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Structural restoration of Mesozoic rifting phases in the northern North Sea

Noman Sajjad

Petroleum Geosciences
Submission date: June 2013
Supervisor: Stephen John Lippard, IGB

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Department of Geology and Mineral Resources Engineering
Norwegian University of Science and Technology (NTNU)
7491 Trondheim,
Norway

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Abstract

Structural restoration has been carried out on the northern North Sea (60-62ºN), based on the reprocessed, interpreted and depth converted seismic lines NSDP84-1 and 2. Two major rifting events have previously been recognized in the area during the Mesozoic: the Permo-Triassic and Jurassic extension phases. Different structures were formed or, in some cases, the same structures were reactivated during the Permo-Triassic and Jurassic rifting phases. Permo-Triassic rifting affected a 125 km wide area from the Øygarden Fault Zone in the east to the Hutton Fault alignment in the west.. By measuring the length of the profiles before and after faulting, the restorations show that the stretching factors for upper crustal stretching during the Permo-Triassic rifting are 1.11 (11%) for NSDP84-1 and 1.10 (10%) for NSDP84-2 respectively. The Jurassic rifting was confined to a narrower zone mainly in the Viking Graben with the major faults formed on the western side of the graben. Low angle faults are identified in the western flank of Viking Graben in the Tampen Spur area. Low angle supra-basement detachments formed in the late Jurassic are found in Gullfaks area, beneath the Gullfaks Sør block and SE of the Visund fault block. Intra-basement detachments are also found in Tampen Spur area. These detachments are formed by normal faults which flatten in the basement. From the restorations, the stretching factor for the Jurassic rifting is calculated to be 1.12 (12%) for NSDP84-1 and 1.19 (19%) for NSDP84-2. The total extensions for the two rifting phases combined are 1.24 (24%) and for NSDP84-1 and 1.30 (30%) for NSDP84-2. Stretching factors (β) can also be measured by crustal thickness changes, stretching is measured before and after rifting for different area (Horda Platform, Shetland Platform, Viking Graben, and Tampen Spur), and β_{mean} calculate for the Permo-Triassic

rifting phase are calculated 1.25 and 1.16 for NSDP84-1 and 2 respectively. For the Jurassic rifting β_{mean} is calculated as 1.16 for NSDP84-1 and 1.17 for NSDP84-2. These values are similar to previous published results using the same methods in the Northern North Sea and represent the minimum amounts of upper crustal extension on large seismically resolved faults.

Chapter 1

Introduction

Restoring a geological cross-section or map to its original pre-deformation state is an important part of making a structural interpretation. Restoring is a technique used to progressively undeform a geological section in an attempt to validate the interpretation used to build the section. Structure restoration is used to measure the stretching factor (β) and extension on a cross-section before and after rifting.

Restoration has been done on two regional cross section lines NSDP84-1 and 2, which were imported into IGEOSS Dynel2D, which is used for the structure restoration. Dynel2D integrates geological and geophysical data on horizons and faults with geomechanical analyses of the deformation (i.e. displacement, strain and stress) associated with the geological structural development using the fundamental principles of physics, which govern rock deformation (Dynel2D). Structural interpretation is done with the help of previous studies and other adjacent lines in northern North Sea. After restoration, the model is used to measure the stretching factor (β). Stretching factors are measured by fault modelling and as well as for crustal thickness changes.

The study area lies between 58ºN and 62ºN and is commonly referred to as the northern North Sea. It covers the Tampen Spur, Viking Graben, Horda Platform, and Bergen High structural elements. Two cross sections (Fig.1.1) based on NSDP84-lines have been used for this work. The deep seismic reflection lines NSDP84 1 and 2 were acquired and processed in 1984-1985 by GECO on behalf of BIRPS and several oil companies. They were further reprocessed in 1991 by BIRPS (Blundell, Hobbs et al. 1991). The dataset was also reprocessed by Norsk Hydro in 1994 for Integrated Basin Studies-Dynamics of the Norwegian Margin (IBS project) to enhance the lower crustal reflectivity and Moho definition (Christiansson, Faleide et al. 2000).

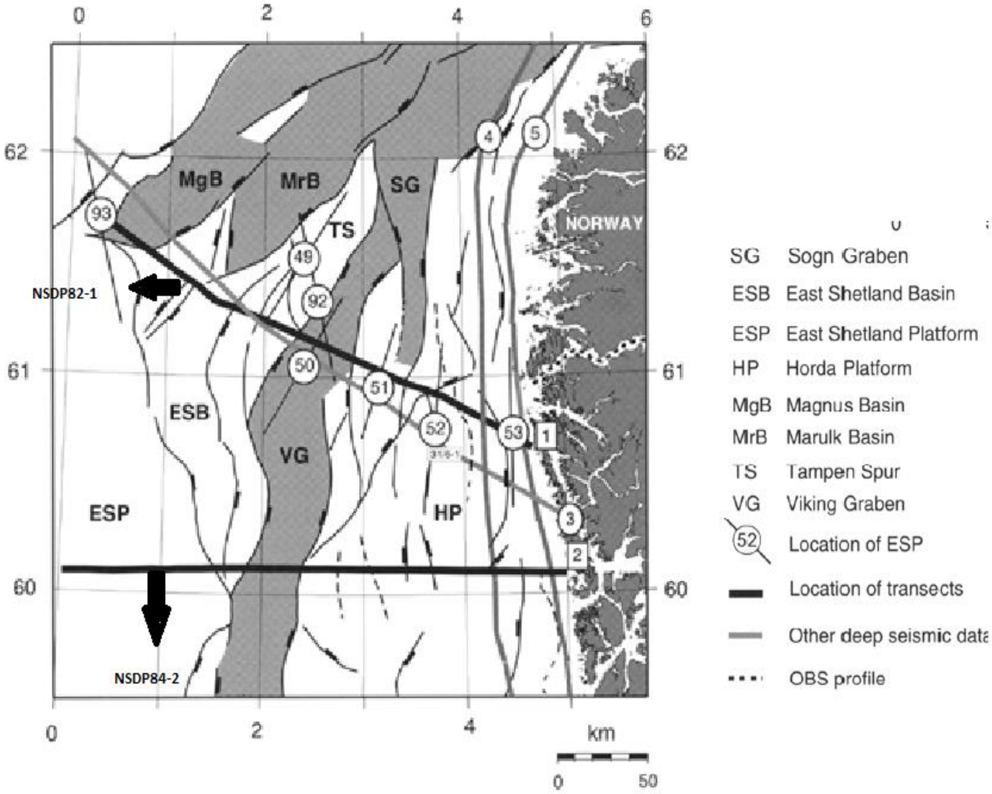

Figure 1.1: Location of the two regional transects, NSDP84-1 and 2 (Christiansson, Faleide et al. 2000)

1.1 Previous studies of deep seismic lines in the North Sea

The NSDP84-lines were first described by Gibbs and Klemperer (1987). Additional interpretations have been presented by Harrison (1987), Kusznir & Matthews (1988), White and McKenzie (1988), Klemperer and White (1989), Pinet (1989), Klemperer and Hurich (1990), Reston (1990), and Brun and Tron (1993).

In 1987 a commercial deep seismic profile, Britoil NNS83-22 that is located close to NSDP84-1, was described by Beach (Christiansson, Faleide et al. 2000). Interpretations and combined models of NSDP84 reflection data gravity data have been published by Holliger (1987), Holliger and Klemperer (1989), and Fichler and Hospers (1990). Zervos (1987)Zervos (1987)Zervos (1987) modeled the gravity field along six regional profiles taken from Ziegler (1982) and Glennie (1984). Hospers & Ediriweera (1991) published a map of depth to the crystalline basement, based on an integrated analysis of magnetic, gravity and seismic data. Several models have been also proposed to explain the crustal thinning and basin formation in the northern North Sea.

The purpose here to present these lines is to restore the rifting layers and to measure the extension and the stretching factor (β) across the northern North Sea. Odinsen and Reemst (2000) also worked on the 2D forward modelling across the northern North Sea on these deep seismic lines to observe the crustal structure and stretching. Ziegler and Van Hoorn (1989) worked on the same area to estimate the stretching factor for the northern North Sea.

Chapter 2

Geology of northern North Sea

The northern North Sea basin was formed due to Mesozoic continental riftiting and it comprises the Viking, Central and Moray Firth-Witch Ground Grabens. Seismic and well data from the northern North Sea basin shows that the Cretaceous sediment thickness is about 2.5 km while the Cenozoic is about 3 km. The northern part of North Sea sedimentary basin is about 170-200 km wide, and is a N-trending zone of extended crust, flanked by the western Norwegian mainland and the Shetland Platform. This part of the basin had a complex structural development for two principal reasons: Firstly, it was subject to multiple stretching with the interference of two major extensional phases. Secondly, extension affected a heterogeneous basin substrate both as regards composition and inherited grain. The overall structure and the composite fault pattern seen now in the northern North Sea resulted from major extensional phases in the Permo-Triassic and Jurassic (Fig.2.1). Upper crustal extension resulted in variably tilted fault-block and basins bounded by planar or listric faults.

The rift axis for the Permo-Triassic rift is thought to lie beneath the present Horda Platform whereas the late Jurassic rift was centered beneath the present Viking Graben. The northern North Sea rift system is bounded by the East Shetland Platform in the west and the Øygarden Fault Zone in the east (Fossen, Odinsen et al. 2000).

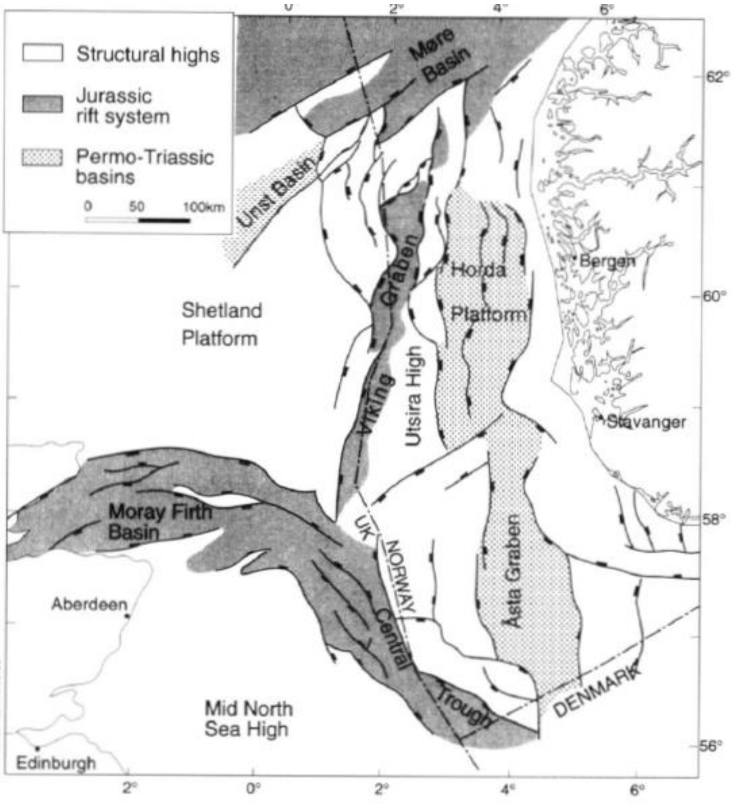

Figure 2.1: Structural elements of the northern and central North Sea (Færseth 1996)

The more obvious fault-related structures seen within the basin are those formed by the Jurassic extension, with the prominent Viking Graben representing part of a Jurassic triple rift-system (Fig. 2.3). However, seismic reflection data from areas outside the axis of the Viking Graben show that an earlier period of rifting had affected these areas (Badley et al.1988; Levik et al. 1989; Gabrielsen et al. 1990; Yielding et al. 1992; Steel & Ryseth 1990; Roberts et al. 1995; Faerseth et al. 1995a) and had produced a series of large deeply-buried, tilted fault-blocks. A Permian to early Triassic age is now generally accepted for this extensional period (Steel & Ryseth 1990).

Structures of this generation located east and west of the Viking Graben have been described and analyzed quantitatively (Roberts et al. 1995).

