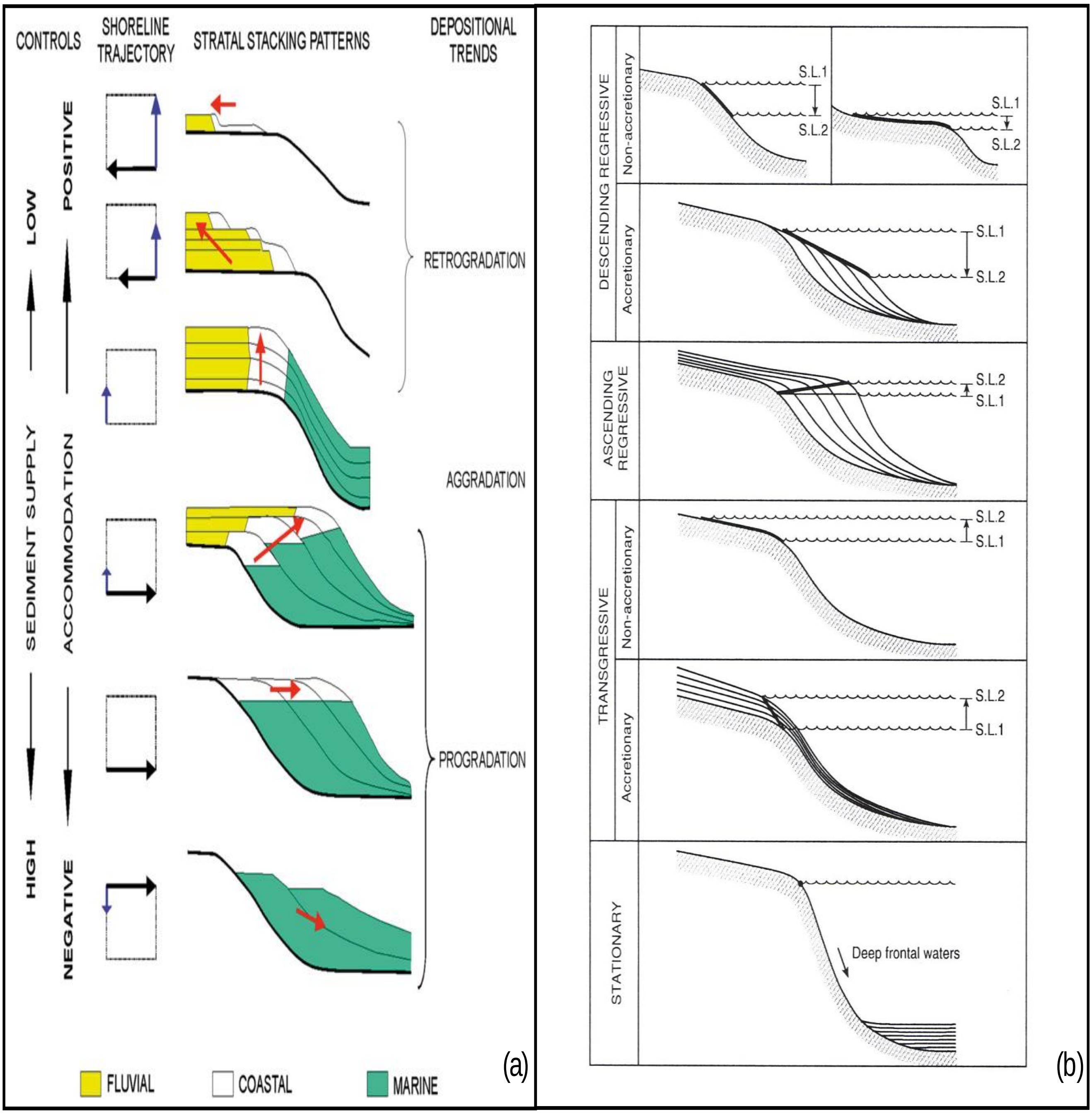


**Figure 3. 8** (a) Depositional trend with trajectory analysis (after Martins-Neto & Catuneanu 2010) (b) shoreline trajectory classes from Helland-Hansen et al., 2009)

# 4. Seismic interpretation and results

This chapter will focus on the interpretation and results of interpreted seismic lines which were part of the dataset from mid-Norwegian Continental Margin (Figure 3.1 and 3.2) after careful interpretation of seismic lines on open seismic interpretation tool “OpendTect” seismic sequence analysis were made.

## 4.1 Description of seismic lines

Seismostratigraphic units are interpreted on the basis of amplitude and continuity of the bounding reflectors, nature of the bounding surfaces (onlaps, downlaps, toplaps and erosional truncations), geometry and extension. In the following description in the subchapters 4.1 and 4.2 some interpretations are given to depositional facies and way of deposition; the reader is referred to subchapter 4.3 for principles of seismic facies interpretation and mechanisms of sedimentation.

The Plio-Pleistocene Naust Formation unconformably overlies the older deposits of Miocene (Evans et al., 2002). From the seismic interpretation it is deduced that this is an angular unconformity made by the downlaping of the westward prograding wedge of Naust Formation. This is a very prominent reflector due to acoustic impedance contrast of the overlying glacial deposits and underlying clay oozes. The velocities in the glaciomarine deposits are higher, but when the seismic waves enter into Miocene strata the velocity dramatically drops, resulting in a great acoustic impedance contrast (Reemst et al., 1996). This is marked as a Regional Downlap Surface (RDS). Along this surface a shift from aggradational stacking pattern to progradational stacking pattern can be recognized (Figure 4.1).

This westward prograding wedge is upward terminated by an erosional unconformity developed by glacial erosion named “Upper Regional Unconformity” (URU) of Vorren et al. (1992) and Henriksen et al. (1996). URU can be traced by its low amplitude reflector, discontinuity and toplap truncations. Westward deep in the basin it appears as a correlative conformity.

Between URU and RDS there is a very thick package of westward prograding clinotherms, internally containing clinoforms and bounded by clinoforms (Figures 4.1-8). By careful interpretation of the dataset 28 seismic sequences have been identified within the clinotherm package between RDS and the URU, defined by the nature of the bounding clinoform surfaces of these seismic sequences.

URU seperates the underlying westward prograding wedge succession from the overlying aggradational units of younger deposits which developed as thin lenses from the floating ice sheets. The youngest three seismic units consist of aggradational and weak progradational sedimentary packages.

A brief description of the seismic lines is given below with emphasis on the most prominent feature of each of the lines. The downlap (red), onlap (blue) and toplap (green) surfaces are marked by arrows.

### 4.1.1 Line A

This seismic line lies in the southern most part of the area covered by the dataset and extends up to 400 km from the Helgeland Basin to the Modgunn Arch (Figure 3.2).

The thickness of prograding clinotherms in the Helgeland Basin is 182 ms TWT (approximately 245 m). The thickness increases in the Halten Terrace and attains a maximum thickness of 880 ms TWT (approximately 1188 m) in the Rås Basin (Figure 4.1). Slide deposits are observed from the lower part of the Naust Formation (Figure 4.1). URU is characterized by maximum amplitude which is continuous in the eastern side, but poor continuity in the western part. Erosional channels of 45 ms (approximately 60 m) are present on the URU, and these unconformity features are thought to represent the erosion made by glaciers moving towards the shelf edge.

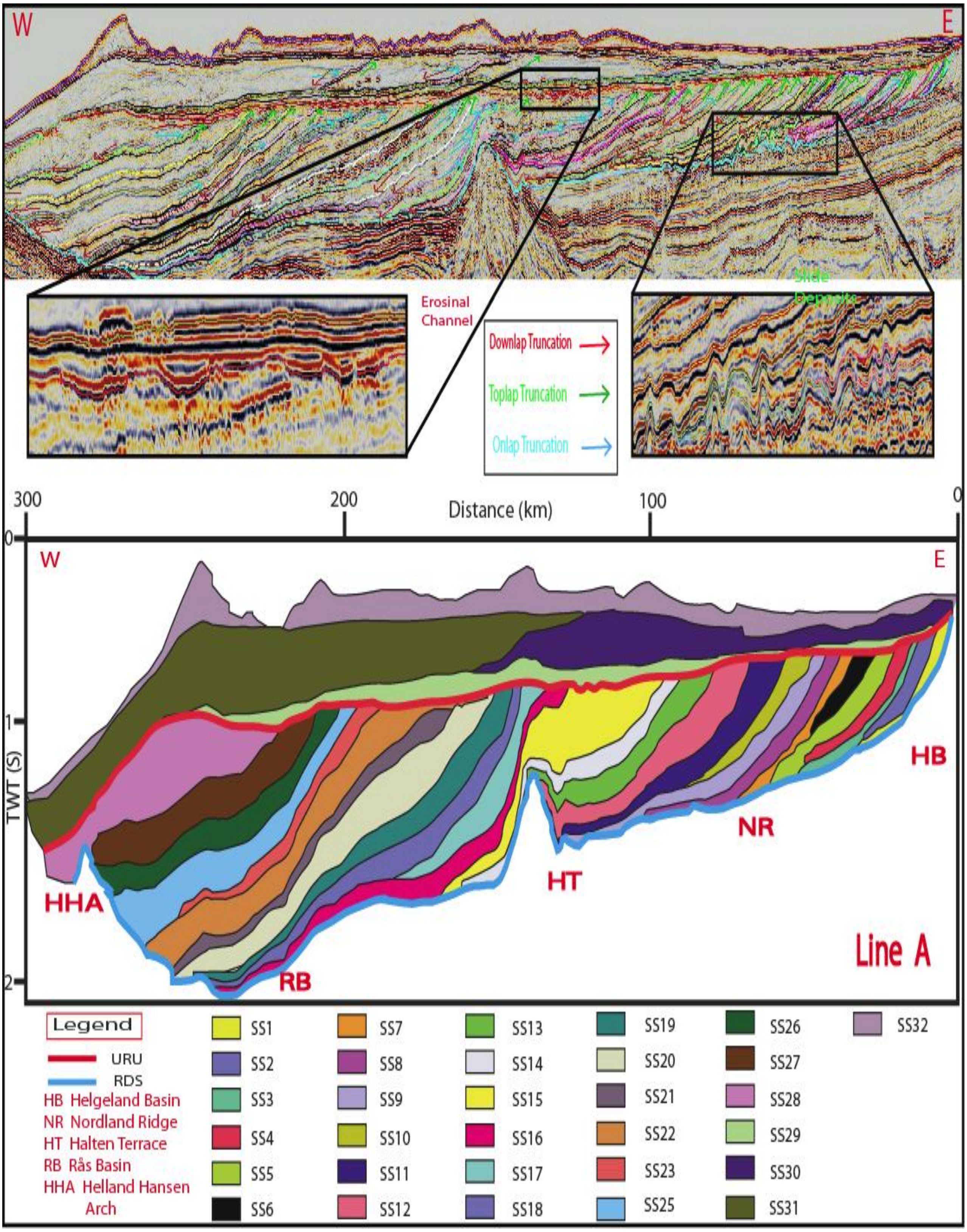


**Figure 4. 1** Seismic line A with seismic section and interpreted profile (see Figure 3.2 for location)

### 4.1.2 Line B

The extension of this seismic line is 427 km from Helgeland Basin to Modgunn Arch (Figure 3.2). The prograding unit of Naust Formation which have been interpreted is built out 230 km westward (Figure 4.2). This prograding wedge is thinnest (i.e. 149 ms TWT, approximately 201 m) in the Helgeland Basin indicating that the basin was not buried so deep and accommodation space was low. In the Rås Basin clinotherms are very thick and the overall thickness of the prograded succession is 886 ms TWT (approximately 1190 m) (Figure 4.2).

Topset beds of SS7, SS15 and SS16 are preserved. Slide deposits are also observed in the eastern part of the Naust Formation, like those on the line A. These deposits are only present in the two southern lines (Figures 4.1 and 4.2) but in the seismic line B their intensity is low. A pronounced feature of this line is a very big erosional channel made by an ice stream or by melt water, observed on the line B (Figure 4.2). This erosional channel has the dimension of 22 km in width in E-W direction and 121 ms TWT (approximately163 m) in depth filled by the horizontal thin sediment lenses (Figure 4.2).

### 4.1.3 Line C

The progradational succession is quite thick with, 303 ms TWT (approximately 409 m) in the area corresponding to the Helgeland Basin, and it gradually thickens towards the area of underlying Nordland Ridge with 444 ms TWT (approximately 590 m), until it reaches the maximum thickness of 737 ms TWT (approximately 990 m) in the area of Rås Basin.

This seismic line is 431 km long and covers the area between Helgeland Basin and Modgunn Arch in E-W direction (Figure 3.2). The upper regional unconformity extends to 183 km along the shelf edge and then behaves as a correlative conformity deep in the basin with no toplap truncations. URU depicts low amplitude and discontinuous reflector marked by toplap

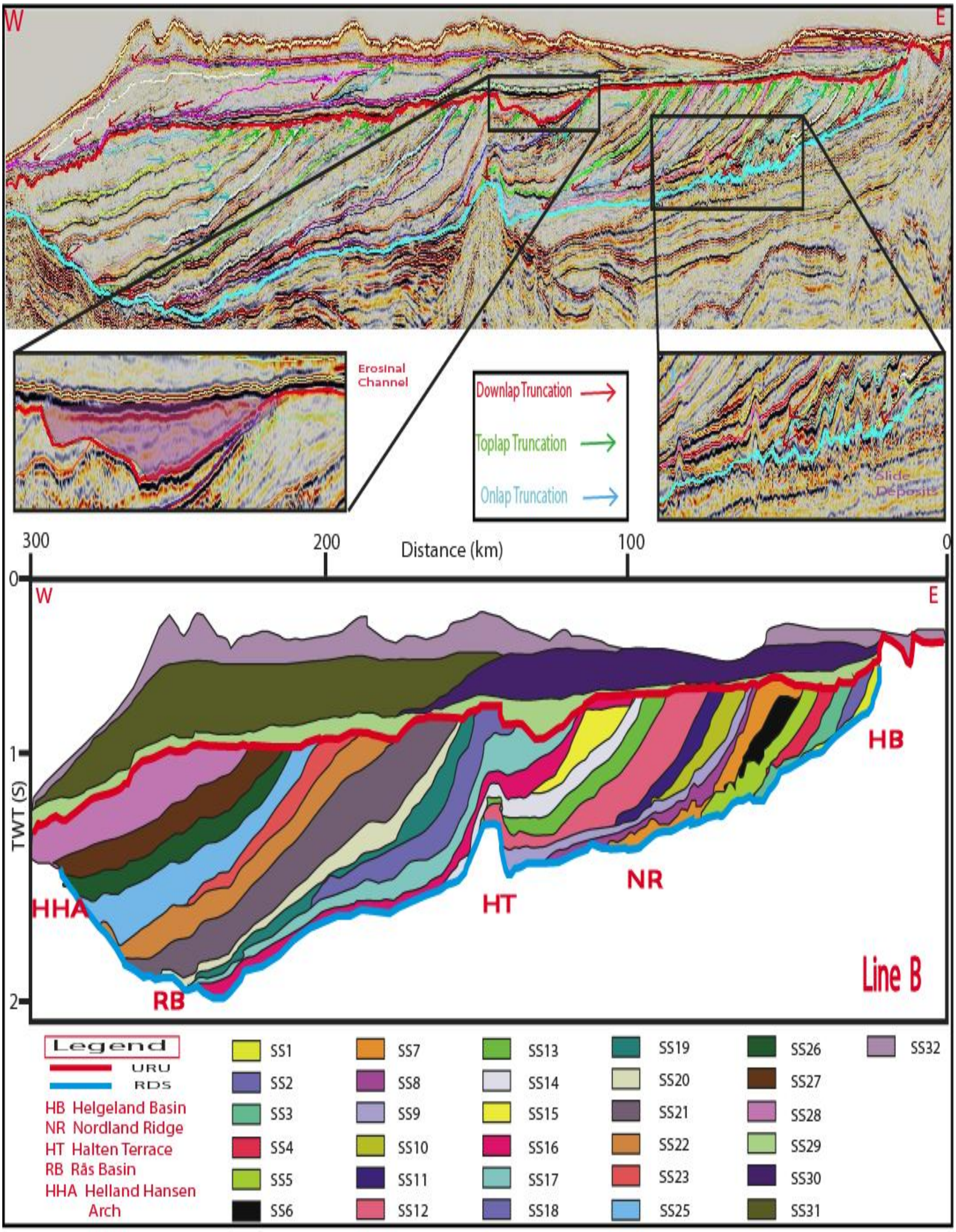


**Figure 4. 2** Seismic line B with seismic section and interpreted profile (see Figure 3.2 for location)

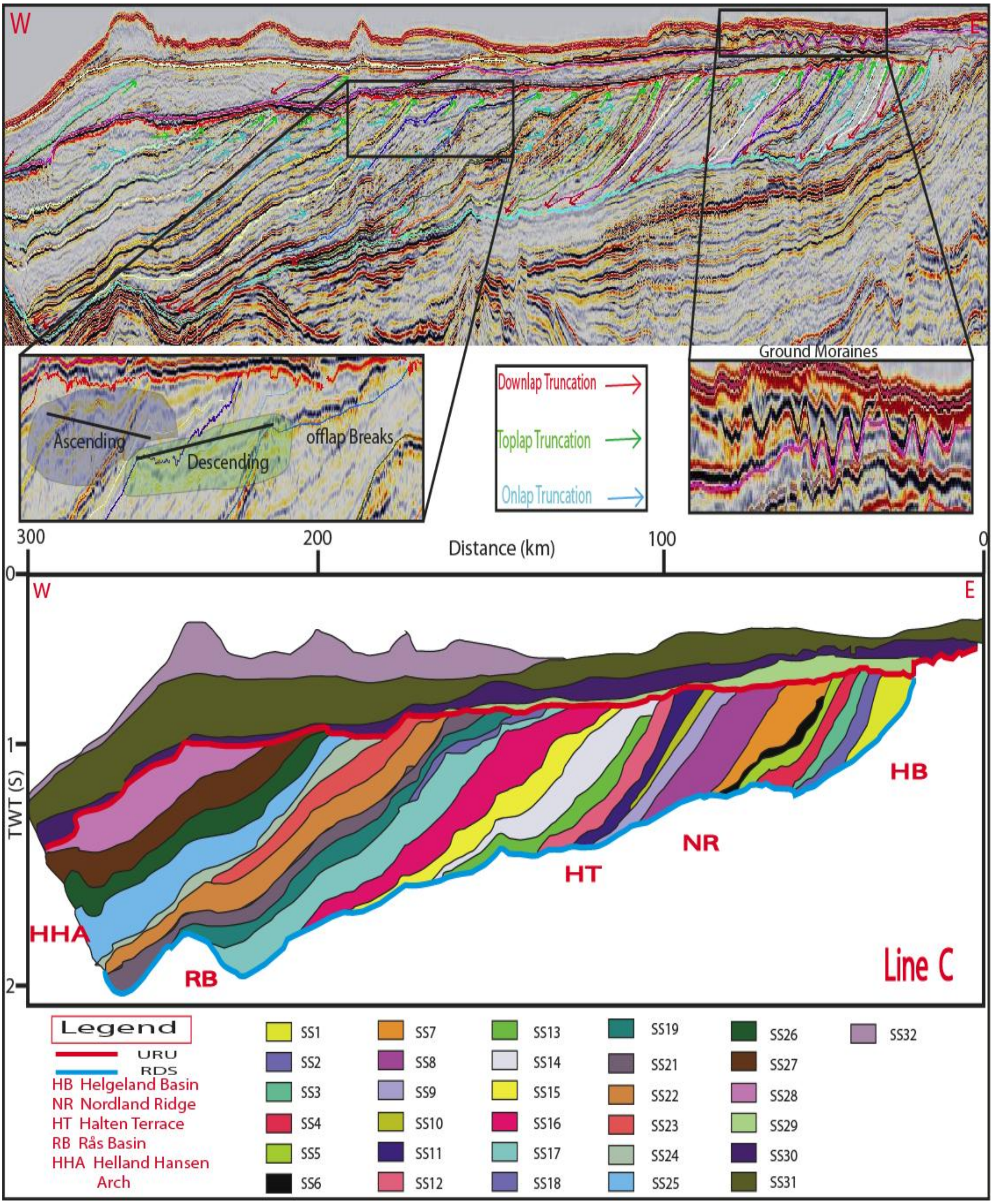


**Figure 4. 3** Seismic line C with seismic section and interpreted profile (see Figure 3.2 for location)

truncations. The RDS is also a low amplitude reflector with good continuity and is picked by downlap truncations (Figure 4.3).

Seismic facies analysis describes the signs of ground morains on this line which is a significant feature of this section (Figure 4.3). Ground moraines are identified by the diffraction caused by the presence of boulders and large blocks (Roksandic, 1978). Offlap breaks are also preserved in the central part of this section. SS31 is very thick in this line (Figure 4.3).

### 4.1.4 Line D

On the seismic line D the identified clinotherms have prograded westward almost 230 km from the base of the Molo Formation to the Helland-Hansen Arch. This seismic line is 433 km long and extends from the Helgeland Basin to the northwestern part of the Modgunn Arch (Figure 3.2).

Along this line the complete prograding wedge is quite thick from the Helgeland Basin to the Helland-Hansen Arch. Its thickness in the Helgeland Basin is 364 ms TWT (approximately 490 m), at Nordland Ridge 473 ms TWT (approximately 638 m) and attains its maximum thickness of 925 ms TWT (approximately 1248 m) in the Rås Basin (Figure 4.4).

URU is characterized by high amplitude and can be traced by toplap truncations. The Regional Downlap Surface (RDS) has low amplitude character with good continuity is distinguished by downlap surfaces of clinoforms (Figure 4.4).

### 4.1.5 Line E

This seismic line is 434 km long and runs perpendicularly to the coast of the Mid-Norwegian Continental Shelf from the Helgeland Basin to the southwestern part of the Gjallar Ridge (Figure 3.2). On the eastern side the offlap breaks are beautifully preserved but still some erosional channels are present on URU made by glacial erosion (Figure 4.5).

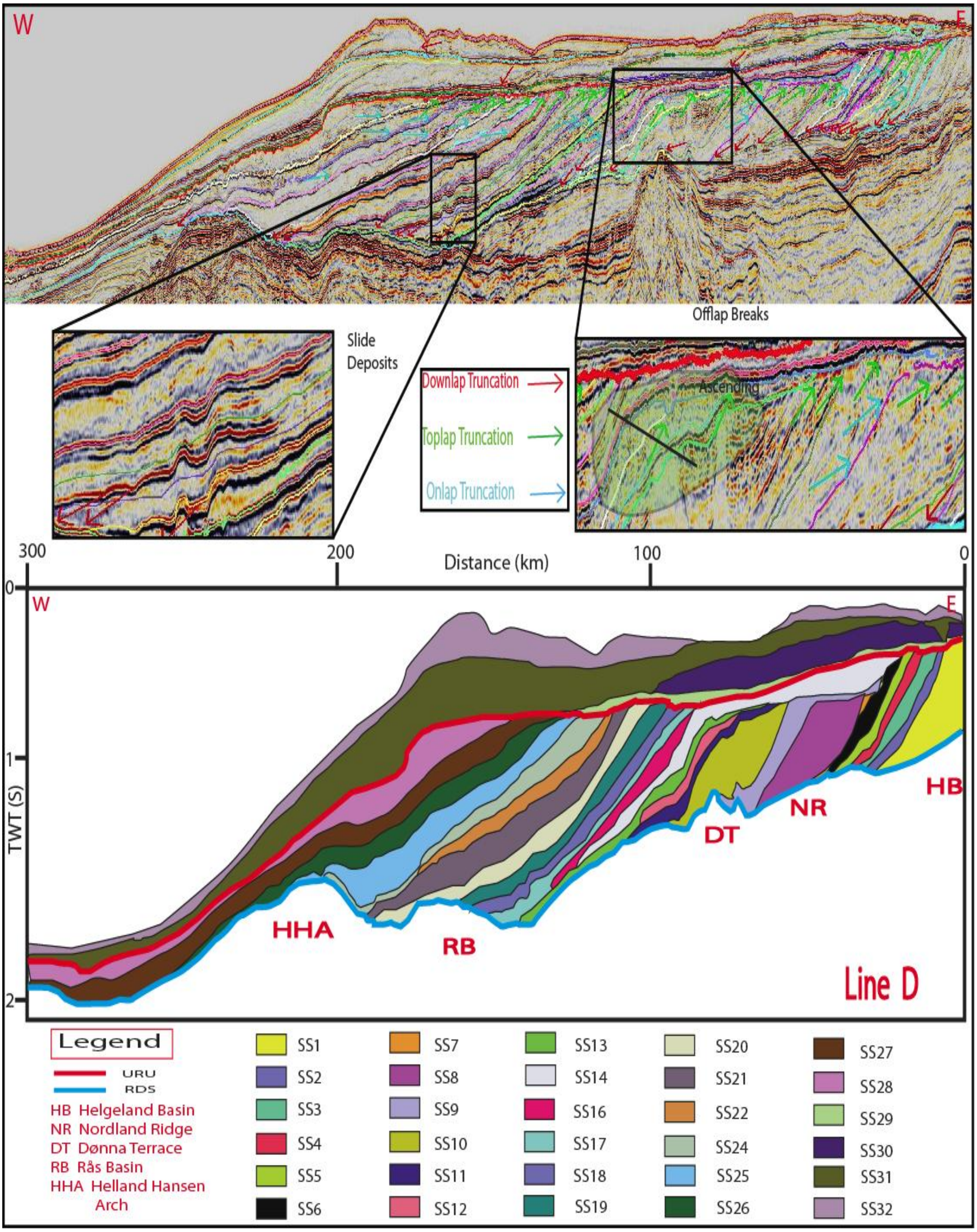


**Figure 4. 4** Seismic line D with seismic section and interpreted profile (see Figure 3.2 for location)

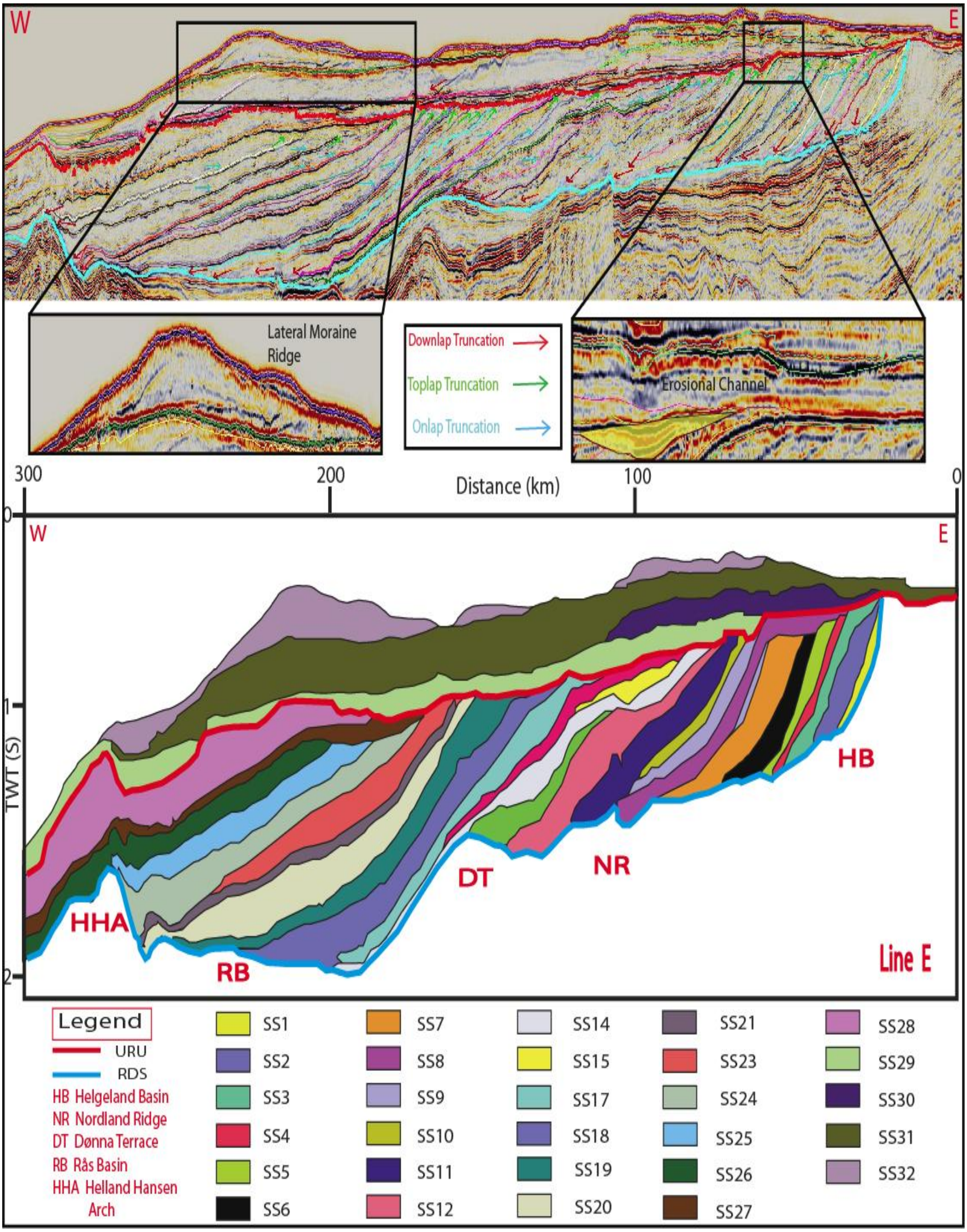


**Figure 4. 5** Seismic line E with seismic section and interpreted profile (see Figure 3.2 for location)

Plio-Pleistocene deposits of the Naust Formation (Dalland et al., 1988) are thickening towards the basin, whereas in the Rås Basin the succession achieves a thickness of 959 ms TWT (approximately 1290 m) due to greater burial of the basin and increased accommodation space (Figure 4.5).

The clinoforms of the prograding wedge have gentle dip on the western side of the line and define here thick and uniform clinotherms. Progradation of the Naust Formation along the interpreted part of the seismic line has been observed to be 280 km westward from the area of the Helgeland Basin to the position of the Helland Hansen Arch (Figure 4.5).

### 4.1.6 Line F

This seismic line is considered to be the reference line for this study. All the seismic sequences SS1-SS32 are best preserved and interpreted on this line. The extension of this line is from the area of the Helgeland Basin to the Gjallar Ridge with a length of 446 km in the E-W direction (Figures 3.1 and 3.2).