2.1 Tectonic events

The North Sea area was the site of a triple plate collision zone during the Caledonian orogeny. Four major tectonic events have influenced the area (Ziegler 1990):

(i) Caledonian collision during Late Ordovician to Early Silurian

(ii) Subsequent rifting and basin formation mainly identified in the Carboniferous to Permian

(iii) Mesozoic rifting and graben formation

(iv) Inversion during late Cretaceous to early Tertiary

2.2 Stratigraphy (Figure 2.2)

Triassic and Lower Jurassic deposits in the northern North Sea comprise the Hegre Group. It consists of interbedded sandstones, shales and marls. The Hegre Group is divided into the Cormorant and Statfjord Formations. The Statfjord Formation was deposited during late Triassic to earliest Jurassic.

The Dunlin Group was deposited during the Lower Jurassic. It is further divided into four formations: the Amundsen, Burton, Cook, and Drake Formations. The Dunlin Group consists of dark shales and interbedded sandstone, and depositional environment was open marine.

The Brent Group was deposited during the middle Jurassic. It is further divided into five formations: Broom, Rannoch, Etive, Ness and Tarbert

Formations. The group mainly consists of sandstone, siltstone and shales, with some coals.

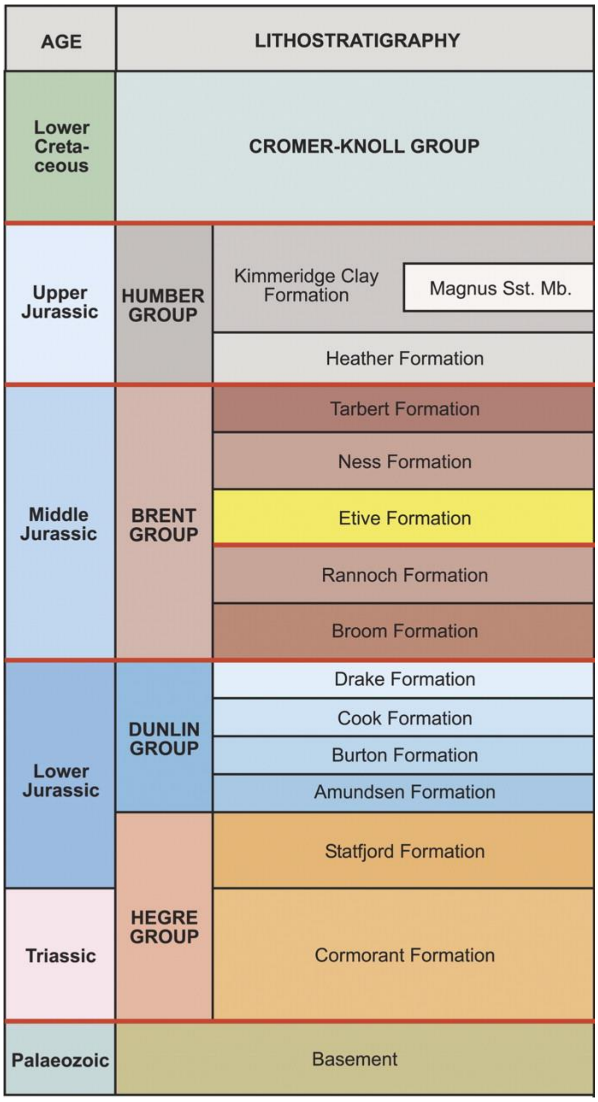

Figure 2.2: Stratigraphic column of the northern North Sea (modified after Dominguez 2007)

The Upper Jurassic deposits comprise the Humber Group. It is divided into the Heather, and Kimmeridge Clay Formations. The Heather Formation consists of grey silty claystones deposited in open marine environment, while the Kimmeridge Clay Formation is mainly dark brown to black shales, deposited in a restricted marine environment.

The Cretaceous deposits in the northern North Sea are fine grained sediments, mainly shales. Tertiary deposits are mainly sandstones and shales.

2.3 Geological history

2.3.1 Paleozoic

The configuration of Lower Paleozoic crystalline and metamorphic basement rocks that underlie the North Sea sedimentary basins was assembled during the Caledonian Orogeny (about 420 - 390 Ma) to form the Caledonian basement.

During the Devonian (about 410 -360 Ma) there was widespread red-bed molasse and lacustrine sedimentation as the newly-formed Caledonian mountain ranges were eroded. Mid-Devonian (about 375 Ma) marine limestones in the south of the Central North Sea were probably formed during an early rift phase. This was a precursor to the main phases of Permo-Triassic (about 290 - 210 Ma) and mid-late Jurassic rifting (about 160 - 140 Ma).

During the early Carboniferous (about 360 - 325 Ma), fluviodeltaic and shallow-marine sediments and local volcanics accumulated in parts of the Central North Sea at times of regional crustal extension, though the Northern North Sea area was mainly a source of clastic sediments. These Carboniferous rocks were gently folded, faulted, uplifted and eroded during the late Carboniferous Variscan orogeny at approximately 300-290 Ma.

During the late Permian (about 270 - 250 Ma) redbeds and local volcanics (Rotliegend Group) accumulated within the Northern Permian Basin. Following a marine transgression, cyclical evaporitic successions (Zechstein Group) were deposited and locally reach over 1000 m in thickness. The evaporites have been deformed by halokinesis intermittently since mid-Triassic times (about 230 Ma), leading to the widespread growth of salt pillows and salt diapirs, especially in the Central North Sea.

2.3.2 Mesozoic

During the early Jurassic there was a spread of marine deposits over much of the North Sea during a phase of thermal subsidence following Permo-Triassic rifting.

During the mid-Jurassic, regressive, paralic sediments accumulated when a major subaerial thermal dome formed within the Central North Sea. The mid-late Jurassic was a time of major extensional faulting (Glennie 1997). The rifting was initially most intense at the extremities of the present graben system and as time elapsed it propagated back towards the centre of the dome (Rattey and Hayward 1993). The onset of major rifting probably occurring in the Middle Oxfordian to Early Kimmeridgian (approximately 157-155 Ma) (Underhill 1991; Glennie and Underhill 1998). Seismic data reveal that the Upper Jurassic sedimentary successions commonly thicken dramatically towards syndepositional faults. This pattern of sediment thickness variation is in contrast with that formed during the ‘thermal sag’ phase of basin development (e.g. McKenzie 1978) in early-mid Jurassic times, when the basin was more ‘saucer-shaped’ and the thickest deposits accumulated at its center.

Rift styles vary substantially between the northern and the central North Sea and there were two principal controlling factors. Firstly, differences in the basement composition and tectonic grain between the two regions strongly influenced structural development. In the central North Sea, the rifts are more complex and were segmented along NE ‘Caledonide’ and NW ‘TransEuropean Fault Zone’ trends (e.g. Errat et al. 1999; Jones et al. 1999). Secondly, in the northern North Sea, Upper Permian salt is largely absent, and there is no major detachment between basement and cover rocks. In contrast, the Zechstein evaporites in the central North Sea provide a major detachment level that essentially separates the basement rocks from the cover sequence of rocks or ‘carapace’ (e.g. Hodgson et al. 1992; Smith et al. 1993; Helgeson 1999). This structural contrast is reflected in the smaller size of the oil and gas fields discovered within the pre- and syn-rift successions of the central North Sea.

2.3.3 Cenozoic

Thermal subsidence in response to mid-late Jurassic rifting, dominated much of the Cenozoic, with some relatively minor pulses of earth movements (e.g. Pegrum and Ljones 1984). Regional patterns of sedimentation changed dramatically in early Paleogene times, with the influx into the basinal areas of huge volumes of coarse clastic detritus including debris flows and turbidites. This detritus was shed from the uplands of northern Scotland and the Orkney-Shetland Platform, which were undergoing thermal uplift in response to the development of the Iceland Plume (White and Mckenzie 1988; White and Lovell 1997).

2.4 Structural setting

The North Sea present day structure mainly formed during the two major rifting phases, the Permo-Triassic and the Jurassic rifting phases. The extension faults defining the largest fault blocks in North Sea rift are mostly of Permo-Triassic origin, although reactivated in Jurassic time. Rifting and extension followed by thermal cooling and subsidence produced the North Sea sedimentary basin.

The rift system of the North Sea is a triple system, with three arms forming the Viking Graben, Central Graben and the Moray Firth Basin (Fig. 2.3). The Viking Graben and Moray Firth basins are asymmetric while the Central Graben is more symmetrical in character. In the Viking Graben the major faults are mostly dipping to east or east-south-east, in the Moray Firth basin the major faults are dipping to southeast or south-south-east.

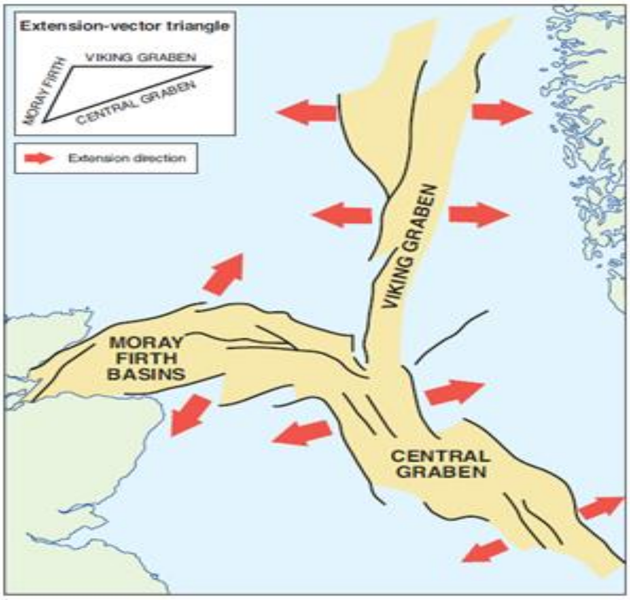

Figure 2.3: Triple arm rift system in North Sea, and red arrows represent the extension directions (Evans, Graham et al. 2003)

The overall structure and composite fault pattern in northern North Sea resulted from major extensional phases in the Permo-Triassic and mid-late Jurassic. Upper crustal extension resulted in variably tilted fault blocks and basins bounded by planar or listric faults.

Although the North Sea basin can be considered in broad terms as a series of elongated, linked half grabens that were assumed to have been formed by more or less orthogonal E-W extension (e.g Badley, Price et al. (1988), Stewart et al. (1992)), the basement structure clearly influenced the geometry of most Permian to Mesozoic basins and their faulted margins. The present crustal thickness of western Norway of about 30-35 km (Sellevoll 1973); (Kinck, Husebye et al. 1991) is taken to represent the pre-Permian crustal thickness of the northern North Sea region. As a result of extension, the basement has been thinned to as little as 11-12 km beneath the Viking Graben (Klemperer 1988; Fichler & Hospers 1990: Hospers & Ediriweera 1991; Odinsen et al. in 2000), while Faerseth, Gabrielsen et al. (1995) argue that crystalline basement thickness beneath the Horda Platform was, in places, alredy reduced to some 12-13 km following late Permian-early Triassic extension.

East of the Viking Graben, interpretation of deep reflection profiles and commercial reflection seismic data tied to wells drilled to basement, suggests that major basement units typical of those seen today over southwest Norway can be identified west of the Øygarden Fault Zone. The basement consists of heterogeneously Caledonized Precambrian rocks as well as metamorphosed igneous and sedimentary rocks of early Palaeozoic age. Boreholes on Norwegian blocks 31/6, 35/3, 35/9, 35/12, 36/1, 36/7 on the east of Sogn and Viking Graben exhibit Early Triassic units as the oldest sediments above the basement.

Devonian sediments were deposited in hangingwall of the NW-dipping Hardangerfjord shear zone which experienced top-to-the-WNW Devonian extensional transport (Fossen, Odinsen et al. 2000). The north trending Permo-Triassic major faults off southwest Norway are discordant both to Caledonian compressional and Devonian extensional structures (Faerseth, Gabrielsen et al. 1995). Devonian sediments have been also found in wells within the East Shetland Basin.

Chapter 3

Extension Phases

Extension is mainly related with tectonic processes associated with the stretching of crust. The types of structures and geometries formed in a basin undergoing extension depend upon the amount stretching involved. Low stretching factors are associated with normal faults, half graben and tilted fault blocks. If the stretching is high it may cause the fault rotated to too low a dip to remain active and a new set of faults may be generated.

The northern North Sea is characterized by a series of large normal faults with predominant N, NE and NW trends. These faults are mainly related to the Permo-Triassic and Jurassic extension events (Fig. 2.1). The eastern margin of the sedimentary basin is largely associated with the Øygarden Fault Zone of Permo-Triassic origin, a prominent N-striking structural element offshore western Norway (Faerseth et al. 1995). The western margin of the basin is associated with the Hutton Fault Alignment.

The large faults in the northern North Sea are basement-involved, and probably cut the whole brittle upper crust (12-14 km). However, the dip changes from typically 25-35° where faults cut down into basement to 40-50° at higher (Jurassic) levels (Nelson & Lamy 1987, Yielding et al. 1991). Major faults with low-angle or listric geometries occur along the western margin of the Viking Graben. They developed during Jurassic rifting and are particularly related to the eastern Tampen Spur (Faerseth et al. 1996; Fossen et al. 2000), the Beryl Embayment (Swallow 1986; Gibbs 1987; Platt 1995) and the Fladen Ground Spur (Harris & Fowler 1987; Cherry 1993), i.e. uplifted footwalls flanking asymmetric graben segments.

3.1 Permo-Triassic Extension Phase

During the transition from Permian to Triassic the area was subjected to regional tensional stresses during early Triassic time, which caused the subsidence of complex and multidirectional grabens. Stratigraphic evidence indicates that during the earliest Triassic the Norwegian-Greenland Sea rift propagated rapidly into the North Sea area causing the differential subsidence of the Viking and Central grabens, the Horda-Egersund half-graben, and the Moray Firth-Witch Ground graben system (Færseth 1996).

The Triassic basin is mainly restricted to N-trending depression and the width is about 170-180 km. Triassic sediments attain maximum thicknesses of about 2000 m in the Central graben and upto 3000 m in the northern Viking Graben.

The eastern margin of this early Mesozoic basin is represented by the Øygarden Fault Complex, south of 61°N (Fig. 3.1), where top basement is vertically displaced 3-5 km across normal faults (Yielding et al. 1991; Færseth et al. 1995). North of 61°N, the structural pattern is controlled by the E-dipping Sogn Graben Fault of Permo-Triassic age. The asymmetry of the Sogn Graben, created a westerly tilted basement, and the top basement surface was covered by progressively younger Mesozoic deposits to the east.

The Hutton Fault Alignment is N-trending fault zone that bounds the limit of thick Triassic sediments to the west. It gradually decreases in the throw to the south, and the basin boundary shifted eastwards to major faults which bound the Hild Fault Block to the east and southeast.

South of 60°N the basin-bounding Permo-Triassic master faults (Fig. 3.1) were located east of the present eastern boundary of the Shetland Platform and they represent the precursors of the faults which became the western boundary of the Jurassic Viking Graben (Gibbs 1987).

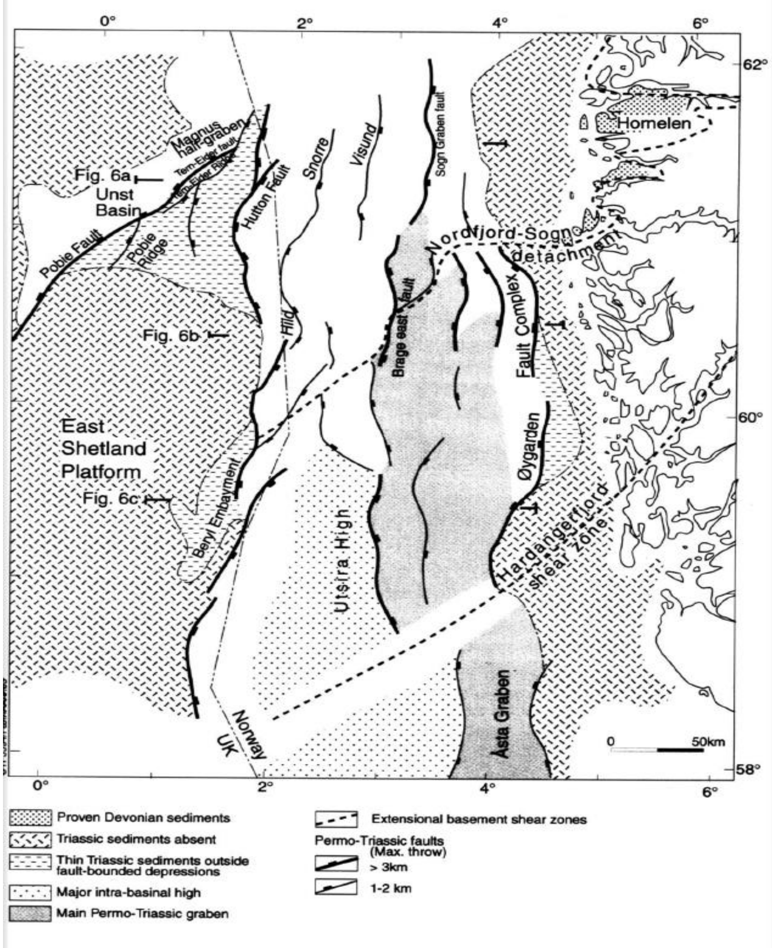

Figure 3.1: Main structural elements of the northern North Sea resulting from Permo-Triassic extension (Færseth 1996)

3.2 Jurassic Extension Phase

During the transition from the Early to the Middle Jurassic, the central North Sea area was uplifted and formed a broad dome transected by the Central Graben. Uplift of this rift dome was coupled with the interruption of connections between the Arctic and Tethys seas (Ziegler 1982). The lateral component in the rifting was responsible for a complex sequence of structural inversions which began in late Jurassic and continued through Cretaceous times.

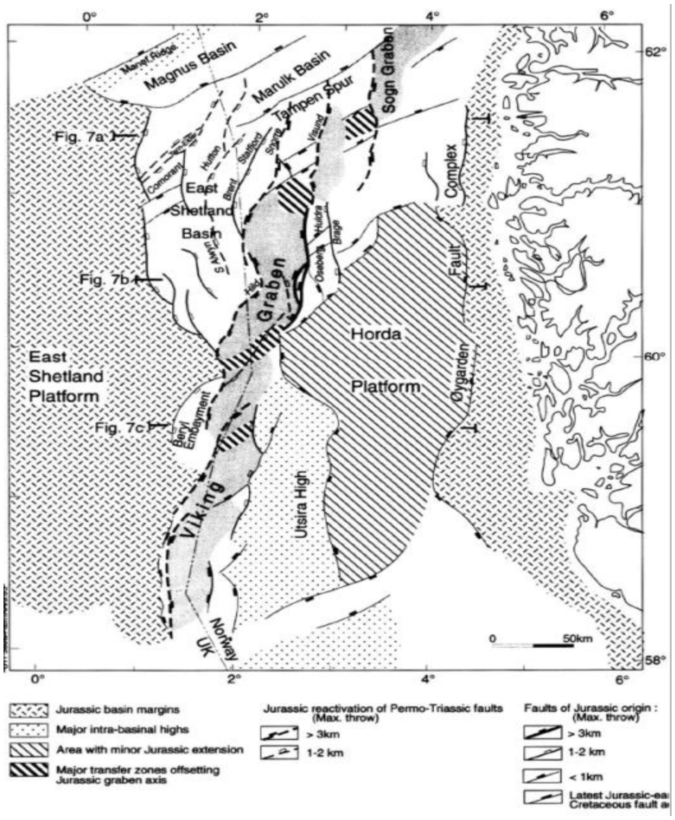

Figure 3.2: Main structural elements of the northern North Sea resulting from mid-late Jurassic extension (Færseth 1996).

The Øygarden Fault Zone separates an eastern area where thin Jurassic sediments may overlie basement, from the basin to the west where Jurassic sediment thicknesses generally are in the range 1-1.5 km, and overlie thick sequences of Triassic and presumed older sediments. The East Shetland Platform represents the western boundary of the Jurassic basin, and to the north of 60°N, the East Shetland Basin occupies an intermediate structural level between the platform and the Viking Graben proper (Fig. 3.2). Most of the major faults of Permo-Triassic age were reactivated in the Jurassic phase.

The Brent-Statfjord fault which apparently was inactive during Permo-Triassic extension came into existence as a major fault (c. 1.5 km of maximum throw) as a result of mid-late Jurassic extension. The Hutton Fault, which exhibits major Permo-Triassic growth, shows only modest Jurassic reactivation (Yielding and Roberts 1992). The faults bounding the Snorre and Visund structures to the east, were established during the Permo-Triassic extension, but the main offsets, c. 3 km (Nelson and Lamy 1987) and c. 5 km (Færseth et al. 1995) respectively, are related to late Jurassic faulting.

Chapter 4

Fault pattern of northern North Sea

The North Sea rift (Fig. 4.1) is a post Caledonian graben system and experienced multiphase extension (Permo-Triassic and Jurassic).

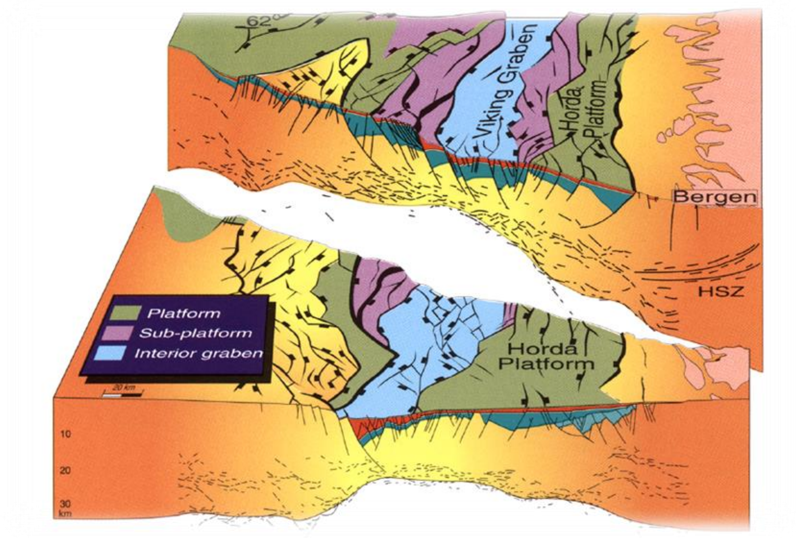

Figure 4.1: Regional overview and internal subdivision of the northern North Sea (Christiansson et al. 2000)

Many complex and composite fault geometries can be seen in Figure 4.1. The Late Jurassic-Cretaceous Viking Graben displays several centers of subsidence indicating that separate graben units exist. Other graben units with same pattern in Permo-Triassic basin with shifting polarities can be recognized on the Horda Platform.

Christiansson et al. (2000) reinterpreted the deep structure of the northern Viking Graben. Their studies show that the area is truncated by the principal east-dipping crustal-scale fault, which subcrops along the eastern margin of East Shetland Basin and flattens in the highly reflective lower crust beneath the western border of the Viking Graben. Eastward dips of the intra-mantle reflections mapped beneath the Horda Platform represent a continuation of the master fault.

4.1 Øygarden Fault Zone and Hutton Fault Alignment:

The transects NSDP84-1 (Fig 4.2a) and NSDP84-2 (Fig 4.2b) across the northern North Sea reveal the asymmetrical geometry of the rift. This part of the North Sea basin is bounded by downward flattening, marginal faults, called the Øygarden Fault Zone and the Hutton Alignment. These faults are of Permo-Triassic origin, but were also reactivated during the mid-late Jurassic time and considered as the master faults within the rift.

The main faults dip towards the Permo-Triassic axis, but more steeply the on the eastern side (Horda Platform). This difference in dip and asymmetry of the system reflect that a larger part of the extension accumulated on the western side of Permo-Triassic rift axis than on the eastern side. Low angle faults that have less regional significance also occur within the basin. These faults are particularly related to the western margin of Viking Graben, while the area on the west of the Hutton Alignment represents the western footwall of the entire asymmetrical Jurassic graben system.

The upper part of the Øygarden Fault zone exhibits steep dips (55-60º), and flattens downwards into basement to locally from low-angle faults. The downward flattening of these marginal faults is reminiscent of that of simple extensional models where rigid footwalls require the marginal faults to be listric to develop sets of rotated (domino) fault blocks in their hanging walls (Burchfiel, Wernicke et al. 1982). Rotation of the domino fault blocks is made possible by the non-planar geometry of the related marginal fault, and consequently, an abrupt change in dip is seen from the relatively horizontal beds in the footwall to rotated beds in the hanging wall (Fossen, Odinsen et al. 2000).