The Plio-Pleistocene prograding wedge has its maximum thickness along this line section. The thickness of the succession between URU and RDS is 493 ms TWT (approximately 660 m) at the Helgeland Basin, 666 ms TWT (approximately 895 m) above the Nordland Ridge and in the area of the Rås Basin 1065 ms TWT (approximately 1430 m). The glaciomarine sediments have prograded 218 km from the Molo formation to westward across the Helland-Hansen Arch (Figure 4.6).

URU is observed to be behaving as an unconformity 168 km westward before it appears as a correlative conformity with no toplap truncations. The URU is characterized by low amplitude and discontinuous reflector with toplap truncations. The RDS is more continuous with low amplitude reflector with downlap terminations. Clinoforms dip steeply in the eastern part as compared to the western part where they dip gently and within thick clinotherms. Erosional channels at URU and top of SS 30 are observed (Figure 4.6).

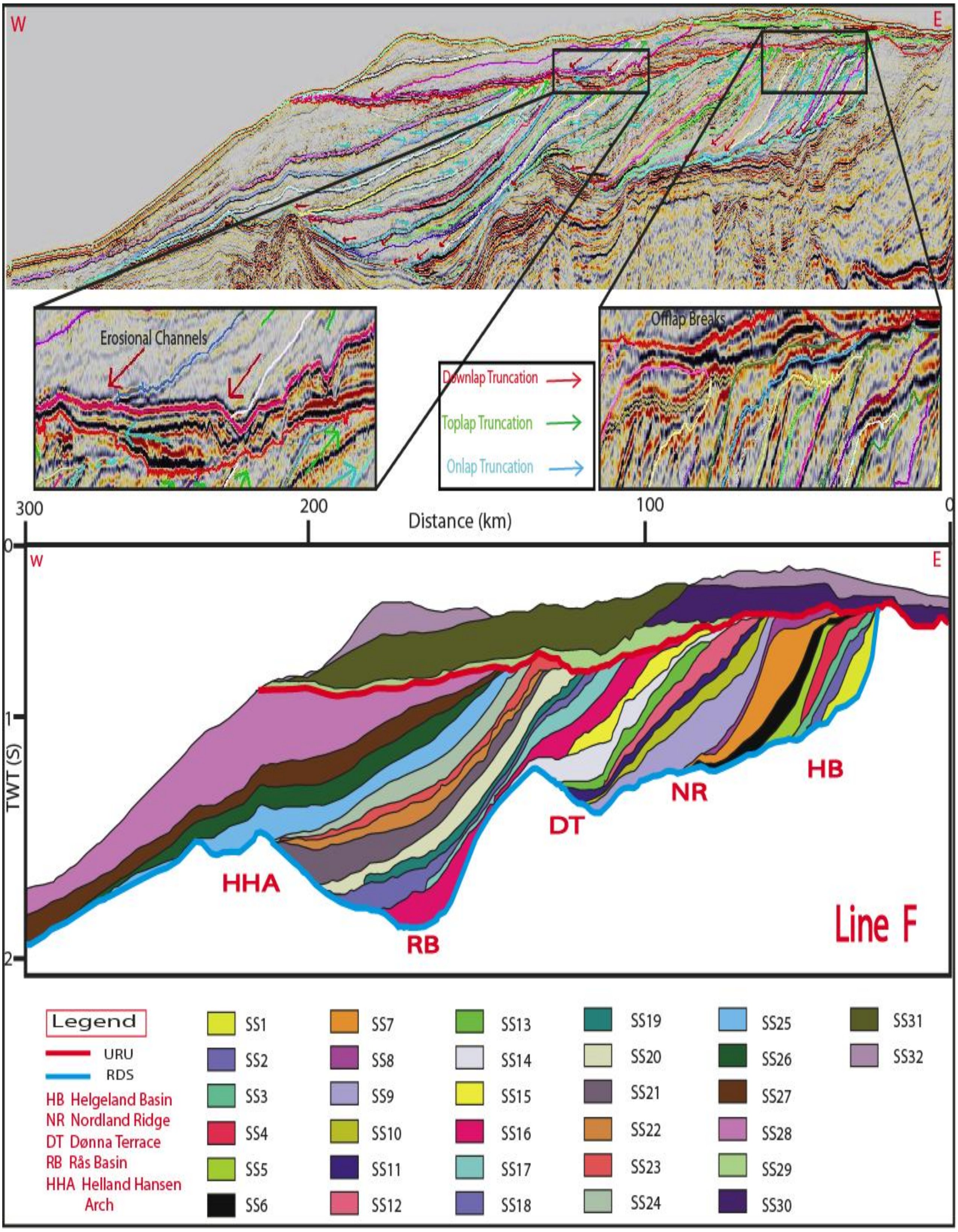


**Figure 4. 6** Seismic line F with seismic section and interpreted profile (see Figure 3.2 for location)

### 4.1.7 Line G

Line G is running from the area of the Helgeland Basin to the western flank of the Gjallar Ridge (Figure 3.2). Offlap breaks display both ascending and descending trajectories (Figure 4.7). Along this section in the Rås Basin the prograding wedge below URU has a maximum thickness of 1203 ms TWT (approximately 1624 m) with gently dipping clinoforms. SS 32 is very thin on this line while SS 29 is very thick and extensive, and erosional channnels are present at top of SS 29 (Figure 4.7).

### 4.1.8 Line H

This seismic line is the northern most line of the narrow corridor data selected for seismic interpretation (Figures 3.1 & 3.2). This line is of particular interest in the way that it does not have the SS 32 which is a moraine ridge.

The extension of this line is 439 km and it extends from the northeastern part of the Trøndelag Platform to the central part of the Gjallar Ridge (Figure 3.2). The maximum thickness of the prograding wedge below URU is 1274 ms TWT (approximately 1715 m) along this profile. Offlap breaks have descending order preserved well in the western part of the wedge (Figure 4.8).

## 4.2 Seismic Sequence Analysis

The interpretation of these seismic lines break out 32 seismic stratigraphic units defined by the nature of the bounding surfaces of these sequences. The surfaces are clinoforms having onlap and downlap seismic lapouts and in the uppermost sediments erosional surfaces. The seismic sequences are described briefly below.

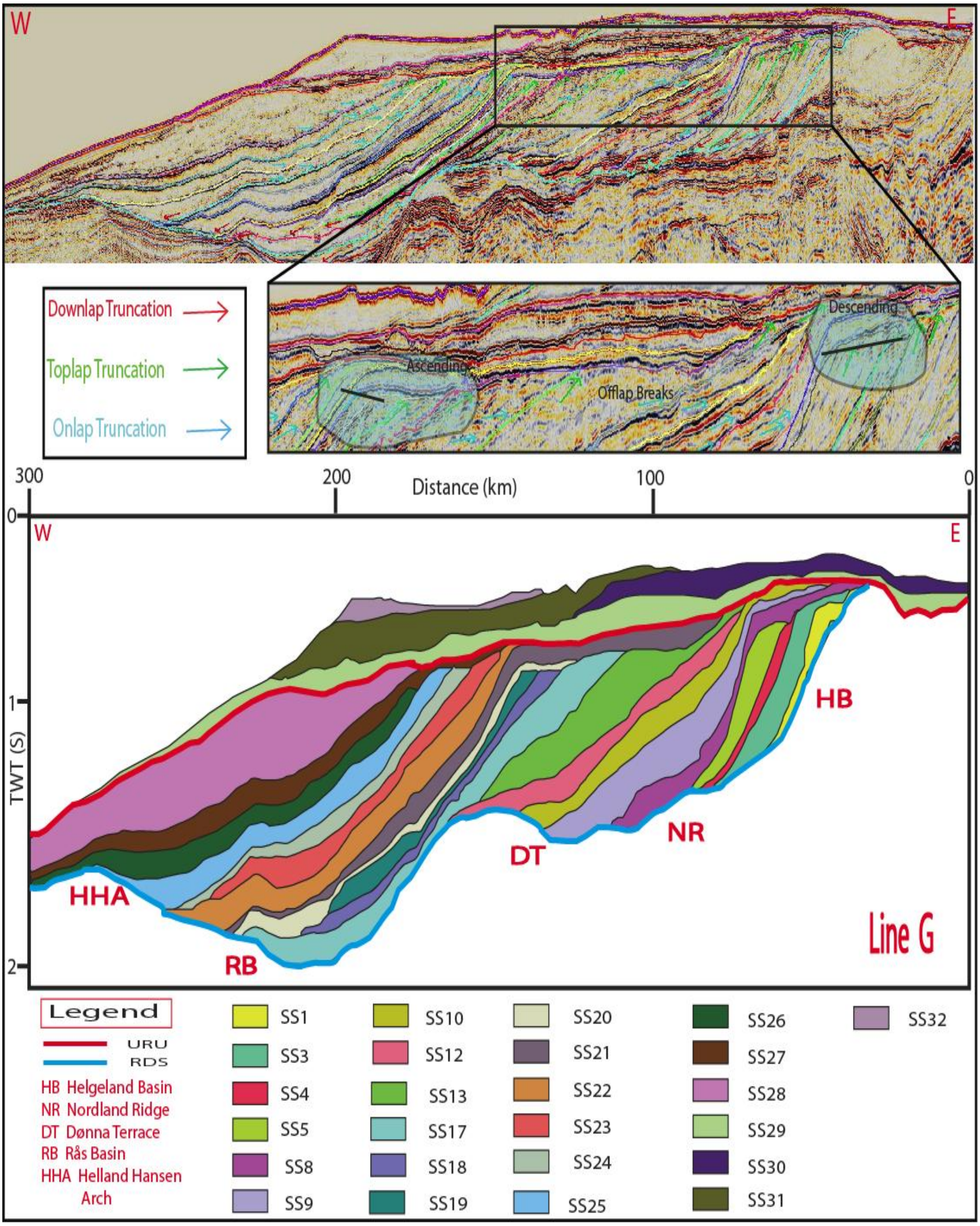


**Figure 4. 7** Seismic line G with seismic section and interpreted profile (see Figure 3.2 for location)

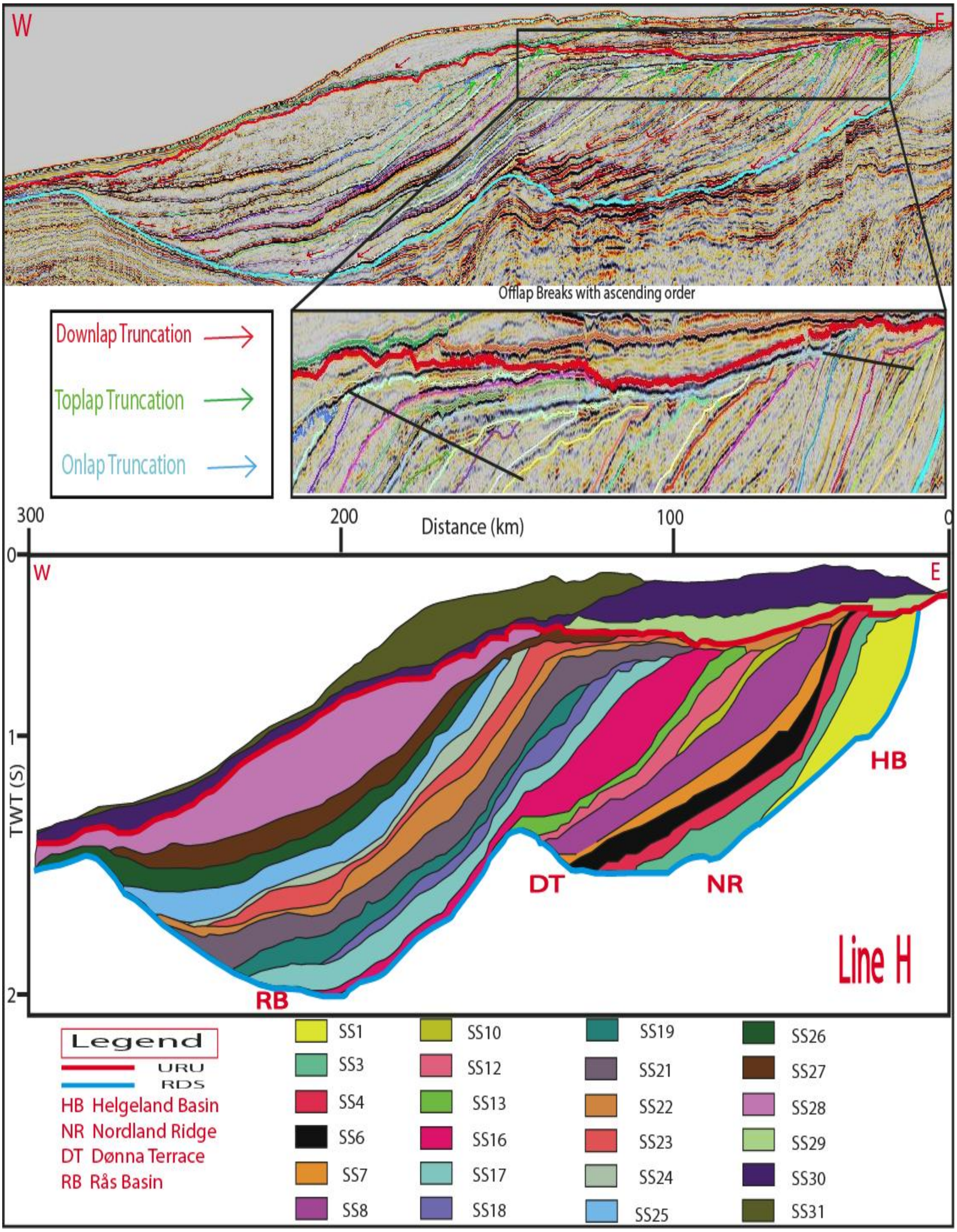


**Figure 4.8** Seismic line H with seismic section and interpreted profile(see Figure 3.2 for location)

**Seismic Sequence 1 (SS1)**

This is the lower most and oldest seismic stratigraphic unit of the Naust Formation. On the eastern Trøndelag Platform area (southern part of this study) it has an oblique sigmoidal geometry while it appears as a sigmoid profile in the northeastern Trøndelag Platform (northern part of this study). This change in style may indicate that ice sheets did not erode the top sets of the SS1 in the northern part of the study area which depicts the rise in sea level as shown in Figure 4.8. The ascending trend of the shoreline trajectory confirms the rise of sea level.

SS1 is bounded at the base by the RDS and on the upper side by a local downlap surface which changes its behaviour to local onlap surface (Lines F, G and H) in the northern part of the study area. This may have been caused by increase in accommodation space and sedimentation rate during rise of relative sea level. The offlap breaks preserved represent the shelf edge at that time. The thickness of SS1 varies from south to north (Figure 4.1-4.8).

**Seismic Sequence 2 (SS2)**

The seismic sequence SS2 is absent on the lines G and H (Figures 4.7 & 4.8). It was deposited only in the eastern part of the Trøndelag Platform area (Helgeland Basin). It has a uniform thickness throughout the area corresponding to the Helgeland Basin before it pinches out towards northwestern part of Helgeland Basin. The sequence is bounded at the base by a local downlap surface and at top also by a local downlap surface which changes into a local onlap surface towards the north before pinching out.

**Seismic Sequence 3 (SS3)**

SS3 is bounded at the base by a local downlap surface in the southeastern Helgeland Basin and a local onlap surface in the northeastern part. The sequence directly overlies SS1 in the northeastern Trøndelag Platform where SS2 is not present. It has oblique tangential geometry which transforms into sigmoid oblique geometry in the northern part of the study area (Lines G and H) (Figures 4.7 & 4.8).

**Seismic Sequence 4 (SS4)**

This seismic stratigraphic unit is extensively developed in the Helgeland Basin area. It is bounded at the base by a local downlap surface and at the top by a local onlap surface. On the lines A and F (Figures 4.1 & 4.6) SS4 pinches down on the upper boundary of SS3 which is a local downlap surface. The clinoform geometry of SS4 is oblique tangential (Figures 4.1-4.8).

### Seismic Sequence 5 (SS5)

The seismic stratigraphic unit SS5 is pinching out towards northeastern Trøndelag Platform and does not appear on the seismic line H. On the line F (Figure 4.6) topset beds are preserved. Before pinching out towards the north, the sequence becomes very thin on the line G (Figure 4.7) and pinches up with the topset beds of SS8.

### Seismic Sequence 6 (SS6)

This seismic stratigraphic unit contains slide deposits (Figures 4.1 & 4.2). The SS6 pinches down into SS5 on lines A and B (Figure 4.1 & 4.8) it pinches up on SS4. The offlap breaks preserved depicts the increase of accommodation and onset of rise in sea level in the southern part of study area. It is bounded at the base by local onlap surface and a local downlap surface at the top.

### Seismic Sequence 7 (SS7)

The lower boundary of the seismic sequence 7 is a local downlap surface and the upper boundary is a local onlap surface which changes its nature towards north into a local downlap surface. This sequence is absent on line G (Figure 4.7). In the southern part it contains slide deposits at its toe (Figures 4.1 & 4.2).

### Seismic Sequence 8 (SS8)

The seismic sequence 8 is bounded at the base by onlap surface of SS7 and directly over SS5 on line G (Figure 4.7) where SS6 and SS7 are not present. The upper boundary of SS8 is a local onlap surface. The clinoform geometry of SS8 is oblique tangential except on line E (Figure 4.5) where the topset beds are preserved and clinoforms have oblique sigmoidal geometry. The thickness of SS8 varies within the basin from north to south in the study area.

### Seismic Sequence 9 (SS9)

The SS9 pinches out on the northeastern part of Nordland Ridge area and is absent on the line H (Figure 4.8). It has a uniform thickness throughout the basin with a well preserved positive offlap break trajectory. The upper limits of SS9 changes its nature from local downlap surface to local onlap towards north. The lower boundary of SS9 is a local downlap surface. The clinoform geometry is oblique tangential.

**Seismic Sequence 10 (SS10)**

This unit is thining towards the north, while in the central part of the Halten Terrace it becomes quite thick with chaotic facies. Its lower boundary is of varying nature from downlap (south) to onlap surface (north) and same behavior of upper limits. It is truncating up with the topset beds of SS22 on seismic line H (Figure 4.8).

**Seismic Sequence 11 (SS11)**

This sequence is extensively developed at western part of the Trøndelag Platform area but pinches out towards the eastern margin of the Vøring Basin (Figures 4.1- 4.8). It is bounded at the base by a local onlap surface. It has oblique tangential geometry except on the line D where it changes into oblique sigmoidal geometry (Figure 4.4).

**Seismic Sequence 12 (SS12)**

This unit is mappable on all the lines with uniform thickness (Figure 4.1- 4.8). It is thick in the area of the Dønna Terrace towards west but thins towards the north in the Vøring Basin. In seismic lines G and H (Figures 4.7 & 4.8) it directly overlies SS10 where SS11 is absent and bounded by local a onlap surface except in the southwestern part, where it is a local downlap surface.

**Seismic Sequence 13 (SS13)**

This seismic unit is absent on the seismic line E (Figure 4.5). The facies analysis depicts chaotic behavior on line G. On the seismic line H (Figure 4.8) it is truncated by the topset beds of SS22. It has oblique tangential geometry except on line D (Figure 4.4) where the clinoform geometry is oblique sigmoidal. It is bounded at the base by a local downlap surface in the south of study area which turns into an onlap surface in the northern part. The upper boundary of SS13 is a local downlap surface of SS12, but on the lines G and H (Figures 4.7 & 4.8) it underlies SS17 and SS 16.

### Seismic Sequence 14 (SS14)

This unit is also absent on lines G and H (Figures 4.7 and 4.8) and pinches out towards the northern part of the Rås Basin. It has well preserved topset beds along the line D (Figure 4.4). Seismic facies analysis of SS14 depicts chaotic nature of the sequence.

### Seismic Sequence 15 (SS15)

SS15 is bounded at the base by a local onlap surface and at top also by a local onlap surface. It also pinches out towards the northeastern part of the Rås Basin (Figures 4.1-4.8). SS15 is thick in the area of the south-western Halten Terrace. It has sigmoidal clinoform geometry. On the seismic line B (Figure 4.1) topset beds are preserved. It has chaotic facies on line A.

### Seismic Sequence 16 (SS16)

SS16 is bounded by local onlap surfaces above and below. SS16 is not present on line G (Figure 4.7). The thickness of SS16 varies from south to north and the seismic facies is chaotic facies as revealed on lines C and F (Figures 4.3 & 4.6). The sequence has oblique tangential geometry.

### Seismic Sequence 17 (SS17)

This sequence is bounded at the base by a local onlap surface and at the top by a local downlap surface. SS17 is thick in the area of the Halten and the Dønna terraces but thins westwards along the eastern flanks of the Rås Basin. SS17 has chaotic facies on line A (Figure 4.1).

### Seismic Sequence 18 (SS18)

This seismic stratigraphic unit is developed throughout the study area. It is very thin on line C (Figure 4.3) and has not prograded far into the area of the Rås Basin towards the west. The seismic sequence has oblique tangential clinoform geometry.

### Seismic Sequence 19 (SS19)

This seismic stratigraphic unit is extensively developed along the eastern margin of the Vøring Basin. It has oblique tangential geometry. It is bounded at the base by an onlap surface and at top by downlop surface in the eastern Vøring Basin and a local onlap surface in the northeastern Vøring Basin on the seismic line F (Figure 4.6). SS19 is very thin and pinches down on the SS 18.

### Seismic Sequence 20 (SS20)

This sequence is bounded at the top by a downlap surface and at the base by varying nature surface from downlap to onlap surface. The thickness also varies within the basin. Topset beds preserved on line G (Figure 4.7) represent shelf edge at that time. It has oblique tangential clinoform geometry.

### Seismic Sequence 21 (SS21)

This seismic sequence is bounded at the base by a downlap surface and at the top by an onlap surface. It is mappable throughout the study area and thickens towards the north (Figures 4.1- 4.8). It has oblique tangential geometry, but in the north-eastern part of the Vøring Basin the sequence has oblique sigmoidal geometry.

### Seismic Sequence 22 (SS22)

This sequence is bounded at the base and top by local onlap surfaces. In the seismic line D (Figure 4.4) the sequence underlies SS24, where SS23 is absent. SS22 is absent on line E (Figure 4.5). The unit is thicker in the southern part but thins towards the northern part of study area. The sequence has oblique tangential geometry but on line H the clinoform geometry is sigmoidal oblique with well preserved topsets (Figure 4.8).

### Seismic Sequence 23 (SS23)

The sequence SS23 does not downlap on the RDS but pinches out into SS22. In the northeastern part the topset beds have preserved the depositional shelf edge which moved up as compared to previous sequence and represents the culmination of relative rise in sea level (Figures 4.7 & 4.8). The sequence is characterized by uniform thickness and oblique tangential geometry. It is bounded on both sides by local onlap surfaces.

### Seismic Sequence 24 (SS24)

The sequence SS24 is absent in the southern part of the study area (lines A and B) (Figures 4.1 & 4.8). SS24 is bounded at the top and base by onlap surfaces. In the western part of Rås Basin it has uniform thickness. The clinoform geometry of SS24 is oblique parallel.

**Seismic Sequence 25 (SS25)**

This seismic stratigraphic unit is bounded at the top and the base by onlap surfaces. This sequence is extensively deposited in the area corresponding to the Rås Basin (Figures 4.1- 4.8). SS25 pinches out to the eastern edge of the Helland-Hansen Arch. The unit is thick in the southern and central parts of the Rås Basin. The geometry of clinoforms is oblique parallel.

**Seismic Sequence 26 (SS26)**

This seismic sequence stratigraphic unit is mappable throughout the study area (Figures 4.1- 4.8). The unit has also prograded across the Helland-Hansen Arch. It is bounded at the top and the base by onlap surfaces. Oblique parallel geometry represents the erosion of topset beds.

**Seismic Sequence 27 (SS27)**

This seismic sequence is thin in the southeastern part of the Rås Basin and gradually thins towards the north where topset beds are preserved (Figures 4.1- 4.8). The lower and upper limits of the seismic sequence 27 are local onlap surfaces.

**Seismic Sequence 28 (SS28)**

This seismic stratigraphic unit is extensively developed in the western part of the Rås Basin and across the Helland Hansen Arch (Figure 4.1- 4.8). It is bounded at the base by a local onlap surface and at top by a correlative conformity. SS28 consists of chaotic seismic facies.

**Seismic Sequence 29 (SS29)**

This sequence is bounded at the base by the Upper Regional Unconformity (URU) and at the top by lower boundaries of SS30 and SS31 marked by erosional surfaces (Figures 4.1- 4.8). SS29 consists of aggradational packages of thin sediment lenses. This aggradational package developed likely when the ice sheet was floating due to rise in relative sea level and could not ground the shelf edge. On seismic lines C, D and H the western part of SS 29 is eroded and SS31 overlies URU.

**Seismic Sequence 30 (SS30)**

This is a package of aggradational and weak progradational units. On the seismic lines C and H (Figures 4.4 & 4.8) SS30 is thick and extends down to the shelf edge in westward direction. SS30 is lobate in shape and has erosional channels at its contact with SS31.

**Seismic Sequence 31 (SS31)**

This sequence is extensively developed from the Helgeland Basin to Helland Hansen Arch on seismic lines C, D and E, the southeastern part of the Trøndelag Platform and the Vøring Basin. SS1 also consists of an aggradational and progradational package which was developed in the form of a lobe. The internal geometry is reflection free but few low angle prograded clinoforms are rcognized. SS 31 has its maximum thickness in the Rås Basin area (Figures 4.1-4.8).

**Seismic Sequence 32 (SS32)**

This seismic stratigraphic unit is the youngest package of the Plio-Pleistocene succession. It represents the present shelf edge position. On the southern side it is extensively mappable from the Helgeland Basin to the Rås Basin and pinches out gradually towards the north. In the Rås Basin it appears as a mound. The seismic facies analysis depicts that this package consists of ground and lateral moraine ridges. Its internal geometry is reflection free which also deduce the homogeneity of sequence (Figures 4.1- 4.7).

## 4.3 Seismic Facies Analysis

Following the seismic sequence analysis, lithofacies and environment within the sequences are interpreted from the seismic data. Seismic facies analysis is the description and interpretation of seismic reflection parameters like continuity, amplitude, configuration and frequency. Each of these parameters is important and provide valuable information about subsurface geology. Reflection configuration provides information about stratification pattern. By the interpretation of stratification pattern depositional processes, erosion and palaeotopography can be deduced. Stratal configuration can be mapped from seismic reflection configuration, this is the first step in seismic facies analysis (Mitchum et al., 1977).

On the basis of reflection configuration six types of seismic facies are analysed on the data set. These are chaotic, channel fill, onlique parallel, oblique sigmoid, parallel to sub parallel and oblique tangential.

### 4.3.1 Parallel to sub parallel facies

This is characteristic of sheet, sheet drape and channel fill facies. Parallel to sub parallel facies describe the uniform rates of sedimentation on shelf to shelf margin and prograding slope (Mitchum et al., 1977). SS29 and SS30 contains parallel to subparallel facies interpreted to have been deposited during the rise of relative sea level when ice sheets were floating and not grounded (Figure 4.9).

Oblique sigmoidal, chaotic and oblique tangential seismic facies belongs to prograding reflection configurations (Mitchum et al., 1977). So we can describe these facies under prograding seismic facies.

### 4.3.2 Prograding seismic facies

This facie is characteristic of prograding wedge succession. Oblique sigmoid, chaotic and oblique tangential seismic facies develop by the laterally prograding gently sloping surfaces called clinoforms. Different clinoform patterns represent different rate of deposition and water depths (Mitchum et al.,1977).

### 4.3.3 Oblique tangential facies

The geometry of oblique tangential facies can be defined by dips of the forest beds dipping gently in the lower parts, developing concave upward geometry and gradually passes into gently dipping bottomset beds which ultimately truncate along a downlap surface (Mitchum et al., 1977). The eastern part of Trøndelag Platform has oblique tangential facies (Figure 4.10).

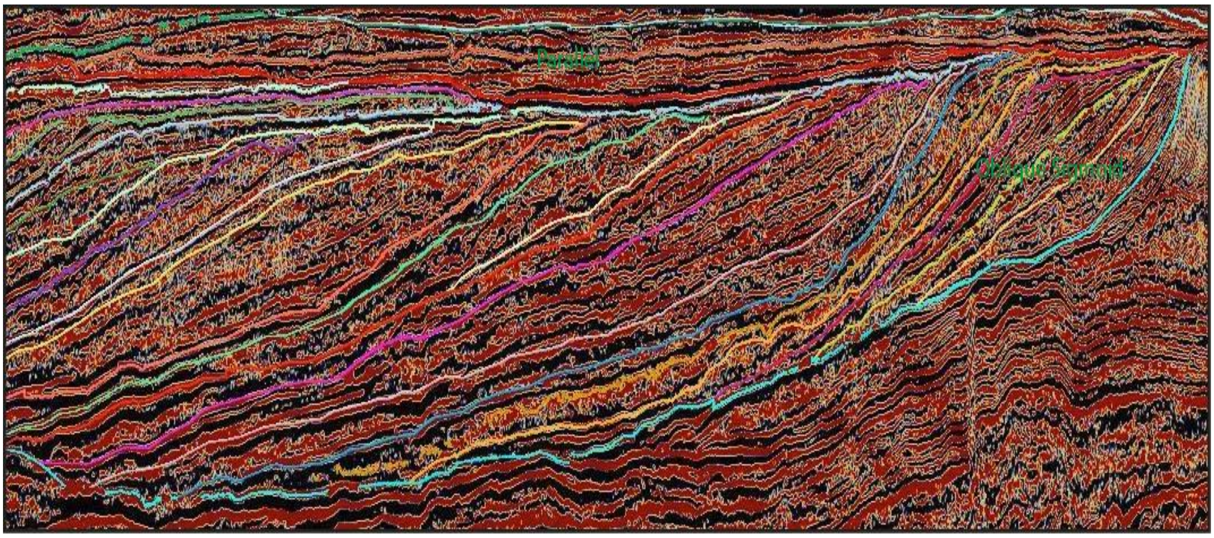


**Figure 4. 9** Seismic section showing parallel to sub parallel and oblique sigmoid seismic facies

### 4.3.4 Oblique parallel Seismic facies

This facies geometry can be defined by the relatively steep dipping parallel foreset beds truncating downdip at high angle along the downlap surface (Mitchum et al., 1977) (Figure 4.11). These are common in the western part of the Rås Basin in the study area. These facies describe the sediments along the shelf slope, eroding the foreset beds. SS23 to SS27 have commonly this kind of geometry.

### 4.3.5 Oblique sigmoid seismic facies

The geometry of this kind of clinoform patterns consists of alternate sigmoid and oblique progradational reflection configurations. The upper part consists of horizontal topset beds and toplapping segments of oblique configuration (Mitchum et al., 1977) (Figure 4.9). The topset beds are preserved because there is minimal erosion and sediments by pass to the shelf edge. The offlap breaks preserved along the oblique sigmoid patterns describe the rise and fall in relative sea level. In the northern part of the Helgeland Basin and the Rås Basin these are well preserved. On seismic line H these offlap breaks describe the rise in relative sea level (Figure 4.8).