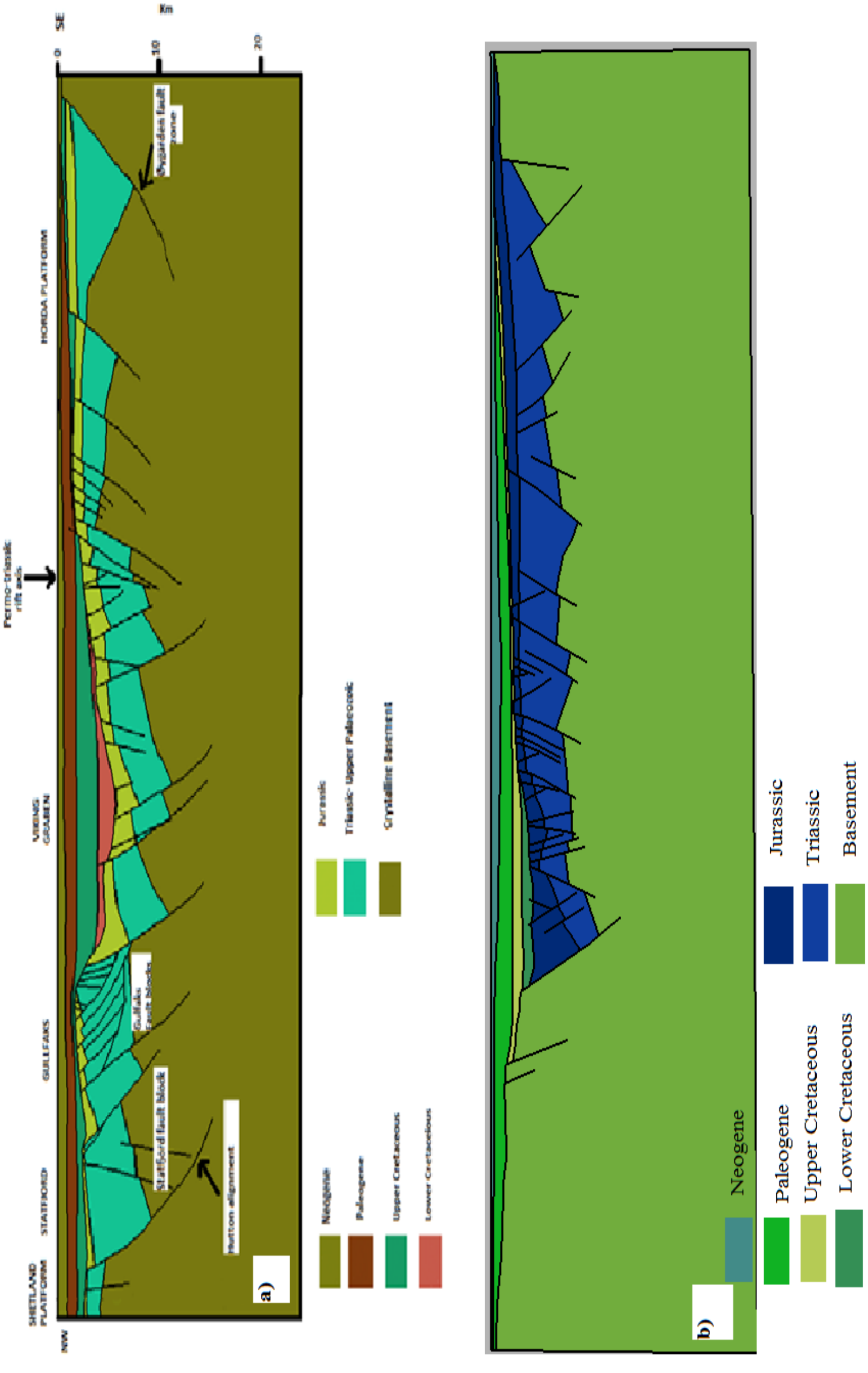

Figure 4.2: Trasnsects across the northern North Sea (a) NSDP84-1 (b) NSDP84-2

4.2 Low angle faults and detachments

Intra-basin low-angle faults or detachments are most common on the western side of the Viking Graben, particularly the Gullfaks-Visund-Snorre part of the Tampen Spur area. The most significant faults in the area are (Fig. 4.3):

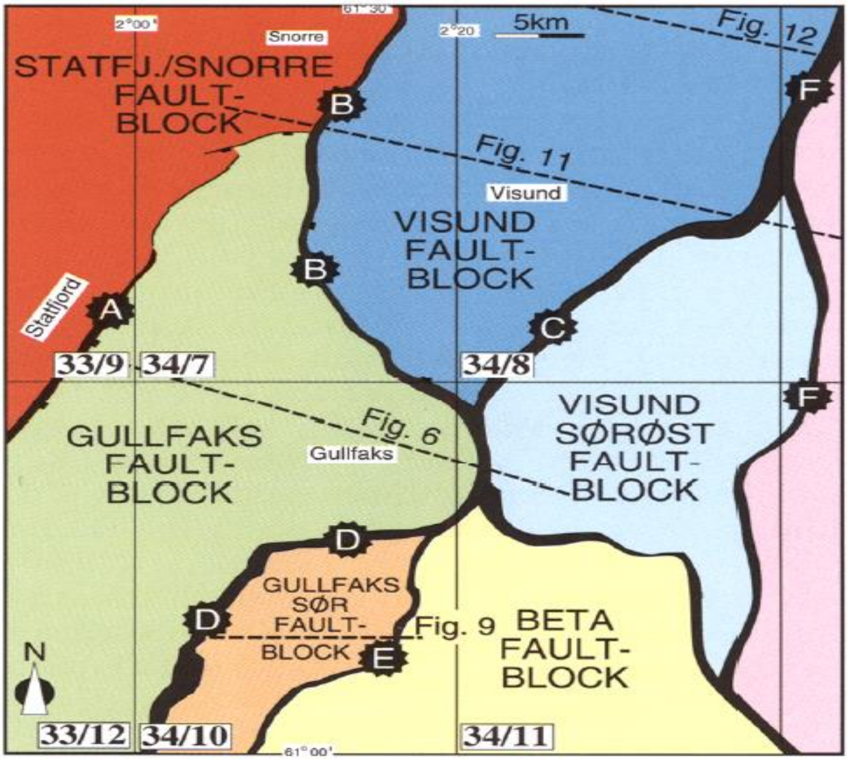

Figure 4.3: Main fault blocks in northern North Sea (Fossen, Odinsen et al. 2000)

Fault A: the Statfjord Fault

Fault B: the Snorre Fault

Fault C; the Visund Fault

Fault D; the Gullfaks Fault

Fault E; the Gullfaks Sør Fault

Fault F; the Viking Graben boundary Fault

Faults A, B, C, D, E, D, F are tilted and the beds are dipping gently to west or north-west between the generally east or southeast dipping faults. Several of these faults (A, B, C, D) have non-planer geometries and are intra-basement detachments. In addition, some supra-detachment faults are also present beneath the Gullfaks Field and south and northeast of Gullfaks.

A supra-basement detachment fault is found beneath the Gullfaks field, on the eastern part of Gullfaks fault block. The master fault with several kilometers of displacement separates the Gullfaks Fault from the Statfjord Fault Block to west (fault A), and the Visund-Gullfaks Sør area to east (faults D &B Fig. 4.3).

The western part of the Gullfaks fault block is a domino fault system. The domino faults are dipping about 30° to east, while the beds dipping within the blocks are dipping more gently (10-18°) to the west (Fig. 4.4). The domino system is very distinct and geometrically uniform, spanning about 10-15 km in E-W extent and slightly more in the N–S direction.

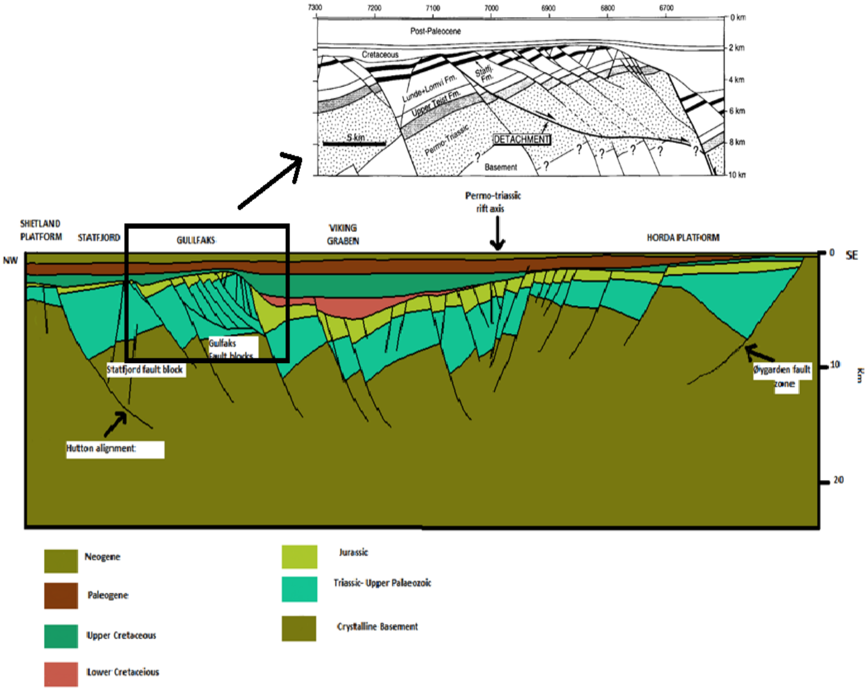

Figure 4.4: Cross-section showing the domino faulted system and the supra-basement detachment fault (Fossen et al. 2000)

The extension in the domino area is considerably higher than in the rest of the Gullfaks Fault Block. A recent map-view restoration of the Gullfaks Field (Rouby, Fossen et al. 1996) shows that the seismically resolvable Jurassic E-W extension across the field is of the order of 40-50% (β= 1.4-1.5). A similar estimate of the western part of the Gullfaks fault block gives only 10-15% extension (β= 1.1-1.15) (Fossen, Odinsen et al. 2000).

Low angle late to post-Caledonian age faults are present on both sides of the North Sea rift. Interpretation of the deep seismic data and 2D seismic lines of Gullfaks area shows the faulted geometries (Fig 4.5).

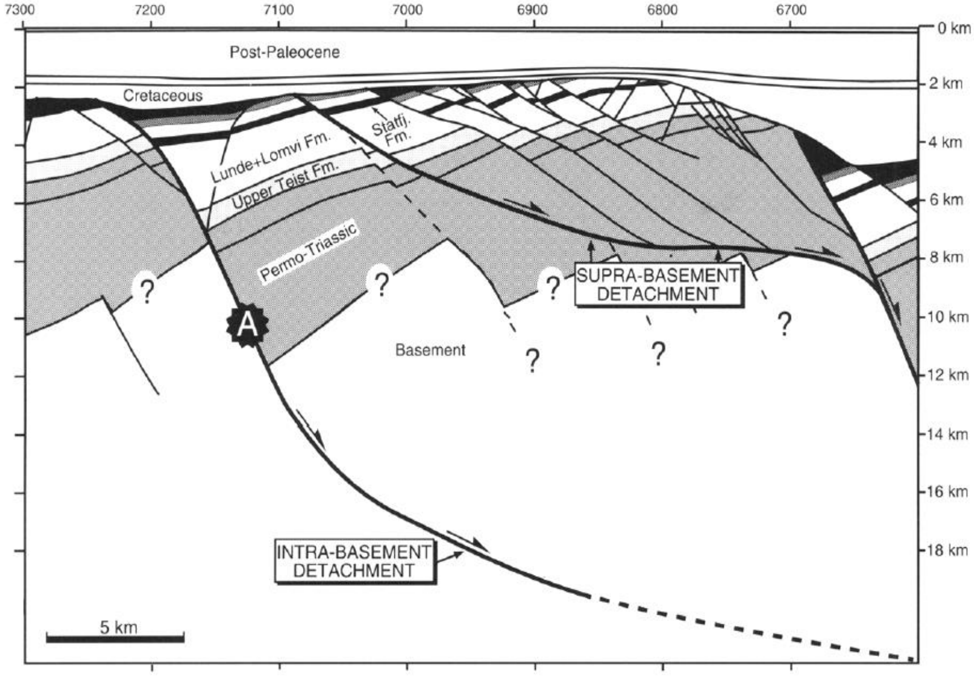

Figure 4.5: Low angle supra-basement and intra-basement detachments below the Gullfaks Fault Block (Fossen, Odinsen et al. 2000)

The Statfjord Fault (A) (Fig. 4.5) is interpreted as a non-planar fault which is a low angle detachment structure in the basement. A domino style fault block is situated above this detachment, similar to the Jurassic domino system above the overlying Gullfaks detachment.