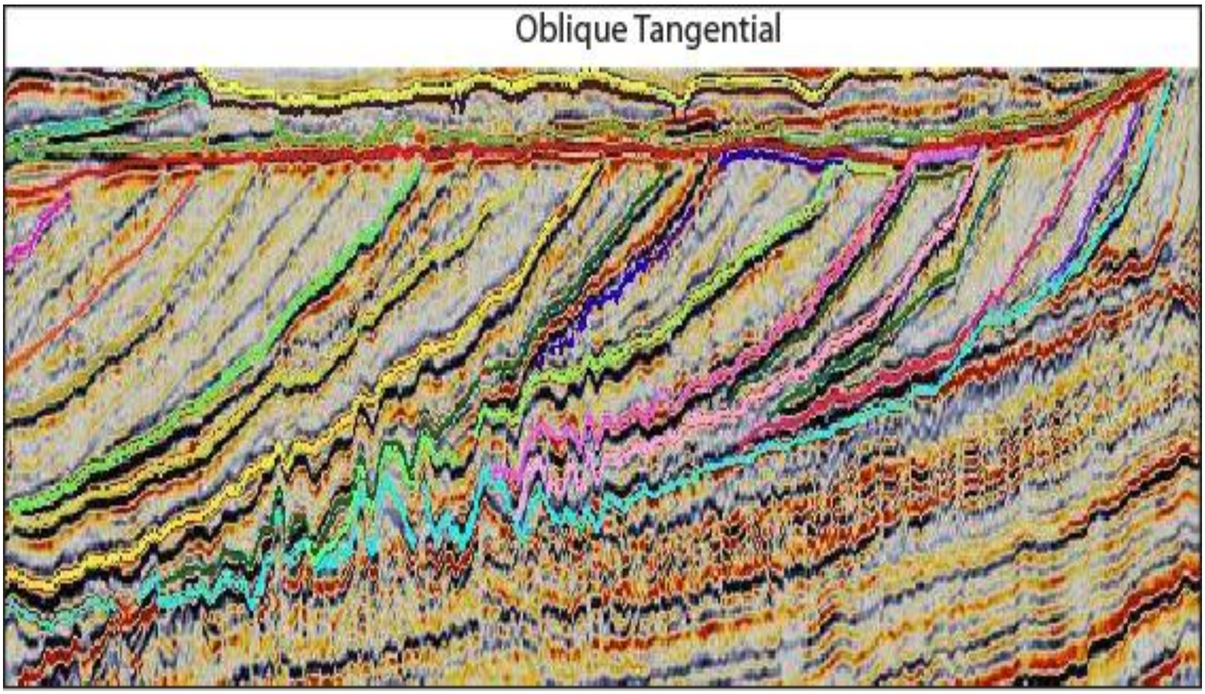


**Figure 4. 10** Seismic section showing oblique tangential seismic facies

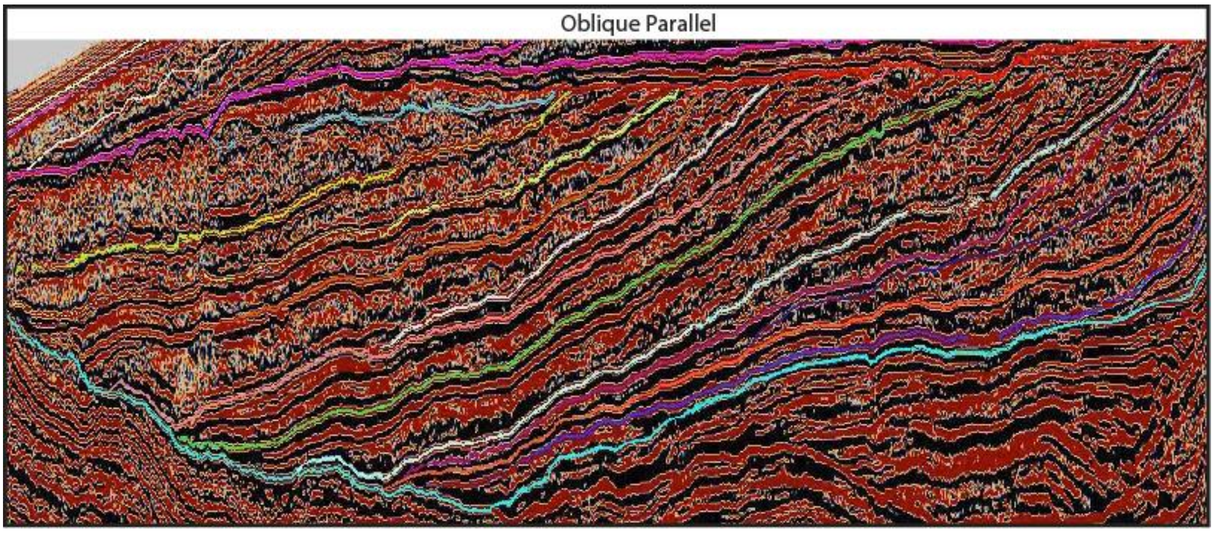


**Figure 4. 11** Seismic section showing oblique parallel seismic facies

### 4.3.6 Chaotic facies

These are discontinuous and discordant reflections describing the disorder arrangement of reflection surfaces (Mitchum et al., 1977) (Figure 4.12). The chaotic facies is observed in the area of the Halten Terrace and the Dønna Terrace. These facies interpreted are to be the response of heterogeneous sediments, fluidized sediments and slump deposits.

### 4.3.7 Channel fill

This kind of facie fills the negative relief features such as erosional channel and canyons with sediments onlap on both side of channel structure. This kind of facies describes the structure which is being filled (Mitchum et al.,1977). On seismic line B a channel fill can be observed (Figure 4.13).

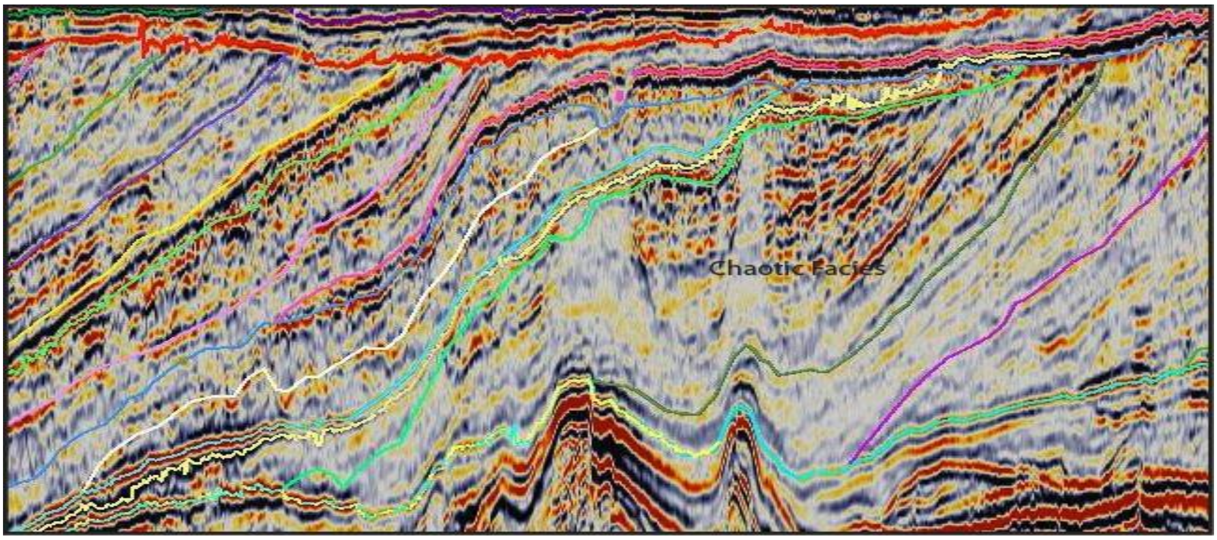


**Figure 4. 12** Seismic section showing chaotic seismic facies

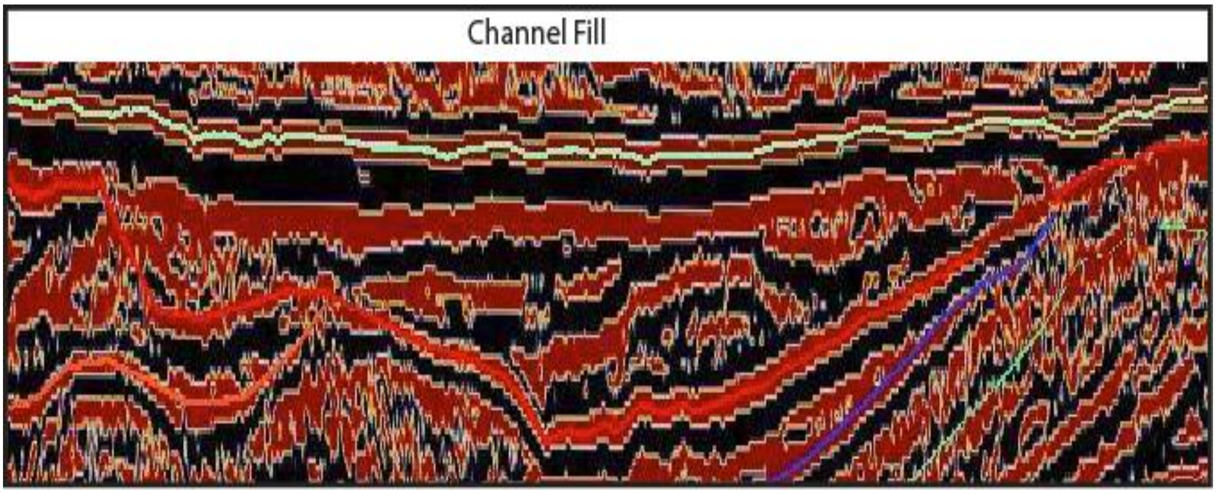


**Figure 4. 13** Seismic section showing channel fill seismic facies

# 5. Discussion

This study has divided the Naust Formation into 32 seismic units. As mentioned in the earlier chapters Naust Formation consists of glacially derived deposits which prograded westward along the mid-Norwegian continental margin. The 32 sequences represent minimum 30 glacial periods as a result of which these sequences developed bounded by either onlap surfaces or downlap surfaces. Glacial ice has moved on to the mid-Norwegian Shelf many times as concluded from this study. The eroded topsets of some of the sequences means that the ice sheet can ground the shelf while moving. On the other hand, in the northern part of the study area topsets are present and have not been eroded by the ice sheet. The offlap breaks are preserved in ascending order reflecting the floating nature of ice sheets.

In this chapter we will discuss ages of the sequences, how the accommodation space was created, glacial mechanisms and processes, sediment supply and chronostratigraphic chart. This study is useful in order to see beyond the conventional sequence stratigraphy and look into the glacial sequence stratigraphy.

## 5.1 Ages of the sequences

The age of the sequences has been assigned interpolated from the units of Naust formation (N, A, U, S, T) of Rise et al. (2010). Eidvin et al. (2000) suggested 2.8 Ma for the base of Naust Formation based on the data collected from biostratigraphic correlation of glacial deposits and dated deep sea drill cores. In the previous study of Rise et al. (2005) proposed 2.7 Ma for the base of Naust Formation, which they refined from current stratigraphic information. Rise et al. (2010) also refined the ages for top of unit N (1.5 Ma) and A (0.8 Ma) which are equivalent to his previous units W (1.7 Ma) and U (1.1 Ma) of Rise et al. (2005) (Figure 5.1).

In this study SS1-SS13 are equivalent to the Rise et al. (2010) unit N. These thirteen units justify the 1.3 Ma of Rise et al. (2010) unit N by 13 glacial periods each having 0.1 m.y. of

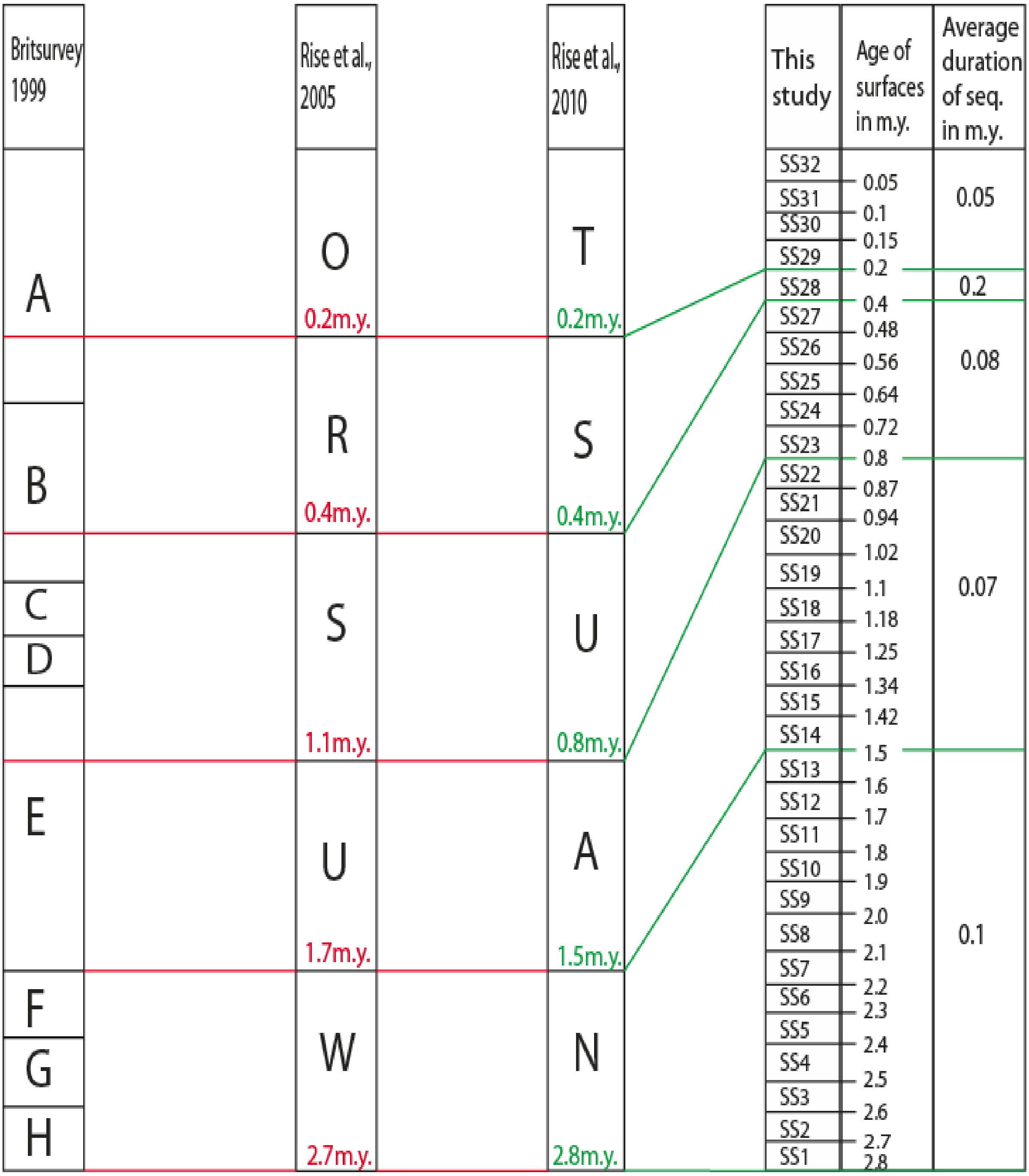


**Figure 5. 1** The proposed ages of SS1-SS32 interpolated to the previous Nuast units of Britsurvey (1999) and Rise et al. 2005 and 2010 (redrawn from Rise et al., 2005)

duration represent one glacial period deposited one sequence while reaching to the shelf edge. For other seismic units (SS14-SS32) corresponding to the Rise et al. (2010) units A, U, S , T ages are interpolated by same method (Figure 5.1). The SS28 represent the duration of 0.2 m.y. which can be further resolved into more sequences on the basis of much better data. The last four sequences SS29 – SS32 equivalent to unit T (0.2-0 Ma) represent the last two glaciations. During the last 0.2 m.y. glaciers expanded and retreated over the Norwegian continental margin. The SS29 has thin horizontal lenses and represent a rise in seal level and floating ice sheets. Then the ice sheet expanded during SS30 time at the top of which we can find melt water erosional channels which developed from the melt water of retreating ice sheet. Then it expanded again (Weichselian) which represent the lateral moraine deposits of SS32.