Seismic line NVGT-88-08 (Fig. 4.6) across the Visund fault block, shows that the Snorre Fault (B) separates the Visund fault block from Snorre Field, and is well defined from fault plane reflections. The lower reflection represents the low-angle fault within basement and it is connected to the Snorre Fault to define the Visund detachment. The depth conversion of third detachment shows that detachment remains sub horizontal at a depth of about 14 km (Fig. 4.7).

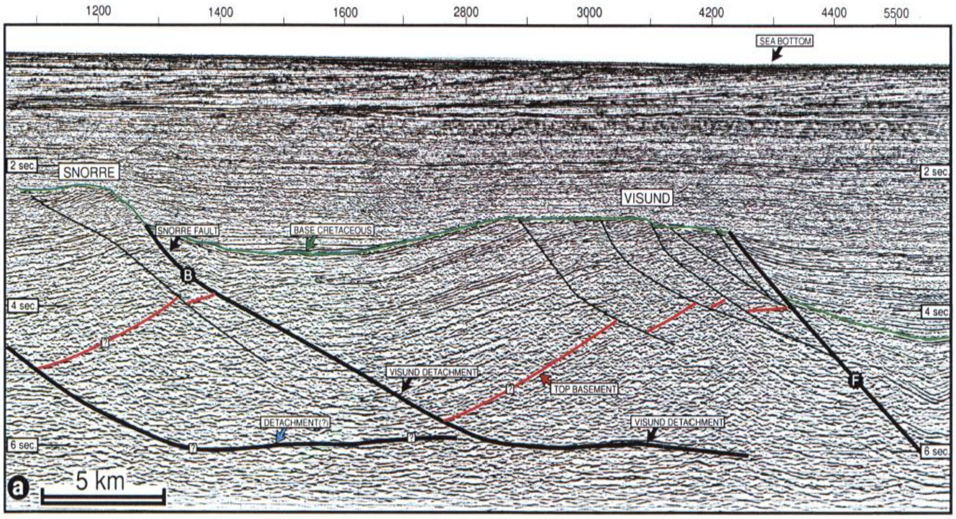

Figure 4.6: Seismic line NVGT-88-08 across the Visund fault block (Fossen, Odinsen et al. 2000)

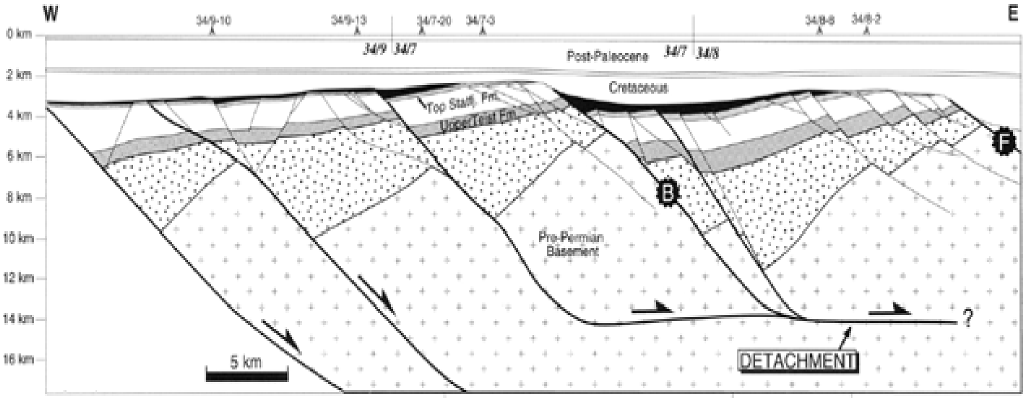

Figure 4.7: Depth converted cross-section of seismic line NVGT-88-08 (Fossen, Odinsen et al. 2000).

It is possible that the detachments were initially steeper faults that rotated to become low angle structures during the Permo-Triassic and mid-late Jurassic extension phase. Most of the intra-basement detachments were formed in the Permo-Triassic extension phases and possibly can be related to the Devonian extension or Caledonian contractional events, while the supra-basement detachments are of younger age, as they occur in rocks of Triassic age.

Chapter 5

Methodology

Geological restoration is a process which geometrically validates the geological cross section. The restoration process rebuilds the original geometry of the layer. Geological cross section restoration is the process which is done in several steps (Fig 5.1). Structural interpretation is based on well and seismic data, which after some processing a geological section is obtained which is used for the restoration.

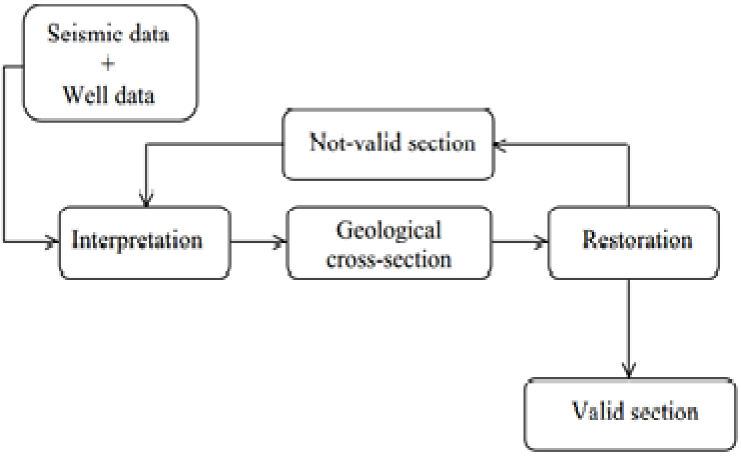

Figure 5.1: Geological section restoration diagram

Restoration enables us to restore the layer to measure the extension of specific layer. During the project stretching factor (β) is measured by the fault modeling and crustal thickness change. The stretching-factor (β) is equivalent to the stretch in structural geology, i.e. it is defined as the ratio of the final length (L) to the original length (Lo) of a line.

$$\beta = L/\ L_o = 1 + \varepsilon$$

where ε is the extension $\quad \varepsilon = (L - L_o)/\ L_o$

The project has been done on two regional transects that have been constructed based on high-quality conventional seismic reflection data and reprocessed deep seismic reflection profiles (NSDP84-1 and 2) (Fig 5.2). The crustal configuration is further constrained by integration of deep seismic refraction, gravity and magnetic data.

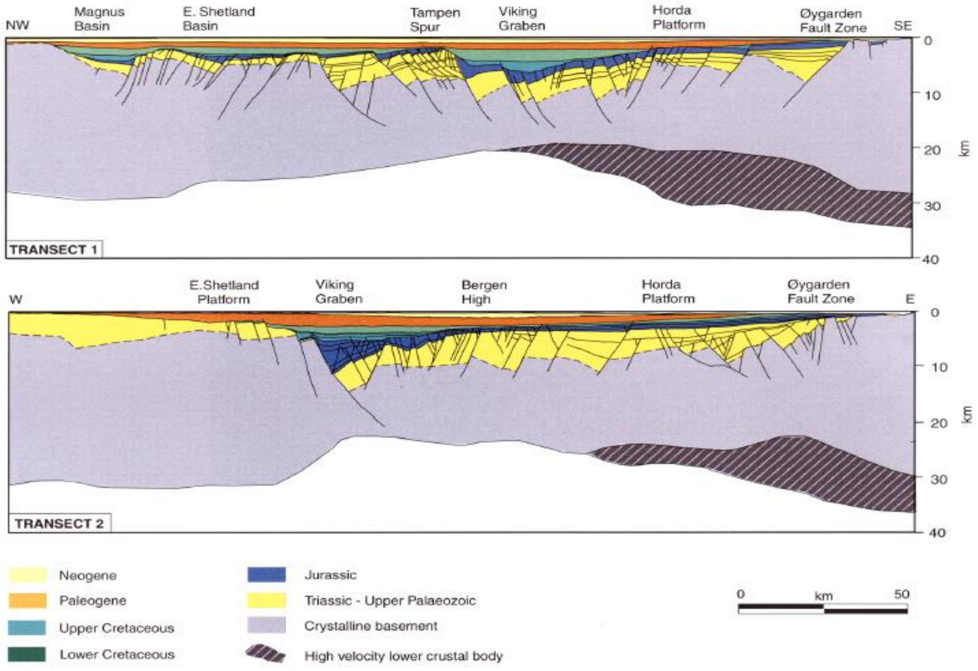

Figure 5.2: Crustal models for Transects 1 and 2, based on integration of geophysical and geological data (Christiansson, Faleide et al. 2000).

The structural restoration presented here is based on the structural interpretation of these lines (NSDP84-1 and 2). For that purpose Schlumberger`s structural geology software “IGEOSS Dynel2D” has been used.

The Igeoss suite enables rapid and easy restoration and forward modelling of complex folded and faulted geological models by simulating mechanical rock behavior using continuum and fracture mechanics. A comprehensive set of boundary conditions (such as mechanical contacts, restoration targets, and far-field stress) enables users to analyze complex geological structures.

5.1 Cross-Sections interpretation

Two regional crustal transects (Figure 5.3, 5.4) are interpreted from the reprocessed deep seismic reflection profiles. NSDP84-1 and 2 cover the area of the Horda platform, East Shetland Platform, Viking Graben, Tampen Spur. It is seen on the profiles that below the base Cretaceous unconformity, the Jurassic and Triassic formations are faulted, tilted, uplifted and eroded. Some faults are interpreted supra basement detachments and some are intra-basement detachments. Due to the complex fault geometry and poor data quality it was very difficult to interpret all these faults and horizons. Faults were generated at different stages and some were reactivated later. All the faults in the area are interpreted as normal faults.

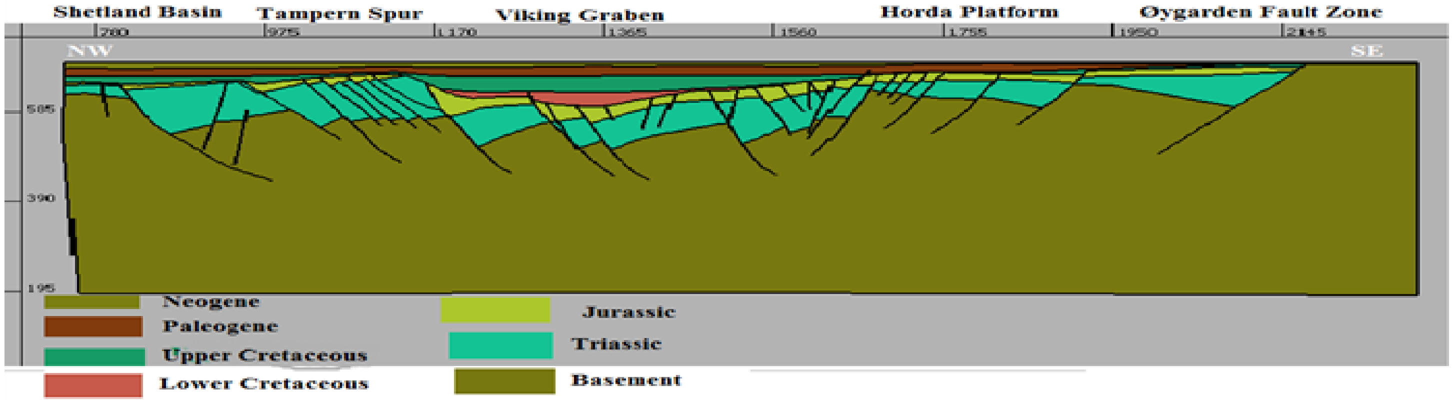

Figure 5.3: Cross-section showing the structural interpretation of NSDP84-1

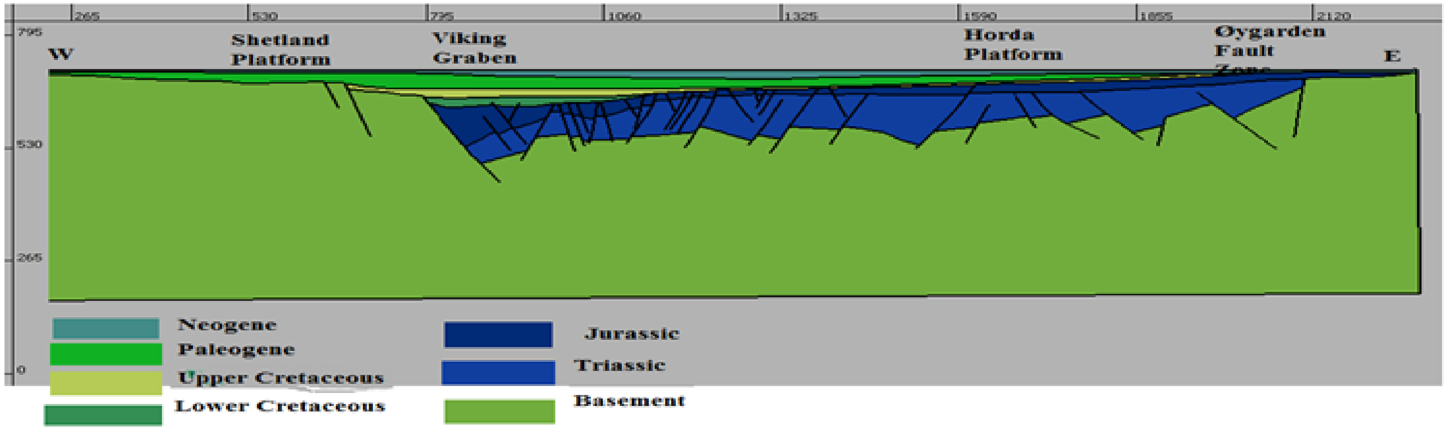

Figure 5.4: Cross-section showing the structural interpretation of NSDP84-2

5.2 Triassic restoration

Figures 5.5(a) and 5.6(a) show the effect of the Permo-Triassic rifting in the northern North Sea. Syn-rift response to extension occurs along planar faults in the upper crust showing half graben formation, footwall uplift and block rotation. Middle Triassic to Lower-Middle Jurassic strata in the North Sea has been assigned a post-rift status.

5.2.1 Fault Modelling

The fault modelling is done by measuring the length of the sections between the Øygarden Fault Zone and Hutton Fault Alignment before and after rifting phases. Permo-Triassic β for the NSDP84-1 is calculated as 1.11(Fig 5.5(a)). For NSDP84-2 extension is measured across Horda platform to Viking Graben and the stretching factor is estimates as β 1.10 (Fig 5.6 (a)). Extension across the NSDP84-1in Permo-Triassic phase is calculated as 11%, while extension for NSDP84-2 is measured as 10%.

5.2.2 Crustal thickness changes for the Triassic phase

The crustal thickness modelling is done by measuring the crustal thickness on the profiles before and after rifting event. It is done for several areas along the profiles and then the average value (β_{mean}) is calculated for the whole profile. The Crustal thickness change β_{mean} for Permo-Triassic stretching is 1.25 for NSDP84-1 and 1.16 for NSDP84-2. Jurassic stretching gives β_{mean} values of 1.16 and 1.17 for NSDP84-1 and NSDP84-2 respectively. Table 1 shows the Permo-Triassic stretching factor for different areas on transects 1 and 2.

Area	NSDP-1	NSDP-2
Horda platform	1.30	1.35
Viking Graben	1.29	1.14
E. Shetland platform	1.24	1.00
Tampen Spur	1.18	____
Average (βmean)	1.25	1.16

Table 1: Modelled β estimates for the Permo-Triassic rift phase.

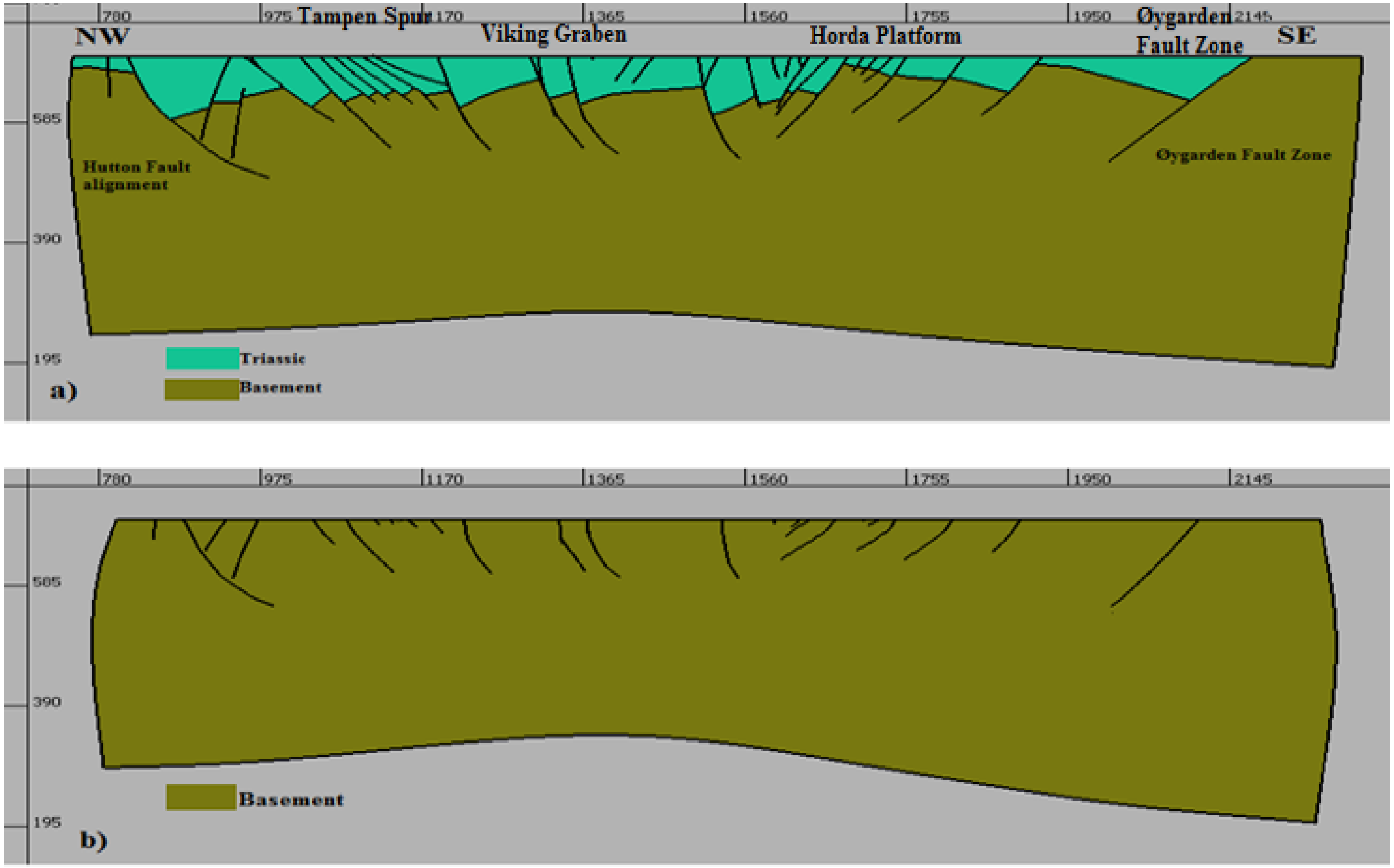

Figure 5.5: NSDP84-1 a) Restoration of Triassic top layer (b) Restoration of top basement surface

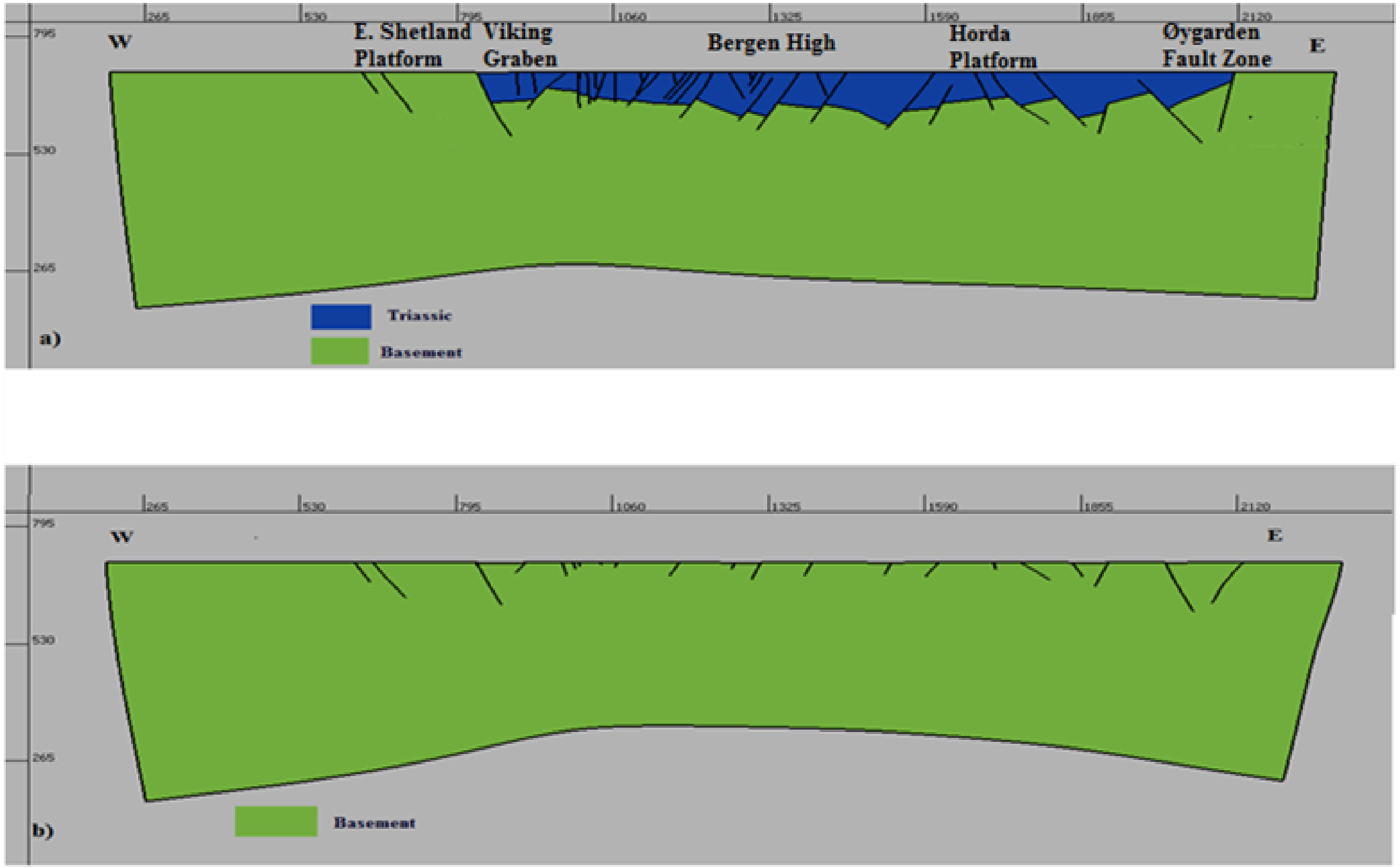

Figure 5.6: NSDP84-2 a) Restoration of Triassic top layer (b) Restoration of top basement surface

5.3 Jurassic restoration

Jurassic extension in northern North Sea is measured on NSDP84-1(Fig 5.7, 5.8) in restoration process is estimated β 1.12 (12%) and for NSDP84-2 stretching factor is measured β 1.19 (19%).

5.3.1 Fault modelling

The total extension of the two rifting phases is given by the product of the β factors. For NSDP84-1, this is 1.11*1.12 =1.24 (24%) and for NSDP84-2 this is 1.10*1.19=1.30 (30%). Table 2 shows the total Permo-Triassic and Jurassic extension for NSDP84-1 and NSDP84-2

Extension phases	NSDP84-1	NSDP84-2
Permo-Triassic	1.11 (11%)	1.10 (10%)
Jurassic	1.12 (12%)	1.19 (19%)
Total Extension	1.24 (24%)	1.30 (30%)

Table 2: Fault extension for Permo-Triassic and Jurassic Phases for NSDP84-1 and 2

5.3.2 Crustal thickness changes for Jurassic phase

The Jurassic βmean measured across the NSDP84-1 and NSDP84-2 is 1.16 and 1.17 respectively. β measured for the Horda Platform is 1.08 and 1.15 in transects 1 and 2 respectively. Similarly the β estimates for the Viking Graben are 1.32 and 1.36 in NSDP84-1 and NSDP84-2 respectively. Table 3 shows the different values for different areas across the NSDP84-1 and 2.