## 5.2 Creation of accommodation space

To accumulate a sediment pile there should be some space available in the basin below base level. This space which is available for the sediment accumulation can be referred to as accommodation space. Accommodation space is a function of sea level fluctuation and subsidence. Changes in accommodation space are correspond to changes in sea level (Jervy, 1988).

The creation of accommodation space and uplifting of mainland Norway in the Late Cenozoic time is not still well understood. There are different suggestions about the mechanism behind Late Pliocene uplift and subsidence of continental margin (Faleide et al., 2002). The most quoted models for this uplifting are isostatic rebound by the removal of ice sheets, intraplate stress by rearrangement of plate or mantle dynamics. Stoker et al. (2005) suggested the tilting of margin is predated to the onset of Late Neogene uplifting and glaciations. But they argued that this large scale tilting was not the response of intraplate stress variations, but was the result of upper mantle convection (Stoker et al., 2005). Conrad et al. (2004) and Smelror et al. (2007) tried to create a connection between the Iceland plume and deep structure of Scandes Norway in response to Late Neogene uplifting.

Sejrup et al. (2004) suggested that the creation of accommodation space along the continental margin was a complex interaction of thermal subsidence, regional tectonic events and sediment loading. According to Sejrup et al., (2004) after the breakup of Norwegian

Greenland Sea the region subsided rapidly due to thermal cooling. Subsidence curves from North Atlantic shows that subsidence increases during Late Neogene due to the increased rate of Plio-Pleistocene sediment (Sejrup et al., 2004). According to Jordt et al. (2000) ridge push from the Atlantic rift zone and Alpine collision created lithospheric stresses and further enhanced the subsidence. The landward part of Norwegian margin was uplifted and eroded throughout the Pleistocene while the outer shelf was experiencing subsidence. Observation of varying subsidence rates along the mid- Norwegian continental margin coincides with the stratal pattern suggested that sediment loading was important factor behind the subsidence (Dahlgren et al., 2002b & 2005) (Figure 5.2).

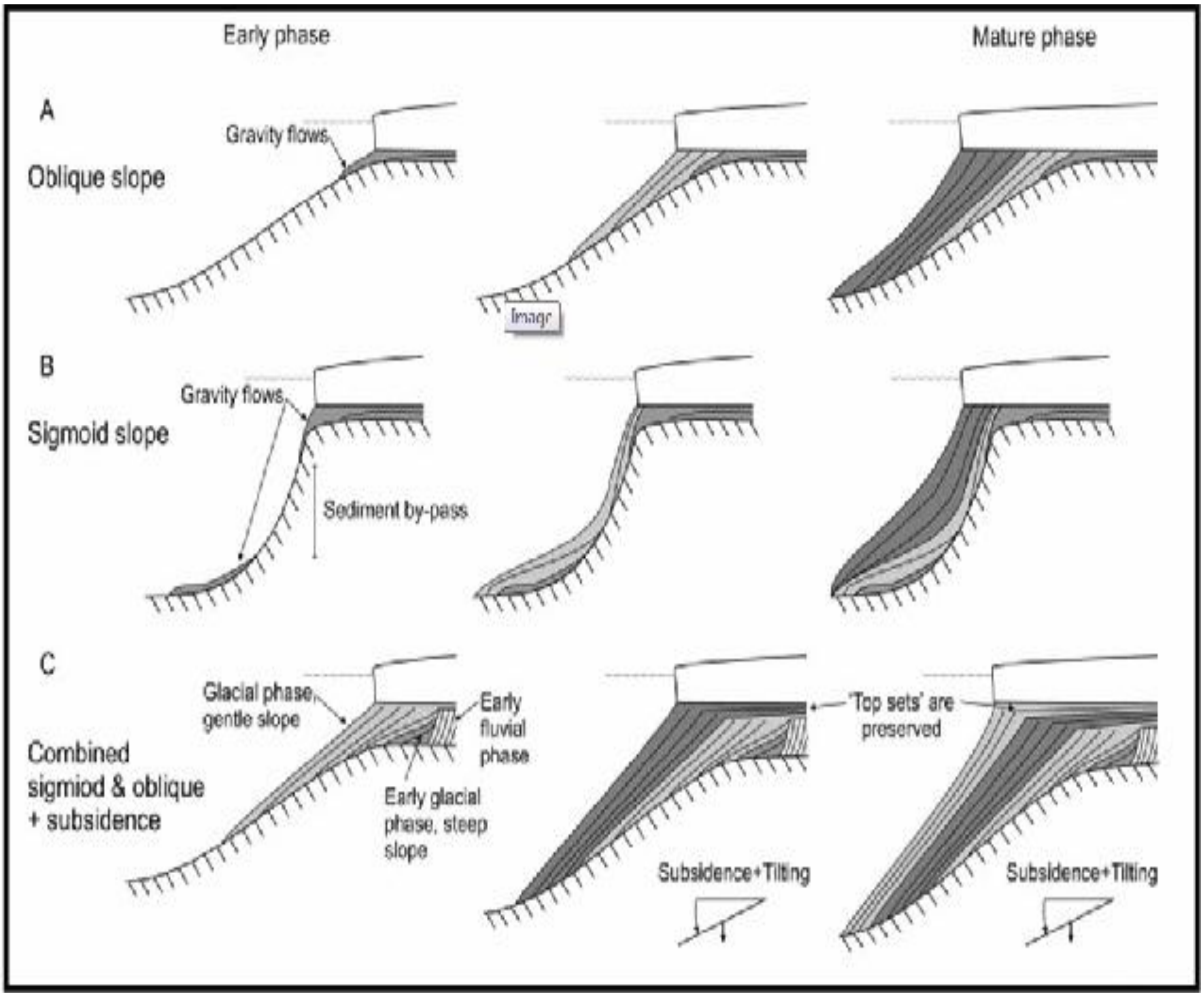


**Figure 5. 2** Conceptual model of prograding wedge influenced by the sediment loading and resulting increse in seubsidence (modified from Dahlgren et al., 2005)

## 5.3 Glaciations on Iceland and Svalbard

Sedimentological and stratigraphic data reveals that Iceland has experienced over 20 glaciations of different intensities during the last 4.5 m.y (Geirsdóttir et al., 2006). These glacial sediments are well preserved because of their position within a rift where volcanic activity occurs intermittently. The laterally extensive flood basalts have protected these glacial sediments. Glacial deposits formed from the different valleys along the southern margins suggest the initial glaciations of Iceland occurred between 5 and 3 Ma (Geirsdóttir et al., 2006). But none of these glacial deposits are traceable over long distances so these glaciations are local rather than regional. The first regional ice sheet in Iceland is dated to 2.9 Ma based on glacial deposits from two different valleys in eastern Iceland. These glaciations were much more extensive and during last 1.5 m.y. seven full cycles of glacial interglacial periods are identified (Geirsdóttir et al., 2006).

The records of ice rafted detritus indicate that at 2.6 Ma Svalbard had local glaciations which become extensive between a transition periods of 1.2 and 0.8 Ma (Jansen et al. 1988; Faleide et al. 1996) (Figure 5.3). However ice sheets did not expanded to the shelf edge until 1.5 Ma (Sejrup et al., 2005). But according to Knies et al. (2009) onset of glaciations on Svabard Margin was 3.5-2.7 Ma which was confined to the mountains and coast line but base of glacial deposits is dated to be 2.7-2.8 Ma from ODP site along northern margins of Svalbard. The seismic interpretation of the northwestern margin of Svalbard indicates sixteen glacial expansions to shelf edge during last 1 Ma (Solheim et al., 1996; Knies et al., 2009). While Anderson et al. (2004) mentioned eight glacial advances to the shelf margin during last 1.5 Ma.

In the figure 5.3 an attempt is made to correlate the sequences of this study with the glaciations of Svalbard/Barent Sea area and Iceland in comparison with the $O^{18}$ curve. $O^{18}$ is a heavy isotope of Oxygen, whose amount reduces in atmosphere during the glacial periods and trapped in the sea rsulting the richness of O18 in sediments e.g. calcite water (http://en.wikipedia.org/wiki/Oxygen_isotope_ratio_cycle). During the last 0.5 m.y. there are five peaks indicating last five glaciations, which are justifying the results of this study and glaciations recorded from Svalbard/Barent Sea. If better data is available like this study, it is

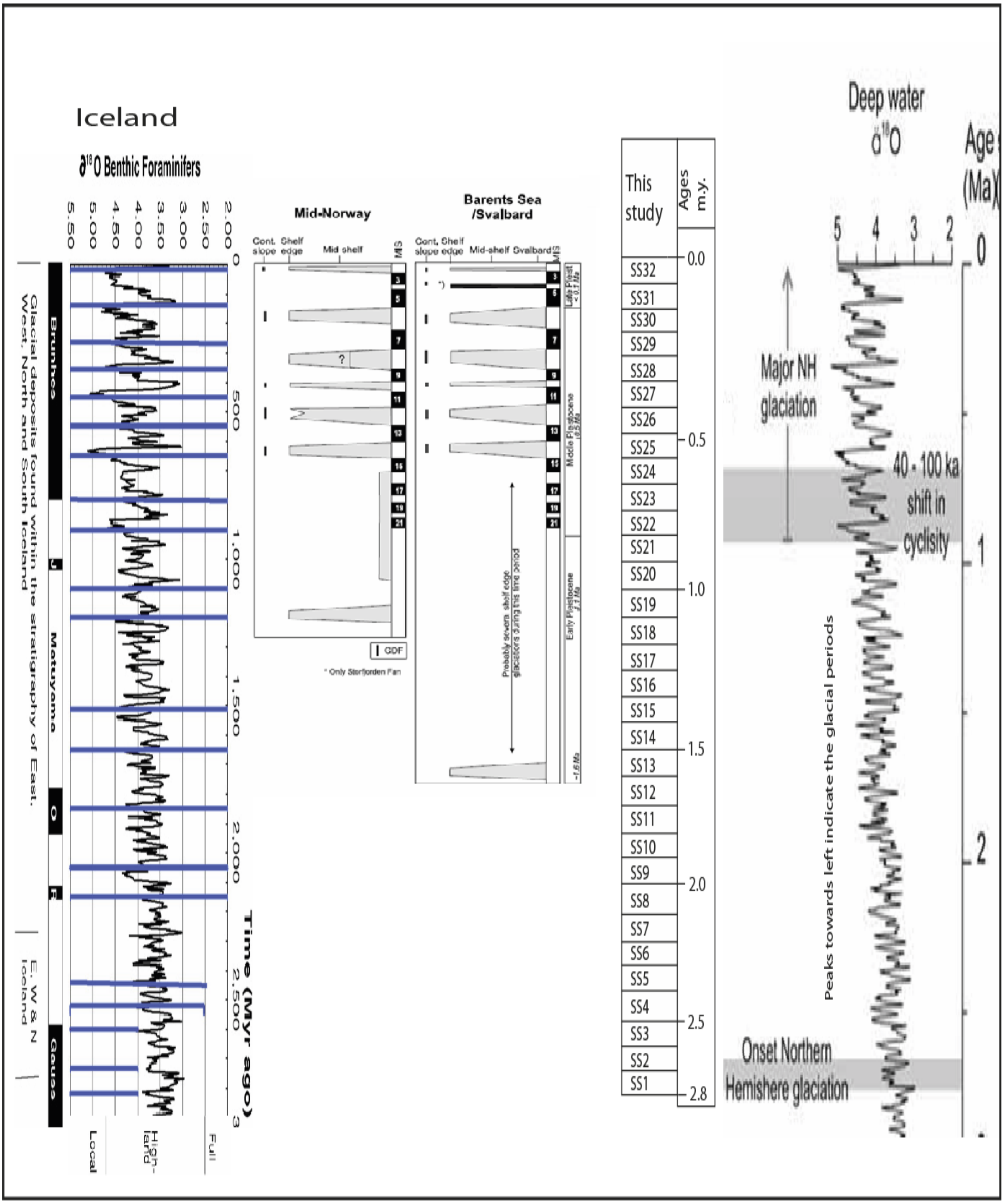


**Figure 5. 3** Correlation of seismic sequences along the mid-Norway, Barents Sea/Svalbard, Iceland and sequences of this study compared with $O^{18}$ curve (modified from Sejrup et al., 2005; Dahlgren et al., 2005 and Geirsdóttir et al. 2006).

possible to break out more sequences in the Svalbard/Barent Sea and Iceland. Because onset of glaciations on both sides is almost same i.e. 2.7-2.8 Ma at Svalbard/Barent Sea (Knies et al., 2009) and 2.9 Ma on Iceland (Geirsdóttir et al., 2006). After that period there are several peaks on the $O^{18}$ curve indicating the chances of more periods of glaciations.

## 5.3 Glacial dynamics

Thick marine based ice sheets are created by the accumulation of snow and freezing of sea water to their base until it reaches to sea floor (Syvitski, 1991). The ice covered shelf morphology and regional stratal geometry can be produced by time integrated effects of glacial erosion and sedimentation and the location of ice grinding line. On a progading shelf the sediments fill the shelf slope position first and when this position is filled to the shelf edge it becomes the part of shelf and new shelf slopes start filling (Brink and Schneider, 1995).

Glacial dynamics are very important for understanding the glacial processes and depositional geometry of the sediments. The ice margins which control the geometric pattern of prograded shelf wedges depends upon the factors like relative sea level changes, ice sheet thickness and buoyancy (Miller, 1996). Buoyancy is a very important factor for glacial erosion and deposition because it determines the boundary at the shelf where the ice sheet starts floating. When the ice sheet on the shelf edge start floating it cannot erode the shelf and provided accommodation space it will start deposition. Buoyancy can be dependent on the thickness of ice sheet and relative sea level because when the ice sheets are floating topsets are preserved. The lateral changes of these parameters give rise to different stratal geometries in the basin. In the study area these factors gave rise to different strata geometry to the sequence and created a pronounced erosional surface (URU) which turn into marine correlative conformity basinward at the top of SS28. Glacial processes on a shelf and sedimentation generating the prograding shelf wedge along the mid-Norwegian continental margin are shown in Figure 5.4.