Area	NSDP-1	NSDP-2
Horda platform	1.08	1.15
Viking Graben	1.32	1.36
E. Shetland platform	1.05	1.02
Tampen Spur	1.21	____
Average (βmean)	1.16	1.17

Table 3: Modelled β estimates for the Jurassic rift phase

The Jurassic stretching values are approximately the same in NSDP84-1 (1.16) and NSDP84-2 (1.17). Although this is similar to the Permo-Triassic results for NSDP84-2, and it is lower for NSDP84-1 (Table 1). The Jurassic βmean across the Horda Platform amounts to 1.08 along transect 1 and 1.15 along transect 2. In other words, Jurassic stretching for the Horda Platform area was substantially less than the Permo-Triassic phase (1.30 and 1.35) for the same area. Estimated Jurassic βmean across the Viking Graben is 1.32 in transect 1 and 1.36 in transect 2. This is higher than the calculated Permo-Triassic values. βmean in the East Shetland Basin is 1.05, which is much less than the Permo-Triassic stretching of 1.29. Stretching across the Shetland Platform (transect 2) is merely 1.02.

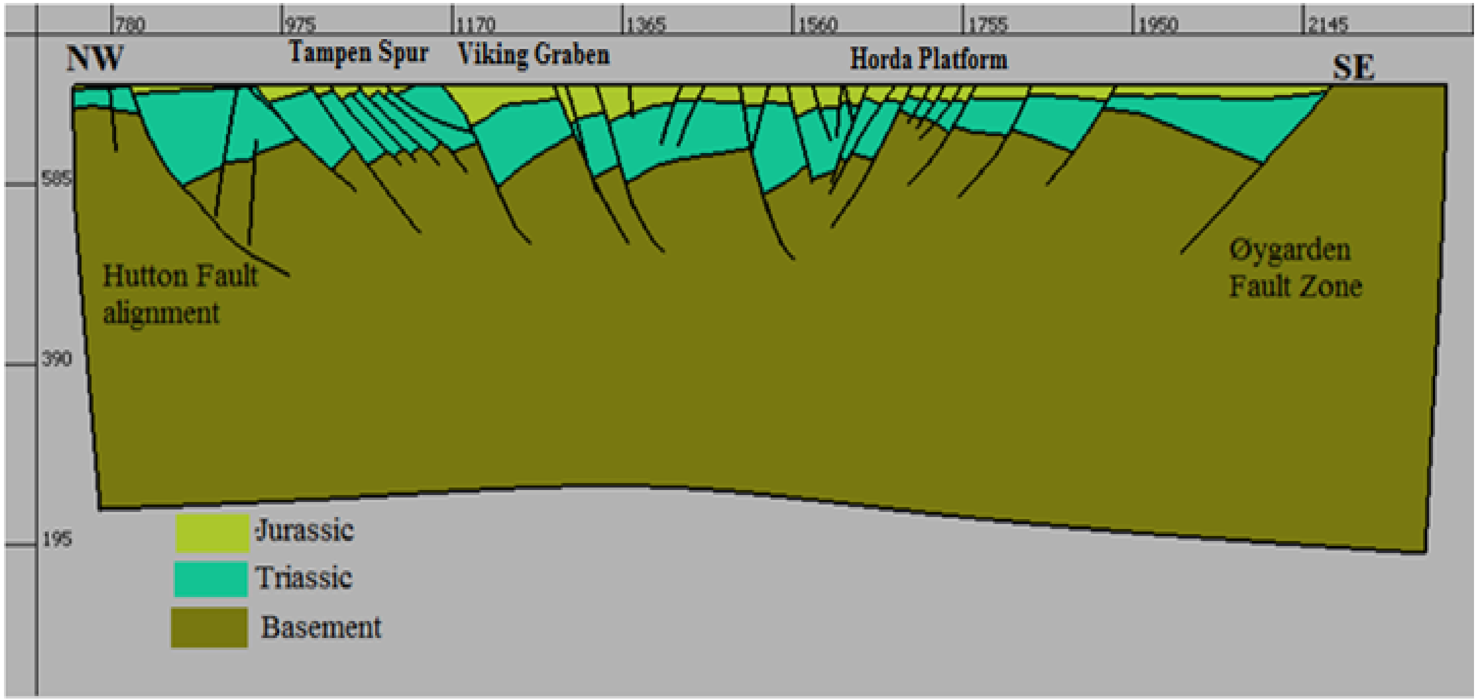

Figure 5.7: Cross-section showing restored Jurassic layer (NSDP84-1)

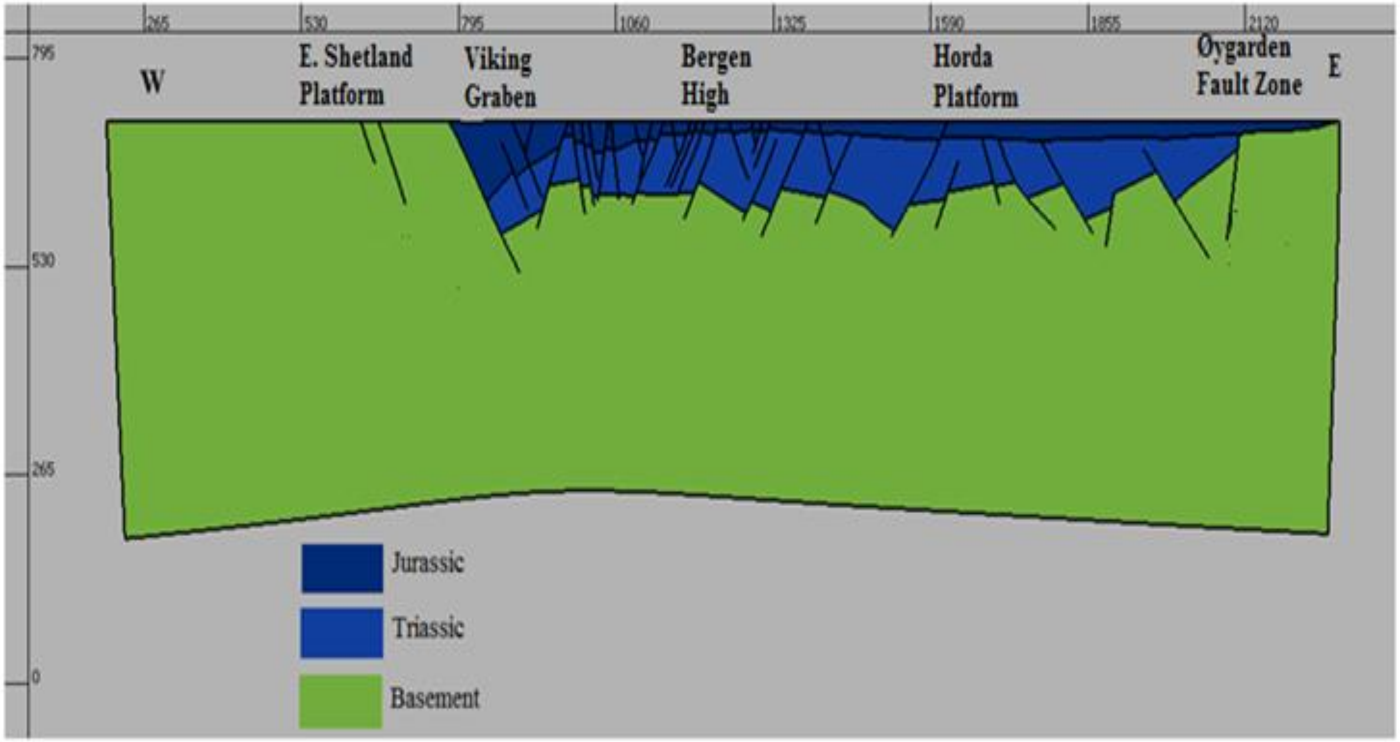

Figure 5.8: Cross-section showing restored Jurassic layer (NSDP84-2)

Discussion

To measure the stretching factor and extension in the basin during the two main rifting phases, the layers are restored during the project and then measured the extension to calculate the stretching factor (β). For the fault modelling on NSDP84-1 the extension is measured between the two major faults (Hutton Fault Alignment and Øygarden Fault Zone). Triassic stretching for NSDP84-1 is measured as β 1.11 and for Jurassic β is calculated as 1.12. Thus the extension across the profile for the Permo-Triassic phase is 11% NSDP84-1 and for the Jurassic extension is 12%. Across NSDP84-2 stretching factors and extensions are measured in between Horda Platform and Viking Graben. Permo-Triassic β value is measured as 1.10 while the Jurassic β measured as 1.19. Then the extension during the Triassic phase is about 10%, and for the Jurassic extension it is 19%. The total extension of the Permo-Triassic and Jurassic rifting phases for NSDP84-1 is 1.24 (24%) and for NSDP84-2 is 1.30 (30%). The values are very similar to those obtained by Ziegler and Van Hoorn (1989), who worked on cross-section which is very close to NSDP84-1. Thus β obtained values for the Permo-Triassic and Jurassic as 1.25 and 1.15 respectively.

For crustal thickness change stretch factor is measured for different areas. The modelled βmean for the Permo-Triassic stretching is 1.25 and 1.16 for transect 1 and 2 respectively. β_{mean} for Jurassic is 1.16 and 1.17 for NSDP84-1 and 2 respectively. Odinsen, Reemst et al. (2000) worked on the same profile (NSDP84-1 and 2). For transect 1 they estimate βmean 1.27 for Permo-Triassic and 1.15 for Jurassic rifting phase. βmean measured for transect 2 is 1.19 for Permo-Triassic and same as 1.19 for Jurassic phase.

Conclusion

The complex structural and fault pattern of the northern North Sea resulted from the two major extensional phases i.e. Permo-Triassic and Jurassic rifting phases. The North Sea is characterized by a series of large normal faults with predominant N, NE, and NW orientations. During the Permo-Triassic rifting phase, the area was subjected into regional tensional stresses which caused subsidence, and a complex graben and trough system. The Hutton Alignment (west) and Øygarden Fault (east) are of Permo-Triassic origin and considered as the master faults boundaries within the Permo-Triassic rift. Most of the Permo-Triassic stretching occurred between the Øygarden Fault Zone to the east and Shetland platform and the Hutton Fault Alignment to the west over a distance of about 120-125km. The important feature of the North Sea rift system is uplift of a major rift dome during early middle Jurassic rifting phase. Low angle detachment faults are also present in northern North Sea which exhibit low dips in the basement. The Jurassic extension phase is largely responsible for the intra-basement detachments. The faults may have had higher initial dips and rotated into less steep orientations through block rotation and internal deformation during the pre-Jurassic rifting phase. Supra-basement detachments are also found in Triassic sediments beneath the Gullfaks Field, SE of the Visund Fault block and underneath Gullfaks Sør.

The restoration process shows that during rifting extension occurs in crust during both phases. The results of restoration on lines NSDP84-1 and 2 show that the extension that occurred during the Jurassic phase was slightly larger than the Permo-Triassic extension. For lineNSDP84-1, the Permo-Triassic and Jurassic rifting phase were more or less the same 11% and 12%

respectively. For NSDP84-2 Jurassic rifting was significantly greater (19%) compared to the Permo-Triassic rifting (10%).

The crustal thickness changes results show the Permo-Triassic stretching factor is 1.25 (NSDP84-1) and 1.16 (NSDP84-2), while the Jurassic stretching values for the NSDP84-1 and NSDP84-2 are approximately the same 1.16 and 1.17 respectively. These Jurassic stretching values are similar to the Permo-Triassic value of NSDP84-2 but less than NSDP84-1.