### 5.3.1 Sedimentation

Pronounced shift in prograding style, gently dipping clinoforms of Naust Formation in Plio/Pleistocene signify the turn over from periglacial to glacial condition on the Norwegion continental shelf (Henriksen et al., 2005). Sedimentation rates during the Naust Formation time were very high which justify the deposition of so thick prograding wedges e.g 1715 m in the area of Rås Basin on the line H. According to Rise et al. (2010) at the time of deposition of Naust T (equivalent to the SS 29-32 of this study) the sedimentation rate was1 m per 1000 years. This high sedimentation rate was due to the rapid erosion of much weathered bed rock and older glacier deposits of older sequences (Dowdeswell et al., 2010).

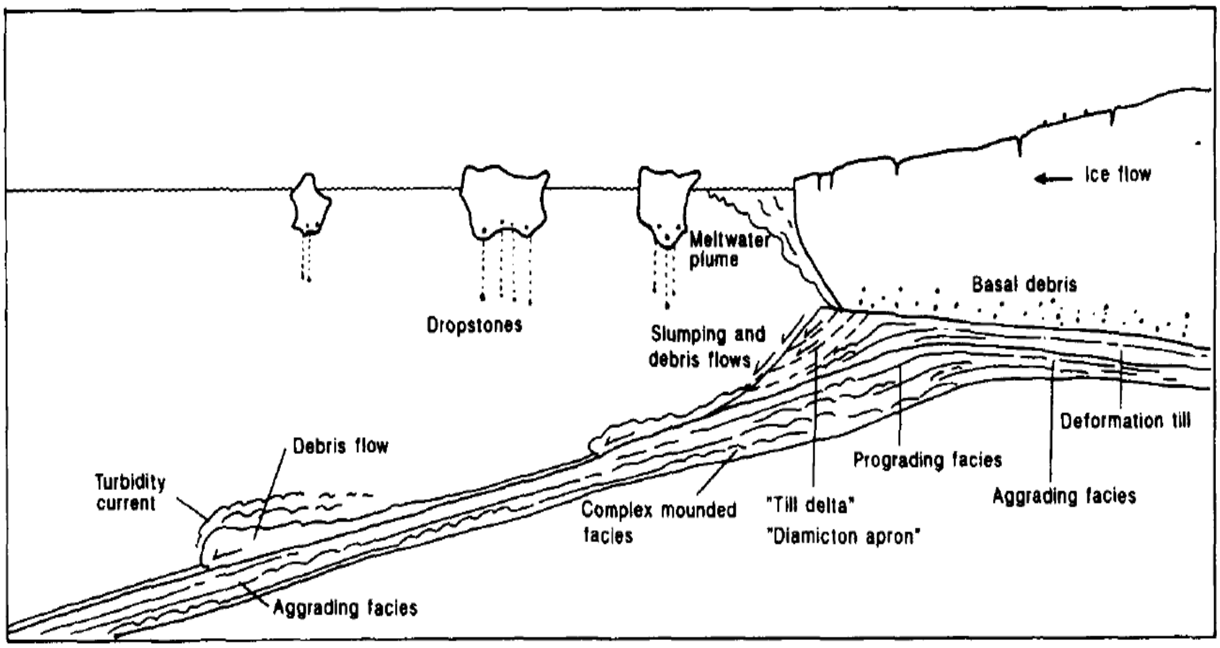


**Figure 5. 4** Ice sheet depositional model for prograding wedge system on a mid Norwegian Continental Shelf (Modified by Henriksen and Vorren(1996) from Laberg and Vorren (1996)

According to Dowdeswell et al. (2010) during last 2.7 my glacial activity deposited 100,000 km$^3$ of sediments which is equal to 80,000 km$^3$ of eroded bed rock. During last 600 Ky the sedimentation rate was 2-3 higher than the earlier Naust sequences N and A of Rise et al. (2010) equivalent to SS1- SS22 of this study (Dowdeswell et al., 2010).

### 5.3.2 Offlap break trajectory analysis and changes in relative sea level

Sufficient supply and water depth give rise to basinward prograded clastic wedges resulting in the deposition of clinoforms (Bullimore et al., 2005).

The clinoform geometries can give important clues for the relative changes in sea level in terms of preserving offlaps breaks. Offlap break trajectory analysis has revealed in two kinds of clinoform geometry:

- oblique tangential/oblique parallel (offlap breaks eroded)
- oblique sigmoidal (ascending or descending order)

### 5.3.3 Oblique tangential /Oblique parallel

These kinds of geometries are common in all the lines. The topset beds have been eroded which indicate that the thick ice sheets were grounding the shelf, as a result the topset beds of prograded clinoforms were eroded. Consequently the oblique tengential and oblique parallel geometry developed (see chapeter 4, Figures 4.10, 4.11, 5.2 and 5.5 ).

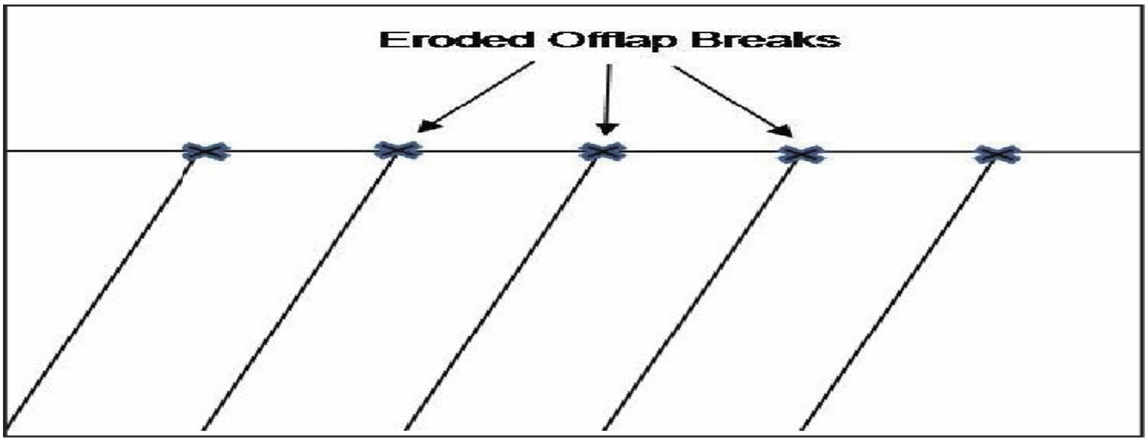


**Figure 5. 5** Diagram showing eroded offlap breaks (from Mandisa, 2007)

### 5.3.4 Oblique sigmoid

This kind of geometry develops when the water depth increased and ice sheets were floating. Beyond the buoyancy limit a grounding ice sheet will start floating and more accommodation space available for the sediments. These floating ice margins will deposits topset beds were preserved.

The offlap break of these clinoforms can describe the change in the relative sea level by analyzing their trajectories in two ways:

### 5.3.5 Ascending (positive) offlap break trajectories

This kind of trajectories indicates the rise in sea level to a limit where the ice sheet starts floating. Due to increase in sea level each clinoform will deposit updipping trajectory of offlap breaks. Positive offlap breaks describes the landward shift of clinoforms. These can be observed on seismic lines C, D, F, G and H (Figures 4.3, 4.4 4.7, 4.8 and 5.6).

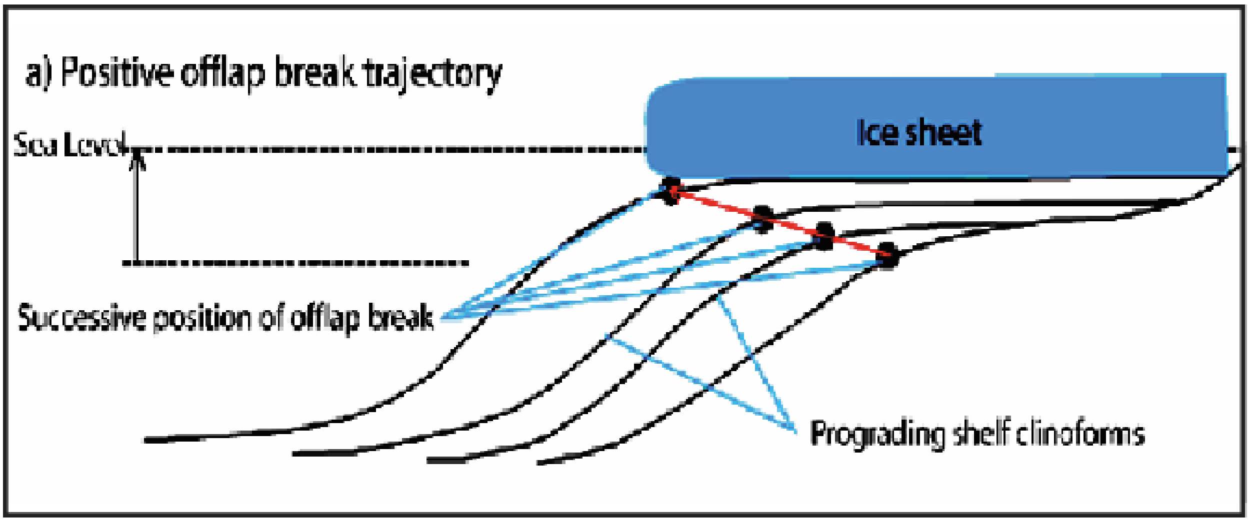


**Figure 5.6** Diagram showing positive offlap break trajectories of prograding wedge (modified by Mandisa, 2007 from Bullimore et al., 2005)

### 5.3.6 Descending (negative) offlap break trajectories

This kind of offlap break trajectories have been preserved along the seismic lines C and G. Negative offlap break trajectory represent fall in relative sea level but still the ice sheet is floating at its front edge, due to its less thickness. The successive clinoforms will build in seaward direction as mentioned by down dipping trajectories (Figures 4.3, 4.7 and 5.7).

An aggradational pattern is observed above URU in SS29 and SS30 on all the seismic lines. The SS29 is composed of thin horizontal lenses and SS30 contains aggradational and progradational packages. This kind of pattern develops when rate of accomodation is equal to the rate of sedimentation (Figure 5.8). Ice sheets were floating rather grounding the shelf. The thickness of the lenses can be related to the amount of sediments released from the melting of ice. Erosional channels are filled by aggradational patterns onlaping on both sides (Figure 4.12).

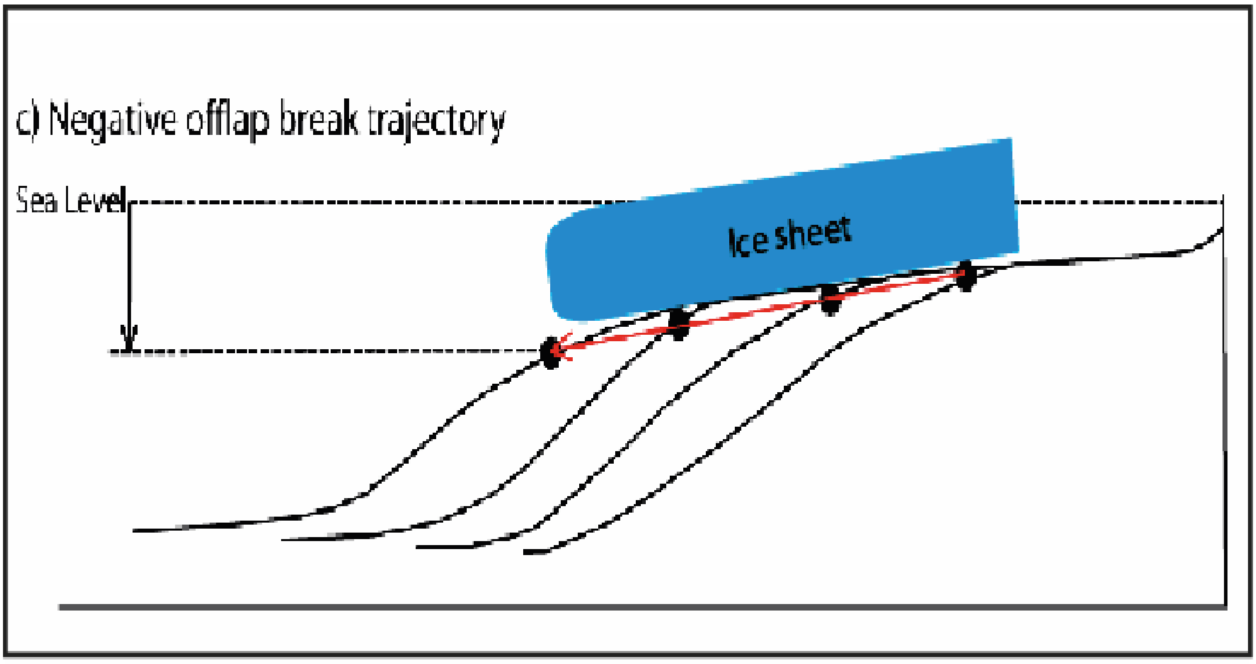


**Figure 5. 7** Diagram showing negative offlap break trajectories of prograding wedge (modified by Mandisa, 2007 from Bullimore et al., 2005)

### 5.3.7 Ice stream flows and deposition of sequences

Ottesen et al. (2001) constructed an ice flow model of Norwegian continental margin for the last Weichselian glaciation from the bathymetric data (Figure 5.8). They described the ice flows in two ways i.e. ice sheets and ice streams. Ice streams are part of ice sheets and occupy the over deepened trough eroding several hundred meters below surrounding seafloor and moves much faster than ice sheets. Ice sheets are supposed to be responsible for depositing the protruding sequences while ice streams carved wide depressions across the shelf and carried sediments to the shelf edge directly (Ottesen et al., 2001).

According to the James Hutton's ((late 18th century) law of uniformiterianism " present is key to the past" (http://en.wikipedia.org/wiki/Uniformitarianism), the ice stream flow model of Ottesen et al. (2001) describes the same process that were acting in the Plio/Pleistocene and developed the present continental margin shape which we see today. Sediments were eroded and transported to the basin from mainland Norway due to tilting and uplifting. After correlating the seismic lines with the ice flow model of Ottesen et al. (2001) (Figure 5.8) and the time thickness maps of Rise et al. (2005) (Figure 5.9) we deduce that the Naust Formation is thickest in the northern Trøndelag Platform area and eastern part of Vøring Basin i.e. Rås Basin. According to Ottesen et al. (2001) model a big ice stream was coming from the Vestfjorden area and depositing the sediments in the Trænabanken area (seismic lines G and H). Along these lines the offlap breaks are preserved and thick sedimentary succession is present (Figures 4.7 & 4.8). This is in contrast to the southern part of the study area where big ice streams have erdoed the topset beds. On the line B (Figure 4.2) there is a big erosive channel observed which indicates the greater erosion in the southern part.

The greater thickness of sediments in the northern part indicates that the area was fed by huge amounts of sediments from the Vestfjorden Basin as it is clear from the time thickness maps of Rise et al. (2005) (Figure 5.9). Naust Formation is thickest with all the 32 sequences in the area of Trænabanken along the lines F, G and H. While the lines in the area of the Skoldryggen indicates an area receiving moderate amounts of sediments. Sequences which have not been encountered in these lines may not have been deposited or eroded by the fast moving ice streams which have capability to dig several hundred meters down and carry the sedimemts directly to shelf edge (Ottesen et al., 2001).

During the deposition of SS1-SS13 (Naust N of Rise et al., 2010 and U of Rise et al. 2005) the depocentere was northeastern Vøring Basin and northeastern Trøndelag Platform which seems to be shifted towards the southern part of the study area because SS14-SS27 are thick in the Trænabanken and Skoldryggen area (Figure 5.9). From the time thickness maps of Rise et al. (2005) it is observed that the deposition during last 0.4 m.y. was concentrated in the area of Skoldryggen. Due to that the seismic sequences SS29-SS32 are thin in the northern parts of the study area (Figure 5.9).

## 5.4 Chronostratigraphic Chart

The chronostratigraphic chart describes the depositional history of the sedimentary succession. In this study the chronostratigraphic chart is created from the interpreted profile of seismic line F (Figure 5.10).

In the chronostratigraphic chart the interpolated ages from Naust units N, A, U, S and T of Rise et al., (2010) have been assigned to its equivalent sequences SS1-SS32 of this study. The chronostratigraphic chart depicts the depositional sequences in terms of time and space. SS1-SS28 represent the progradation package of Naust Formation from 2.8-0.2 Ma. After this there is a markable shift in the stacking pattern from progradation to aggradation. This shift tells that accommodation space and sedimentation rate after 0.2 Ma was equal which may indicate the end of tilting of the continental margin. The accommodation space created was due to changes in relative sea level and sediment loadin. According to the Dahlgren et al. (2005) model (Figure 5.2), the development of a prograding wedge is an interaction of subsidence, tilting, accommodation space and sea level changes. So after 0.2 m.y. tilting stopped working and accommodation space develops due to increase in relative sea level and subsidence. According to Dowdeswell et al. (2010) sedimentation rate at that time was 1 m per 1000 years, taking part in sediment loading and consequently subsidence. Due to rise in relative sea level ice sheets starts floating, although they were extensive but were not able to erode the sea floor, generating thin horizontal lenses in aggradational stacking pattern because on seismic lines A, B, E, F and G SS29 is traceable to continental slope.

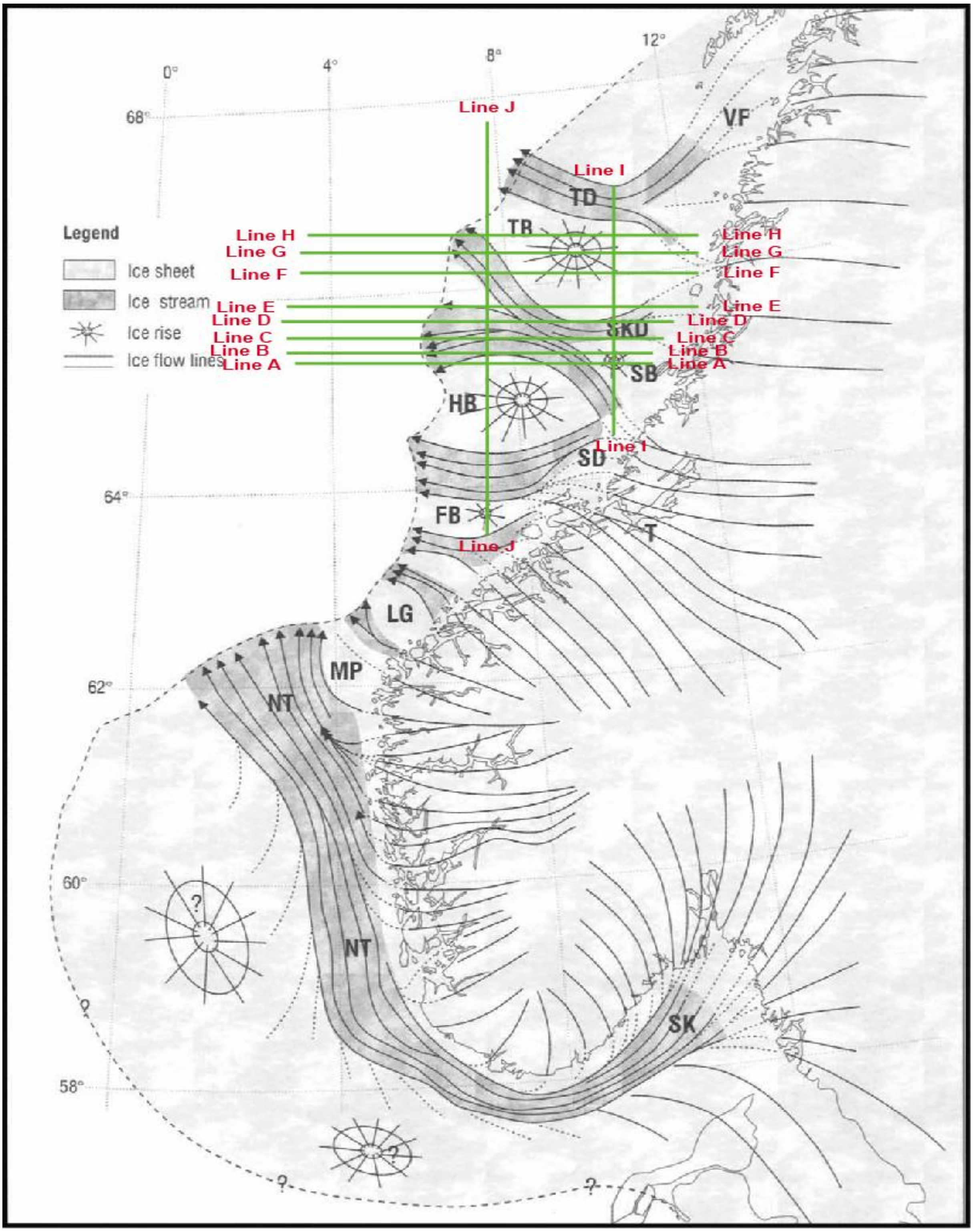


**Figure 5. 8** Interpreted Ice flow model during the late Weichselian and location of seismic lines of this study also shown. VF=Vestfjorden; HB=Haltenbanken; SKD = Sklinnadjupet; TD = Tramadjupet; SB = Sklinnabanken; SD=Suladjupet; FB = Fr0yabanken; MP= Måløyplatået; NT= Norwegian Trench; TB =Trænabanken; LG = Langgrunna; SK - Skagerrak; T = Trondheim (modified from Ottesen et al., 2001).

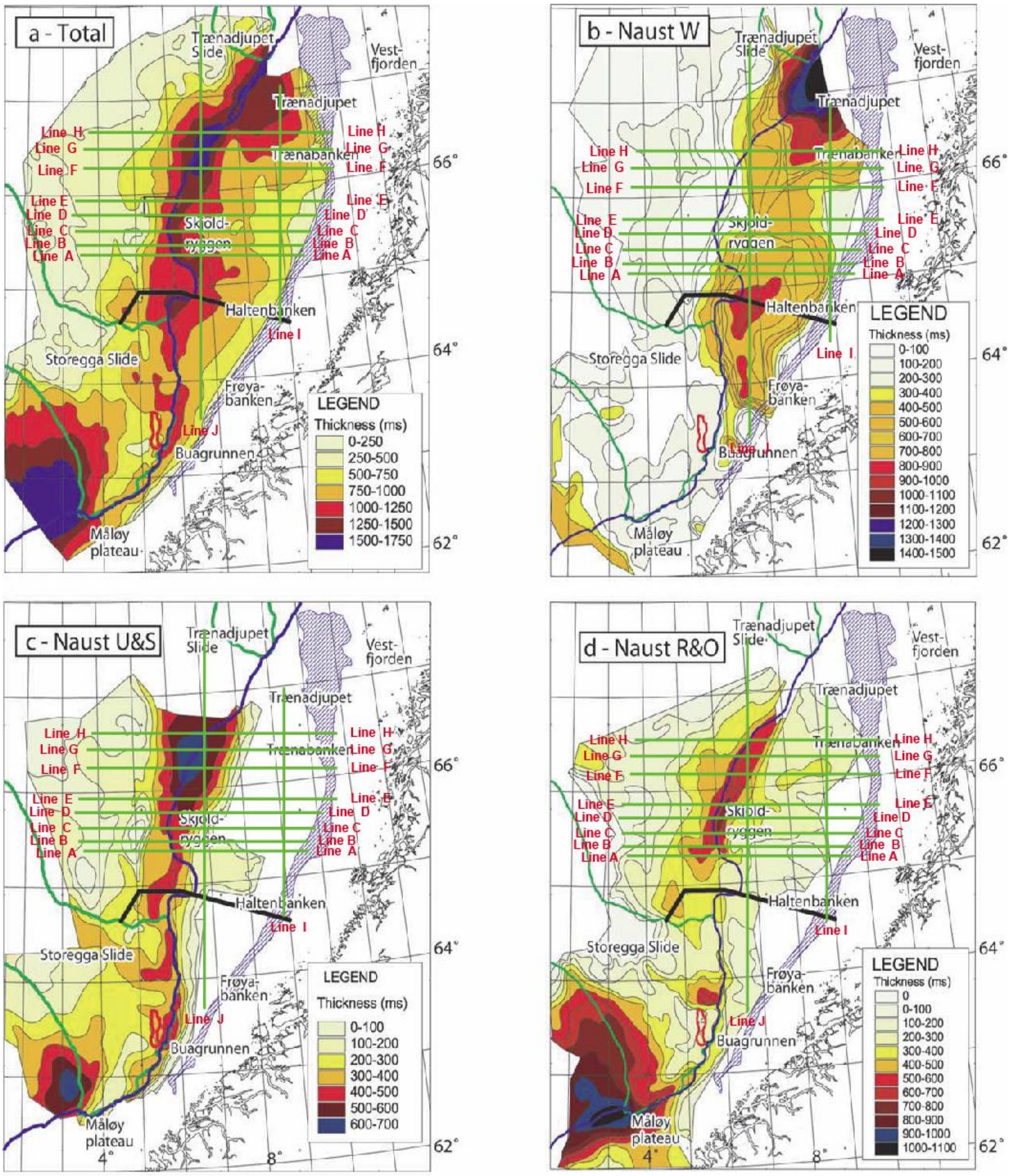


**Figure 5. 9** Time thickness maps (two way travel time; twt) of: (a) Naust Formation; (b) Naust W; (c) Naust U and S; (d) Naust R and O and location of the seismic lines of this study also shown (modified from Rise et al., 2005)

The blank area on right side of the prograding clinoform indicates the erosion made by glaciers resulting in the form of a regional unconformity URU which runs from SS1 to SS28 (Figure 5.10).

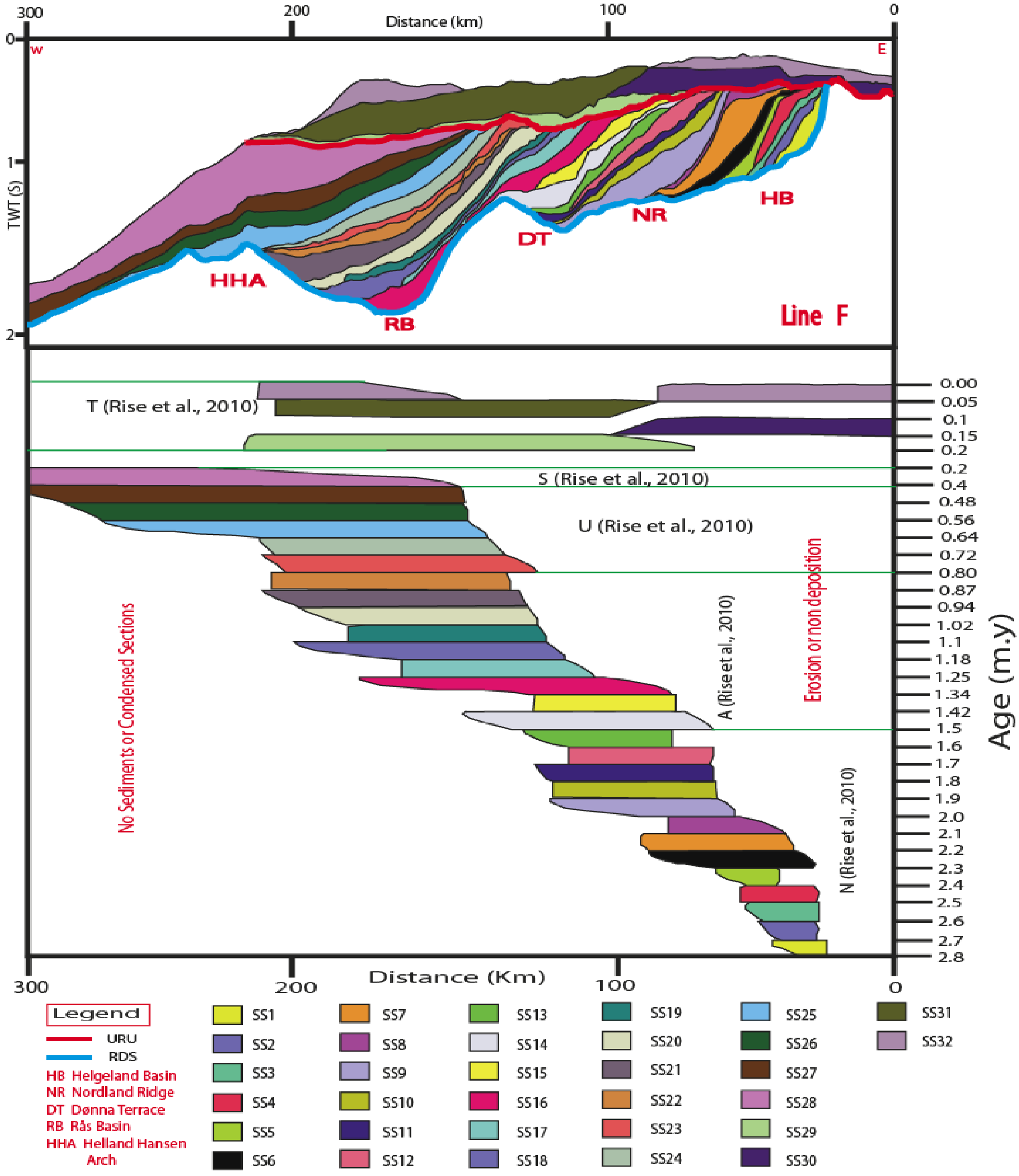


**Figure 5. 10** Chronostratigraphic chart (Wheeler Diagram) of line F (Figure 4.6) with interpolated ages and distribution of sequences

# Conclusions

The present shape of the mid-Norwegian continental shelf developed during last 2.8m.y. Glacial sediments of the Naust Formation prograded westward, creating a thick sedimentary wedge along offshore mid-Norway. Late Neogene uplift, erosion, tilting of the continental margin, glaciations and subsidence due to sediment loading played the major role in shaping the continental margin.

Thirty two seismic sequences bounded by onlap and downlap surfaces are analyzed in the study area. A regional downlap surface of 2.8 Ma is present at the base of Naust Formation along which the prograding clinoforms are downlaping. An Upper Regional Unconformity (URU) developed by the extensive erosion of ice sheets and glaciers.

The age of the sequences have been interpolated with respect to the previous studies. Tilting of the continental margins created the prograded wedge. Sedimentation rated were very high during Late Plio/Pleistocene time and became higher during the deposition of SS29-SS32 due to increased sediment supply by the erosion of earlier deposited sequences.

Offlap breaks preserved reflect the relative sea level fluctuations and thickness of ice sheet. In the northern part of the study area the positive offlap break trajectories reflect thin ice sheet fronts which were not eroding the shelf. After the development of URU a marked shift in stacking pattern from progradation to aggradation occurred. This shift indicates the end of tilting and accommodation space was mainly created by the subsidence due to the sediment loading. The seismic sequence stratigraphic framework of this study has been correlated to previous studies at the mid-Norwegian margin, as well as known glaciations from the Svalbard margin and Iceland. This shows that glaciers were active throughout late Plio/Pleistocene time with the same activity as they did during Weichselian time.

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