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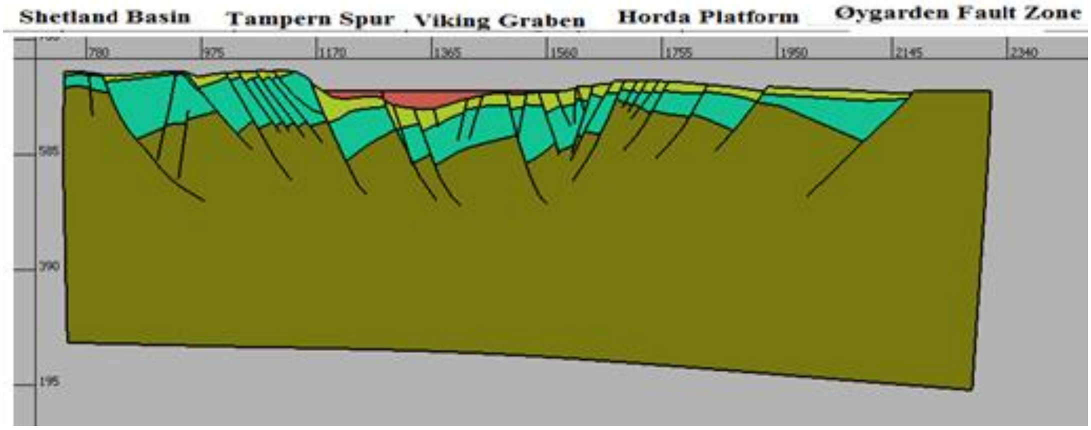
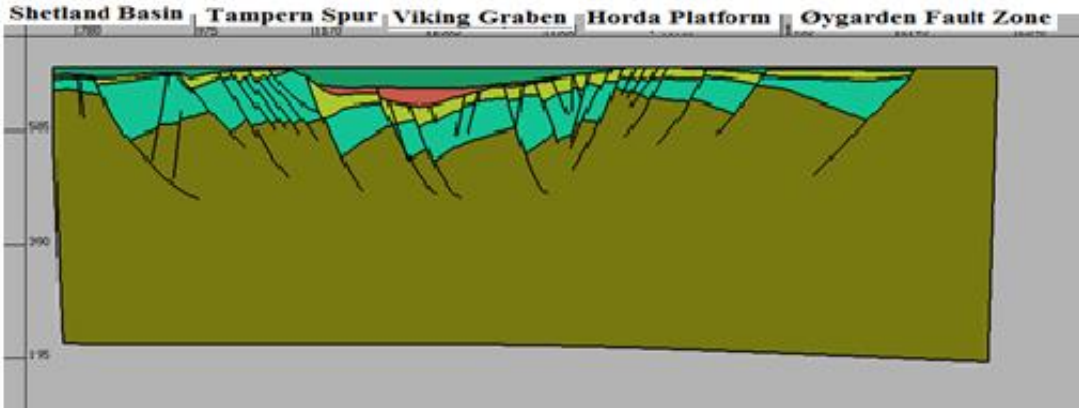
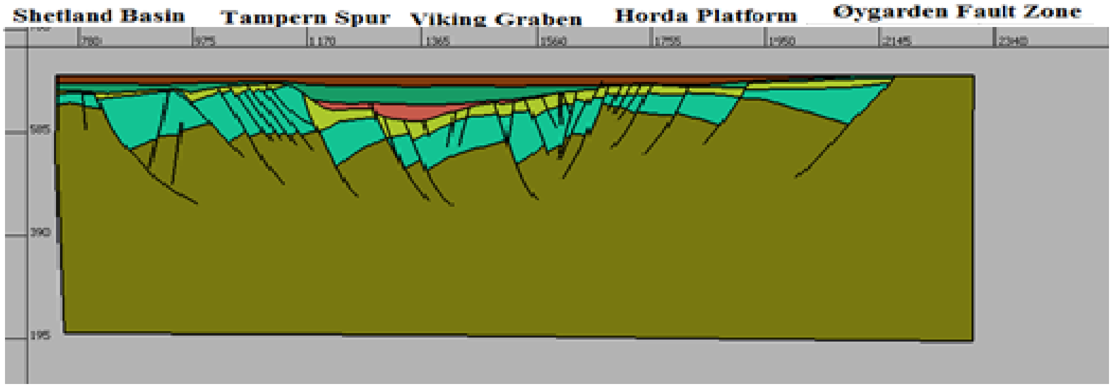
Appendix



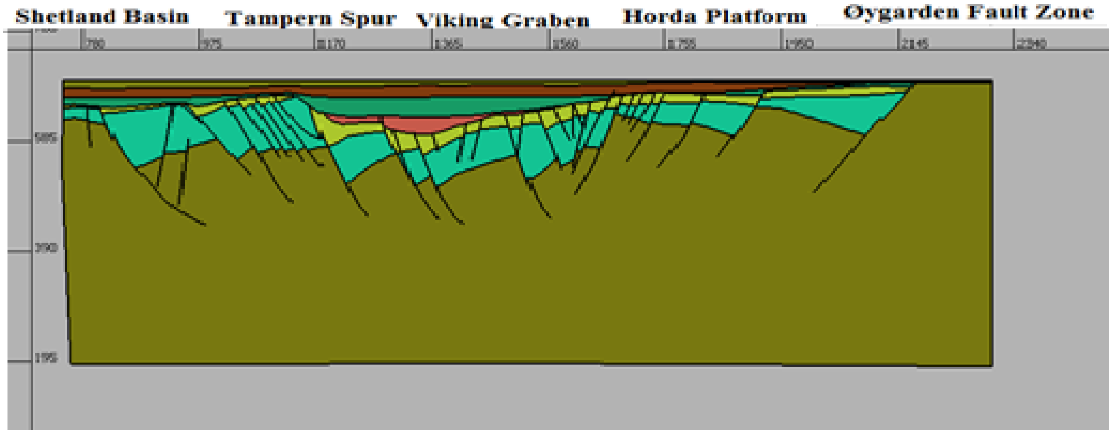
Cross-section showing the restored Lower Cretaceous layer (NSDP84-1)



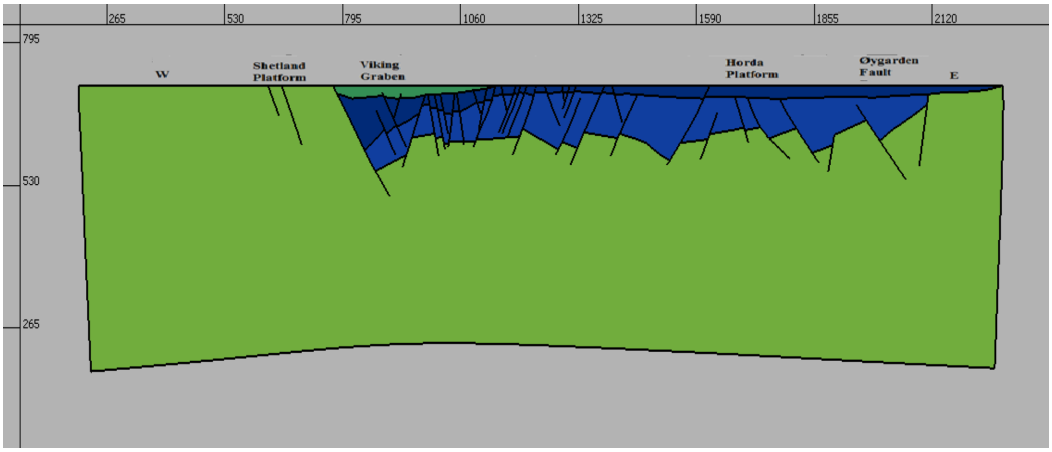
Cross-section showing the restored Upper Cretaceous layer (NSDP84-1)



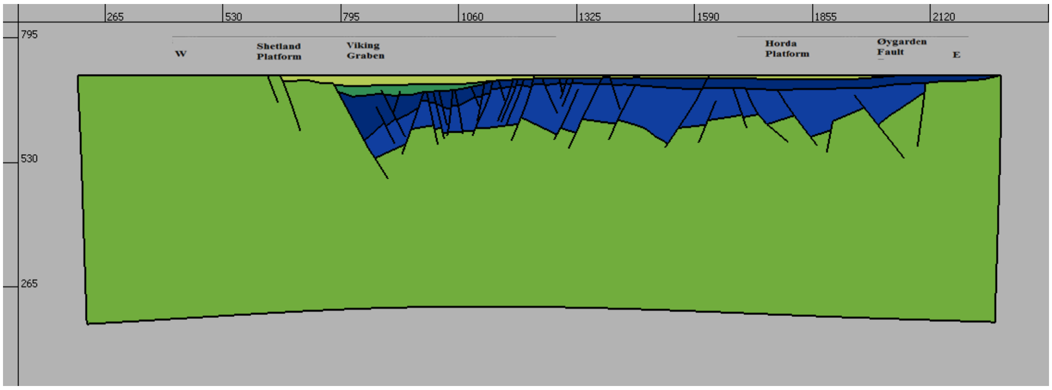
Cross-section showing the restored Paleogene layer (NSDP84-1)



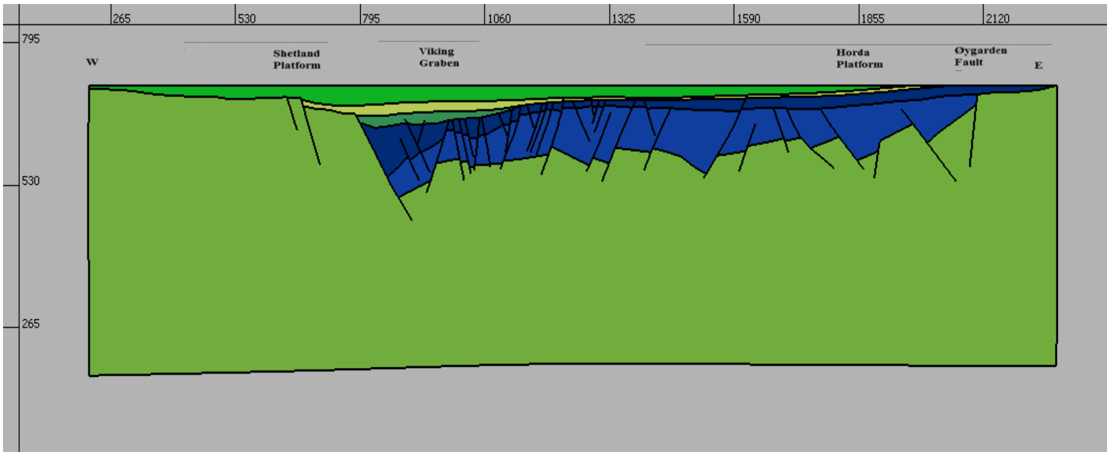
Cross-section showing the restored Neogene layer (NSDP84-1)



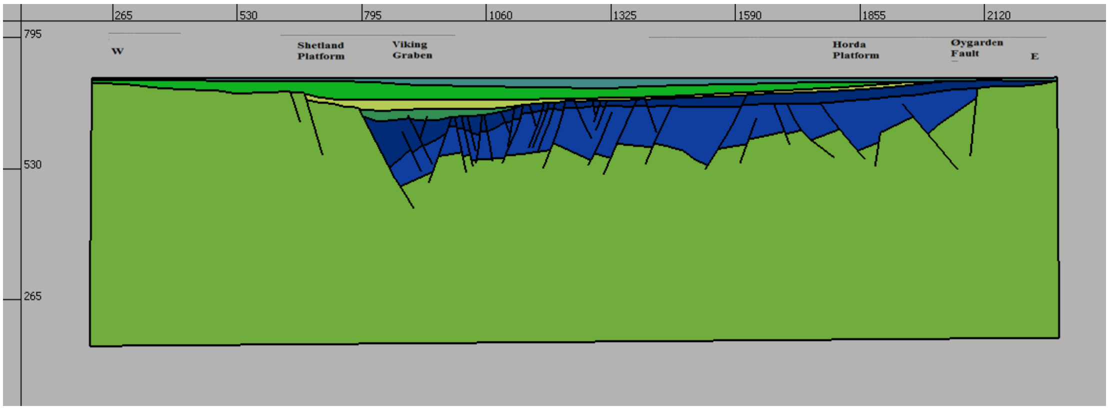
Cross-section showing the restored Lower Cretaceous layer (NSDP84-2)



Cross-section showing the restored Upper Cretaceous layer (NSDP84-2)



Cross-section showing the restored Paleogene layer (NSDP84-2)



Cross-section showing the restored Neogene layer (NSDP84-2)